5th Ultrafast Magnetism Conference 2022

September 12-16, 2022
Nancy, France

Date: Monday 12th September - Friday 16th September 2022
Location: Nancy (France), salle d'honneur du rectorat *

* : Bibliothèque de droit et de sciences économiques, 11 place Carnot

INTRODUCTION

UMC 2022 is dedicated to the field of ultrafast magnetization dynamics and in particular to ultrafast dynamic processes in magnetic materials on femtosecond, picosecond and attosecond time scales. This is the 5th UMC conference. Previous editions have been held in Strasbourg, Nijmegen, Kaiserslautern and York.

The scientific topics of the UMC 2022 conference are the following :

- All optical and helicity dependent switching
- Thermally induced switching
- Laser induced magnetisation dynamics
- Nanoscale magnetisation dynamics
- Plasmonic devices
- Theory and simulation of ultrafast magnetisation dynamics
- Ultrafast Spintronics
- Measurements of ultrafast magnetisation dynamics

Local organisers

Aurore Emonot, Lorraine University
Jon Gorchon, Lorraine University
Michel Hehn, Lorraine University
Gregory Malinowski, Lorraine University
Stéphane Mangin, Lorraine University

Program Committee

Roy Chantrell, University of York
Wolfgang Hubner, Technische Universität Kaiserlautern
Alexey Kimel, Radboud University
Theo Rasing, Radboud University
Richard Evans, University of York

The UMC2022 scientific and organizing committees join the strong condemnation issued by both the European Physical Society (https://www.eps.org/news/597021/) and the American Physical Society (https://aps.org/about/governance/letters/ukraine.cfm#condemn) of the attacks of the Russian Federation against Ukraine. We sympathise with the Ukrainian people and scientific community in their perilous situation and with those Russian scientists who support peace. In this we are proud to keep UMC2022 as an open meeting and a forum to promote peaceful coexistence and diversity.

PARTNERS


UNIVERSITÉ
DE LORRAINE


cnrs


LORRAINE
Université d'Excellence
IMPACT
N4S


UNION EUROPÉENNE
Fonds Européen de Développement Régional


Agence Nationale de la Recherche
ANR


ijl
INSTITUT
JEAN LAMOUR


IEEE
MAGNETICS


FST
FACULTÉ DES SCIENCES ET TECHNOLOGIES
Nancy


IEEE
Sensors Council


RS


INSTITUT
CARNOT
ICÉEL


PÔLE M4
Matière, Matériaux,
Métallurgie, Mécanique


Grand Est
ALSACE CHAMPAGNE-ARDENNE LORRAINE


métropole
GrandNancy


ville de
Nancy


COMRAD

UMC 2022

PROGRAM

Monday, 12th September	Tuesday, 13th September	Wednesday, 14th September	Thursday, 15th September	Friday, 16th September
8:30 - 9:00 coffee				8:30 - 9:30 COMRAD Supervisory board
9:00 - 9:10 Welcome	9:00-9:30 B. Koopmans	9:00-9:30 A. Kirilyuk	9:00-9:30 G.M. Choi	
9:10 - 10:00 Tutorial : P. Oppeneer	9:30 - 9:50 S. Ashok	9:30 - 9:50 Y. Acremann	9:30 - 9:50 A. Kalashnikova	9:30 - 9:45 T. Metzger
10:00 - 10:20 L. Nadvornik	9:50 - 10:20 O. Chubykalo-Fesenko	9:50 - 10:20 J. Bokor	9:50 - 10:20 L. Buda-Prejbeanu	9:45 - 10:00 D. Salomoni
Coffee Break - 20 Min.	Coffee Break - 15 Min.	Coffee Break - 15 Min.	Coffee Break - 15 Min.	10:00 - 10:15 J. Hintermayr
10:40 - 11:00 P. Scheid	10:40 - 11:00 A. Awad	10:40 - 11:00 M. Weinelt	10:40 - 11:00 P.A. Hervieux	10:15 - 10:30 L. Lin
11:00 - 11:30 G. Finocchio	11:00 - 11:30 S. Iihama	11:00 - 11:30 V. Unikandanunni	11:00 - 11:30 M. Bargheer	Coffee Break - 15 min
11:30 - 11:50 V. Belotelov	11:30 - 11:50 J. Mentink	11:30 - 11:50 DP Gweha-Nyoma	11:30 - 11h50 W. Widdra	10:45 - 12:45 Technology Transfer P. Bortolotti C. Sandaldjian R. Lebrun
11:50 - 12:20 J. Besbas	11:50 - 12:20 P. Elliott	11:50 - 12:20 A. Stupakiewicz	11:50 - 12:20 E.E. Fullerton	
Lunch & Posters Session I	Lunch & Posters Session I	Lunch & Posters Session II	Lunch & Posters Session II	
2:00 - 2:30 U. Atxitia	2:00 - 2:30 O. Johansson	2:00 - 2:30 S. van Dijken	2:00 - 6:00 MAGNETOFON project	
2:30 - 2:50 E. Jal	2:30 - 2:50 M. Mattern	2:30 - 2:50 J. Igarashi	2:00 - 2:30 O. Chubykalo-Fesenko	
2:50 - 3:20 T. Silva	2:50 - 3:20 P. Pirro	2:50 - 3:20 R. Wilson	2:30-2:50 L. Wang	
3:20 - 3:40 C. Davies	3:20 - 3:40 D. Hamara	3:20 - 3:40 Y. Peng	2:50 - 3:20 J. Walowski	
Coffee Break - 20 Min.	Coffee Break - 20 Min.	Coffee Break - 20 Min.	3:20 - 3:40 K. Ishibashi	
4:00 - 4:30 J. Akerman	Posters Session I	4:00 - 4:30 C. Ciccarelli	Coffee Break - 20 Min.	
4:30-4:50 G. Lefkidis		Posters Session II	4:00 - 4:30 T. Mertelj	
4:50 -5:20 P. Gambardella			4:30 - 4:50 M. Savoini	
			4:50-5:20 M. Krawczyk	
			5:20 - 5:40 K. Levchenko	
Wine & cheese (musée des Beaux-Arts)	Gala dinner (hôtel de ville de Nancy)			

Monday September 12th

8:30 – 9:00
Coffee
9:00 – 9:10
Welcome
9:10 – 10:00
Tutorial O1: *Ultrafast laser-induced demagnetization – A status update*
Peter Oppeneer
10:00 – 10:20
O2: *Intrinsic and extrinsic components of anisotropic magnetoresistance revealed by terahertz spectroscopy*
Lukas Nadvornik
Coffee break: 20 minutes
10:40 – 11:00
03: A new perspective on the ultrafast demagnetization
Philippe Scheid
11:00 - 11:30
O4: *Micromagnetic modelling of antiferromagnetic dynamics: from switching to antiferromagnetic parametric resonance*
Giovanni Finocchio
11:30 - 11:50
O5: *Optically induced localized spin wave states in all-dielectric nanopillars*
Vladimir Belotelov
11:50 – 12:20
O6: *A comparison of thermal all-optical toggle switching in Mn2RuxGa and rare-earth/transition metal alloys*
Jean Besbas
12:20 AM - 2:00 PM: lunch & posters
2:00 - 2:30
O7: *Bridging atomistic spin dynamics methods and phenomenological models of two-sublattice magnets*
Unai Atxitia
2:30 - 2:50
O8: *Unravelling the Transient Depth Magnetic Profile During Ultrafast Demagnetization of an Iron Thin Film*
Emmanuelle Jal
2:50 - 3:20
O9: *Ultrafast domain reconfiguration via optical pumping: Aggregated evidence from three XFEL studies*
Tom Silva
3:20 - 3:40
O10: *Non-local Switching of Magnetization by the Ultrafast Phononic Barnett Effect*

Carl Davies

Coffee break: 20 minutes

4:00-4:30

O11: *Femtosecond-laser frequency comb enhanced Brillouin light scattering microscopy*

Johan Akerman

4:30 – 4:50

O12: *Theory shakes hands with experiment: toward molecular nanospintronics*

Georg Lefkidis

4:50 - 5:20

O13: *Current-induced switching of rare-earth and transition-metal sublattices in ferrimagnetic alloys: synchronous vs asynchronous dynamics*

Pietro Gambardella

Tutorial O1: Monday 12th, 9:10-10:00

Ultrafast laser-induced demagnetization – A status update

Peter M. Oppeneer
Department of Physics and Astronomy, Uppsala University, P.O. Box 516, S-75120 Uppsala, Sweden

Ultrafast laser-induced demagnetization was a seminal discovery, made by E. Beaurepaire, J.-Y. Bigot and collaborators in 1996 [1]. Their observation of sub-picosecond demagnetization in nickel gave rise to intensive debates in the community, continuing even today. In this talk I will try to summarize what we have understood after much research in the past 25 years. A lot of discussion continues to center around the key questions: "local" or "non-local" mechanism and, related to this, where the angular momentum goes. Moreover, beyond the early experiments on elemental ferromagnets, more complex magnetic materials (e.g. ferri-magnets, hetero-structures, antiferromagnets) have come into the focus.

When one considers *local* mechanisms, i.e. the local dissipation of angular momentum, there are confirming observations [2,3] of both of the main contenders, magnons and phonons. While it is clear that at long time scales the lattice dominantly absorbs the laser *energy*, a major issue is still to determine precisely in how far one of these local angular momentum mechanisms dominates on a short time scale; to this end, direct measurements of phonon/ magnon modes are needed (cf. [3]).

Non-local mechanisms have come into the focus in several variants, such as superdiffusive spin transport [4], optically-induced intersite spin transfer [5], and recently, spin currents due to spin pumping [6]. I will try to address what the salient characteristics of these different spin-transport models are and how one could possibly distinguish between them in experiments.

Even though ultrafast demagnetization in ferromagnets is in itself not considered being a solved problem, new horizons in ultrafast magnetism have meanwhile emerged, such as, ultrafast demagnetization of antiferromagnets and laser-induced magnetization switching of antiferromagnets and of heterostructures holding rich physical phenomena to be further explored in the near future.

[1] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, Phys. Rev. Lett. **76**, 4250 (1996).
[2] E. Carpene, H. Hedayat, F. Boschini, and C. Dallera, Phys. Rev. B **91**, 174414 (2015); S. Eich, M. Plötzing, M. Rollinger, S. Emmerich, R. Adam, C. Chen, H.C. Kapteyn, M.M. Murnane, L. Plucinski, D. Steil, B. Stadtmüller, M. Cinchetti, M. Aeschlimann, C.M. Schneider, and S. Mathias, Sci. Adv. **3**, e1602094 (2017).
[3] S.R. Tauchert, M. Volkov, D. Ehberger, D. Kazenwadel, M. Evers, H. Lange, A. Donges, A. Book, W. Kreuzpaintner, U. Nowak, and P. Baum, Nature **602**, 73 (2022).
[4] M. Battiato, K. Carva, and P.M. Oppeneer, Phys. Rev. Lett. **105**, 027203 (2010).
[5] J.K. Dewhurst, P. Elliott, S. Shallcross, E.K.U. Gross, and S. Sharma, Nano Lett. **18**, 1842 (2018).
[6] M. Beens, R.A. Duine, and B. Koopmans, Phys. Rev. B **102**, 054442 (2020).

O2: Monday 12th, 10:00 – 10:20

Intrinsic and extrinsic components of anisotropic magnetoresistance revealed by terahertz spectroscopy

L. Nadvorník[1,2,3], M. Borchert[1,2], L. Brandt[4], R. Schlitz[5], K. A. de Mare[6,7], K. Výborný[6], I. Mertig[4], G. Jakob[8], M. Kläui[8], S. T.B. Goennenwein[5], M. Wolf[1], G. Woltersdorf[4] and T. Kampfrath[1,2]

[1]Department of Physics, Freie Universität Berlin, 14195 Berlin, Germany
[2]Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, 14195 Berlin, Germany
[3]Faculty of Mathematics and Physics, Charles University, 121 16 Praha, Czech Republic
[4]Institut für Physik, Martin-Luther-Universität, Halle, Germany
[5]Institut für Festkörper- und Materialphysik, Technische Universität Dresden, 01062 Dresden, Germany
[6]Institute of Physics, Academy of Sciences of the Czech Republic, v.v.i., 162 00 Praha, Czech Republic
[7]Department of Applied Physics, Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands
[8]Institut für Physik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Anisotropic magnetoresistance (AMR) is a ubiquitous and versatile probe of magnetic order in contemporary spintronics research [1]. In ferromagnets, the non-crystalline AMR covers the dependence on the relative angle between the applied electric field and magnetization vector and it is invariant under inversion of time (even in magnetization). The origins of the effect are usually ascribed to extrinsic processes (i.e. spin-dependent electron scattering with characteristic time τ), whereas intrinsic (i.e. scattering-independent) contributions are neglected [2].

Here, we perform a broadband measurement of the AMR of prototypical ferromagnets such as Co, Ni or permalloy in a frequency range from DC to $\omega/2\pi = 28$ THz [3]. The large bandwidth covers the regimes of both diffusive ($\omega\tau < 1$) and ballistic ($\omega\tau > 1$) intraband electron transport and, thus, allows us to separate extrinsic and intrinsic AMR components. Analysis of the THz response based on Boltzmann transport theory reveals that the AMR of the Ni and NiFe alloys is of predominantly extrinsic nature. However, the Co thin film exhibits a sizeable intrinsic, frequency-independent AMR contribution, which amounts to more than 2/3 of the DC AMR contrast of 1%. These features are attributed to the lower symmetry of hexagonal structure of the Co crystallites which seems to allow for larger anisotropies. The new insight into the nature of AMR is not only relevant for the fundamental understanding of the magneto-transport but might also advance the ultrafast probing techniques in spintronic devices.

References

[1] T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich, Nature Nanotech. 11, 231 (2016).
[2] T. R. McGuire and R. I. Potter, IEEE Trans. Mag. 11, 1018 (1975).
[3] L. Nádvorník et al., Phys. Rev. X 11, 021030 (2021).

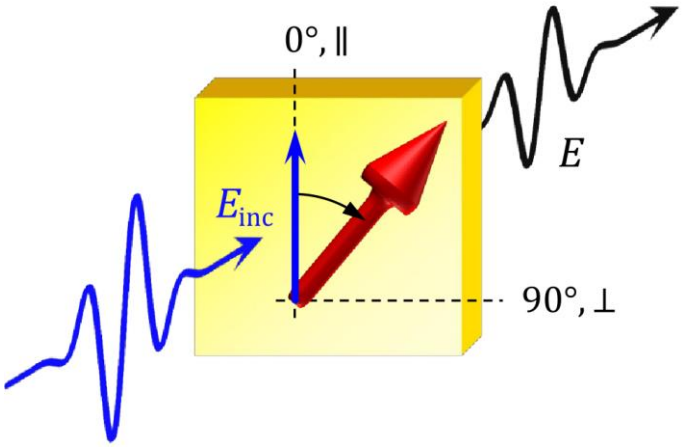


Figure 1: THz detection of the AMR. The incident THz pulse applies transient electric field in the direction of polarization, in which, as a consequence of the AMR, the electrical resistance and the transmission of the THz pulse depend on the angle between the polarization and magnetization. Variations in transmitted amplitude allow us to calculate the AMR contrast.

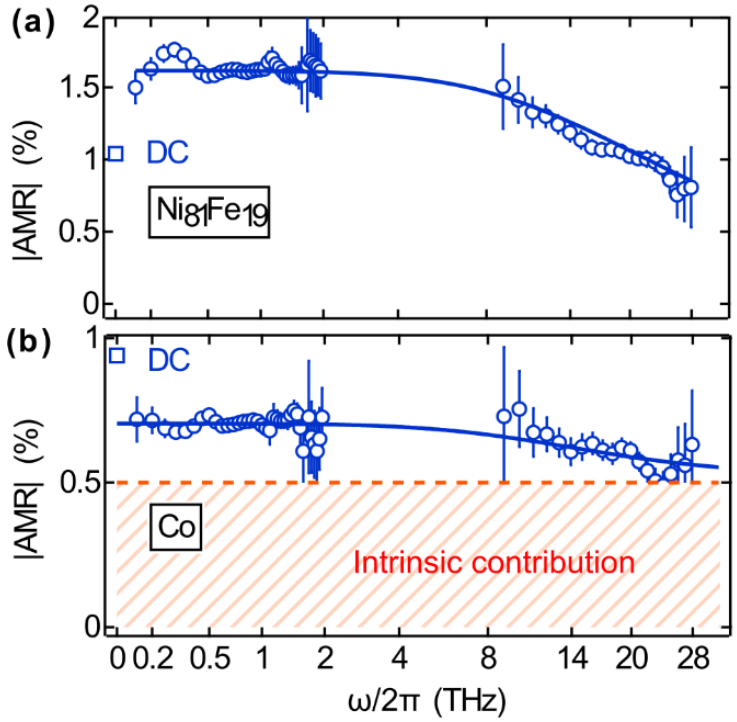


Figure 2: Spectral composition of the AMR in different metals. (a) The absolute value of the AMR contrast in permalloy versus frequency is well described within the Drude formalism (curve) assuming only magnetization-dependent electron scattering rates. (b) The same measurement for a cobalt sample shows a scalable frequency-independent offset which witnesses the intrinsic contribution to the AMR.

O3: Monday 12th, 10:40 – 11:00

A new perspective on the ultrafast demagnetization

P. Scheid[12], W. Zhang[1], G. Malinowski[1], S. Mangin[1], S. Lebègue[2]
[1]Université de Lorraine, CNRS, IJL, F-54000 Nancy, France
[2]Université de Lorraine, LPCT, CNRS, UMR 7019, BP 70239, 54506 Vandoeuvre-lès-Nancy Cedex, France

In 1996, Beaurepaire et al.[1] discovered that the magnetization of a thin film of Ni can be quenched in only a few hundred of femtoseconds by a light pulse of 60 fs.
More than 25 years later, no consensus exists regarding both the nature of the excitations responsible for demagnetized state, and how they are triggered.

In this context, relying on both *ab initio* and classical atomistic magnetization dynamics calculations, and accounting for the effect of the light–pulse by a raised electronic temperature, we discuss the involvement of the reduction of the inter–atomic exchange on the dynamics.
Indeed, including this effects in the three temperature model reveals a previously overlooked source of demagnetization, differing from the traditional point of view relying on a rapid rise of the temperature of the bath of the magnetic moments.
Applying this framework to Fe, Co and Ni has led to experimentally confirmed predictions which could not be explained by the traditional framework.

[1] E. Beaurepaire, J. C. Merle, A. Daunois, and J. Y. Bigot, "Ultrafast spin dynamics in ferromagnetic nickel," *Physical Review Letters*, vol. 76, pp. 4250–4253, may 1996.

O4: Monday 12th, 11:00 – 11:30

Micromagnetic modelling of antiferromagnetic dynamics: from switching to antiferromagnetic parametric resonance

Giovanni Finocchio
University of Messina, I-98166, Messina, Italy
Corresponding author: gfinocchio@unime.it

The magnetic order of antiferromagnetic materials (AFMs) can be manipulated electrically and here, we will discuss the mechanisms, we have identified, at the basis of switching and memristive behaviour driven by spin-orbit torque in metallic (e.g. $PtMn_3$ and $IrMn_3$) antiferromagnetic pillars.[1,2] Those materials are of interest because of their CMOS-compatibility, and the low current density necessary for the manipulation of their magnetic state. In addition to SOT, voltage controlled magnetic anisotropy (VCMA) is a low-energy alternative to manipulate the ferromagnetic state, which has been recently considered also in AFMs. Here, we theoretically demonstrate that VCMA can be used to excite linear and parametric resonant modes in easy-axis AFMs with perpendicular anisotropy, thus opening the way for an efficient electrical control of the Néel vector, and for detection of high-frequency dynamics. Two key results are: (i) VCMA parametric pumping is 1-2 orders of magnitude more efficient than microwave magnetic fields or spin-orbit-torques, and (ii) it also allows for zero-field parametric resonance, which cannot be achieved by other parametric pumping mechanisms in AFMs [2]. Fig. 1 clearly shows that the VCMA-driven parametric excitation is achievable in zero bias magnetic field, as also confirmed by the micromagnetic simulations. This is important both from a fundamental and practical point of view, since this behavior cannot be obtained by any other studied means.

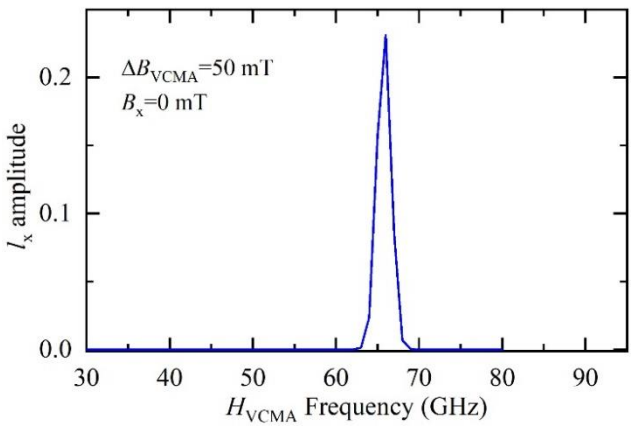


Figure 1. Parametric excitation of the Néel vector x-component when the VCMA drive is 50 mT in an unbiased AFM (applied along the out-of-plane direction z-axis). The effect is now observed on the x-component because Bx=0 mT, being x an in-plane direction.

This work was supported under the Grant 2019-1-U.0. funded by the Italian Space Agency and the project PRIN 2020LWPKH7 funded by the Italian Ministry of University and Research and Petaspin Association (www.petaspin.com).

References

[1] Shi, et al, Nat. Elet. 3, 92-98 (2020); Arpaci, et al, Nat. Comm 12, 3828 (2021)
[2] Riccardo Tomasello, et al, Phys. Rev. Applied 17, 034004 (2022).

O5: Monday 12th, 11:30 – 11:50

Optically induced localized spin wave states in all-dielectric nanopillars

D. Ignatyeva[1,2,3], D. Krichevsky[2,3,4], D. Karki[5], A. Kolosvetov[4], A. Chernov[4], A. Shaposhnikov[3], V. Berzhansky[3], M. Levy[5], V. Belotelov[1,2,3]

[1] Photonic and Quantum Technologies School, Lomonosov Moscow State University, 119991 Moscow, Russia

[2]Russian Quantum Center, 121353 Moscow, Russia

[3]Physics and Technology Institute, Vernadsky Crimean Federal University, 295007 Simferopol, Russia

[4] Moscow Institute of Physics and Technology (MIPT), 141700 Dolgoprudny, Russia

[5] Physics Department, Michigan Technological University, Houghton, MI, USA

The ability to control spin waves (and their quanta - magnons) in magnetic materials opens up opportunities for various applications, such as Boolean logic elements, memory cells, sensors, and elements of quantum computing [1]. Currently, nanophotonics brings a new perspective to light-spin coupling in nanoscale magnetic materials via optical modes excitation [2]. This approach is gaining momentum in current ultrafast nondissipative all-optical control of magnetism. To increase light-matter interaction plasmonic nanostructures made of noble metals are widely utilized [3]. However dissipative nature of the metals decreases the quality factor of the optical resonances and leads to thermal heating. From this perspective, their all-dielectric counterparts are lack of these drawbacks [4].

Here we propose an all-dielectric nanostructure composed of bismuth iron garnet nanopillars (BIG) on SiO2 substrate. The geometric properties of the structure were designed to localize electromagnetic energy inside the nanopillars via specific optical states.

An experimental nanostructure was composed of two-dimensional periodic grating of BIG nanopillars. The period of the structure was 900 nm, the height and diameter of the nanopillars were 500 and 450 nm correspondingly. An atomic force microscopy image of the sample is presented in the inset of Fig. 1.

Transmittance spectra of the sample in the 550-1000 nm range consists of several resonant dips which correspond to localized optical modes excitation inside the nanopillar [5]. Such optical modes are characterized by strongly non-uniform electromagnetic field distribution. We investigated an impact of such field inhomogeneities on spin-wave dynamics using optical time-resolved Faraday rotation (TRFR) method (pump-probe technique) [6]. The sample was placed in the static magnetic field in Voight configuration. A circularly polarized 250 fs laser pump pulses falling on the sample excite the system from the ground state via the inverse Faraday effect (IFE) [6] giving rise to spin-wave dynamics. A delayed probe pulse of linear polarization passing through the sample detect magnetization oscillations via Faraday effect. The wavelength of the pump pulses was adjusted to the dips in the transmittance spectra of the sample, while the probe pulses wavelength was set to 525 nm.

A 730 nm pump wavelength was utilized. The wavelength corresponds to the resonant dip in the transmittance spectra of the sample. At the resonance optical energy is highly concentrated inside nanopillar. As a result, IFE effective magnetic field is also localized and resemble a point source (inset of the Fig. 1). Such a point source-like stimulate sophisticated oscillations in TRFR signal (Fig. 2a). To identify the frequencies of the observed oscillations Fourier analysis of the signals was performed (Fig. 2b).

There are 3 well-defined peaks in the FFT spectra. For the case of 70 mT external field the peaks are located at 1.4, 2.23 and 3.18 GHz. The central one corresponds to backward volume magnetostatic spin wave (BVMSW) of 0-th order, high-frequency satellite corresponds to 1-order BVMSW, while low-frequency one is believed to correspond to so-called “edge” modes. The high-order modes are known to be caused due to standing wave formation inside the nanopillar. The low-frequency mode formation is mainly connected with demagnetization effects in the nanopillar [7]. The frequency of the modes

increases with the increase of the external magnetic field amplitude. For instance, the modes observed for 70 mT shifted to 2.67, 3.51 and 4.43 GHz for 120 mT. Notably, in the case of pristine film of the same thickness (~500 nm) only 0-th order BVMSW mode is observed. Consequently, the localized inhomogeneous optical excitation give rise to high- and low-frequency spin-wave modes that can utilized in nanosized multispectral spin-wave based devices.

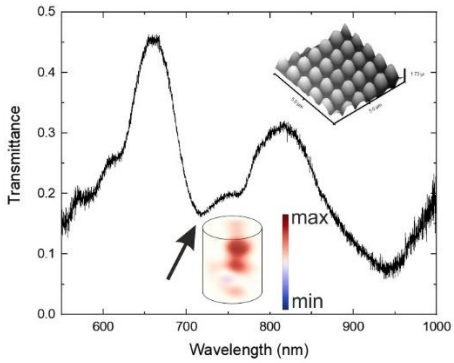
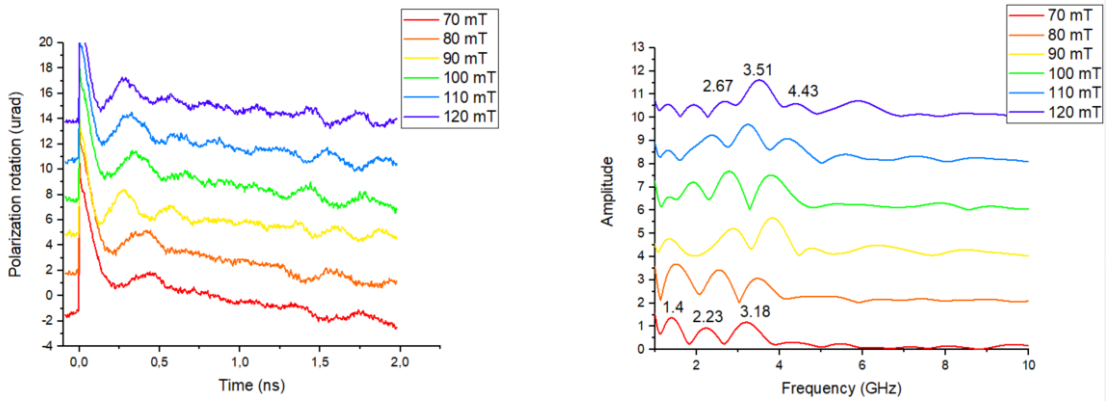


Figure 1: Transmittance spectra of the nanostructure at 17 degrees of polar incident angle. Inset – AFM image of the sample and z-component of the IFE distribution.



a b

Figure 2: TRFR measurements of the sample (a) and the Fourier spectra of the measured oscillations (b).

References:

[1] A. Chumak et al. Nature Phys 11(2015)453
[2] A.I Chernov et al. Nano Lett. 20(2020)5259
[3] A.L. Chekhov et al. Nano Lett. 18(2018)2970
[4] D.M. Krichevsky et al. Phys. Rev. Appl. 15(2021)034085
[5] P.E. Zimnyakova et al. Nanophotonics 11(2022)119
[6] A. Kirilyuk et al. Rev. Mod. Phys. **82**(2010)2731
[7] O. Klein et al. Phys. Rev. B, 78(2008)144410

O6: Monday 12th, 11:50 – 12:20

A comparison of thermal all-optical toggle switching in Mn_2Ru_xGa and rare-earth/transition metal alloys

JEAN. BESBAS[1], C. BANERJEE[1,2], Z. HU[1], G. ATCHESON[1], P. STAMENOV[1], K. RODE[1] and J. M. D. COEY[1]

1. CRANN, AMBER and School of Physics, Trinity College Dublin, Dublin 2, Ireland.

Ferrimagnets (FiM) are made of inequivalent magnetic networks that are antiferromagnetically coupled. FiM can show thermal all-optical toggle magnetic switching (AOS) triggered by picosecond heating. Together with the existence of THz antiferromagnetic modes, the high AOS speed makes FiMs appealing for next generation spin electronics. AOS follows the picosecond demagnetisation of the networks whose magnetisations must reach zero at different time. For a long time the amorphous $Gd_x(FeCo)_{1-x}$ was the only identified FiM showing thermal AOS. There the demagnetisation of the FeCo network is ~200 ps against ~1.1 ps for the Gd network because of the higher Gd magnetic moment.

In this talk I will show that this thermal toggle AOS is more common than initially thought by presenting the cases of Mn_2Ru_xGa and RE_xCo_{1-x} with RE=Dy,Tb and draw conclusions on the thermal AOS mechanism from these two cases study.

Mn_2RuGa (MRG) is a compensated FiM crystal with XA structure. Two inequivalent magnetic sublattices are formed by Mn atoms at the 4a and 4c Wyckoff positions.[1] A compensation temperature with zero magnetisation exists because the 4c magnetisation is higher at low temperature and decays faster than the 4a magnetisation upon increasing temperature. Unlike $Gd_x(FeCo)_{1-x}$ MRG is crystalline and its magnetism comes from one transition metal species only (Mn). The demagnetisation time of the 4a and 4c sublattices are believed to be similar and the 4a and 4c magnetisations should both reach zero on a timescale of 200 fs. Despite that MRG exhibits a robust AOS shown in Fig. 1. with the peculiarity of occuring only below the compensation temperature. [2-3]

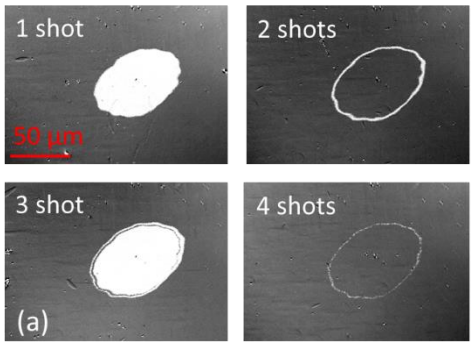


Fig.1. Toggling of magnetisation observed by magneto optical Kerr microscopy after irradiation by multiple 200 fs pulses @800 nm delayed by 1 s.[2] The magnetisation points upward (downward) in the areas in grey (white).

Dy_xCo_{1-x} and Tb_xCo_{1-x} are two amorphous compensated FiMs similar to $Gd_x(FeCo)_{1-x}$. However the irradiation of a $TbCo_3$ film with a single femtosecond pulse shown in Fig. 2 yields an incomplete AOS with a few unswitched domains in the irradiated area. Subsequent irradiation toggles the proportion of magnetic domains of each type and a complete

demagnetisation is gradually reached after ~10 pulses. The rare-earth demagnetisation should be the slowest in $Gd_x(FeCo)_{1-x}$ because Dy and Tb have higher magnetic moments than Gd. Therefore AOS should be robust in Dy_xCo_{1-x} and Tb_xCo_{1-x} in contradiction with our results. We believe that the random anisotropy experienced by Dy/Tb atoms, absent in $Gd_x(FeCo)_{1-x}$, causes a modulation of the Dy/Tb static magnetisation on a spatial scale of 700 nm that explains the inhomogeneous AOS.[4] This result highlights the importance of the random anistropy in the process of thermal AOS.

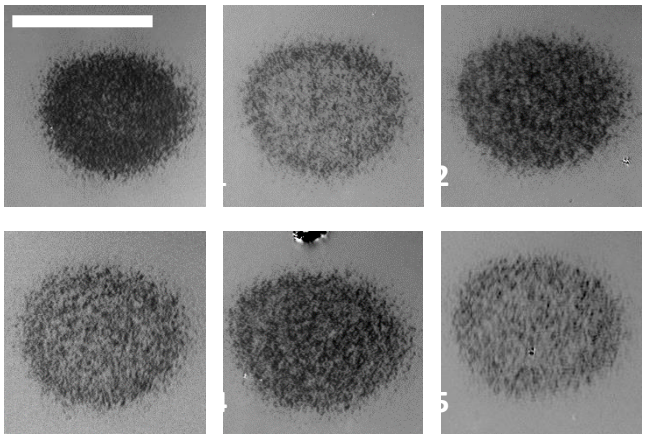


Fig.2. Irradiation of $TbCo_3$ with multiple 200 fs laser pulses @800 nm. The number of shots is displayed in each picture and the scale bar is 50 µm.The magnetisation points upward (downward) in the areas in grey (white). The magnetic domains are ~700 nm in size.

References

[1] H. Kurt, K. Rode, P. Stamenov, M. Venkatesan, Y.-C. Lau, E. Fonda and J. M. D. Coey "Cubic Mn_2Ga Thin Films: Crossing the Spin Gap with Ruthenium" Phys. Rev. Lett. **112**, 027201 (2014).

[2] C. Banerjee, N. Teichert, K. E. Siewierska, Z. Gercsi, G. Y. P. Atcheson, P. Stamenov, K. Rode, J. M. D. Coey, and J. Besbas "Single pulse all-optical toggle switching of magnetization without gadolinium in the ferrimagnet Mn_2Ru_xGa" Nat. Commun. **11**, 4444 (2020).

[3] C. Banerjee, K. Rode, G. Atcheson, S. Lenne, P. Stamenov, J. M. D. Coey, and J. Besbas, "Ultra-fast Double Pulse All-Optical Re-switching of a Ferrimagnet" Phys. Rev. Lett. **126**, 177202 (2021).

[4] Z. Hu, J. Besbas, R. Smith, N. Teichert, G. Atcheson, K. Rode, P. Stamenov, and J. M. D. Coey "Single-pulse all-optical partial switching in amorphous Dy_xCo_{1-x} and Tb_xCo_{1-x} with random anisotropy." Appl. Phys. Lett. **120**, 112401 (2022).

O7: Monday 12th, 2:00 – 2:30

Bridging atomistic spin dynamics methods and phenomenological models of two-sublattice magnets

F. Jakobs and U. Atxitia
Department of Physics, Freie Universitaet Berlin, Germany

In this talk I present how we bridge an essential knowledge gap on the understanding of single femtosecond pulse induced ultrafast switching in ferrimagnets; namely, the connection between atomistic spin dynamics methods and macroscopic phenomenological models. All-optical switching of the magnetization occurs after the application of a single femtosecond laser pulse to specific ferrimagnetic compounds. This strong excitation puts the involved degrees of freedom, electrons, lattice and spins out-of-equilibrium between each other. Atomistic spin models have quantitatively described all-optical switching in a wide range of experimental conditions, while having failed to provide a simple picture of the switching process. Phenomenological models are able to qualitatively describe the dynamics of the switching process. However, a unified theoretical framework is missing that describes the element-specific spin dynamics as atomistic spin models with the simplicity of phenomenology. Here, I present an element-specific macrospin dynamical model which fully agrees with atomistic spin dynamics simulations and symmetry considerations of the phenomenological models , see Ref. [1] and Figure 1 .

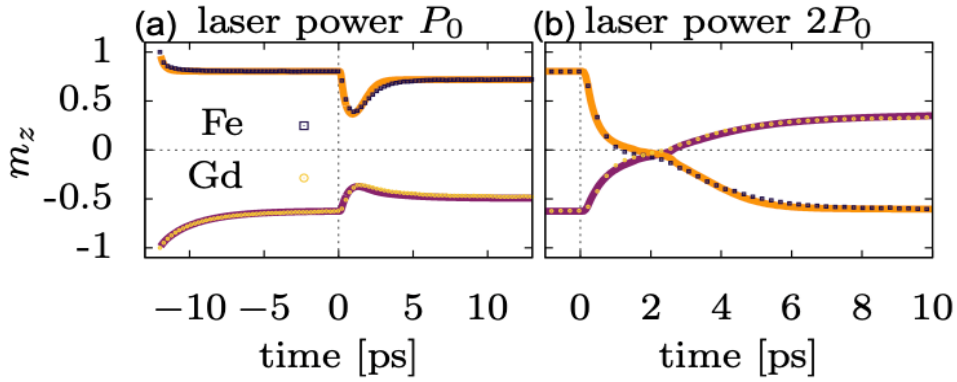
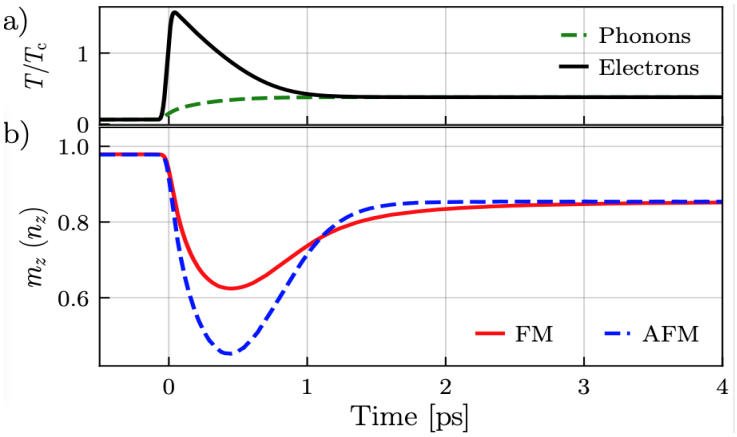


Figure 1: Element-specific magnetization dynamics of GdFeCo calculated using atomistic spin dynamics (symbols) and the unified phenomenological model presented here for two laser pulse power values, (a) $P0$ and (b) $2P0$. Both electron and lattice temperature are kept constant, T = 300 K, for $t < 0$. At $t = 0$ a laser pulse is applied. GdFeCo alloys with xGd = 25% are calculated.

Single-pulse switching has been experimentally demonstrated in ferrimagnetic GdFeCo and Mn_2Ru_xGa alloys. Our theory reproduces quantitatively all stages of the switching process observed in experiments. We directly compare our theory to computer simulations using atomistic spin dynamics methods. We provide explicit analytical expressions for the magnetization relaxation rates in terms of microscopic parameters which allows us to propose simple criteria for switching in ferrimagnets [2].

Finally, we theoretically demonstrate that the ultrafast magnetic order dynamics in antiferromagnets is exchange-enhanced in comparison to their ferromagnetic counterparts. Based on the model for two-sublattice ferrimagnets, we provide an equation of motion for the magnetic order dynamics in AFMs validated by computer simulations using atomistic spin dynamics methods. The exchange of angular momentum between sublattices speeds up the dynamics in antiferromagnets, a process absent in ferromagnets [3]. In particular, we find that the AFM magnetic order responds faster than the FM one to a sudden temperature change due to the exchange-enhancement of the effective AFM damping (see Figure 2 for an example). We show that, contrary to FMs, the effective AFM damping depends on the number of neighbours to which spins are exchange coupled. Thus, low dimension magnets, such as 2D magnets show a more pronounced speed up while for lattices with higher coordination number the exchange-enhancement reduces. As the system approaches the critical temperature, both the FM and AFM present a critical slow down of the relaxation process, however, the AFM critical exponent is smaller than the FM one. In the temperature dominated regime, our model predicts intrinsically different relaxation dynamics for AFMs and FMs. This scenario corresponds to experiments using powerful femtosecond laser pulses. For FMs, magnetic order quenching slows down as the magnetization reduces, while for AFMs speeds up.

Figure 2: (a) Electron and phonon temperature dynamics after an excitation by a 50 fs laser at *t*=0. (b) The magnetic order dynamics of a FM (red solid line), and an AFM (blue dashed line) as a response to the electron temperature dynamics in (a).



References

[1] F. Jakobs and U. Atxitia, arXiv: 2206.13593 (2022)
[2] F. Jakobs and U. Atxitia, arXiv: 2201.09067 (2022)
[3] F. Jakobs and U. Atxitia, arXiv:2206.05783 (2022)

O8: Monday 12th, 2:30 – 2:50

Unravelling the Transient Depth Magnetic Profile During Ultrafast Demagnetization of an Iron Thin Film

V. Chardonnet[1], M. Hennes[1], R. Jarrier[1], R. Delaunay[1], N. Jaouen[2], M. Kuhlmann[3], C. Léveillé[2], K. Yao[4], D. Schick[4], C. von Korff Schmising[4], G. S. Chiuzbaian[1], J. Lüning[5], B. Vodungbo[1] and E. Jal[1]

[1] Sorbonne Université, CNRS, Laboratoire de Chimie Physique-Matière et Rayonnement, LCPMR, 75005 Paris, France

[2] Synchrotron SOLEIL, L'Orme des Merisiers, Saint-Aubin, B.P. 48, 91192 Gif-sur-Yvette, France

[3] Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany

[4] Max Born Institut für Nichtlineare Optik und Kurzzeitspektroskopie, 12489 Berlin, Germany

[5] Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany

During the last two decades, a variety of models have been developed to explain the ultrafast quenching of magnetization following femtosecond optical excitation [1,2,3]. These models can be classified into two broad categories, relying either on a local or a non-local transfer of angular momentum [3]. To distinguish those local and non-local effects we can measure the magnetization depth profile with femtosecond resolution, thanks to time-resolved x-ray resonant magnetic reflectivity [4, 5]. In this presentation, I will show how, from our experimental results gathered at the free electron laser FLASH, we can unravel the dynamics of the transient inhomogeneous depth magnetic profile of an Fe layer after optical excitation.

First our experiment on a polycrystalline Fe sample reveals two distinct dynamics at different time scales for the structure and the magnetization [Fig. 1 (a) and (b)]. Until one picosecond, the magnetic signal is quickly evolving while the structural one stays more or less constant. After that, the magnetic signal is slowly coming back to equilibrium while the structural one changes periodically. For this structural signal, we observe a maximum dilation of 2Å followed by a coherent damped oscillation of the thickness of the sample [Fig. 1 (a)]. This dynamic is due to stresses that are generated by the rapid increase in temperature and might be enhanced via magnetostrictive effects.

Second, the quantitative analysis of our magnetic reflectivity data allows us to retrieve the inhomogeneous depth magnetic profile for different delays after the optical excitations. As shown in Fig. 1 (c), close to the bottom interface there is an overall reduction of the demagnetization. When comparing this result to simulation we can directly show that both local and non-local phenomena [6] take place at the same time scale and that there is probably a contribution from spin currents that could carry the magnetization beyond the magnetic layer [7].

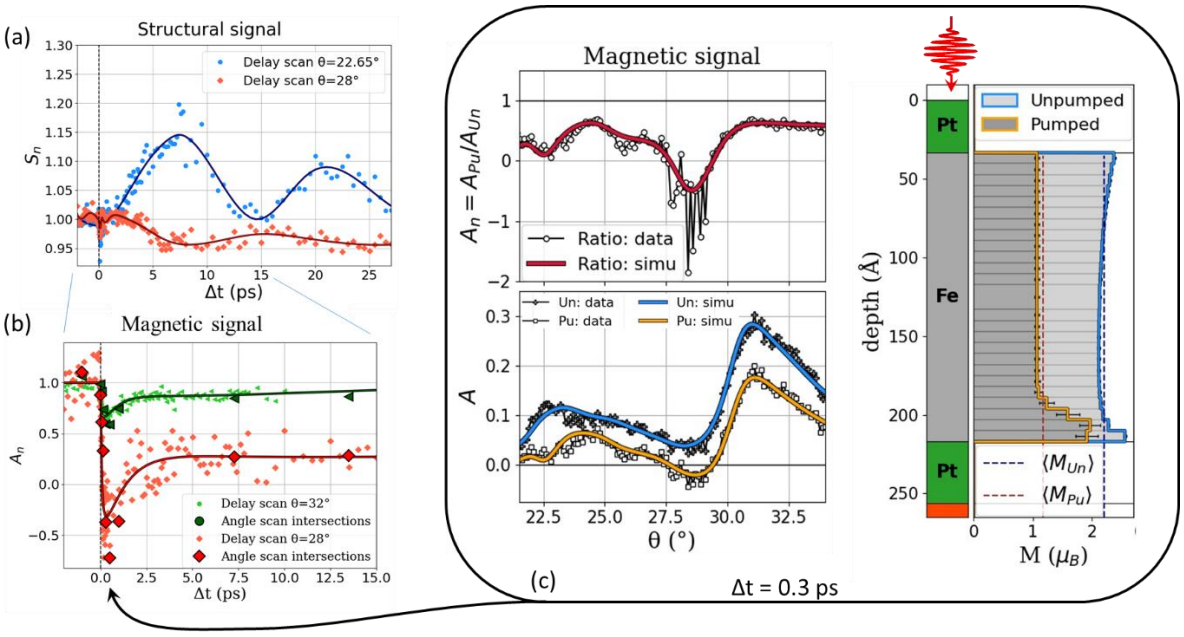


Figure 1: Delay scans for the (a) structural signal and (b) magnetic signal extracted from x-ray magnetic reflectivity as a function of the delay between the pump and the probe for two different reflectivity angles. (c) Magnetic signal as a function of the reflectivity angle θ for a delay of 0.3 ps and its fit, which give the derived depth magnetic profile without optical excitation (blue) and 300 fs after an optical excitation (orange).

References

[1] B. Koopmans et al. *Nat. Mat.* **9**, 259 (2010)
[2] M. Battiato et al. *Phys. Rev. Lett.* **105**, 027203 (2010)
[3] G. P. Zhang et al. *Journ. Phys. Cond. Matt.* **30**, 465801 (2018)
[4] E. Jal et al. *Phys. Rev. B* **95**, 184422 (2017)
[5] V. Chardonnet et al. *Struct. Dyn.* **8**, 034305 (2021)
[6] J. Wieczorek et al. *Phys. Rev. B* **97**, 174410 (2015)
[7] A. Eschenlhor et al. *Nat. Mat.* **12**, 332 (2013)

O9: Monday 12th, 2:50 – 3:20

Ultrafast domain reconfiguration via optical pumping: Aggregated evidence from three XFEL studies

Nanna Zhou Hagström,[1] Rahul Jangid,[2] Meera Madhavi,[2] Diego Turenne,[3] Jeffrey Brock,[4] Erik S. Lamb,[5] Boyan Stoychev,[5] Sheena K. K. Patel,[4,5] Anatoly Shabalin,[5] Nelson Hua,[4,5] Stjepan B. Hrkac,[5] Oleg Shpyrko,[5] Justine Schlappa,[6] Natalia Gerasimova,[6] Benjamin Van Kuiken,[6] Rafael Gort,[6] Laurent Mercadier,[6] Andrey Samartsev,[6] Andreas Scherz,[6] Giuseppe Mercurio,[6] Hermann A. Dürr,[3] Alexander H. Reid,[7] Monika Arora,[8] Hans T. Nembach,[8,9] Justin M. Shaw,[8] Emmanuelle Jal,[10] Eric E.Fullerton,[4] Sergio A. Montoya,[4] Mark W. Keller,[8] Roopali Kukreja,[2] Stefano Bonetti,[1,11] Ezio Iacocca,[13] Kyle Rockwell[13], Dmitriy Zusin,[14] Loïc Le Guyader,[15,16] Alexander H. Reid,[15,17] William F. Schlotter,[17] Tian-Min Liu,[15] Daniel J. Higley,[15] Giacomo Coslovich,[17] Scott F. Wandel,[17,18] Phoebe M. Tengdin,[14] Adam Blonsky,[14] Christian Gentry,[14] Mark A. Hoefer,[19] Margaret M. Murnane,[14] Henry C. Kapteyn,[14] Flavio Capotondi,[20] Matteo Pancaldi,[20] Dario De Angelis,[20] Thomas J. Silva[8]

[1]Department of Physics, Stockholm University, 106 91 Stockholm, Sweden
[2]Department of Materials Science and Engineering, University of California Davis, CA, USA
[3]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[4]Center for Memory and Recording Research, University of California San Diego, La Jolla, CA, USA
[5]Department of Physics, University of California San Diego, La Jolla, CA, USA
[6]European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
[7]Linac Coherent Light Source, SLAC National Accelerator Laboratory, Menlo Park, CA, USA
[8]Quantum Electromagnetics Division, National Institute of Standards and Technology, Boulder, CO, USA
[9]Department of Physics, University of Colorado, Boulder, CO, USA
[10]Sorbonne Université, CNRS, Laboratoire de Chimie Physique – Matière et Rayonnement, LCPMR, Paris 75005, France
[11]Department of Molecular Sciences and Nanosystems,
Ca' Foscari University of Venice, 30172 Venezia, Italy
[13]Center for Magnetism and Magnetic Materials,
University of Colorado Colorado Springs, Colorado Springs, CO, USA
[14]Department of Physics and JILA, University of Colorado, Boulder, CO 80309, USA
[15]Stanford Institute for Materials and Energy Sciences SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[16]European XFEL, Holzkoppel 4, 22869 Schenefeld, Germany
[17]Linac Coherent Light Source, SLAC National Accelerator Laboratory,
2575 Sand Hill Road, Menlo Park, CA 94025, USA
[18]Current address: MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02421, USA
[19]Department of Applied Mathematics, University of Colorado, Boulder, CO 80309, USA
[20]Elettra - Sincrotrone Trieste 34149 Basovizza, Trieste Italy

We report on three separate studies [1-3], conducted at three separate free electron laser sources of coherent ionizing radiation (X-rays at LCLS and the Eu-XFEL, and EUV at FERMI) over the span of four years, that confirm ultrafast optical pumping of perpendicular anisotropy samples with worm-like labyrinth domains results in a spectroscopically detectable reconfiguration of the domain structure, implying that ultrafast motion of domain walls ~10 km/s is possible in far-from-equilibrium states. While the experimental geometries are different, our results are reminiscent of a recent theoretical calculation that predict in-plane superdiffusive spin currents excited by a tightly focused optical pumping can drive a domain wall at 14 km/s [4].

All of our studies relied on resonant magnetic scattering (RMS) of coherent pulsed radiation. The samples were Co/Ni multilayers of varying thickness, grown on either SiN or Si membranes. The radiation was tuned to the magnetically sensitive absorption edge of Ni in all three studies (L_3 for LCLS and Eu-XFEL, M_3 for FERMI). Linear polarized radiation was used for all three studies. The samples were in their remanent state with no applied magnetic field during the pump-probe measurements. The thicker sample of ~40 nm on a SiN membrane supported purely labyrinth domains, whereas the thinner samples of ~20 nm on Si membranes supported a combination labyrinths, stripes, and mixed states between labyrinths and stripes.

The X-ray study at the LCLS at the Stanford Linear Accelerator Center was conducted with the maximum possible pump fluence, and revealed odd-order circular diffraction rings out to 5th order, owing to the high dynamic range of the measurements [1]. The relative quenching of the 3 diffraction rings within the first 1.5 ps was used to definitively quantify non-trivial ultrafast broadening of domain walls by 31%. Unexpectedly, the first- and third-order diffraction rings both broaden in width by 15% and contract in radius by 6% at ultrafast timescales of less than 1.5 ps. This bizarre broadening and contraction scale with the order of the diffraction ring, i.e. the broadening is 15% for both the 1st and 3rd order diffraction rings, and the contraction is 6% for both the 1st and 3rd order diffraction rings. (The 5th order ring fully quenches when pumped, so determination of neither broadening or contraction is possible.) The broadening and contraction of the rings are suggestive that the domain walls both move as well as broaden when pumped. The possibility that the distortions in the diffraction rings were higher order effects of domain wall broadening is conclusively eliminated as a viable explanation; We were able to do so by use of a compact analytical expression that related the ring broadening and contraction to the degree of domain wall broadening. (Our expression was derived under the assumption that the distortions of the diffraction ring were solely due to higher order effects from wall broadening.)

Ultrafast domain wall broadening, while not yet theoretically predicted [4], is presumably still evidence of how superdiffusive spin currents flowing through a straight domain wall can exert symmetrical local torques that affect the wall profile, e.g. a semiballistic “up” spin from an “up” domain passes through a sharp domain wall, then relaxes on the other side of the wall, flipping a local spin in the “down” domain into the “up” direction. This line of speculation was previously suggested by Pfau, et al., [5] as an explanation for the ultrafast contraction in the diffraction ring radius, but, as discussed in the previous paragraph, we have now shown that the contraction effect is not a direct result of wall broadening.

The X-ray study at the Eu-XFEL in Hamburg utilized thinner samples (~20 nm) on Si membranes [2]. While not capable of detecting more than the 1st order diffraction features, the study still reproduces the observation of both the ring broadening and radial contraction in the case of labyrinth domains. However, neither the broadening or contraction are detectable for the case of stripe domains, where the diffraction pattern results in a bimodal lobe pattern. In measurements with mixed domain states of both labyrinthian and stripe character, a unique two-dimensional fitting algorithm was developed to separately analyze the dynamics of labyrinths and stripes in the same data set. It is again confirmed that the broadening and contraction occur with labyrinths but are undetectable for stripes. This empirical result resolves a controversy over whether the ultrafast distortion in the diffraction patterns is an experimental artifact or not, given that previous studies by other groups had also found that the effect was present for samples with labyrinth domains [5], and absent for samples with stripe domains [6,7]. Our results suggest that the symmetry of the domain patterns (zero long-range for labyrinths, 2-

fold rotational for stripes) is an intrinsic determinate as to whether ultrafast distortions in the diffraction pattern occur.

The EUV study at FERMI in Trieste once again confirmed the observation of ultrafast diffraction ring broadening and contraction under optical pumping [3]. While still not able to detect more than 1st order diffraction features, the dynamic range was sufficient to systematically observe how the distortions scaled with pump fluence over an order of magnitude in pump fluence. The 2-dimensional fitting algorithm developed to analyze the Eu-XFEL scattering data was again deployed for the FERMI data sets. It was confirmed that the distortions were strongest for labyrinth domain patterns and much weaker for stripe domains. Surprisingly, we found that both the broadening and the contraction have a nonlinear dependence on pump fluence: The broadening and contraction scale linearly with pump fluence, with a maximum of approximately 1% at 7 mJ/cm^2 (~40% quenching). Above 7 mJ/cm^2, the slope of the linear dependence on pump fluence jumps sharply, with a maximum broadening of ~25% and a maximum contraction of 5% at 13 mJ/cm^2 (~60% quenching). Even more surprising, we observed a third diffraction feature of unknown origin that has a 1-fold rotation symmetry, i.e. a single-sided lobe in the diffraction plane. We confirmed that the lobe is indeed magnetic because it also quenched with pumping. Perhaps most surprising of all, we find that the magnetic quenching of all three diffraction features (isotropic ring, single-sided lobe, and bimodal lobes) scales as the quartic-root of the pump fluence, not linear in pump fluence, as one typically observes when pumping uniformly magnetized samples.

We found that the scaling of both the broadening and contraction with the amount of magnetization quenching of the diffraction rings was consistent between all three studies. It was also consistent with the previous study by Pfau, et al.,[5] where the contraction in the diffraction ring radius for labyrinth domains was first reported, and with the previous study by Hennes, et al. [6] and Fan, et al., [7] where they found that such distortions at ultrafast timescales were absent with stripe domains.

A naïve interpretation of the rather puzzling radial contraction of the diffraction rings is a uniform increase in the domain sizes. However, this is easily dismissed as the requisite domain wall velocities would scale linearly with distance from the center of the pump spot, and quickly approach unphysical velocities [5]. Our observation that the distortions are absent for the most part in samples with stripe-like domains comports with the fact that ultrafast uniform domain broadening is indeed not possible. The other factor that makes such uniform domain growth impossible is the fact that the illumination spot is unform to first order in the domain size. The approximately homogeneous symmetry of the excitation means there isn't a preferred direction for domain wall motion, as a preferred direction requires mirror symmetry-breaking along the direction of motion. Previous theoretical calculations by Baláž, et al., show that superdiffusive spin currents can move a straight domain wall, but the optical pump spot must be focused in such a manner that there is a significant gradient in the optical intensity across the profile of the wall, which thereby breaks the mirror symmetry of the experimental geometry even in the case of a straight symmetrical wall.

One significant difference between stripe and labyrinth domains is the preponderance of semicircular cap domain walls in labyrinth domain patterns. Such cap walls are presumably intrinsic to the labyrinth domain geometry, though the density is likely extrinsic. The density of such walls is not necessarily zero for samples with stripe-like domains, given the possibility of defects that affect the domain geometry, but it should be much smaller than for labyrinths. This is born out in MFM images taken of our samples.

One possible explanation for these puzzling phenomena is that the cap walls, which are present to a much higher degree with labyrinth domain patterns, are mobile under ultrafast optical pumping, and that they move in a manner that locally increases the domain width, but without an overall homogeneous broadening of all the domains. Even under uniform illumination, the curvature of the cap wall intrinsically breaks the mirror symmetry that would otherwise be operative for a straight domain wall. If a cap wall moves in manner such that the length of the domain it caps contracts, then the gap between the cap wall and the adjacent domain wall would increase, resulting in some fraction of the radiation scattering to lower q-values in the diffraction plane. This would also explain why the diffraction rings broaden, as the distribution of domain widths would necessarily broaden if the gaps between randomly distributed cap walls and adjacent walls expand. The microscopic mechanism that drives cap wall motion is not yet understood, but we can estimate how much motion is required of cap walls in our samples to produce the measured amount of contraction of the diffraction rings; 20-40 nm over 1.5 ps. This suggests cap wall velocities ranging from 10 to 30 km/s. This agrees well with the recent calculations of Baláž, et al.,[4] which predicted velocities of 14 km/s under the action of superdiffusive spin currents that exert a net spin transfer torque on the wall.

[1] D. Zusin, et al., arXiv:2001.11719v4 (2022)
[2] N. Hagström, et al., arXiv:2112.09587v2 (2021)
[3] R. Jangid, et al., in preparation.
[4] P. Baláž, et al., Phys. Rev. B, 101, 174418 (2020)
[5] B. Pfau, et al., Nat. Comm., DOI: 10.1038/ncomms2108 (2012)
[6] M. Hennes, et al., Phys. Rev. B, 102, 174437 (2020)
[7] G. Fan, et al., arXiv:1910.14263v1 (2019)

O10: Monday 12th, 3:20 – 3:40

Non-local Switching of Magnetization by the Ultrafast Phononic Barnett Effect

C. S. Davies[1], F. G. N. Fennema[1], A. Tsukamoto[2], I. Razdolski[1,3], A. V. Kimel[4] and A. Kirilyuk[1]

[1]FELIX Laboratory, Radboud University, Nijmegen, The Netherlands
[2]Nihon University, Chiba, Japan
[3]University of Bialystok, Bialystok, Poland
[4]Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

Very recently, a series of pioneering experiments have revealed how ultrafast photo-induced demagnetization transfers angular momentum from the spins to the lattice via the Einstein-de Haas effect [1]-[2]. Here, we explore whether the ultrafast Barnett effect – by which mechanical rotations create magnetization [3] - can reciprocally channel angular momentum from rotating lattice vibrations to spins (Fig. 1a). Using ultrashort optical pulses delivered by the free-electron-laser facility FELIX [4], we coherently excite optical phonons at resonance in a paramagnetic substrate (Fig. 1b). Importantly, the optical pulses are circularly-polarized, thus enabling specific optical phonons to become circularly-polarized as well. The orbital angular momentum of the phonons give rise to a magnetic field $\mathbf{B}_{BE}$, pointing either parallel or antiparallel to the substate's normal. This magnetic field then switches the magnetization in the nearby magnetic GdFeCo nanolayer.

Typical results proving the feasibility of this switching approach are shown in Fig. 1c. In our first set of experiments, we expose the multilayered stack to a bunch of ≈200 3.5-ps-long pulses, with central wavelength λ = 21 μm, that are circularly polarized with helicity $\sigma^{\pm}$. Using magneto-optical imaging in equilibrium, we detect the impact on the magnetic domains of GdFeCo mounted on a sapphire substrate. We clearly see, depending on the combination of initial magnetic polarity and optical helicity, the formation (or lack thereof) of a ring of switched magnetization. By adjusting the duration of the pulses, we are able to distinguish this effect from exchange-driven switching of magnetization observed previously [5].

The helicity-dependence of the effect is rendered even clearer by scanning the laser pulses across the sample at a fixed speed (Fig. 1d). By tuning the central wavelength of the pumping pulses, we identify that the switching efficiency scales with the strength of the transverse optical phonons found in the sapphire substrate. Additional measurements of the same GdFeCo mounted on a fused-silica substrate reveals a different spectral dependence of switching efficiency, that again correlates with the transverse optical phonons in the fused-silica substrate.

We therefore conclude that we have discovered the ultrafast Barnett effect, which can be used to switch magnetization non-locally using coherent lattice vibrations excited within an underlying substrate. Our results represent a breakthrough that could potentially be used to switch magnetic order on a universal scale, since rotational vibrations of ions are found everywhere.

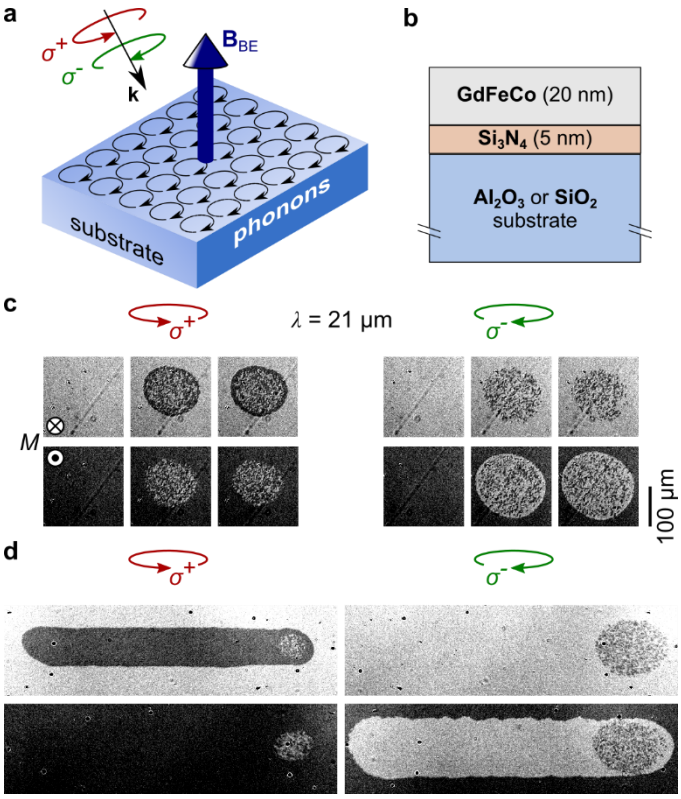


Figure 1: a Sketch of how circularly-polarized phonons vibrating in a paramagnetic substrate, coherently excited at resonance by circularly-polarized light with helicity σ±, give rise to a non-local magnetic field B_{BE}. b The typical nanolayer structure used in our experiments. c Magneto-optical images of GdFeCo, mounted on a sapphire substrate, taken before and after exposure to consecutive 8-μs-long bursts of circularly-polarized pulses with central wavelength λ = 21 μm and duration τ ~3.3 ps. d Result of sweeping the bursts from left to right at a speed of 20 μm/s across a single-domain background. The scale bar is common to all images.

References

[1] C. Dornes *et al*. "The ultrafast Einstein–de Haas effect." *Nature* **565**, 209 (2019).

[2] S. R. Tauchert *et al.* "Polarized phonons carry angular momentum in ultrafast demagnetization." *Nature* **602**,
73 (2022).

[3] S. J. Barnett, "Magnetization by Rotation." *Phys. Rev.* **6**, 239 (1915).

[4] G. M. H. Knippels and A. F. G. van der Meer, "FEL diagnostics and user control." *Nucl. Instrum. Methods Phys. Res.* **144**, 32 (1998).

[5] C. S. Davies *et al.* "Exchange-driven all-optical magnetic switching in compensated 3d ferrimagnets." *Phys. Rev. Res*. **2**, 032044(R) (2020).

O11: Monday 12th, 4:00 – 4:30

Femtosecond-laser frequency comb enhanced Brillouin light scattering microscopy

J. Åkerman[1], A. A. Awad[1], S. Muralidhar[1], A. Aleman[1], R. Khymyn[1], and D. Hanstorp[1]
[1]University of Gothenburg, Kemivägen 9, 41296, Göteborg, Sweden

Brillouin light scattering (BLS) microscopy has evolved into a powerful and versatile method to study acoustic and magnetic phenomena down to sub-micron length scales. Such studies include low-intensity thermal spin waves (SWs) and higher-intensity SWs generated by antennas or spin-transfer torques. SWs can also be generated optically using femtosecond (fs) laser pulses and be studied by time-resolved MOKE microscopy [1,2]. However, due to the decay time of the SWs and the low repetition rate of most fs-lasers, the optically induced emission of SWs is not continuous, and the time-averaged SW intensity is too weak for BLS techniques. Instead, to obtain sustained SWs, much shorter time periods between pulses should be used. This was recently achieved in YIG films using a 1 GHz high-repetition-rate fs-laser frequency comb [3]. In my talk, I will describe how the same type of laser excitation can be used to drive continuous SWs in metallic thin films and be observed using BLS microscopy. The resulting frequency comb-enhanced BLS microscope [4] has been used to excite and study a wide range of different SW modes [5,6,7]. In addition, we see clear evidence of coherent excitation of multiple phonon modes, which results in substrate dependent interference patterns on the micron scale.

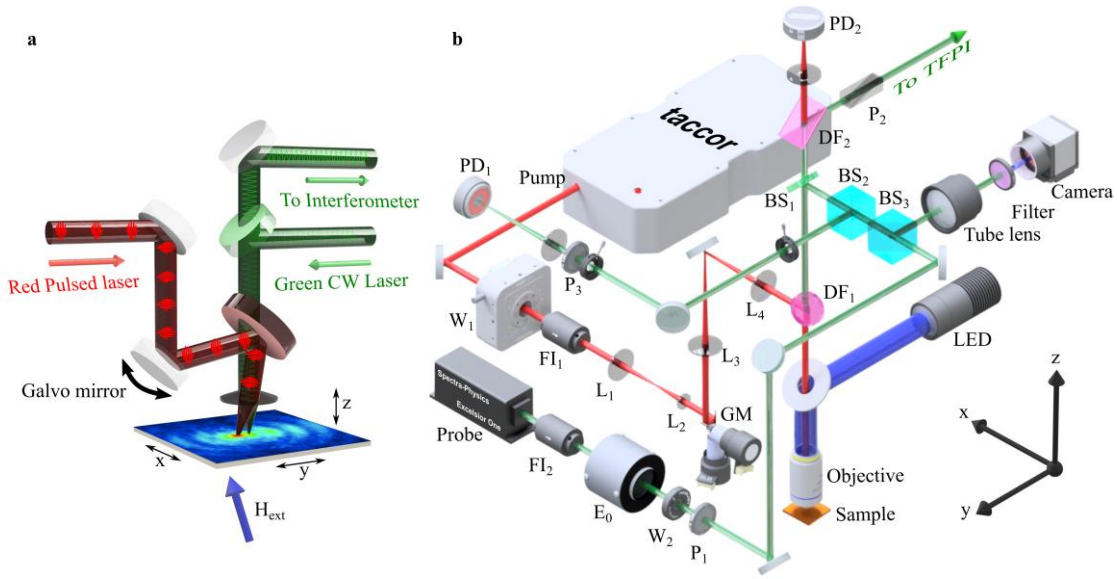


Figure 1: BLS microscope optical layout: (a) Simplified picture of the method. (b) Schematic of the optical setup. W1 - Motorized waveplate, W2 - halfwave plate, FI - Faraday Isolator, L - lenses, P - polarizer, DF - Dichroic Filter, BS - beamsplitter, E - Etalon, PD - photodiode and GM - galvanometer.

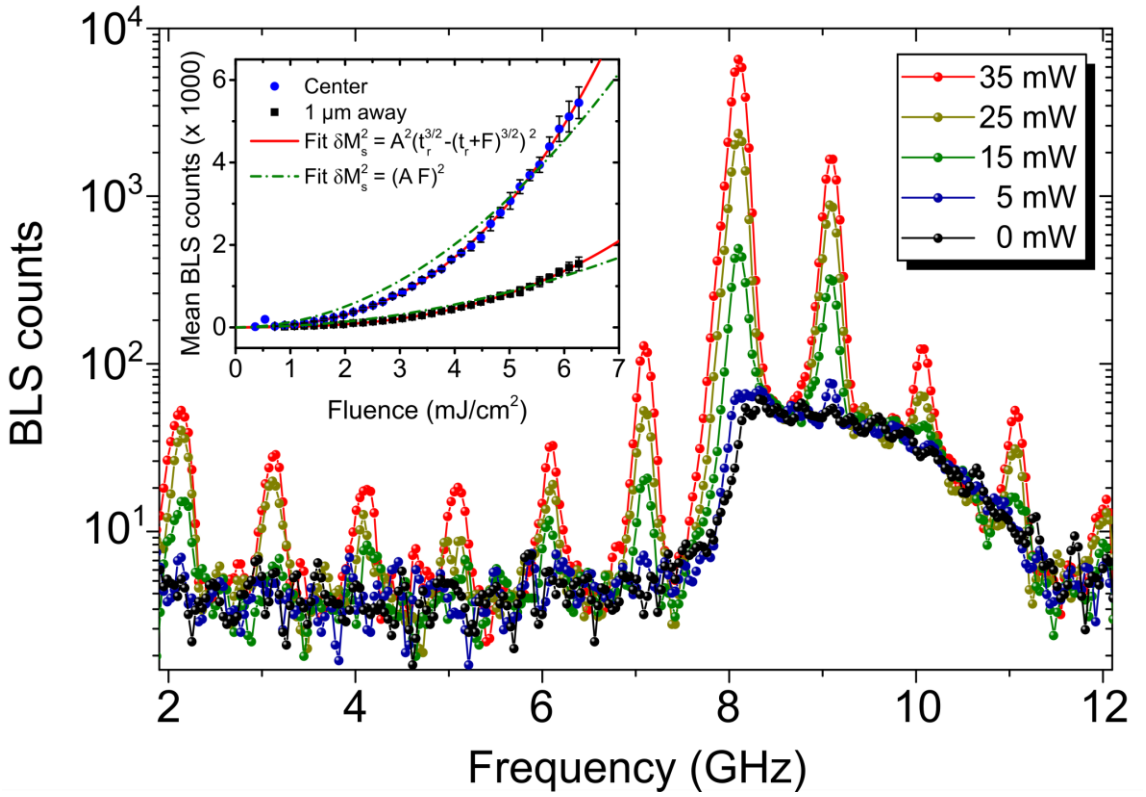


Figure 2: Spin wave spectrum at different laser powers. BLS counts vs. frequency in a field of 600 mT for only thermal SWs (black) and at four different pump powers showing pronounced peaks at the harmonics of the 1 GHz repetition rate. The inset shows the non-linear increase of the BLS counts for the 8 GHz mode with increasing pump fluence (F) at the center of the pump spot and 1 micron away together with two fits, one parabolic and the other based on a Bloch law model [5].

References:

[1]. M. van Kampen et. al., Phys. Rev. Lett. **88**, 22 (2002).
[2]. B. Koopmans et. al., Nature Materials. **9**, 259 (2010).
[3]. M. Jäckl et. al., Phys. Rev. X **7**, 021009 (2017).
[4]. A. Aleman et. al., Optics Express **28**, 29540 (2020).
[5]. S. Muralidhar et. al., Phys. Rev. B **126**, 224423 (2020).
[6]. A. A. Awad et. al., Appl. Phys. Lett. **120**, 012405, (2022)
[7]. S. Muralidhar et. al., Phys. Rev. Lett. **126**, 037204 (2021).

O12: Monday 12th, 4:30 – 4:50

Theory shakes hands with experiment: toward molecular nanospintronics

G. LEFKIDIS[1,2], J. LIU[1], B. C. MUMMANENI[1], R. SHI[1], and W. HÜBNER[1]

[1]Department of Physics, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[2]School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, 710072 Xi'an, China

As the thirst for computer power is ever-growing and computer technology slowly reaches the classical limits of conventional semiconductor electronics, new alternatives are needed. Innovation is thinkable with respect to the materials (e.g., employing nanostructures), and with respect to the logic (using quantum logic). Both paths can be met with magnetic molecules as building blocks. In this talk mainly some joint studies will be presented, from which it becomes clear that experimental results together with the added value of theoretical analysis can help to elucidate the mechanisms behind laser-induced spin dynamics in magnetic molecules and thus to pave the way toward full-fledged magnetic nanologic.

First, the time-dependent photoinduced dynamics in a Fe_3 cluster (Fig. 1a) is investigated. Besides providing an excellent theory-confirming agreement between computations and experiment regarding the peak positions (e.g., in magnetic circular dichroism spectra), by calculating the spin-conserving-to-spin-flipping branching ratios and interference contributions to the electronic excitations for various peaks, we reveal all spin channels in the experiment.

Second, and in order to analyze substrate effects, we exemplarily investigate the adsorption of iron porphyrin on Cu (100) (Fig. 1b) using second-harmonic generation. Once again, by looking into the hybridization and localization degree of the many-body states of the two subsystems (adsorbent and substrate) as well as the virtual inter-subsystem excitations, we extract surface-relevant information from a highly sensitive, yet intrinsically surface-independent experimental method.

Third, look into the magnetic properties of two magnetic polymers of Cu(II) complexes with a 1,2,3-triazole derivative as ligand, which help us better understand intermolecular magnetic interactions, and how to tune them by means of different stacking geometries [2]. More specifically, we study the the degree of polymerization and the arrangement of the monomers, as reflected in the measured and calculated magnetic susceptibility of the system.

Fourth, we study the ultrafast dynamics of the $[Dy_2Ni_2(L)_4(NO_3)_2(DMF)_2]$ compound after UV/Vis photoexcitation (Fig. 1c), and by comparing the theoretical and experimental time-dependent spectra we unveil the (partial) metal-to-oxygen charge transfer, estimate the thermal system-to-bath coupling constant, and detect a trapping intermediate state which explicitly explains the slowest observed relaxation [3].

Finally, we report some significant theoretical progress in coherently controlling the spin of magnetic structures, which we are able to functionalize as quantum gates. As concrete examples we present two functionalities. First we demonstrate the feasibility of a topological charge-spin gearbox on the

synthesized magnetic nanostructure $Co_3Ni(EtOH)$ (Fig. 1d), in which clockwise cyclic charge transfer results in counterclockwise cyclic spin transfer with a charge-to-spin translation ratio of $2:(-1)$ [4]. Second, by selecting special many-body states in $[Dy_2Ni_2(L)_4(NO_3)_2(DMF)_2]$ and using them as quantum bits, we succeed in designing laser-controlled implementations of the Controlled-NOT, Hadamard, SWAP, and Pauli gates, as well as in generating maximally entangled Bell states [5] (Fig. 1e).

Our findings can help us to elucidate the microscopic mechanisms behind ultrafast spin dynamics and pave the way towards designing of future nanospintronic devices.

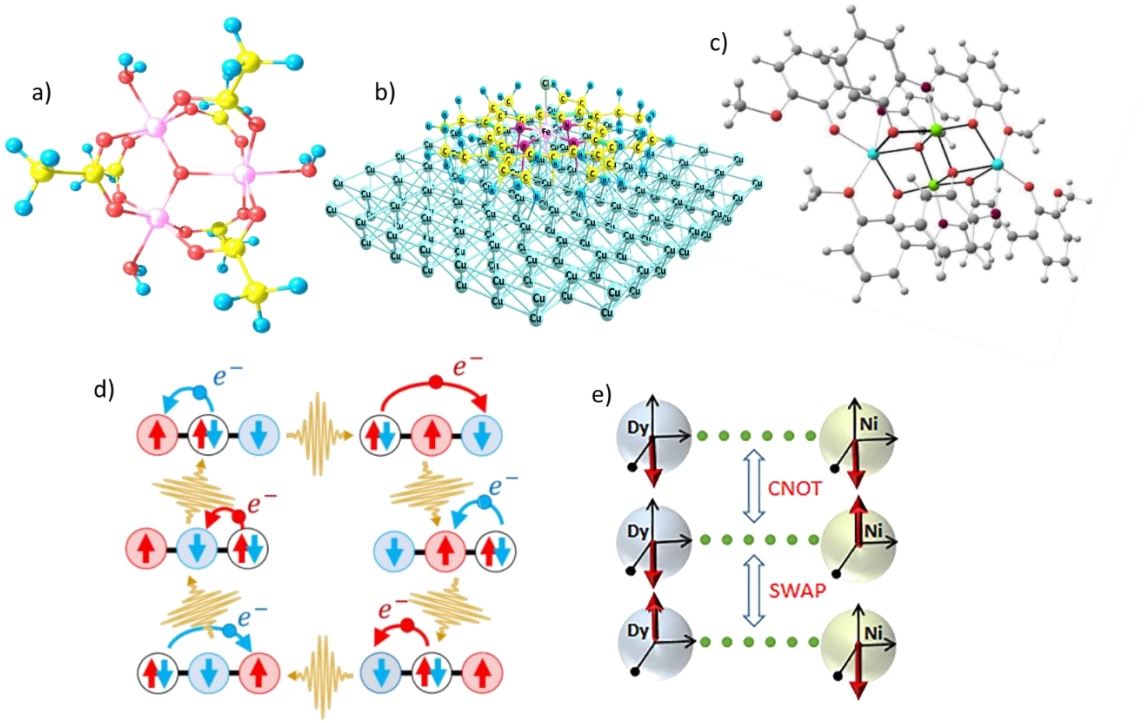


Figure 1: Some of the systems investigated: a) $Fe^{III}_2Fe^{II}O(CH_3CO_2)_6(H_2O)_3$. b) Iron porphyrin on Cu(100). c) $[Dy_2Ni_2(L)_4(NO_3)_2(DMF)_2]$. d) Schematic of charge-spin gearbox in $Co_3Ni(EtOH)$. e) Schematic of unary logic gates in $[Dy_2Ni_2(L)_4(NO_3)_2(DMF)_2]$.

References

[1] F. Liedy, R. Shi, M. Coletta, J. Vallejo, E. K. Brechin, G. Lefkidis, W. Hübner, and J. O. Johansson, J. Magn. Magn. Mater. **501**, 166476 (2020).

[2] S. Chen, B. C. Mummaneni, X. Jiang, Y. Chen, Y. Chen, G. Lefkidis, W. Hübner and L. Jia, Cryst. Growth Des. **21**, 2744 (2021).

[3] S. Sold, B. C. Mummaneni, N. C. Michenfelder, Y. Peng, A. K. Powell, A.-N. Unterreiner, G. Lefkidis, and W. Hübner, ChemistryOpen **11**, e202100153 (2022).

[4] G. Lefkidis, W. Jin, J. Liu, D. Dutta, and W. Hübner, J. Phys. Chem. Lett. **11**, 2592 (2020).

[5] B. C. Mummaneni, J. Liu, G. Lefkidis, and W. Hübner, J. Phys. Chem. Lett. **13**, 2479 (2022).

O13: Monday 12th, 4:50 – 5:20

Current-induced switching of rare-earth and transition-metal sublattices in ferrimagnetic alloys: synchronous vs asynchronous dynamics

Pietro Gambardella
[1]Department of Materials, ETH Zurich

Ferrimagnetic alloys are model systems for understanding domain wall dynamics and ultrafast magnetization switching in materials with antiferromagnetically-coupled sublattices. This talk will focus on the switching dynamics of rare-earth (RE) transition-metal (TM) alloys driven by spin-orbit torques, presenting combined insight into the temporal, spatial, and elemental evolution of the magnetization in GdFeCo/Pt and TbCo/Pt bilayers. Time-resolved anomalous Hall effect measurements during the injection of current pulses show that the spin-orbit-torque-induced dynamics comprises a ns-long incubation delay and a fast reversal phase due to stochastic nucleation of a reversed domain and deterministic domain wall propagation at speed >1 km/s [1]. Scanning x-ray transmission microscopy and micromagnetic simulations, on the other hand, show that the RE and TM magnetizations excited by ns-long current pulses can evolve asynchronously in time and inhomogeneously in space, leading to a delay between propagating domain walls in the two sublattices or even to a transient ferromagnetic state that can last as long as 2 ns [2]. Asynchronous switching of the two magnetizations was previously observed only for ultrafast optical excitations. Here it is ascribed to the master-agent dynamics induced by the spin-orbit torques on the TM-RE sublattices in combination with their weak antiferromagnetic coupling, which is shown to depend sensitively on the alloy microstructure. These results provide new insight into angular-momentum transfer and spin torque dynamics in ferrimagnets and clues on how to achieve maximum and uniform switching speed with minimal after-pulse dynamics.

References

[1] Real-time Hall-effect detection of current-induced magnetization dynamics in ferrimagnets, G. Sala, V. Krizakova, E. Grimaldi, C.-H. Lambert, T. Devolder and P. Gambardella, Nat. Comm. **12**, 656 (2021).
[2] Asynchronous current-induced switching of rare-earth and transition-metal sublattices in ferrimagnetic alloys, G. Sala, C.-H. Lambert, S. Finizio, V. Raposo, V. Krizakova, G. Krishnaswamy, M. Weigand, J. Raabe, M. D. Rossell, E. Martinez, and P. Gambardella, Nat. Mater. **21**, 640 (2022).

Tuesday September 13th

9:00 – 9:30
O14: *Ultrafast laser-induced spin currents and all-optical switching*
Bert Koopmans
9:30 – 9:50
O15: *Modeling diffusive transport in ultrafast demagnetization dynamics*
Sanjay Ashok
9:50 – 10:20
O16: *Ultrafast laser-induced nucleation of metastable skyrmions at zero field*
Oksana Chubykalo-Fesenko
Coffee break: 20 minutes
10:40 – 11:00
O17: *Femtosecond laser pulse trains driven sustained, coherent caustics and PSSW spinwave*
Ahmad Awad
11:00 - 11:30
O18: *Ultrafast photo-spin driven magnetization dynamics in ferromagnet/heavy metal thin film heterostructures*
Satoshi Iihama
11:30 - 11:50
O19: *Supermagnonic propagation in 2D antiferromagnets*
Johan Mentink
11:50 – 12:20
O20: *Ab-initio simulation of ultrafast spin dynamics: phonomagnetism and the giant optical spin hall effect*
Peter Elliott
12:20 AM - 2:00 PM: lunch & posters
2:00 - 2:30
O21: *Vibrational coherences in manganese single-molecule magnets after ultrafast photoexcitation*
Olof Johansson
2:30 - 2:50
O22: *Laser-induced metamagnetic phase transition of FeRh studied by combined UXRD and MOKE experiments*
Maximilian Mattern
2:50 - 3:20
O23: *Novel spin-wave sources for hybrid magnonic circuits*
Philipp Pirro
3:20 - 3:40
O24: *Helicity-Dependent THz emission from a Weyl semimetal Mn3Sn*
Dominik Hamara

O14: Tuesday 13th, 9:00 – 9:30

Ultrafast laser-induced spin currents and all-optical switching

Bert Koopmans
Department of Applied Physics, Eindhoven Hendrik Casimir Institute,
Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Novel schemes for controlling the ferromagnetic state at femtosecond time scales by pulsed laser excitation have received great interest. By driving systems into the strongly non-equilibrium regime, it has been shown possible not only to quench magnetic order, but also to switch the magnetization by single laser pulses – so-called all-optical switching (AOS). In parallel, it has been found that pulsed laser excitation can also induce spin currents over several to tens of nanometers, which can act as an additional source of sub-picosecond magnetization dynamics. Thereby, a scientifically exciting link between the fields of 'femtomagnetism' and spintronic transport physics has emerged. Moreover, it is being envisioned that combining the two fields could pave the way to a new class of hybrid spintronic-photonic devices, in which data is copied between photonic and magnetic (spintronic) domain without any intermediate electronic steps, leading to ultrafast and highly energy-efficient IT solutions.

In this presentation, some of the underlying phenomena will be addressed, new theoretical insights will be shared [1], and a selection of recent experimental results combing AOS and spin transport will be presented. A first focus will be on highly efficient AOS and current-induced domain wall motion in the very same system: Pt/Co/Gd trilayers, displaying strong spin-orbit torques and Dzyaloshinskii-Moriya interaction. It will be shown that the magnetization of this synthetic ferrimagnetic thin film system can be reversed fully deterministically using single fs pulses [2]. Although the switching displays toggle characteristics, transfer of angular momentum by laser-induced spin currents from a reference layer can be used to deterministically set the magnetization to the up and down state [3]. More recently, we explored spin currents generated in the Co/Gd bi-layer upon pulsed laser irritation [4]. Currents due to Co and Gd could be distinguished by carefully analyzing the GHz and THz spin waves in a neighboring non-colinearly aligned ferromagnetic layer experiencing a torque by the absorbed spin current [5]. Finally, examples of progress towards integrated spintronic-photonic devices will be presented, including current-induced domain wall motion in Pt/Co/Gd-based conduits that display efficient AOS [6] with domain-wall velocities over 2000 m/s [7], AOS of MTJs [8], as well on-chip magneto-optical reading of 300 x 400 nm^2 magnetic elements structured on top of InP photonic waveguides [9].

[1] M. Beens et al., Phys. Rev. B, 220409 (R), (2019); Phys. Rev. B 102, 05442 (2020).
[2] M.L.M. Lalieu, et al., Phys. Rev. B 96, 220411(R) (2017).
[3] Y.L.W. van Hees et al., Nat. Commun. 11, 3835 (2020).
[4] G.-M. Choi et al., Phys. Rev. B 97, 014410, (2018).
[5] T. Lichtenberg, Y.L.W. van Hees et al., in preparation.
[6] M.L.M. Lalieu et al., Nat. Commun. 10, 110 (2019).
[7] P. Li, T. Kools, et al., arXiv:2204.11595.
[8] L. Wang et al., PNAS 119, e2204732119 (2022).
[9] F.E. Demirer, et al., Nanophotonics (2022), in press.

O15: Tuesday 13th, 9:30 – 9:50

Modeling diffusive transport in ultrafast demagnetization dynamics

S. Ashok, S. T. Weber, C. Seibel, J. Briones, H. C. Schneider and B. Rethfeld
Fachbereich Physik and OPTIMAS Research Center, TU Kaiserslautern, Kaiserslautern, Germany

Ultrafast demagnetization dynamics in thick metallic magnetic films is greatly influenced by diffusive heat and charge transport processes [1]. In this contribution we present the space-resolved magnetization dynamics in a thick Nickel film induced by a femtosecond laser pulse. Starting from the thermodynamic T-model [2], we explicitly include diffusive heat transport, spin-resolved charge transport, as well as Seebeck and Peltier effects.

We find that the diffusive transport has an influence on the spin-resolved temperatures, chemical potentials and magnetization dynamics closer to the excited surface as well as in regions deeper than the penetration depth of the laser. Our results in Figure 1 show that the spatial dependence of maximal *magnitude* of quenching is induced by a depth-dependent energy deposition and is only moderately equilibrated by transport processes. We reveal a stronger influence of transport on the *time* of quenching which becomes nearly independent of depth [1].

We further study the influence of pump-wavelength on spatially resolved magnetization dynamics as revealed experimentally [3]. Additionally, we discuss the role of non-equilibrium electrons and superdiffusive transport [4]. We present first results on coupling Monte-Carlo methods with the thermodynamic T-model.

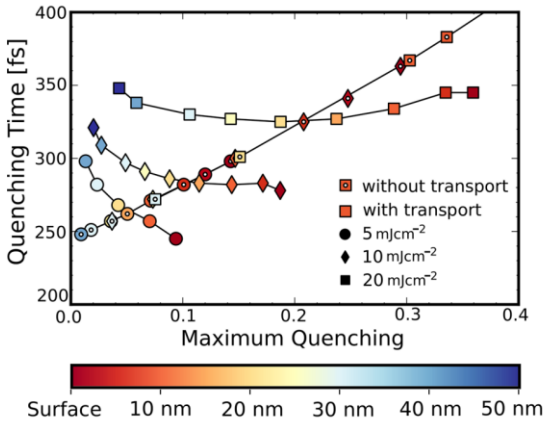


Figure 1: Quenching time over the maximum magnitude of quenching at various depths of the material for fluences of 5; 10; and 20 mJ/cm^{-2} . Hollow and filled markers denote calculations without and with-transport, respectively. The color map (color online) denotes the depth from the surface of the thick film. The black solid lines behind the data points are a guide to the eye.

References:
[1] S. Ashok, C. Seibel, S. T. Weber, J. Briones and B. Rethfeld, Appl. Phys. Lett. 120, 142402 (2022)
[2] B.Y. Mueller and B. Rethfeld, Phys. Rev. B. 90, 144420 (2014)
[3] U. Bierbrauer, S. T. Weber, D. Schummer, M. Barkowski, A.-K. Mahro, S. Mathias, H. C. Schneider, B. Stadtmueller, M. Aeschlimann and B. Rethfeld, JOP Cond. Mat., 29 (24), 244002 (2017)
[4] J. Briones, H. C. Schneider and B. Rethfeld, J. Phys. Commun. 6, 035001 (2022)

O16: Tuesday 13th, 9:50 – 10:20

Ultrafast laser-induced nucleation of metastable skyrmions at zero field

P. Olleros-Rodríguez[1] , M. Strungaru[2], S. Ruta[2], P. Gavriloaea[3], P. Perna[1], R. Chantrell[2], and O. Chubykalo-Fesenko[3]

[1]IMDEA Nanoscience Institute, Madrid, Spain
[2]Physics Department, University of York, UK
[3] Instituto de Ciencia de Materiales de Madrid, CSIC, Spain

Nucleation of skyrmions in ultrathin films composed of transition and high spin-orbit metals by ultra-fast femtosecond laser pulses has been very recently reported both experimentally and theoretically [1,2], albeit under applied field, i.e. when skyrmion are the ground state of the system. In the present work we explore the nucleation of magnetic skyrmions in realistically parametrised Pt/Co/Heavy-Metal magnetic trilayers via atomistic simulations by ultrafast heating produced by a femtosecond laser pulse. Quasi-static simulations by increasing temperature above the Curie one and cooling the system down produce a stable state in the form of stripe domains. However, we report that ultrafast heating at zero field with specific duration can create non-adiabatic processes leading to the nucleation of unstable magnon droplets, similar to the formation of supercooled ice droplets in the gas state. Then, the subsequent rapid energy removal provides the conditions for the creation and quenching of the skyrmion topological protection. The interplay between different processes corresponds to a specific excitation window which can be additionally controlled by external fields. Our results provide insight into the dynamics of the highly non-equilibrium pathway for spin excitations and pave additional routes for skyrmion-based information technologies.

[1] S. G. Je et al Nano Lett. 18 (2018) 7362
[2] F.Buttner et al Nat. Mater. 20 (2021) 30.

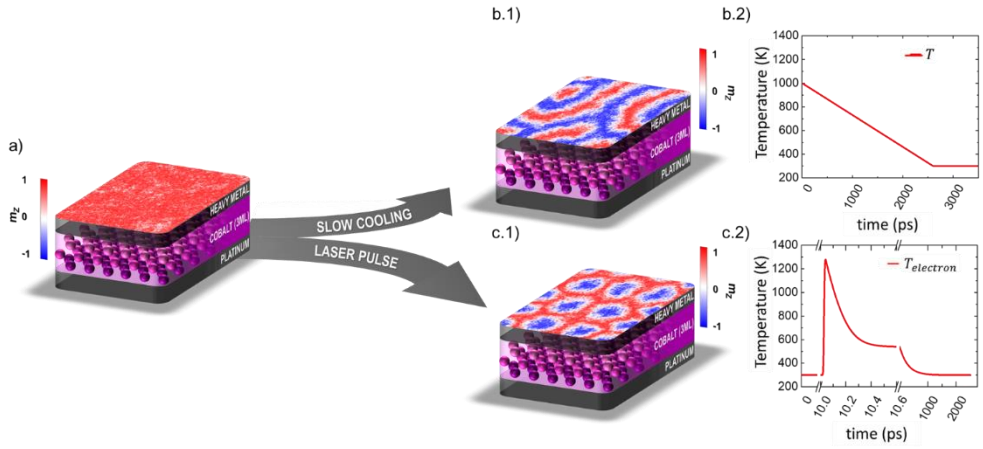


Figure 1: Simulated images: initial state at 300K (left images), the stripe domain state after slow cooling down from Curie temperature (right upper image),, skyrmion state after ultrafast heating (right down image)

O17: Tuesday 13th, 10:40 – 11:00

Femtosecond laser pulse trains driven sustained, coherent caustics and PSSW spinwave

A. A. Awad[1], S. Muralidhar[1], A. Aleman[1], R. Khymyn[1], D. Hanstorp[1] and J. Åkerman[1,2]
[1]University of Gothenburg, Kemivägen 9, 41296, Göteborg, Sweden
[2] KTH Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden

Spinwaves provide an immense potential for information technology with scalable, faster and energy-efficient tunable devices. Thanks to Spinwave group velocity, low power operation and easy tunability using different means including magnetic, electrical field and spin polarized currents. Sustained SWs could be excited electrically using either microwave sources or direct current and by focused optical pulses [1] on a thin magnetic film. It has been observed that the optical excitation of the magnetic order occurs a few orders of magnitude faster than electrical excitation [2]. However, due to the decay time of the SWs, the optically induced emission of SWs is not continuous. To obtain sustainable spinwaves, repetitive pulses with a very short time period between pulses should be used. Meanwhile such approach presents an attractive means of excitation for magnonics research, there are still very few works addressing such an option [3]. moreover, optical pump-probe measurements have primarily been based on Magneto-Optical Kerr Effect (MOKE) using low repetition rate. A recent approach uses instead a μ-focused Brillouin light scattering (BLS) technique to investigate the optically excited spin dynamics [4]. Using such approach provide a much higher sensitivity to coherent and incoherent SWs and provide additionally information on elastically excited excitations, the pioneer results showed spinwave stimulated emission tunable using the applied magnetic field magnitude and direction, and wavevector selective [5].

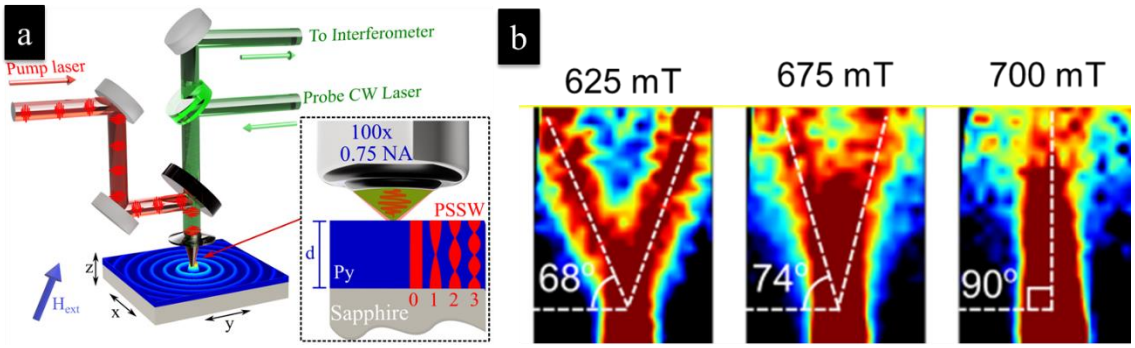


Figure 1: (a) Schematic of the 1 GHz-pulsed femtosecond laser comb BLS experiment on Py films. (b) stimulated spinwaves at 8 GHz with propagation and caustic characteristics the color plots are compensated for the SW decay.

Here, we show that high-frequency laser combs (Fig.1.a) be used to generate coherent, sustained spin waves (SWs) in a range of thicknesses of Permalloy films. The emission is fully modeled using a simple rapid demagnetization model for all film thicknesses. In thicker films, perpendicular standing spin waves PSSWs are excited up to the third order (18 multiples of the 1 GHz laser repetition rate) are observed [6]. Additionally, we demonstrate that the excitation scheme could be considered as a point-

like source of continuous spin waves, as predicted by theory, caustic spinwave patterns (Fig.1.b) are observed [7]. As the repetition rate of the light source approaches the FMR, the caustic pattern gives way to a uniaxial spin wave propagating perpendicular to the in-plane component of the applied field. This field-controlled propagation pattern and directionality of optically driven short-wavelength spin waves provide additional degrees of freedom when designing magnonic devices. We believe that our demonstration of using a high repetition rate femtosecond laser for the stimulated excitation of selective continuous spin waves, probed using, averaging technique, BLS microscopy, will enable a wide range of additional photo-magnonic research on magnetic thin films, magnonic and spintronic devices.

References:

[1]. M. van Kampen et. al., Phys. Rev. Lett. **88**, 22 (2002).
[2]. B. Koopmans et. al., Nat. Mats. **9**, 259 (2010).
[3]. M. Jäckl et. al., Phys. Rev. **X 7**, 021009 (2017).
[4]. A. Aleman et. al., Optics Express **28**, 29540 (2020).
[5]. S. Muralidhar et. al., Phys. Rev.**B 126**, 224423 (2020).
[6]. A. A. Awad et. al., App. Phys. Lett. **120**, 012405, (2022)
[7]. S. Muralidhar et. al., Phys. Rev. Lett. **126**, 037204 (2021).

O18: Tuesday 13th, 11:00 – 11:30

Ultrafast photo-spin driven magnetization dynamics in ferromagnet/heavy metal thin film heterostructures

Satoshi Iihama[1,2], Kazuaki Ishibashi[3,2], Shigemi Mizukami[2,4]
[1]Frontier Research Institute for Interdisciplinary Science (FRIS), Tohoku University, Japan
[2]WPI-Advanced Institute for Materials Research (AIMR), Tohoku University, Japan
[3]Department of Applied Physics, Tohoku University, Japan
[4]Center for Science and Innovation in Spintronics (CSIS), Tohoku University, Japan

All-optical magnetic recording of ferromagnetic thin films using circularly polarized laser pulses has been reported [1-4]. In the all-optical helicity-dependent magnetization switching, magnetization directions after irradiation of circularly polarized laser pulses are determined by photon-helicities. However, mechanism of the magnetization switching has been considered to be stochastic thermal process such as magnetic circular dichroism, leading to slower control of magnetization direction. If one uses direct coupling between photon and magnetization such as the inverse Faraday effect, much faster excitation of magnetization dynamics can be realized by using femtosecond laser pulses. Recently, magnetization dynamics driven by direct coupling between photon and spin in metallic heterostructures has been reported, which can be used to excite magnetization dynamics in thin film metallic ferromagnets [5-8]. We have observed photon-helicity driven magnetization dynamics in ferromagnet/heavy metal heterostructure thin films such as FeCo/Pt, Co/Pt and Co/Au bilayers [7,8]. The ferromagnetic layer and heavy metal layer thickness dependencies of photon-helicity driven magnetization dynamics were studied in details. Measurement results were discussed in terms of the inverse Faraday effect in ferromagnets, photon spin injection into heavy metals, and photonic spin generation by the optical Rashba-Edelstein effect owing to structural inversion symmetry breaking of the heterostructure.

Thin film samples were prepared by magnetron sputtering technique. The ferromagnet/heavy metal heterostructures with different thicknesses were deposited on thermally oxidized silicon substrate. Photon-helicity driven magnetization dynamics was measured using stroboscopic pump-probe technique. Wavelength, pulse duration and repetition rate of femtosecond laser pulse were 800 nm, ~ 120 fs and 1 kHz, respectively. Figure 1(a) shows schematic illustration of circularly polarized laser pulse induced magnetization dynamics in ferromagnet/heavy metal bilayers. In-plane external magnetic field was applied in the measurement. In this configuration, magnetization precession excited by a change in anisotropy/demagnetizing field cannot be induced. Figure 1(b) shows circularly polarized laser-induced change in normalized Kerr rotation angle for Co(2)/Pt(3) bilayer sample (thickness is in nm) where pump fluence of 7.8 J/m^2 was used. The phase of magnetization precession is reversed when photon-helicity changes, indicating photon-helicity driven torques. To evaluate photon-helicity driven torques, difference between signals measured with right-circularly polarized (RCP) light and left-circularly polarized (LCP) light was taken as shown in Fig. 1(c). The photon-helicity induced signals were analyzed by fitting. By using the procedure mentioned above, one can evaluate photon-helicity driven spin-transfer torque and field-like torque. In the presentation, quantitative discussion of the photon-helicity driven spin-transfer torque and field-like torque with different ferromagnet/heavy metal heterostructures will be presented.

This work is partially supported by KAKENHI (Nos. 19K15430, 21H05000), the Asahi Glass Foundation, the Murata Science Foundation, and FRIS Creative Interdisciplinary Collaboration Program in Tohoku

University. K. I. acknowledges Grant-in-Aid for JSPS Fellow (No. 22J22178) and GP-Spin at Tohoku University. S. M. acknowledges CSRN in CSIS at Tohoku University.

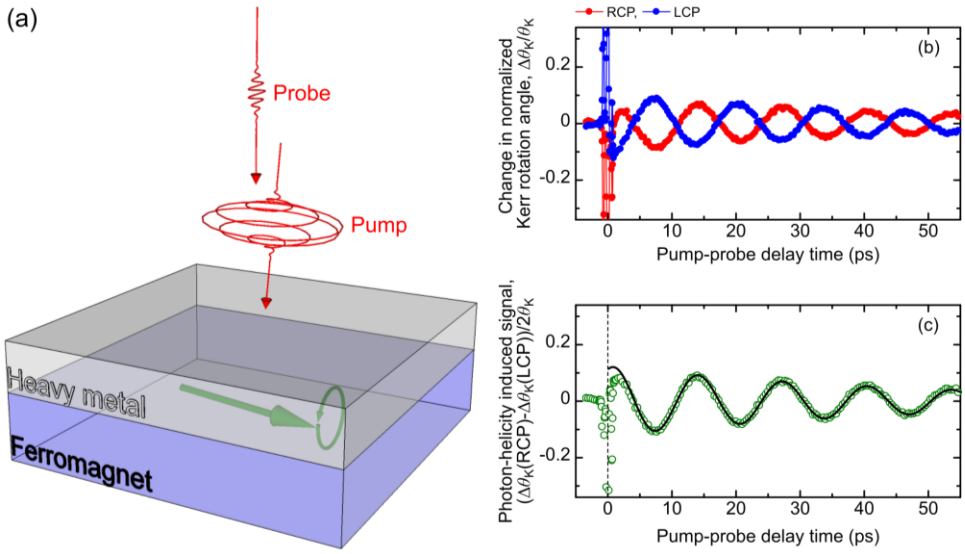


Figure 1(a) Schematic illustration of circularly polarized laser pulse induced magnetization dynamics measurement in ferromagnet/heavy metal heterostructure. (b) Circularly polarized laser pulse induced magnetization dynamics in 2-nm-thick Co/3-nm-thick Pt bilayers deposited on thermally oxidized Si substrate with different photon-helicities (RCP: right-circularly polarized laser pulse, LCP: left-circularly polarized laser pulse). (c) Difference of signals measured with different photon-helicities. Solid curve is fitted results by using sinusoidal decayed function.

Reference

[1] C. H. Lambert, S. Mangin, B. S. D. C. S. Varaprasad, Y. K. Takahashi, M. Hehn, M. Cinchetti, G. Malinowski, K. Hono, Y. Fainman, M. Aeschlimann, and E. E. Fullerton “All-optical control of ferromagnetic thin films and nanostructure” Science **345**, 1337 (2014)

[2] M. S. El Hadri, P. Pirro, C. H. Lambert, S. Petit-Watelot, Y. Quessab, M. Hehn, F. Montaigne, G. Malinowski, and S. Mangin “Two types of all-optical magnetization switching mechanisms using femtosecond laser pulses” Phys. Rev. B **94**, 064412 (2016)

[3] R. Medapalli, D. Afanasiev, D. K. Kim, Y. Quessab, S. Manna, S. A. Montoya, A. Kirilyuk, T. Rasing, A. V. Kimel, and E. E. Fullerton “Multiscale dynamics of helicity-dependent all-optical magnetization reversal in ferromagnetic Co/Pt multilayers” Phys. Rev. B **96**, 224421 (2017)

[4] R. John, M. Berritta, D. Hinzke, C. Müller, T. Santos, H. Ulrichs, P. Nieves, J. Walowski, R. Mondal, O. Chubykalo-Fesenko, J. McCord, P. M. Oppeneer, U. Nowak, and M. Münzenberg “Magnetization switching of FePt nanoparticle recording medium by femtosecond laser pulses” Sci. Rep. **7**, 4114 (2017)

[5] G. M. Choi, A. Schleife, and D. G. Cahill “Optical-helicity-driven magnetization dynamics in metallic ferromagnets” Nat. Commun. **8**, 15085 (2017)

[6] G. M. Choi, J. H. Oh, D. K. Lee, S. W. Lee, K. W. Kim, M. Lim, B. C. Min, K. J. Lee, and H. W. Lee “Optical spin-orbit torque in heavy metal-ferromagnet heterostructures” Nat. Commun. **11**, 1482 (2020)

[7] S. Iihama, K. Ishibashi, and S. Mizukami “Interface-induced field-like optical spin torque in a ferromagnet/heavy metal heterostructure” Nanophotonics **10**, 1169 (2021)

[8] S. Iihama, K. Ishibashi, and S. Mizukami “Photon spin angular momentum driven magnetization dynamics in ferromagnet/heavy metal bilayers” J. Appl. Phys. **131**, 023901 (2022)

O19: Tuesday 13th, 11:30 – 11:50

Supermagnonic propagation in 2D antiferromagnets

G. Fabiani[1], M.D. Bouman[1] and J.H. Mentink[1]:
[1]Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

Magnons, the collective excitations of magnetically ordered materials can oscillate up to 100 THz over less than one nanometer. With intrinsically small energy loss, such magnons have great potential for smaller, faster and more energy-efficient data processing. However, understanding the magnon spectrum at such short wavelengths has been challenging even for the simplest model: the antiferromagnetic Heisenberg model in 2D [1]. Furthermore, studying the space-time dynamics of this model defines an intricate quantum many-body problem out of equilibrium, for which until recently no accurate methods were available.

Beyond the limitations of existing methods, we adopt a machine learning inspired ansatz [2] to simulate the dynamics of the 2D Heisenberg model [3-4]. In this approach, the wavefunction of the system is approximated with a restricted Boltzmann machine, which allows us to simulate systems up to 24x24 spins. We show that quench-like perturbations of the exchange interaction excite dynamics of spin correlations, which spread highly anisotropically in space. Interestingly, we find that magnon-magnon interactions enhance the spreading speed up to 40% above the highest magnon velocity. Furthermore, opposed to well-known results in one dimension, we find that the dynamics of entanglement is not determined by the highest magnon velocity, but changes much faster on the time scale determined by the oscillation frequency of zone-edge magnon pairs [5]. We believe that our results are fundamental for understanding magnetism on the shortest length and timescale and may have high impact on the future development of faster and smaller magnon-based information processing.

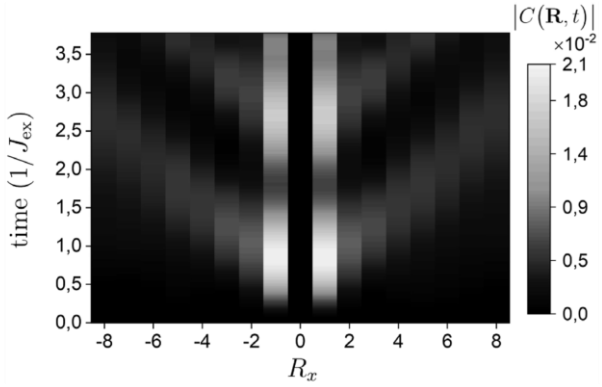


Figure 1: Snapshots of spin correlations in the Heisenberg model on a 20x20 lattice. Following small impulsive perturbations of the exchange interaction leads to spreading of correlations with a speed that is transiently higher than the highest magnon velocity.

References

[1] H. Shao et al, Phys Rev X 7, 041072(2017)
[2] G. Carleo & M. Troyer, Science 355, 602(2017)
[3] G. Fabiani & J.H. Mentink, SciPost Phys 7, 004(2019)
[4] G. Fabiani, M.D. Bouman and J.H. Mentink, Phys. Rev. Lett 127, 097202 (2021)
[5] G. Fabiani & J.H. Mentink, Phys. Rev. B 105, 094438 (2022)

O20: Tuesday 13th, 11:50 – 12:20

Ab-initio simulation of ultrafast spin dynamics: phonomagnetism and the giant optical spin hall effect

P.Elliott[1], S. Shallcross[1], J.K. Dewhurst[2], S. Sharma[1]
[1]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin 12489, Germany
[2]Max Planck Institute of Microstructure Physics, Halle 06120, Germany

Real-time time-dependent density functional theory (TDDFT) is an ab-initio simulation method to study the quantum-mechanical electron dynamics on ultrafast time scales. In recent years, we have applied TDDFT to study ultrafast demagnetization[1], optically induced spin transfer between sub lattices[2], and transient EUV MCD spectra[3].

In our latest work, we show that coupling phonon excitations of the nuclei to spin and charge leads to femto-phono-magnetism, a powerful route to control magnetic order at ultrafast times. We identify strong non-adiabatic spin-phonon coupled modes that dominate early time spin dynamics. Activating these phonon modes we show leads to an additional (up to 25\%) loss of moment in FePt occurring within 4 femtoseconds of the pump laser pulse. Our finding demonstrates that the nuclear system, often assumed to play
only the role of an energy sink aiding long time re-magnetisation of the spin system, can play a profound role in controlling femtosecond spin-dynamics in materials.

We also study the spin Hall effect which plays a crucial role in spintronics, as both a generator (and detector) of spin current, which may be subsequently be used in spin-orbit-torque devices. We generalize the spin Hall angle to laser pulses of finite frequencies in the linear response regime and predict a giant optical spin Hall effect. Namely, for certain transition metal elements, at particular frequencies, the spin current can be a significant fraction of the charge current, and even exceed it for XUV frequencies.

References

[1] Krieger et al., Laser-induced demagnetization at ultrashort time scales: Predictions of TDDFT, J. Chem. Theor. Comp. **11**, 4870 (2015).
[2] Elliott et al., Ultrafast laser induced local magnetization dynamics in Heusler compounds, Sci. Rep. **6**, 38911 (2016).
[3] Dewhurst et al., Element specificity of transient extreme ultraviolet magnetic dichroism, Phys. Rev. Lett. **124**, 077203 (2021).

O21: Tuesday 13th, 2:00 – 2:30

Towards ultrafast optical control of single-molecule magnets

K. Barlow,[1] R. Phelps,[1] J. Eng,[2] E. Sutcliffe,[1] E. K. Brechin,[1] T. J. Penfold,[2] and J. O. Johansson[1]
[1]EaStCHEM School of Chemistry, University of Edinburgh, UK
[2]Chemistry, School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK

Despite the rapid expansion of femtomagnetism, molecular magnets have so far been under-explored using ultrafast techniques. These materials offer interesting possibilities because it is possible to systematically fine-tune the magnetic interactions due to the vast library of molecular structures accessible with synthetic chemistry, which is not as trivial in conventional magnets.

We have studied a range of large molecular systems with exchange-coupled electrons, ranging from single-molecule magnets to magnetic coordination polymers, to explore ultrafast spin dynamics in molecules with several magnetic centres. Specifically, we have carried out measurements on a tri-nuclear Mn^{3+}-based single-molecule magnet (SMM), whose magnetic anisotropy is closely related to the Jahn-Teller (JT) distortion. Ultrafast transient absorption spectroscopy in solution at room-temperature reveals oscillations superimposed on the decay traces with corresponding energies around 200 cm^{-1}, coinciding with a vibrational mode along the JT axis. The oscillations arise due to a vibronic wavepacket forming as the molecule adjust to the new JT geometry in the excited state [1]. Because of the strong connection between the JT distortion and the magnetic anisotropy, forming vibronic wavepackets along the JT axis open up possibilities to coherently manipulate the magnetisation in SMMs. We have more recently shown that it is possible to synthetically control the decoherence time of the wavepackets by restricting certain bonds and thereby steering the nuclear motion in the excited state [2,3].

We will also report on a newly-developed broadband time-resolved magnetic circular dichroism (TRMCD) spectrometer we have constructed and tested in order to study low-dimensional materials with magneto-optics [4]. Because of the reduced dimensionality, the spectral dependence of the MCD signal becomes important, which we have demonstrated in thin flakes of the layered ferromagnet $Cr_2Ge_2Te_6$ [5].

References

[1] F. Liedy, J. Eng, R. McNab, R. Inglis, T. Penfold, E. K. Brechin, and J. O. Johansson, *Nature Chemistry.*, **12**, 452 458 (2020).
[2] K. Barlow, J. Eng, I. Ivalo, M. Coletta, E. K. Brechin, T. J. Penfold, and J. O. Johansson, *Dalton Transactions*, DOI: 10.1039/D2DT00889K (2022).
[3] Phelps, R., A. Etcheverry Berrios, E. K. Brechin, and J. O. Johansson, *in prep.* (2022).
[4] J. Sutcliffe and J. O. Johansson, Rev. Sci. Instrum. **92**, 113001 (2021).
[5] E. Sutcliffe, I. Verzhbitskiy, X. Sun, G. Eda, and J. O. Johansson, *submitted* (2022).

O22: Tuesday 13th, 2:30 – 9:50

Laser-induced metamagnetic phase transition of FeRh studied by combined UXRD and MOKE experiments

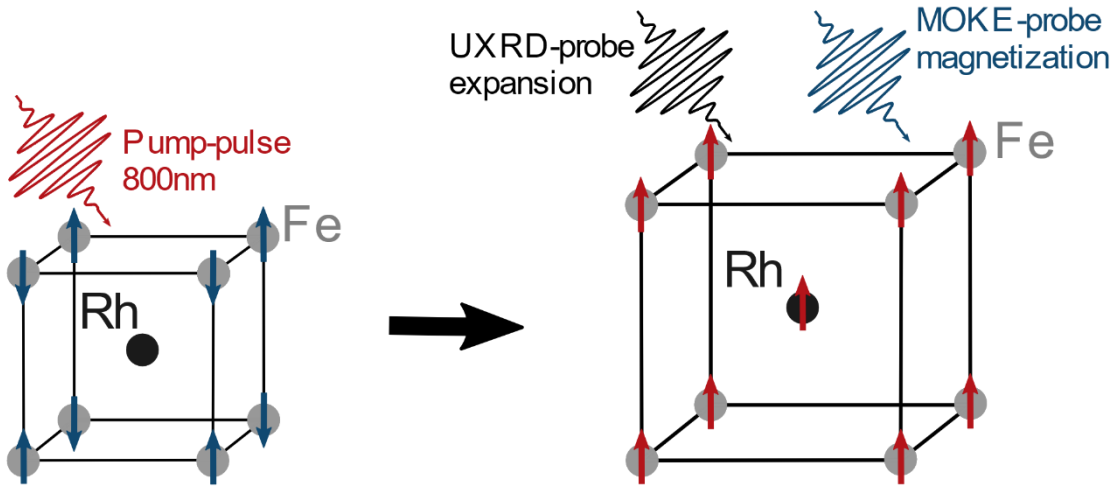
M. Mattern[1], J. Jarecki[1], V. Uhlir[2], J. A. Arregi[2], and M. Bargheer[1,3]

[1]Institute of Physics and Astronomy, University of Potsdam, Germany
[2]CEITEC BUT, Brno University of Technology, Czech Republic
[3]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

We use time-resolved X-ray diffraction (UXRD) and the polar magneto-optical Kerr effect (MOKE) to study the laser-induced metamagnetic phase transition in FeRh. FeRh undergoes a first-order phase transition from an antiferromagnetic (AFM) to a ferromagnetic (FM) phase upon equilibrium heating at ~360K. This phase transition is accompanied by a gigantic (~0.6%) which we use to assign the magnetic phases.

Using X-ray diffraction, we determine the ferro- and antiferromagnetic volume fraction by measuring the contributions with large (FM) and small (AFM) lattice constants. The UXRD measurements with sub-picosecond time-resolution access the laser-induced time-dependent ferromagnetic volume fraction independent of the orientation of the magnetic moment of different domains. In contrast, polar MOKE probes the net magnetization along the out-of-plane direction and is therefore sensitive to different orientations of the magnetization of the arising ferromagnetic order. With our combined UXRD and MOKE experiments we investigate the nucleation, growth and coalescence dynamics of the metamagnetic phase transition.

Figure 1: Schematic sketch of the laser-induced metamagnetic phase transition of FeRh changing the magnetic order (arrows) and the lattice constant probed by MOKE and UXRD, respectively.



We disentangle the timescales of the in- and out-of-plane expansion of the laser-induced ferromagnetic domains by measuring two samples, with a thickness below and above the optical penetration depth. The homogeneously excited thin FeRh film displays a fluence-independent rise time

of the FM phase of 8ps in the UXRD experiment. In contrast, the MOKE measurements display a slow rise of the net magnetization within the first 150ps starting 5-10ps after excitation. These results indicate the nucleation of small super-paramagnetic FM domains within the first picoseconds which slowly merge to a large domain with a net magnetization. For low fluences, the inhomogeneously excited thick FeRh film shows a similar behavior as the thin film. However, with increasing fluence the rise of the ferromagnetic volume fraction measured by UXRD becomes slower reaching its maximum at 150ps. By the MOKE measurements, we prove that the slow rise of the FM phase originates from the out-of-plane growth of the FM domains by heat diffusion from the excited near surface region to the bottom of the layer.

O23: Tuesday 13th, 2:50 – 3:20

Novel spin-wave sources for hybrid magnonic circuits

M. Geilen[1], Q. Wang[2], R. Verba[3], B. Heinz[1], A. Nicoloiu[4], D. Narducci[5], A. Dinescu[4], A. Hamadeh[1], M. Schneider[1], F. Ciubotaru[5], M. Weiler[a], A. Müller[d], B. Hillebrands[a], C. Adelmann[e], A. Chumak[b] and P. Pirro[a]

[a] Fachbereich Physik and Landesforschungszentrum OPTIMAS, TU Kaiserslautern, Germany

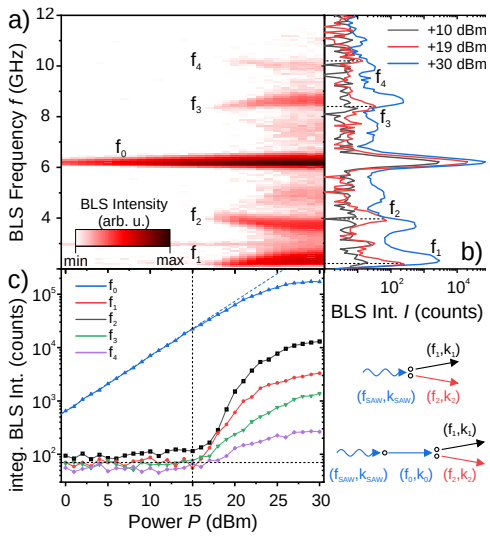
[b]Faculty of Physics, University of Vienna, Vienna, Austria

[c]Institute of Magnetism, Kyiv, Ukraine

[d]National Institute for Research and Development in Microtechnologies, Bucharest, Romania

[e] imec, Leuven, Belgium

Spin waves are ideal candidates for wave-based computing since they offer pronounced nonlinear properties, wavelengths scalable to the nanometre range and GHz clock rates compatible with CMOS-based circuits. Recently, numerous linear and nonlinear magnonic building blocks have been demonstrated [1]. However, a technologically competitive implementation of magnonic circuits requires novel magnon sources with higher excitation efficiencies, the capability to excite short wavelengths, and an efficient way to create normalized signals. In this context, I discuss two routes towards novel magnon sources.



Parametric phonon-to-magnon instability in a CoFeB film excited by SAW at frequency f_0. (a) and (b) BLS spectra (c) intensity of the involved modes as a function of SAW power.

The first route is magneto-elastic excitation, where mechanical strain is used to excite spin waves. First, I present the generation of spin waves by surface acoustic waves (SAW) in a thin metallic ferromagnetic film of CoFeB. Micro-focused Brillouin light scattering spectroscopy (μBLS) proves that the magneto-elastic excitation can efficiently drive the spin waves into the nonlinear regime (see Figure) [2]. Analytical and numerical modelling is used to reveal the different phonon-magnon instability processes by identifying the involved mechanisms and magnon modes. As a further step towards nanoscaled magneto-elastic emitters, I present results on magnon-phonon interaction in nano devices composed of piezoelectric elements with lateral dimensions down to 80 nm mechanically coupled to magnon waveguides.

The second route for novel sources is the use the spin-wave nonlinearity itself in the excitation process. Using μBLS, we demonstrate an unprecedented nonlinear frequency shift of more than 2 GHz for spin waves in out-of-plane magnetized nano-waveguides. This shift enables the excitation of exchange spin waves of wavelength down to tens of nanometers. Moreover, the amplitude of the excited spin-wave is independent of the input microwave power due to self-locking by the nonlinear shift. This nonlinear method removes the wavelength limitations imposed by the size of inductive antennas, increases the excitation efficiency of short-wavelength spin waves, provides a way to robustly set the output amplitude to a fixed value, and enables direct on-chip integration.

[1] A. V. Chumak, et al., *IEEE T Magn*, **58**, 0800172 (2022).

[2] M. Geilen et al., arXiv:2201.04033 (2022).

O24: Tuesday 13th, 3:20 – 3:40

Helicity-Dependent THz emission from a Weyl semimetal Mn_3Sn

D. F. Hamara[1], G. Lange[1], R. J. Slager[1], C. Felser[2], C. Ciccarelli[1]
[1]University of Cambridge
[2]Max Planck Institute

Noncollinear antiferromagnets (AFs) are becoming increasingly important in the field of spintronics. Over the past few years, they have been shown to display various phenomena, such as large anomalous Hall[1,2] and Nernst effects[3], normally absent in AFs. One prominent member of this group is Mn_3Sn, characterised by a 120° noncollinear spin ordering in a Kagome-type lattice[1].

Recent *ab initio* calculations, followed by experimental works, have discovered fascinating topological properties of the material and demonstrated Mn_3Sn as a magnetic Weyl semimetal (WSM) with broken time-reversal symmetry[4,5]. The characteristic feature of WSMs is the existence of Weyl nodes, points in momentum space where the conduction and valence bands cross. Every Weyl node has a definitive chirality that determines the response to circularly polarised light, depending on its helicity. Asymmetric transitions in k-space lead to the emergence of photocurrents in real space due to photogalvanic and photon drag effects. These phenomena have been demonstrated in other WSMs, such as TaAs[6] and RhSi[7].

Here, we report an experimental observation of helicity-dependent photocurrents in Mn_3Sn using Terahertz (THz) time domain spectroscopy. In our contactless experiments, we pump a thin Mn_3Sn film with ultrafast optical pulses. The quasi-dc photocurrents generated at a sub-picosecond timescale lead to the emission of electric fields in the THz frequency range. The THz radiation is detected as a function of various parameters, such as the pump polarisation, the sample orientation, and the applied magnetic field. We have discovered that varying the helicity of circularly polarised pump pulses leads to a full polarity change of the detected THz transients (see **Figure 1**).

To interpret the experimental results, we have performed tensor analysis for the Mn_3Sn magnetic point group, for both interface and bulk. Our considerations verify the crucial role of the film interface and the noncollinear magnetic ordering. We attribute the helicity-dependent photocurrents to the circular photogalvanic and circular photon drag effects.

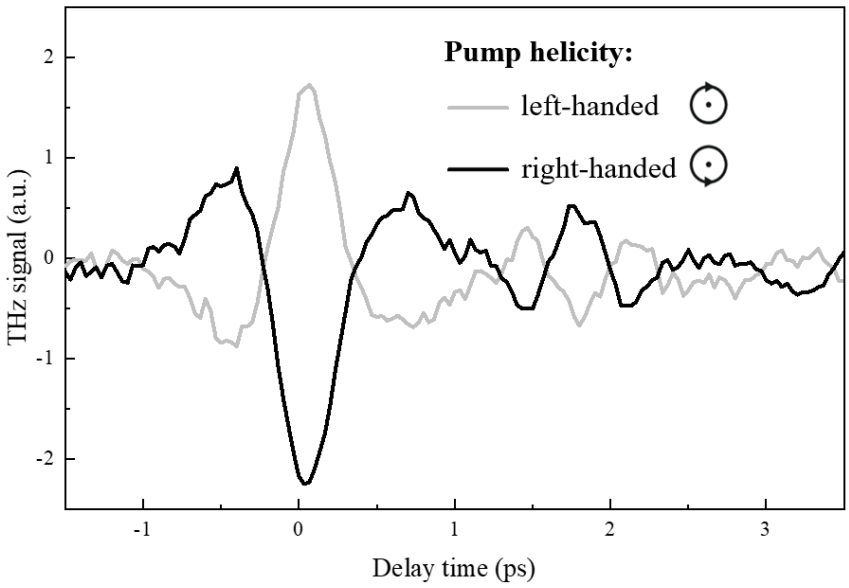


Figure 1. THz transients emitted from Mn_3Sn for two opposite optical pump helicities. The generated THz electric field is measured as a function of time. Changing the helicity of circularly polarised light leads to a full polarity switching of the THz electric field.

References:

(1) Nakatsuji S, Kiyohara N, Higo T, Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature. Nature 527, 212–215 (2015).

(2) Higo T, Qu D, Li Y, Chien C L, Otani Y and Nakatsuji S, Anomalous Hall effect in thin films of the Weyl antiferromagnet Mn_3Sn Appl. Phys. Lett. 113 202402 (2018).

(3) Ikhlas M, Tomita T, Koretsune T et al., Large anomalous Nernst effect at room temperature in a chiral antiferromagnet. Nature Phys 13, 1085–1090 (2017).

(4) Hao Yang et al., Topological Weyl semimetals in the chiral antiferromagnetic materials Mn_3Ge and Mn_3Sn, New J. Phys. 19 015008 (2018)

(5) Tsai H, Higo T, Kondou K et al. Electrical manipulation of a topological antiferromagnetic state. Nature 580, 608–613 (2020).

(6) Gao Y, Kaushik S, Philip EJ et al. Chiral terahertz wave emission from the Weyl semimetal TaAs. Nat Commun 11, 720 (2020).

(7) Rees D et al., Helicity-dependent photocurrents in the chiral Weyl semimetal RhSi, Sci. Adv.6, eaba0509 (2020).

Wednesday September 14th

9:00 – 9:30
O25: *Ultrafast magnetic switching by resonant excitation of optical phonons*
Andrei Kirilyuk
9:30 – 9:50
O26: *Observation of spin voltage and -accumulation by spin resolved femtosecond photoelectron spectroscopy*
Yves Acremann
9:50 – 10:20
O27: *Spin-Orbit Torque Induced Ultrafast Magnetization Switching in a Ferromagnet*
Jeff Bokor
Coffee break: 20 minutes
10:40 – 11:00
O28: *Ultrafast manipulation of 4f moments – implications for all optical switching*
Martin Weinelt
11:00 - 11:30
O29: *Inertial spin dynamics in ferromagnets*
Vivek Unikandanunni
11:30 - 11:50
O30: *Interface engineering for single pulse all optical toggle switching in a ferromagnet*
Danny-Petty Gweha Nyoma
11:50 – 12:20
O31: *Pathways for cold all-optical magnetic recording*
Andrzej Stupakiewicz
12:20 AM - 2:00 PM: lunch & posters
2:00 - 2:30
O32: *Magnetic on-off switching of a plasmonic laser*
Sesbastiaan van Dijken
2:30 - 2:50
O33: *Sub-picosecond magnetization switching driven by ultrafast-spin transfer in rare-earth-free spin valves*
Junta Igarashi
2:50 - 3:20
O34: *Relationship in Metals between Quasiparticle Interaction Strengths and Ultrafast Energy Dynamics*
Richard Wilson

3:20 - 3:40

O35: *Robust toggle switching in Tb-based multilayers by single shot linearly-polarized laser pulse*
Yi Peng

Coffee break: 20 minutes

4:00-4:30

O36: *Picosecond Spin Seebeck effect in ferromagnets and antiferromagnets*
Chiara Ciccarelli

O25: Wednesday 14th, 9:00 – 9:30

Ultrafast magnetic switching by resonant excitation of optical phonons

Andrei Kirilyuk
FELIX Laboratory, Radboud University, Toernooiveld 7, 6525 ED Nijmegen, The Netherlands

Identifying an efficient pathway to change the order parameter via a subtle excitation of the coupled high-frequency mode is the ultimate goal of the field of ultrafast phase transitions [1,2]. This is an especially interesting research direction in magnetism, where the coupling between spin and lattice excitations is required for switching [3]. Control of the crystal environment arguably represents the most universal mechanism to act on magnetization, as it is present in all materials regardless of their magnetic structure. One interesting approach to manipulate crystal lattice is via the anharmonic interaction of different phonon modes, which transfers the high-frequency excitation of an infrared-active mode into a rectified coordinate shift along a coupled Raman-active coordinate. Despite several attempts [4,5] however, the switching between magnetic states via resonant pumping of phonon modes has not yet been demonstrated.

To provide resonant excitation of the optical phonon modes, we use pulses from FELIX (Free Electron Lasers for Infrared eXperiments, Nijmegen, The Netherlands). Single pulses of IR/THz light with photon energy ranging between 25-124 meV (wavelength 10-50 μm) are typically used. The pulses of FELIX have been shown to be Fourier-transform limited [6], with their bandwidth experimentally tunable in the range of 0.5-2.0%, corresponding to the typical pulse width of 1-10 ps, depending on the wavelength range.

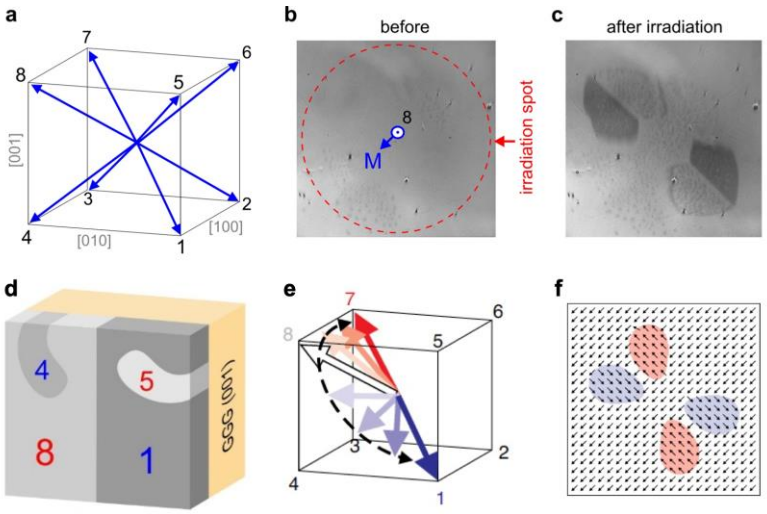


Figure 1. **a.** Four easy axes of magnetization in relation to the cubic crystal symmetry. **b.** Image of the initial state of the magnetic domain structure. **c.** Image of the magnetic domain structure after radial strain is generated by a pump pulse. **d.** Typical equilibrium domain structure in Co:YIG. **e.** Pathway of switching between the different magnetic phases. **f.** Micromagnetic simulations of switching.

And thus we show how an ultrafast resonant excitation of the longitudinal optical phonon modes in magnetic garnet films switches magnetization into a peculiar quadrupolar magnetic domain pattern, unambiguously revealing the magneto-elastic mechanism of the switching [7]. In contrast, the

excitation of strongly absorbing transverse phonon modes results in thermal demagnetization effect only. The mechanism appears to be very universal, and is shown to work in samples with different crystallographic symmetry and magnetic properties, including antiferromagnets [8], but also in ferroelectrics. Using single-shot time resolved microscopy, we demonstrate that the dynamics of the domain formation proceeds via a strongly inhomogeneous magnetic state [9], arguably related to the spin-wave instabilities [10].

In the future, ultrafast modification of the crystal field environment, and thus of magnetocrystalline anisotropy, may become the most universal way to manipulate magnetization. Magneto-elastic interactions are present in all materials and thus can be used every- where, for example in antiferromagnets. Development of a full understanding of how to control magnetocrystalline anisotropy is also important for applications in devices, for example, because this anisotropy is key to the stability of magnetization in magnetic memories.

References:

[1] T. Kubacka et al, Science **343**, 1333 (2014).
[2] A. Kirilyuk, A.V. Kimel, T. Rasing, Rev. Mod. Phys. **82**, 2731 (2010).
[3] N. Li et al., Re

v. Mod. Phys. **84**, 1045 (2012).
[4] T.F. Nova et al., Nature Physics **13**, 132 (2017).
[5] S.F. Maehrlein et al., Science Advances **4**, 5164 (2018).
[6] G.M.H. Knippels et al., Phys. Rev. Lett. **83**, 1578 (1999).
[7] A. Stupakiewicz et al., Nature Physics **17**, 489 (2021).
[8] P. Stremoukhov et al., New J. Physics **24**, 023009 (2022).
[9] M. Gidding et al., to be published
[10] A. Kashuba, Phys. Rev. Lett. **96**, 047601 (2006)

O26: Wednesday 14th, 9:30 – 9:50

Observation of spin voltage and -accumulation by spin resolved femtosecond photoelectron spectroscopy

Kevin Bühlmann[1], Francisco Carrión[1], Grégoire Saerens[2], Andreas Vaterlaus[1], and Yves Acremann[1]

[1]Lab. For Solid State Physics, ETH Zurich, Zurich, Switzerland
[2]Institute for Quantum Electronics, ETH Zurich, Zurich, Switzerland

The generation of spin current pulses by laser-driven demagnetization links the field of ultrafast magnetism to spintronics. So far, this spin transport and its cause could only be observed indirectly. We demonstrate that femtosecond spin injection can be observed on the femtosecond time scale by spin and time resolved photoemission experiments.

We study thin, epitaxial iron films which are excited by a 800 nm pump laser beam. Photoemission by a higher harmonic generation source (photon energy: 21 eV) in combination with an energy and spin-sensitive electron detector is used to measure the chemical potentials of the minority- and majority electrons. This way, we observe the spin voltage pulse [1], which acts as the driving force for the spin current.

If we deposit a thin gold film onto the iron sample and excite the iron film through the transparent substrate, we can study spin injection and accumulation upon spin injection. The setup is shown in figure 1. The Fe layer is deposited onto a transparent MgO substrate and excited by the pump laser pulse. We measure the spin polarization in a thin Au layer deposited on top of the iron film. The spin polarization rises on the femtosecond time scale and decays within < 1ps [2]. The decay time depends on the Au film thickness: in thicker films the spin polarization decays slower. This thickness dependence shows, that the loss of polarization is partially caused by spin transport. We can model the decay using the discharge of a "spin capacitance" postulated by Zhu et al. [3]. This spin capacitance is exclusively visible in dynamic transport experiments in a similar way as the charge capacitance is only relevant in dynamic circuits.

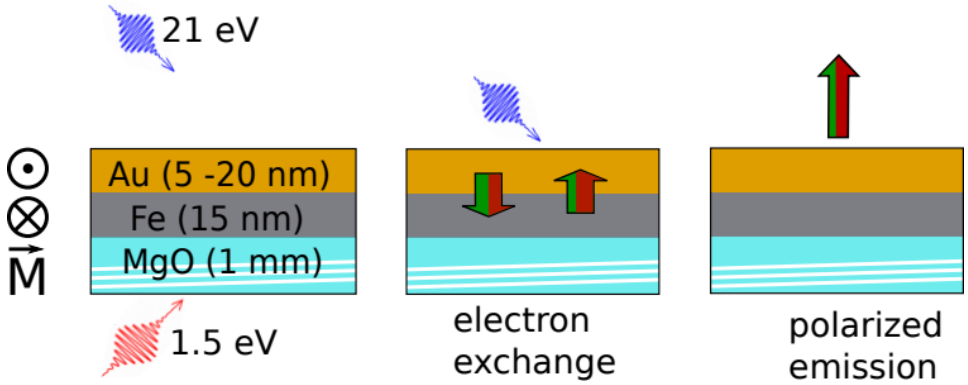


Figure 1: Experimental setup for measuring the spin accumulation in a gold film. The ferromagnetic film is excited from the backside through a transparent substrate. Due to the ultrafast demagnetization effect a spin current is injected into the gold cap layer. The spin polarization in the gold layer is detected by spin-resolved photoelectron spectroscopy.

[1] K. Bühlmann, G. Saerens, A. Vaterlaus, Y. Acremann, Struct 7, 065101 (2020)
[2] K. Bühlmann, G. Saerens, A. Vaterlaus, Y. Acremann, Sci. Rep. 10, 12632 (2020)
[3] Y.H. Zhu, X.X. Zhang, J. Liu, P.S. He, J. Appl. Phys. 122, 043902 (2017)

O27: Wednesday 14th, 9:50 – 10:20

Spin-Orbit Torque Induced Ultrafast Magnetization Switching in a Ferromagnet

J. Bokor[1,2], D. Polley[1,2], A. Pattabi[1], A. Rastogi[1], K. Jhuria[2,3], E. Diaz[3], A. Lemaitre[4], M. Hehn[3], and J. Gorchon[3]

[1]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720, USA

[2]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA

[3]Université de Lorraine, CNRS, IJL, Nancy, France

[4]C2N, CNRS, Université Paris Sud, Université Paris-Saclay, Palaiseau, France

Spin-transfer-torque and spin-orbit-torque (SOT) based magnetic devices [1] have gained considerable attention due to their non-volatility, speed, and energy-efficiency. Studies of SOT-induced magnetization switching speed have been limited by the risetime and duration of available pulsed current sources. However, recently ultrafast SOT switching has been demonstrated using ~psec current pulses [2], obtained from an optically excited photoconducting switch (Auston switch), although the time-resolved switching dynamics have not yet been reported.

We have generated ~9 psec long current pulses [3] using a high-speed photoconducting (Auston) switch excited by 60 fs duration laser pulses centered at 800 nm from a 252 KHz amplified Ti:sapphire laser. Such current pulses are used to induce ultrafast SOT switching in a ferromagnet (shown at the inset of Fig. 1) with perpendicular magnetic anisotropy (PMA). In this talk, we will discuss the ultrafast magnetization switching dynamics due to ~psec SOT effect, measured using a conventional time-resolved polar magneto-optical Kerr effect (MOKE) apparatus [3]. The current pulse (in the absence of in-plane magnetic field) introduces an ultrafast demagnetization close to ~30%. A symmetry-breaking in-plane magnetic field of 1600 Oe is utilized to induce SOT-induced magnetization switching in PMA magnets [2,4,5]. As expected, for positive in-plane field with negative current pulses (upper traces in Fig. 1), the SOT does not induce switching, but combined with the ultrafast demagnetization, shows a reduced initial demagnetization coupled with coherent oscillations at longer timescales. However, for positive ~psec current pulses (lower trances in Fig. 1), the SOT induces a rapid coherent rotation of the partially demagnetized magnetic moments towards the -z direction and the magnetization crosses zero in ~65 psec with full switching after about ~200 psec. Previous reports of sub-nsec current pulse induced SOT switching show the dynamics are dominated by domain-wall propagation with an additional incubation delay due to domain nucleation [6,7]. With ~psec duration current pulses, we have not observed such incubation delay, which we believe is directly related to the ultrafast heating due to the ~psec current pulse excitation.

We have used micromagnetic simulation coupled with a 2-temperature ultrafast heating model and $\pm 8\times10^{12}$ A/cm^2 peak current density to analyze the effects of ultrafast demagnetization due to non-equilibrium heating and current-induced torque in the observed dynamics (shown in the solid lines in Fig. 1). Excellent agreement between the experimental results and the simulation are found.
This work opens up a new realm of ultrafast magnetism combining non-equilibrium heating with SOT effects and points the way towards achieving integrated, on-chip SOT switching on deep sub-ns timescales.

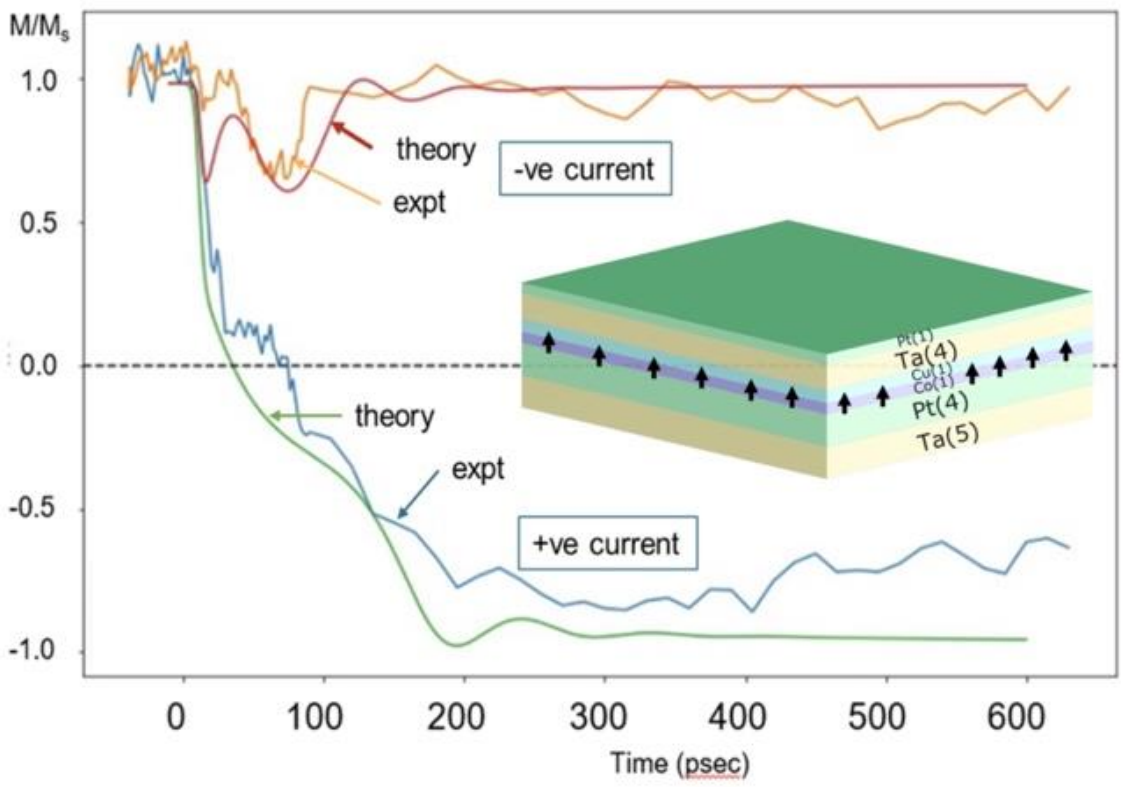


Figure 1: The 9 psec electrical pulse-induced time-resolved magnetization dynamics in the presence of 1600 Oe in-plane symmetry breaking magnetic field using positive and negative ~psec current pulses. The theoretical analysis is performed by solving a temperature dependent LLG equation. A schematic of magnetic sample is shown in the inset.

References

[1] D. Polley, A. Pattabi, J. Chatterjee, S. Mondal, K. Jhuria, H. Singh, J. Gorchon, and J. Bokor, Appl. Phys.Lett. **120**, 140501 (2022).
[2] K. Jhuria, J. Hohlfeld, A. Pattabi, E. Martin, A.Y. Arriola Córdova, X. Shi, R. Lo Conte, S. Petit-Watelot, J.C. Rojas-Sanchez, G. Malinowski, S. Mangin, A. Lemaître, M. Hehn, J. Bokor, R.B. Wilson, and J. Gorchon, Nat. Electron. **3**, 680 (2020).
[3] Y. Yang, R.B. Wilson, J. Gorchon, C.-H. Lambert, S. Salahuddin, and J. Bokor, Sci. Adv. **3**, e1603117 (2017).
[4] I.M. Miron, K. Garello, G. Gaudin, P.J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Nature **476**, 189 (2011).
[5] K. Garello, C.O. Avci, I.M. Miron, M. Baumgartner, A. Ghosh, S. Auffret, O. Boulle, G. Gaudin, and P. Gambardella, Appl. Phys. Lett. **105**, 212402 (2014).
[6] E. Grimaldi, V. Krizakova, G. Sala, F. Yasin, S. Couet, G. Sankar Kar, K. Garello, and P. Gambardella, Nat. Nanotechnol. **15**, 111 (2020).
[7] V. Krizakova, K. Garello, E. Grimaldi, G.S. Kar, and P. Gambardella, Appl. Phys. Lett. **116**, 232406 (2020).

O28: Wednesday 14th, 10:40 – 11:00

Ultrafast manipulation of 4f moments – implications for all optical switching

Tim Amrhein, Jan Böhnke, Wibke Bronsch, Corvin Krohn, Dominic Lawrenz,
Bo Liu, Christian Strüber, Nele Thielemann-Kühn, Jonathan Weber, Martin Weinelt,
Huijuan Xiao, Xinwei Zheng

Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany

Understanding ultrafast spin dynamics is not only a complex and fascinating challenge in fundamental physics, but carries the potential for magnetic recording based on all-optical switching (AOS) of the magnetic order [1]. AOS triggered by a single femtosecond laser pulse was first observed in the ferrimagnetic alloy FeCoGd [2] and more recently in Pt/Co/Gd stacks [3]. The key to AOS is exchange of angular momentum between the oppositely aligned magnetic moments of the transition metal and rare earth sublattices [4]. What is the responsible microscopic process for this momentum transfer?

Gadolinium-based compounds seem to be particular suitable for AOS. Based on strong *intra*-atomic exchange often the 5d and 4f magnetic moments in rare earth metals are treated as a single spin system. This assumption was apparently confirmed by our early study of the rare earth metals Gd and Tb using X-ray magnetic circular dichroism (XMCD), which probed the $3d_{5/2}$ to 4f transition (M_5 edge) and thus the 4f magnetic moment [5]. The study was performed in transmission on Y-sandwiched polycrystalline samples and showed a two-step demagnetization with an ultrafast demagnetization time τ of about 750 fs identical for both metals and slower times of 40 ps for Gd and 8 ps for Terbium. These findings would imply that spin-lattice coupling in the electronically excited state is enhanced up to 50 times compared to equilibrium. The result was challenged by our photoemission study of Gd/W(110). We observed disparate dynamics for 5d and 4f spins, when probing the 5d and 4f magnetic moments via the valence-band exchange-splitting and the 4f linear magnetic dichroism (MLD), respectively [6]. While the exchange splitting changes within $\tau \sim 750$ fs, the MLD signal decays with a 15-ps time constant. The study was confirmed following the spin polarization of the Gd surface state on Gd/W(110), which likewise decays with $\tau \sim 15$ ps [7].
A latter comparison of Gd and Tb revealed that 5d and 4f magnetic moments show identical ultrafast dynamics in Tb with a demagnetization time of about 400 fs [8]. Compared to Gd this difference is attributed to a strong coupling of the 4f spins to lattice vibrations via the Tb 4f orbital moment (L=3). In a follow-up spin-resolved photoemission study probing the surface state of the rare earth metals we confirmed the formation of magnon polarons in Tb, *i.e.* the intimate coupling of phonons and magnons to form a new quasiparticle, while this coupling does not occur in Gd (L=0) [9].
To eliminate film quality as a source of different magnetization dynamics, we studied in situ prepared Gd films on W(110) by XMCD in reflection. Again we found a two-step behavior with an ultrafast component, which can be well described by an extension of the microscopic 3-temperature model [10] with a spin-flip scattering rate similar to Co and Fe.
However, XMCD-R and photoemission response became finally comparably slow when increasing the Gd film thickness from 10 to 60 nm. Thus we conclude that spin currents across the Gd/W interface lead to a decrease of the 4f magnetic moment, which we probe in XMCD but not in surface-sensitive photoemission.

Moreover, we can exclude exchange scattering as the driver for 4f spin excitations in Gd. While we observe this new channel for 4f multiplet excitations (m_l = 3 to m_l = 2) in Tb metal via spin-flip scattering of optically excited 5d electrons this excitation channel remains dark for Gd metal due to the much higher excitation energy (4.1 eV in Gd vs. 0.28 eV in Tb).
In summary, we show strong indications that 4f spin manipulation in Gd *requires* spin transport with obvious consequences for AOS [11]. The spin polarization of the valence electrons is intimately coupled to the 4f magnetic moment and vice versa.

References:

[1] A. V. Kimel and Mo Li, Nat. Rev. Mater. **4**, 189 (2019).
[2] C. D. Stanciu, F. Hansteen, A. V. Kimel et al., Phys. Rev. Lett. **99**, 047601 (2007); T. Ostler et al., Nat. Commun. **3**, 666 (2012).
[3] M. L. M. Lalieu, M. J. G. Peeters, S. R. R. Haenen et al., Phys. Rev. B **96**, 220411R (2017); M. Beens, M. L. M. Lalieu, A. J. M. Deenen et al., Phys. Rev. B **100**, 220409R (2019).
[4] I. Radu, K. Vahaplar, C. Stamm *et al.*, Nature **472**, 205 (2011); C. E. Graves, A. H. Reid, T. Wang *et al.*, Nature Materials **12**, 293 (2013).
[5] M. Wietstruk, A. Melnikov, C. Stamm *et al.*, Phys. Rev. Lett. **106**, 127401 (2011).
[6] B. Frietsch, J. Bowlan, R. Carley *et al.*, Nature Communication **6**, 8262 (2015).
[7] B. Andres *et al.*, Phys. Rev. Lett. **115**, 207404 (2015)
[8] B. Frietsch, A. Donges, R. Carley *et al.*, Science Advances **6**, eabb 1601 (2020).
[9] B. Liu, H. Xiao and M. Weinelt, Phys. Rev. B **104**, 024434 (2021).
[10] B. Koopmans, G. Malinowski, F. Dalla Longa *et al.*, Nature Materials **9**, 259 (2010).
[11] C. E. Graves, A. H. Reid, T. Wang *et al.*, Nature Materials 12, 293298 (2013); Yong Xu et al., Advanced Materials **29**, 1703474 (2017); F. Jakobs, T. A. Ostler, C.-H. Lambert *et al.* Phys. Rev. B 103, 104422 (2021).

This work is based on collaborations of the projects **A01** *Martin Weinelt*, **A03** *Niko Pontius* / *Christian Schüßler-Langeheine* (Helmholtz-Zentrum Berlin), **A08** *Unai Atxitia* (now ICMM, Madrid) and **B02** *Georg Woltersdorf* (Martin-Luther Universität Halle-Wittenberg) of the **CRC/TRR 227** Ultrafast Spin Dynamics. Research on multiplet excitations in rare-earth metals was carried out at FLASH and XFEL in Hamburg in collaboration with the groups of *Martin Beye* and *Andreas Scherz*. Theory stems from the groups of *Ulrich Nowak* (Univ. Konstanz) and the TRR 227 Mercator fellow, *Peter M. Oppeneer* (Univ. Uppsala).

We acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG) via CRC/TRR 227 and by the Bundesministerium für Bildung und Forschung (BMBF).

O29: Wednesday 14th, 11:00 – 11:30

Inertial spin dynamics in ferromagnets

Vivek Unikandanunni[1], Rajasekhar Medapalli[2,3], Marco Asa[4], Edoardo Albisetti[4], Daniela Petti[4], Riccardo Bertacco[4], Eric E. Fullerton[2], and Stefano Bonetti[1,5]

[1] Department of Physics, Stockholm University, 10691 Stockholm, Sweden
[2] Centre for Memory and Recording Research, University of California San Diego, San Diego, CA 92093, USA
[3] Department of Physics, Lancaster University, Bailrigg, Lancaster LA1 4YW, United Kingdom
[4] Department of Physics, Politecnico di Milano Technical University, Milano, Italy
[5] Department of Molecular Sciences and Nanosystems,
Ca' Foscari University of Venice, 30172 Venice, Italy

We investigate the spin dynamics driven by terahertz magnetic fields in epitaxial thin films of cobalt in its three crystalline phases. The terahertz magnetic field generates a torque on the magnetization which causes it to precess for about 1 ps, with a sub-picosecond temporal lag from the driving force. Then, the magnetization undergoes natural damped THz oscillations at a frequency characteristic of the crystalline phase (see Figure. 1). We describe the experimental observations solving the inertial Landau-Lifshitz-Gilbert equation. Using the results from the relativistic theory of magnetic inertia, we find that the angular momentum relaxation time η is the only material parameter needed to describe all the experimental evidence. Our experiments suggest a proportionality between η and the strength of the magneto-crystalline anisotropy.

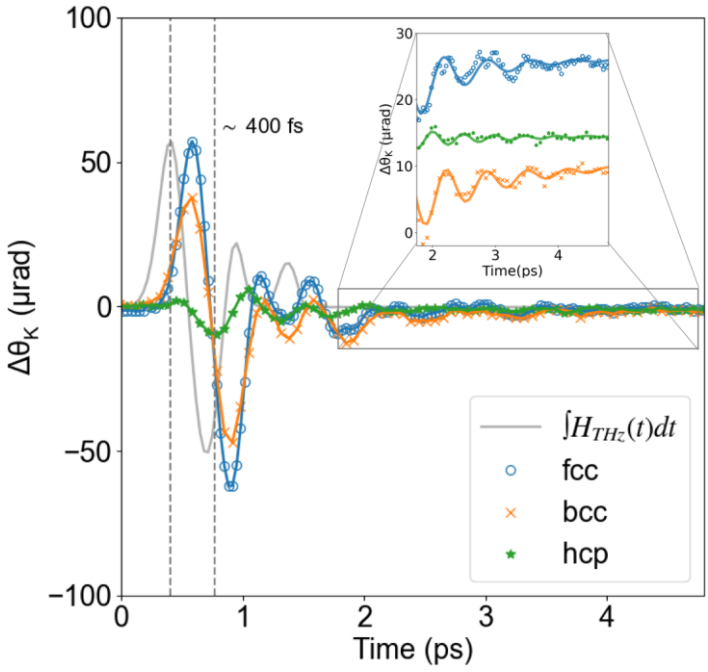


Figure 2: Symbols: time-resolved Kerr rotation measurements on fcc, bcc and hcp cobalt thin films. Dashed line: integral of the pump THz magnetic field H_{THz}. Inset: zoomed-in main panel data for t > 1.7 ps. The data is shifted vertically for clarity

O30: Wednesday 14th, 11:30 – 11:50

Interface engineering for single pulse all optical toggle switching in a ferromagnet

Danny Petty Gweha Nyoma[1], M. Verges[1], D. Lacour[1], J. Hohlfeld[1], W. Zhang[1], G. Malinowski[1], S. Migot[1], J. Ghanbaja[1], S. Mangin[1], M. Hehn[1], F. Montaigne[1]

[1] Institut Jean Lamour, Université de Lorraine – CNRS, 54000 Nancy (France)

The reversal of the magnetization by one ultrashort femtosecond pulse present a high interest for the scientific community due to the potential for ultrafast and energy-efficient memory applications. This type of switching was first observed by T.A. Ostler et al. in ferrimagnetic GdFeCo alloy [1]. Recently, experimental observation demonstrate Single Pulse All Optical Helicity Independent Switching (SP-AOHIS) in rare-earth-free Heusler alloy Mn_2Ru_xGa [2], TbCo alloys doped with small amount of Gd[3], Gd/Co[4] and Tb/Co synthetic ferrimagnets [5]. In particular**,** M. Beens et al demonstrated in 2019 single toggle switching with 35 fs laser pulse in Pt/FM/Gd(3nm) in the absence of a magnetization compensation temperature [6]. In this work, we investigate the effect of the thickness of the Gd layer and show that it can be drastically reduced.

$Pt/Co_{0.7\ nm}/Gd_{wedge}/Pt$ and $Pt/Gd_{wedge}/Co_{0.7\ nm}/Pt$ have been grown and optical switching is systematically investigated as a function of the Gadolinium thickness. For single 35 fs long linearly polarized pulses, different regimes are identified: no switching, multidomain state, switching, Perfect Toggle Switching (PTS). **The perfect toggle switching is shown to be maintained down to 0.1 nm Gd thickness. Surprisingly the effect of Gadolinium is very different on top and bottom interfaces.**

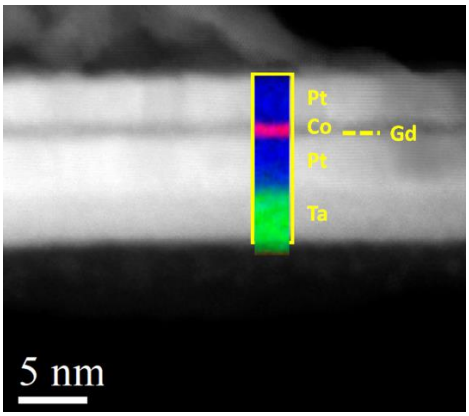


Figure 1: HAADF – STEM micrograph of the heterostructure:
Ta (3 nm) / Pt (3,7 nm) / Gd / Co (0,7 nm) / Pt (3 nm)

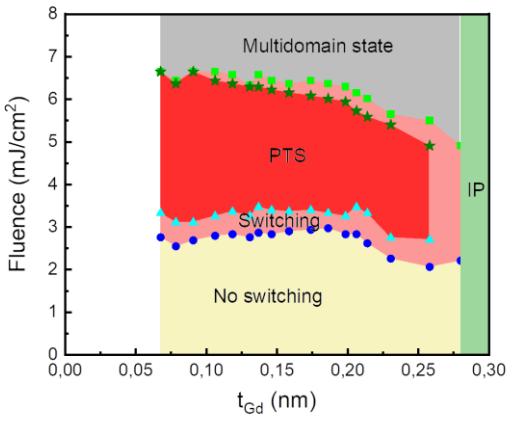


Figure 2: *AO-HIS state diagram for Pt(3,7 nm)/Gd(x nm)/Co(0,7 nm)/Pt(3 nm).*

References :

[1] T.A. Ostler. et al. Ultrafast heating as a sufficient stimulus for magnetization reversal in ferrimagnet. Nat. Commun, ***3****(666), 2012.*
[2] C. Banerjee et al. Single pulse all-optical toggle switching of magnetization without gadolinium in the ferrimagnet Mn_2Ru_xGa*. Nat. Commun,* ***11****(444), 2020.*
[3] W. Zhang et al. Role of spin-lattice coupling in ultrafast demagnetization and all optical helicity-independent single-shot switching in $Gd_{1-x-y}Tb_yCo_x$ *alloys. Phys. Rev. B* ***15****, 054410, (2022).*
[4] M. L. M. Lalieu et al. Deterministic all-optical switching of synthetic ferrimagnets using single femtosecond laser pulses. Phys. Rev. B ***96****, 220411(R) 2017.*
[5] L. Avilés-Félix et al. Single-shot all-optical switching of magnetization in Tb/Co multilayer-based electrodes, Scientific Reports, ***10****(5211), 2020.*
[6] M. Beens et al. Comparing all-optical switching in synthetic-ferrimagnetic multilayers and alloys. Phys. Rev. B ***100****, 220409(R), 2019.*

O31: Wednesday 14th, 11:50 – 12:20

Pathways for cold all-optical magnetic recording

A. Stupakiewicz
Faculty of Physics, University of Bialystok, Poland

In the last decade ultrafast magnetism enjoys bright perspective of providing the possibility to all-optical control of spins at an ultrashort, femtosecond time scale [1]. In the applications, the magnetic recording in medium with is expected to provide for the increasing efficiency writing requirements. This in turn strongly fuels the research into alternative approaches, among which very promising seems to be the all-optical magnetization switching based on ultrafast laser pulses, demonstrated in multiple metallic systems in the last years [2,3]. However, the all-optical switching in metals requires heating the whole system close to the Curie temperature and demagnetization.

One of the most elegant approaches for nonthermal controlling spins with light is the photo-magnetism which is based on a resonant optical excitation of strongly anisotropic ions using linearly polarized light [4]. This enables generation of an effective field of photo-induced magnetic anisotropy with a lifetime longer than the femtosecond pulse duration, and with magnitudes comparable to the intrinsic magnetocrystalline anisotropy, thus exerting an ultrafast torque on magnetization and enabling its precession. In general, the efficiency of photo-magnetic excitation in crystalline dielectrics is strongly dependent on the pump fluence, wavelength and polarization of the optical stimulus.

To find the nonthermal all-optical recording we proposed using the monocrystalline cobalt-doped yttrium iron garnet (YIG:Co) thin films which is the optical transparent dielectric. The low concentration Co^{2+} and Co^{3+} ions substitute Fe^{3+} in both tetrahedral and octahedral sublattices. The Co ions enhance the magnetocrystalline anisotropy and result in a strong photo-magnetic effect, allowing to manipulate the magnetization with light. Incorporation of Co ions also increases the Gilbert damping parameter to a large value of α= 0.2 [4]. In YIG:Co films polarization dependence has been demonstrated through the opposite phase of the magnetization precession excited by the optical pump pulses with orthogonal linear polarizations. Furthermore, employing femtosecond laser pulse with the fluence above the threshold and by changing the linear polarization between the [100] and [010] directions, the photo-induced magnetization precession in YIG:Co was demonstrated to enable switching of the magnetization states (i.e. recording the ”0” and “1” magnetic bits) [5]. In such a way, magnetic information can be written and erased at will by rotation of the linear polarization of the laser pulses. The precessional mechanism of photo-magnetic effect is provide remarkably low heat load and fastest switching [5], making magnetic dielectrics an attractive candidate medium for cold (dissipation-free) ultrafast magnetic recording.

Recently have been demonstrated the spectral and polarization selectivity of ultrafast photo-magnetic recording [6]. The all-optical magnetic recording under both single pulse and multiple-pulse sequences can be achieved at room temperature, in near-infrared spectral ranges with light polarized either along <110> or <100> crystallographic axes of the YIG:Co garnet. The experimental results indicate that the excitations responsible for the coupling of light to spins are *d*-electron transitions in octahedral and tetrahedral Co-sublattices, respectively. The wavelength for the photo-magnetic recording is not fixed but can be tuned in the range relevant to optical telecommunication systems (L- and O-bands) [7]. Moreover, have been demonstrated the possibility of a plasmon-driven control of the spin in Au/YIG:Co heterostructures at nanoscale [8]. Due to the subwavelength localization of plasmons, our results provide a fruitful perspective for the future high-density all-optical photo-magnetic recording below optical diffraction limit.

For the investigation of the time photo-magnetic switching, we employed a single-shot time-resolved magneto-optical microscopy with a high sensitivity of magneto-optical rotation [9]. The measurements of the time-resolved photo-magnetic switching were performed as a function of pump laser parameters at zero magnetic field. As a result of differential image analysis, the intensity of the magnetic signal in the local spots at the domain structures as a function of time delay was determined. Through modifying the pump light fluence we were able to introduce a change in light-induced anisotropy field. It allowed us to observe the change of switching times of magnetization and decrease it even more by two times but at the expense of the greater energy required to achieve the switching threshold using single pump laser pulse. On the other hand, by steering the sample temperatures in the 100-450 K range we triggered a change in the magnetocrystalline anisotropy field. Changing it allowed us to decrease the energy dissipation threshold required for switching over five times. However, decreasing the switching threshold comes at the expense of a longer switching time. Moreover, we demonstrate that the photo-magnetic recording based garnet medium operates within extremely large temperature range.

Additionally, we demonstrated that with femtosecond pulses it is possible to write and rewrite magnetic bits with a frequency of up to 20 GHz, with the maximum repetition rate being defined by the frequency of ferromagnetic resonance in the field of photo-induced magnetic anisotropy [10]. Our results reveal the principles to be employed in achieving cold and ultrafast magnetic recording in dielectrics far beyond today's state of the art, thus approaching the Landauer limit.

References

[1] A. Kirilyuk, A.V. Kimel, Th. Rasing, *Rev. Mod. Phys.* 82, 2731 (2010).

[2] C. D. Stanciu, et al. *Phys. Rev. Lett.* 99, 047601 (2007).

[3] C-H. Lambert, et al. *Science* 345, 1337 (2014).

[4] F. Atoneche, A.M. Kalashnikova, A.V. Kimel, A. Stupakiewicz, A. Maziewski, A. Kirilyuk, and Th. Rasing, *Phys. Rev. B* 81, 214440 (2010).

[5] A. Stupakiewicz, K. Szerenos, D. Afanasiev, A. Kirilyuk, and A.V. Kimel, *Nature* 542, 71 (2017).

[6] A. Stupakiewicz, K. Szerenos, M.D. Davydova, K.A. Zvezdin, A.K. Zvezdin, A. Kirilyuk, and A.V. Kimel, *Nature Comm.* 10, 612 (2019).

[7] A. Frej, A. Maziewski, and A. Stupakiewicz, *Appl. Phys. Lett.* 118, 262401 (2021).

[8] A. Kazlou, A. Chekhov, A. Stognij, I. Razdolski, and A. Stupakiewicz, *ACS Photon.* 8, 2197 (2021).

[9] T. Zalewski and A. Stupakiewicz, *Rev. Sci. Instrum.* 92, 103004 (2021).

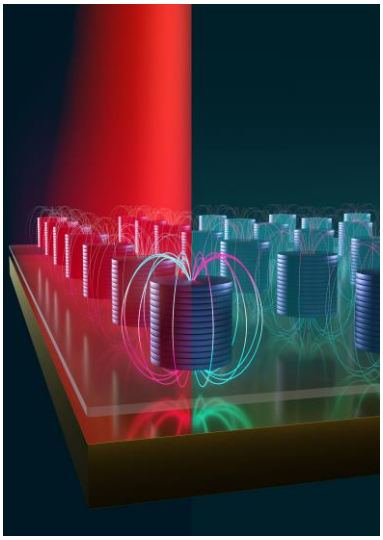
[10] K. Szerenos, A.V. Kimel, A. Maziewski, A. Kirilyuk, and A. Stupakiewicz, *Phys. Rev. Appl.* 12, 044057 (2019).

O32: Wednesday 14th, 2:00 – 2:30

Magnetic on-off switching of a plasmonic laser

Sebastiaan van Dijken
Department of Applied Physics, Aalto University, Finland

Plasmonic lasers have been realized with architectures ranging from single nanoparticles and metal-insulator thin films to random, aperiodic, periodic and superperiodic arrays of nanoparticles [1-3].



Although the effects of the nanoparticle shape and arrangement have been extensively studied, the material choice has been mostly limited to noble metals. Due to inherently high ohmic losses, nanostructures made of magnetic materials have been largely overlooked as a platform for plasmonic lasers, even when they, in principle, would offer the powerful possibility of modifying the optical modes by a magnetic field during device operation [4]. Here, I report the first experimental realization of a magnetic plasmonic laser that can be switch on and off by the application of an external magnetic field (Fig. 1) [5]. This strong magnetoplasmonic effect is attained by the design of chiral plasmonic modes in Co/Pt multilayer nanodisk arrays patterned onto Au/SiO2 bilayers. The results demonstrate how one can amplify the inherently weak effects of magnetization on light in the lasing regime, opening new perspectives for topological photonics [6-8].

Figure 1. Schematic illustration of plasmonic lasing in a Co/Pt multilayer nanodisk array. If the magnetization of the nanodisks points up (down) the system lases depending on the helicity and fluence of the laser pump pulse.

References

[1] R. F. Oulton et al. Plasmon lasers at deep subwavelength scale. Nature 461, 629 (2009).
[2] M. T. Hill and M. C. Gather. Advances in small lasers. Nat. Photon. 8, 908 (2014).
[3] D. Wang et al. Structural engineering in plasmon nanolasers. Chem. Rev. 118, 2865 (2018).
[4] S. Pourjamal et al. Lasing in Ni nanodisk arrays. ACS Nano 13, 5686 (2019).
[5] F. Freire-Fernández et al. Magnetic on-off switching of a plasmonic laser. Nat. Photon. 16, 27 (2022).
[6] F. D. Haldane and S. Raghu. Possible realization of directional optical waveguides in photonic crystals with broken time-reversal symmetry. Phys. Rev. Lett. 100, 013904 (2008).
[7] B. Bahari, et al. Nonreciprocal lasing in topological cavities of arbitrary geometries. Science 358, 636 (2017).
[8] T. Ozawa et al. Topological photonics. Rev. Mod. Phys. 91, 015006 (2019).

O33: Wednesday 14th, 2:30 – 2:50

Sub-picosecond magnetization switching driven by ultrafast-spin transfer in rare-earth-free spin valves

J. Igarashi[1], W. Zhang[1,2,3], Q. Remy[4,1], E. Díaz[1], J. X. Lin[1], J. Hohlfeld[1], M. Hehn[1], S. Mangin[1,4], J. Gorchon[1], and G. Malinowski[1]

[1] Université de Lorraine, CNRS, IJL, F-54000 Nancy, France

[2]Anhui High Reliability Chips Engineering Laboratory, Hefei Innovation Research Institute, Beihang University, Hefei 230013, China

[3]MIIT Key Laboratory of Spintronics, School of Integrated Circuit Science and Engineering, Beihang University, Beijing 100191, China

[4]Cavendish Laboratory, University of Cambridge, Cambridge, UK

The discovery of spin-transfer torque (STT) [1,2] allowed us to control the magnetization direction electrically in magnetic devices within nanoseconds, which paved the way for non-volatile applications such as spin-transfer-torque magnetoresistive random access memory (STT-MRAM). However, current-induced STT switching below a few hundred picoseconds with low power consumption while maintaining high thermal stability is challenging. Ultra-short optical pulses can also be used to manipulate the magnetization direction without a magnetic field, which is called all-optical switching (AOS). So far, only specific materials containing ferrimagnet have shown ultrafast AOS [3-6]. Thus, these methods to manipulate magnetization have been mostly developed independently within the fields of spintronics and ultrafast magnetism. Here we demonstrate an optically induced sub-picosecond magnetization reversal in archetypical rare-earth-free spin valves of [Pt/Co]/Cu/[Co/Pt] that are used for current-induced STT switching [7]. We find two events depending on the laser fluence: the reflection of minority spin current from the free layer at the reference layer (Fig. 1a) and the transmission of majority spin current from the reference layer to the free layer. These events can be understood as an analogy for current-induced STT switching [8]. Our finding strengthens the parallels between STT and ultrafast magnetism, suggesting that the spintronic playground can be further exploited at ultrafast timescales.

References

[1] J. C. Slonczewski, Journal of Magnetism and Magnetic Materials **159**, L1–L7 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353–9358 (1996).
[3] I. Radu *et al.*, Nature **472**, 205–208 (2011).
[4] T. A. Ostler *et al*., Nat. Commun. **3**, 1–6 (2012).
[5] L. Avilés-Félix *et al.*, Sci Rep **10**, 5211 (2020).
[6] C. Banerjee *et al*., Nat. Commun. **11**, 4444 (2020).
[7] S. Mangin *et al*., Nature Mater **5**, 210–215 (2006)
[8] J. Igarashi *et al*., submitted.

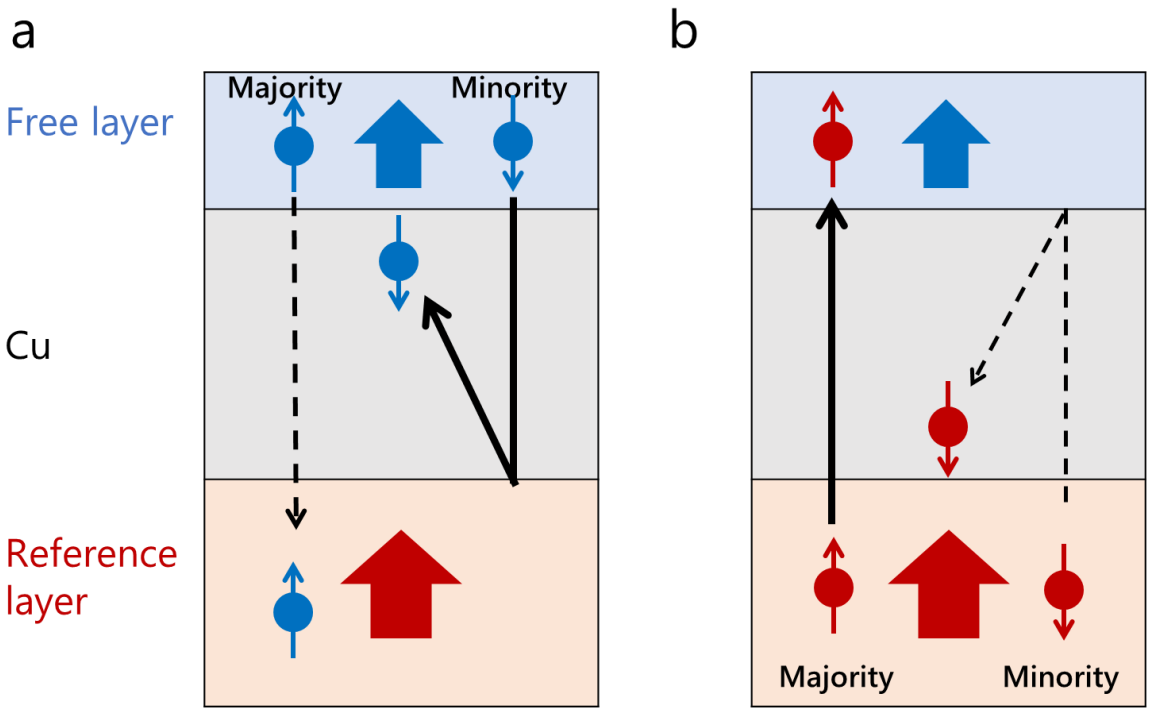


Figure 1 Schematic illustration of generated spin current from: a, Free layer and b, Reference layer. The thick lines in b and c show the electron mainly contributing to the magnetization switching in the free layer.

O34: Wednesday 14th, 2:50 – 3:20

Relationship in Metals between Quasiparticle Interaction Strengths and Ultrafast Energy Dynamics

Richard Wilson, Xinping Shi, Victor Ortiz, Ramya Mohan, Kevin Moseni, Sinisa Coh

Mechanical Engineering, Materials Science and Engineering, University of California, Riverside

Understanding the ultrafast energy dynamics in a metal after laser heating is critical for many engineering applications, including nanoscale thermal engineering, photocatalysis, and spintronics. Despite the topic's importance, and decades of study, fundamental questions about the topic remain unanswered. In this talk, I discuss my group's experimental work to answer two such questions. (i) Do photoexcited electrons transport energy ballistically, super-diffusively, or diffusively before thermalizing with phonons? (ii) Can we control the energy dynamics in metal alloys by using the effect of alloy composition on electronic band structure to control the strength of quasi-particle interactions? To answer the first question, we perform a series of time domain thermoreflectance measurements on Al, Cu, Ag, and Au wedge thin-films and bilayers. Our experiments show that, while the energy dynamics in Au after photoexcitation are nonthermal, heat transport by nonequilibrium electrons is almost entirely diffusive. To answer the second question, we perform pump/probe experiments on Co1-xFex alloys. We find the ultrafast magnetization dynamics in these alloys depends strongly on composition. Alloy compositions with weak electron-phonon interaction strengths are also observed to have distinct ultrafast dynamics and low Gilbert damping parameters. I conclude my talk by discussing the implications of our findings to the plasmonics and spintronics communities.

O35: Wednesday 14th, 3:20 – 3:40

Robust toggle switching in Tb-based multilayers by single shot linearly-polarized laser pulse

Y. Peng[1], D. Salomoni[2] , G. Malinowski[1], L. D. Buda-Prejbeanu[2], R. C. Sousa[2], I. L. Prejbeanu[2] , J. Hohlfeld [1], M. Verges[1], S. Mangin[1] and M. Hehn[1]

[1] Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, Nancy 54011, France

[2] Univ. Grenoble Alpes, CNRS, CEA, Grenoble INP, SPINTEC, 38000 Grenoble, France

Since the first all-optical switching experiment carried on GdFeCo ferrimagnet [1], it has been shown that its magnetization can be switched by a single fs-laser pulse independently of the light helicity [2-3]. The all-optical switching represents an ultrafast and field-free method to control the magnetization state. To date, two mechanisms of all-optical switching were identified, namely: 1) multiple pulse helicity dependent all-optical switching (HD-AOS), which has been observed in many materials and ascribed to the dependence of absorption of circularly polarized light on the magnetization direction; 2) single pulse helicity independent all-optical switching (HI-AOS) which relies on transfer of angular momentum between the rare earth (RE) and transition metal (TM) sublattices combined with different demagnetization timescales. This last mechanism has been demonstrated in ferrimagnetic GdFeCo alloy, GdFeCo based spin valves, Gd/FM bilayers where FM is a ferromagnet, and recently in Tb/Co multilayers [4] and ferrimagnetic Heusler alloy [5].

In this work, HI-AOS magnetization toggle has been studied in $[Tb/Fe]_4$ multilayers and $[Tb/Co]_5$ multilayers (Fig.1a-b). Two specific features have been identified that contrast with GdFeCo alloys[6]. First, the toggle switching of Tb/Co or Tb/Fe multilayers occurs both with 50fs and 10ps pulse duration. The threshold switching fluence is independent of the laser pulse duration at least up to 10 ps (Fig. 1c). Moreover, the multidomain fluence (F_{multi}), above which a multidomain state is observed in the center of the spot, increases slightly for pulse durations below 3 ps and then remains constant for longer pulse durations. This indicates that the mechanisms responsible for the Tb-based multilayers switching differ from those pointed-out for Gd-based alloys. Second, at high fluences, the equilibrium state after the first laser pulse excitation shows a complex structure composed of rings of opposite magnetization directions. This ring structure was observed in all Tb/Co and Tb/Fe multilayer films we have studied so far. The number and the size of the rings depend on the sample composition (thickness of the Tb and transition metal layers) as well as on the annealing condition.

These results will contribute to the development of ultra-fast and energy-efficient memory utilizing AOS.

Acknowledgements : UFO, COMRAD
COMRAD - EU grant no. 861300

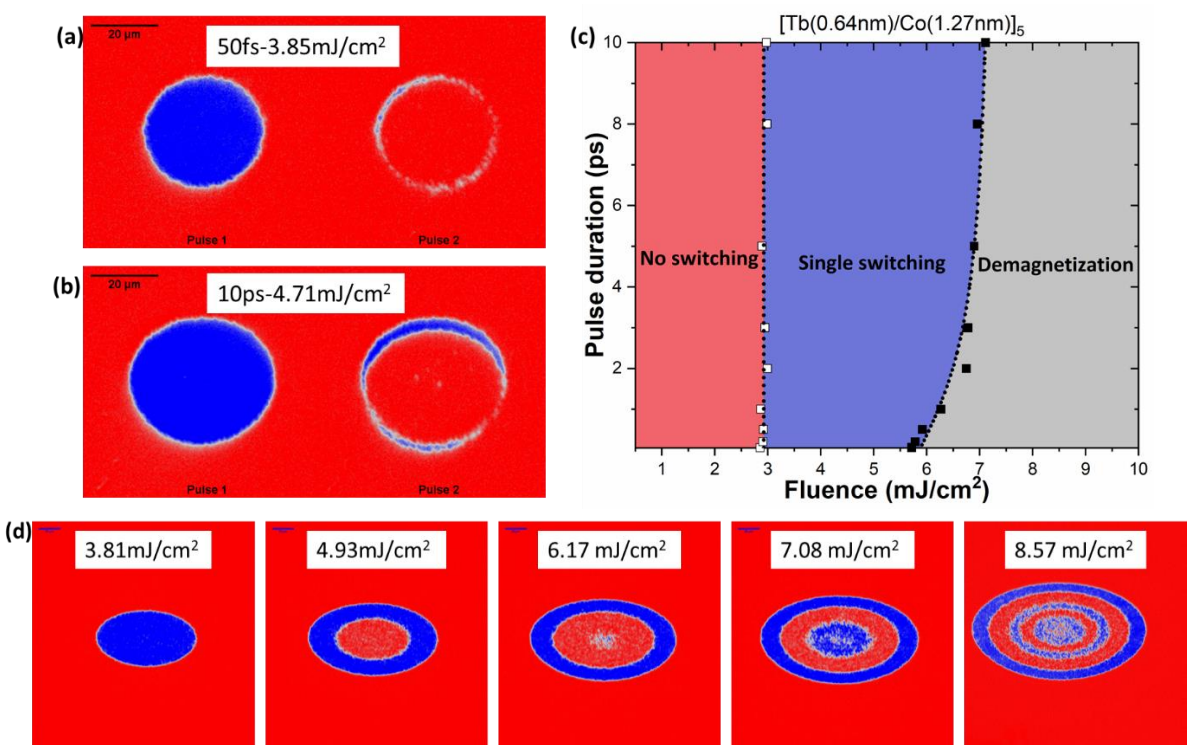


Figure 1: (a-b)Background subtracted images after each single linearly-polarized laser pulse with (a) 50 fs and (b) 10 ps; (c) State diagram obtained with CoFeB/[Tb(0.64 nm)/Co(1.27 nm)]$_5$. F_{switch} (open squares) and F_{multi} (solid squares) as a function of the pulse duration; (d) Background subtracted images after first single laser pulse with 50 fs of different laser fluences for [Tb(1.06 nm)/Co(1.78 nm)]$_5$. The laser spot has an ellipsoidal shape because the sample surface is not perfectly perpendicular to the plane of the incident light.

References

[1] C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh, Th. Rasing, All-Optical Magnetic Recording with Circularly Polarized Light, Phys. Rev. Lett. 99, 047601, 2007.

[2] I. Radu, K. Vahaplar, C. Stamm, T. Kachel, N. Pontius, H. A. Durr, T. A. Ostler, J. Barker, R. F. L. Evans, R. W. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, Th. Rasing, A. V. Kimel, Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins, Nature, 472, 205, 2011.

[3] T. A. Ostler, J. Barker, R. F. L. Evans, R. W. Chantrell, U. Atxitia, O. Chubykalo-Fesenko, S. El Moussaoui, L. Le Guyader, E. Mengotti, L. J. Heyderman, F. Nolting, A. Tsukamoto, A. Itoh, D. Afanasiev, B. A. Ivanov, A. M. Kalashnikova, K. Vahaplar, J. Mentink, A. Kirilyuk, Th. Rasing, A. V. Kimel, Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet, Nat. Commun. 3, 666, 2012.

[4] L. Avilés-Félix, A. Olivier, G. Li, C. S. Davies, L. Álvaro-Gómez, M. Rubio-Roy, S. Auffret, A. Kirilyuk, A. V. Kimel, T. Rasing, L. D. Buda-Prejbeanu, R. C. Sousa, B. Dieny, I. L. Prejbeanu, Single-shot all-optical switching of magnetization in Tb/Co multilayer-based electrodes, Sci. Rep. 10, 5211, 2020.

[5] C. Banerjee, N. Teichert, K. Siewierska, Z. Gercsi, G. Atcheson, P. Stamenov, K. Rode, J. M. D. Coey, J. Besbas, Single pulse all-optical toggle switching of magnetization without gadolinium in the ferrimagnet Mn2RuxGa, Nature Communications, 11, 4444, 2020.

[6] J. Wei, B. Zhang, M. Hehn, W. Zhang, G. Malinowski, Y. Xu, W. Zhao and S. Mangin, Phys. Rev. Applied, All-optical Helicity-Independent Switching State Diagram in Gd - Fe - Co Alloys, 15, 054065, 2021.

O36: Wednesday 14th, 4:00 – 4:30

Picosecond Spin Seebeck effect in ferromagnets and antiferromagnets

C. Ciccarelli
University of Cambridge

The longitudinal spin Seebeck effect describes the transfer of a spin current from a magnetic insulator driven by a temperature gradient. Here we present our recent studies on the longitudinal spin Seebeck effect on the picosecond timescale in both ferromagnets and antiferromagnets using THz emission spectroscopy. As a function of temperature, we observed a different temperature dependence compared to DC electrical studies carried out in the same temperature range. By comparing different antiferromagnets belonging to the same family of fluoride perovskites we are able to correlate the spin transfer efficiency with the bands of the magnon spectrum.

Thursday September 15th

9:00 – 9:30

O37: *Ultrafast spin current driven by phase transition of FeRh*

Gyung-Moi Choi

9:30 – 9:50

O38: *Ultrafast spin-reorientation transition and features of magnetization precession in magnetite Fe3O4*

Alexandra Kalashnikova

9:50 – 10:20

O39: *Single-shot all-optical switching of Tb based nanolayers*

Liliana Buda-Prejbeanu

Coffee break: 20 minutes

10:40 – 11:00

O40: *Ultrafast Driving of Orbital Magnetism in Metallic Nanoparticles using Circularly Polarized Light*

Paul-Antoine Hervieux

11:00 - 11:30

O41: *Coupled Spin and Phonon Dynamics in Heterostructures Excited by Ultrafast Laser Pulses*

Matias Bargheer

11:30 - 11:50

O42: *NiO: Magnetic coupling and ultrafast electron dynamics in thin films*

Wolf Widdra

11:50 – 12:20

O43: *Optical excitation and control of the spin and charge density wave order of Cr*

Eric E. Fullerton

O37: Thursday 15th, 9:00 – 9:30

Ultrafast spin current driven by phase transition of FeRh

Kyuhwe Kang[1], Hiroki Omura[2], Tomoyasu Taniyama[2], Gyung-Min Choi[1,3*]

[1]Department of Energy Science, Sungkyunkwan University, Suwon 16419, South Korea
[2]Department of Physics, Nagoya University, Nagoya 464-8601, Japan
3Center for Integrated Nanostructure Physics, Institute for Basic Science (IBS), Suwon 16419, South Korea

Magnetic phase transition requires a drastic change in the angular momentum. Considering the Einstein–de Hass effect, the ultimate source of angular momentum is the lattice. However, the exact passage and process of angular momentum transfer are under debate. In particular, the role of conduction electrons is unknown. Here, we demonstrated that the magnetic phase transition of FeRh from an antiferromagnet to a ferromagnet generates an ultrafast spin current in the FeRh/Cu heterostructure *via* conduction electrons. Using the time-resolved magneto-optical Kerr effect, we simultaneously measured the dynamics of the phase transition of FeRh and spin accumulation on Cu. The sign, time delay, and magnitude of the spin accumulation on Cu are strongly correlated with the magnetization dynamics of FeRh, confirming the phase-transition-driven spin current. Our results clearly reveal that the conduction electrons act as a momentary reservoir for angular momentum during the phase transition, and they enable spatial transport of angular momentum, that is, spin current.

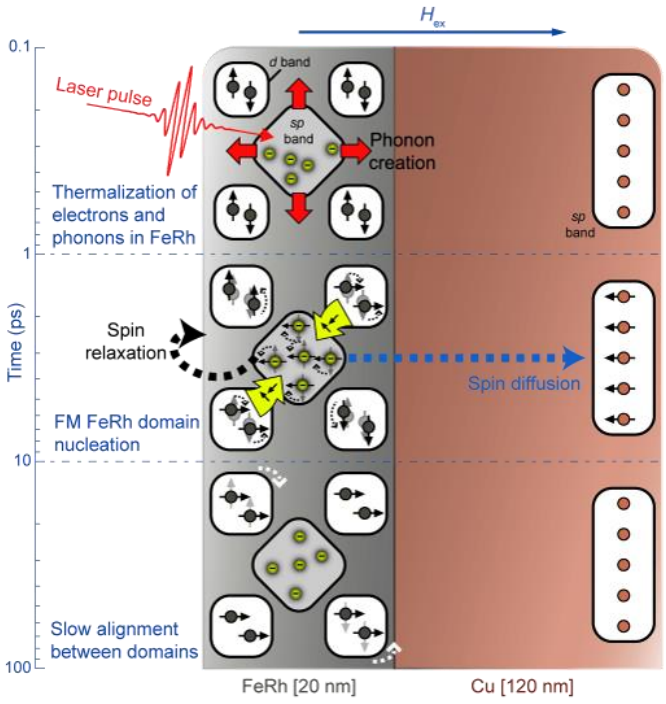


Figure 1: Schematics for the phase-transition driven spin current. The laser pulse excites electrons of the AFM phase of FeRh, and energy transport among electrons, magnons, and phonons occurs in a sub-picosecond timescale. The phase transition from AFM to FM phase occurs in two steps: 1) a fast nucleation of the FM domains in picoseconds; 2) a slow expansion of the FM domains in tens of picoseconds. The fast nucleation of the FM domains generates a spin current from FeRh to Cu *via* the conduction electrons (*sp* band).

O38: Thursday 15th, 9:30 – 9:50

Ultrafast spin-reorientation transition and features of magnetization precession in magnetite Fe_3O_4

A.V. Kuzikova[1], L.A. Shelukhin[1], R.V. Pisarev[1], and A.M. Kalashnikova[1]
[1]Ioffe Institute, St. Petersburg, Russia

Phase transitions in solids can be employed for pronounced and abrupt changes of electric, optical, magnetic, and other properties by using moderate external impact. With the development of femtosecond lasers, it was demonstrated that a medium can be switched from one phase state to another at picosecond timescales, and even to phases unachievable in equilibrium via ultrafast photo-induced transitions (PIPT) [1]. The path which the medium follows during PIPT is especially intriguing in materials, where several transitions can occur simultaneously, with examples being magnetic and structural transition in FeRh [2, 3] and Verwey transition VO_2 [4], and LCMO [5].

Magnetite Fe_3O_4 is a unique material where PIPT could lead to concomitant changes of structure, electric conductivity and change of magnetic state. Indeed, magnetite possesses a first-order Verwey transition from a monoclinic insulating to a cubic metallic phase at a temperature of 123 K. Mechanism of equilibrium as well as of laser-driven Verwey transition in Fe_3O_4 is being actively investigated [6,7]. At temperature of 130 K, Fe_3O_4 possesses a spin-reorientation transition (SRT) when the sign of the magnetic cubic anisotropy parameter changes. The relationship between the Verwey transition and the SRT still remains open [8], while laser-driven SRT is still to be explored.

To study PIPT, a sample prepared from a bulk single crystal of magnetite with the [110] orientation was chosen. The measurements were performed in the temperature range of 80-140 K and in an external magnetic field of 0.25 T applied along the easy magnetization axis of the sample in the low-temperature phase. This geometry is optimal for observing laser-induced spin-reorientation transitions. The magneto-optical femtosecond pump-probe setup was used. Laser pulses with a central wavelength of 1030 nm and a duration of 170 fs excite the material, and its transient optical and magneto-optical responses are detected by 515 nm probe laser pulses. This approach enables revealing of both the SRT and Verwey transitions. Laser-induced the reflectivity changes and magnetization precession and were registered at different pump fluences and initial sample temperature.

Based on the characteristic thresholds of the reflectivity change as a function of the pump fluence, it could be reliably concluded that a laser pulse induces the ultrafast Verwey transition only when its fluence exceeds certain threshold. At the same time, observation of laser-induced magnetization precession yielded counterintuitive result, showing that SRT is induced at fluences well below the threshold for a Verwey transition. By carefully examining evolution of the precision parameters with temperature and pump fluence, as well as of equilibrium magnetic hysteresis loops, we unambiguously show that this result does not indicate that the SRT and Verwey transitions are independent when induced by the laser pulses. Instead, we demonstrate that laser-induced magnetization precession appears to be a very sensitive mean for revealing nucleation of domains of new phase which are expected for the 1st order PIPT even when low pump fluences are used, while reflectivity measurements used to observe ultrafast Verwey transition fail to do so.

We further demonstrate that ultrafast spin-reorientation and Verwey transitions are clearly coupled. In particular, above the threshold fluence both the laser-induced reflectivity and magnetization precession follow the same trends with temperature and pump fluence.

It has been previously shown that ultrafast Verwey transition in Fe_3O_4 is essentially non-thermal at the first stages and, thus occurs within a picosecond [7]. Our observations suggest that SRT in Fe_3O_4 can be also ultrafast, in contrast to previously investigated SRT in orthoferrites relying on relatively slow energy transfer between different subsystems [9].

The samples used in our study were prepared from a magnetite single crystal grown by A. M. Balbashov.

References

1. S. Koshihara, et al., Phys. Rep. **942**, 1 (2022).
2. G. Ju, et.al., Phys. Rev. Lett. **93**, 197403 (2004).
3. G. Li, et.al., arXiv:2001.06799.
4. D. Wegkamp and J. Stähler, Prog. Surf. Sci. **90**, 464 (2015).
5. J. Zhang, et al., Nature Mater. **15**, 956 (2016).
6. M. S. Senn, et al., Nature **481**, 173 (2012).
7. S. de Jong, et al., Nature Mater. **12**, 882 (2013).
8. J. E. Lorenzo, et.al., Phys. Rev. Lett. **101**, 226401 (2008).
9. J. A. de Jong, et al., Phys. Rev. B **84**, 104421 (2011).

O39: Thursday 15th, 9:50 – 10:20

Single-shot all-optical switching of Tb based nanolayers

D. SALOMONI[1], Y. PENG[2], S. AUFFRET[1], G. MALINOWSKI[2], J. HOHLFLED[2], M. VERGES[2], S. MANGIN[2] , M. HEHN[2], D. DIENY[1], R. C. SOUSA[1], I. L. PREJBEANU[2] , L. D. BUDA-PREJBEANU[1]

[1]Spintec, Université Grenoble Alpes, CNRS, CEA, Grenoble INP, IRIG-SPINTEC, 38000 Grenoble, France
[2]Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, Nancy 54011, France

The development of the next generations of spintronic devices relies on the engineering of innovative materials whose properties can be controlled by combining several physical phenomena. The first observation of all-optical magnetization switching in GdFeCo ferrimagnetic alloy using femtosecond laser pulses [1] has opened exciting perspectives for efficient data recording applications. In particular, the ultrafast speed of magnetic reversal can potentially push the write speeds associated with magnetic memory devices toward THz frequencies.

Our work reports the development of perpendicular magnetic tunnel junctions incorporating a film composed of Tb/Co nanolayers whose magnetization can be all-optically controlled via helicity-independent single-shot switching. The choice of Tb/Co nanolayers has been motivated by their strong out-of-plane anisotropy providing the stability required by the memory application. Reliable switching was demonstrated for Co-rich compositions of the stack either Tb/Co layers alone or coupled to a CoFeB electrode/ MgO-barrier tunnel-junction stack (Fig.1a).

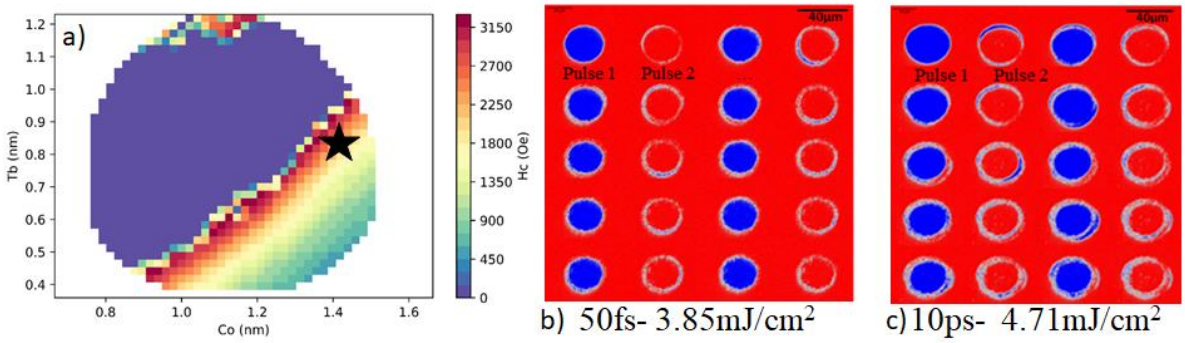


Figure 1: a) Mapping of the out-of-plane coercive field of double wedge Tb/Co nanolayers. Single shot magnetization switching for Co-rich region (black star) with a laser pulse of b) 50fs and c) 10ps respectively.

Toggling of the magnetization was achieved using laser pulse duration varying from 50 fs up to 10 ps and fluences from 3.0 mJ/cm² to 6.5 mJ/cm² (Fig. 1b and c). This behaviour is in contrast to that reported for ferromagnetic alloys [2] and relaxes the constraint of strict control of the laser duration during the writing operation. Furthermore, very similar results have been obtained when Co is replaced by Fe pointing out that the mechanisms responsible for the Tb-based multilayers switching differ substantially from those controlling the switching of the Gd-based alloys.

This work is a significant technological breakthrough in both the emerging fields of photo-spintronics and ultrafast magnetism, enabling the development of hybrid spintronic-photonic systems with unique features of THz MTJ switching speeds.

The authors acknowledge the funding support from ITN project COMRAD (Horizon Europe grant agreement No. 713481) and from French grant UFO (ANR-20-CE09-0013).
[1] C. D. Stanciu et al. Phys. Rev. Lett. 99, 047601, 2007.
[2] J. Wei et al., Phys. Rev. Applied 15, 054065, 2021.

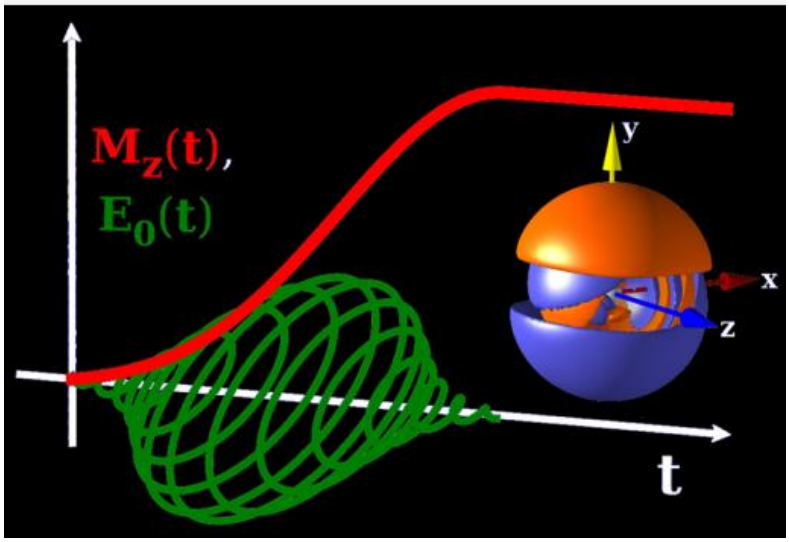
O40: Thursday 15th, 10:40 – 11:00

Ultrafast Driving of Orbital Magnetism in Metallic Nanoparticles using Circularly Polarized Light

P. -A. Hervieux[1], R. Sinha-Roy[2], J. Hurst[1], G. Manfredi[1]
[1]Université de Strasbourg and CNRS, IPCMS, Strasbourg, France
[2]Laboratoire des Solides Irradiés, Ecole Polytechnique, CNRS, CEA, Université Paris-Saclay, France

Transfer of angular momentum from helicity-controlled laser fields to a nonmagnetic electronic system can lead to the creation of magnetization [1]. The underlying mechanism in metallic nanoparticles is based on the inverse Faraday effect and has been studied using different theoretical approaches [2]. In this work, the dynamics using an orbital-based quantum-mechanical method within a many-body theoretical framework is investigated [3]. To this end, the real-time formulation of time-dependent, density-functional theory is used to study induced orbital magnetism in metallic nanoparticles excited by circularly polarized light. The nanoparticles are described by a spherical jellium model on a real-space grid. The polarized laser field gives rise to an angular momentum and, hence, a magnetic moment, which is maximum at the surface plasmon frequency of the nanoparticle, revealing that this is a resonant plasmonic effect. The primary contribution to the magnetic moment comes from surface currents generated by the plasmonic field, although some bulk contributions due to the quantum-mechanical nature of the system (Friedel oscillations) still persist. We compare several nanoparticles of K, Na, and Au having the same size and excited at their respective plasmon frequencies and show that the generated magnetic moment per energy pumped into the system is maximum for K and minimum for Au. A similar trend is observed for nanoparticles of the same chemical species but different sizes.

references
[1] O. H.-C. Cheng, D.H. Son, M. Sheldon, Nat. Photonics **14**, 365 (2020).
[2] J. Hurst, P. M. Oppeneer, G. Manfredi and P. –A. Hervieux, Phys. Rev. B **98**, 134439 (2018).
[3] R. Sinha-Roy, J. Hurst, G. Manfredi and P.-A. Hervieux, ACS Photonics **7**, 9, 2429 (2020).



O41: Thursday 15th, 11:00 – 11:30

Coupled Spin and Phonon Dynamics in Heterostructures Excited by Ultrafast Laser Pulses

M. Bargheer[1,2]
[1]Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany
[2]Helmholtz-Zentrum Berlin für Materialien und Energie, Wilhelm-Conrad-Röntgen Campus, BESSY II, Albert-Einstein-Strasse 15, 12489 Berlin, Germany

Ultrafast X-ray diffraction (UXRD) experiments provide a unique access to coherent longitudinal acoustic phonons (coherent strain wave packets) [1-3] and heat transport at the nanoscale (flow of incoherent excitations) [4-7]. Bragg-peak shifts are especially useful experimental observables in nano-layered heterostructures [2-10], and contemporary laser-based sources of hard x-rays with femtosecond pulse duration have sufficient x-ray flux and stability to analyze the dynamics of films with single-digit nanometer thickness [4]. We combine these UXRD experiments with time-resolved magneto-optical Kerr measurements that are conducted under identical excitation conditions and tailor nanoscale heterostructures of metallic and nonmetallic materials in order to disentangle the excitation mechanism of magnetization dynamics: Electron transport, strain pulses and heat conduction that change the magnetic anisotropy. The presentation discusses standard examples such as Ni and Bi:YIG as well as rare earth heterostructures.

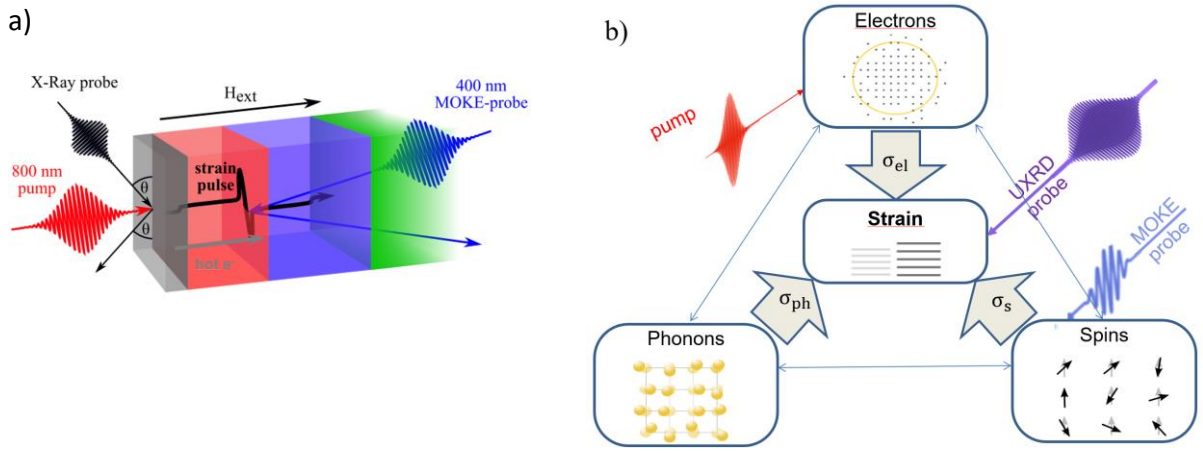


Figure 1: a) Heterostructures allow for tailoring the transport of optically deposited energy. b) Ultrafast optical pump pulses typically excite the electron system, which couples energy to phonons and spin excitation. The energy density in each subsystem creates stress $\sigma_{e,ph,s}$ on the lattice. The layer-specific UXRD probe senses the transient energy density and MOKE is sensitive to the spin dynamics of the magnetic layer.

References

[1] A. Bojahr et al, *Physical Review Letters*, **115**, 195502 (2015).
[2] S. Zeuschner et al., *Structural Dynamics* **6**, 024302 (2019).
[3] A. von Reppert et al., *Science Advances* **6**, eaba1142 (2020)
[4] J. Pudell et al., *Nature Communications*, **9**, 3335 (2018) .
[5] J. Pudell et al., *Advanced Functional Materials* **30**, 2004555 (2020).
[6] M. Mattern et al., *Applied Physics Letters* **120**, 092401 (2022).
[7] M. Herzog et al. *Advanced Functional Materials* (2022) DOI:10.1002/adfm.202206179.
[8] J. Pudell et al., *Physical Review B* **99**, 094304 (2019).
[9] A. von Reppert et al., *Structural Dynamics*, doi: 10.1063/1.5145315 (2020).
[10] M. Deb et al., *Physical Review B* **103**, 024411 (2021)

O42: Thursday 15th, 11:30 – 11:50

NiO: Magnetic coupling and ultrafast electron dynamics in thin films

K. Gillmeister,[1] D. Golez,[2,3] Y. Pavlyukh,[4] J. Berakdar,[1] P. Werner,[3] and W. Widdra[1]
[1] Institute of Physics, Martin-Luther-Universität Halle-Wittenberg, Halle, Germany
[2] Center for Computational Quantum Physics, Flatiron Institute, New York, USA
[3] Department of Physics, University of Fribourg, Fribourg, Switzerland
[4] Department of Physics, Technische Universität Kaiserslautern, Kaiserslautern, Germany

Charge excitation across an electronic band gap plays an important role in optoelectronics and light harvesting. In contrast to conventional semiconductors, studies of above-band-gap photoexcitation in strongly correlated materials are still in their infancy. One prominent example is the antiferromagnetic oxide NiO, a material that is also used in spintronics and for which the ultrafast electron dynamics and the coupling between charge transfer and antiferromagnetic spin system is largely unexplored. Here we present a study by combining scanning tunnelling microscopy (STM) and spectroscopy (STS) with time-resolved two-photon photoemission (2PPE) for NiO(001) ultrathin films with special emphasis on the electronic response upon optical excitation [1-4].

At the surface of epitaxial NiO(001) films grown on Ag(001), we find series of well-defined image potential states below the vacuum level with film thickness dependent lifetimes in the range of 30 to 120 fs [2]. In contrast to these rather long lifetimes, we find an ultrafast (<10 fs) relaxation for electrons that are excited just across the charge-transfer gap into the conduction band, which corresponds to the upper Hubbard band of a charge-transfer insulator [3]. We identified an ultrafast relaxation of the initial excitation into long-lived many-body in-gap states. Remarkably, the spectral weight of these in-gap states displays coherent THz oscillations up to 2 ps at low temperature [3]. The frequency of these oscillations corresponds to the strength of the antiferromagnetic superexchange interaction in NiO and their lifetime vanishes slightly above the Néel temperature. These observations indicate a strong coupling of the excited states to the antiferromagnetic spin system and pave the way for addressing antiferromagnetic spin-spin correlation in oxides on the ultrafast time scale [3].

Support by the Sonderforschungsbereich SFB/TRR-227 “Ultrafast spin dynamics” is gratefully acknowledged.

References

[1] K. L. Kostov, F. O. Schumann, S. Polzin, D. Sander, and W. Widdra, Phys. Rev. B 94, 075438 (2016).
[2] K. Gillmeister, M. Kiel, and W. Widdra, Phys. Rev. B 97, 085424(2018).
[3] K. Gillmeister, D. Golež, C.-T. Chiang, N. Bittner, Y. Pavlyukh, J. Berakdar, P. Werner, and W. Widdra, Nat. Commun. 11, 4095 (2020).
[4] Y. W. Windsor, D. Zahn, R. Kamrla, J. Feldl, H. Seiler, C.-T. Chiang, M. Ramsteiner, W. Widdra, R. Ernstorfer, and L. Rettig, Phys. Rev. Lett. 126, 147202 (2021).

O43: Thursday 15th, 11:50 – 12:20

Optical excitation and control of the spin and charge density wave order of Cr

Sheena Patel[1], Jiaruo Li[2], Oleg Yu. Gorobtsov[1], Nelson Hua[3], Benjamin Gregory[2], Anatoly G. Shabalin[3], Stjepan Hrkac[3], James Wingert[3], Devin Cela[3], James M. Glownia[4], Matthieu Chollet[4], Diling Zhu[4], Rajasekhar Medapalli[1], Oleg G. Shpyrko[3], Andrej Singer[2], & Eric Fullerton[1]

[1]Center for Memory and Recording Research, University of California, La Jolla, CA 92093, USA.
[2]Materials Science and Engineering Department, Cornell University, Ithaca, NY 14853, USA.
[3]Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA.
[4]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA.

In strongly correlated systems, the coupling between spin, charge, and lattice degrees of freedom results in the emergence of complex order such as antiferromagnetism and density wave systems. One example is chromium, which exhibits an incommensurate spin-density wave (SDW) below its Néel temperature of 311 K and a commensurate charge-density wave (CDW) that appears as a second harmonic of the SDW ordering. The CDW can be measured by X-ray diffraction as satellite peaks around the (002) Bragg peak. In this talk we described measurements of the ultrafast CDW dynamics in response to photoexcitation pumps with an X-ray free-electron laser (XFEL) probe of a epitaxial Cr film.[1-5] In Cr[001] films, the SDW and CDW are directed normal to the film surface and are pinned at the interfaces such that the number of wavelengths of the SDW and CDW is quantized and jumps hysteretically as the temperature is varied.[1] By analyzing the amplitude and position of the CDW satellite peaks, we are able to directly measure the CDW order and, indirectly, the SDW order following ultrafast photoexcitations. [2-5] Immediately following this photoexcitation, the magnetic order in Cr is suppressed and the static CDW becomes a dynamic coherent phonon.[2,3] With weak excitation, we observe a transient enhancement of the CDW order by up to 30%.[2] A second weak excitation can either dampen the phonon oscillation or can further enhance the CDW order and sustain the oscillation longer depending on the timing.[4,5] We find that by manipulating intermediate vibrational states in the vicinity of the SDW critical point, where the SDW order parameter changes dramatically, dynamic control of the SDW order is possible. We apply Landau theory to identify the mechanism of control as a repeated partial quench and sub picosecond recovery of the SDW. Stronger photoexcitation suppresses the SDW and CDW order in the system through heating above its Néel temperature. After the phonons are damped, there is no lattice distortion remaining in the system. The recovery of SDW and CDW order is expected to be consistent with cooling times, however we see that the recovery slows by orders of magnitude as the sample is excited from temperatures that approach the hysteretic region where there is a change in the number of wavelengths of the CDW in the sample.

[1]. A. Singer, S. K. K. Patel, *et al*., Phys. Rev. B **94**, 174110 (2016).
[2]. A. Singer, S. K. K. Patel, *et al*. Phys. Rev. Lett. **117**, 056401 (2016).
[3]. J. Wingert, A. Singer, S. K. K. Patel, *et al*., Phys. Rev. B **102**, 041101 (2020)
[4]. O. Y. Gorobtsov, L. Ponet, S. K. K. Patel *et al*., Nature Comm. **12** 2865 (2021).
[5]. J. Li, O. Y. Gorobtsov, S. K. K. Patel, *et al*., Communications Physics **5**, 125 (2022).

MAGNETOFON project

Thursday September 15th

2:00 – 2:30
M1: *Modeling of spin-lattice dynamics and THz phonon assisted switching*
Oksana Chubykalo - Fesenko
2:30 – 2:50
M2: *Picosecond Optospintronic Tunnel Junctions for Non-volatile Photonic Memories*
Luding Wang
2:50 – 3:20
M3: *Ultrafast spintronics: from attosecond to picosecond time scales*
Jakob Walowski
3:20 – 3:40
M4: *Terahertz emission from Bi/Co bilayer films*
Kazuaki Ishibashi
Coffee break: 20 minutes
4:00 – 4:30
M5: *Ultrafast optical polarimetry in magnetic phases of Kondo semimetal CeSb*
Tomaz Mertelj
4:30 – 4:50
M6: *Multidimensional pathways for coherent control of ferroic order via soft phonon modes*
Matteo Savoini
4:50 – 5:20
M7: *From magnetization pattern to spin waves and back from spin waves to stripe domains*
Maciej Krawczyk
5:20 – 5:40
M8: *Nanoscale partially compensated Ga:YIG for fast exchange magnonics*
Khrystyna Levchenko

Modeling of spin-lattice dynamics and THz phonon assisted switching

Mara Strungaru[1], Matthew O A Ellis[2], Sergiu Ruta[1], Roy W Chantrell[1], and Oksana Chubykalo-Fesenko[3]

[1]*University of York, York, United Kingdom*
[2]*University of Sheffield, Sheffield, United Kingdom*
[3]*Instituto de Ciencia de Materiales de Madrid, Spain*

The main equation governing the dynamics of magnetic systems is the Landau-Lifshitz-Gilbert equation for the precession of spin. The damping term in this approach assumes a separation of timescales, i.e. the bath (electrons or phonons) are assumed in the (quasi-) equilibrium. Recent experiments of ultrafast magnetization dynamics on femto or pico- seconds are conducted in the situations where this assumption is questionable. In this work I will present our recent model based on the classical coupled dynamics of spin and phonons without the assumption that phonon are in equilibrium [1]. Unlike many similar models used in the literature, our model works equally well in the canonical and micro-canonical ensembles and produces a reliable angular momentum transfer from spins to lattice and vice versus. The model also allows the evaluation of the temperature dependence of the macroscopic damping parameter in insulators, giving experimentally reasonable values.

Furthermore, novel possibilities for ultrafast magnetisation switching have been presented recently using ultrafast phonon excitations in Terahertz (THz) regime [2]. Within our model we demonstrate the possibility of a very energy efficient switching in one-specie insulating material in the conditions when phonons are excited with high k-values near P-point and with THz frequencies, corresponding to a maximum in the density of states and no possibility of spinwave excitation. The mechanism of switching is via local magneto-elastic fields created by atom's displacements. In the conditions of the absence of spinwave excitations, practically all phonon angular momentum is transferred to a precessional magnetisation switching. The spin temperature calculated during the switching process shows a minimum increase (in the order of mK), hence the switching process can be considered non-dissipative.

[1] M.Strungaru et al Phys Rev B 103 (2021) 024429
[2] A. Stupakiewicz et al Nat. Phys. 17 (2021) 489.

M2: Thursday 15th, 2:30 – 2:50

Picosecond Optospintronic Tunnel Junctions for Non-volatile Photonic Memories[1]

Luding Wang[1], Weisheng Zhao[2], Martijn Heck[1], and Bert Koopmans[1]

[1]Eindhoven Hendrik Casimir Institute, Center for photonic integration, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.
[2]Fert Beijing Institute, MIIT Key Laboratory of Spintronics, School of Integrated Circuit Science and Engineering, Beihang University, 100191 Beijing, China.

Perpendicular magnetic tunnel junctions (p-MTJs) are one of the building blocks for spintronic memories, which allow fast nonvolatile data access, offering substantial potential for next-generation nonvolatile memory applications[2-3]. However, the performance of such devices is fundamentally hindered by spin-polarized-current-based schemes[2-4], with a nanosecond-spin-precession-time limitation and excessive power dissipation. How to overcome these physical constraints have remained a long-lasting scientific challenge for the modern spintronics community[3,4].

To address these issues, here, we report an optospintronic tunnel junction (OTJ) device using a photonic-spintronic combination. By integrating an all-optically-switchable Co/Gd bilayer[5] with a CoFeB/MgO-based p-MTJ, an all-optical "writing" of the OTJ within 10 ps is experimentally demonstrated. It also shows a reliable electrical "read-out" with a relatively high TMR of 34%, as well as promising scaling towards the nanoscale with a low energy consumption.

A brief circuit-level analysis on the technology assessment aligned with other memory technologies, as well as the ultimate limits of this hybrid spintronic-photonic platform are also provided.

Our proof-of-concept demonstration might pave the way towards a new category of nonvolatile integrated photonic memory devices. This development is considered highly promising towards next-generation ultrafast (picosecond) opto-MRAM technology thus further stimulating the innovation of future & emerging technologies.

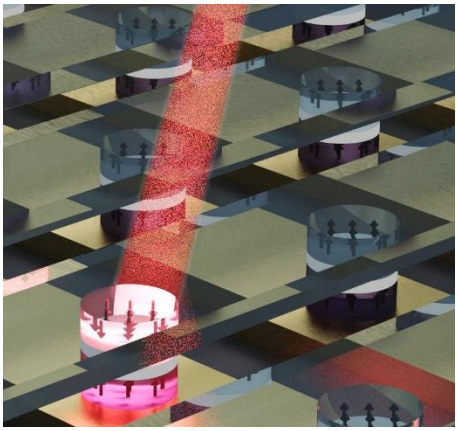


Figure 1: Artistic illustration of the optospintronic tunnel junction device.

References:

[1] Luding Wang *et al*., Picosecond optospintronic tunnel junctions, PNAS, in press (DOI: 10.1073/pnas.2204732119, arXiv: 2011.03612).
[2] Dieny, B. *et al*. Opportunities and challenges for spintronics in the microelectronics industry. Nat. Electron. 3, 446 (2020).
[3] Guo, Z. *et al*. Spintronics for energy-efficient computing: an overview and outlook. Proc. IEEE. 109, 8 (2021).
[4] Kimel, A. V. & Li, M. Writing magnetic memory with ultrashort light pulses. Nat. Rev. Mater. 4, 189 (2019).
[5] Lalieu, M. L., Lavrijsen, R. & Koopmans, B. Integrating all-optical switching with spintronics. Nat. Commun. 10, 110 (2019).

M3: Thursday 15th, 2:50 – 3:20

Ultrafast spintronics: from attosecond to picosecond time scales

Jakob Walowski
[1]Institute of Physics, University of Greifswald, Germany

Magnetization manipulation has become an indispensable tool for both basic research and application development. I will discuss a current overview on ultrafast magnetization dynamics and THz spintronics [1].

The energy transfer from the electron system to the spin system builds the foundation for the response dynamics triggered by optical laser excitation. Therefore, it governs the speed of ultrafast magnetization within the first femtoseconds [1]. Additionally, a non-equilibrium electron distribution after photon energy absorption, generates ultrafast spin currents in layered nanoscale spintronic devices. The application of attosecond laser pulses allows to break new frontiers and observe processes on ever shorter time scales. Recently we have been able to apply this technology and observe coherent spin processes, reaching Petahertz light frequency spintronics. Laser pulses with a duration of a few cycles drive light wave coherent charge transfer. I will present the first experiments showing coherent attosecond magnetism in layered spintronic devices [2]. These fastest spin-dynamics experiments are perfectly described by time-resolved density-functional-theory on the theoretical side, as they perfectly fit the timescale. Those calculations reveal a coherent electron transfer at interfaces in operando. This opens applications for coherent spin current processes. One of those applications for laser-driven ultrafast spin currents is the conversion via the spin-Hall effect into charge currents and thus be used as THz emitters. THz spectroscopy based on spintronic THz emitters allows to map spin structures and their THz dynamics, with a potential for sub micrometer resolution, as has been demonstrated recently [3].

We greatly acknowledge research funding by PetaSpin, Horizon 2020 FET Open and META-ZIK Plasmark-T, BMBF Unternehmen Region.

References

[1] J. Walowski and M. Münzenberg, J. Appl. Phys. 120 140901 (2016).
[2] F. Siegrist et al. Nature 571 (2019).
[3]F.-F. Stiewe, et al. Appl.Phys. Lett. 120, 032406

M4: Thursday 15th, 3:20 – 3:40

Terahertz emission from Bi/Co bilayer films

K. Ishibashi[1,2], S. Iihama[3,2,4] and , S. Mizukami[2,4,5]
[1]Dept. of Applied Physics, Tohoku Univ.
[2]WPI-Advanced Institute for Materials Research (AIMR), Tohoku Univ.
[3]Frontier Research Institute for Interdisciplinary Sciences (FRIS), Tohoku Univ.
[4]Center for Spintronics Research Network (CSRN), Tohoku Univ.
[5]Center for Science and Innovation in Spintronics (CSIS), Tohoku Univ.

Bismuth (Bi) or Bi-based heterostructures has been attracted as candidates for spin current generator. Recently, helicity-dependent (HD) photocurrent in Bi or Bi/Cu(or Ag) thin films was observed via pulse laser-induced terahertz (THz) emission and transport measurement[1, 2]. A circularly polarized laser induces electron spin in Bi depending on optical helicity via conversion from photon spin angular momentum (SAM) to electron SAM, which is called the photo-spin conversion effect. The spin current caused by the gradient of laser-induced spin density is converted into charge current via spin-charge conversion effect. The efficient photo-spin conversion probably originated from the band structure inherent to semi-metallic Bi. However, the detail of photo-spin conversion in Bi has not been clarified yet because the photo-spin conversion and the spin-charge conversion effect are observed simultaneously, thus, one cannot distinguish two spin-related conversion effects. In this study, we measured THz emission induced by spin-current generation using the photo-spin conversion in Bi and the laser-induced demagnetization in an adjacent ferromagnetic Co layer in Bi/Co films to separate two spin-related conversion effects and investigate the photo-spin conversion in Bi.

The samples, glass sub./Bi(t_{Bi})/Co(5)/MgO(2)/Ta(2) (thickness in nm), were prepared by using a DC/RF magnetron sputtering method. Laser-induced THz emission from Bi/Co films was investigated by the THz time-domain spectroscopy (THz-TDS) with a 120-fs Ti: Sapphire laser[3]. Figures 1(a) and 1(b) show linearly-polarized laser pulse induced THz-TDS signals with two opposite M orientations and circularly-polarized laser pulse induced THz-TDS signals with different optical helicities. Here, to observe spin-current generated by photo-spin conversion sample angle was tilted to 45 degrees. It was found that the shape of THz-TDS signals was different with two experiments, which indicates that time-scale of spin-current generated by laser-induced demagnetization in Co and by photo-spin conversion in Bi are different. Figures 2(a) and 2(b) show the Bi thickness t_{Bi} dependence of peak values of helicity-independent THz signal V_{THz} induced by laser-induced demagnetization of Co with linearly-polarized laser pulses and HD-THz signal $V_{\mathrm{THz}}^{\mathrm{HD}}$ induced by photo-spin conversion effect with circularly-polarized laser pulses, respectively. Here, $V_{\mathrm{THz}}^{\mathrm{HD}}$ was the difference between signals measured with left- and right-circularly polarized laser pulses. We clearly observed different t_{Bi} dependence of THz signal with two experiments, which is possibly caused by the difference in spin-relaxation length. In the talk, we will discuss the physics behind the difference in THz signal obtained with two experiments and quantitative consideration of photo-spin conversion effect in Bi.

This work is partially supported by KAKENHI (19K15430, 21H05000). K. I. acknowledges Grant-in-Aid for JSPS Fellow (No. 22J22178) and GP-Spin at Tohoku University.

References

[1] Y. Hirai *et al.* Phys. Rev. Appl. **14**, 064015 (2020).

[2] H. Hirose *et al*. Phys. Rev. B **103**, 174437 (2021).

[3] H. Idzuchi, *et al*., AIP Advances **11**, 015321 (2021); Y. Sasaki *et al*. Appl. Phys. Lett. **111**, 102401 (2017).

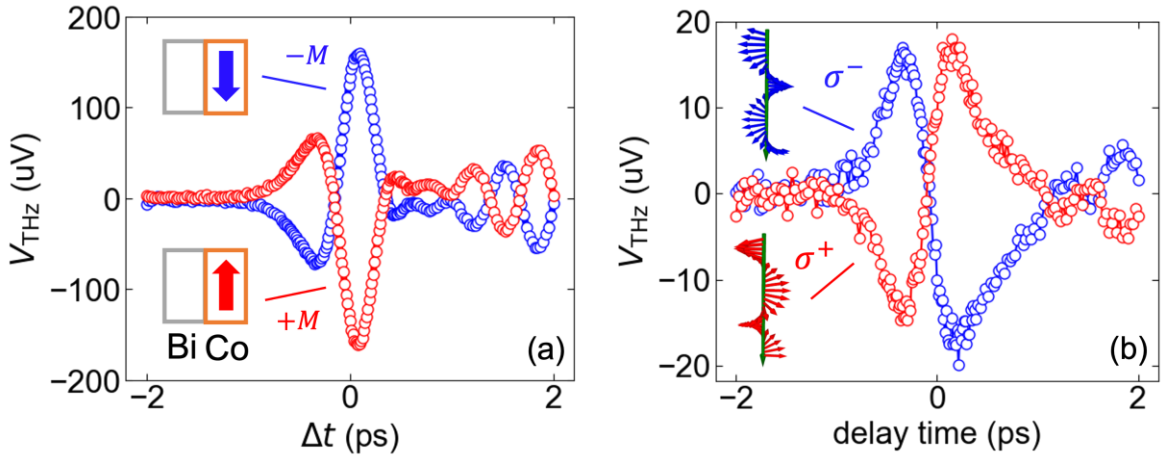


Figure 1 (a) Linearly-polarized laser-induced THz emission from Bi(70)/Co(5) bilayer film with two opposite M orientations. (b) Circularly-polarized laser-induced THz emission from Bi(70)/Co(5) bilayer film with different optical-helicities.

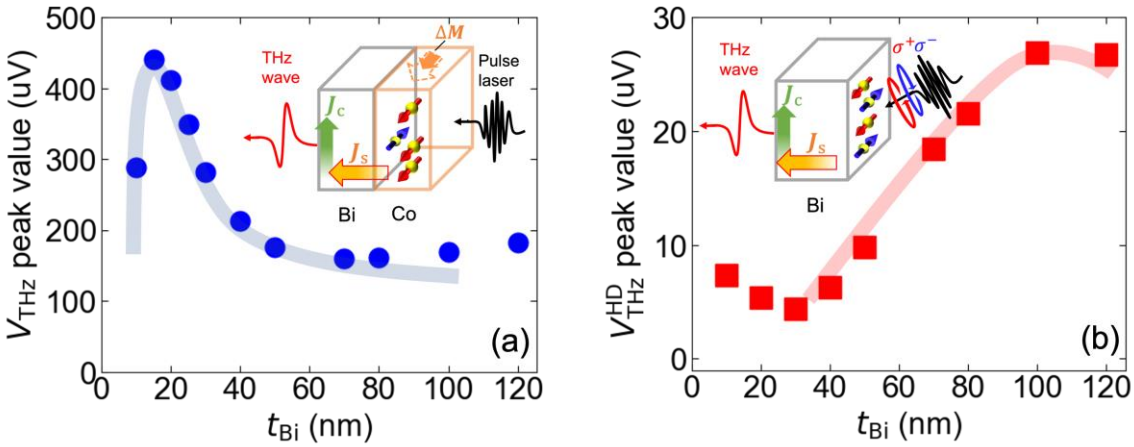


Figure 2 (a) Peak values of linearly-polarized laser-induced THz signal V_{THz} from Bi/Co films plotted as a function of Bi thickness t_{Bi}. (b) Peak values of helicity-dependent (HD)THz signal $V_{\mathrm{THz}}^{\mathrm{HD}}$ with circularly-polarized laser from Bi/Co films plotted as a function of t_{Bi}.

M5: Thursday 15th, 4:00 – 4:30

Ultrafast optical polarimetry in magnetic phases of Kondo semimetal CeSb

M. Naseska[1], A. Bavec[1], E. Goreshnik[2], Z. Jagličić[3], N. Zhigadlo[4], D.Mihailović[1,5] and T.Mertelj[1,4]

[1]Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[2]Department of Inorganic Chemistry and Technology, Jozef Sefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[3]Institute of Mathematics, Physics and Mechanics and Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jadranska 19, SI-1000, Ljubljana, Slovenia
[4]CrystMat Company, CH-8037 Zurich, Switzerland
[5]Center of Excellence on Nanoscience and Nanotechnology - Nanocenter (CENN nocenter), Jamova 39, SI-1000 Ljubljana, Slovenia

The CeSb magnetic phase diagram is one of the most complex among lanthanide monopnictides. It contains at least 16 different magnetic phases in the H-T plane [1] comprising different sequences of ferromagnetic, with either up or down spin orientation, and paramagnetic (001) planes stacked along the *c*-axis. The complexity is thought to arise from the interplay of Kondo, spin orbit and crystal field effects. [1, 2] Lattice modulation in the magnetic phases was also observed [3].

The phase diagram [4, 5] and the magnetic excitations [1] were thoroughly studied by neutron scattering. Recently the sensitivity of the electronic structure to the magnetic phase has been demonstrated [6] and additional magnetic excitations were found in the ordered phases [7].

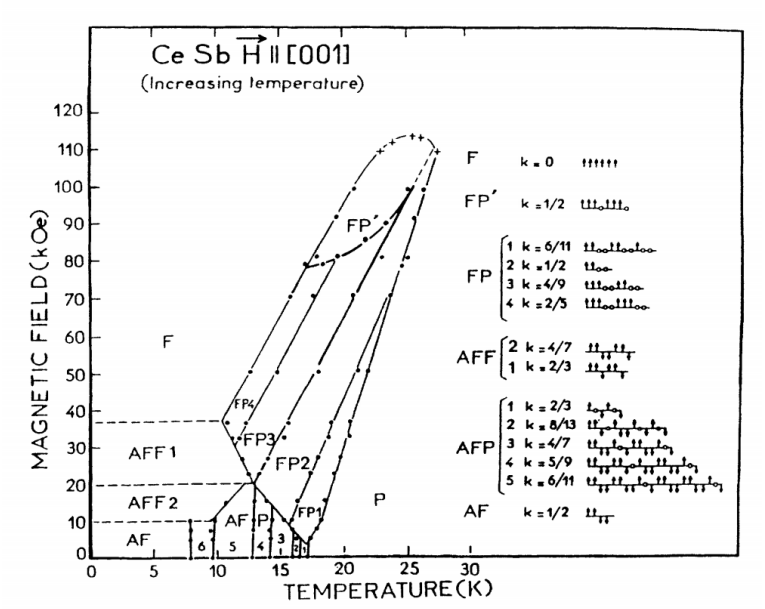


Figure 1: CeSb magnetic phase diagram [5] in the field applied along the [001] direction.

While the main features of the magnetic behavior are understood and successfully modeled using effective interaction approach [8] the microscopic origin of the interactions is still puzzling [2, 7]. An

insight into non equilibrium dynamics of different phases might therefore shed some light to interplay of the different degrees of freedom. Here we present and discuss our investigation of the ultrafast non-equilibrium dynamics upon photo excitation in different magnetic phases in CeSb with focus on the magnetic excitations in the weakly nonequilibrium photoexcited state.

[1] B Hälg and A Furrer, Physical Review **B34**, 6258 (1986).
[2] Jang *et al.*, Sci. Adv. **5**, 7158 (2019).
[3] D. F. McMorrow et al., J. Phys.: Condens. Matter 9, 1133 (1997).
[4] J. Rossat-Mignod *et al.*, Physical Review **B16**, 440 (1977).
[5] T. Chattopadhyay *et al.*, Physical Review **B49**, 15096 (1994).
[6] Kuroda *et al.*, Nat. Comm **11,** 2888 (2020).
[7] Y. Arai *et al.*, Nat. Mat. **21**, 410 (2022).
[8] T. Kasuya *et al.*, JMMM **90 & 91** 389 (1990).

M6: Thursday 15th, 4:30 – 4:50

Multidimensional pathways for coherent control of ferroic order via soft phonon modes

M. Savoini

Physics Department, ETH Zurich, Auguste-Piccard-Hof 1, 8093 Zurich, Switzerland

savoinim@phys.ethz.ch, http://www.udg.ethz.ch

Soft-mode ferroelectrics are materials with a spontaneous electrical polarization driven predominantly by the condensation of an infrared active vibrational mode to zero frequency. Our aim is to understand whether it is possible to use coherent control of these vibrational modes to control ferroelectric polarization on (sub-)picosecond timescales via multi-dimensional phonon excitation.

Here I will present our work on a model system, GeTe, an ionic semiconductor below TC ~ 650 K, performed using a multi-pulse excitation scheme of the IR- and Raman-active phonon modes. Our results indicate that this multidimensional approach in the excitation scheme can pave the way towards a much wider exploration of the energy potential landscape, allowing for strong nonlinearities in the measured dynamics.

M7: Thursday 15th, 4:50 – 5:20

From magnetization pattern to spin waves and back from spin waves to stripe domains

Maciej Krawczyk, Paweł Gruszecki
Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

Spontaneous pattern formation is an intriguing process that can start from linear dynamics and ends in spontaneously broken translational symmetry after a phase transition. Such effect was observed in hydrodynamic systems, such as thermal convection or parametric-wave instabilities, in nonlinear optics, chemical reactions, as well as in biological systems [1]. In ferromagnetic materials, such a phase transition can result in a magnetization pattern formation, usually appearing as a result of a change of the bias magnetic field. From the opposite side, the regular magnetization pattern forms a periodic potential for the formation of the spin-wave band structure and thus can be treated as a natural magnonic crystal [2].
We realized spontaneous translational symmetry breaking by strong homogeneous microwave pumping of a micron-sized permalloy stripe with the resulting transition directly imaged by scanning transmission x-ray microscopy [3]. For an understanding of the experimental findings, the micromagnetic simulations are adapted. Beyond the formation of discrete translational symmetry in space, we also observed regular oscillations in time, indicating the generation of the magnonic space-time crystals. Periodicity allows for observing the formation of a magnonic band structure, which clearly demonstrates interactions of spin waves with this space-time crystal, and results in the generation of ultrashort spin waves down to 100-nm wavelengths.

The research leading to these results has received funding from the Polish National Science Centre project UMO-2020/37/B/ST3/03936.

References:
[1] M. C. Cross and P.C. Hohenberg, Pattern formation outside of equilibrium, Rev. Mod. Phys. 65, 851 (1993).
[2] C. Banerjee, et al., Magnonic band structure in a Co/Pd stripe domain system investigated by Brillouin light scattering and micromagnetic simulations, Phys. Rev. B 96, 024421 (2017).
[3] N. Träger et al., Real-space observation of magnon interaction with driven space-time crystals, Phys. Rev. Lett. 126, 057201 (2021).

M8: Thursday 15th, 5:20 – 5:40

Nanoscale partially compensated Ga:YIG for fast exchange magnonics

K. O. Levchenko[1], T. Böttcher[2, 3], M. Ruhwedel[2], Q. Wang[1], H. L. Chumak[4], M. A. Popov[4], I. V. Zavislyak[4], C. Dubs[5], O. Surzhenko[5], B. Hillebrands[2], A. V. Chumak[1], and P. Pirro[2]

[1] *Faculty of Physics, University of Vienna, Austria*
[2] *Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Germany*
[3] *MAINZ Graduate School of Excellence, Mainz, Germany*
[4] *Faculty of Radiophysics, Electronics and Computers, Taras Shevchenko National University of Kyiv, Ukraine*
[5] *INNOVENT e.V. Technologieentwicklung, Jena, Germany*

Spin-wave based logic proved to be a CMOS-competitive technology, with an exemplary concept of the magnonic half-adder, demonstrated by Wang et al., [1], surpassing the conventional devices in energy consumption and optimized fabrication methodology. To further facilitate the magnonics technology, the delay time in nanostructures should be improved by utilizing fast exchange spin-waves and reaching higher operational frequencies, respectively. Since the exchange contribution to the group velocity v_{gr} is directly proportional to the exchange stiffness λ_{ex}, where $\lambda_{\mathrm{ex}} = 2A/\mu_0 M_{\mathrm{s}}$ and A is the Heisenberg exchange constant, materials with enhanced stiffness and low saturation magnetization M_{s} are promising candidates for further investigation.

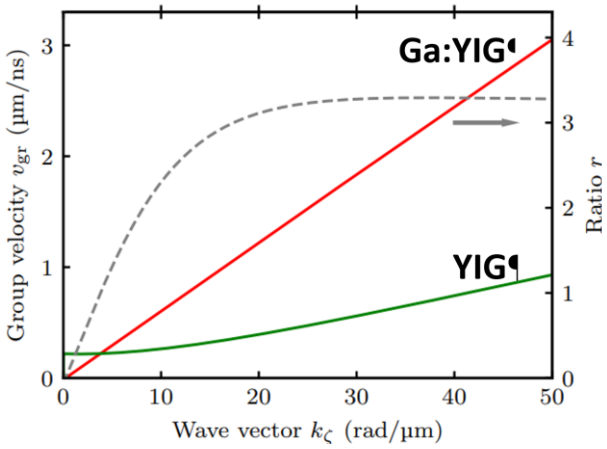


Figure 1: Group velocity [3] calculated from the dispersion relations for 59 nm thick Ga:YIG film (red) and pure YIG (green) at an applied field of 300 mT. The ratio *r* of the group velocities for Ga:YIG and YIG is plotted by a grey dashed line.

For this purpose, single-crystalline sub-100 nm thick films of $Y_3Fe_{5-x}Ga_xO_{12}$ ($0 < x < 1.5$) and 97 nm reference YIG were fabricated via Liquid Phase Epitaxy (LPE) [2]. First, Ga-substituted YIG and reference YIG specimens were characterized via angle-resolved Ferromagnetic Resonance Spectroscopy (FMR), demonstrating a small saturation magnetization ($\mu_0 M_{\mathrm{s}} \sim 20$ mT), an enhanced uniaxial anisotropy ($\mu_0 H_{\mathrm{u1}} \sim 90$ mT) and a good Gilbert damping parameter $\alpha = 6.1 \cdot 10^{-4}$ [3]. The strong increase of the uniaxial anisotropy (~ 27 times) indicates the out-of-plane easy axis of Ga:YIG thin films [4], which also facilitates entirely isotropic Forward Volume waves.

The dispersion relation of thermally excited dipole-exchange spin-waves propagating perpendicularly to the applied field in 59-nm Ga:YIG film was probed by Brillouin light scattering spectroscopy (BLS). The exchange stiffness in the film under investigation $\lambda_{\mathrm{ex}} = (13.54 \pm 0.07) \times 10^{-11}$ T·m^2 is about three times as large as the one for pure YIG, that results in much higher (~ 3.4 times) group velocities for $k > 30$ rad/μm (Fig. 1). Even the spin waves of the relatively small wave

vector $k \approx 4$ rad/μm exhibit an exchange nature and their dispersion relation is significantly more isotropic compared to the waves of the same wavelength in YIG. Moreover, spin-wave properties in Ga:YIG do not depend on the geometrical sizes of magnonic conduits.

Thus, **Ga:YIG opens access to the operation with the fast isotropic exchange spin-waves** of variable wavelengths in future magnonics networks.

References:

[1] Q. Wang, et al., *Nat. Electron.* **3**, 765–774 (2020).
[2] C. Dubs et al., *Phys. Rev. Materials* **4**, 024416 (2020).
[3] T. Böttcher, et al., *Appl. Phys. Lett.* **120**, 102401 (2022).
[4] J. J. Carmiggelt, et al., *Appl. Phys. Lett.* **119**, 202403 (2021).

COMRAD project

Friday September 16th

8:30 – 9:30
COMRAD surpervisory board
9:30 – 9:45
C1: *Propagation of nearly single-cycle THz pulse in antiferromagnetic CoF2*
Thomas Metzger
9:45 – 10:00
C2: *Reliable all-optical-switching in Tb/Co multilayers based tunnel junctions*
David Salomini
10:00 – 10:15
C3: *Exploring THz exchange resonances in ferrimagnetic Co/Gd multilayers with all-optical spin currents*
Julian Hintermayr
10:15 – 10:30
C4: *In-Plane Magnetization Switching of a Ferromagnet via Femtosecond Laser Pulses*
Leo Lin
Coffee Break – 15 min
10:45 – 12:45
Technology Transfer
P. Bortolotti, C. Sandaldjian, R. Lebrun

C1: Friday 16th, 9:30 – 9:45

Propagation of nearly single-cycle THz pulse in antiferromagnetic CoF_2

T.W.J. Metzger[1], K. Grishunin[1], R. Dubrovin[2], E. Mashkovich[3], D. Afanasiev[1], R. Pisarev[2], and A.V. Kimel[1]

[1]Radboud University, Institute for Molecules and Materials, 6525 AJ Nijmegen, The Netherlands
[2]Ioffe Physical-Technical Institute, Russian Academy of Sciences, 194021 St Petersburg, Russia
[3]Institute of Physics II, University of Cologne, Cologne, Germany

Antiferromagnets (AFM) have attracted tremendous attention in spintronics and magnonics because of their spin-wave resonances lying in the high-frequency terahertz (THz) range and unique functionalities when compared to conventionally used ferromagnets [1]. Although much is known on how a THz pulse influences spin order, surprisingly little is known about the opposite. In fact, how interaction with the spins influences the THz pulse itself upon propagation inside of thick antiferromagnetically ordered media. Here we study the archetypal low-temperature antiferromagnet CoF_2 (T_N = 39 K). In this easy-axis AFM, it has been recently shown that linearly polarized THz pulses can be used to coherently control both spin and lattice on the ultrafast timescale [2-3]. Using polarization-sensitive THz time-domain transmission spectroscopy, we explored how single-cycle linearly polarized THz pulse (Fig. 1 (a)) changes upon propagation through CoF_2. The changes are found to depend strongly on the sample temperature (Figure 1 (b)) and can be explained in terms of magnetic linear birefringence and dichroism. The ellipticity is showing a pronounced growth upon cooling below T_N and is accompanied by a giant rotation of the polarization plane. The parameters plotted as a function of temperature are found to resemble the antiferromagnetic L-vector dependence in excellent agreement.
Although the magneto-optical effects in the THz spectral range are often considered to be relatively small, our experiments reveal that the polarization of the THz pulse substantially changes along with the pulse

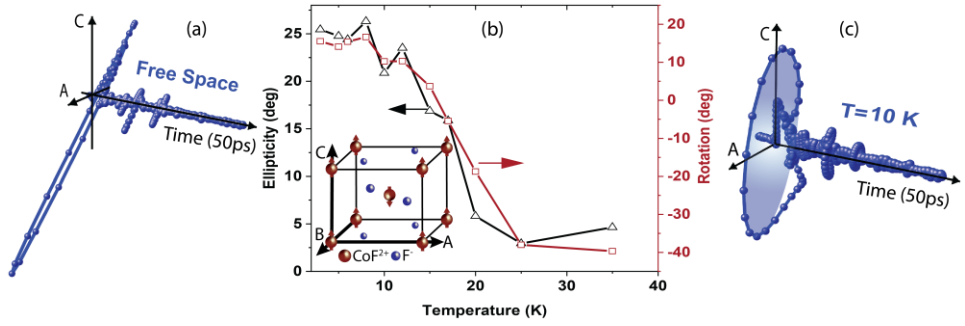


Figure 1: Linear polarized THz pulse before (a) and after (c) propagation through AFM CoF_2 (b) Extracted rotation and ellipticity as a function of temperature and CoF_2 unit cell.

duration as shown in figures 1 (a, c). The pulse shape is further complicated by the emergence of pronounced beatings, indicative of the formation of magnon-polaritons highlighting a regime of strong coupling.
Our findings demonstrate the importance of accounting for propagation effect in THz control of AFMs in spintronics and magnonics and thus help to develop methods for the fastest possible and the most energy-efficient logic operations based on AFMs.

References

[1] T. Jungwirth et al., Nature Nanotech. 11, 231 (2016).
[2] T. Kampfrath et al. Nature Photon 5, 31–34 (2011).
[3] A. S. Disa et al., Nat. Phys. 16, 937–941 (2020).

C2: Friday 16th, 9:45 – 10:00

Reliable all-optical-switching of Tb/Co multilayers based tunnel junctions

D. Salomoni[1], Y. Peng[2], L. Avilés-Félix[1], L. Farcis[1], S. Auffret[1], M. Hehn[2], G. Malinowski[2], S. Mangin[2], B. Dieny[1], L. D. Buda-Prejbeanu[1], R. Sousa[1] and I. L. Prejbeanu[1]

[1] *Spintec, Université Grenoble Alpes, CNRS, CEA, Grenoble INP, IRIG-SPINTEC, 38000 Grenoble, France*
[2] *Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, Nancy 54011, France*

Controlling the magnetization of storage elements through ultrashort laser pulses could be very beneficial for memory applications in terms of speed and energy efficiency. The first complete magnetization reversal driven by ultrashort light pulses have been reported in GdFeCo ferrimagnetic alloy [1]. Since then, this phenomenon has been studied and observed in other types of materials. One example is the single-shot helicity independent all-optically-switching (AOS) of MTJ stacks based on [Tb/Co] multilayers (ML) [2][3]. A [Tb/Co] multilayer system is particularly interesting due to its large perpendicular magnetic anisotropy allowing for high retention of the information even at small dot sizes. In this work, through extensive studies of the magnetization response to ultrashort laser pulses, we demonstrate reliable and robust toggle switching for specific Tb and Co thickness range (between 0.6 nm and 0.9 nm for Tb and between 1.3 nm and 1.5 nm for Co) – see fig. 1(**a**) Sample 1. The magnetization reversal is still reliable even after 150.000 pulses, as shown in fig. 1(**b**). Single shot AOS is achievable using laser pulse duration varying from 50 fs up to 10 ps and fluences from 3.0 mJ/cm² to 6.5 mJ/cm². If the thickness range is not fully optimized (+/- 0.5nm), the magnetization reversal becomes less reproducible and can drive the sample into a multi-domain state after multiple pulses – see fig. 1(**c**) Sample 2. The single shot AOS have been observed for different stacks including: pristine non-annealed [Tb/Co]ML fig. 1(**d**); annealed [Tb/Co]ML coupled to the FeCoB free layer fig. 1(**e**); full MTJ stack with [Tb/Co]ML having as reference layer a synthetic antiferromagnet (SAF), annealed at 250°C fig. 1(**f**).

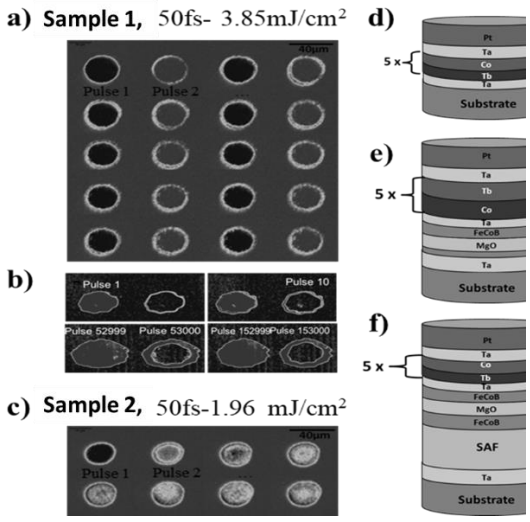


Figure 1: (**a-b**) Background corrected magneto-optical images showing robust and reliable single shot AOS of half-MTJ stack shown in (e); (c) unsaturated state after few pulses. (**d-e-f**) Stacks investigated that show single shot AOS.

These results pave the way towards the development of an ultra-fast and energy-efficient memory that exploits AOS.

Acknowledgements: UFO, COMRAD - EU grant no. 861300

[1] C. Stanciu e al., Phys. Rev. Lett. **99**, 047601 (200
[2] A. Olivier et al., Nanotechnology **31**, 425302 (2020).
[3] L. Avilés-Félix et al., Scientific Reports **10**, 1 (2020).

C3: Friday 16th, 10:00 – 10:15

Exploring THz exchange resonances in ferrimagnetic Co/Gd multilayers with all-optical spin currents

J. Hintermayr[1], Y. L. W. van Hees[1], and B. Koopmans[1]
[1] Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands

Magnetic materials with several spin-sublattices such as ferrimagnets can show exchange resonance modes (EXMs), where magnetic moments from different sublattices precess in the exchange fields of one another (schematically shown in Fig. 1**c**). These precessions have a high frequency (THz – infrared range) in the case of certain antiferromagnets [1] and have recently been attracting much attention in the newly emerging research area of THz spintronics [2].

Due to their high frequency, it is non-trivial to coherently excite these modes. We report a novel route in which we utilize interlayer spin currents generated by fs laser pulses.

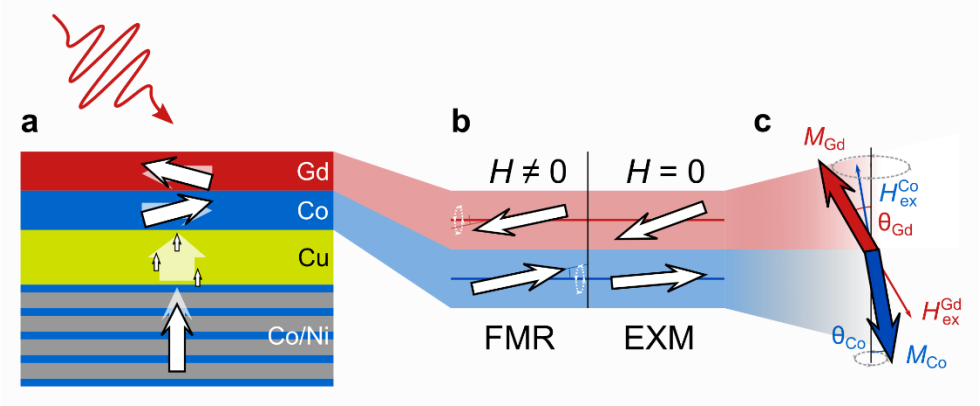


Figure 3. Cartoon of a, sample architecture showing local arrangements of magnetization and the resonance excitation mechanism b, stable spin precession configurations and c, local directions of exchange fields in canted magnetization states between Co and Gd, allowing for fast resonance frequencies.

In this work, we explore EXMs in synthetic ferrimagnetic Co/Gd-based multilayers with an in-plane magnetic easy axis, in which magnetic compensation can easily be adjusted by varying layer thicknesses. Coherent resonance modes in the Co/Gd system are excited by injecting a spin current from a neighbouring Pt/Co/Ni multilayer with perpendicular magnetic anisotropy following fs laser excitation (see Fig. 1**a**). A weak fs probe pulse is used to measure time-resolved dynamics by virtue of the magneto-optical Kerr effect. We observe EXMs with frequencies in the sub-THz range, in addition to ferromagnetic resonance (FMR) modes in the GHz regime, when an in-plane field is applied. By comparing experimental results to micromagnetic simulations, we confirm the origin of the observed oscillations.

Next to offering a completely new route towards coherently exciting EXMs, the technique gives valuable insights on dynamic magnetic properties and coupling phenomena in the highly interesting Co/Gd platform.

Acknowledgments:
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861300.

References:
[1] F. Keffer, C. Kittel, *Phys. Rev.* **85**, 329 (1952).
[2] M. Münzenberg, *Nat. Phys.* **17**, 985 (2021).

C4: Friday 16th, 10:15 – 10:30

In-Plane Magnetization Switching of a Ferromagnet via Femtosecond Laser Pulses

J.-X. LIN[1], J. HOHLFELD[1], M. HEHN[1], M. VERGES[1], J. IGARASHI[1], Q. REMY[1,2], T. HAUET[1], J. GORCHON[1], G. MALINOWSKI[1], D. LACOUR[1], and S. MANGIN[1,2]
[1]Université de Lorraine, Institut Jean Lamour, UMR CNRS, Nancy 7198, France
[4]University of Cambridge, Cavendish Laboratory, Cambridge CB3 0HE, United Kingdom

Since the pioneering discovery of the switching of magnetization direction induced by laser pulses was observed in the ferrimagnetic GdFeCo opening the field named All-Optical Switching (AOS). This result shines a light on future ultrafast and energy-efficient opto-magnetic storage devices [1,2]. It has been demonstrated that a wide variety of magnetic materials exhibit AOS, especially pointing out the application of ferromagnet which is the essential element in a nowadays advanced magnetic random-access memory. However, multiple laser pulses are usually required [3]. As a consequence, finding an alternative way to reduce the number of pulses in a ferromagnetic material is being sought.

In 2018, Iihama, S. *et al*. revealed one promising approach to achieving single-shot magnetization reversal of ferromagnetic [Co/Pt] multilayers in GdFeCo/ Cu/ [Co/Pt] spin-valve structures with perpendicular magnetic anisotropy [4]. The important key is to take advantage of the nature of the heating offered by a laser pulse: the magnetization of Gd is demagnetized creating the spin current and this spin current is injected into [Co/Pt] which has sufficiently demagnetized. Accordingly, [Co/Pt] experiences the reversal and the following reconstruction of its magnetization. Further evidence of the effect of the spin current generated by Gd on the magnetization reversal of a ferromagnet has been shown recently [4-6] including how spin-polarized current makes the reversal faster [7]. However, similar studies involving in-plane magnetic anisotropy (IMA) have not yet been studied, this benefits from the understanding of demagnetization-driven spin currents via terahertz emission [8].

In this work, we demonstrate the magnetization switching of a ferromagnetic [$Co_{20}Ni_{80}$] alloy in GdFeCo/ Cu/ [$Co_{20}Ni_{80}$] spin-valve structures whose both magnetic layers exhibit IMA. The complete magnetization switching of [$Co_{20}Ni_{80}$] is successfully observed after two linearly polarized laser pulses with no external magnetic field, whereas a partial magnetization switching was obtained when only one laser pulse was shone on the spin-valve. We found that the magnetization switching of [$Co_{20}Ni_{80}$] is also established when the magnetization direction of Gd is antiparallelly aligned to [$Co_{20}Ni_{80}$], which is consistent with previous studies with a similar structure [4-6]. We attribute these results to an energy barrier to overcome in order to orient all the domains in a direction opposite to the initial one. This work offers the possible structure to examine the recent efforts in demagnetization-driven spin currents reversing the magnetization direction of a ferromagnetic film.

References

[1] C. D. Stanciu *et al*., *Phys. Rev. Lett.* **99**, 047601 (2007).
[2] A. V. Kimel *et al*., *Nat. Rev. Mater.* **4**, 189-200 (2019).
[3] C.-H. Lambert *et al.*, *Science* **345**, 1337 (2014).
[4] S. lihama *et al*., *Adv. Mater.* **30**, 1804004 (2018).
[5] Q. Remy *et al*., *Adv. Sci.* **7**, 2001996 (2020).
[6] J. Igarashi *et al*., *Nano. Lett.* **20**, 8654-8660 (2020).
[7] Q. Remy *et al*., *Submitted* (2022).

[8] R. Gupta *et al.*, arXiv:2205.07974v1 (2022).

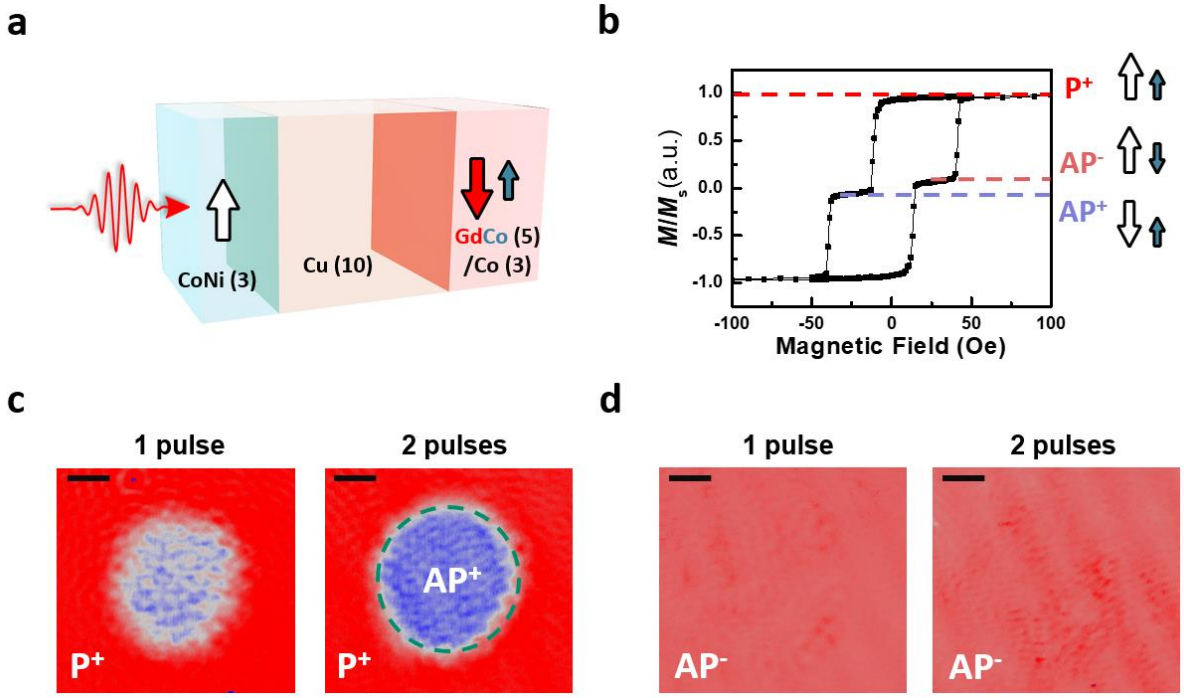


Figure: (a) Cross-section of the in-plane spin-valve structure for AOS assessments. The arrows represent the initial magnetization direction of each element. (b) Magnetic field-dependent magnetization was measured by the vibrating-sample magnetometer. Magneto-optical Kerr images were obtained after different numbers of laser pulses: when the sample with a (c) P^+ and (d) AP^+ initial magnetic configuration, respectively. The scale bar indicates 50 μm.

Training on "Technology transfer, industrial business and start-ups creation"
10h45-12h45, 16th of September

- Description of Innovation & Technology transfer processes: The importance of knowledge valorisation through technology transfer – Europe's path from Research to Impact. Managing the transition from Research to Products in a large industrial group: R&T in Thales. Camille Sandaldjian – Thales TRT

- Technology transfer from a industrial research center to a business unit : The example of cold cathodes, based on carbon nanotube (CNT). Pierre-Louis Gautherin - Thales AVS (remote)

- Technology transfer by start-up creation from an academic lab : The example of DAUMET, from spintronic to luxury. From the leap of faith to the march of industrialisation, an example of deeptech entrepreneurship. Cyril Deranlot, CEO – DAUMET (remote).

POSTERS I

PI-1: THz emission from exchange-coupled Fe/Pt/Cr/Pt/Fe spintronic emitter pair

R. Adam[1], D. Cao[1,5], D. E. Bürgler[1], G. Chen[2], S. Heidtfeld[1], D. Chakraborty[2], J. Cheng[2], F. Wang[1], I. Komissarov[2], A. Alostaz[1], C. Greb[1], M. Büscher[1], H. Hardtdegen[3], M. Mikulics[3], Roman Sobolewski[2], and C. M. Schneider[1,4]

[1]Research Centre Jülich, Peter Grünberg Institute (PGI-6), 52425 Jülich, Germany
[2]University of Rochester, Rochester, New York 14627-0231, USA
[3]Research Centre Jülich, Ernst Ruska Centre (ERC-2), 52425 Jülich, Germany
[4]Department of Physics, University of California Davis, Davis, California 95616-5270, USA
[5]College of Physics, Qingdao University, 266071 Qingdao, China

In FM/HM bilayers, THz bursts can be generated by optically injecting a spin current (j_S) from FM into a HM thin film. Inverse spin Hall effect then in turn, converts j_S into picosecond transient charge current (j_C) directed perpendicular to j_S and to the FM material's magnetization M [1,2]. Here we show that the amplitude of the THz transients can be finely tuned by controling the strength of the interlayer exchange coupling between ferromagnetic thin films. We simultaneously illuminated two MBE-grown Fe/Pt spintronic emitters separated by a 0- to 3-nm-thin Cr wedge. We observed that for low laser fluence of 12.5 nJ/cm^2 intensity of generated THz transients can be precisely tuned both by the magnetic field and by the Cr-mediated interlayer coupling strength. Our measurements, shown in the Figure below, indicate that the intensity of the THz transients can be tuned by more than 500% by controlling the relative alignment of the magnetizations of the ferromagnetic layers.

The work at the Research Centre Jülich (FZJ) was performed within the JuSPARC strategy project funded by the BMBF. The research at the University of Rochester was supported in part by the DOE Grant DE-SC0022473.

[1] E. Saitoh et al., Appl. Phys. Lett. 88, 182509 (2006).
[2] R. Adam et al., Appl. Phys. Lett. 114, 212405 (2019).

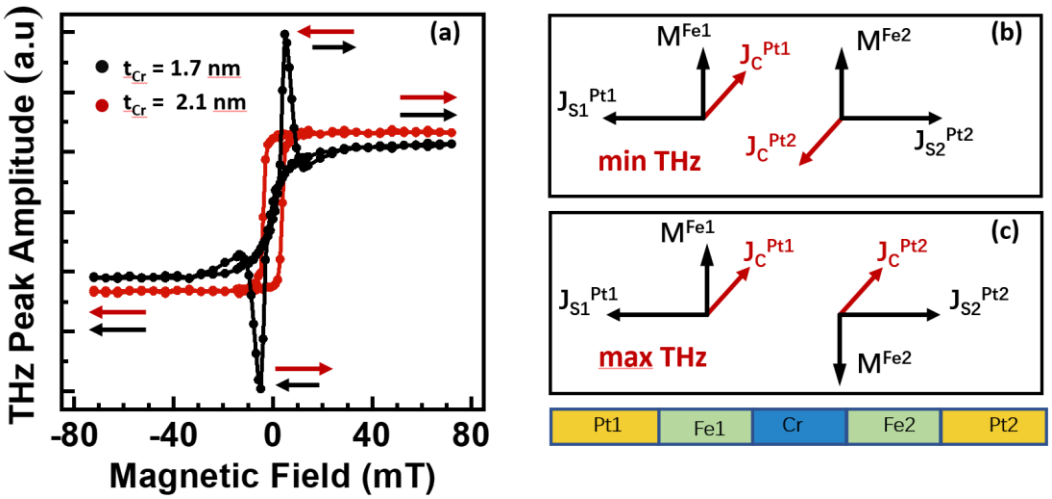


Figure: THz peak amplitude as a function of external magnetic field for Cr thicknesses of 2.1 nm (red), and 1.7 nm (black). Arrows show the magnetization alignments for weak (parallel) and strong (antiparallel) THz generation. (b) and (c) show the alignment of M, j_S, and j_C in the two emitters at maximum and minimum THz generation assuming pure ISHE mechanism and signal generation at the Fe/Pt interfaces. The layer sequence of the exchange coupled spintronic emitter pair is indicated below (c).

PI-2: Laser-induced charge and spin photocurrents in $BiAg_2$ surface from first-principles

T. Adamantopoulos[1,2*], M. Merte[1,2,3], F. Freimuth[1,3], D. Go[1,3], S. Blügel[1], and Y. Mokrousov[1,3]

[1]Peter Grünberg Institut and Institute for Advanced Simulation,
Forschungszentrum Jülich and JARA, 52425 Jülich, Germany
[2]Department of Physics, RWTH Aachen University, 52056 Aachen, Germany
[3]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

The physics of photo-induced effects in interfacial systems is intensively researched these days owing to numerous potential applications. Owing to the complexity of the problem, a comprehensive theoretical picture of photogalvanic effects taking place at realistic metallic surfaces and interfaces is still lacking. In the past, it was shown that in the ferromagnetic Rashba model with in-plane magnetization charge and spin photocurrents which are of second order in the electric field are allowed by symmetry. Additionally, second order spin photocurrents are allowed by symmetry in the non-magnetic Rashba model. These responses stem from the interfacial spin-orbit interaction (SOI) and can be generated by the application of femtosecond laser pulses [1,2]. Here, we report calculations of laser-induced currents within the Keldysh non-equilibrium formalism combined with the Wannier interpolation scheme which can be applied to metallic and insulating materials of any complexity. We perform our first-principles electronic structure calculations with the DFT code FLEUR [www.flapw.de], and study in detail a $BiAg_2$ surface alloy, which is a well-known material realization of the Rashba model. The in-plane magnetization is introduced by the addition of a Zeeman splitting term in the Wannier-interpolated Hamiltonian. We calculate the laser-induced charge photocurrents for the ferromagnetic case and the laser-induced spin photocurrents for both the non-magnetic and the ferromagnetic case. Our results confirm the appearance of in-plane photocurrents as predicted by the Rashba model. The resulting photocurrents satisfy all the predicted symmetry restrictions with respect to the light helicity and the magnetization direction. We provide microscopic insights into the symmetry and magnitude of the computed currents based on the electronic structure of the system. Our work contributes to the study of the role of the interfacial Rashba SOI as a mechanism for the generation of in-plane photocurrents, which are of great interest in the field of ultrafast and terahertz spintronics [3].

References

[1] F. Freimuth, S. Blügel, and Y. Mokrousov, Phys. Rev. B **103**, 075428 (2021).
[2] F. Freimuth, S. Blügel, and Y. Mokrousov, Phys. Rev. B **94**, 144432 (2016).
[3] T. Adamantopoulos, M. Merte, F. Freimuth, D. Go, S. Blügel, and Y. Mokrousov, arXiv:2201.07122 (2022).

PI-3: Spin conversion in epitaxial monolayer graphene structures

Alberto Anadón[1], Adrián Gudín[2], Iciar Arnay[2], Heloise Damas[1] Rubén Guerrero[2], Alejandra Guedeja-Marron[2,3], Jose Manuel Díez Toledano[2,4] Rodolfo Miranda[2,4,5], Julio Camarero[2,4,5], Junior Alegre[1], Sébastien Petit-Watelot[1], Paolo Perna[2], Juan-Carlos Rojas-Sánchez[1]

[1]1Institut Jean Lamour, Université de Lorraine CNRS UMR 7198, Nancy, France∗
[2]IMDEA Nanociencia, C/Faraday 9, 28049 Madrid, Spain
[3]Departamento de Física de Materiales and Instituto Pluridisciplinar, Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain
[4]Departamento de Física de la Materia Condensada and Departamento de Física Aplicada and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, 28049 Madrid, Spain
[5]IFIMAC, Universidad Autónoma de Madrid, 28049 Madrid, Spain

The search for materials with efficient spin-to-charge interconversion is currently a highly sought-after objective in spintronics. In current spintronics, functional devices are typically made of a bilayer composed of a normal metal with large spin-orbit coupling (NM) and a ferromagnet (FM). These types of stacks allow functionalities like the manipulation of the FM magnetization by the spin Hall effect (SHE) [1] in the NM or thermal energy harvesting by means of its inverse counterpart the inverse spin Hall effect [2]. These effects can also be utilized for thermal management purposes, where a high efficiency of spin conversion is needed.

In order to obtain more efficient devices based on thermo-spin phenomena, the role of interfaces is relevant. Here, we explore the effect of a graphene monolayer between a FM and a NM layer and its interfacial spin transport properties by measuring the thermo-spin and spin pumping voltages. To do it, we have fabricated epitaxial Ir(111)/FM/gr/NM structures in-situ on Al2O3(0001) substrates by a combination of different growth techniques.

We show that the gr monolayer plays an important role in the spin conversion process and its effect can be detected in both the thermo-spin and the spin pumping voltages. We have used two different FM: Co and Fe. In the case of Co, we observe a net reduction in the sum of the spin Seebeck and interfacial contributions due to the presence of gr and independent from the spin Hall angle sign of the NM used [3]. In the case of Fe, we observe a significant voltage increase in the spin pumping signal when the NM is Pt and a decrease in the cases of Ta and Al, suggesting an important inverse Rashba-Edelstein effect in the Fe/gr interface.

This work by supported by ANR TOPTRONIC ANR-19-CE24-0016-01 and FUN-SOC: FEST from the Spanish ministry of science and innovation.

[1]. Anadon, A. et al. ACS Applied Nano Materials 4 (1), 487-492. (2020)

[2]. Ramos, R. et al. APL Mater. 4. (2016).

[3] Anadón, et al. APL Materials, 9(6), 061113. (2021).

[4] F.Ajejas et al. Nano Lett 18, 5364-5372 (2018)

[5] F. Ajejas et al. Appl. Mat & Inter. 12, 4088-4096 (2020)

PI-4: Thermal spin current generation in multifunctional materials and interfaces

Alberto Anadón,[1] Elodie Martin,[1] Suvidyakumar Homkar,[2] Benjamin Meunier,[2] Heloise Damas,[1] Junior Alegre,[1] Maxime Verges,[1] Christophe Lefevre,[2] Francois Roulland,[2] Carsten Dubs,[3] Olivier Copie,[1] Rafael Ramos,[4] Francisco Rivadulla,[4] Daniele Preziosi,[2] Jon Gorchon,[1] Sébastien Petit-Watelot,[1] Nathalie Viart,[2] and Juan-Carlos Rojas-Sánchez[1]

[1]Institut Jean Lamour, Universit ́e de Lorraine CNRS UMR 7198, Nancy, France∗

[2]Universit ́e de Strasbourg, CNRS, IPCMS, UMR 7504, F-67000 Strasbourg, France

[3]INNOVENT e.V. Technologieentwicklung, Jena, Germany

[4]Departamento de Química-Física, Universidade de Santiago de Compostela, Spain

The seach for ferromagnetic insulating materials with multifunctional properties is currently a highly sought after objective in spintronics. In current spintronics, functional devices are typically made of a bilayer composed of a material with large spin-orbit coupling (NM) and a ferromagnet (FM). These type of devices allow functionalities like the manipulation of the FM magnetization by the spin Hall effect (SHE)[1] in the NM or energy harvesting by means of its inverse counterpart the inverse spin Hall effect [2]. Insulating ferrimagnets are preferred for this purpose to pave the way towards low dissipation spintronics devices.[3] Additional functionalities like the possibility of the electric field control of the magnetic properties of such systems could be given to these heterostructures through the introduction of multifunctional ferromagnets opening the possibility of having more efficient and versatile devices [4].

We have studied the thermo-spin current generation in bilayers composed of Pt and the multifunctional magnetoelectric Ga0.6Fe1.4O3 (GFO).[5] We compare the performance of this new system with the widely used yttrium iron garnet obtaining a similar value of the spin Seebeck effect [6], likewise to what was observed previously in spin Hall magnetoresistance[7]. In addition, by fabrication of thermo-spin devices with controlled dimensions we are able to accurately quantify the relevant parameters of the thermal effects.

In order to obtain more efficient devices based on thermo-spin phenomena, the role of interfaces and 2D materials can also be relevant.

These results pave the way for the use of the magnetoelectric multiferroic GFO with a view to control the spin current production of NM/FM heterostructures by an electric field and the use of graphene interfaces for tuning the spin conversion.

This work was funded by the French National Research Agency (ANR) through the ANR-18-CECE24-0008-01 ‘ANR MISSION’ and the No. ANR-19-CE24-0016-01 ‘Toptronic ANR’.

[1] Anadon, A. et al. ACS Applied Nano Materials 4 (1), 487-492. (2020)

[2] Ramos, R. et al. APL Mater. 4. (2016).

[3] Avci, C. O. et al. Nature 461, 1218–1219. (2009).

[5] Roy, A. et al. Ferroelectrics 473, 154–170. (2014).

[6] Anadon A. et al. In preparation. (2022)

[7] Homkar, S. et al. ACS Applied Electronic Materials, 3(10), 4433-4440. (2021).

[8] Anadón, et al. APL Materials, 9(6), 061113. (2021).

PI-5: Spin current volume effect in a ferromagnet $Tb_{0.3}Dy_{0.7}Fe_2$

H. Arisawa,[1] H. Shim,[2] S. Daimon,[3] T. Kikkawa,[1,3,4] Y. Oikawa,[4] S. Takahashi,[4] T. Ono,[2,5] and E. Saitoh[1,3,4,6]

[1] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan.*

[2] *Department of Mechanical Systems Engineering, Tohoku University, Sendai 980-8579, Japan.*

[3] *Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan.*

[4] *WPI, Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan.*

[5] *Micro System Integration Center (μ-SiC), Tohoku University, Sendai 980-8579, Japan.*

[6] *Institute for AI and Beyond, The University of Tokyo, Tokyo 113-8656, Japan.*

The interplay between magnetization and strain in a magnet has long been an important issue in magnetism. The typical example is the magneto-volume effect (MVE) [1] in a ferromagnet, the volume change connected to the spin fluctuation modulation. Extensive studies on the MVE have been made by controlling spin fluctuation via magnetic field application or temperature modulation, leading to remarkable progress in the physics of spin fluctuation and electronic correlation. Now, owing to the recent progress of spintronics, spin fluctuation can be directly modulated by using a spin current [2], enabling us to expand the physics of magnetomechanical dynamics in the MVE into a spintronics framework.

We have investigated a spin current volume effect [3], volume manipulation by using a spin current, in a giant magnetostrictive material $Tb_{0.3}Dy_{0.7}Fe_2$. By injecting a spin current into a $Tb_{0.3}Dy_{0.7}Fe_2$ film, we demonstrated that the $Tb_{0.3}Dy_{0.7}Fe$ film thickness changes in response to the spin current injection (Fig. 1). We performed theoretical calculation and found that the spin-current induced modulation of magnetization fluctuation well reproduces the experimental results, which offers a way for magnetomechanical control of mechanical actuators based on spintronics.

References

[1] M. Shiga, J. Phys. Soc. Jpn. **50**, 2573-2580 (1981).

[2] K. Ando, S. Takahashi, K. Harii, K. Sasage, J. Ieda, S. Maekawa, and E. Saitoh, Phys. Rev. Lett. **101**, 036601 (2008).

[3] H. Arisawa, H. Shim, S. Daimon, T. Kikkawa, Y. Oikawa, S. Takahashi, T. Ono, and E. Saitoh, Nat. Commun. **13**, 2440 (2022).

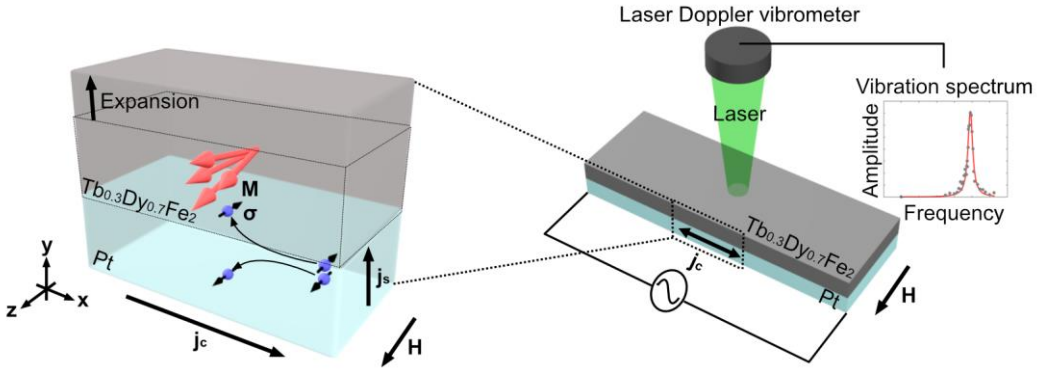


Figure 1: A schematic illustration of a measurement setup.

PI-6: Ultrafast laser-induced spin flip or spin transfer on the three-magnetic-center $Ni_3@C_{48}H_{37}$ carbon system via Λ processes

MOHAMED BARHOUMI[1], J. LIU[1], G. LEFKIDIS[1,2], and W. HÜBNER[1]

[1]Department of Physics, Technische Universität Kaiserslautern, P.O. Box 3049, 67653 Kaiserslautern, Germany
[2]School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710072, China

Current (nano)spintronics research seeks to shrink logic devices down to the atomic scale [1] by exploiting the spin degree of freedom as information carrier [2]. Ultrafast optical manipulation of spins, allows both for efficient data storage, and, more promising, also for performing quantum-logic on molecular systems [3].

Here we use *ab initio* calculations to investigate ultrafast spin processes on the three-magnetic-centers $Ni_3@C_{48}H_{37}$ carbon system. Spin-flip and spin-transfer scenarios are achieved via Λ processes (Fig. 1). We exemplarily show two kinds of processes. (a) Local spin flips on individual Ni atoms. These scenarios are reversible with the use of the same laser pulses. (b) Long-distance spin transfer between two Ni atoms, localized on opposite ends of the structure. Our calculations indicate that a direct transfer is possible, only if some spin density is also localized on the third Ni atom, which in this case acts as a control switch. If not, then a two-step transfer is necessary. We tentatively attribute this unexpected behavior to the specific geometry of our structure, in which long-distance spin transfer follows the least-resistance path via the magnetic center sitting in-between the initial and the final magnetic sites.

The ability to flip the spin locally and transfer the spin from one center to another is a prerequisite for any nanospintronic functionality. Consequently, the current theoretical results suggest the use of carbon atoms as bridging agents, with which one can integrate individual magnetic centers in larger optically driven magnetic-logic circuits.

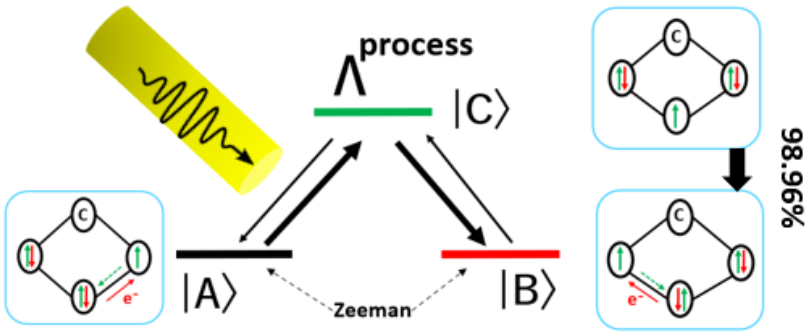


Figure 1 : Λ process. |A⟩, |C⟩, and |B⟩ are initial, intermediate, and final states, respectively.

[1] G. Lefkidis, W. Jin, J. Liu, D. Dutta, and W. Hübner, J. Phys. Chem. Lett. **11**, 2592 (2020).
[2] J. Liu, C. Li, W. Jin, G. Lefkidis, and W. Hübner, Phys. Rev. Lett. **126**, 037402 (2021).
[3] M. B. Chowdary, J. Liu, G. Lefkidis, and W. Hübner, J. Phys. Chem. Lett. **13**, 2479 (2022).

PI-7: Nanophotonics for ultrafast magnetism

V.I. Belotelov[1,2]
[1]Russian Quantum Center, Skolkovo, Moscow, Russia
[2]Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia

Optical control of the magnetization at ultrashort time scales attracts a significant research attention. Launching and controlling magnons with laser pulses opens up new routes for applications including optomagnetic switching and all-optical spin wave emission and enables new approaches for information processing with ultralow energy dissipation. However, optical pumping of spins encounters several obstacles which partially prevent its further progress towards applications. In particular, laser beam spot is diffracted limited, which limits minimal magnetic bit size by a few hundred on nanometers. Secondly, it is not possible to write bits with in-depth resolution. As for the spin wave optical excitation, the efficiency is rather law which is not competitive with conventional microwave means.

Here, we propose to marriage the laser-induced ultrafast magnetism and nanophotonics to overcome the aforementioned obstacles and to gain new functionalities. In this talk a kind of review of recent advances in this direction achieved in our group will be presented (Fig. 1) [1-6].

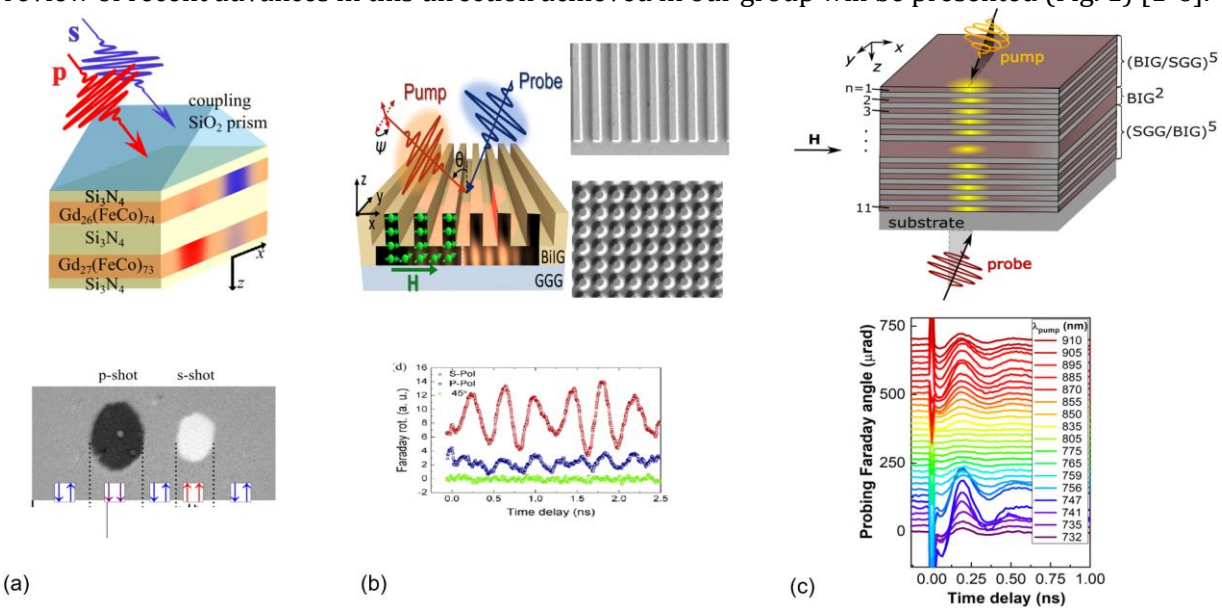


Figure 1. Three examples of marriage of nanophotonics with ultrafast magnetism: (a) Plasmonic layer-selective all-optical switching of magnetization with nanometer resolution [1]; (b) All-dielectric nanophotonics enables tunable excitation of the exchange spin waves [2]; (c) Spatially selective excitation of spin dynamics in magneto-photonic crystals by spectrally tunable ultrashort laser pulses [3].

In particular, we experimentally demonstrated that using light with the wavelength of 800 nm and without any magnetic fields, it is possible to obtain full control over two magnetic bits separated by just 80 nm in depth [1] (Fig. 1a). Two bits in our experiment are represented by two 10-nm thick GdFeCo layers separated by a 80-nm thick layer of Si3N4. Using a single femtosecond laser pulse, we can toggle the magnetization exclusively within a single magnetic nanolayer, without affecting the other one. The choice of the toggled layer is enabled by the excitation of a plasmon-polariton at a targeted interface of the nanostructure, and realized merely by rotating the polarization-axis of the linearly-polarized ultrashort optical pulse by 90°. The underlying mechanism is robust, well reproducible and relies on the polarization-dependent excitation of

plasmon-polaritons in the magnetic nanostructure. Our results unveil a new tool that can be deployed to switch magnetization in targeted nanolayers of heterostructures, and paves the way to increase the density of opto-magnetic recording by a factor of at least 2.

Second example is related to optical excitation of spin waves, in particular, exchange ones. Here, we demonstrate that nanopatterning of a transparent magnetic dielectric film by a 1D or 2D grating of stripes or nanocylinders allows to localize light in spots of tens nanometer size and thus launch the exchange standing spin waves of different orders (Fig. 1b) [2-4]. Relative amplitude of the exchange and magnetostatic spin waves can be adjusted on demand by modifying laser pulse polarization, incidence angle and wavelength. Nanostructuring of the magnetic media provides a unique possibility for the selective spin manipulation, a key issue for further progress of magnonics, spintronics and quantum technologies.

And the third application of nanophotonics concepts for ultrafast magnetism is given by magnetophotonic crystals (MPC). We found that a spectral dependence of the inverse Faraday effect (IFE) on the laser pulse wavelength in the band gap of the magnetophotonic crystal has a sharp peak leading to a significant enhancement of the IFE. This phenomenon is explained by strong confinement of the electromagnetic energy and angular momentum within the magnetic film. Calculated near field distribution of the IFE effective magnetic field indicates its subwavelength localization within 30 nm along the film thickness. These excited volumes can be shifted along the sample depth via e.g. changing frequency of the laser pulses. We also achieved magnetization dynamics with spatial tunability in an all-garnet MPC presented by a magnetic layer sandwiched between two magnetic Bragg mirrors: tuning of the pump wavelength allows localization of a larger spin precession either in the cavity layer or in the Bragg mirror layers selectively.

Therefore, the magnetophotonic structures are demonstrated to be very useful for spin control and manipulation by femtosecond laser pulses. We believe that going into this direction will provide much more advances for ultrafast magnetism not only for ferrimagnets but for antiferromagnets as well [7].

Reference

[1] D.O. Ignatyeva, C.S. Davies, D.A. Sylgacheva, A. Tsukamoto, H. Yoshikawa, P.O. Kapralov, A. Kirilyuk, V.I. Belotelov, and A.V. Kimel, Nature Communications 10(1), 4786 (2019).
[2] D.O. Ignatyeva, A.A. Voronov, D. Karki, M.A. Kozhaev, D.M. Krichevsky, A.I. Chernov, M. Levy, V.I. Belotelov, Nature Communications 11, 5487 (2020).
[3] A.I. Chernov, M.A. Kozhaev, D.O. Ignatyeva, E.N. Beginin, A.V. Sadovnikov, A.A. Voronov, D. Karki, M. Levy, V.I. Belotelov, Nano Lett. 20(7), 5259-5266 (2020).
[4] P.E. Zimnyakova, D.O. Ignatyeva, D. Karki, A.A. Voronov, A.N. Shaposhnikov, V.N. Berzhansky, M. Levy, V.I. Belotelov, Nanophotonics **11**, 119-127 (2021).
[5] D.A. Sylgacheva, N.E. Khokhlov, P.I. Gerevenkov, et al., Nanophotonics (2022) (in press).
[6] D.M. Krichevsky, D.O. Ignatyeva, V.A. Ozerov, V.I. Belotelov, Physical Review Applied 15, 034085 (2021).
[7] A.A. Voronov, D.O. Ignatyeva, A.K. Zvezdin, T.B. Shapaeva, V.I. Belotelov, Physical Review Applied 16, L051001 (2021).

PI-8: Spin reorientation in antiferromagnet-ferromagnet phase transition in FeRh-like materials

A.G. Buzdakov[1,2], K.A. Zvezdin[3], A.V. Kimel[4], A.K. Zvezdin[3]
[1]Moscow Institute of Physics and Technology, Moscow, Russian Federation
[2]I-FEVS, Torino, Italy
[3]Prokhorov General Physics Institute, Moscow, Russian Federation
[4]Radboud Universiteit, Nijmegen, Netherlands

Mechanism of the spin-reorientation antiferromagnetic-ferromagnetic phase transition in FeRh remains unclear. More and more papers appear every year with complex explanation of this type of phase transition, including ab-initio and atomistic simulations. In our work we propose new easy-to-use approach for description of spin-reorientation phase transitions in FeRh-like materials (see Figure 1a).

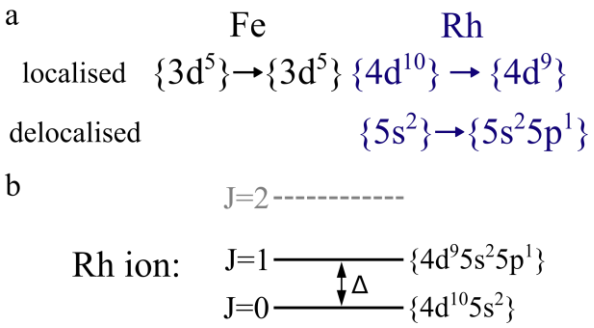


Figure 4: a – representation of transition, b – Rh ion energy levels.

Our approach invokes using specific nature of changing valency of Rh ion. Upon increasing temperature more and more electrons go from non-excited non-magnetic level to closely located first excited magnetic level (see Figure 1b).

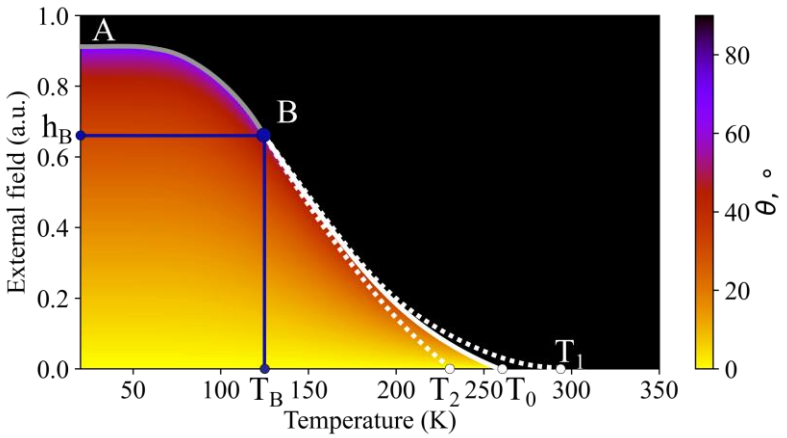


Figure 5: Example of H – T phase diagram with critical point.

We analyze H-T phase diagram for the proposed model and see that for certain parameters FeRh-like material can have tricritical point (see Figure 2). We also derive analytical expressions of field and temperature in critical point. Proposed model will be useful for quick experiment interpretation and for analysis of Rh-like materials ultrafast dynamics.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861300.

PI-9: Theoretical description of THz pumped magnetic systems

K. Carva [1], I. Radu[2,3], and P. M. Oppeneer[4]

[1]Department of Condensed Matter Physics, Charles University, Ke Karlovu 5, 121 16 Praha 2, Czech Republic
[2]European XFEL GmbH , Holzkoppel 4, 22869 Schenefeld, Germany
[3]Max Born Institute Berlin, Max Born Str. 2A, 12489 Berlin, Germany
[4]Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden

Strong pulsed coherent photon pumping with suitably chosen frequencies and timing can drive the matter to so far unexplored transient or quasistatic states otherwise inaccessible in equilibrium conditions. This may lead to the development of new nanoelectronic devices based on novel classes of materials. Particularly high field intensities can be achieved for irradiation at THz frequencies. THz field directly affects the magnetization via the Zeeman interaction. This may drive coherent precession of magnetization by the THz pump pulse. In metals, an important role is also played by THz field-induced direct excitations of conduction electrons to higher energies above the Fermi level. This leads to incoherent quenching of magnetism on a femtosecond time scale; at longer times this dissipative behavior leads to similar consequences as the heating. Since the Zeeman torque due to the magnetic component of radiation is rather weak, a competition between these coherent and incoherent effects occurs in ferromagnetic metals irradiated at THz frequencies [1].

THz electromagnetic waves can also coherently excite soft polar lattice vibrations into nonlinear regime enabling new couplings to the magnetic properties and to the material structure itself, this is particularly important in non-metals and may even lead to a change of magnetic order or insulator-to-metal transitions. Phonons excited in a controlled way may break the symmetry between two antiferromagnetically coupled moments to form a ferrimagnet [2] or modify magnetic interactions so that the system turns transiently from a collinear antiferromagnet to a canted weak ferromagnet [3]. The phonon population then lowers the energy of the state with spontaneously broken symmetry (ferro- of ferrimagnetic one), but to decide what is the resulting magnetization one necessarily needs to understand the transfer of angular momentum in the system.

To describe the excited state we start with an approach based on the assumption of small perturbations, where electrons occupy different energy levels than in the ground state, but energy levels remain unchanged as compared to the ground state. State-of-the-art method for this case is the Kubo formula. This method has already been successfully used for the cases of optical pumping with x-ray or extreme UV probe [4].

However, the THz spectral range represent a peculiar and very intriguing regime between the long and short wavelength limits, and achieved field strengths push it beyond linear response regime. Many current approaches to nonlinear field induced effects in metals treat electrons as free within a plasma. We employ more precise first principles calculation methods to reveal the properties of the strongly nonequilibrium THz pumped state. For this state we evaluate optical and magneto-optical properties upon strong-field THz excitation. These are used to understand interesting experimental results associated to THz induced toggle switching in the intensively studied GdFeCo metallic systems [5].

We also investigate microscopic aspects of nonlinear spin-phonon interactions leading to magnetic order modifications. We have evaluated magnetic exchange interactions under influence of specific non-equilibrium phonon populations for prospective systems. The evolution of phonon mode population on the picosecond timescale is simulated using our method developed for describing phonon distribution dynamics [6]. In summary we present a novel theoretical framework addressing resonant and off-resonant THz excitations of magnetic solids that accounts for both linear and

nonlinear regimes of light-matter interactions using THz electromagnetic radiation as an external stimulus.

References

[1] M. Shalaby et al., Phys. Rev. B 98, 014405 (2018).
[2] A. S. Disa et al., Nat. Phys. 16, 937 (2020).
[3] D. Afanasiev et al., Nat. Mater. 20, 607 (2021).
[4] E. Turgut et al., Phys. Rev. B 94, 220408 (2016)
[5] I. Radu et al., (to be submitted)
[6] P. Maldonado, K. Carva, M. Flammer, P. M. Oppeneer, Phys. Rev. B 96, 174439 (2017)

PI-10: Observation of Femtosecond Laser Comb Driven Magnetoelastic Modes

A. K. Chaurasiya[1], A. A. Awad[1], S. Muralidhar[1], R. Khymyn[1], and J. Åkerman[1]
[1]Department of Physics, University of Gothenburg, 412 96 Gothenburg, Sweden

Recent advances in magnon spintronics have led to a rapidly increasing research interest into investigating phenomena involving magnons (quanta of spin waves) and phonons (quanta of the elastic crystal lattice waves) from both a fundamental research viewpoint and for potential applications in data communication and information processing [1-2]. Most recently, ultrafast electron diffraction studies of Ni films revealed that ultrafast interactions of spins with high frequency phonons are decisive for the dynamics of rapidly demagnetized magnetic materials [3]. In our work, we use μ-Brillouin light scattering (μ-BLS) microscopy combined with a high repetition rate (1 GHz) femtosecond (fs) laser frequency comb [4] to study the polarization characteristics of both phonons and magnons in NiFe thin films.

Films of permalloy ($Ni_{80}Fe_{20}$) were sputtered onto *c*-plane sapphire substrates by dc magnetron sputtering under a 3 mTorr Ar atmosphere in an ultrahigh vacuum chamber. In the μ-BLS experiment, the sample is excited with a 1 GHz rep-rate fs-laser of wavelength 816 nm and probed with a continuous wave laser of wavelength 532 nm. The scattered beam from the sample is passed through a polarizer (which can be rotated from 0° to 360°) and guided to the tandem Fabry-Pérot interferometer for spectral decomposition of the light. Analysis of the polarization angle of the inelastically scattered light without fs-laser excitation reveals that phonons and magnons do not interact as their BLS counts add up incoherently with the expected 90° phase shift between their polarization angles. However, in the presence of fs-laser excitation, a giant rotation in the phonon polarization angle is observed for frequencies close to ferromagnetic resonance (FMR) [see Fig. 1(a) and (b)].

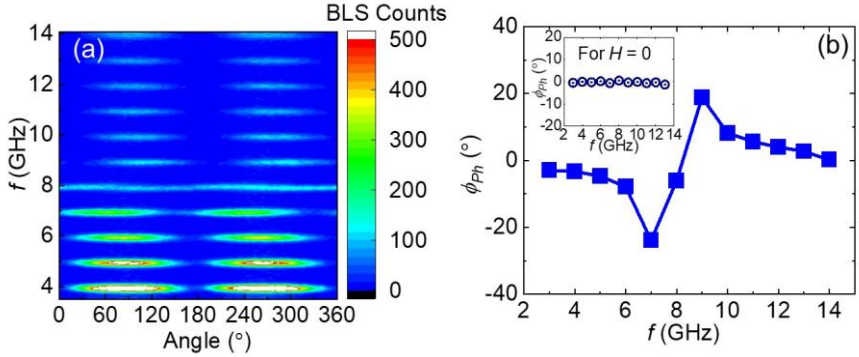


Figure 1: (a) Polarization maps for 20 nm NiFe thin film measured at an applied magnetic field H = 6 kOe and pump power (P) = 40 mW. (b) The variation of the extracted angle for phonons as a function of frequency (obtained using Eq. (1)). Solid line is guide to the eye. Inset: The extracted angle (ϕ_{Ph}) in the absence of applied magnetic field.

We model the observed BLS counts (I) for various frequencies by considering the contribution of both phonons and magnons which is in good qualitative agreement with a $\sin^2$ dependence of the polarization angle

$$I = A_{Ph}\sin^2(x - \phi_{Ph}) + A_m \sin^2(x - \phi_m) \quad (1)$$

The respective parameters of the phonons and magnons (A_{Ph} and A_m) as well as the polarization angle for phonons (ϕ_{Ph}) have been extracted as a function of frequency. Our work underlines the

versatility of the frequency comb for the generation of magnon-phonon coupled modes in magnetic thin film.

References:

[1] A. V. Chumak *et al*., *Nat. Phys*. **11**, 453 (2015)
[2] J. Holanda *et al*., *Nat. Phys.* **14**, 500 (2018)
[3] S. R. Tauchert *et al*., *Nature* **602**, 73 (2022)
[4] A. Aleman *et al*., *Opt. Express* **28**, 29540 (2020)

PI-11: Ultrafast Magnetization Dynamics in Co-rich Amorphous Ribbons

Alexander Chizhik[1], Andrzej Stupakiewicz[2], Arcady Zhukov[1,3,4]
[1]Department of Advanced Polymers and Materials, Physics, Chemistry and Technology, University of Basque Country, UPV/EHU, San Sebastian 20018, Spain
[2]Faculty of Physics, University of Bialystok, 15-245 Bialystok, Poland
[3]Department of Applied Physics I, EIG, University of Basque Country, UPV/EHU, San Sebastian 20018, Spain
[4]IKERBASQUE, Basque Foundation for Science, Bilbao 48011, Spain

Rapid recent development of the ultrafast spectroscopy provides a unique tool to access elementary scattering and relaxation processes by optically exciting the electronic and spin subsystems [1]. Rapid recent development of the ultrafast spectroscopy provides a unique tool to access elementary scattering and relaxation processes by optically exciting the electronic and spin subsystems. A particular interest are amorphous microwires and ribbons exhibiting giant magnetoimpedance (GMI) effect. These objects are interesting for fundamental research and strongly relevant for functional technologies as an ultra-sensitive sensors based on GMI. We present the study of magnetization precession in a Co-rich ribbon induced by femtosecond laser pulses. We deduce the frequency and amplitude of the magnetization precession from stroboscopic magneto-optical measurements as a function of the laser intensity and external magnetic field H_z (Fig. 1) [2].
The magnetization precession in the sample is triggered by a thermal change in the effective field of the magnetic anisotropy on a single-picosecond timescale. We reveal an excellent correlation between the frequency of magnetization precession obtained by laser induced excitation and the resonance frequency of GMI response.
The magnetic field dependence of the frequency is fitted by the Kittel formula in the gigahertz range. These results enable detection of the GMI effect in the ultrahigh-frequency regime, which appears highly attractive for gigahertz applications. Magnetic amorphous ribbons are promising structures for use in GMI sensors because their sensitivity exceeds that of conventional Hall magnetic sensors.

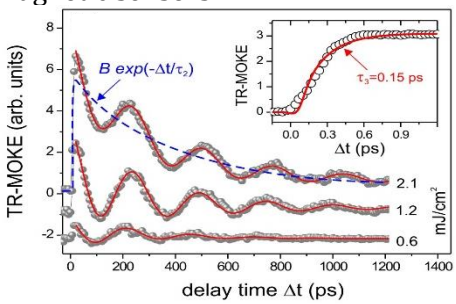


Figure 1: Time-resolved Kerr rotation as a function of the delay time Δt for several fluences of the pump beam (0.6, 1.2, and 2.1 mJ/cm^2) with H_z =3 kOe. The red lines display the damped sine function with a single frequency fitted to the data. The curves are offset vertically. The inset shows the time-resolved Kerr rotation for a pump fluence of 2.1 mJ/cm^2 on a short timescale below 1 ps, with a decay time τ * ~0.3 ps.

The improvements in the properties of GMI materials will facilitate the development of multifunctional microwave-stress-, temperature-, and magnetic-field-tunable composites suitable for wireless and nondestructive monitoring of external stimuli [3]. From another perspective,

thermal processing of metallic ribbons provides a fruitful playground for engineering their properties. For instance, during long-time annealing at relatively low temperatures, changes in the internal stress in amorphous metallic ribbons result in an improvement of their magnetic softness and modification of the surface magnetic anisotropy. Naturally, the GMI effect in these ribbons is sensitive to annealing too. We conjecture that local ultrafast heating of such ribbons by femtosecond laser pulses may have an impact on their transient GMI response. Substituting annealing procedures with laser heating may open up additional possibilities for tuning the properties of the ribbons. The similarities and differences of these approaches may provide a useful background for future studies of metallic ribbons.

References

[1] A. Kirilyuk, A. V. Kimel, and T. Rasing, Ultrafast optical manipulation of magnetic order, Rev. Mod. Phys. 82, 2731 (2010).

[2] A. Stupakiewicz, A. Chizhik, A. Zhukov, M. Ipatov, J. Gonzalez, and I. Razdolski, Ultrafast magnetization dynamics in metallic amorphous ribbons with a giant magnetoimpedance response, Phys. Rev. Appl. 13, 044058 (2020).

[3] A. Allue, P. Corte-León, K. Gondra, V. Zhukova, M. Ipatov, J. M. Blanco, J. Gonzalez, M. Churyukanova, S. Taskaev, and A. Zhukov, Smart composites with embedded magnetic microwire inclusions allowing non-contact stresses and temperature monitoring, Compos. Part A: Appl. Sci.Manuf. 120, 12 (2019).

PI-12: Self Spin-Orbit Torque in GdFeCo ferrimagnet

H. Damas[1], D. Céspedes-Berrocal[1,2], J-L Bello[1], D. Maccariello[3], A. Anadon[1], V. Desbuis[1], A. Arriola-Córdova[1,2], J. Alegre-Saenz[1,2], P. Tang[4], P. Vallobra[1], Elodie Martin[1], Y. Xu[1], Sylvie Migot[1], Jaafar Ghanbaja[1], D. Lacour[1], S. Zhang[4], S. Mangin[1], C. Panagopoulos[5], V. Cros[3], M. Hehn[1], S. Petit-Watelot[1], A. Fert[3] and J-C. Rojas-Sánchez[1]

[1] Université de Lorraine, CNRS, Institute Jean Lamour, F-54000 Nancy, France
[2] Universidad Nacional de Ingeniería, Rímac 15333, Peru
[3] Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France
[4] Department of Physics, University of Arizona, Tucson, Arizona 85721, USA
[5] Division of Physics and Applied Physics, Nanyang Technological University, 637371 Singapore

Spin currents and spin-torques generated through spin-orbit coupling (SOC) are exploited in spintronics to address the high demand for data in information technology. Nowadays, the large SOC of 5d non-magnetic heavy metals (HM) is required to generate a pure spin current through the spin Hall effect (SHE). In turn, the pure spin current generates a spin-orbit torque (SOT) on an attached magnetic layer [1,2].

Here, we introduce a new class of materials that combine the properties of the magnetic layer and the HM layer. We study GdFeCo ferrimagnet in which the 5d band of Gd induces a large SOC. GdFeCo is the source of spin currents of different symmetries: the SAHE-like and the SHE-like symmetries emerging from the spin anomalous Hall effect [3,4] and the spin Hall effect [5-7] respectively. The latter symmetry can induce a torque on the ferrimagnet magnetization. We show that strong current-induced torques are generated in and exerted on GdFeCo, which we coined *self-torque* [8].

We present the study of the *self-torque* performed using harmonic Hall voltage measurements on GdFeCo interfaced with a light metal. We first focus on the temperature dependence of the effective fields associated to the *self-torque.* We show that the effective fields are magnified near the magnetic compensation temperature T_M and reverse sign across it (see Figure 1) [8]. We show that the *self-torque* exhibits different features compared to the conventional SOT. Our results pave the way for new architectures to exploit *self-torque* generated in single magnetic layer.

[1] A. Manchon *et al., Reviews of Modern Physics*, vol. 91, no 3, p. 035004, 2019.
[2] Q. Shao *et al.*, *IEEE Transactions on Magnetics,* 2021.
[3] T. Taniguchi *et al*., *Phys. Rev*. Appl. 3, 044001, 2015.
[4] S. Lihama *et al*., *Nat. Elecron*. 1, 120, 2018.
[5] V. Amin *et al*. *J. Appl. Phys*. 128, 151101, 2020.
[6] K-W. Kim & K-J. Lee PRL 125, 207205, 2020.
[7] H. Damas, *et al*. *Phys. Status Solidi RRL*, 2200035, 2022.
[8] D. Céspedes-Berrocal *et al.*, *Advanced Materials* 33.12: 2007047, 2021.

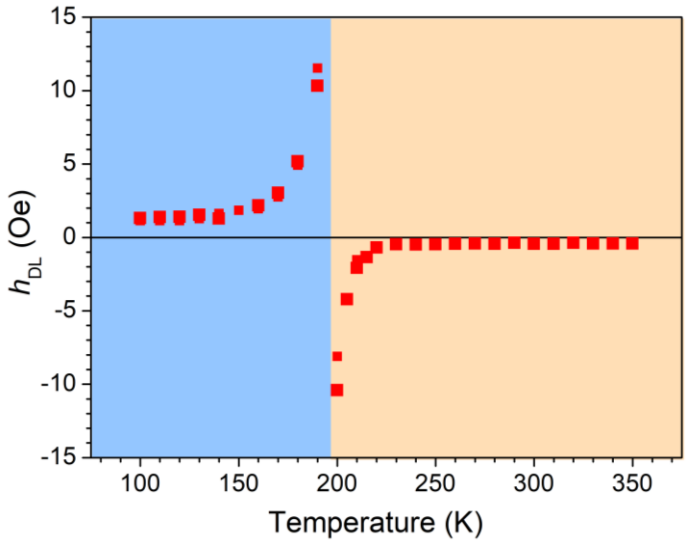


Figure 1: Temperature dependence of the damping-like effective field h_{DL} in GdFeCo(10)/Cu(2)/AlOx. Its sign changes while crossing the compensation temperature of the ferrimagnet, depicted by the background change of color.

This work was supported partially from Agence Nationale de la Recherche (France) under contract N° ANR-18-CE24-0008 (MISSION), ANR-19-CE24-0016-01 (TOPTRONICS) and ANR-17-CE24-0025 (TOPSKY), from the French PIA project "Lorraine Universite d'Excellence", reference ANR-15IDEX-04-LUE. D. C.-B., A.Y.A.C and H. D, acknowledge SPIN IJL team for their internship fellow 2018, 2019 and 2020, respectively. DCB also thanks "LUE Graduated" program internship 2019 from "Lorraine Université d'Excellence".

PI-13: A guide to helicity-independent all-optical switching of magnetization in ferrimagnets

C. S. Davies[1], J. H. Mentink[2], A. V. Kimel[2], Th. Rasing[2] and A. Kirilyuk[1]

[1]FELIX Laboratory, Radboud University, Nijmegen, The Netherlands
[2]Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

For almost a decade, the phenomenon of helicity-independent all-optical switching of magnetization was only consistently observed in specific rare-earth-transition-metal ferrimagnetic alloys of GdFeCo [1,2]. Breakthrough experiments in recent years have revealed that the same behavior can be achieved in a wide range of multi-sublattice magnets including TbCo alloys doped with minute amounts of Gd, Gd/Co and Tb/Co synthetic ferrimagnets and the rare-earth-free Heusler alloy Mn_2Ru_xGa. Aiming to resolve the conditions that allow switching, a series of experiments have shown that the process in the ferrimagnetic alloys GdFeCo and Mn_2Ru_xGa is highly sensitive to the pulse duration, starting temperature and the alloy composition [3,4]. We argue here that the switching displayed by these two very different systems can be generally understood within a single phenomenological framework describing the flow of angular momentum between the constituent sublattices and from the sublattices to the environment [5]. The conditions that facilitate switching stem naturally from these channels of angular momentum flow in combination with the size of the angular momentum reservoirs (Fig. 1).

References

[1] T. A. Ostler *et al.* "Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet." *Nature Commun.* **3**, 666 (2012).
[2] J. H. Mentink *et al.* "Ultrafast spin dynamics in multisublattice magnets." *Phys. Rev. Lett.* **108**, 057202 (2012).
[3] C. S. Davies *et al.* "Pathways for single-shot all-optical switching of magnetization in ferrimagnets." *Phys. Rev. Appl.* **13**, 024064 (2020).
[4] C. S. Davies *et al.* "Exchange-driven all-optical magnetic switching in compensated 3*d* ferrimagnets." *Phys. Rev. Res.* **2**, 032044(R) (2020).
[5] C. S. Davies *et al.* "Helicity-independent all-optical switching of magnetization in ferrimagnetic alloys." Preprint at arXiv (2022).

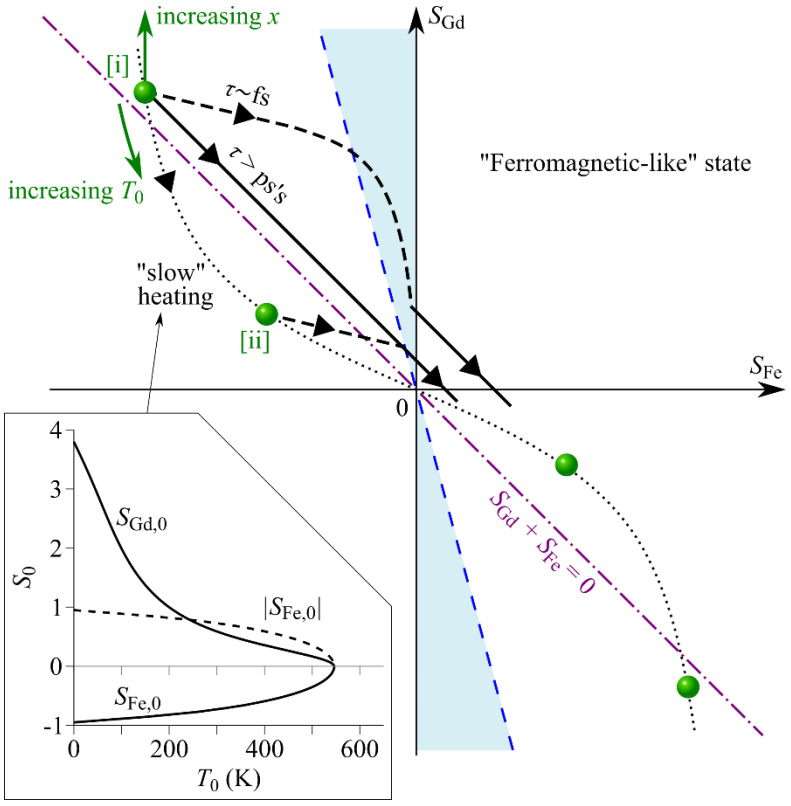


Figure 1: Conceptual phase diagram showing the different pathways for thermally-induced relaxation of the sublattice-resolved angular momentum S_{Fe} and S_{Gd} of the ferrimagnetic alloy Gd_xFe_{100-x}. The green spheres in the top-left and bottom-right quadrants indicate example positions of equilibrium (labelled [i] and [ii]), with the dotted line corresponding to the scenario of ``slow" heating in equilibrium. Excitation of the ferrimagnet by a thermal pulse of duration τ leads to different trajectories of demagnetization, with a femtosecond pulse activating decoupled Bloch relaxation (dashed black line) followed by exchange-relaxation (solid black line line), and with a longer pulse activating exchange-relaxation only (solid black line). Inset: thermal dependence of the equilibrium angular momentum $S_{Gd,0}$ and $S_{Fe,0}$ (solid lines). To facilitate comparison, we also show $|S_{Fe,0}|$ (dashed line).

PI-14: Manipulation of low-energy spin precession in a magnetic thin film by tuning its molecular field

V. Desbuis[1], D. Lacour[1], C. Tiusan[2], C. Vautrin[1], Y. Lu[1], W. Weber[3] and , M. Hehn[1]
[1]Institut Jean Lamour, CNRS – Université de Lorraine, 54011 Nancy France
[2]Center of Superconductivity, Spintronics and Surface Science (C4S), Technical University of Cluj-Napoca, 4000114 Romania
[3]Institut de Physique et Chimie des Matériaux de Strasbourg, UMR 7504 CNRS – Université de Strasbourg, 23 Rue de Loess, BP 43, 67034 Strasbourg Cedex 2, France

In the case of non-collinear magnetizations structure (Fig.1 left), a spin-polarized electron beam entering multilayered system is affected by the ferromagnetic layer magnetization $\mathbf{M_{AL}}$. The polarization vector **P** will exhibit a precessional motion around $\mathbf{M_{AL}}$ described by the precession angle ε. The reorientation of the polarization vector towards $\mathbf{M_{AL}}$ is given by the filtering angle θ. Previous studies [1,2] showed that ε could very up to several tens of degrees per nanometer at high energies using free-electron beam experiments. The associated molecular field of the ferromagnetic layer is estimated to be of the order of several 100T to 1000T. The out-of-equilibrium behavior of the electronic spin at energies lower than that of the vacuum level of the ferromagnetic layer (~4-5eV) remains little know due to the impossibility to probe this energy range with such experiment. All solid-state devices [4-7] lift this difficulty as an electron beam is directly injected into the studied metallic base and never has to go out of the device.

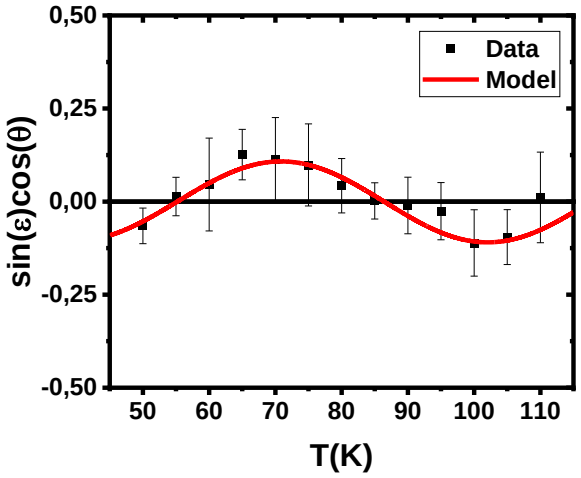
Recent lab-on-chip experiments [3] has given first answers. A precession angle of 700°/nm evaluated from k-resolved band structure calculation agrees well with experimentally measured ε considering smearing induced by layer roughness. As a next step, a continuous variation of one precession parameter is mandatory to consolidate the result. A strategy consists to induce a variation of the molecular field which rules the spin precession phenomena. A ferromagnetic material with a low Curie temperature used as the active precession layer would strongly modulate the spin precession angle with temperature. Transition metals alumnides (CoAl, NiAl, FeAl) are known to have a paramagnetic-ferromagnetic transition for compositions close to 50% of Al [8]. Therefore, a small change in the Al concentration can induce a strong dependence of the magnetization on the temperature.

In order to analyze the low energy transport regime, we used a Magnetic Tunnel Transistor architecture [7,8]. Our lab-on-a-chip houses: a magnetic tunnel junction which allows us to control and vary the injection energy of the electrons, a spin-valve base and a Schottky diode (Fig. 1 right). The Cu/Si Schottky diode allows a double analysis: firstly by selecting in energy the electrons collected in the semiconductor (only those with an energy higher than 0.7eV are collected). Secondly, in wave vector thanks to an acceptance cone of less than 10°. Typical stacks used in the studies presented here are as follows, where numbers in brackets indicate the layer thicknesses in nm:

Pt(5)/IrMn(7.5)/Co(2)/Ta(0.5)/CoFeB(2)/MgO(2.5)/$Co_{50}Al_{50}$(5)/Cu(3.5)/[Ni(0.6)/Co(0.2)]x5/Ni(0.6)/Cu(5)/Ta(1)/Cu(5)//Si[100]

In a first step, RXD, magnetic (on thin films) and electrical (MTT) measurements were performed on our CoAl samples in order to characterize its properties. Surprisingly, the tunnel magnetoresistance is different from zero (and so M_s) for temperatures larger than Tc. Transmission electron microscopy enabled us to image our stack both structurally and chemically, highlighting Al segregation as the mechanism explaining this non-zero TMR. The precession measurement between 50K and 110K for low energy (V_E = -1V) are reported on (Fig. 2). The oscillatory behavior of the precession is the proof the molecular field variation with the temperature. A model based on measured M_s(T) and layer roughness at the interface enables to fit the data and to extract a precession angle at 0K (200°/nm) and the spin asymmetry mean free path of our CoAl layer ($\lambda^- = 0.9nm$).

Figure 2: Mean sin(ε)cos(θ) vs. T for V_E =-1.0 V



References

[1] D. Oberli, *et al.,* Phys. Rev. Lett. **81**, 4228 (1998)
[2] W. Weber, *et al.*, Science **291**, 1015 (2001)
[3] C. Vautrin, *et al.*, Ann. Phys. **533**, 2000470 (2020)
[4] C. Vautrin, *et al.*, J. of Phys. D : Appl. Phys. 49, 355003 (2016)
[5] C. Vautrin, *et al.*, Phys. Rev. B 96, 174426 (2017)
[6] R. Jansen, J. Phys. D : Appl. Phys. **36** (2003)
[7] S. van Dijken *et al.* Phys. Rev. Lett. **90**, 197203 (2003)
[8] S.R. Butler, *et al.*, J. Phys. Chem. Solids **30**, 1929-1934 (1969)

PI-15: Spin-orbit torque switching by picosecond-wide electrical pulses

Eva Díaz[1], Alberto Anadón[1], Sébastien Petit-Watelot[1], Grégory Malinowski[1], Stéphane Mangin[1], Juan Carlos Rojas-Sánchez[1], Michel Hehn[1] and Jon Gorchon[1]
[1]Institute Jean Lamour, Université de Lorraine, Nancy, France

Spintronic phenomena, which focus around the electron spin as a degree of freedom, offer novel ways of manipulating information and could potentially lead to devices with lower energy consumption than current electronics. Nowadays, spintronic devices are based upon the utilization of spin-transfer torque (STT) switching mechanism on magnetic tunnel junctions (MTJ) [1], but its efficiency remains restricted by the maximum current that can be applied before damaging the tunnel barrier of the device. This results in a limited switching time that makes it unable to compete with the speed of current conventional electronic devices.

A faster switching time has been achieved by Yang *et al*. in a GdFeCo layer using a 9 ps electrical pulse generated by an Auston photoswitch [2]. The magnetization reversal was achieved on an almost identical timescale (10 ps) by thermal energy transfer from the electrical pulse to the sample. However, while energetically viable, this reversal mechanism presents two inconveniences: it is limited to materials such as GdFeCo and the magnetization reversal is achieved regardless of the injected electrical current polarity. For technological applications, to have the possibility to switch (or not) depending on the injected current polarity, would be a desirable quality.

In this aspect, the spin-orbit torque (SOT) mechanism represents a good alternative [3]. It offers a substantial improvement in terms of speed, since the injected spin polarity is transverse to the magnetization and acts immediately on it and, in addition, it has the advantage that, by its very nature, the achievement of magnetization reversal will be determined by the polarity of the electrical pulse.

Currently, the fastest magnetization switching via SOT has been achieved using a 6 ps electrical pulse, over a PtCoTa sample [4]. The ps electrical pulse is generated by exciting a photoconductive switch with an amplified laser system around 780 nm. Next, this electrical pulse is turned into a spin-polarized current in the Pt layer and transmitted to the magnetic layer. Finally, the reversal of the Co layer is achieved by injecting the appropriate current polarity relative to an in-plane magnetic field, which helps to break the in-plane symmetry of the magnetization. Furthermore, a macrospin model applied to this system predicts that in addition to the SOT mechanism, the reversal is substantially assisted by Joule heating, which contributes to weaken the anisotropy field, demagnetize the sample, and henceforth decrease the energy cost of going from one stable state to the other.

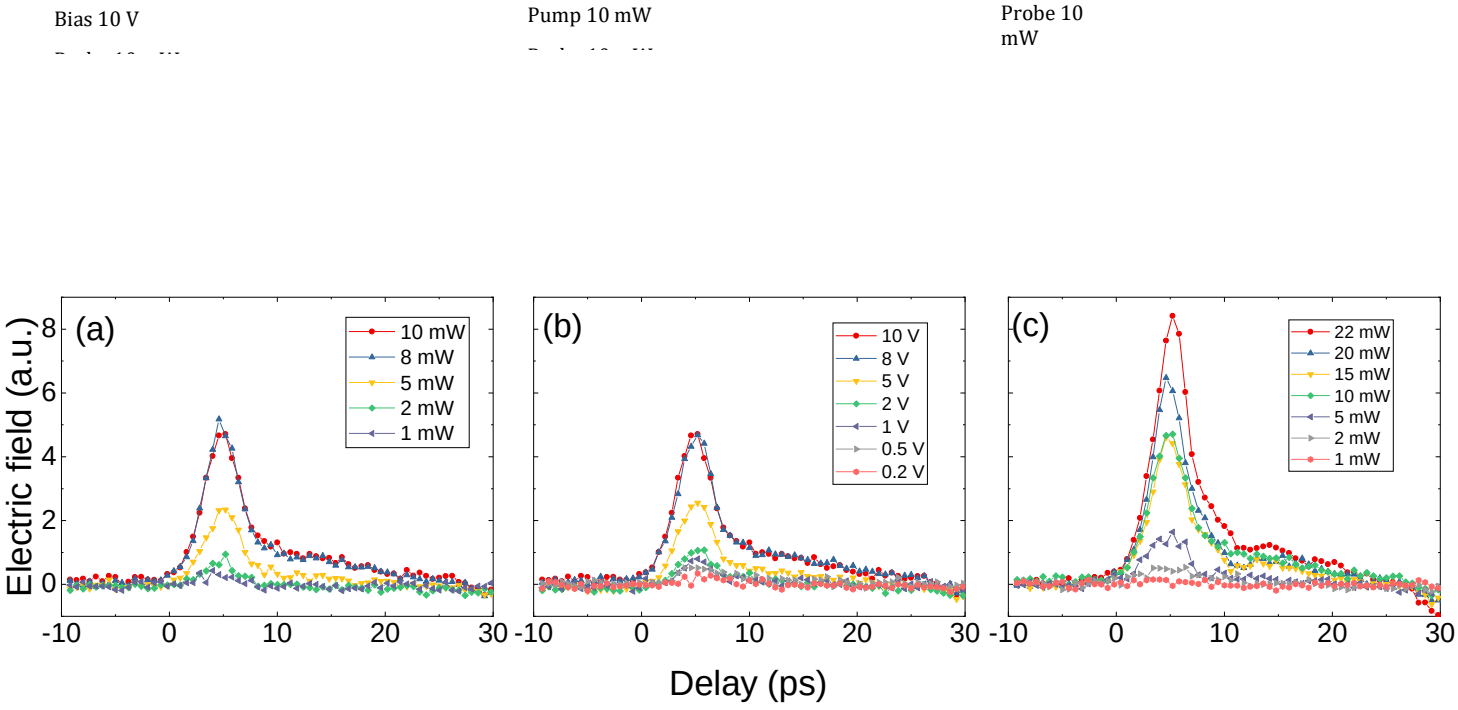
In this work, our objective is to study the SOT switching characteristics and dynamics induced by ps electrical pulses over different kinds of samples with the same experimental conditions as described above. We are characterizing the magnetization reversal as a function of different parameters: pulse duration, in-plane magnetic field, and so on. The dependence of the critical current for switching as a function of pulse duration is essential for characterizing the energy consumption of the device, but its study has only been performed in the pulse-duration range from the ms scale up to 200 ps [5]. We are attempting to further explore the critical current down to the pulse duration of only a few ps. To this aim, we have recently developed a waveguide design containing a photoconductive probing arm, which allows to measure the time-resolved electric field of any incoming electrical pulse, on-chip, with picosecond resolution and a scanning range of 13 ns. Figure 1 shows the electrical field transient induced as a function of pump power and bias voltage applied across the source photoconductive switch (PS), and also as a function of probe power on the detector photoswitch. This method allows for a reproducible in situ characterization of our THz pulses.

The dynamics of the picosecond SOT-switching mechanism still remain unexplored. To this day, magnetization reversal dynamics of a Co layer has only been reported up to the ns scale [6], while the ps scale remains largely unexplored. Using a pump-probe measurement to observe the switching dynamics induced by such a short electrical pulse represents an interesting experimental challenge. In this paper our current efforts in this direction will be presented, which may eventually allow us to learn more about the switching speed and mechanisms.

References

[1] Y. Liu *et al*.: MRAM gets closer to the core. Nat. Electron. **2**, 555-556 (2019).
[2] Y. Yang *et al*.: Ultrafast magnetization reversal by picosecond electrical pulses. Sci. Adv. **3**, e1603117 (2017).
[3] C. O. Avci: Picosecond switching in a ferromagnet. Nat. Electron. **3**, 660-661 (2020).
[4] K. Jhuria *et al*.: Spin-orbit torque switching of a ferromagnet with picosecond electrical pulses. Nat. Electron. **3**, 680-686 (2020).
[5] K. Garello *et al*.: Ultrafast magnetization switching by spin-orbit torques. Appl. Phys. Lett. **105**, 212402 (2014).
[6] M. Baumgartner *et al*.: Spatially and time-resolved magnetization dynamics driven by spin-orbit torques. Nat. Nanotechnol. **12**, 980-986 (2017).

Figure 1. Electric field transient as a function of (a) pump power over the source PS, (b) bias voltage across the source PS, and (c) probe power over the detector PS.



PI-16: Ultrafast imaging of heat assisted magnetization switching in (Bi,Lu) substituted iron garnet

A.Dolgikh[1], D. Afanasiev[1], V.V. Yurlov[2], A.K. Zvezdin[3], M.V. Logunov[4], A. Kimel[1]

[1] Radboud University, Nijmegen, Nijmegen
[2] Institute for Physical Problems, Russian Academy of Sciences, Moscow, Russia
[3] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
[4] Moscow Institute of Physics and Technology, Dolgoprudny, Russia

Large amplitude magnetization precession in external magnetic field is triggered by ultrafast laser induced heating of iron garnet. In particular, the studied sample is Bi and Lu substituted ferrimagnetic iron garnet film $(Bi,Lu)_3(Fe,Ga,Al)_5O_{12}$ with compensation point T_{comp} = 50K and Currie temperature T_c = 600K. Magnetic properties of the compound are defined by the spins of Fe^{3+} ions in the octahedral and the tetrahedral sites, which form two non-equivalent antiferromagnetically coupled spin sublattices, respectively [1]. In our study we employed pump-probe technique, where pump pulse with the central wavelength 625 nm (photon energy 1.98 V) was focused (d = 100 μm) on the sample. Unfocused probe pulse (800 nm) was delayed from pump up to 8 ns and produced the magneto-optical image of the sample. Such a pump pulse heats up the sample reducing the anisotropy field and thus resulting in magnetization precession around new equilibrium orientation. The dynamics is studied as a function of magnetic field, laser fluence and sample temperature. Exploring the whole space of parameters, we identify the conditions for which the amplitude of the precession is high enough to achieve heat-assisted magnetic recording. Figure 1 shows the magnetization changes obtained with the CCD camera in 8 ns after the lattice was excited with femtosecond laser pulse (fluence 80 mJ/cm^2). It is seen that the dynamics of the largest amplitude is achieved either at high fields and low temperatures or at high temperature and low fields. We propose a model that can explain these results.

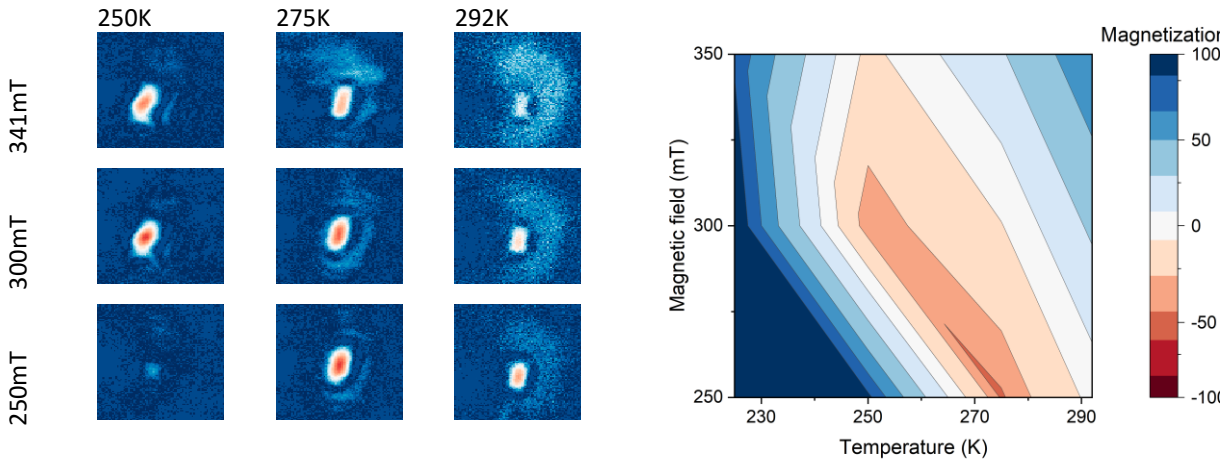


Fig. 1 Magneto-optical images obtained from the sample after the pump excitation (left). Two-dimensional diagram of the magnetization changes for external magnetic field and temperature (right).

[1] V.J. Fratello, S.E.G. Slusky, C.D. Brandle, et al. Growth-induced anisotropy in bismuth: Rare-earth iron garnets, Journal of Applied Physics 60, 2488 (1986)

PI-17: Ultrafast emergence of ferromagnetism in antiferromagnetic FeRh in high magnetic fields

I. A. Dolgikh[1,2], T. G. H. Blank[1], G. Li[1], K. H. Prabhakara[1], S. K. K. Patel[3], R. Medapalli[3], E. E. Fullerton[3], P. C. M. Christianen[1,2] & A. V. Kimel[1]

[1] Radboud University, Institute for Molecules and Materials, 6525 AJ Nijmegen, The Netherlands.
[2] High Field Magnet Laboratory (HFML—EMFL), Radboud University, 6525 ED Nijmegen, The Netherlands.
[3] Center for Memory and Recording Research, University of California, San Diego, La Jolla, California 92093-0401, USA.

The future of magnetic data storage crucially depends on our understanding of the mechanisms and fundamental limits on the speed of angular momentum transfer between lattice and spins. In the case of antiferromagnetic FeRh, this is a particularly interesting problem. Upon a temperature increase, the spins of Fe in FeRh suck angular momentum from the lattice - the medium becomes ferromagnetic, while the lattice expands [1].

Aiming to reveal the mechanism and the fastest possible time-scale of the magneto-structural phase transition resulted in a spin-and-lattice causality dilemma also known as a chicken-and-egg problem we carried out a time-resolved optical measurement in extreme conditions [2].

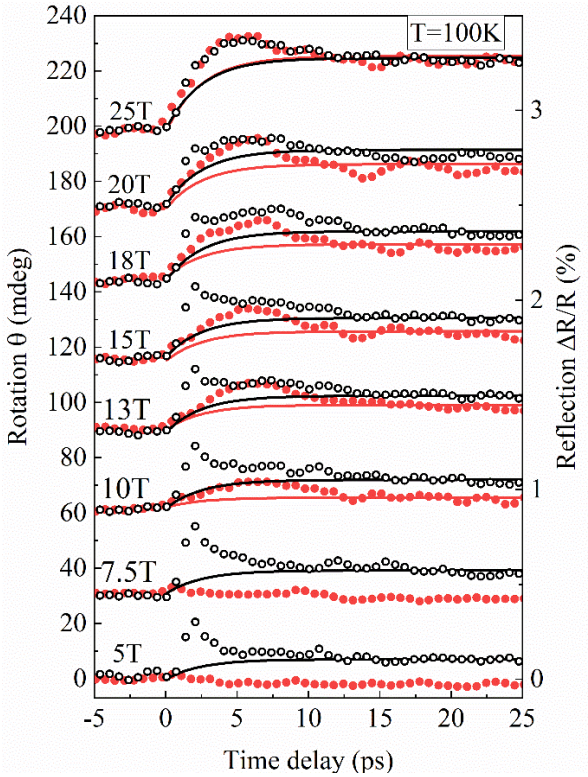


Figure 1: The polarization rotation induced by the magneto-optical Kerr effect (red) and reflectivity change (black) at 100 K and various magnetic fields. The open circles represent the experimental data and the solid lines are their respective fits. The curves are plotted with an offset.

Here we resolve the problem by accelerating the spin dynamics in high (25 T) fields and observing both structural and spin dynamics with the help of time-resolved optical and magneto-optical

measurements, respectively (see Fig.1). We observe that the fastest possible induction of ferromagnetism occurs on a time scale of the lattice expansion (3 ps). The regime implies that the laser excitation first modifies the exchange interaction on a sub-ps time-scale launching coupled magneto-structural spin dynamics such that the total spin-lattice angular momentum can be conserved.

References:

[1] L. H. Lewis, C. H. Marrows, & S. Langridge. J. of Phys. D: Appl. Phys. **49** (2016), 323002.

[2] I. A. Dolgikh, T. G. H. Blank, G. Li, et al. *Prepr*. arXiv:2202.03931 (2022).

PI-18: Electron-Magnon Scattering Dynamics in a two-band Stoner Model

Félix Dusabirane, K. Leckron, B. Rethfeld and H. C. Schneider
Physics Department & Research Center OPTIMAS, TU Kaiserslautern, Germany

We theoretically study the carrier dynamics in ferromagnets due to electron-magnon scattering on ultrafast timescales using a microscopic model. We employ a simple model band structure ("Stoner model") shown in Figure 1, and the electron magnon-interaction is formally obtained as coupling to a Heisenberg model, which incorporates the magnetic properties of the itinerant ferromagnet [1,2]. Using magnon operators to describe the excitation of the magnetic system, one obtains the Hamiltonian

$$\widehat{H}_{\mathrm{em}} = \sum_{\boldsymbol{k},\boldsymbol{q}} M_{em}\left(c^{\dagger}_{\boldsymbol{k}-\boldsymbol{q},\uparrow}\, c_{\boldsymbol{k},\downarrow}\, b^{\dagger}_{\boldsymbol{q}} + c^{\dagger}_{\boldsymbol{k}+\boldsymbol{q},\downarrow}\, c_{\boldsymbol{k},\uparrow}\, b_{\boldsymbol{q}}\right)$$

where $b^{\dagger}_{\boldsymbol{q}}(b_{\boldsymbol{q}})$ and $c^{\dagger}_{\boldsymbol{k}}(c_{\boldsymbol{k}})$ are creation (annihilation) operators for magnons and electrons, respectively, and M_{em} is the matrix element for electron-magnon coupling.

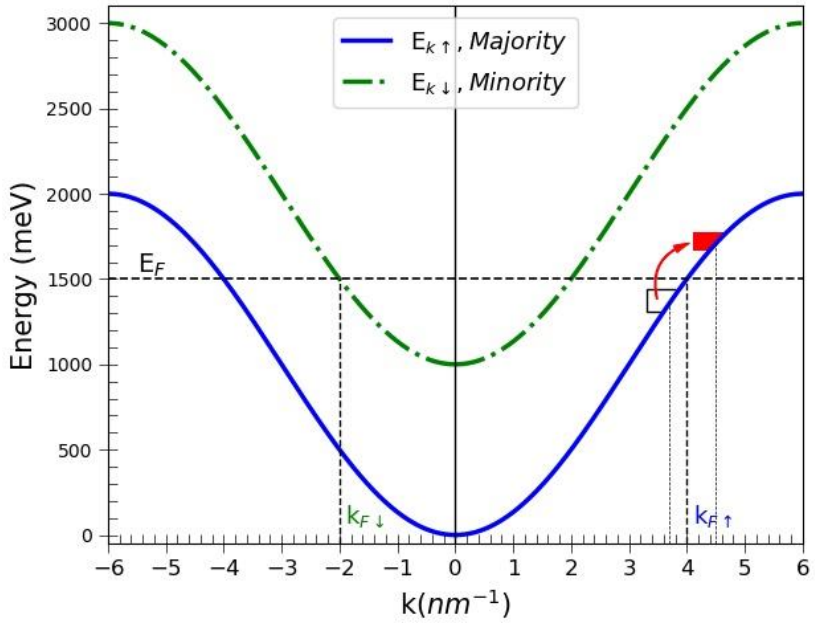


Figure 1: Energy band dispersion for majority (spin-up) and minority (spin-down) electrons with excitation in the majority spin channel. The excitation process is assumed to be instantaneous.

We compute the dynamics of momentum resolved electron and magnon distributions due to electron-magnon and statically screened Coulomb electron-electron scattering, which are treated at the level of Boltzmann scattering integrals [3]. The coupled equations for the dynamical distributions for electrons with spin-up (majority spin carriers) and magnons for electron-magnon scattering take the form

$$\frac{\partial}{\partial t} n_{\boldsymbol{k},\uparrow} = \frac{2\pi}{\hbar} \sum_{\boldsymbol{q}} M^2_{em}\, \delta\left(\epsilon^{\uparrow}_{\boldsymbol{k}} - \epsilon^{\downarrow}_{\boldsymbol{k}+\boldsymbol{q}} + \hbar\omega_{\boldsymbol{q}}\right)\left[n_{\boldsymbol{k}+\boldsymbol{q},\downarrow}\left(1 - n_{\boldsymbol{k},\uparrow}\right)\left(1 + N_{\boldsymbol{q}}\right) - N_{\boldsymbol{q}} n_{\boldsymbol{k},\uparrow}\left(1 - n_{\boldsymbol{k}+\boldsymbol{q},\downarrow}\right)\right]$$

$$\frac{\partial}{\partial t}N_{\boldsymbol{q}} = \frac{2\pi}{\hbar}\sum_{\boldsymbol{k}} M_{em}^2\,\delta\left(\epsilon_{\boldsymbol{k}}^{\uparrow} - \epsilon_{\boldsymbol{k+q}}^{\downarrow} + \hbar\omega_{\boldsymbol{q}}\right)\left[n_{\boldsymbol{k+q},\downarrow}\left(1-n_{\boldsymbol{k},\uparrow}\right)\left(1+N_{\boldsymbol{q}}\right) - N_{\boldsymbol{q}}n_{\boldsymbol{k},\uparrow}\left(1-n_{\boldsymbol{k+q},\downarrow}\right)\right]$$

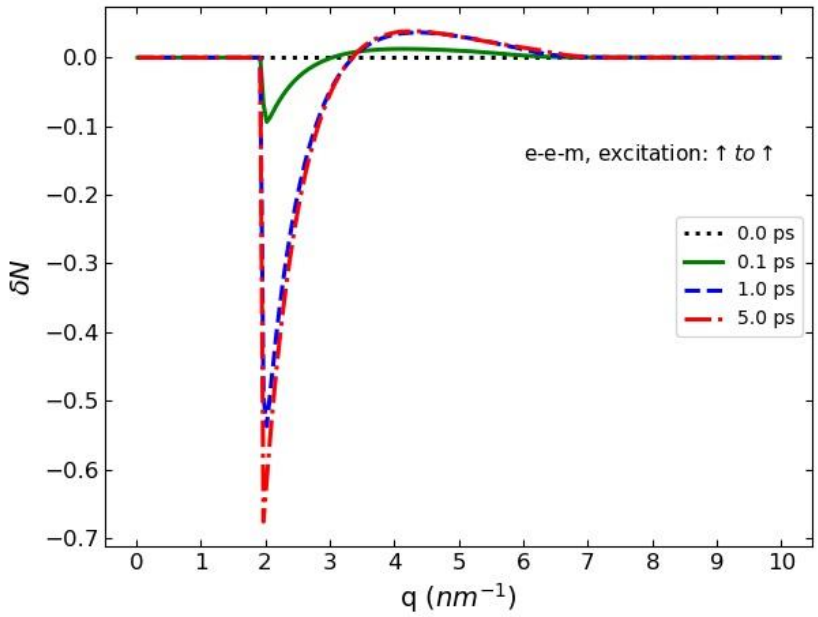


Figure 2: The change in magnon occupation number at different times during electron-electron and electron-magnon (e-e-m) scattering dynamics for excitation shown in Figure 1.

We find that electron-magnon scattering leads to a pronounced non-equilibrium for magnon modes that couple directly to Stoner transitions as shown in Figure 2. For reasonable parameters for iron, the electronic spin-flip scattering with magnons results in a transient electron spin polarization on a timescale of a few ten femtoseconds. We find that the transient electronic spin polarization and magnon distributions are similar for excitations either within the minority or the majority band. Qualitatively, this independence of the spin dynamics of the details of the excitation process is supported by recent experiments [4]. In addition, we study the influence of parameters such as band filling and coupling strengths.

References

[1] B. Woolsey and R. M. White, Phys. Rev. B **1**, 4474 (1970).
[2] L. Davis and S. Liu, Phys. Rev. **163**, 503 (1967).
[3] H. Haug and A.-P. Jauho, Quantum Kinetics in Transport and Optics of Semiconductors, Springer (2007).
[4] M. Stiehl et al., Appl. Phys. Lett. **120**, 062410 (2022).

PI-19: Amplification of coherent propagating spin waves in BiYIG waveguides using spin-orbit-torques.

A. El Kanj[1], H. Merbouche[2], B. Divinskiy[2], V. E. Demidov[2], S. O. Demokritov[2], D. Gouéré[1], I. Boventer[1], R. Lebrun[1], P. Bortolotti[1], V. Cros[1] and, A. Anane[1]

[1] Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, 91767, Palaiseau, France
[2] Institute for Applied Physics and Center for Nanotechnology, University of Muenster, Muenster, Germany

The investigation of Spin Waves (SW) and their quanta, magnons, in thin magnetic films has emerged as an attractive field of research due to their very short wavelength reaching down to nanometers at GHz frequencies. SWs also have a rich dispersion relation, that depends on their propagation direction with respect to a magnetic field. Hence, SW -based devices are promising candidates for microwave information processing, and eventually for overcoming the limitations encountered with CMOS devices [1]. Yet, a key challenge is to achieve long propagation distances of the spin waves[2].

Recent studies [3] with Platinum stripes placed on top of a 20 nm thick YIG waveguide (Pt/YIG) showed that SOT could generate a full compensation of the damping, leading to auto-oscillations of the magnetization above a critical injected current density. When excited with a microwave field, spin waves propagation length was increased by a factor of 10 in the bilayer. However, the possibility to achieve an amplification of propagating spin-waves was not observed, due to the onset of nonlinear dissipative processes above the critical current. This issues can be solved by using materials having perpendicular magnetic anisotropy, these materials have recently demonstrated a full damping compensation along SW emission, such behavior is accomplished by doping Bismuth in YIG [4].

Here, we propose a new pathway towards SOT-based SW amplification. Using micromagnetic simulations (Mumax3), we demonstrate that pulsed SOT does induce a lossless SWs propagation when the pulse duration is shorter than 200 ns. Remarkably, amplification is achieved when injecting currents exceeding the auto-oscillation threshold (Figure 1). A key condition is however to minimize non-linear coupling. In our case, we achieved this condition in a 20 nm thick Bi-YIG film structure with a vanishing effective magnetization *i.e.* the out-of-plane magnetic anisotropy compensates the demagnetization field [5].

In addition, the simulations results show an accordance with the realized experiment.
The Bi-YIG waveguide used is 21 μm long, 20 nm thick and covered with 7 nm of Platinum.
The SOT driven SW by an applied DC pulse in the Pt/Bi-YIG waveguide are detected using micro-focused Brillouin Light Scattering spectroscopy (BLS). The experiment thus shows the propagation of rf-excited magnons and in the supercritical regime where amplification of propagating magnons was observed. These results emphasize on the rich physics of the spin orbit torque magnonics and open the pathway towards integrated spin-wave magnonic amplifiers.

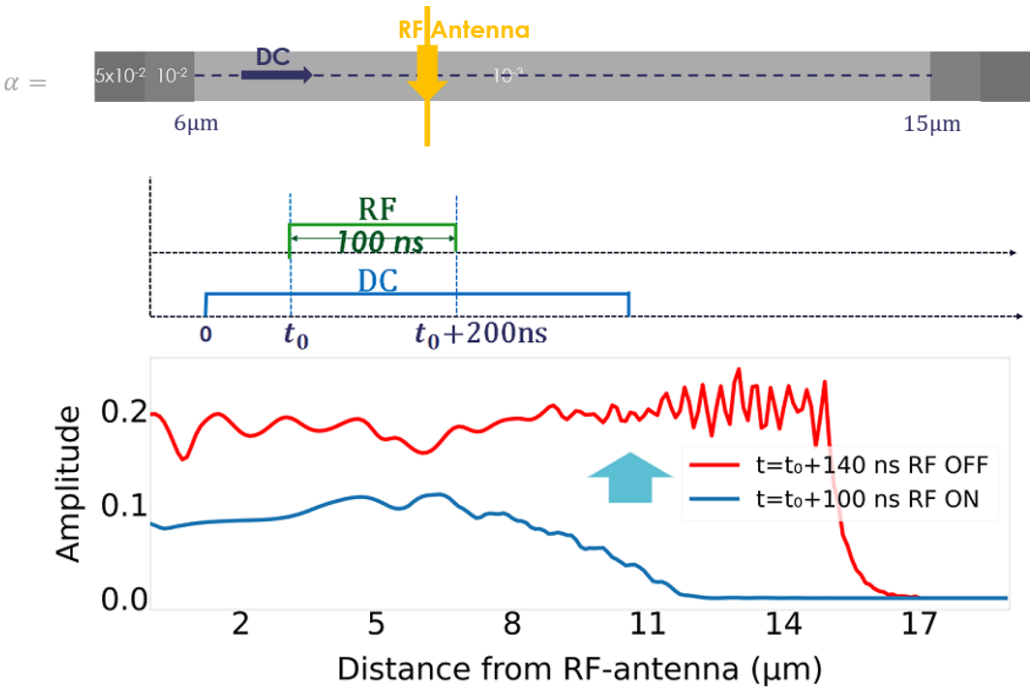


Figure 1: Spin Waves Amplitude evolution in the simulated waveguide when injecting a DC current larger than the auto-oscillation threshold. The blue curve is a snapshot at 100 ns after turning on the RF showing the SW front at a distance of 11µm from the antenna. The red curve is a snapshot taken 40 ns later showing the amplification of the full SW wave packet induced by SOT.

References:

[1] A. V. Chumak *et al.*, Nat Phys, vol.11, no. 6, pp 453-461, (2015).
[2] B. Heinz *et al.*, Appl Phys. Lett., vol. 118, no. 13, p. 132406, (2021).
[3] M. Evelt *et al.*, Appl Phys. Lett., vol. 108, no. 17, p. 172406, (2016).
[4] L. Soumah *et al.*, Nat. Commun., vol. 9, no. 1, p. 3355, (2018).
[5] M. Evelt *et al.*, Phys. Rev. Appl., vol. 10, no. 4, p. 041002, (2018).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861300.

PI-20: Selection rules for ultrafast laser excitation and detection of spin correlations in an antiferromagnet

A. E. Fedianin[1], A. M. Kalashnikova[1], J. H. Mentink[2]
[1]Ioffe Institute, Saint-Petersburg, Russia
[2]Radboud University, IMMN, the Netherlands

The use of femtosecond laser pulses offers new possibilities to control spins in materials through affecting magnetic-dipolar, spin-orbital [1], and even exchange interactions governing magnetic properties [2-4]. Interestingly, even a weak perturbation of the exchange interaction can trigger spin dynamics which involves magnon modes at the edge of the Brillouin zone, possessing ultimately short wavelengths and energies in the range of 10-100 THz [5-7]. However, existing experimental observations [1,2] and theoretical descriptions [3,6] of this ultrafast regime of spin dynamics leave a number of open questions, impeding interpretation of experimental results and limiting further development of exchange-driven coherent spin dynamics.

Here we report on a theoretical analysis of optical excitation and detection of two magnon mode, which can be realized in pump-probe techniques. We consider dielectric Heisenberg antiferromagnet with cubic structure and weak magnetic anisotropy to compare results with experimental data in such model antiferromagnets as $KNiF_3$, $RbMnF_3$. Excitation with a few fs short laser pulse was described as an impulsive perturbation of the exchange integral depending on the laser pulse polarization. We used Holstein-Primakoff magnons and Bogoliubov transformations to diagonalize the Heisenberg Hamiltonian and introduce two magnon operators. By solving the equation of motion for two magnon operators we calculate temporal evolution of spin correlations in response to such perturbation. As the most representative cases we considered Néel vector and easy-axis aligned either along cube diagonal or along bonds between the nearest neighbors.

We find that the considered perturbation excites a two-magnon mode described by oscillating spin correlation function. The highest amplitude of the laser-driven two-magnon mode can be obtained with the electric field of the laser pulse directed along the bond between nearest neighbor spins. Importantly, we found that laser-induced perturbation of exchange energy excites experimentally detectible dynamics of the Neel vector, i.e. contribute to macroscopic magnetic dynamics, only if the medium possesses magnetic anisotropy.

To reveal how such nontrivial dynamics of spin correlations can be detected in experiment, we analyzed the corresponding changes of the dielectric permittivity tensor. We show that time-dependent spin correlations have a two-fold impact on optical properties, either through direct modulation of tensor components or indirectly through modulation of magnetic birefringence proportional to the length of the Néel vector. The results of theoretical analysis are compared with the available experimental data [6,7].
This work was partly supported by the Foundation “BASIS” (grant № 20-1-5-95-1) and EU COST Action CA17123 "Magnetofon".

References
[1] Stupakiewicz A., et al., Nature 542, 71–74 (2017)
[2] Radu, I., et al, Nature 472, 205 (2011)
[3] Mentink, J. H., Journal of Physics: Condensed Matter 29, 45 (2017)
[4] Afanasiev, et al., Nature Materials, 20, 607–611(2021)
[5] Zhao J., et al., PRL 93, 107203 (2004)
[6] Bossini D., et al., Nat Commun 7, 10645 (2016)
[7] Bossini D., et al., Physical Review B 100, 024428 (2019).

PI-21: Universal switching of magnetization by circularly-polarized phonons

C. S. Davies[1], F. G. N. Fennema[1], A. Tsukamoto[2], I. Razdolskiy[1,3], A. V. Kimel[4] and A. Kirilyuk[1]

[1] FELIX Laboratory, Radboud University, Nijmegen, The Netherlands
[2] Nihon University, Chiba, Japan
[3] University of Bialystok, Bialystok, Poland
[4] Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

Due to the explosive growth of data worldwide, intense research activities are now concentrating on finding more energy-efficient methods for writing data i.e., switching magnetic bits [1]-[2]. Here, we present evidence of a novel and potentially highly-efficient pathway for magnetic switching via the excitation of circularly-polarized phonons at resonance in substrates.

In our experiments performed at the free-electron laser facility FELIX [2], we expose ferrimagnetic GdFeCo samples grown on c-cut sapphire (Al_2O_3) substrates to infrared and ultrashort circularly-polarized pulses. A single pulse, with wavelength λ = 21 µm and sufficiently short in duration, switches the magnetization deterministically via the ultrashort heating of the ferrimagnet (Fig. 1a). By extending the duration of the pulse to more than ≈1.5 ps, we observe a clear failure of all-optical switching, with only randomized domains being formed (Fig. 1b). In contrast, upon exposing the sample to hundreds of circularly-polarized 3.3-ps-long pulses (λ = 21 µm), we achieve switching of magnetization. This is made clearer by scanning the laser pulses across the sample surface (Fig. 1c). This unambiguously indicates that a different mechanism is at the root cause of switching at these longer pulse durations [3].

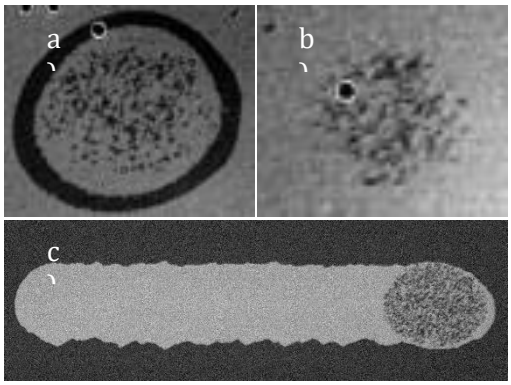


Fig. 1 (a)-(b) Magneto-optical images showing the effect of a single pulses (wavelength λ = 21 µm) with duration τ = 0.7 ps and 3.3 ps respectively. (c) Magneto-optical image showing the effect of sweeping circularly-polarized pulses (λ = 21 µm, τ = 3.3 ps) across the sample at a speed of 5 µm/s.

Upon tuning the central wavelength of the optical pulses, we observe that the switching efficiency depends dramatically on the pumping wavelength (Fig. 2). The efficiency of switching scales with the absorption spectrum of the substrate, which correlates to the spectrum of transverse optical phonons in the sapphire substrate.

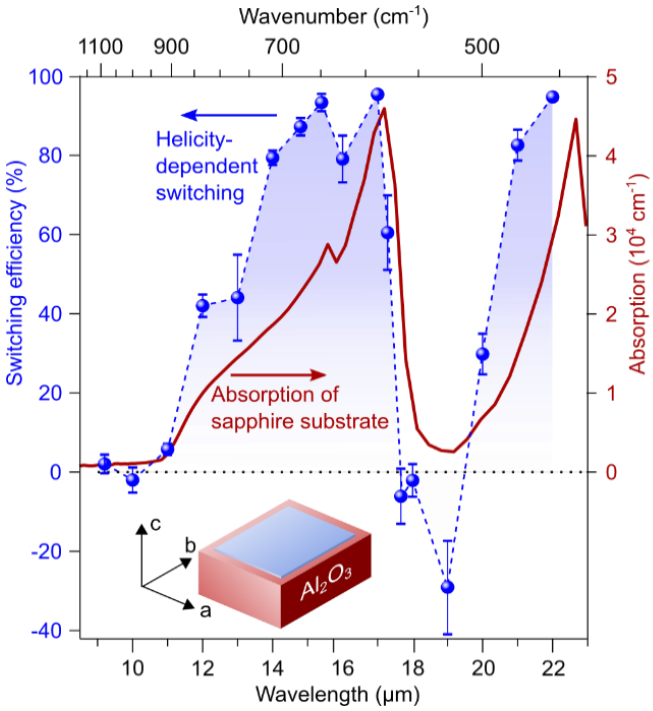


Fig. 2 Spectral dependence of the helicity-dependent magnetic switching measured in the GdFeCo-based nanostructure grown on a sapphire substrate, obtained with a sweeping speed of 50 μm/s. Overlaid are the respective absorption spectra characteristic of the substrate.

We argue that our results can be understood in terms of the incident optical pulses coherently driving circularly-polarized optical phonons in the substrate [5]. This then generates a magnetic field pulse normal to the substrate's plane, which then grows the magnetization in the nearby magnetic layer in a certain direction. This phononic mechanism is potentially universal since it relies on excitations of the substrate rather than the magnetic material of interest.

References

[1] A. Stupakiewicz, K. Szerenos, D. Afanasiev, A. Kirilyuk, and A. V. Kimel, "Ultrafast nonthermal photo-magnetic recording in a transparent medium." *Nature* **542**, 71 (2017).

[2] G. M. H. Knippels and A. F. G. van der Meer, "FEL diagnostics and user control." *Nucl. Instrum. Methods Phys. Res.* **144**, 32 (1998).

[3] A. Stupakiewicz, C. S. Davies, K. Szerenos, D. Afanasiev, K. S. Rabinovich, A. V. Boris, A. Caviglia, A. V. Kimel, and A. Kirilyuk, "Ultrafast phononic switching of magnetization." *Nature Physics* **17**, 489 (2021).

[4] C. S. Davies *et al.* "Exchange-driven all-optical magnetic switching in compensated 3d ferrimagnets." *Phys. Rev. Res.* **2**, 032044(R) (2020).

[5] S. R. Tauchert et al. Polarized phonons carry angular momentum in ultrafast demagnetization. *Nature* **602**, 73–77 (2022).

PI-22: Magnetic and transport properties of epitaxial Co_2MnSi Heusler thin films with ultralow Gilbert damping

Anna M. Friedel[1,2], C. de Melo[1], V. Palin[1,3], C. Guillemard[4], P. Pirro[2],
S. Petit-Watelot[1] and S. Andrieu[1]
[1]Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, 54000 Nancy, France
[2]Fachbereich Physik und Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[3]Synchrotron SOLEIL-CNRS, L'Orme des Merisiers, 91192 Gif-sur-Yvette, France

Magnetic materials with low Gilbert damping are indispensable for future spintronic and magnonic applications. Half-metallic Co_2Mn-Heusler compounds are promising candidates for such applications mainly due to their 100% spin polarisation at the Fermi level and the associated low Gilbert damping. Amongst them, Co_2MnSi thin films are of particular interest combining high saturation magnetisation, high Curie temperature and ultralow Gilbert damping in the 10^{-4} range [1], when epitaxially grown with decent control over stoichiometry to ensure the desired $L2_1$ chemical ordering [2].

Yet, downscaling towards ultrathin films or microstructures is a critical necessity for applications and is known to impact the properties of magnetic materials. We report on the successful fabrication of epitaxial Co_2MnSi thin films with maintained excellent properties for thicknesses in the range of 4 – 44 nm [3]. Predominant $L2_1$ ordering was obtained as shown in the high angle annular dark field scanning transmission electron microscopy (HAADF-STEM) micrograph in figure 1 (a).

After confirming the structural quality of the samples, the evolution of the magnetic and transport properties were investigated. Magnetisation dynamics were studied by ferromagnetic resonance (FMR) spectroscopy on the thin film samples. Low Gilbert damping values in the 10^{-4} to 10^{-3} range were found as shown in figure 1 (b) reaching down to 7.8×10^{-4} for the 8 nm film. Transport properties were measured on Hall bars that were patterned out of the thin film samples. Longitudinal and transverse resistivity measurements were performed as a function of thickness and temperature. The upper part of the minority spin band gap shown in figure 1 (c) was extracted from the temperature dependence of the resistivity and negative anisotropic magnetoresistance (AMR) ratios were obtained for the whole thickness series, see figure 1 (d), all of which confirm the half-metallicity of all samples.

In this study, a degradation of the Heusler thin films' desired properties was only apparent for the film of 4 nm thickness, demonstrating that the excellent qualities of the Heusler thin films can be retained down to film thicknesses of 8 nm.

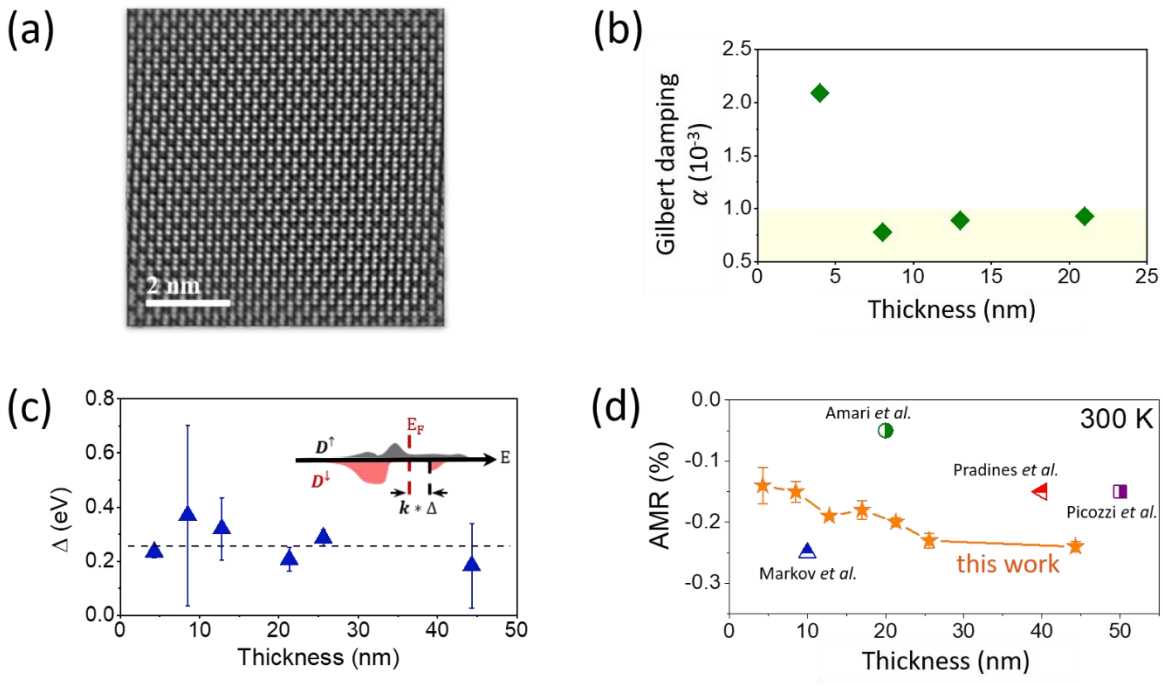


Figure 1: (a) $L2_1$ ordering in filtered HAADF-STEM micrograph of the Co_2MnSi film. (b) Ultralow Gilbert damping parameters were extracted from FMR measurements on the thin films in the out-of-plane configuration. (c) The upper part of the Co_2MnSi band gap was extracted from the temperature dependent resistivity measurements. (d) Negative AMR ratios were measured for the whole series, confirming the half-metallicity of the films.

References :

[1] C. Guillemard, *et al.*, Phys. Rev. Applied **11**, 064009 (2019)
[2] C. Guillemard, *et al.*, J. Appl. Phys. **128**, 241102 (2020)
[3] C. de Melo, *et al.*, Appl. Mater. Today **25**, 101174 (2021)

PI-23: Laser-induced THz coherent dynamics of rare-earth magnetic moments in $DyFeO_3$

T. Gareev, D. Afanasiev, S. Semin, A. Kimel
Radboud University, Nijmegen, the Netherlands

Ultrafast laser control of magnetism is one of the most exciting and challenging topics in physics and technology, which provides a new route to control magnetic states with high speed and low energy consumption. To explore the mechanisms of ultrafast magnetization dynamics researchers frequently appeal to the rare-earth compounds, in which strong spin-orbit coupling results in the non-trivial spin dynamics [1].

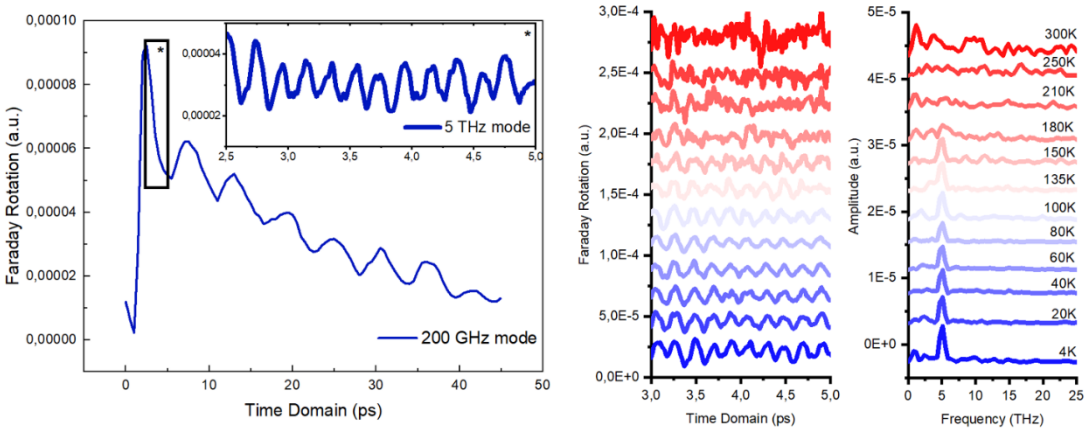


Figure 1: On left: Time-resolved ultrafast dynamics of the Fe^{3+} ions and the Dy^{3+} (inset) for circularly polarized light at the 4K temperature. On right: temperature dependence of crystalline lattice oscillations.

To probe and to control magnetic properties on a femto/picosecond timescale antiferromagnetic (AFM) rare earth orthoferrites are an interesting object to study due to the presence of two types of magnetic ions: transition metal iron (Fe^{3+}) and rare-earth (R^{3+}) ions. $DyFeO_3$ is one of the most intriguing representatives of the orthoferrites family. The striking demonstrations of the ultrafast inverse Faraday effect [1], ultrafast spin-reorientation phase transition [2], generation of propagating coherent THz spin wavepackets [3] are to name a few. The collective dynamics of the rare-earth ions are addressed only indirectly and as consequence remains largely unexplored. Recent theoretical analysis [4] showed that magnetization dynamics triggered by an ultrashort laser pulse are owed due to the coherent oscillations of magnetic moments of Dy^{3+} ions in $DyFeO_3$.

Using time-resolved pump-probe measurements of the magneto-optical Faraday effect we explore magnetization dynamics triggered in $DyFeO_3$ by sub-10 fs laser pulses. The study reveals 5 THz mode which corresponds to an f-f transition in Dy^{3+} ions. The measurements reveal that the phase of the magnetization dynamics can be controlled by the helicity of the pump pulses. The results are explained in terms of the inverse Faraday effect on the rare-earth ions, where femtosecond laser pulses trigger magnetization dynamics composed of both spin and orbital degrees of freedom.

[1] A.V. Kimel, A. Kirilyuk, et al., Nature, 435, 655–657 (2005);
[2] K. Yamaguchi, T. Keita, et al., Physical Review B, 92.6, 064404 (2015);
[3] J.R. Hortensius, D. Afanasiev. et al. Nat. Phys., 17, 1001–1006 (2021);
[4] A.I Popov, K.A. Zvezdin et al., Physical Review B, 103 (1), 014423, (2021).

PI-24: Micromagnetic modeling of domain wall dynamics under the Inverse Faraday Effect

P.-I. GAVRILOAEA[1*], R.M. OTXOA[2], O. CHUBYKALO-FESENKO[1]

[1]*Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, 28049 Madrid, Spain*
E-mail: paul.gavriloaea@csic.es
[2]*Hitachi Cambridge Laboratory, Hitachi Europe Limited, Cambridge CB3 0HE, United Kingdom*

Ultrafast laser pulse excitation enables unprecedentedly fast magnetisation dynamics, [1] holding the promise for the next generation of memory and logic devices. In the ongoing debate regarding the dominant contribution to helicity-dependent switching and domain-wall (DW) motion under the action of ultrafast laser pulses in ferromagnets, the Inverse Faraday Effect (IFE) has been previously claimed to play the leading role at the expense of magnetic circular dichroism (MCD). [2]

The traditional approach to modeling the IFE considers an additional effective field acting in the direction of the light propagation axis. [2,3] At the same time, *ab-initio* studies have described the effect in terms of an induced helicity-dependent magnetic moment or torque. [4,5] Attempting to mimic the role of the IFE and aiming at future large-scale modelling, we employ high temperature micromagnetics based on the Landau-Lifshitz-Bloch equation, [6] inquiring the possibility to displace a DW solely by elongating or shrinking the length of the magnetisation vectors during the action of the laser pulse. Assuming a 180^0 Néel wall, we induce an initial magnetisation modulus gradient across the DW and explore the possibility to convert the subsequent longitudinal relaxation of the spins into a translational motion of the Néel wall in the absence of any additional field, torque or thermal gradient. Our results show that under the action of the IFE, the DW displaces to the region where the magnetisation length was reduced, similar to the action of spin-Seebeck and MCD effects. We compare this effect with that of the field and torque and investigate the maximum displacement and acquired velocity of the DW as a function of the intrinsic damping (proportional to the spin-flip rate) and electron temperature.

We determine that the motion is qualitatively identical within the three approaches, showcasing the maximum DW displacement is proportional to the temperature while an increase in intrinsic damping leads to an increase of the DW velocity without affecting the final displacement. Furthemore, in the presence of the Dzyaloshinskii-Moriya interaction, we interestingly show the possibility to augment the observed motion and achieve large displacements of the DW even under one laser pulse.

References

[1] Kimel, A.V., Li, M. (2019). Writing magnetic memory with ultrashort light pulses. Nat. Rev. Mater. 4,189–200
[2] Raposo, V. et al. (2020). Micromagnetic Modeling of All Optical Switching of Ferromagnetic Thin Films: The Role of Inverse Faraday Effect and Magnetic Circular Dichroism. Appl. Sci. 10, 1307
[3] Vahaplar, K. et al. (2012). All-optical magnetization reversal by circularly polarized laser pulses: Experiment and multiscale modeling. Phys. Rev. B 85, 104402
[4] John, R. et al. (2017). Magnetisation switching of FePt nanoparticle recording medium by femtosecond laser pulses. Sci. Rep. 7, 4114
[5] Freimuth, F. et al. (2016). Laser-induced torques in metallic ferromagnets. Phys. Rev. B 94, 144432
[6] Atxitia, U., Chubykalo-Fesenko, O. et al. (2007). Micromagnetic modeling of laser-induced magnetization dynamics using the Landau-Lifshitz-Bloch equation. Appl. Phys. Lett. 91, 232507

PI-25: Ultrafast spin dynamics of a topological phase transition

K. Gerlinger,[1] R. Liefferink,[2] B. Pfau,[1] J. H. Mentink,[2] F. Büttner,[3] M. Schneider,[1] L.-M. Kern,[1] C. Klose,[1] D. Metternich,[3] D. Engel,[1] F. Capotondi,[4] D. De Angelis,[4] M. Pancaldi,[4] E. Pedersoli,[4] and S. Eisebitt[1,5]

[1]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, 12489 Berlin, Germany
[2]Radboud University, Institute for Molecules and Materials, 6525 AJ Nijmegen, the Netherlands
[3]Helmholtz-Zentrum Berlin, 14109 Berlin, Germany
[4]Elettra Sincrotrone Trieste, 34149 Basovizza TS, Italy
[5]Technische Universität Berlin, Institut für Optik und Atomare Physik, 10623 Berlin, Germany

Magnetic skyrmions are topological nanometer-scale spin textures that can be stabilized in ferromagnetic multilayers with perpendicular anisotropy by Dzyaloshinskii-Moriya interaction and dipolar fields. It has been demonstrated recently that single femtosecond IR laser pulses can create skyrmions in these materials in the presence of a symmetry-breaking applied magnetic field [1,2]. The laser pulse drives the ferromagnetic multilayer system into a high-temperature fluctuation phase where large-scale topological switching leads to the formation of a skyrmion phase. This topological phase transition proceeds on a time scale of a few hundreds of picoseconds which is significantly faster than any magnetic switching process in a ferromagnet observed so far.

Here, we investigate the influence of the applied magnetic field on the dynamics of the topological switching. To this end, we performed time-resolved scattering experiments at the free-electron laser FERMI in Italy, which we combine with atomistic simulations. In the experiments, the sample is excited from a field-polarized state into the fluctuation phase by a femtosecond IR laser pulse and probed by resonant x-ray scattering to detect emerging magnetic order. In accordance with previous static imaging experiments [3], we observe a clear reduction of the density of the skyrmion phase with increasing applied fields. Above a certain field threshold, a stable skyrmion phase cannot be formed anymore and the material returns to a homogeneously magnetized state. Surprisingly, however, we find that the transient fluctuation phase is characterized by emerging short-range magnetic order and the formation of topological charge even at applied fields above the threshold for a stable skyrmion phase. Entering the fluctuation phase is, thus, not a sufficient condition to the formation of the skyrmion phase. Using atomistic simulations, we explain the non-equilibrium skyrmion formation dynamics based on a relaxation time of the excited magnetic system that strongly depends on the temperature and the magnetic field. Our results provide important insights into the dynamics of the topological phase transition as a foundation for an ultrafast control of skyrmions for potential application in future data processing applications.

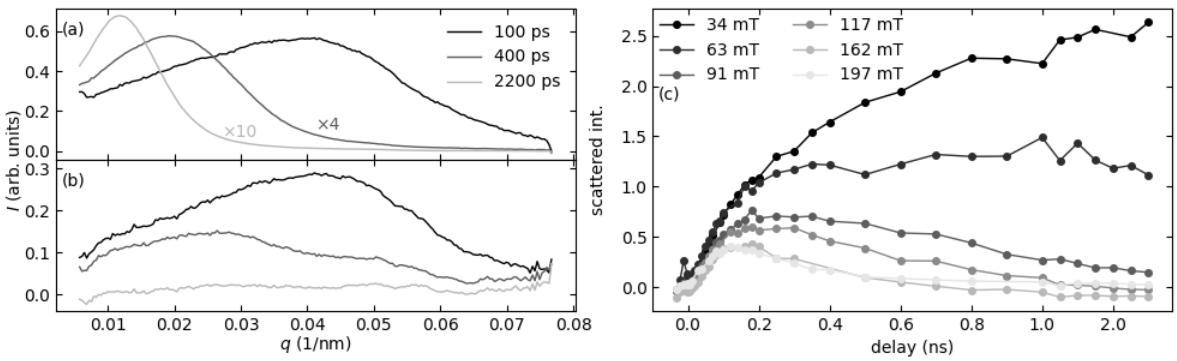


Figure 1: (a), (b) 1D azimuthal integrations of the scattering patterns 100 ps, 400 ps and 2.2 ns after the IR at 34 mT and 197 mT, respectively. (c) The total scattered intensity for six different applied magnetic fields as a function of the delay between IR pump and x-ray probe.

[1] Soong Geun Je *et al.*, Creation of Magnetic Skyrmion Bubble Lattices by Ultrafast Laser in Ultrathin Films, *Nano Letters*, **18** (11):7362–7371, 2018.
[2] Felix Büttner, Bastian Pfau, *et al.*, Observation of fluctuation-mediated picosecond nucleation of a topological phase, *Nature Materials* **20,** 30–37, 2021.
[3] Kathinka Gerlinger, *et al.*, Application concepts for ultrafast laser-induced skyrmion creation and annihilation, *Appl. Phys. Lett.* **118**, 192403, 2021

PI-26: Ultrafast optical generation of texture-antitexture pairs

S. Ghosh[1,2], S. Blügel[1] and , Y. Mokrousov[1,2]
[1]Forschungzentrum Jülich, Germany
[2]Johannes Gutenberg University, Mainz, Germany

The experimental demonstration of ultrafast skyrmion nucleation [1] is one of the most promising results in the field of ultrafast optical manipulation of magnetic order. The theoretical understanding of the underlying physics, however, is still not very clear. Most of the theoretical explanation is based on the classical magnetization dynamics which completely ignores the electronic interactions and as a result overlooks the proper channels of energy transfer from laser to the magnetic system. These features can be captured with time dependent DFT based approaches, however, due to the high computational demand, they are limited within orders of 100fs and therefore fails to capture the slow magnetization dynamics that takes place after several picoseconds. One way to bridge this gap is to adopt a hybrid quantum-classical evolution scheme which is found to be quite successful in capturing both the fast electronic dynamics at sub-femtosecond scale as well as the slow magnetisaiton dynamics after several picoseconds [2]. The method has successfully captured the emergent chiral spin mixing interaction which leads to the formation of a laser induced spin spiral. This mechanism is inherently different from thermal demagnetisaiton process which can be explained in terms of phenomenological three temperature model.

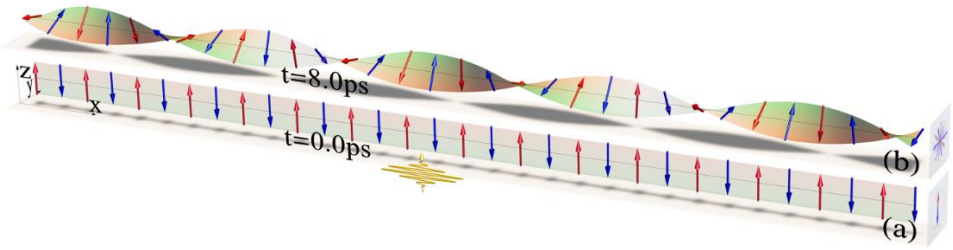


Figure 1: Formation of antiferromagnetic spin spiral with ultrafast laser [2].

In two dimensions, this mechanism can give access to even more exotic phases. Recently we demonstrate that for a two-dimensional antiferromagnet, this mechanism can lead to the formation of a meron-antimeron pair [3] which can survive for 100ps. By analysing the topological structure factor, we are able to show that such texture-antitexture pairs are most preferable intermediate state before the excited phase goes back to its initial collinear antiferromagnetic phase.

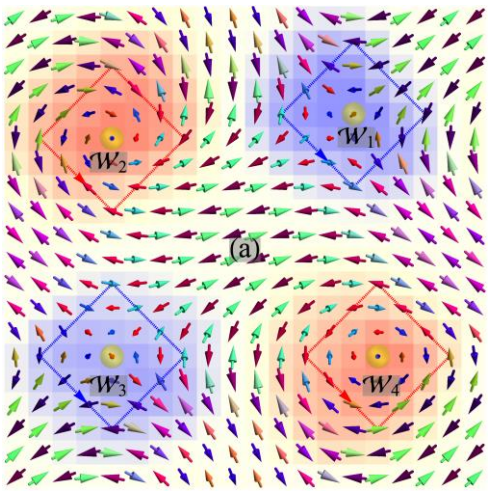


Figure 2: Formation of meron-antimeron pair with ultrafast laser [3].

These results therefore open new possibilities to explore more exotic magnetic texture with ultrafast laser.

References:

[1] F. Büttner *et al.*, *Nat. Mater.*, vol. 20, no. 1, pp. 30–37, 2021.
http://www.nature.com/articles/s41563-020-00807-1

[2] S. Ghosh, et.al. Comm. Phys., 5(1), 69, 2022. [arXiv:2011.01670]
https://www.nature.com/articles/s42005-022-00840-3

[3] S. Ghosh, S. Blügel and Y. Mokrousov. arXiv:2205.12100. http://arxiv.org/abs/2205.12100

PI-27: Nanosecond scale time evolution of phononic switching in magnetic garnet

M. Gidding, T. Janssen, C.S. Davies, A. Kirilyuk

FELIX Laboratory, Radboud University, Toernooiveld 7, 6525 ED Nijmegen, The Netherlands

We have recently shown how an ultrafast resonant excitation of the longitudinal optical phonon modes in magnetic garnet films switches magnetisation into a peculiar quadrupolar magnetic domain pattern, unambiguously revealing the magneto-elastic mechanism of the switching [1]. In contrast, the excitation of strongly absorbing transverse phonon modes results in thermal demagnetization effect only. The mechanism appears to be very universal and is shown to work in samples with very different crystallographic symmetry and magnetic properties, such as antiferromagnets [2]. However, the main question about the intrinsic dynamics of the switching can only be answered by the time-resolved domain imaging experiments.

Using single-shot time resolved microscopy with a nanosecond resolution, we follow the magnetisation dynamics in a thin film of magnetic garnet induced by resonantly pumping various optical phonon modes. As the pump pulse, we used wavelength-tuneable single pulses from the free-electron laser facility FELIX with possible pulse energy in excess of 100 microjoule [3] and wavelengths of 10-30 μm. For the probe, we used an electronically synchronized frequency-doubled Nd-YAG laser with 5 ns long pulses.

We observe a switching pattern consisting of four domains, which do not match the shape of the pump pulse and which grow during the first 300 ns after being pumped, far longer than the pulse width of 1-2 ps, and which decay within about 1 ms. Furthermore, we observe magnetic domains with a short period of a few micrometres, in the form of ripples, that propagate from the excitation centre as fast as 1000 m/s. Given the gaussian form of the excitation pulse with FWHM larger than 200 μm, the appearance of these ripples is quite unexpected. We tentatively link the appearance of these ripples to the generation of magnon-polarons [4].

References

[1] A. Stupakiewicz, C.S. Davies, K. Szerenos, D. Afanasiev, K.S. Rabinovich, A.V. Boris, A. Caviglia, A.V. Kimel and A. Kirilyuk, Nat. Phys. 17, 489(2021).
[2] P. Stremoukhov, C.S. Davies, A. Safin, S. Nikitov, and A. Kirilyuk, New J. Physics 24, 023009 (2022).
[3] T. Janssen, C.S. Davies, M. Gidding, V. Chernyy, J.M. Bakker, and A. Kirilyuk, Rev. Sci. Instrum. 93, 043007 (2022).
[4] K. Shen and G.E.W. Bauer, Phys. Rev. Lett. 115, 197201 (2015).

PI-28: Is THz emission a good probe of the spin current attenuation length?

J. Gorchon[1], S. Mangin[1], M. Hehn[1], G. Malinowski[1]
[1]Université de Lorraine, Institut Jean Lamour, UMR CNRS, Nancy 7198, France

Terahertz (THz) emission from magnetic films has recently become an important characterization tool of spintronic properties, particularly since no patterning is required [1,2]. One such property of interest is the spin-current attenuation length. When separating a magnetic film from a spin-to-charge converter with a light metal, the emitted intensity reduces almost exponentially with the thickness of the spacer [3-5]. However, the extracted characteristic length is more than an order of magnitude smaller than the spin diffusion length measured in equilibrium. In this work [7], we experimentally and theoretically demonstrate that most of the observed decay in the THz emission is of optical (THz) origin. We are able to estimate a spin current attenuation length for Cu of ~50 nm in much closer agreement with spin diffusion length measurements. We conclude that THz emission remains a powerful characterization technique, but due to the high number of intricate conversion mechanisms, and most importantly, due to the high sensitivity to changes in the optical properties, extracting absolute numbers for spintronic phenomena remains extremely challenging.

References

[1] T. Kampfrath, M. Battiato, P. Maldonado, et al., *Nat. Nanotechnol*. **8**, 256 (2013).
[2] T. Seifert, S. Jaiswal, U. Martens, et al., *Nat. Photonics* **10**, 483 (2016).
[3] G. Li, R. V. Mikhaylovskiy, K. A. Grishunin et al., *J. Phys. D* **51**, 134001 (2018).
[4] T. S. Seifert, N. M. Tran, O. Gueckstock et al., *J. Phys. D* **51**, 364003 (2018).
[5] M. B. Jungfleisch, Q. Zhang, W. Zhang et al., *Phys. Rev. Lett.* **120**, 207207 (2018).
[6] J. Gorchon, S. Mangin, M. Hehn, G. Malinowski *Appl. Phys. Lett.* **121**, 012402 (2022)

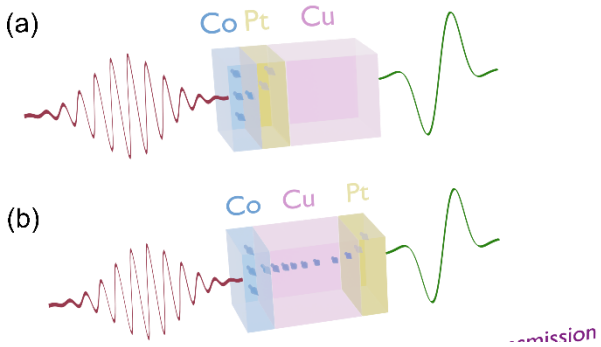


Figure 6: THz emission experiments carried with either a Cu spacer or capping. Our work shows that most of the variations in the emitted THz are due to THz optics, and not to spin transport

PI-29: Proximity effects and non-reciprocal transport in superconducting Nb/EuS

L. Gorzawski[1], H. Matsuki[1], S. Wang[1], N. Stalmashenko[1], A. Gutfreund[2], V. Plasovets[3], A. Bouzdine[3], O. Millo[2], Y. Anahory[2], J. Robinson[1]

[1]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom

[2] The Racah Institue of Physics, The Hebrew University of Jerusalem 91904, Israel

[3] The University of Bordeaux, LOMA UMR-CNRS 5798, F-33405 Talence, France

This work reports proximity effects in the s-wave superconductor Nb interfaced by the ferromagnetic insulator EuS. We have demonstrated that the superconducting transition temperature (T_c) of EuS/Nb/EuS spin switches is extremely sensitive to the magnetisation-alignment of the EuS layers, achieving a difference in T_c between parallel and antiparallel magnetisations of up to 1.8 K indicating a large magnetic exchange effect (MEF) in Nb (equivalent to MEFs in Al/EuS [1]). Furthermore, it has been shown that superconducting Nb on EuS retains a sharp superconducting transition (< 50 mK) down to a Nb thickness of only 1.8 nm. Nb has strong spin orbit coupling (SOC) which, in conjunction with a large MEF indicates that Nb/EuS is an ideal platform for investigating the superconducting diode effect in which supercurrents preferentially flow in one direction depending on the orientation of magnetisation i.e., a nonreciprocal behaviour of the critical supercurrent. Here we present magnetic and superconducting measurements on Nb/EuS structures and wires and show preliminary evidence for a diode effect. The exact origin of the diode effect is unclear but could be related to SOC [2] (conventional superconducting diode effect) or an exotic asymmetric flow of vortices [3].

References

[1] E. Strambini, V. N. Golovach, G. De Simoni, J. S. Moodera, F. S. Bergeret, and F. Giazotto, Revealing the magnetic proximity effect in EuS/Al bilayers through superconducting tunneling spectroscopy, *Phys. Rev. Materials 1*, 054402 (2017)

[2] Ando, F., Miyasaka, Y., Li, T. *et al.* Observation of superconducting diode effect. *Nature* 584, 373–376 (2020)

[3] Hou, Y., Nichele, F., Chi, H., Lodesani, A., Wu, Y., Ritter, M. F. & Moodera, J. S., Ubiquitous Superconducting Diode Effect in Superconductor Thin Films. *arXiv preprint arXiv:2205.09276* (2022)

PI-30: Ising machine with ultrafast dynamics in superparamagnetic tunnel junction

A. Grimaldi[1], N. A. Aadit[2], M. Carpentieri[3], K. Camsari[2] and, G. Finocchio[1]
[1]Department of Mathematical and Computer
Sciences, Physical Sciences and Earth Sciences, University of Messina, Messina, Italy
[2]Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA, USA
[3]Department of Electrical and Information Engineering, Politecnico di Bari, Bari, Italy

With the near end of Moore's law, one of the most heated research topics is unconventional computing – that is, new computational paradigm different from the standard Von Neumann's architecture in use nowadays. The necessity comes from the many still open problems in science that require higher, currently unachievable performance to be solved [1]. A very general approach to these issues is that of Ising machines (IMs): devices designed to find the ground state of an Ising model, often using probabilistic algorithms.
One of the strengths of IMs is the possibility of applying the same architecture to a great variety of problems so long as one knows how to encode them into an Ising model that has a ground state corresponding to the solution of the problem [2]. The main reason for IMs relevance, however, lies in the potential hardware application of these devices using spintronic components such as superparamagnetic tunnel junctions (MTJs) [3][4]. Fig. 1(a) shows an example of time domain trace of a p-bit implemented with the numerical solution of the LLG equation within the macrospin approximation where the continuous jumps between two states of the MTJ occurs at the nanosecond scale [3]. Those two states code the binary information needed for the implementation of PC.
In this work we adopted the paradigm of probabilistic computing (PC) with p-bits [5][6], as it is characterized by a high affinity with spintronics and compatibility with CMOS technology.
In fact, by carefully choosing the design parameters of an MTJ [4], it is possible to obtain a p-bit that achieves ultrafast dynamics with random jumps between two metastable states in the order of the ns. With this architecture we can solve hard combinatorial optimization problems (COPs) in the sub-microsecond timescale. This IM is simulated by solving macromagnetics simulations based on coupled Landau-Lifshitz-Gilbert (LLG) equations.

A potential application is the maximum satisfiability (Max-SAT) problem. Fig. 1(b) shows the results achieved with this spintronic implementation of PC considering the Max-SAT instance "s3v70c700-1.cnf". The simulation based on the solution of 771 coupled LLG equations is long 100 ns. The IM get to the optimal state in less than 60 ns which is potentially 4 to 5 orders of magnitude better than state-of-the-art competition-winning solvers. This result, which is a key finding of this work, is a motivation to push the efforts in a future hardware implementation of PC with spintronic devices. We wish to highlight that this approach can be scalable being the electrical connections between different invertible logic gates the same as the ones used today for conventional CMOS circuits.

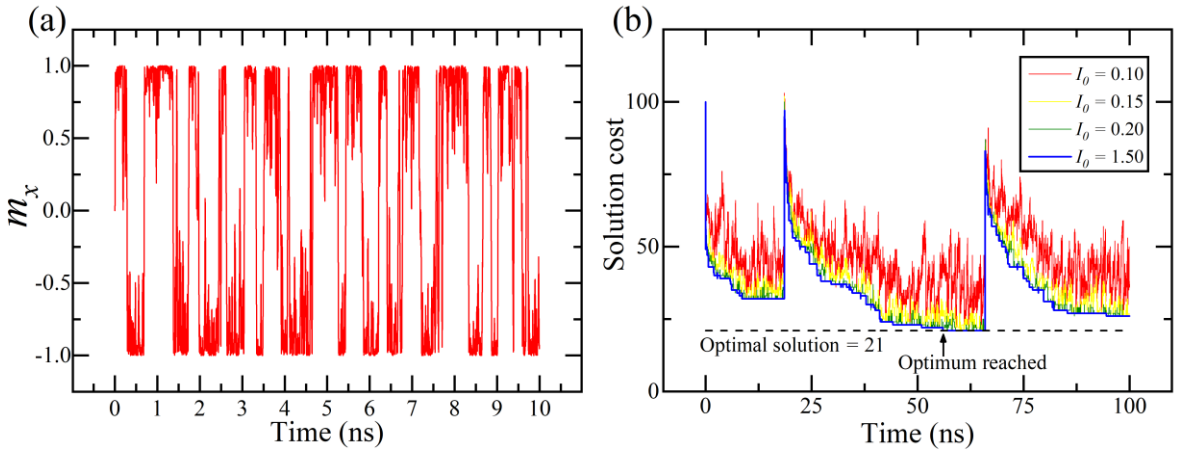


Fig.1 (a) Time domain traces of the x component of the magnetization dynamics of a superparamagnetic MTJ. The two bistable states code the binary information of a p-bit. The simulation dynamics has been computed numerically with the LLG equation. (b) Solution of the Max-3SAT instance "s3v70c700-1.cnf" (70 variables and 700 clauses) with the spintronic based PC solver. The number of p-bits for this instance is 771. Four replicas are used (parallel tempering), one of them is kept at very cold temperature to have frozen-like state. If that state does not improve for many iterations, the states are reset. The time step used is 10^{-3} ns and the simulation was run for 100 ns. In this instance, the optimal solution is 21 and the system obtains it at less than 60 ns.

References

1. Garey, M. R. & Johnson, D. S. Computers and intractability: a guide to the theory of NP-completeness. W. H. Freeman (1979).
2. Lucas, A. Ising formulations of many NP problems. Front. Phys. 2, 1–14 (2014).
3. Safranski, C. et al. Demonstration of Nanosecond Operation in Stochastic Magnetic Tunnel Junctions. Nano Lett. 21, 2040–2045 (2021).
4. Faria, R., Camsari, K. Y. & Datta, S. Low-Barrier Nanomagnets as p-Bits for Spin Logic. IEEE Magn. Lett. 8, 1–5 (2017).
5. Camsari, K. Y., Faria, R., Sutton, B. M. & Datta, S. Stochastic p-bits for invertible logic. Phys. Rev. X 7, 031014 (2017).
6. Borders, W. A. et al. Integer factorization using stochastic magnetic tunnel junctions. Nature 573, 390–393 (2019).

PI-31: Manipulating exchange bias with a single femtosecond laser pulse

ZX. Guo[1,2], G. Malinowski[2], BY. Zhang[1], W. Zhang[1,2], HT. Wang[1,2], P. Vallobra[1], S. Mangin[2], WS. Zhao[1] and M. Hehn[2]

[1]*School of Integrated Science and Engineering, Beihang University, Beijing, China.*
[2]*Université de Lorraine, CNRS, IJL, F-54000 Nancy, France*

Exchange bias phenomena have found widespread use in fundamental scientific research and a large variety of spintronic devices, including sensors and magnetic random-access memory (MRAM) [1]. In ferromagnetic (FM)/antiferromagnetic (AFM) bilayers, exchange bias arises from the interfacial exchange coupling between the two layers and results in a field shift (H_e) of the FM layer hysteresis loop. Many studies have focused on the possibility to manipulate the exchange bias effect using thermal annealing with or without applied magnetic field and spin polarized current [2][3]. Here we demonstrate the possibility to manipulate the exchange bias (change of the sign and amplitude of H_e) with a single femtosecond laser pulse in perpendicular to film plane magnetized IrMn/CoGd bilayers. We have studied the influence of the laser fluence and the number of pulses for various IrMn thicknesses to determine the fastest and the most energy-efficient way to set the exchange bias field. Our results establish a method to set the exchange bias in a bilayer system that has potential application for ultrafast and energy-efficient spintronic devices.

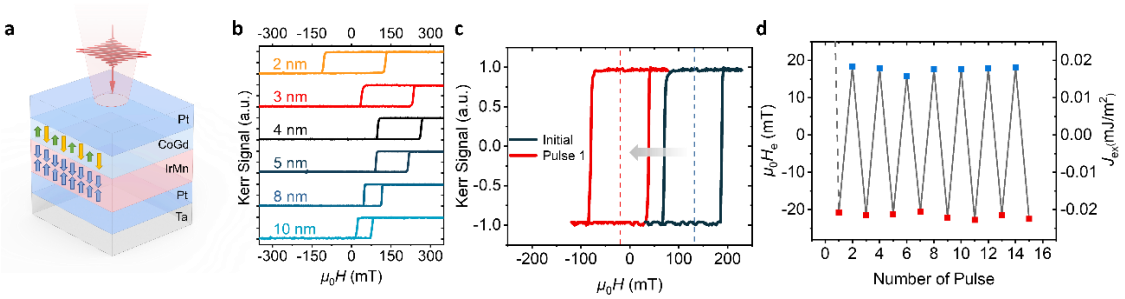


Figure. a, Sketch of the IrMn/CoGd bilayer. **b,** Hysteresis loops obtained on the annealed stacks for IrMn thickness t_{IrMn} from 2 to 10 nm measured by MOKE. **c,** Hysteresis loop of IrMn(5)/$Co_{77}Gd_{23}$(4) before and after exposure to a single linearly polarized laser pulse with a pulse duration of 40 fs and a fluence of 17 mJ/cm^2 **d,** Modulation of the exchange bias field as a function of the number of pulses with a pulse duration of 40 fs and a laser fluence of 17 mJ/cm^2.

References

[1] Nogués, J. & Schuller, I. K. Exchange bias. J. Magn. Magn. Mater. 192, 203–232 (1999).

[2] Prejbeanu, I. L. *et al.* Thermally assisted MRAM. *J. Phys. Condens. Matter* **19**, (2007).

[3] Lin, P. H. *et al.* Manipulating exchange bias by spin-orbit torque. *Nat. Mater.* **18**, 335–341 (2019).

PI-32: Size effect on interface engineering for all optical helicity independent switching in a ferromagnet

Danny Petty Gweha Nyoma[1], T.X. Huang[1], D. Lacour[1], J. Hohlfeld[1], W. Zhang[1], G. Malinowski[1], S. Migot[1], J. Ghanbaja[1], S. Mangin[1], M. Hehn[1], F. Montaigne[1]

[1] Institut Jean Lamour, Université de Lorraine – CNRS, 54000 Nancy (France)

Achieving control of the magnetization at smaller length scale and faster timescale is the horizon of research in magnetism. This interest stems from the ever-increasing need to decrease the reading and writing rate of magnetic memory devices which are made of nanosized magnetic bits. For the manipulation of magnetism in 100 ps range, single femtosecond laser pulse turned out to the best candidate due to the demonstration of ultrafast Single Pulse All Optical Switching Helicity Independent Switching (SP-AOHIS) in GdFeCo ferrimagnetic amorphous alloys [1,2].
In this work, we investigate the size effect on $Pt_{3.7\ nm}/Gd/Co_{0.7\ nm}/Pt_{3\ nm}$ that exhibited both PMA and single shot AO-HIS at room temperature in continuous full film. Indeed, we present a systematic study of the magnetization reversal for $Pt_{3.7\ nm}/Gd/Co_{0.7\ nm}/Pt_{3\ nm}$ dots whom diameter ranges from 2 µm to 400 nm with 35 fs linear polarization laser pulses. The effect of laser excitation was investigated in-situ using a polar MOKE microscope and the quantitative analyze of the switching probability were performed ex-situ by magnetic force microscopy.

By varying the number of pulses, it appears that a single toggle switching probability can describe the behavior. The variation of this switching probability can be precisely measured in a range from 90% to 99.99%. The switching probability degrades as the diameter of the dots is reduced.

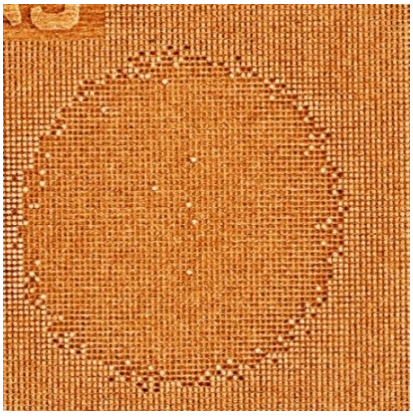


Figure 1: Magnetic Force Microscopy (MFM) mapping of an array of 800 nm diameter dots after exposure to a single laser pulse (35 fs). The black contrast corresponds to the reversed dots. The field of view is 80 µm

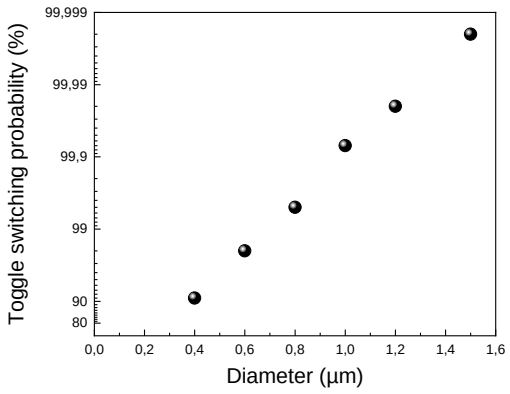


Figure 2: Variation of the switching probability with the dot diameter in $Pt_{3.7\ nm}/Gd/Co_{0.7\ nm}/Pt_{3\ nm}$ heterostructure.

The "exponential" variation of the switching probability with the dot diameter size is quite particular and cannot be explained by specific optical effects. On the other hand, a highly non uniform switching process with a small microscopic switching probability explains our experimental data. A simple

probabilistic model, analog to Condorcet's jury theorem, will be proposed and compared to micromagnetic simulations.

References :

[1] T.A. Ostler. et al. Ultrafast heating as a sufficient stimulus for magnetization reversal in ferrimagnet. Nat. Commun, ***3****(666), 2012.*
[2] Amal El-Ghazaly et al. *Ultrafast magnetization switching in nanoscale magnetic dots. Appl. Phys. Lett.* ***114,*** *232407* (2019).

PI-33: Size effect for all optical helicity independent switching in GdFeCo nanostructures

Danny Petty Gweha Nyoma[1], M. Verges[1], D. Lacour[1], Y. Guen[1,2], S. Dijken[2], G. Malinowski[1], M. Hehn[1], S. Mangin[1], F. Montaigne[1]

[1] Institut Jean Lamour, Université de Lorraine – CNRS, 54000 Nancy (France)
[2]Nanospin, Department of Applied Physics, Aalto University School of Science, P.O. Box 15100, FI-00076 Aalto, Finland

Achieving control of the magnetization at smaller length scale and faster timescale is the horizon of research in magnetism. Among the different possible factors (magnetic fields, spin-polarized charge currents, spin currents…), ultra-fast laser pulses turned out to be the fastest, with All Optical Switching (AOS) in the picosecond range. AOS has been intensively studied in ferrimagnetic materials like GdFeCo, but mainly in continuous thin film [1,2].
In this contribution, we present a systematic study of the reversal for glass/Ta(5nm)/Cu(5nm)/Gd_{24}FeCo(20nm)/Pt(5nm) dots whom diameter ranges from 3 µm to 400 nm with 35 fs laser pulses. Perfect toggle switching is observed for all sizes and the intrinsic reversal threshold is precisely deduced from fluence variations. The threshold fluence is shown to vary by almost 30% over the studied diameter range, with a tendency to lower threshold at smaller diameters. However a specific non-monotonic size variation is revealed in the 1-2 µm range. Variation in the nanostructure period and comparison with simulations highlights the importance of the specific light absorption in our nanostructures.

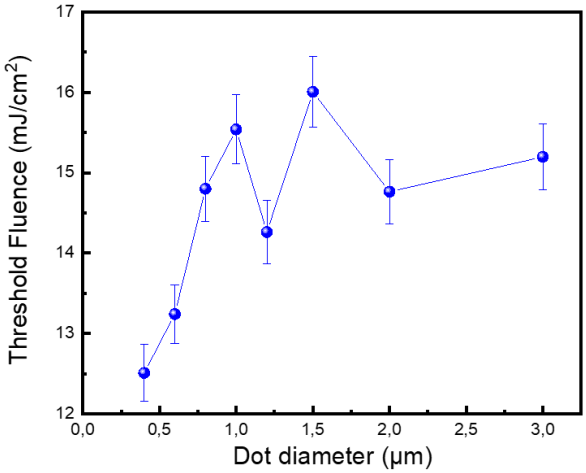


Figure : Variation of the threshold fluence with the dot diameter in Gd_{24}FeCo(20 nm) alloy.

References :

[1] T.A. Ostler. Et al. *Ultrafast heating as a sufficient stimulus for magnetization reversal in ferrimagnet. Nature Communication, **3**(666)*, 2 2012.
[2] J. Wei Et al. *All-optical Helicity-Independent Switching State Diagram in Gd-Fe-Co Alloys. Phys. Rev. Applied **15**,* 054065, 5 (2021).

PI-34: Spontaneous symmetry breaking of vortex trajectories in auto-oscillating coupled systems

A. Hamadeh[1], A. Koujouk[1], V. Lomakin[2], G. De Loubens[3], O. Klein[4] and, P. Pirro[1]
[1] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Kaiserslautern, Germany
[2]Center for Magnetic Recording Research, Uni. of California San Diego, La Jolla, California 92093-0401, USA
[3]SPEC, CEA, CNRS, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[4]Univ. Grenoble Alpes, CEA, CNRS, Grenoble INP, INAC-Spintec, 38054 Grenoble, France

The magnetic vortex state in nano-magnetic structures is a subject of intensive research since it offers many applications. To gain key insight into engineering and manipulating the vortex core orientation reversal t is crucial to fully understand their coupled dynamics. For this purpose, we have studied both experimentally and micromagnetically, the auto-oscillating modes in a spin-transfer vortex oscillator with two coupled thin and thick layers for different applied magnetic fields and currents. Experimentally, we observed four different classes of GMR frequency spectra patterns for the coupled dynamics of our system's VCs (see Figure 1). By means of micromagnetic simulations, we show that the varying core-to-core distance between the VCs of the two magnetic layers explains the experimental observations. Every class of GMR spectra shows characteristic coupled VC trajectories. The symmetry breaking of the VCs' trajectories makes the GMR signal's appearance no longer exclusive for the trivial case with a frequency of 2F (case 4). Indeed, the trajectories of the respective VCs admit spontaneous symmetry breaking determined directly by the initial positioning of the VCs.

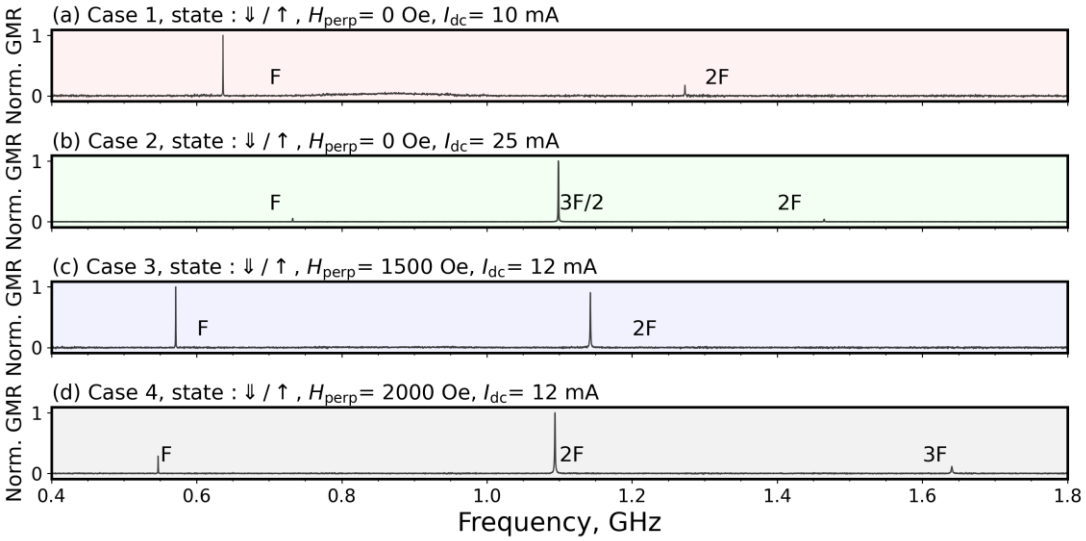


Figure 1: Experimental exemplary power spectra plots of the 4 different GMR frequencies classes obtained from the experimental studies of the system for opposite VC's polarity. (a) case 1: the GMR signal has the most power at a frequency F. (b) Case 2: the power of the GMR signal is at its highest at 3F/2, and almost negligible elsewhere. (c) Case 3: the GMR signal has almost equal power for a frequency F and 2F. (d) Case 4: most power of the GMR signal is centered at 2F, and is minimal elsewhere

PI-35: The role of intersite and interlayer spin transfer for the ultrafast magnetization dynamics of Py thin films

Simon Häuser[1], M. Anstett[1], J. Hoefer[1], L.Scheuer[1], G.Zinke[1], J. Seyd[2], P. Pirro[1], M. Albrecht[2], B. Hillebrands[1], B. Stadtmüller[1,3], and M. Aeschlimann[1]

[1]Department of Physics and Research Center OPTIMAS, TU Kaiserslautern, Erwin-Schroedinger-Str. 46, 67663 Kaiserslautern, Germany
[2]Institute of Physics, University of Augsburg, Universitätsstraße 1, 86135 Augsburg, Germany
[3]Institute of Physics, Johannes Gutenberg University Mainz, Staudingerweg 7, 55128 Mainz, Germany

Optical manipulation of magnetic materials on extremely short, sub-ps timescales can be achieved e.g. by (local) spin flips [1, 2] or by the generation of optically induced (ballistic) spin currents [3]. More recently, an addition mechanism, the optically induced spin transfer (OISTR) effect, was proposed and experimentally confirmed that allows to change the spin order of magnetic sub-systems directly by the optical excitation of the spin system [4, 5].
In this work, we aim to reveal the mutual interplay of these spin transfer effects on ultrafast time scales. Therefore, we investigate the ultrafast demagnetization of a thin $Fe_{20}Ni_{80}$ alloy on a non-magnetic Au substrate and how it is affected by the spin-dependent charge transport into the Au substrate.
As an element-resolved probe of the spin dynamics, we employ time resolved Kerr spectroscopy with fs-XUV radiation in transversal geometry to disentangle the spectroscopic signatures of the OISTR and ballistic spin transport in this material. Our results will be compared to the magnetization dynamics of a $Fe_{20}Ni_{80}$ film on an insulating substrate.

References:
[1] Koopmans et al., Nat. Materials 9, 259-265 (2010)
[2] Krauss et al., Phys. Rev. B 80, 180407 (R) (2009)
[3] Battiato et al., Phys.Rev.Lett. 105, 027203 (2010)
[4] Dewhurst et al., Nano Lett., 18, 3, 1842−1848 (2018)
[5] Hofherr et al., Sci. Adv., 6, 3, eaay8717 (2020)

PI-36: Modelling of the Antiferromagnet Mn2Au: From Density Functional Theory to Micromagnetics

J. Hirst[1], U. Atxitia[2], S. Ruta[1], J. Jackson[3], T. Ostler[1]
[1]Materials & Engineering Research Institute, Sheffield Hallam University, Howard Street, Sheffield S1 1WB, United Kingdom
[2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universitat Berlin, 14195 Berlin, Germany
[3]Scientific Computing Department, STFC Daresbury Laboratory, Warrington WA4 4AD, United Kingdom

Antiferromagnetic (AFM) materials are strong candidates for next generation data storage and processing. They remain robust to external fields and have intrinsically fast THz magnetisation dynamics. Simulations of AFM dynamics using atomistic models have been used for several years [1,2], but are generally restricted to system sizes of tens of nanometers. Micromagnetic models based on the LLG equation are unable to account for changes in the magnetisation length, and are therefore not appropriate to be used in scenarios where the temperature changes dynamically or where there is a spatial variation in temperature, thus requiring a new approach.
In this work, we present the first full multiscale model of the AFM Mn_2Au. Mn_2Au has been drawing much attention from the community largely because its ground state properties are preserved well above room temperature. We use values for the exchange interaction and anisotropy taken from *ab-initio* calculations as input into an atomistic model - from which we calculate the temperature dependent equilibrium parameters including the magnetisation, susceptibilities and exchange stiffness. These are then used as inputs into an AFM LLB model.
Our results show that the calculated Néel temperature of 1340 ± 10 K is in good agreement with previous experimental results [3]. We have determined the exchange stiffness through

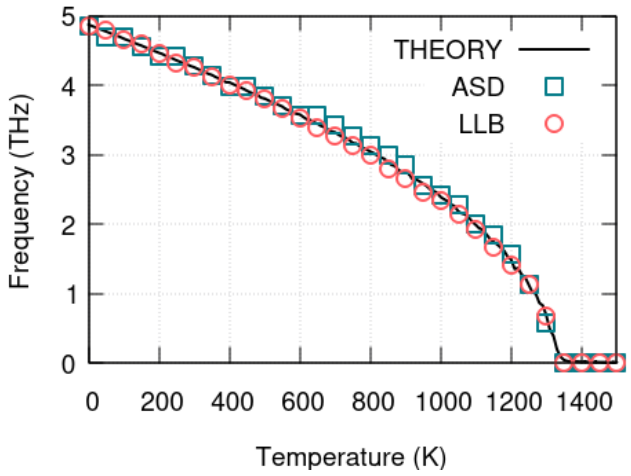


***Figure 7**: AFMR results for Mn_2Au. The transverse dynamics are of the order of THz, orders of magnitude faster than ferromagnets*

calculations of the temperature dependence of the domain wall width. As a key test of the transverse dynamics, we calculated the temperature-dependence of the antiferromagnetic resonance (AFMR) frequency, which is in excellent agreement with the results of the atomistic and analytical approximations, as shown in Figure 1. We also show that the modified longitudinal effective damping parameter in the LLB model as derived by Jakobs & Atxitia [4] yields excellent agreement between the longitudinal relaxation in both atomistic and LLB frameworks.

The development of this methodology is an important step forward in micromagnetic modelling where there are spatial and/or temporal variations in temperature, which lead to localized variations in the magnetisation. For example, in studies of ultrafast magnetisation dynamics or the dynamics of magnetic structures, such as domain walls under thermal gradient - which have been proposed for use in the next generation of logic and memory devices [5,6]. We show that the LLB model gives good agreement to atomistic results - which are computationally heavy and noisy for finite temperature DW simulations.

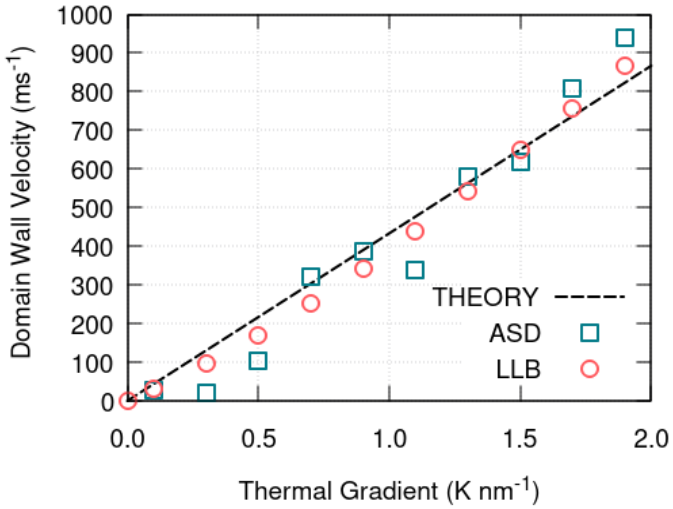


***Figure 2**: DW velocity for Mn2Au. Showing good agreement between theory, atomistic and LLB simulations.*

References

1. Kazantseva, N. et al. *Phys. Rev. B* 77. (2008): 184428.
2. Szunyogh, L. et al. ***Phys. Rev. B*** 79. (2009): 020403.
3. Barthem, V.M.T.S. et al. ***Nature Communications*** 4. (2013).
4. Jakobs, F. & Atxitia, U. **Private Communication**.
5. D. A. Allwood, et al. ***Science*** 309. 5741(2005): 1688-1692.
6. Stuart S. P. Parkin, ***Science*** 320. 5873(2008): 190-194.

PI-37: Deterministic all-optical magnetic switching in ferromagnetic nanomagnets via low-power, continuous-wave illumination

H. H. Holder[1], K. D. Stenning[1], X. Xiao[1], J. C. Gartside[1], A. Vanstone[1], O. W. Kennedy[1,2], D. M. Arroo[2,3], T. Dion[4,2], F. Caravelli[5], H. Kurebayashi[2], R. F. Oulton[1], and W. R. Branford[1]

[1]Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
[2]London Centre for Nanotechnology, University College London, London WC1H 0AH, United Kingdom
[3]Department of Materials, Imperial College London, London SW7 2AZ, United Kingdom
[4]Solid State Physics Lab., Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan
[5]Theoretical Division (T4), Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

We have demonstrated continuous-wave all-optical switching, without the application of an external magnetic field, in Permalloy nanomagnets at room temperature. This result has been shown in $Ni_{81}Fe_{19}$ and $Ni_{50}Fe_{50}$, in both artificial spin ice and isolated structures, at powers as low as 2.74 mW.

Previously helicity-dependent switching has been observed in ferromagnetic systems via multi-pulse ultrafast laser illumination, with a thermomagnetic inverse Faraday effect mechanism proposed, whereby the spin temperature of the system is raised sufficiently for angular momentum transfer to drive a complete magnetic reversal [1]. Helicity-independent switching has been observed, but primarily in ferrimagnetic systems such as GdFeCo [2].

By focussing a λ = 633 nm continuous-wave laser through a 100x 0.9NA objective lens, and aligning the linear polarisation with the long axis of a nanomagnet, we demonstrate magnetic reversal with high fidelity, even into energetically unfavourable spin-ice states. Switching was not observed in Cobalt nanomagnets, suggesting interplay between magnetic sub-lattices is important in the reversal process.

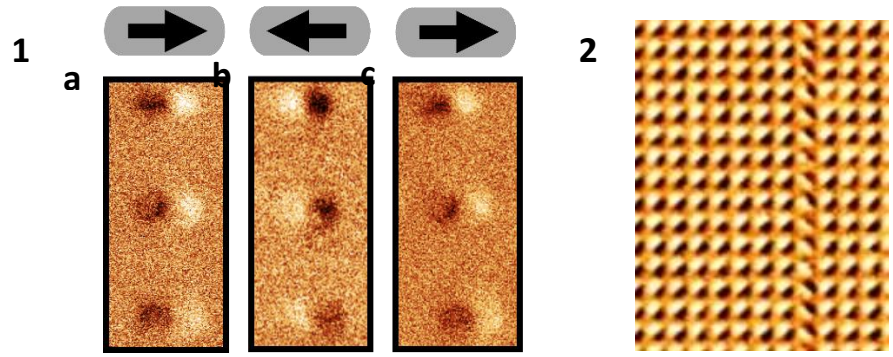


Figure 1: MFM image of three 280 nm × 78 nm × 20 nm Py nanomagnets illuminated using P = 3.75 mW laser illumination. a) Initially saturated state. b) Magnetic switching of the nanomagnets after illumination by moving laser spot at 20 µm/s. c) Magnetic re-switching after identical illumination protocol as in b). Figure 2: Artificial Spin Ice showing selective magnetic switching of single column, achieved via laser y-polarisation.

References

[1] C-H. Lambert *et al.* All-optical control of ferromagnetic thin films and nanostructures. *Science*, **345**:6202, 1337-1340 (2014)

[2] I. Radu, *et al*. Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins. *Nature* **472**, 205–208 (2011)

PI-38: The effect of thermal gradient on all-optical helicity dependent switching in FePt nanograins

K. Hovořáková[1], J. Walowski[2], M.Kohlmann[2], E. Schmoranzerová[1], P.Němec[1] and M. Münzenberg[2]
[1]Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[2]Institute of Physics, University of Greifswald, Greifswald, Germany

Integration of spintronic devices in electronics may provide a potential solution to the demand for high-bit-density and fast data-processing storage media. Ultrafast switching of magnetization induced by femtosecond laser pulses shows vast potential for enhancing the data processing speed [1]. All-optical helicity-dependent switching (AOHDS) is of particular interest as it can trigger the magnetization switching on the ultrashort timescales of tens of femtoseconds. Two effects are known to be responsible for the magnetization switching via AOHDS - inverse Faraday effect (IFE) and magnetic circular dichroism (MCD) [2]. IFE provides a direct angular momentum transfer from the circularly polarized light to the magnetization of the media, which triggers the magnetization dynamics that can lead to the switching. MCD, on the other hand, increases the switching probability, and thus supports the impact of the IFE on the sample. Experimental demonstrations of single laser pulse AOHDS was shown on Co/Pt multilayers in [3] proving the importance of IFE in the switching process.

In this work, we study the magnetic response of a demagnetized L10 FePt granular media sample to the circularly polarized light aiming to evaluate and optimize the efficiency of AOHDS in this material. We investigated the dependence of switching efficiency on the laser fluence, which helps to identify the mechanisms promoting the switching process in this system. Example of the AOHDS patterns, imaged by Kerr microscopy, is given if Fig. 1(a). To determine the threshold laser fluence F_{min} for the magnetization switching, we have to determine the intensity profile of the laser beam on the sample surface. Based on the knowledge of the total power of the laser beam deposited during the writing process and the beam diameter, we are able to reconstruct the intensity profile as demonstrated in Fig. 1(b).Furthermore, from the recorded MOKE images [Fig 1(a)], we can determine the width of the written line $\boldsymbol{w}$ which allows us to recalculate the laser fluence at the point where the magnetization switching still occurs F_{min} [indicated schematically in Fig. 1(b,c)]. The resulting width of written lines $\boldsymbol{w}$ was corelated against the minimum laser fluences that trigger magnetization switching F_{min}, as shown in Fig. 1(d) for different beam sizes.

In contrast to the initial belief that the FePt grains switch with the same probability at a specific laser fluence, our measurements have consistently shown that the minimum laser fluence that triggers magnetization switching exhibits a strong nonlinear behaviour dependent on the beam radius and the total deposited laser power. The non-linear behaviour is more prominent for smaller beam sizes. Moreover, for small beam sizes and large laser power, the magnetization switching occurs at effectively “zero” laser fluence [See Fig. 1(c)], which can be understood as switching outside the laser beam [Fig. 1(d)]. The first possible explanation is the large in-plane thermal gradient generated by the laser beam can give rise

to the spin-dependent Seebeck effect (SDSE) [4]. The SDSE generates an in-plane spin current and, consequently, torque on the magnetization in the oppositely oriented grains. The second mechanism is based on the increase of switching efficiency assisted by MCD at elevated temperatures. Owing to a large number of pulses (250k pulses deposited in each laser spot) the lattice gradually cumulates heat, which could facilitate magnetization switching even for laser fluences below the switching threshold.

It is worth noting that both SDSE and MCD can be present simultaneously during the switching process. However, their contribution to the switching process can be distinguished unambiguously, i.e. by their different spectral dependence or by different heat-sink layers. Our findings thus would help us understand underlying mechanisms for the AOHDS in FePt nanograins and help to optimize the conditions for the efficient switching in this system.

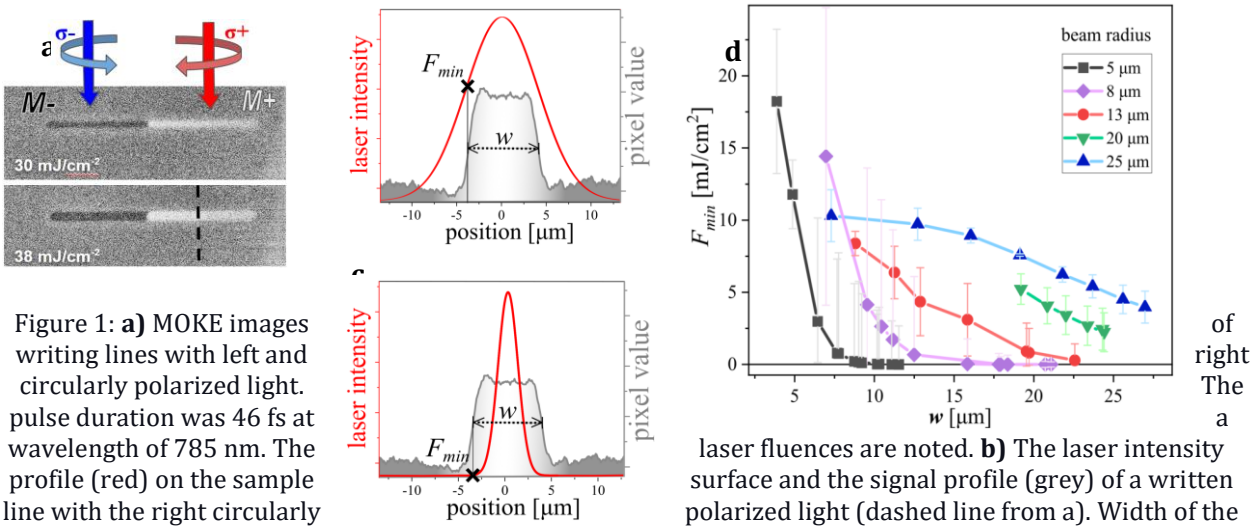


Figure 1: **a)** MOKE images of right writing lines with left and right circularly polarized light. The pulse duration was 46 fs at a wavelength of 785 nm. The profile (red) on the sample line with the right circularly polarized light (dashed line from a). Width of the written line is noted ***w***. The minimum laser intensity F_{min}(black cross) for switching was determined on the edge of the written line. **c)** Calculated minimum laser fluence from the laser intensity at the edge of the written line as a function of the width of the written line ***w*** for different beam sizes. **d) Switching occurring outside the laser beam.**

References

[1] C-H. Lambert et al., *Science* 345, 1337 (2014)
[2] R. John et. al., *Scientific Reports* 7, 4114 (2017)
[3] G. Kichin et.al., *Phys. Rev. Applied* 12, 024019 (2019)
[4] F. Bello et al., *ACS Photonics* 6, 1524 (2019)

PI-39: Role of Domain Nucleation and domain wall motion in All-Optical Helicity-Dependent Switching

Tianxun Huang[1], Julius Holfeld[1] and Stéphane Mangin[1]

[1]IJL CNRS UMR 7198, Université de Lorraine, 2 allée André Guinier, 54000 Nancy

Understanding the origin of All-optical helicity dependent switching (AO-HDS)[1] is still largely debated. Two mechanism is often opposed one based on magnetic circular dichroism[2] and the other on inverse Faraday effect[3]. Here, we study a Pt/Co/Pt multilayered stack showing clear AO-HDS and fabricated 10×10 μm^2 square Hall cross to combine Magneto-Optic Microscopy and anomalous hall effect measurements to be able to probe switching dynamics at different length and time scale. We demonstrated the full switching of a 10×10 μm^2 square with about ten pico-second circularly polarized laser pulses. The magnetization dynamic can be understood in terms of magnetic domain nucleation and domain wall propagation driven by magnetic circular dichroism induced thermal gradient.

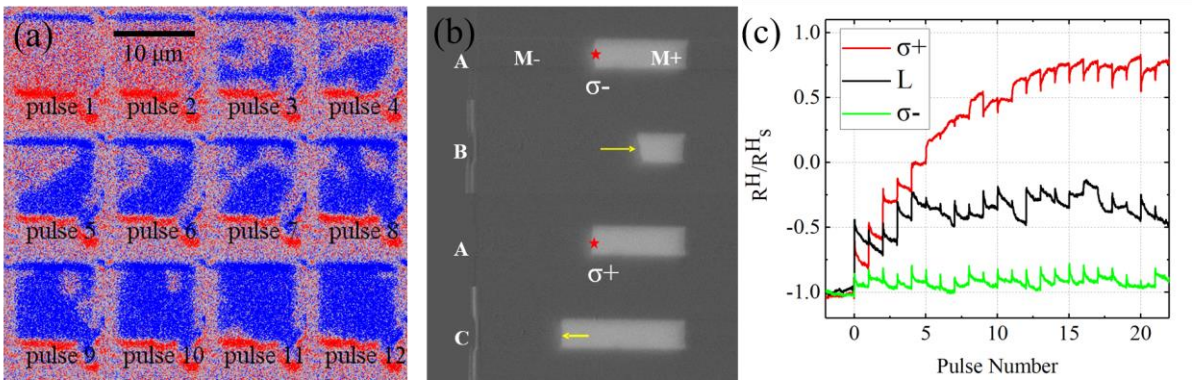


Figure 1: (a) The MOKE images after each pulse in a typical AO-HDS phenomenon. (b) The M+ domain will absorb more σ- light and will be hotter, the domain wall will move from cold domain to hot domain. (c) The dynamics after each pulse for different helicities of laser by measuring the hall resistance

References:

[1] S. Mangin et al., Engineered Materials for All-Optical Helicity-Dependent Magnetic Switching, Nat. Mater. 13, 286 (2014).

[2] P. J. Stephens, Theory of Magnetic Circular Dichroism, J. Chem. Phys. 52, 3489 (1970).

[3] J. P. van der Ziel, P. S. Pershan, and L. D. Malmstrom, Optically-Induced Magnetization Resulting from the Inverse Faraday Effect, Phys. Rev. Lett. 15, 190 (1965).

PI-40: Controllable laser-induced ultrafast spin-dynamics scenarios on zigzag carbon-chain or carbon-cross systems

WOLFGANG HÜBNER[1], J. LIU[1], and G. LEFKIDIS[1, 2]

[1]Department of Physics, Technische Universität Kaiserslautern, P.O. Box 3049, 67653 Kaiserslautern, German
[2]School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710072, China

The idea of using spintronics or magnetic heterostructures to build logical-functionality networks is growing in popularity at the moment [1]. Incorporating logic elements in a circuit (Fig. 1, left panel) requires a physical coupling between the participating magnetic molecules or clusters [2]. Here, employing high-level quantum chemistry, we investigate the ultrafast laser-induced spin-manipulation scenarios on one-dimensional zigzag carbon chains comparable to the current CMOS sizes (Fig. 1, middle panel), as well as on a two-dimensional zigzag carbon cross (Fig. 1, right panel). In both structures, two attached Ni induce spin polarization and spin-density localization. The achieved long-distance spin transfer between the two Ni atoms proves the feasibility of intersite spin manipulation at the subpicosend timescale.

The combination of the local symmetry of the participating carbon atoms and the global symmetry of the whole structure yields a long-range coupling of the two Ni atoms, which we term *the dynamical Goodenough-Kanamori rules*. Since local spin-flip processes on single Ni atoms sensitively depend on the external static magnetic field, a magnetic gradient allows us to selectively address each site. By means of double laser pulses, which also induce quantum coherences in the system, the individual addressability of the local spin-flips can be substantially enhanced, thus increasing the spatial resolution. Our findings emphasize the significant potential of carbon chain systems as assembling blocks for designing future all-optical integrated logic processing units.

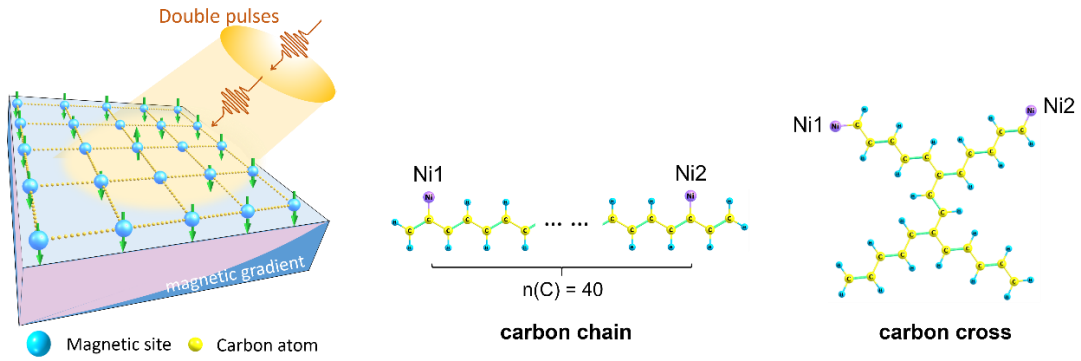


Figure 1: Schematic of an optical integrated logic unit and $Ni_2[2,38]@C_{40}$ geometry [3].

[1] G. Lefkidis, W. Jin, J. Liu, D. Dutta, and W. Hübner, J. Phys. Chem. Lett. **11**, 2592−2597 (2020).
[2] M. Xie, Y. Zheng, J. Liu, W. Jin, C. Li, G. Lefkidis, and W. Hübner, Phys. Rev. B **103**, 054433 (2021).
[3] J. Liu, C. Li, W. Jin, G. Lefkidis, and W. Hübner, Phys. Rev. Lett. **126**, 037402 (2021).

PI-41: Fluence dependent delay of Ni in an FeNi alloy challenges the Role of Optical Intersite Spin Transfer

S. Jana[1], R. Knut[2], K. Yao[1], D. Engel[1], C. von Korff-Schmising[1], S. Eisebitt[1]
[1]Max Born Institute for Short Pulsed Spectroscopy, Germany
[2]Department of Physics and Astronomy, Uppsala University, Sweden

In ultrafast magnetization dynamics (UMD), the loss of magnetization from a given volume occurs either via spin orbit coupling (SOC) mediated spin flips, or via non-local processes such as spin super diffusion (SSD) or optical intersite spin transfer (OISTR). While many of the observed phenomena in UMD are still not understood at the microscopic levels, advancement of measuring techniques such as element specific spectroscopy in the extreme ultraviolet spectral range has started allowing to disentangle different competing mechanisms. Guided by a recent theoretical prediction on OISTR [1], we have measured the fluence dependent delay of the onset of the Ni demagnetization in an $Fe_{50}Ni_{50}$ alloy by probing transverse MOKE (T-MOKE) asymmetries at the Fe and Ni *M*-edges employing high harmonic radiation [2]. Contrary to Ref. [1], our result shows a *decreasing* delay of Ni with *increasing* fluence. Further, emergence of a second ultrafast demagnetization channel after a threshold fluence for both elements suggests a SSD driven magnetic phase transition at high pump fluences as earlier proposed for elemental Ni [3].

Ref. [1] shows that the effect of OISTR can be significantly enhanced over SOC by tuning the pump pulse parameters. Here, an apparent delay in the demagnetization of Pd relative to Fe is observed in an $FePd_3$ compound for a short pump pulse which develops into a dramatic increase of the magnetic moment in Pd for an increased pump fluence. While these effects are not experimentally verified, a conceptually similar system FeNi has been studied and a delay in Ni demagnetization relative to Fe has been reported and confirmed utilizing both T-MOKE and XMCD by several research groups [4, 5]. Theoretical modelling has proposed two different explanations: Knut et al., suggested an inhomogeneous magnon generation scheme for the observed delay in Ni [6], while Hofherr et al., explained the delay by OISTR between the Fe and Ni sublattices [7]. In this work, we tested the fluence dependence of OISTR as predicited by Ref. [1] using an FeNi alloy.

Figures 1(a), (b) and (c) show T-MOKE asymmetries measured at the Fe and Ni *M*-edges of an $Fe_{50}Ni_{50}$ alloy as a function of

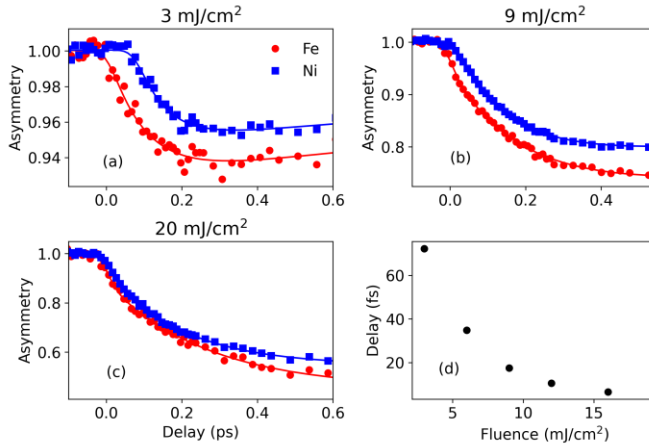


Figure 8: (a), (b), (c) show normalized asymmetries vs pump-probe delay measured at Fe and Ni M-edges with a fluence of 3, 9 and 20 mJ/cm², respectively. (d) Delay in Ni demagnetization as a function of fluence.

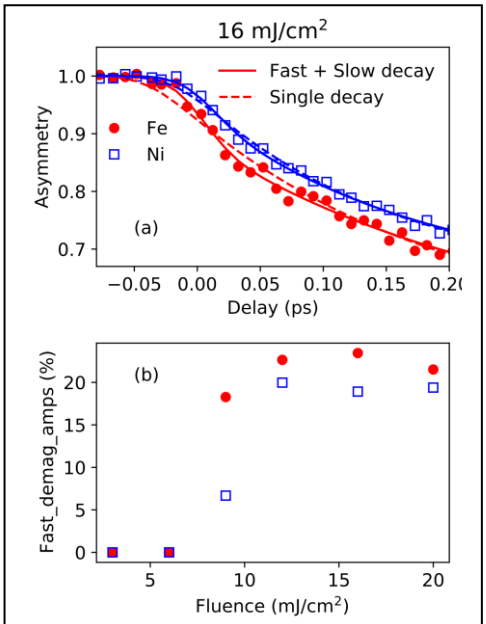


Figure 9: (a) Compares fits to the data measured for 16 mJ/cm² modelled with single and double decay time constants. (b) Fraction of the fast demagnetization amplitude as a

pump-probe delay for 3 exemplary pump fluences. Fig. 1(d) summarizes the observation of a rapid decrease of the delay in Ni demagnetization with increasing pump fluence. Evidence of a two-step demagnetization in both Fe and Ni is highlighted in Fig. 2(a) by displaying the response modelled with a single (dashed lines) and double exponential (solid lines) function. In Fig. 2(b), we analyse the fraction of the fast demagnetization component as a function of fluence, reaching ~20% beyond a threshold fluence of 10 mJ/cm².

Our experimental observation of a rapid decrease of the delay in Ni demagnetization (cf. Fig. 1(d)) with increasing fluence is clearly contradicting the calculation for OISTR as reported in Ref. [1] for $FePd_3$. Furthermore, delays as large as 70 fs have to be compared to the pump pulse width of <30 fs during which OISTR is expected to dominate. This suggests that the observed delay in Ni is unlikely to be dominated by OISTR. However, the emergence of a fast time constant above a threshold fluence (Fig. 2(a)) hints towards a different mechanism at early times. Apart from OISTR, spin super diffusion can occur at a faster time scale compared to SOC mediated spin-flips. While a signature of OISTR is *fast and mirrored dynamics*, i.e., one element (Ni) gains and the other element (Fe) loses spin moment due to the intersite spin transfer, SSD causes both elements to lose moments due to diffusion of majority spin carriers to the interior of a metallic sample or to the metallic cap/seed layers. Since both Fe and Ni lose a similar fraction (~20%) of the total lost moments (cf. Fig. 2(b)) during the initial fast component of the demagnetization, we propose that SSD is active at very early times. Tengdin et. al. [3], reported an ultrafast ferromagnetic to paramagnetic phase transition within ~20 fs above a threshold fluence observing a critical slowdown of the electron temperature rise and anticipating SSD as a driving mechanism. Emergence of the second, faster demagnetization channel above a threshold fluence in our results hints towards such a phase transition, which would obscure the delayed response in Ni stemming from SOC mediated spin-flips occurring at a slower time scale.

References:

[1] M. F. Elhanoty, O. Eriksson, R. Knut et. al., Phys. Rev. B. **105**, L100401, (2022).
[2] K. Yao, F. Willems, C. von Korff Schmising et. al., Rev. Sci. Instrum. **91**, 093001 (2020).
[3] P. Tengdin, W. You, C. Chen et. al., Sci. Adv. **4**, eaap9744, (2018).
[4] S. Mathiasa, C. La-O-Vorakiata, P. Grychtol et. al., PNAS **109**, 4792, (2012).
[5] S. Jana, R. Knut, S. Muralidhar et. al., APL **120**, 102404 (2022).
[6] R. Knut, E. K. Delczeg-Czirjak, S. Jana et al., Preprint arXiv:1810.10994 (2018).
[7] M. Hofherr, S. Häuser, J. K. Dewhurst et. al., Sci. Adv. **6**, eaay8717, (2020).

PI-42: Electronic and lattice dynamics of chiral helimagnets

J. Kalin[1], S. Sievers[1], H. W. Schumacher[1], A. Bauer[2], C. Pfleiderer[2], and M. Bieler[1]
[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Physik-Department, Technische Universität München, Garching, Germany

We investigate the influence of magnetic order on the electronic and lattice dynamics of chiral helimagnets in optical pump-probe reflectivity experiments. The transient reflectivity changes drastically from a bolometric behavior in the paramagnetic phase to a bipolar signal in the magnetically ordered states. The comparison of the transient reflectivity with time-resolved MOKE measurements and predictions of the Two-Temperature (2T) model suggests that the slower, non-electronic reflectivity contribution changes sign at the magnetic ordering temperature T_c, indicating an influence of the magnetic order on the electron-lattice coupling strength.

Transient reflectivity measurements give insights into thermal relaxation processes on a sub-picosecond time scale. Therefore, they are often used to extract characteristic time scales like the electron-lattice thermalization and heat diffusion time. The influence of magnetic order on the optical reflectivity of complex magnetic systems is rarely studied so far. Yet, it is essential to determine time scales adequately, as this often serves as important input for simulations or parameter extraction.
Here, we study the optically induced reflectivity changes of the chiral helimagnet MnSi in time-resolved pump-probe measurements using a Ti:sapphire laser amplifier with a 76-MHz repetition rate and 150-fs pulse duration. The transient reflectivity measurements of the different magnetic phases of a bulk MnSi sample (see Fig. 1a), which we identified in TR-MOKE experiments as reported in [1], are shown in figure 1b. In the paramagnetic phase for temperatures above $T_c = 29$ K, the reflectivity initially increases rapidly due to transient heating of the electrons by the laser pulse and subsequently decays due to electron-lattice thermalization and subsequent heat diffusion into the bulk (see Fig. 1b top left panel). This behavior is known as bolometric response [2]. In comparison, below T_c, the rapid increase of the reflectivity is followed by a zero-crossing and a negative transient, leading to a bipolar temporal course of the reflectivity (Fig. 1b lower left panel). The negative contribution of the reflectivity vanishes when exceeding the magnetic ordering temperature T_c as shown in figure 1c. The transient reflectivity only shows a small dependence on the magnetic field direction and strength (see Fig. 1b left panels), indicating its independence on the specific magnetization structure.
We analyze the transient reflectivity data with a phenomenological approach based on the 2T model [3], which separates the electronic (R_{el}, fast) and phononic (R_p, slow) reflectivity contributions according to $R = R_{el} + R_p$ (see Fig. 1b right panels). Within this model, we find that the observed bipolar behavior of the reflectivity below T_c is attributed to a negative lattice reflectivity contribution (see Fig. 1b lower right panel) and is combined with a reduced electron-lattice coupling in the presence of magnetic order (see Fig. 1d). This study points towards a complex interplay between spins, hot electrons, and lattice in chiral

helimagnets and gives insights into the electron-lattice coupling in the presence of magnetic order.

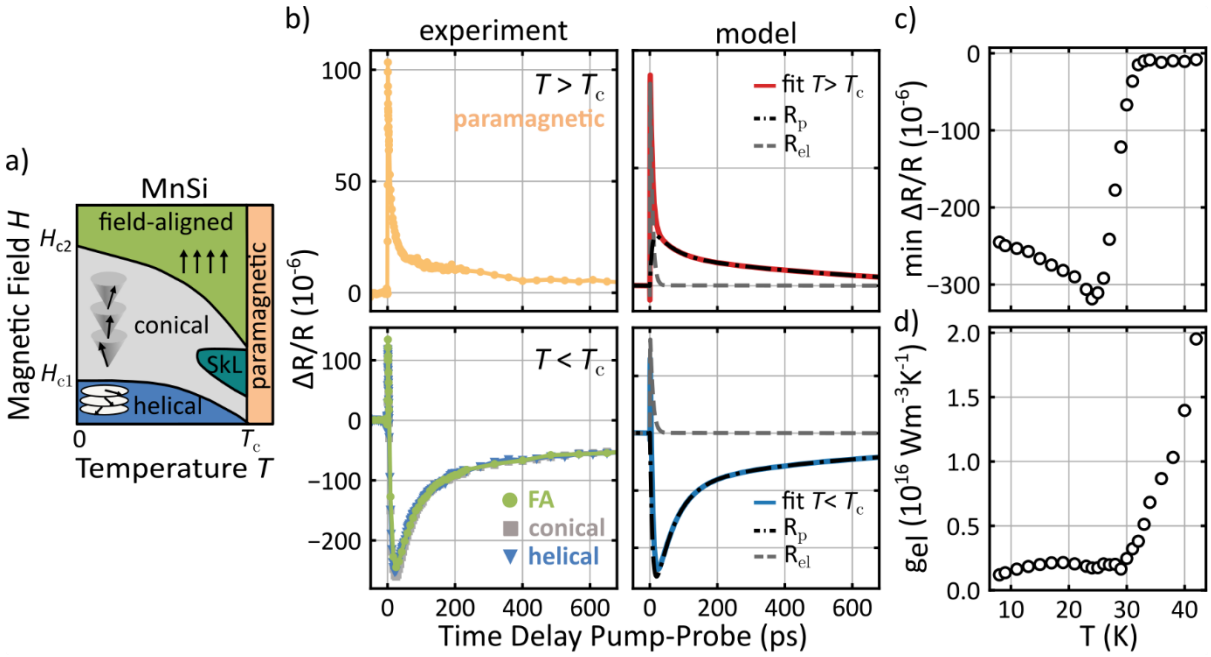


Figure 1: a) Sketch of the magnetic phase diagram of MnSi. b) Transient reflectivity measurements of MnSi in different magnetic phases (left panels) and the fits with the phenomenological model (right panels). c) + d) The minimum $\Delta R/R$ and the electron lattice coupling g_{el} as a function of temperature.

references
[1] J. Kalin et al., Phys. Rev. B (submitted).
[2] J. Koralek et al., Phys. Rev. Lett. 109, 247204 (2012).
[3] M. Djordjevic et al., Phys. Stat. Sol. (c) 3, No. 5 (2006).

PI-43: Spectrum evolution of laser-induced spin wave packets in anisotropic ferromagnetic films

N. E. Khokhlov, Ia. A. Filatov, P. I. Gerevenkov, and A. M. Kalashnikova
Ferroics Physics laboratory, Ioffe Institute, St. Petersburg, Russia
n.e.khokhlov@mail.ioffe.ru

Spintronics is the area of modern magnetism there the spin of elementary particles rather than their charge is used to code the information. Spintronics is promising in problems inherent to traditional electronics, such as high ohmic losses. Regarding this, spin waves (SWs), serving a pure angular momentum transport without a charge current, are currently an object of intensive study in a sub-field of spintronics – magnonics [1]. Recently, all-optical methods of SWs excitation and detection have been demonstrated experimentally [2]. On the other hand, active optical control of SWs propagation is up-to-date task in magnonics [3]. Thus, exploiting femtosecond laser pulses in reconfigurable magnonics is modern challenge for fundamental magnetism with potential impact on future applications of data processing.

In the presented study, we use two-color optical pump-probe technique with spatial scanning to check the influence of femtosecond laser pulses on propagation of magnetostatic surface waves (MSSW) in ferromagnetic metallic films of iron and galfenol ($Fe_{81}Ga_{19}$). The films exhibit the pronounced in-plane magnetic anisotropy. The feature provides the opportunity to excite MSSW via ultrafast thermal magnetocrystalline anisotropy changes [4]. Next, we demonstrate experimentally the narrowing of the spectrum of the laser-excited MSSW wave packet as it propagates away from the excitation area [4-6]. Moreover, we control whether the low or high frequency part of the spin wave spectrum is suppressed upon propagation by changing the orientation of external magnetic field with respect to the anisotropy axes. The theoretical description of the effect is given in terms of spatial gradient of the magnetization and anisotropy parameters of the film induced by the laser pulse. The wavelet analysis of the MSSW packets shows the frequency modulation growing with distance [6]. We theoretically describe the modulation as a result of dispersion of group velocity in the film. The concept of MSSW control by fs laser pulses is extended further by analyzing properties of the MSSW optically excited near a Néel domain wall in a ferromagnetic strip [7]. Micromagnetic modelling reveals the appearance of controllable resonance peaks in the MSSW spectrum. We show the combination of femtosecond optical excitation with magnetic nonuniformity of the film, e.g. domain wall, acts as a tunable source of MSSW wavepackets.

Authors thank A. W. Rushforth and M. Wang for the provided samples and the Russian Science Foundation for financial support (project 22-22-00326).

References

[1] S. A. Nikitov, et al. Phys. Usp. 58, 1002 (2015).
[2] T. Satoh, et al. Nat. Photonics 6, 662 (2012).
[3] M. Vogel, et al. Nat. Physics 11, 487-491 (2015).
[4] N. E. Khokhlov, et al. Phys. Rev. Applied 12, 044044 (2019).
[5] Ia. A. Filatov, et al., J. Phys. Conf. Ser. 1697, 012193 (2020).
[6] Ia. A. Filatov, et al., Applied Physics Letters 120, 112404 (2022).
[7] N. E. Khokhlov, et al. JMMM, 534, 168018 (2021).

PI-44: Polarization control in a composite multiferroic THz emitter by an electric field

D. Khusyainov[1], S. Ovcharenko[2], A. Buryakov[2], A. Klimov[2], P. Pernod[3], E. Mishina[2], A. Sigov[2], V. Preobrazensky[4] and, N. Tiercelin[3]

[1] Institute for Molecules and Materials, Radboud University, 6525 AJ Nijmegen, Netherlands.
[2] MIREA - Russian Technological University, Moscow 119454, Russia
[3] University of Lille, CNRS, Centrale Lille, Université Polytechnique Hauts-de-France, UMR 8520 - IEMN, 59000 Lille, France
[4] Prokhorov General Physics Institute of RAS, Moscow 119991, Russia

The main trend in THz technology now is spintronic emitters. Properties of generated pulsed THz radiation in these structures depend not only on charges but also on their spins[1]. Spin-to-charge conversion allows controlling characteristics of generated THz radiation by manipulating the magnetization in such emitters using an external magnetic field [2,3]. Electromagnets are needed to control the polarization of THz radiation in such devices. This work presents the possibility of controlling the polarization parameters of THz radiation in a spintronic emitter without an electromagnet only by applying an electric field.

For this purpose, a composite multiferroic THz emitter was grown. It consisted of 25 layers of (TbCo/FeCo) magnetostrictive superlattice which was deposited on Pb(Mg1/3Nb2/3)0.7Ti0.3O3 (PMNPT) piezoelectric substrate by radio frequency sputtering. THz generation was measured by THz time-domain spectroscopy in reflection geometry with the ability to apply a magnetic field along the sample surface plane. To measure the angle of THz polarization rotation wire-grid polarizer was used. The generated THz emission from the sample with the maximal spectral amplitude was observed at a frequency of 0.8 THz, and the spectral bandwidth was limited to 3.5 THz due to the spectral range of the detector. Applying voltage on piezoelectric substrate allowed for manipulating summary magnetization in the magnetostrictive superlattice. The highest rotation angle ~70° was obtained at a voltage of 60, -60 V on the piezoelectric substrate and a constant magnetic field of 0.7 kOe. In conclusion, we report on electric field control over the magnetization direction and, therefore, on the control over the THz-wave polarization without changing the THz-pulse amplitude.

The work is supported by RSF (Grant No. 20-12-00276). Fabrication of the samples was performed in the frame of French RENATECH network.

references

1. Seifert T. et al. Efficient metallic spintronic emitters of ultrabroadband terahertz radiation // Nat. Photonics. 2016. Vol. 10, № 7. P. 483–488.
2. Kong D. et al. Broadband Spintronic Terahertz Emitter with Magnetic-Field Manipulated Polarizations // Adv. Opt. Mater. 2019. Vol. 7, № 20. P. 1900487.
3. Khusyainov D. et al. Polarization control of THz emission using spin-reorientation transition in spintronic heterostructure // Sci. Rep. 2021. Vol. 11, № 1. P. 697.

PI-45: Ultrafast laser induced local crystallization in amorphous spin-glass PrDyFeCoB microwires

O. Koplak[1], R. Morgunov[2]
[1]Politechnico di Milano, Milano, Italy
[2]Institute of Problems of Chemical Physics, Chernogolovla, Russia

Selective laser melting (SLM) also known as additive manufacturing technology has already been used to print permanent magnets of very fine microstructure with programmable shape and stable magnetization [1]. The fully metallic 3D printed magnets basically allow one to develop technology of micro- and nanomagnets necessary in medical and biology applications. Enhanced magnetic properties of the PrDy-FeCo-B microwires [2, 3], and high residual magnetization has been applied for micro device creation [4]. We propose local laser treatment of the micronized areas of the microwires, where initially amorphous material is converted to microcrystalline state very quickly. Continuous laser irradiation has been used to modify magnetic properties of the amorphous films and bulk materials in RE-TM-B [5] and RE-TM [6] magnets (RE are rare-earth atoms, TM are transition metals, B is boron). Because heat conductivity is time-limited and small volume of the microwire is rapidly heated, extremely rapid conditions of crystallization can be created. Our work is aimed at the development of laser treatment, resulting in very rapid local crystallization of the spin glass amorphous PrDyFeCoB microwires under single short impulse.

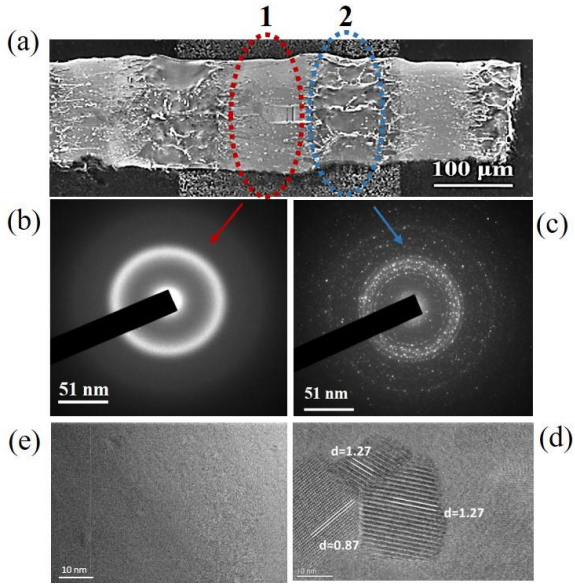


Figure 1. (a) Non irradiated (1) and irradiated (2) areas of microwire; (b, c) Electron diffraction patterns in non irradiated (b) and irradiated (c) areas; (d, e) TEM images of irradiated (d) and non irradiated (e) areas.

The melted drop was splashed out on a rotating water-cooled brass cylinder and it was pulled out at 55 m/s linear speed corresponding to the ~10^6 K/s cooling rate [3]. Laser spot of 8-10 µm diameter moved perpendicular to the main axis of the microwire imprints alternating bands on the

microwire surface (Figure 1 a). Irradiation of the ytterbium pulsed fiber laser with wave length 1070 nm and maximal power P ~ 20 W was used for the microwire local heating. Energy of single pulse was 1 mJ, its duration was 120 ns, and impulse frequency was 25 kHz.

Initially amorphous PrDyFeCoB microwires (Figure 1 b, e) were locally transformed by single laser impulse to nanocrystalline $(PrDy)_2(FeCo)_{14}B_1$, and $(PrDy)_1(FeCo)_2$, $(PrDy)_1(FeCo)_4B_1$ magnetic phases (Figure 1 c, d). Alternating magnetic patterns imprinted by laser irradiation have magnetization component perpendicular to the microwire main axis. MOKE experiments revealed magnetic anisotropy and coercivity of the irradiated areas in contrast with non irradiated amorphous spin-glass areas with zero coercivity. Nanocrystalline phase $(PrDy)_2(FeCo)_{14}B_1$ created by short laser annealing manifests enhanced magnetic properties in comparison with initial amorphous phase.

Perpendicular component of stray fields of crystallized areas can be used for practical applications. This allows creating magnetic micro tweezers, magnetic tips, necessary in medicine. Magnetic periodicity of microwire is convenient for moving part of linear micro-electro-motors. Obtained results contribute to micro additive laser technologies. Fast imprinting of the magnetic micro labels along the microwire provides designing programmable microstructures.

[1] A.S.Volegov, S.V.Andreev, N.V.Seleznev, I.A.Ryzhikhin, N.V.Kudrevatykh, L.Mädler, I.V.Okulov, Additive manufacturing of heavy rare earth free high-coercivity permanent magnets, Acta Mater. 188 (2020) 733-739.
[2] P. Szary, I. Luciu, D. Duday, E.A. Périgo, T. Wirtz, P. Choquet, A. Michels, 2015. Synthesis and magnetic properties of Ta/NdFeB-based composite microwires, J. Appl. Phys. 117 17D134.
[3] R.B.Morgunov, O.V.Koplak, 2021. Exchange bias and spin-reorientation transition in α-Fe/PrDyCoFeB core/shell microwires, Mat. Sci. and Eng. B. 263, 114845.
[4] R.B.Morgunov, O.V.Koplak, 2020. Focused magnetization in sharpened rare-earth microwires with four switchable magnetic states, Mat. Lett. 273, 127954.
[5] K-T.Chu, Z.Q. Jin, V.M.Chakka and J.P.Liu, Rapid magnetic hardening by rapid thermal annealing in NdFeB-based nanocomposites. J. Phys. D 38 (2005) 4009-4014.
[6] J.J.Croat, A.R.Chraplyvy, and J.F.Herbst, Crystallization of amorphous Pr0.27Co0.73: Magnetic properties and laser induced coercivity, Appl. Phys. Lett. 37 (1980) 962-964.

PI-46: Influence of the laser-induced strain on the ultrafast magnetization dynamics of nickel

O. Kovalenko[1], J.-W. Kim[2], M. Vomir[1]
[1]Université de Strasbourg and CNRS, IPCMS UMR 7504, Strasbourg, France
[2]Department of Physics, Kunsan National University, Kunsan 54150, South Korea

The physical mechanisms leading to the ultrafast demagnetization in metals have been longtime debated [1-6]. The proposed scenarios include the spin diffusion, spin-flip scattering and more recently a direct transfer of angular momentum to the lattice in the 150 fs time frame via excitation of coherent transverse phonons [7,8].

We have investigated here the demagnetization time (τ_M) and the magnetization precession dynamics of Ni thin films excited by femtosecond laser pulses. They are measured as a function of the absorbed pump energy density E_{abs} and indicate a direct connection between τ_M and the precession phase ϕ. We interpret the nonlinear variation of the magnetization precession phase as a competition between the temperature-dependent anisotropy and the laser-induced quasi-static surface strain. The dynamical properties of M are described using a Landau-Lifshitz-Gilbert model taking into account the time-dependent charge, spin and lattice temperatures, as well as the temperature-dependent anisotropies including the magnetoelastic energy [9].

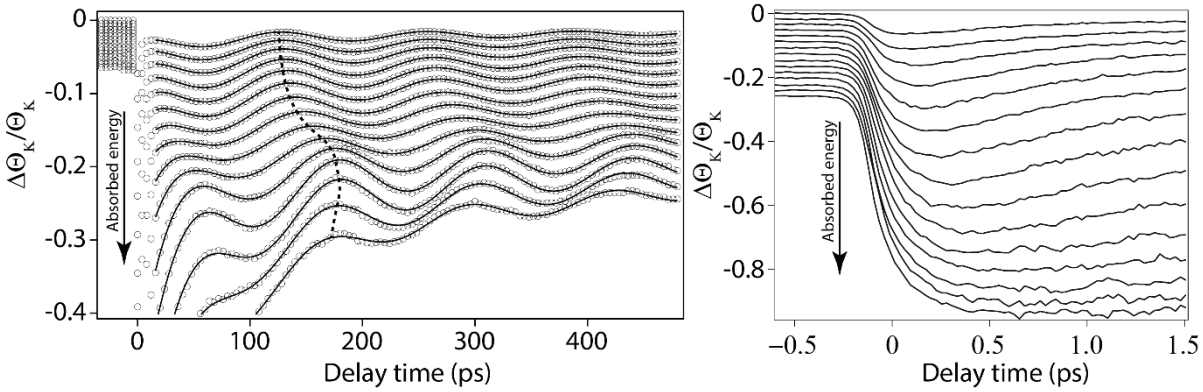


Figure 1: (a) Magnetization precession for several densities of excitation (0.48 mJcm^{-2} – 1.33 mJcm^{-2}) in 7.5 nm Ni film. The line is a guide to the eye showing the nonlinear phase change. (b) Demagnetization curves are measured in the longitudinal geometry for the same energy densities as in (a). The traces are shifted proportionally to E_{abs}.

The samples are polycrystalline thin films of Ni deposited by magnetron sputtering on glass substrates. We have chosen here to show the results obtained for a Ni thickness of 7.5 nm, well below the skin depth of the laser pulses (pump @800 nm; probe @400 nm). Two magneto-optical geometries have been used to measure either the polar or the longitudinal components of the magnetization. In the first case (polar) the static magnetic field has been applied at an angle θ_H = 15° (165°) with respect to the sample normal. The magnetization precession for all the excitation densities and the corresponding fitting curves are displayed in figure 1a. The dashed line is a guide for the eye showing the nonlinear phase change as a function of E_{abs}. We interpret the phase change as the competition between the temperature-dependent terms in the free energy of the system. We emphasize the importance of the time-dependent magneto-elastic energy due to the quasi-static surface strain that has been recently shown to govern the precession at all timescales [9].

Figure 1b shows the short delay dynamics (<1.5 ps) for the same excitation density as figure 1a. To ensure no influence of the long delays precession dynamics in the analysis of the demagnetization times, we compared the polar and longitudinal geometries. Figure 2a shows an example of the analysis procedure for E_{abs} = 0.97 mJcm^{-2} in longitudinal geometry with the magnetic field applied in the sample plane (θ_H = 90° (180°)) where no precession occurs. The analysis results for all densities of excitation are displayed in figure 2b, where a clear connection between the precession phase and the thermalization time of the spins. Note that for the maximum density of excitation used below the damage threshold, a demagnetization of 70% would correspond to a spin temperature of 600K.

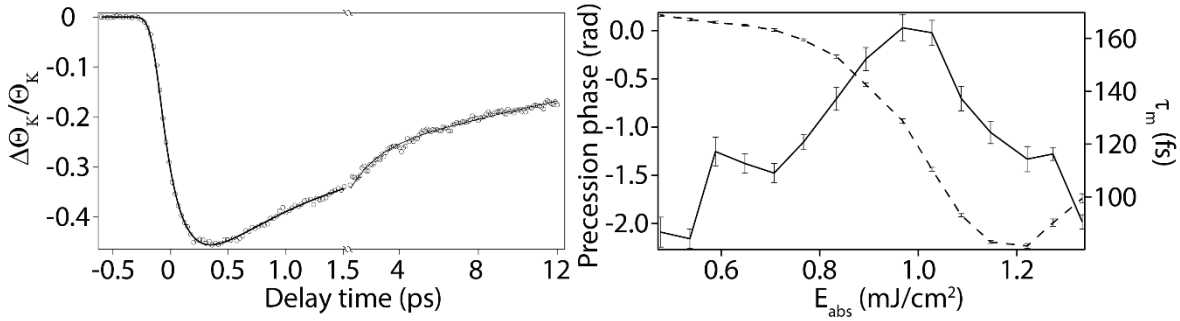


Figure 2: (a) Ultrafast demagnetization measurement in the longitudinal geometry for short (<1.5 ps) and medium (<12ps) time delays the long time exponential decay serves as a fixed input for the error function fit. (b) The retrieved precession phase (dashed line) and the thermalization time of the spins τ_m (full line) as a function of the absorbed energy density E_{abs}.

In conclusion, we will show that the thermalization time of the spins is related to the precession dynamics governed by the surface strain. The laser-induced surface strain is therefore a key parameter that has to be taken into account in any ultrafast laser-induced processes in metallic thin films.

References

[1] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, Phys. Rev. Lett. 76, 4250 (1996).
[2] G.P. Zhang and W. Hübner, Phys. Rev. Lett. 85, 3025-3028 (2000).
[3] B. Koopmans et al., Phys. Rev . Lett. 95, 267207 (2005)).
[4] C. Stamm et al., Nat. Mater. 6, 740–743 (2007).
[5] C. Boeglin et al., Nature 465, 458–461 (2010).
[6] M. Battiato, K. Carva and , P.M. Oppeneer, Phys. Rev. Lett. 105, 027203 (2010).
[7] C. Dornes et al., Nature 565, 209 (2019).
[8] S. R. Tauchert et al., Nature 602, 73 (2022).
[9] Y. Shin, M. Vomir, D.-H. Kim, P. C. Van, J.-R. Jeong, and J.-W. Kim, Commun. Phys. 5, 56 (2022).

PI-47: Spin dynamics in the vicinity of magnetization compensation point in non-collinear state of rare earth garnet

D.M. Krichevsky[1,2,3], N.A. Gusev[2,3], D.O. Ignatyeva[2,3,4], A.V. Prisyazhniuk[3], E.Y. Semuk[3], V.N. Berzhansky[3], A.K. Zvezdin[2,5], V.I. Belotelov[2,3,4]

[1]Moscow Institute of Physics and Technology (MIPT), 141700 Dolgoprudny, Russia
[2]Russian Quantum Center, 121353 Moscow, Russia
[3]Physics and Technology Institute, Vernadsky Crimean Federal University, 295007 Simferopol, Russia
[4]Photonic and Quantum Technologies School, Lomonosov Moscow State University, 119991 Moscow, Russia
[5]Prokhorov General Physics Institute of the Russian Academy of Sciences, 119991, Moscow, Russia

Ferrimagnets are unique among ordered magnetic materials as they combine properties of both ferromagnets and antiferromagnets. Being composed of several antiferromagnetically coupled magnetic ions these materials allow investigation antiferromagnetic ultrafast dynamics and spin transport which is nowadays intensively studied in antiferromagnets [1]. In contrast to metals and alloys, such as GdFeCo or CoGd, insulating oxides are almost losses at optical frequencies. It makes them perfect materials for essential applications such as all-optical non-thermal magnetic recording [2]. Magnetic properties of these materials are governed by sublattice magnetization and exchange interaction between sublattices. This leads to coexistence of angular momentum (T_A) and magnetization (T_M) temperature compensation point. At the T_M net magnetization vanishes due to the sublattices magnetization equality. Near this point a noncollinear magnetic phase can be achieved. Previously, experimental studies with rare earth ferrimagnetic garnets (REIG) were mainly concentrate on collinear phase [3]. An impact of noncollinear phase on spin dynamics in the vicinity of T_M in REIGs has not been investigated.

In these research, we investigated spin dynamics in a 2.2 μm film of $(Bi_1Gd_2)Fe(Al_{0.1}Ga_{0.4})0_{12}$ epitaxially grown on CMZ GGG (111) substrate with easy axis magnetic anisotropy. To determine TM, we measured magnetooptical hysteresis at temperatures ranging from 303 to 393 K. The sample was placed in in-plane magnetic field and normally incident linearly polarized 515 nm light was used do detect Faraday rotation induced by magnetization. We observed (fig.1a) hysteresis flip after crossing temperature of T_M=336 K. Furthermore, increasing the sample temperature resulted in a significant increase in coercivity near TM (fig.1b).

The optical pump-probe technique was used to investigate spin dynamics. 200 fs circularly polarized pulses with a wavelength of 787 nm were used to pump the system at a 10 deg angle of incidence. Pump induced magnetization dynamics was measured by a delayed 200 fs linearly polarized normally incident probe pulse with 515 nm wavelength. Magnetic field was applied in Voigt configuration. Figure 1c depicts a time-resolved Faraday rotation signal measured at various sample temperatures. There are two distinct types of oscillations at 303 K: low frequency and high frequency modes. The latter is thought to be a quasi-aniferromagnetic (quasi-AFM) mode, whereas the first is thought to be a quasi-ferromagnetic (quasi-FM) mode (quasi-FM). The frequencies of the modes were extracted from Fourier spectra of the oscillations and plotted as a function of the temperature (fig 1d). We found that the frequency of quasi-FM mode increases with the temperature, but the frequency of quasi-AFM mode decreases up to T_M. The behavior changes in the opposite direction after crossing TM. Notably, the frequency of quasi-FM mode reaches minimum at ~383 K. The observed frequencies' features in the vicinity of T_M is believed to be connected with noncollinear magnetic phase near this point.

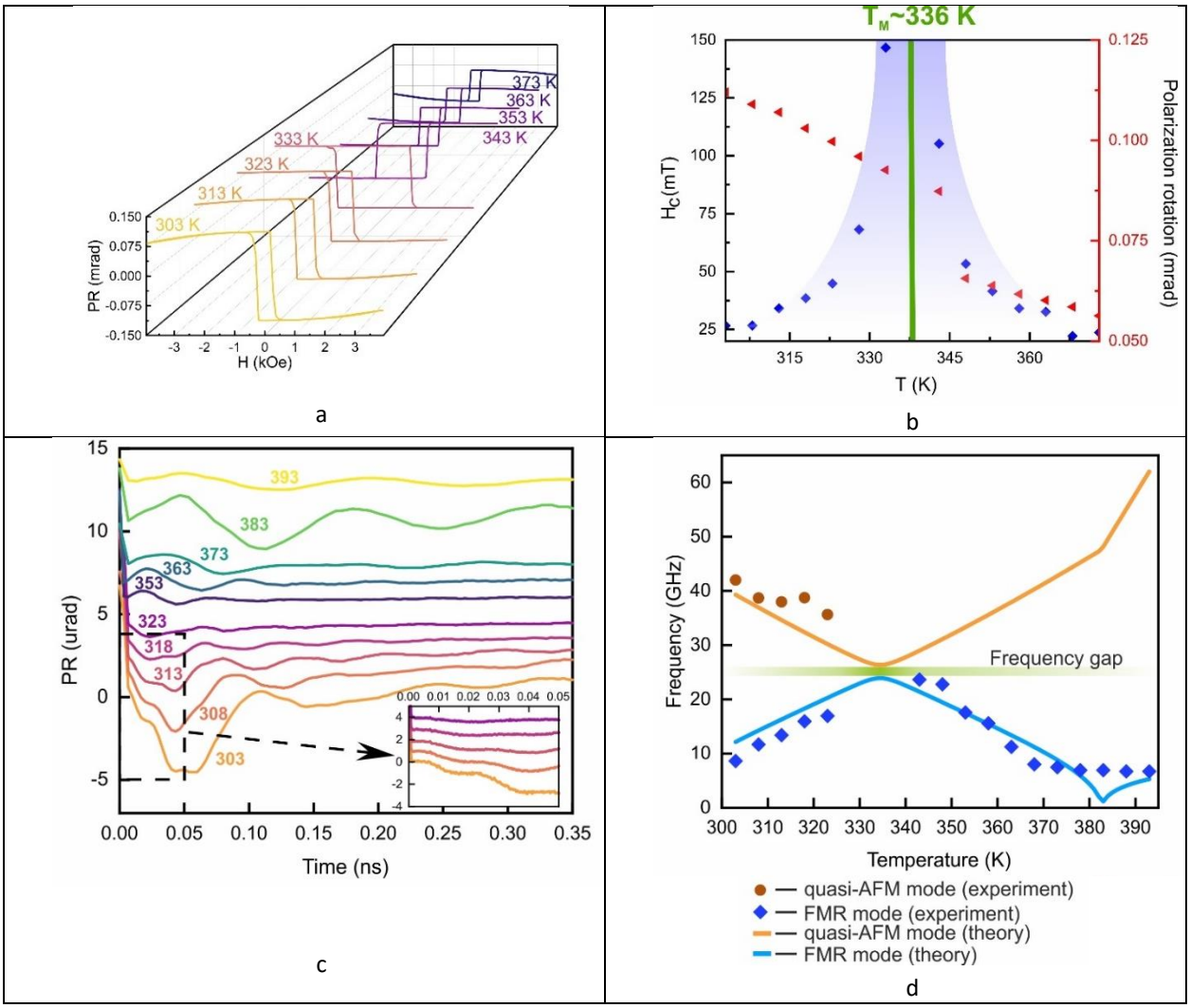


Figure 1: Magnetooptical hysteresis loops for different sample temperature (a); coercivity and Faraday rotation as a function of temperature (b); time-resolved magnetooptical signal (c); frequencies of the modes as a function of temperature (d)

References:
[1] Hortensius, J. R. et al. Coherent spin-wave transport in an antiferromagnet. Nature Physics 17, 1001–1006 (2021).
[2] Stupakiewicz, A., Szerenos, K., Afanasiev, D., Kirilyuk, A. & Kimel, A. V. Ultrafast nonthermal photo-magnetic recording in a transparent medium. Nature 542, 71–74 (2017).
[3] Deb, M., Molho, P., Barbara, B. & Bigot, J. Y. Temperature and magnetic field dependence of rare-earth↔iron exchange resonance mode in a magnetic oxide studied with femtosecond magneto-optical Kerr effect. Physical Review B 94, 1–5 (2016).

PI-48: Broadband terahertz spectroscopy of spin-Hall magnetoresistance

L. Nádvorník[1,2,3], P. Kubaščík[3], R. Schlitz[4,5], O. Gueckstock[1], D. Reiß[1], Kevin Geishendorf[4,8], Michaela Lammel [4,8] , M. Borchert[1,2,6], G. Jakob[7], M. Wolf[2], G. Woltersdorf[6], M. Kläui[7], P. W. Brouwer[1], S. T. B. Goennenwein[4,8] and
T. Kampfrath[1,2]

[1]Department of Physics, Freie Universität Berlin, 14195 Berlin, Germany
[2]Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, 14195 Berlin, Germany
[3]Faculty of Mathematics and Physics, Charles University, 121 16 Prague, Czech Republic
[4]Institut für Festkörper- und Materialphysik, Technische Universität Dresden, 01062 Dresden, Germany
[5] Department of Materials, ETH Zürich, 8093 Zürich, Switzerland
[6]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, 12489 Berlin, Germany
[7]Institut für Physik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[8]Department of Physics, University of Konstanz, 78457 Konstanz, Germany

In recent years, magnetoresistive phenomena which are even in the magnetic order parameter, such as anisotropic magnetoresistance (AMR), have attracted attention for their utility as efficient probes of antiferromagnetic materials. Unlike AMR, the spin-Hall magnetoresistance (SMR) is observed in bilayers of a heavy metal (HM) and a magnetically ordered layer and allows for probing of a complex interplay of various spintronic phenomena, for example spin accumulation, spin Hall effect, spin-orbit torque and spin mixing conductance [1]. Because the recently observed terahertz (THz) AMR [2] has yielded new insight into the ultrafast spin transport in ferromagnets, one can expect that the THz investigation of SMR is an efficient tool for studying the ultrafast regime of the above-mentioned phenomena. Conventionally SMR has been described in the framework of spin transport in insulating ferrimagnet|HM bilayers (e.g., YIG|Pt) in the DC regime [1].

In this work, we study DC and terahertz (0.2-2 THz) response of SMR in YIG|Pt heterostructures. By analyzing the spectral dependence and comparison to the DC responses, we identify specifics in the THz coupling of spin accumulation and magnetic moments. In particular, our results show that SMR in insulator|HM stacks has different amplitude in comparison to DC regime and we observe a significant suppression of the SMR contrast. These conclusions are corroborated by recent theoretical predictions [4]. Our findings are helpful to better identify the possible contributions to SMR and understand spin-orbit torques in the ultrafast regime.

References:

[1] H. Nakayama et al., Spin Hall Magnetoresistance Induced by a Nonequilibrium Proximity Effect. Phys. Rev. Lett. 110, 206601 (2013)
[2] L. Nádvorník et al., Broadband Terahertz Probes of Anisotropic Magnetoresistance Disentangle Extrinsic and Intrinsic Contributions. Phys. Rev. X 11, 021030 (2021)
[3] J. Kim et al., Spin Hall Magnetoresistance in Metallic Bilayers. Phys. Rev. Lett. 116, 097201(2016)
[4] D.A. Reiss et al., Theory of spin-Hall magnetoresistance in the ac terahertz regime Phys. Rev. B 104, 024415(2021)

PI-49: Surface plasmon polariton induced magnetic manipulation

Yann. Le Guen[1],S. Mangin[1],S. van Dijken[2],J. Hohlfeld[1],M. Hehn[1],M. Verges[1],N. Kuznetsov[2]
[1]SPIN, Département Physique de la Matière et des Matériaux, Institut Jean Lamour
[2]NanoSpin, Department of Applied Physics, Aalto University School of Science

All Optical Switching (AOS) has been an active research area in the past few years as it has a great number of possible applications. It has been shown that it is possible to reliably switch magnetisation with circular polarised femtosecond laser pulses [1]. This phenomenon, named All Optical Helicity Dependent Switching (AO-HDS), and its underling mechanism are not yet fully understood. Multiple origins for this effect have been proposed such as the Inverse Faraday Effect (IFE) [2] and magnetic circular dichroism (MCD) [3]. The IFE describe the emergence of a static magnetisation in magnetic materials when excited with a circular polarised light.

Plasmonic and plasmonic systems are of great interest as it has been shown that they can confine and enhance electromagnetic fields at the nano-metric scale [4]. Surface Plasmon Polaritons (SPP) can confine fields near the interface between a metal and a dialectic [5]. Furthermore, it can be shown that due its nature of propagating surface wave, SPP are intrinsically circularly polarised, and its direction of polarisation is locked perpendicular to its propagation direction [6].

Given their properties, SPP are prime candidates for efficient in plane magnetic manipulation and the study of the IFE. SPP induced magnetic precession enhancement have been demonstrated in Au/garnet plasmonic grating [7]. This promising result could lead to SPP induced magnetic manipulation and even SPP induced AOS.

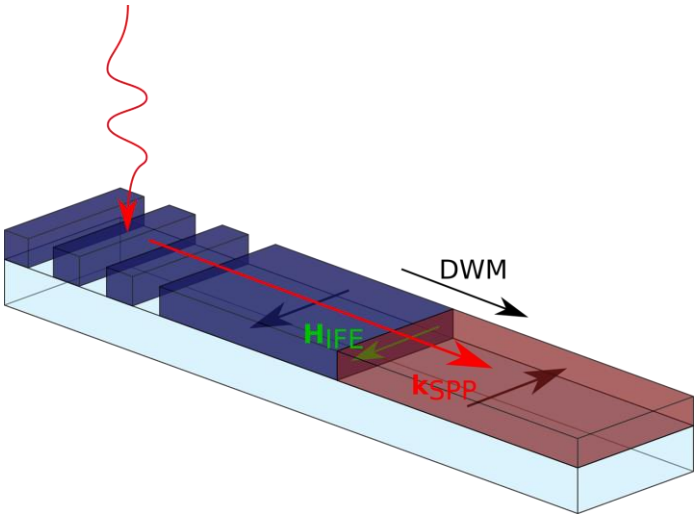


Figure 1: SSP induced magnetic domain wall motion

First some simulations were run to optically model SPP excitation and propagation using the Finite Element Method (FEM) with COMSOL. The impact of the different modes on field distribution, polarisation and therefore on this induced magnetisation has been analysed. This shows that this induced magnetisation

is mainly localised near the interface and confirm this polarisation locking. Gratings have also been optimised to couple incident light to different SPP modes. Mumax3 magnetic simulation will be realised to study the evolution of magnetisation under IFE induced excitation.

In this project, $Co_{40}Fe_{40}B_{20}$ thin film waveguide with grating are patterned onto fused quartz substrates and caped with SiO2. This enables the excitation of different SPP modes to study their impact on in plane magnetisation. This will be done through Time Resolved Magneto-optical Kerr Effect (TR-MOKE) measurements. The system will be pumped by a femtosecond laser with one or multiple laser pulses. In a second time, TR-MOKE imaging will also be conducted to see the impact of SPP propagation on magnetic domains wall motion.

Other material such as YIG/Au or doped-YIG/Au are also of interest since it would allow to have the good plasmonic response of Au coupled with the magnetic properties of YIG.

Overall, this study will provide a deeper understanding of the interaction between light, matter and magnetisation. This type of system could allow ultra-fast, densely packed, photonic computing and storage using SPP waveguide and optical-magnetic interactions.

References:

[1] C. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007)
[2] J. P. van der Ziel et al., Phys. Rev. Lett. 15, 190 (1965)
[3] A. R. Khorsand et al., Phys. Rev. Lett. 108, 127205 (2012)
[4] W. L. Barnes et al., Nature 424, 824–830 (2003)
[5] D. K. Gramotnev et al., Nature Photon 4, 83–91 (2010).
[6] Todd Van Mechelen et al., Optica Vol. 3, Issue 2, pp. 118-126 (2016)
[7] Alexander L. Chekhov et al., Nano Lett. 2018, 18, 5, 2970–2975 (2018)

POSTERS II

PII-1: Phonon-induced dynamics of the magnetic order in canted antiferromagnet $FeBO_3$

T. Janssen, M. Gidding, C. S. Davies and, A. Kirilyuk

FELIX laboratory, Radboud University, Toernooiveld 7, 6525 ED Nijmegen, the Netherlands

Ferromagnetic materials have formed the backbone of large scale digital storage since its development in the mid-50s. The sheer scale to which our current digital infrastructure has grown comes with one downside, the amount of electric energy that is consumed within is simply not sustainable. Using light to write bits is faster and much more energy efficient [1,2]. In addition to using light, more can be gained from switching to antiferromagnetic [3] storage media. Antiferromagnets (AFMs) benefit from exchange enhanced dynamics making them orders of magnitude faster [4], they produce no stray field, and are much more abundant in nature. However, their robustness to external stimuli also makes reading and writing domains extremely difficult [5].

Strain represents one of the most promising stimuli for manipulating the order parameter in AFMs on ultrafast timescales [6]. Resonances in general offer the most energy-efficient and fastest means to affect change in condensed-matter systems. Already, studies of non-linear phononics have revealed its capability to introduce complex structural transformations in materials [7], leading to striking phenomena such as the transient stimulation of insulator-to-metal phase-transitions in correlated oxides, the enhancement of superconducting properties, phonon-induced AFM-to-ferromagnet phase transition, and manipulation of the magnetic order in garnets [8].

Iron borate is a so-called canted antiferromagnet (or weak-ferromagnet (WFM)) making it an ideal material to study the consequences of strain. These WFMs occupy an unique place in the spectrum of magnetically ordered materials. The non-zero net magnetic moment allows for probing of the magnetization using light and magneto-optics. At the same time, WFMs benefit from the fast (exchange-driven) dynamics that is found in AFMs. This interesting combination leads, for example, to high propagation speed and non-linearity of domain wall dynamics [9].
Iron borate has a trigonal lattice, a Néel temperature close to room temperature of 348 K, and easy-plane type anisotropy. The strong magneto-elastic interaction in the linear coupling regime [10] will cause the magnetic anisotropy to be altered by strain.
We found that a domain pattern is created after resonantly pumping phonons using single ps-long pulses of infrared light. There are a variety of IR-active and Raman active phonons in the 6-45 micrometer region. The wavelength dependence of the effect leads us to believe that the formation of this pattern is caused by strain induced through aforementioned non-linear phononic mechanism. Tuning the pump laser wavelength to the 14.8 micrometer TO phonon yielded the largest response from the material. The figure below shows typical domain patterns created by the application of FELIX pulses in various applied magnetic fields.

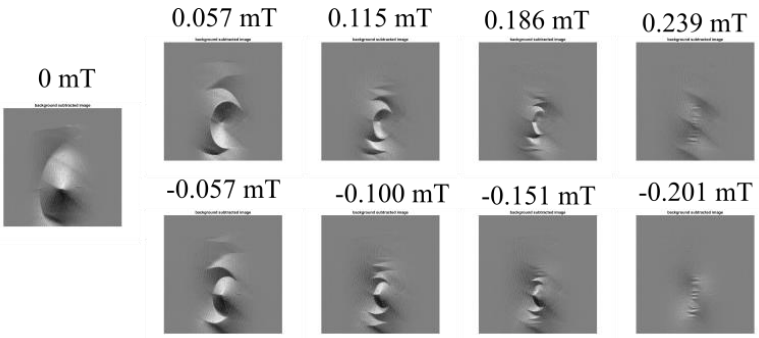


Figure 1: Domain pattern in iron borate at different strengths of the external magnetic field observed directly after the infrared pump pulse.

Further investigation of the phenomena in upcoming experiments and attempts to reproduce these domain patterns with micromagnetic simulations will hopefully further our understanding of this universal mechanism in manipulating magnetic order of antiferromagnets.

References

[1] T.A. Ostler, *et al., Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet,* Nature Communications **3**, 666 (2012)

[2] C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh, and Th. Rasing, *All-Optical Magnetic Recording with Circularly Polarized Light*, PRL **99**, 047601 (2007)

[3] P. Němec, M. Fiebig, T. Kampfrath, A.V. Kimel, *Antiferromagnetic opto-spintronics*, Nature Physics, **14**, 229-241 (2018)

[4] A.V. Kimel, A. Kirilyuk, A. Tsvetkov, R. V. Pisarev & Th. Rasing, *Laser-induced ultrafast spin reorientation in the antiferromagnet $TmFeO_3$*, Nature **429**, 850 (2004)

[5] S-W, Cheong, M. Fiebig, W. Wu, L. Chapon, V. Kiryukhin, *Seeing is believing: visualization of antiferromagnetic domains,* npj Quantum Materials **5**, 3 (2020)

[6] C. Song, Y. You, X. Chen, X. Zhou, Y. Wang, F. Pan, *Terahertz pulse-induced Néel vector switching in α-Fe2O3/Pt heterostructures*, Nanotechnology, 29, 112001, (2021)

[7] R. Mankowsky, M. Först, A. Cavalleri*, Non-equilibrium control of complex solids by nonlinear phononics,* Rep. Prog. Phys. **79**, 064503 (2016)

[8] A. Stupakiewicz, C. S. Davies, K. Szerenos, D. Afanasiev, K. S. Rabinovich, A. V. Boris, A. Caviglia, A. V. Kimel, A. Kirilyuk, Ultrafast Phononic Switching of Magnetization, Nature Physics, 17, 489-492, (2021).

[9] V.G. Bar'yaktar, B.A. Ivanov, M.V. Chetkin*, Dynamics of domain walls in weak ferromagnets*, Usp. Fiz. Nauk, **146**, 417-458, (1985).

[10] M.B. Strugatsky, K.M. Skibinsky, *Acoustic resonances in antiferromagnet $FeBO_3$*, Journal of magnetic materials, **309**, 64-70 ,(2007).

PII-2: Ultrafast magnetization precession in metallic heterostructures driven by different excitation mechanisms

J. Jarecki,[1] M. Mattern,[1] J.-E. Pudell,[2,3] M. Hehn,[4] M. Herzog,[1] A. von Reppert,[1] and M. Bargheer[1,3]
[1]Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany
[2]European X-Ray Free-Electron Laser Facility, Schenefeld, Germany
[3]Helmholtz-Zentrum Berlin für Materialien und Energie, Wilhelm-Conrad-Röntgen Campus, BESSY II, Albert-Einstein-Strasse 15, 12489 Berlin, Germany
[4]Institut Jean Lamour (UMR CNRS 7198), Université Lorraine, 54000 Nancy, France

We study the magnetization precession induced by different excitation mechanisms, i.e. ultrafast demagnetization, temperature dependent anisotropy change and magneto-elastic coupling, in 20 nm Ni films within metallic hetero-structures. For that we combine time-resolved x-ray diffraction (UXRD) and magneto-optical Kerr effect measurements (MOKE) to access the strain dynamics and therefore also the energy transfer within the sample and the out-of-plane component of the Ni magnetization.

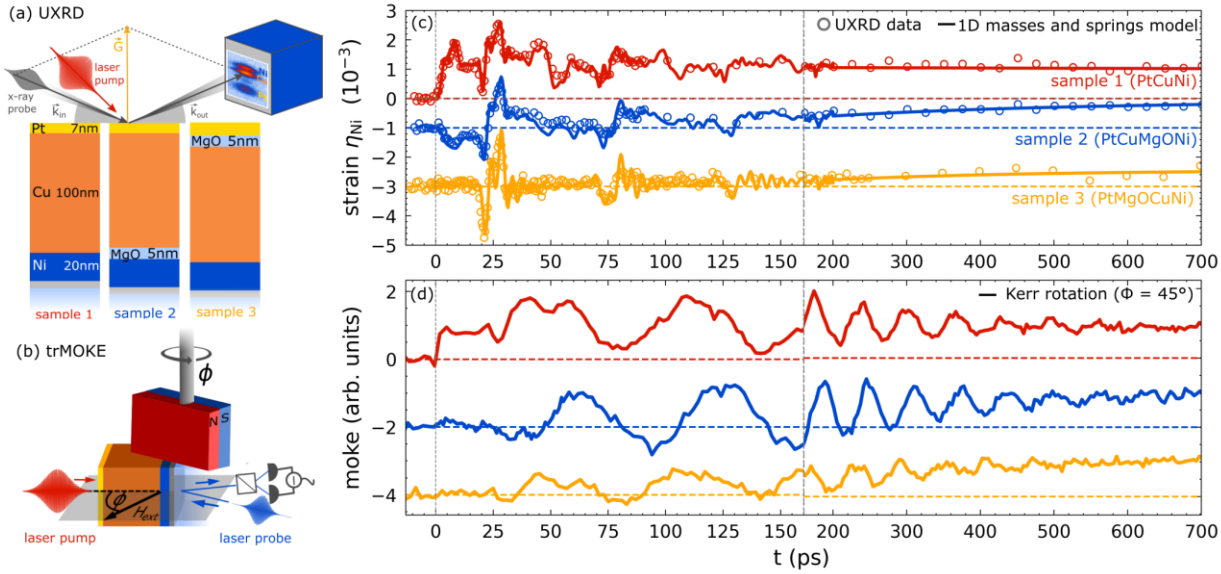


Figure 1: Combined UXRD and MOKE measurements: In a and b) schematics of the UXRD and MOKE setups are shown. We investigate three similar metallic heterostructures under equal excitation conditions. The corresponding data are shown in c), d).

We look at three similar PtCuNi-structures, where the Pt layer has a thickness of 5 nm to support hot electron and large strain generation, and the 100 nm Cu layer is thick enough to protect the 20 nm Ni film from any light irradiation. The samples are excited by an ultrashort laser pulse from the Pt side, and spin precession is detected by MOKE from the substrate side.
By inserting an insulating MgO layer at different positions within the sample, it is possible to separate heat and strain arriving in Ni and tailor the predominant excitation mechanism of the precession. The transient strain and heat are characterized by means of our UXRD measurements for each sample (see Fig. 1a, c). Characteristic signatures in the UXRD data confirm the main differences: Sample 1 shows strain in the Ni film immediately after excitation, because the hot electrons created in Pt rapidly heat and expand Ni by electron phonon coupling. In addition, the strain waves launched in Pt und Cu traverse the Ni film, in the same way as in sample 2. In sample 2, a thin MgO between Cu and

Ni prevents the rapid coupling of energy into Ni. Therefore, we only observe the strong and sharp bipolar strain wave originating from Pt and the weaker and longer bipolar wave originating from Cu. In sample 3, an MgO layer right after Pt prevents rapid energy distribution into Cu and Ni. Therefore, only the sharp bipolar strain wave originating from Pt is observed in the UXRD response of the Ni layer

The MOKE measurements are conducted in a polar MOKE geometry. We vary the effective field direction by applying the external magnetic field along several angles (see Fig 1b).

The MOKE results show clearly that the magnetization starts to precess within the first 25 ps (see Fig 1d).

In agreement with measurements on Ni films without heterostructure, we observe a distinct angle-dependence of the precession amplitude (see Fig. 2). The (the low amplitude pulse created in Cu) pronounced maxima at 45° for sample 2, 3 confirm that magneto-elastic coupling is most efficient when the magnetization is tilted out to this angle. Furthermore, resonant strain pulses induce a much stronger precession amplitude than very short perturbations (the strong acoustic pulse emitted from Pt). For sample 1 in contrast, we see two maxima in the data at 0 and 45° originating from a heat and strain induced precession, respectively, consistent with the heat-transport analysis guided by UXRD. From this analysis we estimate the relative efficiency of both mechanisms.

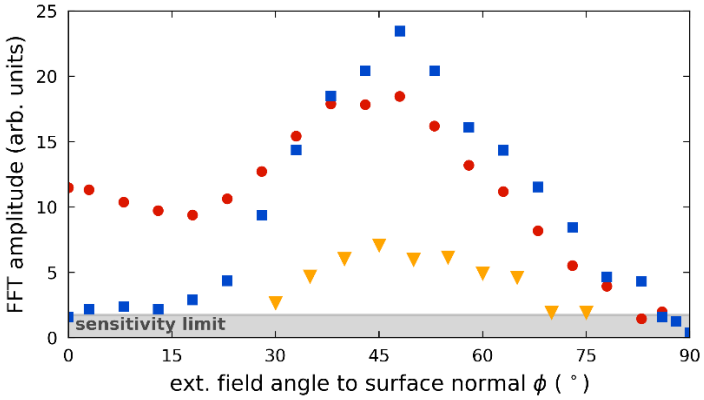


Figure 2: Analysis of the precession's amplitude depending on the external field angle.

PII-3: Magnetoelasticity-driven inversion of spin precession in Ni_xFe_{100-x} alloy films: competition between magnetoelastic and thermal energies

Yooleemi Shin[1], Seongsoo Yoon[2], Jung-Il Hong[2], and Ji-Wan Kim[1]
[1]Department of Physics, Kunsan National University, Kunsan 54150, South Korea
[2]Department of Emerging Materials Science, DGIST, Daegu 42988, South Korea

We find the clue that the spin precession induced by femtosecond laser pulses is driven by the magnetoelastic energy rather than magnetocrystalline and the demagnetizing energy, which have been considered to be main terms so far. With polycrystalline Ni_xFe_{100-x}(250nm) alloy films (x = 87.0 ~ 97.5) having the different magnetostrictions and the Curie temperatures, we measured the time-resolved differential magneto-optical Kerr rotation signals using 400nm pump and 800nm probe pulses.

As shown in Fig. 1(a), depending on the composition, we found that the phase inversion in spin precession is shown up and the spin precession dynamic becomes indefinite around x = 92.3. Fig. 1(b) shows that the phase (δ_0) is not constant, rather varies with the pump intensity from -90 deg to 0 deg for x = 95.3 implying the competition between the magnetoelastic and demagnetizing energy.

By solving Landau-Lifshitz-Gilbert equation considering both the magnetoelastic and demagnetizing effects, we found that for a low x, the demagnetizing effect is dominant due to the positive magnetostriction value and for a high x, the magnetoelastic effect becomes dominant leading to the phase inversion due to the negative magnetostriction value. Interestingly, it is also confirmed that for x = 92.3 where there shows no precession, the demagnetizing and magnetoelastic effects are in competition.

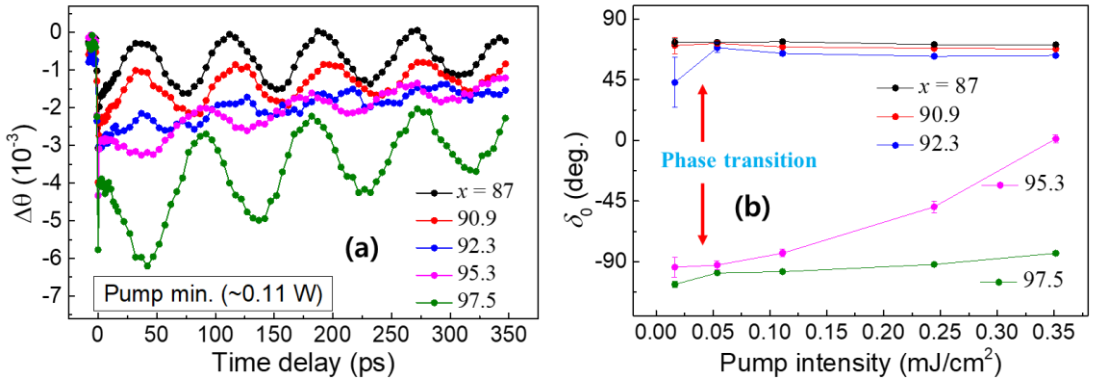


Figure 1. (a) Differential Kerr rotation signals and (b) the phase of spin precession (δ_0) of polycrystalline Ni_xFe_{100-x}(250nm) films.

PII-4: Origin of ultrafast lattice contraction in ferromagnets explored by Sagnac interferometer

Yooleemi Shin and Ji-Wan Kim
Department of Physics, Kunsan National University, Kunsan 54150, South Korea

It has been believed that the lattice dynamics induced by femtosecond laser pulses is much slower than the electron or the spin dynamics. Generally, in order to infer the ultrafast lattice dynamics, it is conventional to measure the transient reflectivity data and analyze with the three temperatures model. Recently, the ultrafast x-ray and electron diffraction instruments measure the lattice strain directly with a good temporal resolution and provide crucial information about the relation between the lattice and the spin.

The ultrafast x-ray diffraction (UXRD) measurements performed by Reppert et al. proved that the ultrafast lattice contraction instead of expansion in the FePt gragular film after photo-excitation was driven via lateral expansion of the lattice and magnetoelastic pressure due to demagnetization [1]. In addition, the ultrafast electron diffraction (UED) measurements conducted by Reid et al. demonstrated that the lattice oscillation dynamics was originated also from magnetoelastic pressure due to demagnetization [2].

To apply those results to typical ferromagnets (Ni, Fe, Co and their alloys), we recently developed the modified ultrafast Sagnac interferometer capable of the simultaneous detection of the lattice displacement, the magneto-optical Kerr effect, and reflectivity signals, which is essential in figuring out the relation between the spin and the lattice.

Figure 1 shows the lattice displacements (δz: blue) and transient Kerr rotations ($\Delta\theta$: red) for (a) MgO(3nm)/Ni(20nm), (b) MgO(3nm)/$Ni_{80}Fe_{20}$(20nm), (c) MgO(3nm)/$Ni_{60}Fe_{40}$(20nm), and (d) Al_2O_3(5nm)/Co(15nm). All samples were deposited on sapphire(0001) substrates. The wavelengths of the pump and probe are 400 and 800 nm, respectively. Here, we found that the lattice contraction ($\delta z < 0$) around 0 ps coincides with the demagnetization for all samples. As our samples are not nanograins but continuous films, the vertical contraction of the lattice (z-direction) due to the lateral expansion can be ignorable. In addition, if the magnetoelastic pressure by the demagnetization drives the lattice contraction, the displacive lattice oscillation with a delay of half-period would have been measured. However, this is not shown in our results. Rather, we propose that the lattice contraction may be originated from the nonthermal electrons. When the electrons are dumped from Fermi surface to higher energy levels by the pump pulses, the change in the instantaneous electron distribution function generates stress [3]. To prove this, the further experiments with the different pump wavelengths need to be explored.

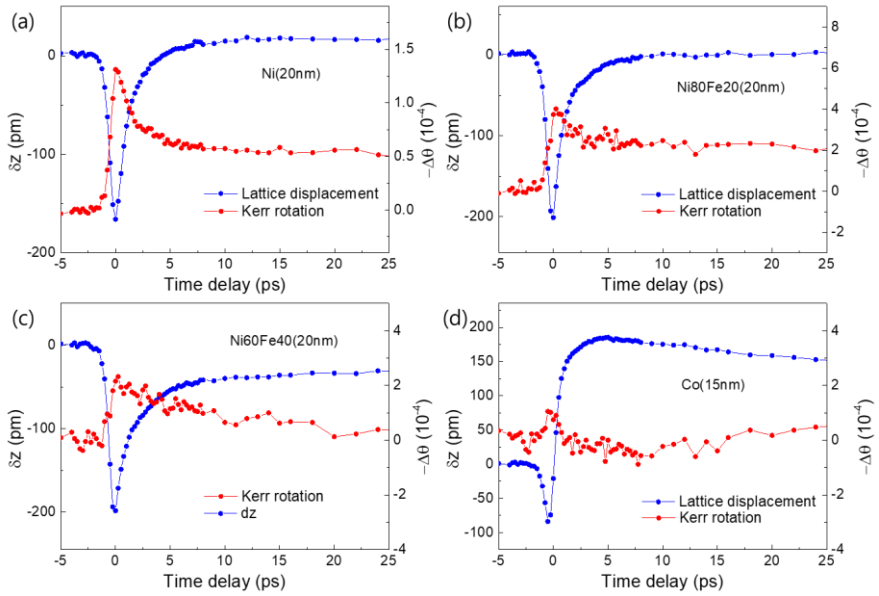


Figure 1: The lattice displacements (δz: blue) and transient Kerr rotations (Δθ: red) for (a) MgO(3nm)/Ni(20nm), (b) MgO(3nm)/$Ni_{80}Fe_{20}$(20nm), (c) MgO(3nm)/$Ni_{60}Fe_{40}$(20nm), and (d) Al_2O_3(5nm)/Co(15nm).

"references"

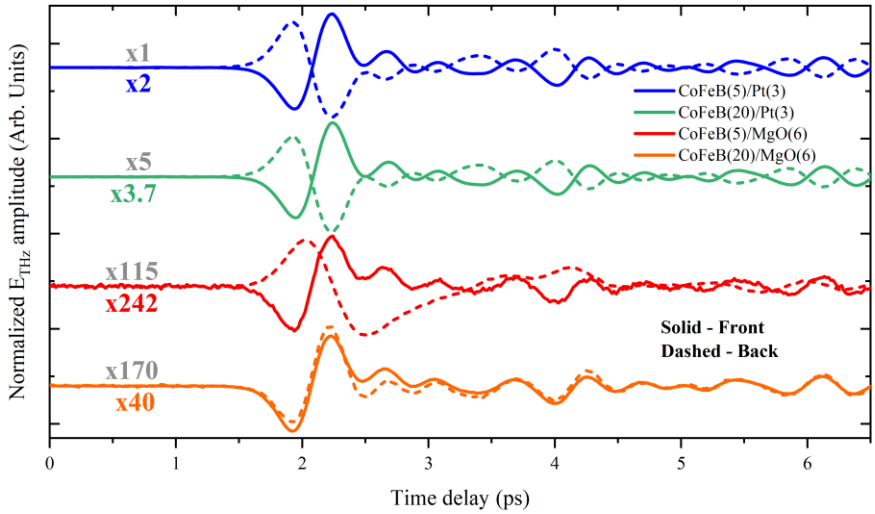
[1] A. von Reppert, L. Willig, J.-E. Pudell, S. P. Zeuschner, G. Sellge, F. Ganss, O. Hellwig, J. A. Arregi, V. Uhlíř, A. Crut, and M. Bargheer, Sci. Adv. 6, 1142 (2020).
[2] A. H. Reid et al., Nat. Commun. 9, 388 (2018).
[3] O. B. Wright, Phys. Rev. B 49, 9985 (1994).

PII-5: Inverse Rashba-Edelstein effect in CoFeB/MgO magnetic bilayers revealed with THz emission spectroscopy

A. Levchuk[1], V. Juvé[1], T. Otomalo[1], Anas El-Hamdi[2], G. Vaudel[1],
J.Y Chauleau[2], P. Ruello[1], M. Viret[1]
1. Institut des Molécules et Matériaux du Mans, UMR 6283 CNRS,
Le Mans Université, Avenue Olivier Messiaen, 72085 Le Mans, France
2. CEA Saclay, DRF/IRAMIS/SPEC, UMR 3680 CEA-CNRS,
F-91191 Gif-sur-Yvette, France

Spintronics is the thriving field of research to control the electron spin degree of freedom for potential applications in computing, storage and memory, and fundamental science. Spintronic devices are promising for lower power consumption, higher information density, and non-volatility compared to conventional electronics. However, to utilize the electron spin to its fullest potential, the question about efficient generation, detection, transport, and inter-conversion of the electron's intrinsic angular momentum has to be answered. Over the last three decades, the scientific community has mastered spin control in the static regime (DC) [1]. The breakthrough in transient and ultrafast spintronics can be attributed to the detection of the terahertz (THz) radiation emitted as a consequence of an ultrafast demagnetization [2] and ultrashort spin-current burst injection from a ferromagnet into a metallic layer [3]. In such a Ferromagnet/Metal heterostructure, the THz emission is mediated via the Inverse Spin-Hall effect (ISHE). Recently, it has been demonstrated that the time-varying charge current can be generated via spin injection at a Rashba-split interface [4-6] (IREE) or via hot-carrier gradient established in the magnetic heterostructures [7] (AHE).

Figure 10 : Normalized THz emission measured from the CoFeB(5nm)/Pt(3nm), CoFeB(20nm)/Pt(3nm), CoFeB(5nm)/MgO(6nm), and CoFeB (20 nm)/MgO(6nm) hybrid nanostructures. The solid lines show the signal obtained when the pump pulse impinges on the capping Pt/MgO layer and the dashed curves are measured when excited from the side of the substrate. If any, the change in the THz polarity between the two sample orientations (solid vs. dashed) is directly associated with a reversal of



the in-plane charge current related to a reversal of the relevant light-induced spin-polarized current.

In this work, we use 165 femtosecond, 805 nm laser pulses to generate the ultrafast spin-current bursts in 5 and 20 nm thick ferromagnet CoFeB. This net spin current can then be converted into a transient in-plane charge current within the ferromagnet itself (via AHE, for example), through the injection into the Rashba states established at the CoFeB/MgO interface [6] (IREE) or injection into the 3 nm thick Pt layer (ISHE) deposited onto the CoFeB. The ultrafast spin-to-charge conversion mediated by the Hall or Rashba conversion subsequently leads to a charge current burst and free-space emission of broadband THz electromagnetic radiation.

Employing THz-Time Domain spectroscopy, we have recorded the THz radiation emitted from a set of CoFeB/MgO and CoFeB/Pt bilayers due to the spin-to-charge conversion at the sub-picosecond timescale. Specifically, we address the symmetry of the spin-to-charge conversion inside the bulk of the ferromagnet and inside the heavy-metal Pt or at the CoFeB/MgO Rashba interface. For fixed experimental conditions, Figure 1 shows that the sample reversal and excitation from the capping Pt or MgO layers (solid lines) compared to the pumping from the substrate side (dashed lines) leads to the complete reversal of the direction of the injected spin-polarized current and reversal of the polarity of the emitted THz. On the other hand, the symmetric THz emission from CoFeB (20 nm)/MgO (6 nm) strongly suggests that the generation of the transient charge current and subsequent THz emission is driven by the spin-orbit coupling within the 20 nm thick CoFeB ferromagnetic film (i.e., bulk contribution such as AHE). Conducting a comparative analysis of experiments on CoFeB/Pt and CoFeB/MgO bilayers, we have identified that in the CoFeB (5 nm)/MgO (6 nm) bilayer, the THz emission is mainly driven by spin-injection and subsequent spin-to-charge conversion at the Rashba-split interface along with a significant contribution of bulk effects. This is associated to a strong decrease of the total emission intensity for the IREE system. We suggest that this is due to the spread in energy of the emitted spin carriers and their relative inefficiency to fill the “optimised” Rashba split electron band structure close to the Fermi level [6]. This latter effect has been addressed by changing the pump pulse photon energy. Doing so, we demonstrate the tuneability of the Inverse Rashba-Edelstein spintronic emitter, opening new perspectives for ultrafast spintronics [8].

References:

[1] I. Žutić, J. Fabian, and S. das Sarma, Spintronics: Fundamentals and Applications, Reviews of Modern Physics 76, 323 (2004).

[2] E. Beaurepaire, G. M. Turner, S. M. Harrel, M. C. Beard, J. Y. Bigot, and C. A. Schmuttenmaer, Coherent Terahertz Emission from Ferromagnetic Films Excited by Femtosecond Laser Pulses, Applied Physics Letters 84, 3465 (2004).

[3] T. Kampfrath, M. Battiato, P. Maldonado, G. Eilers, J. Nötzold, S. Mährlein, V. Zbarsky, F. Freimuth, Y. Mokrousov, S. Blügel, M. Wolf, I. Radu, P. M. Oppeneer, and M. Münzenberg, Terahertz Spin Current Pulses Controlled by Magnetic Heterostructures, Nature Nanotechnology 8, 256 (2013).

[4] T. J. Huisman, R. v. Mikhaylovskiy, J. D. Costa, F. Freimuth, E. Paz, J. Ventura, P. P. Freitas, S. Blügel, Y. Mokrousov, T. Rasing, and A. v. Kimel, Femtosecond Control of Electric Currents in Metallic Ferromagnetic Heterostructures, Nature Nanotechnology 11, 455 (2016).
[5] M. B. Jungfleisch, Q. Zhang, W. Zhang, J. E. Pearson, R. D. Schaller, H. Wen, and A. Hoffmann, Control of Terahertz Emission by Ultrafast Spin-Charge Current Conversion at Rashba Interfaces, Physical Review Letters 120, 207207 (2018).
[6] O. Rousseau, C. Gorini, F. Ibrahim, J-Y. Chauleau, A. Solignac, A. Hallal, S. Tölle, M. Chshiev, M. Viret. Spin-charge conversion in ferromagnetic Rashba states. Phys. Rev. B 104, 134438 (2021).
[7] Q. Zhang, Z. Luo, H. Li, Y. Yang, X. Zhang, and Y. Wu, Terahertz Emission from Anomalous Hall Effect in a Single-Layer Ferromagnet, Physical Review Applied 12, 1 (2019).
[8] A. Levchuk, A. El Hamdi, V. Juvé, T. Otomalo, T. Chirac, O Rousseau, A. Solignac, G Vaudel, P. Ruello, M. Viret, under review

PII-6: All-Optical Switchable Racetrack based on Compensated Co/Gd quadlayers

Pingzhi Li*, Thomas J. Kools, Reinoud Lavrijsen, Bert Koopmans
Eindhoven University of Technology, 5612 AZ

Co/Gd based synthetic ferrimagnets have received considerable attention owing to the coexistence of both ultrafast all-optical switching (AOS) [1-2] and current driven domain wall motion (CIDWM) [3-4], allowing for novel, hybrid devices connecting spintronics with integrated photonics. So far, the velocity of CIDWM of Co/Gd is low due to large net magnetic moment.

Here, we experimentally demonstrate a fully layered based synthetic ferrimagnet Co/Gd(x)/Co/Gd quadlayer systems which shows simultaneously fast CIDWM and AOS. We first show the magnetic moment can be compensated at room temperature conditions(see inset of Fig. 1), where single pulse AOS is found to be present in the full range of Gd thickness[5]. The compensation can be seen by the reverse of Kerr contrast and divergence of the coercivity at the compensation thickness. From the wedge of the same batch, we carried out current induced domain wall velocity measurement and plotted the results in Fig. 1 (b). It can be observed that the domain wall velocity spikes at the thickness close angular momentum compensation. As the current density is increased the optimum in the velocity is found to shift towards larger Gd thicknesses, we attribute this to the difference in temperature dependence of the magnetization in Co and Gd leading to a shift in the compensation thickness due to joule heating. We further conducted numerical and theoretical modelling of the domain wall motion considering the Joule heating effect, a reasonable agreement with experiment was found [5].

Our study shows a significant improvement of the room temperature domain wall velocity in synthetic ferrimagnetic systems through stack engineering paving ways for hybrid integration of racetrack memory and AOS (with integrated photonics).

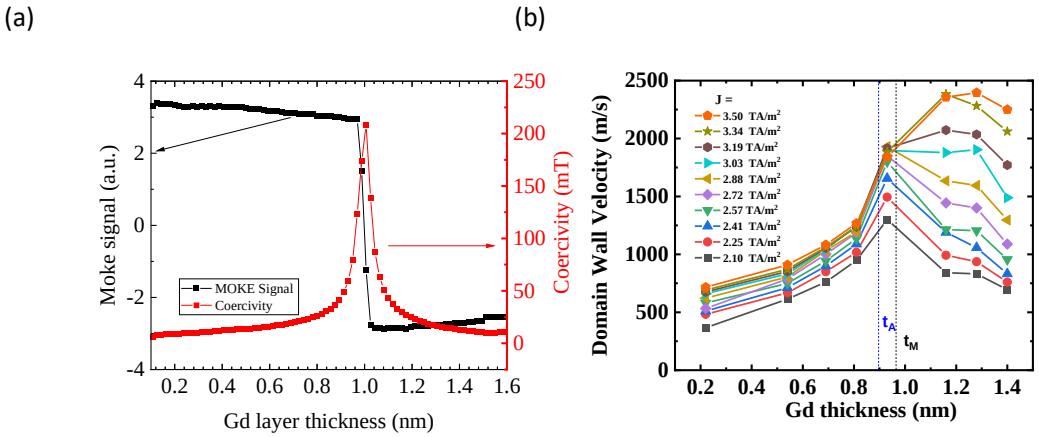


Fig. 1: Coercivity, polar MOKE signal (a) and current-driven domain wall velocity (b) as a function of Gd thickness in a Si/SiO_2(100)//Ta(4)/Pt(4)/Co(0.6)/Gd(x)/Co(0.7)/Gd(1.5)/TaN(4) multilayer system, where the numbers between brackets denote layer thicknesses in nm, and the x indicates the wedged layer given on the x-axis. The dashed vertical line in (b) indicates the Gd thickness where angular momentum compensation is achieved (see(a)).

[1] Lalieu, M.L.M., *et al*. *Physical Review B* 96.22 (2017): 220411.
[2] van Hees, Youri LW, *et al*. *Nature communications* 11.1 (2020): 1-7.
[3] Caretta, L. *et al*. *Nature Nanotechnology* 13.12(2018): 1748-3395
[4] Blaesing, R. *et al*. *Nature Communications* 9.1(2018): 2041-1732
[5] Li *et al*. *In Progress* (2021).

PII-7: Space-time dynamics of topological magnetic fluctuation states

R. Liefferink[1], K. Gerlinger[2], B. Pfau[2] and J.H. Mentink[1]
[1]*Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands*
[2]*Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, 12489 Berlin, Germany*

Magnetic skyrmions are 2-dimensional swirling patterns of magnetization. The skyrmion stability combined with their nanometer range size, makes them very interesting for applications, such as data storage and processing technologies based on racetrack memory [1]. Therefore, investigating the ultimate limits for fastest possible nucleation is both of fundamental interest and practical relevance. Recently, optical skyrmion nucleation with femtosecond laser pulses has been demonstrated in ferromagnetic multilayers [2,3,4], while X-ray studies [4] revealed that the switching was completed in less than 300ps, which is significantly faster than the characteristic timescale of skyrmions dynamics. Interestingly, atomistic spin dynamics simulations suggested that the nucleation mechanism stems from a transient topological fluctuation state in which the topological energy barrier is significantly reduced. Further understanding of the topological fluctuations state may therefore disclose the fastest possible skyrmion nucleation.

To gain insight into topological magnetic fluctuations, we present extensive atomistic spin dynamics simulations of a two-dimensional chiral ferromagnet. We focus on the region of the phase diagram in between the ferromagnetic phase and paramagnetic phase, where Monte Carlo simulations disclosed an intermediate phase with a fluctuating number of skyrmions [5]. The spin dynamics in space and time reveals that these fluctuations can be understood as a competition between skyrmion nucleation and decay, with characteristic time scales given by τ_N and τ_D respectively, both of which are dependent on temperature and magnetic field. We develop a simple rate-equation model using fits of simulated relaxation at fixed temperature and field, which yields an intuitive picture of nonequilibrium topological fluctuation states featuring excellent qualitative agreement with the much more advanced atomistic spin dynamics simulations. Specifically, we are able to explain the nucleation of skyrmions by an ultrashort heat pulse, as well as the magnetic field-dependence of this process. Interestingly, next to heat-induced skyrmion nucleation, the model predicts ultrafast skyrmion erasure with short magnetic field pulses. This suggest great potential for skyrmion write-erase cycles at THz rates and constitutes an important step towards ultimately fast ferromagnetic switching.

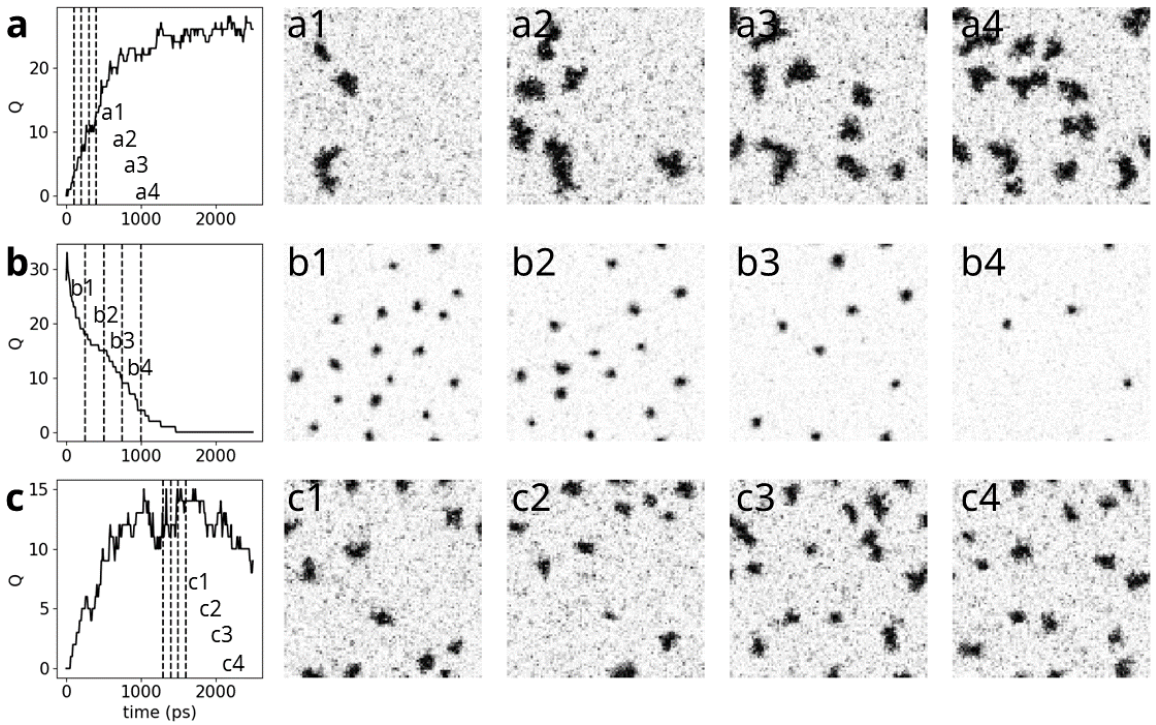


*Figure: Time evolution of the topological charge Q (number of skyrmions) and selected snapshots of the out-of-plane magnetization at different constant temperatures and fields in the atomistic simulations. The timestamps of the snapshots are shown as dashed vertical lines and encoded 1-4. Row (**a**) corresponds to a regime with spontaneous formation of skyrmions. The starting configuration was the ferromagnetic state. Row (**b**) shows a regime where skyrmions spontaneously decay, starting from completely randomly aligned spins. Row (**c**) represents the regime featuring both nucleation and decay, with an initial ferromagnetic state.*

References

[1] Fert, A., Reyren, N. & Cros, V. Magnetic skyrmions: advances in physics and potential applications. Nature Reviews Materials **2** (June 2017).

[2] Berruto, G. *et al.* Laser-induced skyrmion writing and erasing in an ultrafast cryo-Lorentz transmission electron microscope. Phys. Rev. Lett. **120**, 117201 (2018).

[3] Je, S.-G. *et al*. Creation of magnetic skyrmion bubble lattices by ultrafast laser in ultrathin films. Nano Lett. **18**, 7362–7371 (2018).

[4] Büttner, F. *et al*. Observation of fluctuation-mediated picosecond nucleation of a topological phase. Nature Materials **20**, 30–37 (Oct. 2020).

[5] Böttcher, M. *et al*. B-T phase diagram of Pd/Fe/Ir(111) computed with parallel tempering Monte Carlo. New Journal of Physics **20**, 103014 (Oct. 2018).

PII-8: Spin-transport-driven ultrafast magnetization dynamics in a ferrimagnetic Gd/Fe bilayer

Bo Liu[1], Huijuan Xiao[1], Martin Weinelt[1]

[1] Fachbereich Physik, Freie Universität Berlin

Laser-induced spin transport has been proven to be a key ingredient in ultrafast spin dynamics, such as femtosecond demagnetization and all-optical switching (AOS). However, it is still debated to what extent ultrafast demagnetization generates spin currents or vice versa. We use time- and spin-resolved photoemission spectroscopy of the gadolinium surface state to study spin dynamics in a ferrimagnetic Gd/Fe bilayer. This prototype system for AOS was epitaxially grown on W(110). The magnetization M of the Gd and Fe film are in-plane and antiparallel aligned. First, we studied the temperature dependence of M_{Gd} via the spin polarization of the Gd surface state. The compensation temperature T_{CP}, where $M_{Gd} = -M_{Fe}$, depends on layer thicknesses. For a Gd(5 nm)/Fe(3 nm) bilayer, we observe reversal of the spin polarization of the Gd surface state at $T_{CP} \sim 230$ K. For Gd(2 nm)/Fe(3 nm) the compensation temperature is about 130 K. At higher temperature M_{Fe} aligns always parallel to the external field. For this case we have studied the ultrafast spin dynamics in a pump-probe experiment. Our findings suggest that spin transport between the antiferromagnetically coupled gadolinium and iron layers leads to an ultrafast drop of the spin polarization and an increased exchange splitting at the Gd surface. In the Gd/Fe bilayer, we find that after optical excitation the Gd surface state shows an ultrafast decrease of the spin polarization by 20 % within the first ~100 fs and a subsequent slower decrease by about 5% on the picosecond timescale. The increase of the exchange splitting counteracts the overall demagnetization of the Gd layer. In contrast, the pure Gd/W(110) film shows a constant spin polarization and a reduced exchange splitting of the surface state upon optical excitation [1]. This helps to exclude significant contributions of local spin-flips to spin-polarization dynamics. Therefore, any variation of spin polarization in the Gd/Fe bilayer must be attributed to spin transport. This is corroborated by the transient electron temperature that decays within 1 ps to the initial temperature before optically excited electrons can heat the lattice. In pure Gd/W(110) ultrafast spin transport is ignored and at a pump-probe delay of 1.5 ps an elevated electron temperature of about 380 K is reached via electron-phonon coupling. Our results provide clear evidence that magnetization dynamics in the Gd/Fe bilayer is mainly driven by spin transport. We see distinct signatures in the spin-dependent electronic structure that allow us to gain microscopic insights into ultrafast spin dynamics in response to spin transport. These findings are of general importance for the understanding of magnetization switching in ferrimagnetic Gd-Fe compounds.

References:

[1] Andres, B. et al. Separating Exchange Splitting from Spin Mixing in Gadolinium by Femtosecond Laser Excitation. Phys. Rev. Lett. 115, 207404–5 (2015).

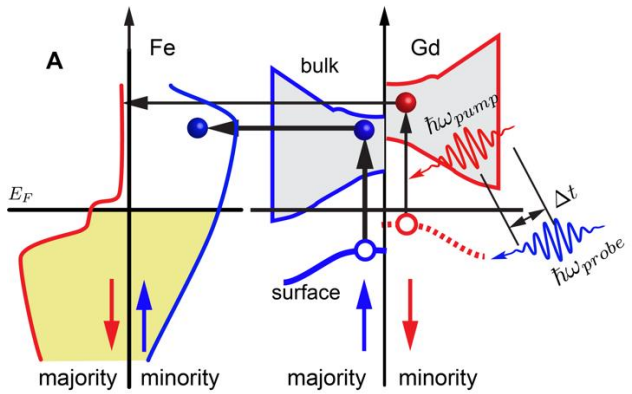


Figure 1: Schematic spin-resolved density of states of Fe and Gd. Due to the opposite in-plane magnetization of the Fe and Gd layers majority spin electrons in Gd (blue) become minority spin electrons in Fe and vice versa for spin minority electrons (red). The IR pump pulse excites electrons from the Gd surface state into Gd bulk states. While spin-majority electrons are transported into the Fe layer as indicated by the thick arrow, the transfer of spin-minority electrons is minor (thin arrow). The spin-dependent density of states of Fe acts as a spin filter. This leads to an ultrafast drop of the Gd spin polarization probed at the Gd surface.

PII-9: Magnonic computing with GHz frequency layered antiferromagnets

S. Lord and J. F. Gregg
Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom

Magnonic computing is a novel computing paradigm that exploits the unusual behaviour of magnons to develop faster, more efficient devices. These devices have the potential to rival existing CMOS technologies and provide a viable solution to the significant challenges facing conventional computing hardware. Antiferromagnetic materials are a prime candidate for such applications, since their typical THz resonant frequencies, and two degenerate modes of polarisation promise to create computing devices with faster processing times and greater flexibility. However, studying the THz frequencies of these materials, using conventional electronic methods, is challenging. Layered antiferromagnetic materials offer a promising solution to this challenge, since the weak interlayer coupling results in resonant frequencies that exist in the easily accessible microwave range. Furthermore, these materials can be artificially created by coupling two ferromagnetic layers via a non-magnetic spacer layer to create a synthetic antiferromagnet. Synthetic antiferromagnets are particularly interesting since their magnetic properties can be easily tuned, by changing the ferromagnetic material or the interlayer thickness, and hence a wide range of magnetic behaviour can be explored. In this contribution, we report on the experimental setup designed to explore the magnetic properties of such materials.

PII-10: Ultrafast switching of ferroelectric polarization by infrared laser pulses

D.G. Lourens, M. Kwaaitaal, C.S. Davies, and A. Kirilyuk

FELIX Laboratory, Radboud University, Toernooiveld 7, 6525 ED Nijmegen, The Netherlands

In the field of ferroics, magnetic materials have received a lot of attention for the possibility of all-optical switching of the magnetization direction. Several mechanisms that allow such switching have been discovered at present [1,2,3]. In addition, a heated interest is also directed on multiferroics, the materials where different order parameters coexist and can affect each other. The most studied example is the combination of magnetism and ferroelectricity [4]. However, all-optical switching of ferroelectric order is by far less understood, the only existing example showing a partially reversed state with a very short life-time triggered by the excitation of optical phonons [5]. The latter mechanism in fact, was nevertheless shown rather effective in switching of magnetic domains in thin films of iron garnets [6]. We therefore attempt to apply the same approach to the ferroelectric perovskite barium titanate ($BaTiO_3$).

We used infrared laser pulses from the FELIX free electron laser in the wavelength range of 8 to 35 μm to excite single-domain crystals of $BaTiO_3$. Strikingly, we have discovered that at certain conditions, such excitation can lead to the appearance of switched domains (Figure 1). These domains were observed both via optical birefringence (in the case of 90° domains) and using optical second harmonic generation (for 180° domains). The lifetime of such switched domains depends on their size and ranges from hundreds of microseconds to infinity. Interestingly, a subsequent excitation of these permanent domains with another laser pulse from FELIX can also lead to their erasure. The area that was switched is strongly dependent on the wavelength of the laser pulses, and was the largest in the vicinity of the longitudinal optical phonon modes of the crystal. The latter suggests that a strain-generating mechanism similar to that of magnetic garnets [6] is responsible for the observed switching.

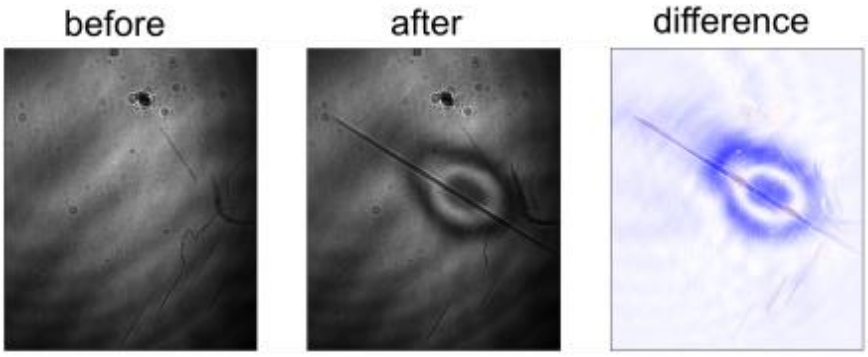


Figure 1: Birefringence images before (left) and shortly after (middle) excitation with a FELIX pulse. The difference in intensity of these images is shown in the right image. The diagonal line shows a switched domain whose polarization is 90 degrees rotated with respect to the rest of the crystal. The dark- and white rings are explained by a thermal effect.

Our results thus show the possibility for the well-controlled all-optical switching of electric polarization in ferroelectrics, which indicates the possibilities for the manipulation of ferroelectrics on truly ultrafast time scale. As an outlook, it would be really intriguing to study a similar switching in multiferroics, to observe the simultaneous behaviour of two different order parameters.

References

[1] T.A. Ostler, et al. *Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet*, Nature Commun. **3**, 66 (2012).

[2] C.-H. Lambert, et al., *All-optical control of ferromagnetic thin films and nanostructures*, Science **345**, 1337 (2014).

[3] A. Stupakiewicz, K. Szerenos, D. Afanasiev, A. Kirilyuk, A. V. Kimel, *Ultrafast nonthermal photo-magnetic recording in a transparent medium*, Nature **542**, 71 (2017).

[4] M. Fiebig, Th. Lottermoser, D. Meier and M. Trassin, *The evolution of multiferroics*, Nature Rev. Mater. **1**, 16046 (2016)

[5] R. Mankowsky, A. von Hoegen, M. Först, and A. Cavalleri, *Ultrafast Reversal of the Ferroelectric Polarization*, Phys. Rev. Lett. **118**, 197601 (2017)

[6] A. Stupakiewicz, C. S. Davies, K. Szerenos, D. Afanasiev, K. S. Rabinovich, A. V. Boris, A. Caviglia, A. V. Kimel, A. Kirilyuk, *Ultrafast phononic switching of magnetization*. Nature Phys. **17**, 489-492 (2021)

PII-11: Spin transport-induced damping of THz transverse spin dynamics in iron

L. Brandt[1], R. Verba[2], N. Liebing[1], M. Ribow[1], I. Razdolski[3], V. Tyberkevych[4], A. Slavin[4], Kh. Zakeri[5], G. Woltersdorf[1], and A. Melnikov[1]

[1]Martin Luther University Halle-Wittenberg, Institute of Physics, Optics Group, Von-Danckelmann-Platz 3, 06120 Halle, Germany
[2]Institute of Magnetism, Kyiv 03142, Ukraine
[3]Faculty of Physics, University of Bialystok, 15-245 Bialystok, Poland
[4]Department of Physics, Oakland University, Rochester, MI 48309, USA
[5]Heisenberg Spin-dynamics Group, Physikalisches, Karlsruhe Institute of Technology, Wolfgang-Gaede-Str. 1, D-76131, Karlsruhe, Germany

Understanding dissipation mechanisms is an important problem of dynamical systems. Ferromagnetic materials exhibit a wide variety of dissipation processes contributing to the total decay rate Γ of spin waves (SW) depending on the material, static magnetization state, geometry, etc. Here we analyze the SW damping in single crystalline Fe and demonstrate that at sufficiently large wave vectors *k* the damping is dominated by transverse spin transport effects scaling with 4th power of the wave vector. Although this contribution is known to originate in the spin diffusion, we argue that at moderate and large *k* a more general description is necessary and develop a model where the 'transverse spin mean free path', λ_s is the key parameter which we estimate to be ~0.5 nm.

In the first place, we study the damping of perpendicular standing SWs (PSSWs) in ultrathin Fe films following the experimental approach presented in Ref. [1]. The PSSWs are excited by optically generated ultrashort spin current pulses, and probed optically in the time domain using the magneto-optical Kerr effect (MOKE). We use Fe/Au/Fe(001) multilayers grown on MgO(001) with high epitaxial quality. The sample consists of 4.4 nm-thick Fe emitter, 70 nm-thick Au spacer, and Fe collector grown as a wedge with the thickness d_{Fe} ranging from 1 to 17 nm (Fig. 1c). MOKE traces are measured with 20 fs time resolution and fit with a sum of exponentially damped cosine functions [2]. Thus a set of frequencies f_n and lifetimes $\tau_n = \Gamma_n^{-1}$ is obtained. In addition to the homogeneous precession (FMR mode, *n*=0), we resolve up to 5 PSSW modes at frequencies of up to 2.4 THz (Fig. 1a). Here we analyze the effective damping $\alpha_{eff,n} = \Gamma_n/\omega_n\epsilon_n = (2\pi\tau_n f_n \epsilon_n)^{-1}$ (Fig. 1b), where the ellipticity-related coefficient $\epsilon_n \approx 1$ for $f_n \gtrsim 100$ GHz. Dashed curves in Fig. 1b represent the fit employing the following phenomenological non-local damping model:

$$\alpha_{eff,n} = \alpha_G + \frac{\Gamma_{nu}}{\omega_n\epsilon_n} + \frac{c_n \mathrm{G}_{nu}}{\omega_n\epsilon_n d_{Fe}} + \alpha_{sp} + \alpha_{st}; \qquad \alpha_{sp} = \eta_s \frac{c_n}{d_{Fe}}, \qquad \alpha_{st} = \eta_\perp k_n^2, \qquad (1)$$

where $c_0 = 1$, $c_n = 2$ for $n \geq 1$. The intrinsic Gilbert damping $\alpha_G = (2.0 \pm 0.7) \cdot 10^{-3}$ matches the recent results [3]. Next two terms describe the non-uniform resonance line broadening due to volume and interface defects, respectively. We obtain $\Gamma_{nu} \approx 0$ and $\mathrm{G}_{nu} \approx 0$ for $n \geq 1$ while $\mathrm{G}_{0u} = (6.0 \pm 0.7) \cdot 10^{-3}$ nm ps^{-1}, so that the interface magnon scattering dominates the damping of FMR mode at small d_{Fe}. The spin pumping term $\alpha_{sp} \propto k_n = n\pi/d_{Fe}$ is less than 5% of the total damping, which is within the noise. Therefore, we fix $\eta_s = 3 \cdot 10^{-3}$ nm [4]. Thus, we unambigously demonstrate the dominant role of α_{st} arising from the transport of transverse spin component along the SW *k*-vector and determine $\eta_\perp = (38 \pm 3) \cdot 10^{-3}$ nm^2 in Eq. (1).

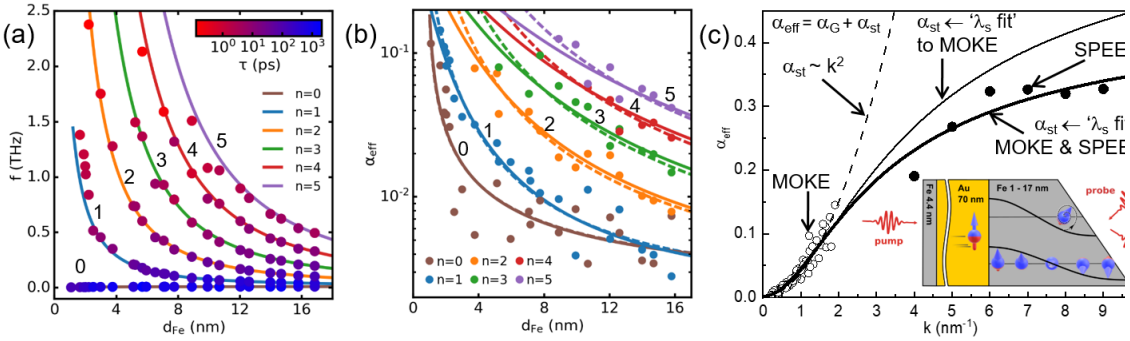


Figure 1: (a) FMR (*n*=0) and PSSW (*n*=1-5) frequencies (y-axis) and lifetimes (color-code) obtained by fits to the time-resolved MOKE traces. Solid lines are the fit with Kittel formula [2]. (b) Effective damping α_{eff} as a function of the Fe thickness; points are the experimental data, dashed and solid lines represent the fit with Eq. (1) and 'λ_s model' (see text), respectively. (c) α_{eff} as a function of the wave vector *k* of PSSWs measured by MOKE (open circles, all modes) and SWs measured by SPEELS (filled circles); lines represent fit results with different leading spin transport contribution α_{st}, as indicated (see text). The inset illustrates the back-pump front-probe approach for the studies of PSSWs.

Fig. 1c shows $\alpha_{eff}(k)$ for $n \geq 1$ with open circles and $\alpha_G + \alpha_{st}$ with the dashed curve. An extrapolation results in $\alpha_{eff} \approx 4$ at $k = 10$ nm^{-1}. We complement this data set with the effective SW damping in 10 ML Fe(001) film grown on Ir(001), measured with spin-polarized electron energy loss spectroscopy (SPEELS) and shown by filled circles (cf. Ref. [5] for the technique). At large *k*, Eq. (1) overestimates α_{eff} by one order of magnitude. The saturation of $\alpha_{eff}(k)$ at $k_s \gtrsim 6$ nm^{-1} hints at a characteristic length scale $\lambda_s = 2\pi/k_s \lesssim 1$ nm, much smaller than the typical spin diffusion length λ_{sd}^{Fe}=7 nm [6]. As such, spin transport needs to be analyzed beyond the diffusion model resulting in a non-local dissipative term $-\eta_\perp \boldsymbol{m} \times \nabla^2 \partial \boldsymbol{m}/\partial t$. Keeping the time-dependent part, we revise the spatial non-locality description considering the transverse spin transport in itinerant ferromagnets based on the *s-d* exchange interaction. We assume that *s*-electrons move ballistically with an isotropic velocity distribution and drag the transverse component of spin momentum along their trajectory. This component is transferred from precessing localized *d*-moments to neighboring *d*-moments. The spatial decay of transferred spin density is characterized by the 'transverse spin mean free path' λ_s. This approach results in $\alpha_{st} = \frac{3\eta_\perp}{\lambda_s^2}\left[1 - \frac{\arctan(\lambda_s k_n)}{\lambda_s k_n}\right]$ which recovers the form $\alpha_{st} = \eta_\perp k_n^2$ at small k_n. Using this 'λ_s model' for α_{st} in Eq. (1), we fit the MOKE data (solid curves in Fig. 1b,c) and obtain $\lambda_s = 0.46 \pm 0.16$ nm and $\eta_\perp = (45 \pm 6) \cdot 10^{-3}$ nm^2. To increase the accuracy, owing to the similarity of crystallographic structures of both Fe films and the bulk nature of non-vanishing terms, we fit MOKE and SPEELS data sets together with $\alpha_{eff} = \alpha_G + \alpha_{st}$. This fit shown in Fig. 1c with the thick solid curve provides $\eta_\perp = (52 \pm 3) \cdot 10^{-3}$ nm^2 and $\lambda_s = 0.58 \pm 0.02$ nm (4 ML of bcc Fe). Remarkably, this value exactly matches the spin transfer torque penetration depth λ_{STT} estimated to 0.56 nm from the shortest observed PSSW wavelength [2]. In fact, $\lambda_{STT} \approx \lambda_s$ is expected because the spin is transported across the Au spacer by *s*-electrons.

[1] I. Razdolski, et al., Nat. Comm. **8**, 15007 (2017).
[2] L. Brandt, et al., Phys. Rev. B **104**, 094415 (2021).
[3] S. Wu, et al., Phys. Rev. B **105**, 174408 (2022).
[4] R. Urban, G. Woltersdorf, and B. Heinrich, Phys. Rev.Lett. **87**, 217204 (2001).
[5] Y. Zhang, T. Chuang, K. Zakeri, and J. Kirschner, Phys.Rev. Lett. **109**, 087203 (2012).
[6] K.-H. Ko and G.-M. Choi, J. Magn. Magn. Mater. **510**, 166945 (2020).

PII-12: Ultrafast coherent THz lattice dynamics coupled to spins in a van der Waals antiferromagnetic flake

F. Mertens[1], D. Mönkebüscher[1], E. Coronado[2], S. Mañas-Valero[2], C. Boix-Constant[2], A. Bonanni[3], M. Matzer[3], R. Adhikari[3], A. M. Kalashnikova[4], U. Parlak[1], D. Bossini[1,5] and, M. Cinchetti[1]

[1]Department of Physics, TU Dortmund University, Otto-Hahn-Straße 4, 44227 Dortmund, Germany
[2]Instituto de Ciencia Molecular (ICMol) Universidad de Valencia, Spain
[3]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria
[4]alexandra.kalashnikova@gmail.com
[5]Department of Physics and Center for Applied Photonics, University of Konstanz, Germany

We employed the time-resolved magneto-optical setup described in [1] to study the optically driven lattice and spin dynamics of a 380 nm thick exfoliated flake of the antiferromagnetic van der Waals semiconductor $FePS_3$ as a function of excitation photon energy, sample temperature and external magnetic field [2]. We found evidence of a coherent optical lattice mode with a frequency of 3.2 THz. The amplitude of the coherent signal vanishes as the phase transition to the paramagnetic phase occurs, revealing its close connection to the long-range magnetic order. The observed phonon mode is known to hybridize with a magnon mode in presence of an external magnetic field [3], which we utilize to excite the hybridized phonon-magnon mode optically. These findings open a pathway towards the generation of coherent THz photomagnonic dynamics in a van der Waals antiferromagnet, possibly scalable down to thinner flakes.

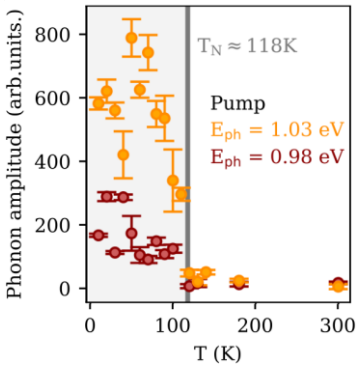


Figure 1: Temperature dependence of the phonon amplitude for excitation photon-energies of 1.03 eV and 0.98 eV.

References

[1] F. Mertens et al., *Rev. Sci. Instrum.* **91** (2020)
[2] F. Mertens et al., arXiv:2111.01464 [cond-mat.mtrl-sci] (2021)
[3] S. Liu et al., *Phys. Rev. Lett.* **127** (2021)

PII-13: THz emission spectroscopy of GdFeCo/Cu/Pt multilayers

G. Nava Antonio[1], Q. Remy[1, 2], M. Hehn[2], S. Mangin[1, 2] and, C. Ciccarelli[1]
[1]Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
[2]Institut Jean Lamour, Université de Lorraine, Nancy F-54000, France

Over the last decade, spintronic emitters–structures comprising magnetic films interfaced with layers with a strong spin-orbit coupling–have emerged as intense, broadband sources of THz radiation. Through engineering of material properties and device architecture, researchers have optimized several aspects of these emitters. For instance, the incorporation of ferrimagnetic materials has resulted in the ability to tune the THz pulses through temperature and chemical concentration.

In this work, we employed time-domain THz spectroscopy to characterize the THz emission from samples based on ferrimagnetic Gd(23%)FeCo(77%) and Pt. Temperature-dependent experiments displayed a change in the polarity of the THz transients associated with the crossing of the magnetization compensation temperature (T_M) of the GdFeCo layer. Datasets taken with different bias magnetic fields together with equilibrium magnetometry measurements elucidated the vanishing of the THz signal close to T_M in terms of the magnetocrystalline anisotropy of the sample.

Furthermore, by placing a Cu spacer of variable thickness between the GdFeCo and Pt layers, we estimated the out-of-equilibrium spin propagation length in this intermediate layer. The experimental data were interpreted by comparing them with a numerical simulation based on an extension of the transfer matrix method capable of considering a charge current source. This analysis revealed that the observed exponential decrease of the THz signal as a function of the Cu thickness was primarily caused by optical effects (THz and optical pump absorption and interference) and not by spin transport properties. Our results constitute a systematic study of GdFeCo THz emitters and confirm the versatility of this alloy as a source of sub-picosecond spin current.

PII-14: Hybrid plasmonic-photonic device enabling all-optical switching of nanoscale magnetic domains on integrated photonic platform

Hamed Pezeshki[1,2*], Pingzhi Li[1], Reinoud Lavrijsen[1], Jos van der tol[2] and, Bert Koopmans[1]
[1]Department of Applied Physics and [2]Department of Electrical Engineering, Eindhoven Hendrik Casimir Institute, Center for Photonic Integration, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands
[*]h.pezeshki@tue.nl

All-optical switching of magnetization has turned into a hot topic in the field of nanomagnetism as it can enable a direct link between integrated photonics and spintronics for energy efficient and ultrafast on-chip applications. So far, a photonic design to provide a bridge between the two domains has been little studied. A practical challenge for such a device is to simultaneously address the magnetic element beyond the diffraction limit, as well as avoiding excessive power in the semiconductor waveguide that will induce nonlinear absorption.

In this presentation, we introduce an integrated hybrid plasmonic-photonic device for all-optical switching of nanoscale ferromagnetic domains with perpendicular magnetic anisotropy on an indium phosphide (InP) membrane on silicon (IMOS) photonic platform [1]. The hybrid device (see Figure 1), which is coupled orthogonally to a magnetic racetrack [2], consists of a doublet V-shaped gold plasmonic nanoantenna placed at the center of a one-dimensional photonic crystal cavity. The hybrid device increases the absorbed energy density in the coupled racetrack by taking advantage of a localized and enhanced electric field at the center of the cavity. Based on a three-dimensional finite-difference time-domain method [3], we illustrate that the proposed device improves the absorbed energy density in the racetrack locally by more than 7 times compared to the case with bare waveguide coupling.

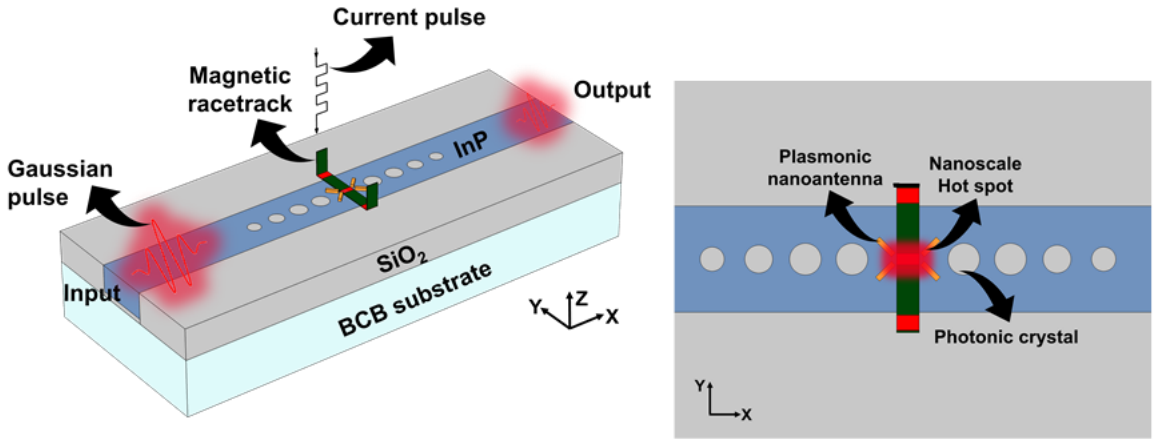
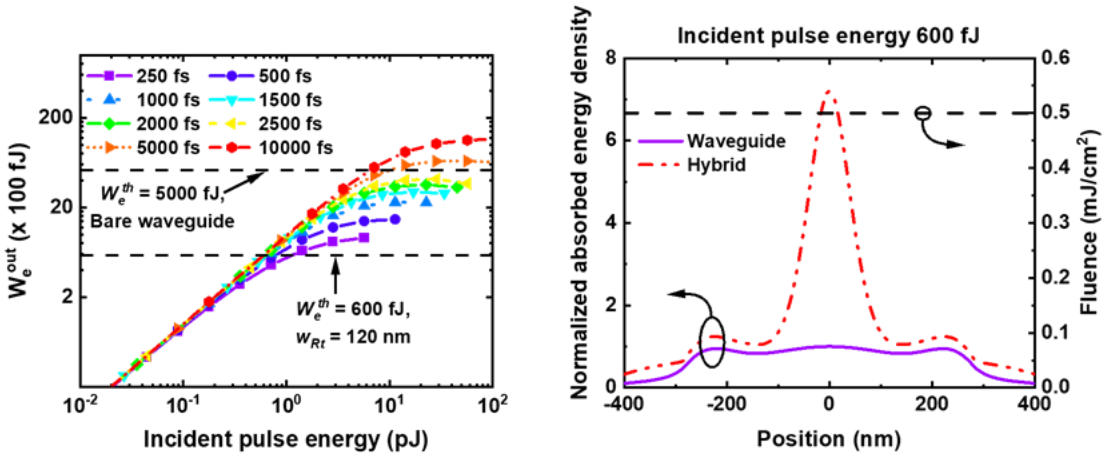


Figure 1: (a, b) A conceptual schematic of the integrated hybrid plasmonic-photonic device for all-optical switching of nanoscale ferromagnetic domains, illustrating the operation principle.



(a) (b)

Figure 2: (a) Numerical study of the effect of nonlinear absorption on all-optical switching in the IMOS platform using "PHIsim" [4]. The output energy, W_e^{out}, as a function of the incident pulse energy for various pulse duration in a 1 mm long waveguide. The horizontal dashed lines in (a) represent the threshold incident input pulse energies (W_e^{th}) for two different cases of the bare waveguide and hybrid devices for a racetrack width of w_{Rt} 120 nm. (b) Normalized absorbed energy density and the projected fluence, averaged along the width of the waveguide for the bare waveguide and hybrid devices.

We further conducted theoretical modeling of the optical pulse propagation in the InP IMOS waveguide with incorporation of the nonlinear effects (see result in Figure 2 (a)) with parameters obtained both from available experimental characterization and numerical simulations. Here, we found that a certain power/energy limit exists due to nonlinear absorption. For instance, to reach the absorbed threshold fluence for the case of the bare waveguide, the required energy cannot be delivered (see Figure 2 (a)). With our hybrid design, for a racetrack width of 120 nm, we have achieved simultaneously a sub-diffraction limit focusing (120 nm) as well as achieving the threshold fluence with 7 times lower incident pulse energy (600 fJ) compared with the case of the bare waveguide (See Figure 2). Such a low energy can be reliably delivered in photonic distribution networks without suffering from nonlinear effects.

Our result demonstrates a hybrid plasmonic-photonic design that enables all-optical switching of sub-diffraction limit domains with high energy efficiency, which enables the integration between integrated photonics and spintronics. With the combination of the racetrack memory, we are convinced our platform opens new paradigms for on-chip ultrafast applications.

References

[1] Jos JGM van der Tol, *et al.*, IEEE J. Quantum Electron., 56.1 (2019).
[2] S, Parkin, and SH Yang, Nat. Nanotechnol. 10.3 (2015).
[3] Lumerical inc. (https://www.lumerical.com/products/fdtd/).
[4] E. Bente, Phisim - a photonic integrated circuit simulator (https://sites.google.com/tue.nl/phisim/home).

PII-15: Growth of epitaxial MgB2 thin films for superconducting spintronic

C. Pfaff[1], K. Dumesnil[1], J.-X. Lin[1], S. Andrieu[1], L. Pasquier[1] and T. Hauet[1]
[1]Institut Jean Lamour

One of the main superconducting spintronics goal is to conciliate superconductivity and spin transport. Studies showed the possibility to generate polarizable quasi-particle at the interface of a ferromagnet and a superconductor [1]. The possibility to generate and polarize such spin current could open the way to a spintronic with lower or no energy-loss.

As it is a conventional superconductor with a critical temperature much larger than the other ones (up to between 30 and 40K) [2], the magnesium diboride (MgB2) is a good candidate to study proximity effect and spin generation and transport on a wide temperature range.

Most reports on MgB2 growth deal with single crystal bulk materials or polycrystalline films. Here we used molecular beam epitaxy to deposit both textured and single crystal MgB2 thin films with thicknesses from 6 nm to 30 nm. The influence of various growth parameters on the structural and superconducting properties of the MgB2 films have been investigated by X-ray diffraction, refraction and confirmed with Transmission Electron microscopy (TEM). X ray photoelectron spectroscopy confirmed absence of oxidation and MgB2 stoichiometry. Magnetic and electrical measurements were realized to determine critical temperature and upper critical field. For the epitaxial samples, critical temperature up to 31K have been obtained. An anisotropy of the coherence lengths has been found to be $\xi_{ab} \approx 3{,}5\ nm$ and $\xi_c = 6nm$ with Ginzburg Landau model [3].

References

[1] M. Eschrig, 'Spin-polarized supercurrents for spintronics: a review of current progress', *Rep. Prog. Phys.*, vol. 78, no. 10, p. 104501, Oct. 2015, doi: 10.1088/0034-4885/78/10/104501.
[2] M. Naito and K. Ueda, 'MgB2 thin films for superconducting electronics', *Supercond. Sci. Technol.*, vol. 17, no. 7, pp. R1–R18, Jul. 2004, doi: 10.1088/0953-2048/17/7/R01.
[3] C. Buzea and T. Yamashita, 'Review of the superconducting properties of MgB2', *Supercond. Sci. Technol.*, vol. 14, no. 11, pp. R115–R146, Nov. 2001, doi: 10.1088/0953-2048/14/11/201.

PII-16: Twisted light affects ultrafast demagnetization

E. Prinz[1], B. Stadtmüller[1,2], and M. Aeschlimann[1]
[1]Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Erwin-Schrödinger-Straße 46, 67663 Kaiserslautern, Germany
[2]Institute of Physics, Johannes Gutenberg University Mainz, Staudingerweg 7, 55128 Mainz, Germany

Optical fields can carry an orbital angular momentum (OAM) of $L = l\hbar$ with the OAM quantum number $l \in \mathbb{Z}$. Since its discovery in 1992 [1], there has been a variety of applications of light with additional OAM, such as quantum entanglement, micromanipulation, communication, and microscopy [2].

Our research focuses on exploring the potential impact of the OAM of light (often referred to as twisted light) on laser-induced ultrafast demagnetization of ferromagnetic materials. In this field, the question of how the angular momentum is conserved during the optically induced loss of magnetic order has not yet been fully answered. It has been shown that the spin angular momentum of light does not affect ultrafast demagnetization in ferromagnetic thin films such as Ni [3, 4]. However, pumping such a system with photons carrying OAM offers the potential to provide new insights, not only into the dissipation of angular momentum in the material but also into the interaction of optical OAM with matter in general.

We investigate ultrafast demagnetization of a thin nickel film induced by OAM light with time-resolved magneto-optic Kerr-effect measurements. We observed peculiar demagnetization dynamics that have so far not been observed for light without OAM: depending on the excitation geometry, the photonic OAM either supports (speeds up) or obstructs (slows down) the demagnetization process.

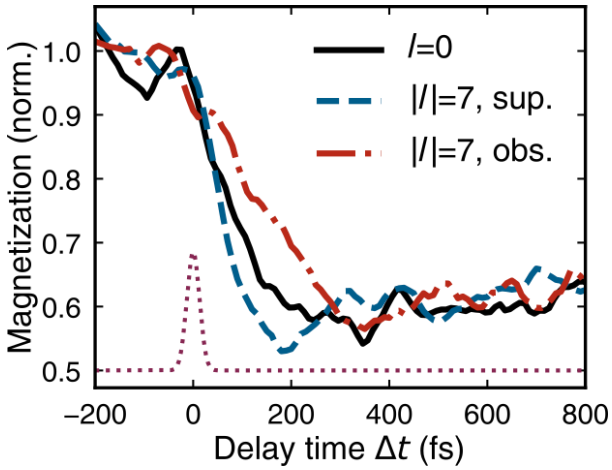


Figure 1: Demagnetization of the sample after irradiation of a pump pulse with $|l| = 7$ in the supporting (dashed line) and the obstructing (dash dotted line) geometry in comparison to demagnetization with an $l = 0$ (solid line) beam. For better visualization, the data was smoothed. The dotted curve visualizes the pump pulse duration.

References

[1] L. Allen, et al., Phys. Rev. A 45, 8185 (1992).
[2] Y. Shen, et al., Light: Science & Applications 8, 1 (2019).
[3] B. Koopmans, et al., Phys. Rev. Lett. 85, 844 (2000).
[4] F. Dalla-Longa, et al., Phys. Rev. B 75, 224431 (2007).

PII-17: Overcoming the Critical Slowing Down of Magnetization Dynamics

Q. Remy[1,2], J. Hohlfeld[1], M. Vergès[1], Y. LeGuen[1], J. Gorchon[1], G. Malinowski[1], S. Mangin[1,2], M. Hehn[1]
[1]Université de Lorraine, Institut Jean Lamour, UMR CNRS, Nancy 7198, France
[2]Cavendish Laboratory, University of Cambridge, Cambridge, UK

In order to develop ultrafast and energy efficient storage devices based on magnetic media, it is usually believed that magnetization must undergo a longitudinal dynamics [1,2] as opposed to a precessional one [3,4]. It must then be completely quenched at the sub-picosecond timescale [5] before recovering in the opposite direction. However, when magnetization approaches zero, its dynamics slows down, a phenomenon called Critical Slowing Down (CSD) [6,7] which generally exists when a system is close to a phase transition [8].
In order to explain CSD and explain how it can be avoided in magnetic systems, we introduce a two level mean field model for localized spins (Figure 1) [9]. Magnetization dynamics is then understood as transfers of energy and angular momentum, and to each magnetic configuration, one can define a temperature for the spin system even under out of equilibrium conditions. We then show that only angular momentum transfers can lead to magnetization reversal and suppress CSD via two mechanisms referred to as spin heating and spin cooling: the heating and respectively cooling of the magnetic system via exchange of spin with an external bath. These effects are simulated using a s-d model of magnetization dynamics [10], consistent with this framework. Experimentally, we demonstrate the existence of these two mechanisms by monitoring the ultrafast magnetization dynamics of a ferromagnetic [Co/Pt] multilayer when it is subjected to an external spin current emitted by a GdFeCo alloy [11]. We show that magnetization crosses zero in 400 fs and reaches equilibrium in 2 ps. Moreover, using the bipolarity of the source spin current [12], we show that magnetization can be reversed twice consecutively in 650 fs. This shows that one can achieve a complete control of magnetization dynamics at the sub-picosecond timescale, close to the ferromagnetic/paramagnetic phase transition, using ultrashort pulses of spin with tunable polarization.

References

[1] Kazantseva, N., Hinzke, D., Chantrell, R. W. & Nowak, U. Linear and elliptical magnetization reversal close to the Curie temperature. EPL (Europhysics Lett. 86, 27006 (2009).
[2] Wienholdt, S., Hinzke, D., Carva, K., Oppeneer, P. M. & Nowak, U. Orbital-resolved spin model for thermal magnetization switching in rare-earth-based ferrimagnets. Phys. Rev. B 88, 020406 (2013).
[3] Tudosa, I. et al. The ultimate speed of magnetic switching in granular recording media. Nature 428, 831–833 (2004).
[4] Shalaby, M. et al. Coherent and incoherent ultrafast magnetization dynamics in 3*d* ferromagnets driven by extreme terahertz fields. Phys. Rev. B 98, 014405 (2018).
[5] Beaurepaire, E., Merle, J.-C., Daunois, A. & Bigot, J.-Y. Ultrafast Spin Dynamics in Ferromagnetic Nickel. Phys. Rev. Lett. 76, 4250–4253 (1996).
[6] Kazantseva, N., Nowak, U., Chantrell, R. W., Hohlfeld, J. & Rebei, A. Slow recovery of the magnetisation after a sub-picosecond heat pulse. EPL (Europhysics Lett. 81, 27004 (2008).
[7] Koopmans, B. et al. Explaining the paradoxical diversity of ultrafast laser-induced demagnetization. Nat. Mater. 9, 259–265 (2010).
[8] Scheffer, M. et al. Early-warning signals for critical transitions. Nature 461, 53–59 (2009).

[9] Remy Q., Hohlfeld J., Vergès M., LeGuen Y., Gorchon J., Malinowski G., Mangin S., Hehn M., Accelerating ultrafast magnetization reversal by non-local spin transfer (2022) (Submitted).
[10] Beens, M., Duine, R. A. & Koopmans, B. S-d model for local and nonlocal spin dynamics in laser-excited magnetic heterostructures. Phys. Rev. B 102, 054442 (2020).
[11] Remy, Q. et al. Energy Efficient Control of Ultrafast Spin Current to Induce Single Femtosecond Pulse Switching of a Ferromagnet. Adv. Sci. 7, 2001996 (2020).
[12] Choi, G.-M. & Min, B.-C. Laser-driven spin generation in the conduction bands of ferrimagnetic metals. Phys. Rev. B 97, 014410 (2018).

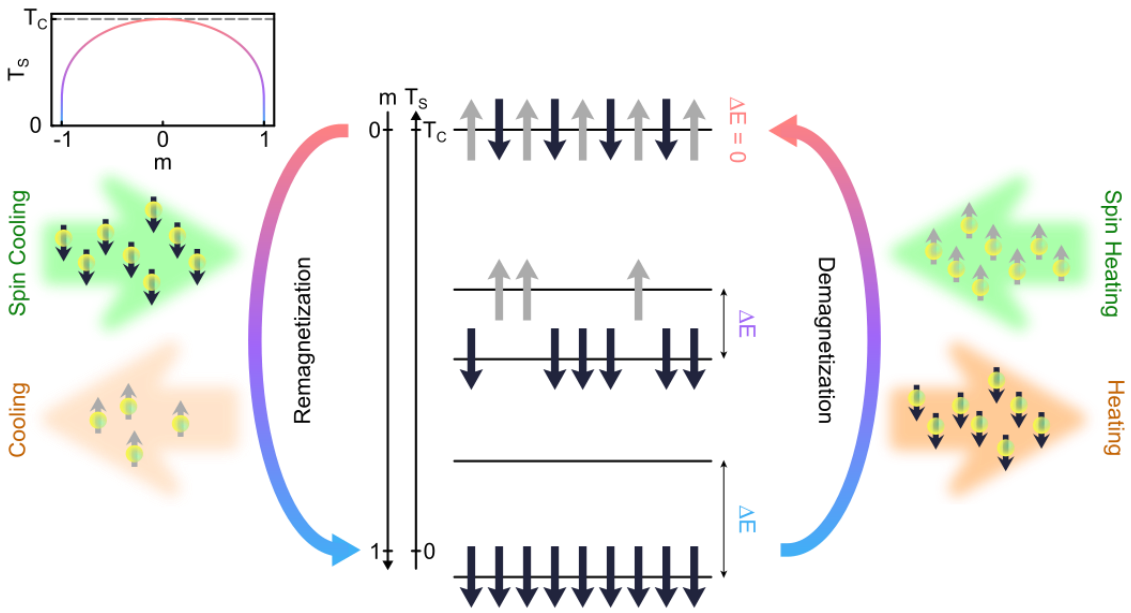


Figure 11: Two level model of ultrafast magnetization dynamics. A system with magnetization m formed by localized spins can be represented by the population of its different energy levels. Here the two levels can be populated by up (grey arrows) and down (black arrows) spins (center of the figure). To different populations correspond different energy splittings $\Delta E = 2mk_BT_C$ in the mean field approach considered. For each magnetization and its corresponding possible configurations, one can associate a spin temperature T_S (see inset) even in out of equilibrium conditions. Due to the coupling of the (two level) spin system with its external environment, there can be exchange of angular momentum which will either cool down the spin system (remagnetization) or heat it up (demagnetization) depending on the polarization of the transferred angular momentum. The standard way to obtain ultrafast magnetization dynamics is to heat up the system (energy transfer) leading to an ultrafast dissipation of angular momentum. It is not possible to achieve a similarly fast remagnetization in general because cooling of the system relies on heat dissipation via the sample substrate on a much longer timescale, and CSD may happen around m = 0. Spin cooling and spin heating work analogously but via angular momentum transfer. However, contrary to standard cooling and heating, spin cooling and

PII-18: Enhancing spin pumping voltage at ferromagnetic resonance by improving antenna design

A. Anadon[1], J. Alegre[1,2], H. Damas[1], M. Hehn[1], S. Petit-Watelot[1], and J-C. Rojas-Sánchez[1]
[1]Université de Lorraine, CNRS, Institute Jean Lamour, F-54000 Nancy, France
[2] Universidad Nacional de Ingeniería, Rímac 15333, Peru

One widely method to quantify spin -charge current conversion efficiency is to measure the spin pumping dc voltage, *V*sp, generated at the ferromagnetic resonance condition[1,2], Fig. 1. Here, one of the key parameters is the generation of the microwave excitation and the intensity of the microwave field, h_{rf}. In a resonant cavity h_{rf} can be homogeneous and quite strong, i.e. ~1 G for 10 GHz[1]. Antennas or coplanar wave guides, CPW, have also become popular and are gaining ground[2]. CPW also allow also to perform frequency dependence.

We present results using different CPW designs. First, using an *external* CPW, V_{sp} is only tens of nV. Then, different CPW are integrated to the sample and made by lithography. The total sample size is much smaller, and V_{sp} can reach hundreds of nV or μV for the same Pt/CoFeB sample and measurement conditions. We then present qualitative results but which fulfill all the characteristics of the V_{sp} as depicted in Fig. 1b. Finally, for the correct quantification of the h_{rf} field we carried out microwave resistance measurements. That is, we measure the voltage at resonance condition but adding a dc current to the sample. This allows us, together with the analytical model we developed, to know h_{rf} value. Finally, we verify this quantification using different CPW designs. The independent results match in all the designs. This work allows us to establish another way to correctly quantify h_{rf} and consequently the efficiency of interconversion of spin current into charge current.

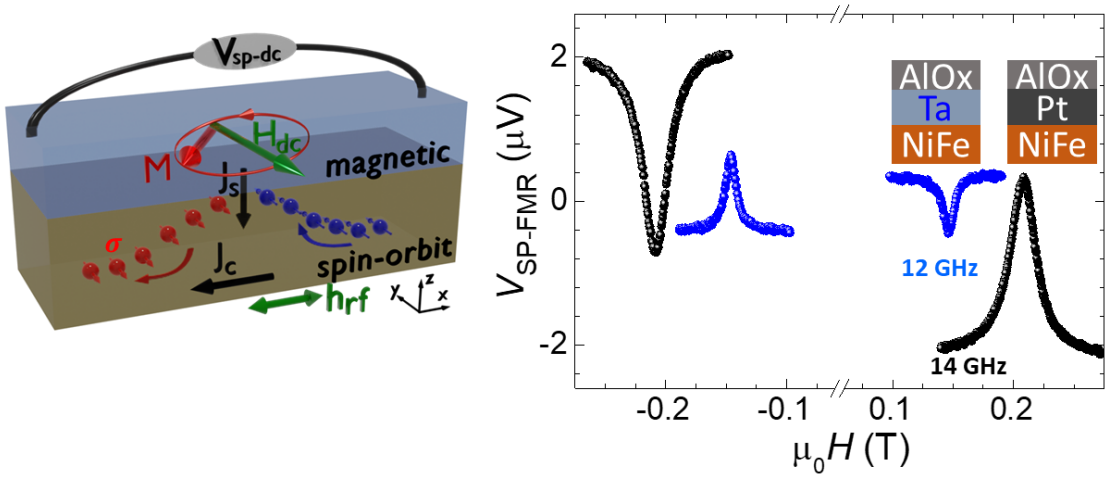


Figure 1: (a) Schematic of spin pumping - FMR and dc voltage detection on a bilayer. At resonance condition of magnetic layer, a spin current Js is injected into the no-magnetic layer and converted into a charge current $J_c \propto \theta_{SHE}(J_s \times \sigma)$ (detected as a voltage in an open circuit). θ_{SHE} is the spin Hall angle and accounts for the conversion efficiency. (b) Raw data examples. V_{sp} is a symmetric lorenztianne curve around the resonance field. Its sign changes upon field ($\sigma \rightarrow -\sigma$), stacking order ($J_s \rightarrow -J_s$) and sign of θ_{SHE} or spin-orbit coupling.

[1] J.C. Rojas-Sanchez et al. Phys. Rev. Lett. 112, 106602 (2014)
[2] T. Fache et al., Phys. Rev. B 102 (6), 064425 (2020).

PII-19: Emission of coherent THz magnons in an antiferromagnetic insulator triggered by ultrafast spin-phonon interactions

E. Rongione[1,2], O. Gueckstock[3], M. Mattern[4], O. Gomonay[5], H. Meer[5], C. Schmitt[5], R. Ramos[6], E. Saitoh[6], J. Sinova[5], H. Jaffrès[1], M. Mičica[2], J. Mangeney[2], S. T. B. Goennenwein[7], S. Geprägs[8], T. Kampfrath[3], M. Kläui[5], M. Bargheer[4], T. S. Seifert[3], S. Dhillon[2], R. Lebrun[1]

[1] Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, F-91767 Palaiseau, France

[2] Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, F-75005 Paris, France

[3] Institute of Physics, Freie Universität Berlin, D-14195 Berlin, Germany

[4] Institut für Physik und Astronomie, Universität Potsdam, D-14476 Potsdam, Germany

[5] Institute of Physics, Johannes Gutenberg-University Mainz, D-55128 Mainz, Germany

[6] Institute for Materials Research and Center for Spintronics Research Network, Tohoku University, J-980-8577 Sendai, Japan

[7] Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

[8] Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, D-85748 Garching, Germany

Antiferromagnets (AFM) have a strong potential for future spintronic devices due to their insensitivity to perturbative external magnetic fields, absence of stray fields, and for accessing to frequencies up to the terahertz (THz) regime [1-2]. AFMs could thus enable the development of faster dynamics devices [3-5], and in particular tunable narrowband spintronic THz emitters [6]. However, until now the functionalization of their THz properties in thin films remains a challenging and ongoing task [7-8].

In this work, we achieve a coherent emission of THz magnons in 10 nm thick NiO thin films capped with 2 nm of Pt layer [9] triggered by ultrafast near-infrared 100 fs pulses and detect the emitted signal by THz time-domain emission spectroscopy (Fig. 1a). The generated THz signal of NiO(001)(10nm)/Pt(2nm) bilayer has two main components as shown in Fig. 1b: *i*) a broadband contribution (up to 3 THz – cut-off frequency of our detector) alongside *ii*) a narrowband contribution centered at 1.1 THz (periodic oscillations of period around 1 ps). NiO possesses two magnon modes (*i.e.* precession of the Néel vector components $\mathbf{n} = \mathbf{M}_1 - \mathbf{M}_2$): one low-frequency mode around 180 GHz and one high-frequency mode around 1.1 THz. The latter can be associated with the measured narrowband 1.1 THz contribution of the THz radiation from NiO/Pt bilayers. We evidence that the THz signal originates from the spin-to-charge conversion of the magnonic current flowing from the NiO layer to the Pt layer via the inverse spin Hall effect.

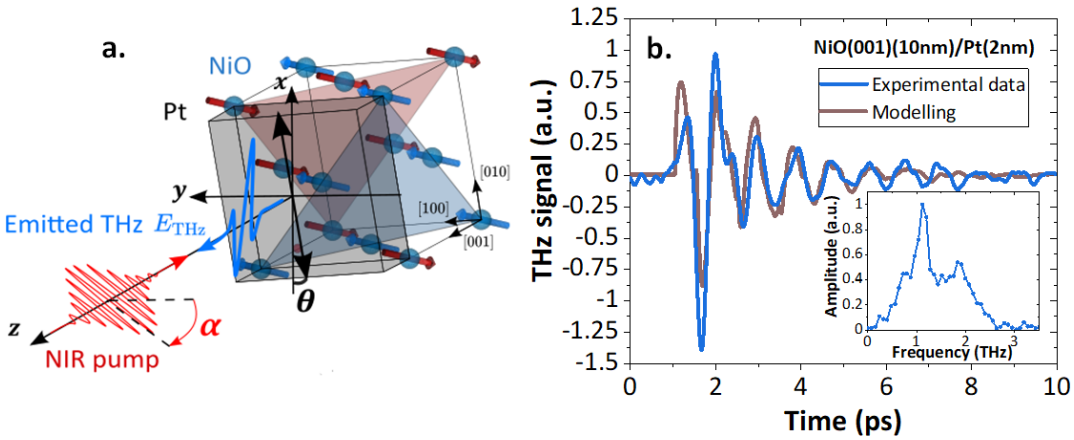


Figure 1: Ultrafast near-infrared pump induced coherent and uncoherent THz emission from NiO/Pt bilayers. (a) Experimental pumping geometry for THz emission spectroscopy. (b) THz emission from NiO(001)(10nm)/Pt(2nm) bilayer (blue) presenting oscillations in the time-domain (period about 1 ps) and supporting magnetization dynamics modelling (brown). The inset presents the spectral components in the frequency domain with broadband and narrowband contribution (centered at 1.1 THz).

We further explore the THz radiation for different growth orientations of NiO thin films (not shown here). We identify that the THz signal arises from an off-resonant optical-spin torque for the (111) orientation as reported recently [10], and from spin-phonon interactions for (001) orientation. Using ultrafast X-ray diffraction, we evidence the presence of a strain wave that can effectively trigger an out-of-plane precession of the Néel vector in NiO via magneto-strictive interactions, which had only been reported in the static regime until now [11]. We further evidence the different physics in (111) and (001) oriented films by measuring that the decay times of the emitted THz spin currents vary by one order of magnitude between the optical torque (< 30 fs) and spin-phonon (> 300 fs) excitation processes. These results highlight promising perspectives for the development of AFM optomagnonics and AFM THz devices.

References

[1] V. Baltz et. al. “Antiferromagnetic spintronics”. *Rev. Mod. Phys.*, 90:015005 (2018).

[2] T. Jungwirth et. al. “Antiferromagnetic spintronics”. *Nat. Nanotechnol.*, 11:11 (2016).

[3] T. Chirac et. al. “Ultrafast antiferromagnetic switching in NiO induced by spin transfer torques”. *Phys. Rev. B*, 102:134415 (2020).

[4] R. Lebrun et. al. “Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide”. *Nature*, 561:222–225 (2018).

[5] R. Cheng et. al. “Terahertz Antiferromagnetic Spin Hall Nano-Oscillator”. *Phys. Rev. Lett.*, 116:207603 (2016).

[6] T. Seifert et. al. “Efficient metallic spintronic emitters of ultrabroadband terahertz radiation”. *Nature Photon.*, 10:483–488 (2016).

[7] J. Li et. al. “Spin current from sub-terahertz-generated antiferromagnetic magnons”. *Nature*, 578, 70–74 (2020).

[8] P. Vaidya et. al. “Subterahertz spin pumping from an insulating antiferromagnet”. *Science*, 368, 160–165 (2020).

[9] E. Rongione et. al. “Emission of coherent THz magnons in an antiferromagnetic insulator triggered by ultrafast spin-phonon interactions”. *arXiv preprint*, arXiv:2205.11965 (2022).

[10] H. Qiu et. al. “Ultrafast spin current generated from an antiferromagnet”. *Nat. Phys.*, 17:388–394 (2021).

[11] H. Meer et. al. “Direct Imaging of Current-Induced Antiferromagnetic Switching Revealing a Pure Thermomagnetoelastic Switching Mechanism in NiO”. *Nano Lett.*, 21,1:114–119 (2021).

PII-20: Electronic heat bath simulations for ultra-fast spin dynamics

J. Ross[1], R. W. Chantrell[1] and R. F. L. Evans[1]
[1]Department of Physics, University of York, Heslington, York, YO10 5DD

Magnetic modelling for ultrafast simulations at the atomistic and micromagnetic scale make common use of Langevin Dynamics to model the effect of thermal fluctuations on the procession of the magnetic moment. Such a model is simple to add to any finite-temperature simulation: a Gaussian distribution scaled against a collection of material dependent parameters are included in effective field term in the LLG spin Hamiltonian, and at pico-second timescales is uncorrelated in space or time [1].

In general, however, the thermal fluctuations in a material are correlated through collective occupation of electron, phonon, and magnon modes in the system. Analytical solutions for these relationships require simple materials or drastic approximations, conditions ill-suited to ultrafast ferri and antiferromagnetic materials. We present an improved thermostat for ultrafast atomistic scale magnetic simulations using a computationally determined conduction band environment based on semi-classical electron-electron and electron-phonon scattering events [2][3]. The use of a dynamically determined electron environment would allow for coupling of spatially and temporally correlated thermal and spin transport phenomena to the atomistic magnetic moment. Currently, our environment simulates charge and heat transport in metals on ultra-fast time scales during severe non-equilibrium caused from applied electric fields or laser-heating pulses. The electron-electron and electron-phonon relationship is parametrized into the relaxation time approximation using constants derived from experimental data [3][4]. Our environment successfully reproduces the popular *two-temperature model* (TTM) used to simulate laser-heating of experimental samples (fig. 1) with the added advantage of considering local correlation effects. In the future, this will offer the ability to include correlated spin effects not possible in Langevin Dynamics.

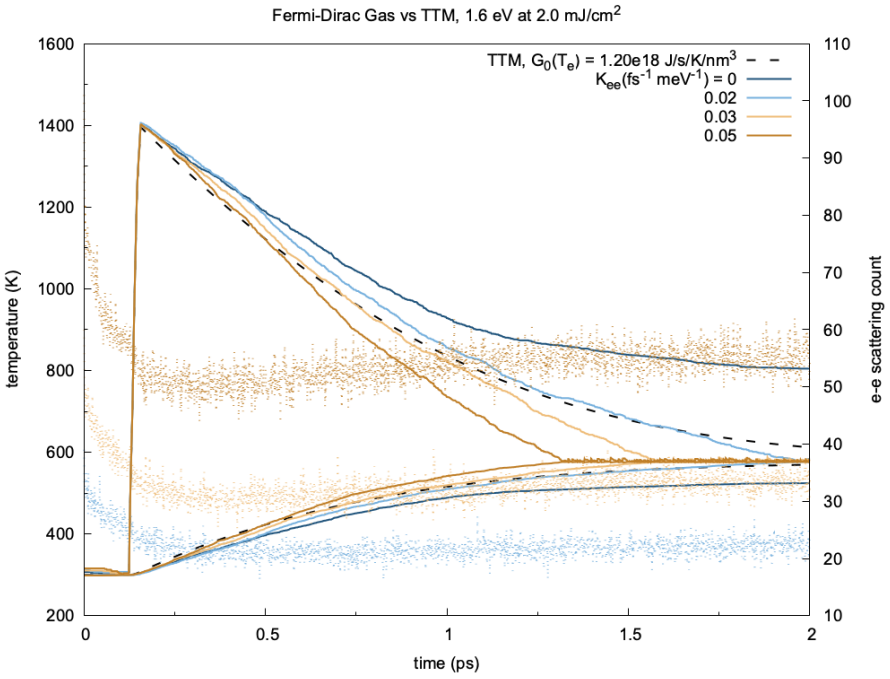


Figure 12. S simulated electron and lattice temperatures (solid) following laser exposure compared to the standard TTM (dash). The varying colours and dynamics are a result of varying the electron-electron scattering constant.

References

[1]. R F L Evans *et al* 2014 *J. Phys.: Condens. Matter* **26** 103202
[2]. M van Kampen *et al* 2005 *J. Phys.: Condens. Matter* 17 6823
[3]. W Miao *et al* 2019 *Phys. Rev. B* 99, 205433
[4]. L Jiang *et al* 2005 *ASME. J. Heat Transfer* 127(10): 1167.

PII-21: THz emission spectroscopy of ultrafast exchange bias modulation in IrMn/CoFeB/Ta heterostructures

Y. Saito[1], F. N. Kholid[1], E. Karashtin[2], A. Fraerman[2], R. V. Mikhaylovskiy[1]
[1]Department of Physics, Lancaster University, UK
[2]Institute for Physics of Microstructures, Nizhny Novgorod, Russia

Terahertz (THz) emission from a spintronic structure, consisting of a ferromagnetic (FM) layer and a nonmagnetic (NM) layer with high spin Hall angle, was discovered a decade ago [1]. This breakthrough has led to a new research direction THz spintronics [2-3]. The spintronic terahertz emitter is not only a new type of THz sources but a concept to explore the ultrafast phenomena in magnetic heterostructures. For example, laser-induced phase transition of FeRh from an antiferromagnetic (AFM) phase to a FM phase was monitored by double-pump THz emission spectroscopy recently [4]. Here, we report THz emission from heterostructure with AFM layer in addition to FM/NM layer, which provides the exchange coupling at the FM and AFM interface Figure 1.

We fabricated two different samples, IrMn / CoFeB / Ta (SampleA) and IrMn / CoFeB / MgO / CoFeB / Ta (SampleB), where the former has a simple exchange bias between IrMn and CoFeB and the latter has more complicated structure, forming a tunnel magnetic resistance (TMR) device. The typical THz waveform emitted from SampleA is shown in Figure 2. When we fixed the time delay at THz peak and sweep the external magnetic field, we obtained the hysteresis loop with the shift derived from the exchange bias. The hysteresis reproduced the results measured by magneto-optical Kerr effect (MOKE). Also, we observed dynamical flip of the pinning axis by intense lase pulse, see Figure 3. We will discuss the fluence dependence and data of sample B. Moreover, we will investigate the potential of the double-pump THz emission to reveal the mechanism of the pinning reset.

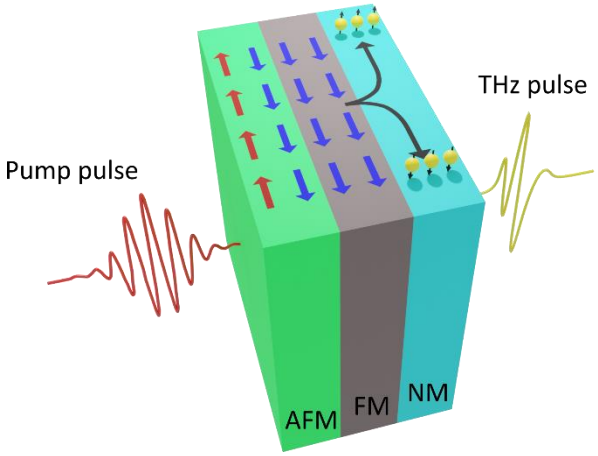


Figure 13: Schematic of the THz emission and the exchange

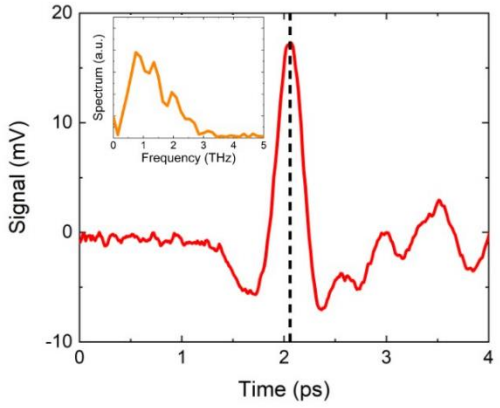


Figure 2: Emitted THz waveform from the spintronic sample**.** Black dotted line means the fixed position to measure hysteresis loops as shown in Fig. 3. Inset depicts the Fourier spectrum.

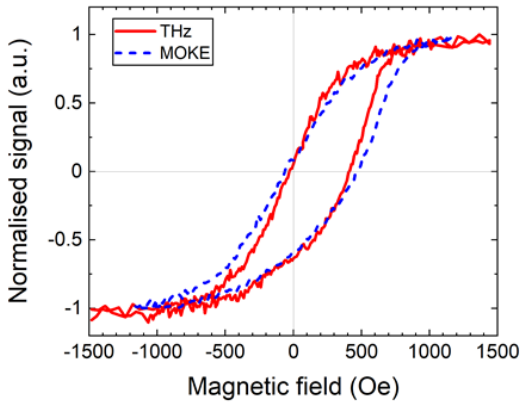


Figure 3: The hysteresis measured by two different methods, the THz emission and MOKE

References

1. Kampfrath, T. et al. Terahertz spin current pulses controlled by magnetic heterostructures. Nature Nanotech 8, 256–260 (2013).
2. Seifert, T. et al. Efficient metallic spintronic emitters of ultrabroadband terahertz radiation. Nature Photon 10, 483–488 (2016).
3. Gueckstock, O. et al. Impact of gigahertz and terahertz transport regimes on spin propagation and conversion in the antiferromagnet IrMn. Appl. Phys. Lett. 120, 062408 (2022).
4. Li, G. et al. Ultrafast kinetics of the antiferromagnetic-ferromagnetic phase transition in FeRh. Nat Commun 13, 2998 (2022).

PII-22: Ultrafast magnetization dynamics in 2D van der Waals magnets

Elton J. G. Santos[1,2]
[1]Institute of Condensed Matter and Complex Systems,
School of Physics and Astronomy, The University of Edinburgh, EH9 3FD, UK
[2]Higgs Centre for Theoretical Physics, The University of Edinburgh, EH9 3FD, UK

The family of 2D compounds has grown almost exponentially since the discovery of graphene and so too the rapid exploration of their vast range of electronic properties. Some family members include superconductors, Mott insulators with charge-density waves, semimetals with topological properties, and transition metal dichalcogenides with spin-valley coupling [1]. Among several compounds, the realization of long-range ferromagnetic order in van der Waals (vdW) layered materials has been elusive till very recently. Long searched but only now discovered 2D magnets are one of the select group of materials that retain or impart strongly spin correlated properties at the limit of atomic layer thickness [2,3]. In this presentation I will discuss how different layered compounds (e.g., CrX_3 (X=F, Cl, Br, I), VI_3, $MnPS_3$, Fe_3GeTe_2, $FePS_3$, $CrGeTe_3$) can provide new playgrounds for exploration of spin correlations involving quantum-effects, topological spin-excitations, and coupling with light. I will show our recent results [4,5] in modelling the laser-driven magnetisation dynamics on vdW magnets, and the manipulation of spin textures in the likes of skyrmions, merons and hybrid spin quasiparticles via femtosecond laser pulses (Figure 1). Moreover, different strategies for creation and manipulation of topological spin textures using external driving forces (e.g., light, current) will be shown. I will discuss some challenges at the forefront of 2D vdW magnets and new opportunities to understand spin-light interactions towards fundamental and practical problems.

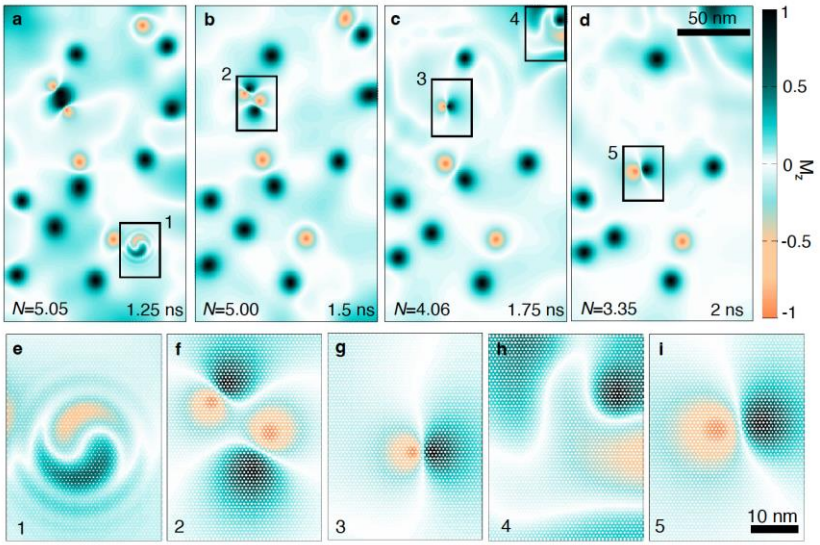


Figure 1: a-d, Spin dynamics at long times (1.25–2 ns) showing the dynamics of the topological spin textures after the application of a laser pulse of fluence 0.01 mJ cm^{-2}. The topological number *N* is computed at each snapshot. The highlighted areas (1, 2, 3, 4, 5) display specific events of the interactions between vortex and antivortex. **e-i,** Zoom-in at the small areas showing an annihilation event (**e,h**) followed by the emission of spin-waves, collisions between two pairs of vortex and antivortex (**f**), collision between single vortex and antivortex (**g**) and precession of vortex and antivortex pair (**i**).

References:

1. Q. Wang *et al. ACS Nano* 16, 6960 (2022).
2. J. Macy *et al., Appl. Phys. Rev.* 8, 041401 (2021).
3. D. Wahab *et al. Adv. Mater.* 33, 2004138 (2021).
4. M. Dabrowski *et al.* Under review (2022).
5. M. Strungaru *et al.* Under review (2022).

PII-23: Ultrafast element- and depth-resolved magnetization dynamics probed by transverse magneto-optical Kerr effect spectroscopy in the soft x-ray range

M. Hennecke[1], Daniel Schick[1], T. Sidiropoulos[1], F. Willems[1], A. Heilmann[1], M. Moerbeck-Bock[1], L. Ehrentraut[1], D. Engel[1], P. Hessing[1], B. Pfau[1], M. Schmidbauer[2], A. Furchner[3,4], M. Schnuerer[1], C. von Korff Schmising[1], and S. Eisebitt[1,5]

[1]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, Max-Born-Straße 2A, 12489 Berlin, Germany

[2]Leibniz-Institut für Kristallzüchtung, Max-Born-Straße 2, 12489 Berlin, Germany

[3]Helmholtz-Zentrum Berlin für Materialien und Energie, Division Energy and Information, Schwarzschildstraße 8, 12489 Berlin, Germany

[4]Leibniz-Institut für Analytische Wissenschaften – ISAS – e.V., Department Berlin, Schwarzschildstraße 8, 12489 Berlin, Germany

[5]Institut für Optik und Atomare Physik, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

The combination of spatio-temporal spin manipulation and structure design on the nanoscale is highly relevant for novel ultrafast and energy-efficient information technology, thermoelectrics, and THz emitters. While common optical and transport-based magnetometry only provides an indirect access to the spatial dependence of the relevant non-local spin dynamics, ultrafast resonant magnetic soft x-ray scattering combines magnetic contrast with element selectivity and at the same time enables nanoscale depth resolution via variation of the penetration length across atomic resonances. Thus far it has only been explored for ultrafast magnetization depth profiling at large-scale facilities, without being able to provide a quantitative analysis of the spatially inhomogeneous evolution of the magnetization with sub-picosecond temporal resolution.

In this work, we study the spatial evolution of the ultrafast magnetization dynamics in a ferrimagnetic Ta/GdFe/Pt nanolayer system [1]. We conduct femtosecond time- and angle-resolved transverse magneto-optical Kerr effect (TMOKE) spectroscopy at the Gd $N_{5,4}$ resonances around 150 eV photon energy, selectively probing the magnetization of the Gd sublattice. A laser-driven higher-harmonic generation (HHG) setup provides the probing soft x-rays with a broad and continuous spectrum spanning the 100-200 eV region [2]. The TMOKE measurements are carried out employing a combined ϑ–2ϑ reflectometry and spectroscopy setup, see Fig. 1.

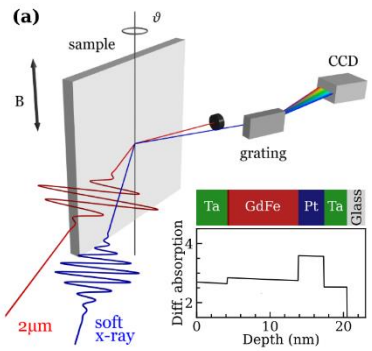


Figure 1: Schematic illustration of the ϑ–2ϑ spectroscopy setup used for the angle- and time-resolved experiments. The inset shows the depth-dependent differential absorption of the 2.1 μm pump pulse (incident from the left side onto the Ta layer) that drives the

Our analysis reveals significant differences in the ultrafast evolution of the TMOKE asymmetry for different photon energies, see Fig. 2(a, b). Comparing the experimental TMOKE asymmetries to polarization dependent magnetic scattering simulations [3], we can quantitatively relate these spectral changes to transient, depth-dependent de- and re-magnetization profiles within the GdFe layer after photoexcitation, see Fig. 2(c, d). Analysis of the evolving magnetization depth profiles allows us to disentangle femtosecond dynamics dominated by non-equilibrium electron transport (≤ 100 fs) and nanoscale heat

diffusion on a picosecond time scale (≥ 1 ps). Based on our experimental data, we rule out significant contributions arising from femtosecond non-local spin transport phenomena as Gd shows spatially homogeneous demagnetization during these early times. The subsequent emergence of a magnetization gradient within the Gd-sublattice on time scales of ≥ 1 ps can be linked to phononic heat injection at the interface with the buried Pt seed layer.

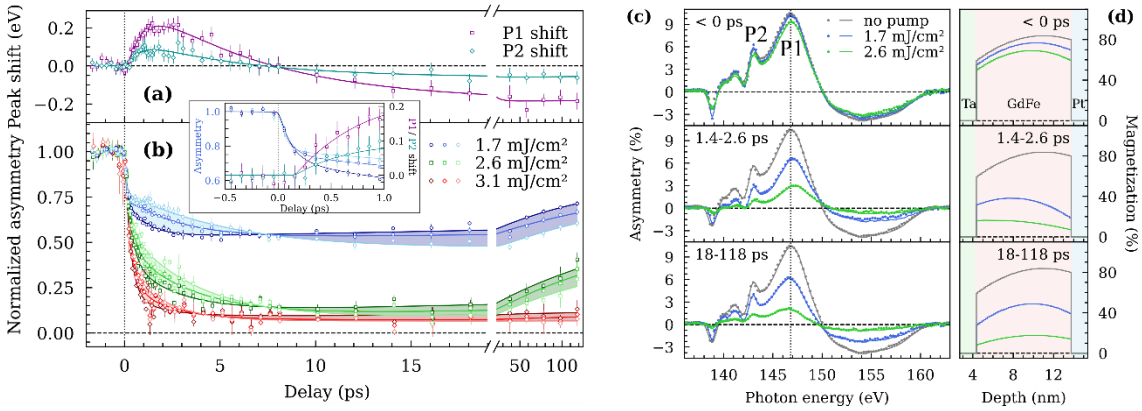


Figure 2: (a) Transient shift of the main TMOKE asymmetry peaks (P1, P2) upon 1.7 mJ/cm2 excitation as a function of pump-probe delay. (b) Integrated asymmetry as a function of excitation fluence and pump-probe delay. The colored data points for each fluence result from integrating over different photon energy intervals. The inset zooms into the first picosecond revealing a delayed onset of the spectral peak shift. (c) Recorded transient asymmetry spectra (dots) and fitted simulations (lines) averaged over different time intervals as a function of the incident excitation fluence. (d) Resulting magnetization depth profiles obtained for the respective excitation fluence and time interval.

Our results emphasize the importance of a careful analysis of magnetic scattering data, as inhomogeneous spin dynamics in layered magnetic systems result in a complicated spectral dependence of the TMOKE observable. In turn, this allows us to disentangle local and non-local processes on ultrafast time scales. Importantly, our findings directly correlate experimental observables with functionality in nanoscale device structures, e.g., controlled by charge or spin currents as well as nanoscale heat transfer.

[1] M. Hennecke et al., *Ultrafast Element- and Depth-Resolved Magnetization Dynamics Probed by Transverse Magneto-Optical Kerr Effect Spectroscopy in the Soft x-Ray Range*, Phys. Rev. Res. **accepted**, (2022).

[2] M. van Mörbeck-Bock, T. Feng, A. Heilmann, L. Ehrentraut, H. Stiel, M. Hennecke, T. Sidiropoulos, C. von Korff Schmising, S. Eisebitt, and M. Schnuerer, *High Average Power OPCPA MIR-Systems for Coherent Soft x-Ray Generation Accessing Inner-Shell Absorption Edges of Metals*, in *High Power Lasers and Applications*, edited by T. J. Butcher, J. Hein, P. Bakule, C. L. Haefner, G. Korn, and L. O. Silva (SPIE, 2021), p. 5.

[3] D. Schick, *Udkm1Dsim – a Python Toolbox for Simulating 1D Ultrafast Dynamics in Condensed Matter*, Comput. Phys. Commun. **266**, 108031 (2021).

PII-24: Laser-driven resonant magnetic scattering in the soft-x-ray range

Daniel Schick[1], M. Borchert[1], L. Lunin[1], D. Engel[1],
C. von Korff Schmising[1], B. Pfau[1], and S. Eisebitt[1,2]
[1]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie,
Max-Born-Straße 2A, 12489 Berlin, Germany
[2]Institut für Optik und Atomare Physik, Technische Universität Berlin,
Straße des 17. Juni 135, 10623 Berlin, Germany

Time-resolved resonant magnetic scattering in the soft-x-ray range is a powerful tool for accessing the spatially-resolved and element-specific spin dynamics in magnetic materials. So far, this photon-hungry technique has been limited to large-scale facilities. However, upgrades to diffraction-limited storage rings supporting only x-ray pulses beyond 100 ps and the shift of x-ray free-electron lasers towards attosecond pulses aggravate the competition for beamtime in the picosecond time window, which is of utmost relevance for magnetism research.

Here, we present the development of a lab-based instrument providing sufficient photon flux for

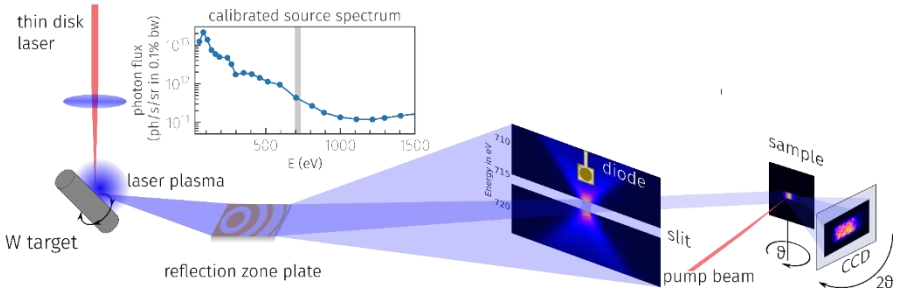


Figure 14: A high-energy laser pulse is focused onto a rotating tungsten cylinder, emitting broadband soft-x-ray radiation. The inset shows the emitted spectral distribution as measured at the source. A reflection-zone-plate captures part of the x-rays that are simultaneously focused and dispersed onto a slit for monochromatization. Part of the soft x-rays pass the slit and scatter off a sample in a ϑ/2ϑ-geometry onto a

resonant scattering up to 1.5 keV photon energy covering the soft-x-ray resonances of transition and rare-earth metal atoms. Our setup features the mandatory tunability in energy- and reciprocal-space combined with sub-10 ps temporal resolution exploiting the broadband emission of a laser-driven plasma x-ray source, which can be monochromatized to about 1 eV bandwidth by a reflection zone plate.

We benchmark our approach against accelerator-based soft-x-ray sources in a series of resonant magnetic scattering and spectroscopy experiments: (i) we probe the time-resolved evolution of the magnetic and structural Bragg peaks of an antiferromagnetically-coupled Fe/Cr superlattice

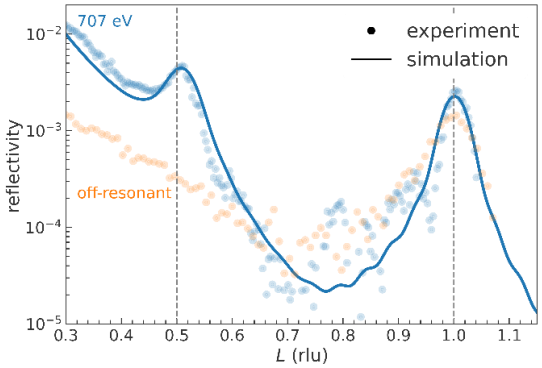


Figure 15: First laser-driven resonant magnetic scattering from AFM as well as structural Bragg peaks at resonance, E=707 eV (blue dots) and off resonance, E=680 eV (orange dots) of the Fe/Cr SL. The blue solid line represents a magnetic scattering simulation of the sample. At the relative momentum transfer L=1 the structural Bragg peak is present for both photon energies, while the AFM Bragg peak at L=0.5 only appears on-resonance.

at the Fe *L*-edges [1], see Fig. 2; (ii) we characterize the lateral domain formation of a Gd/Fe superlattice by magnetic small-angle x-ray scattering (SAXS) in transmission at the Fe *L* and Gd *M*-edges, see Fig. 3; (iii) we enable white-light x-ray magnetic circular dichroism (XMCD) at the Fe *L*-edges utilizing ferromagnetic thin-film polarizers, see Fig. 4.

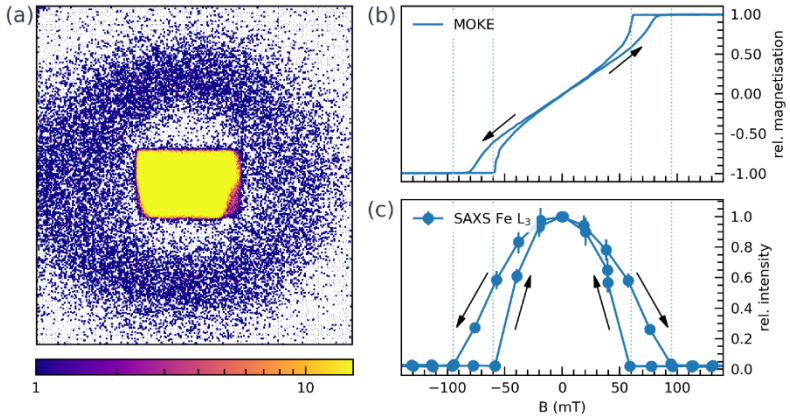


Figure 16: (a) First laser-driven magnetic SAXS scattering pattern (blue ring shape) of an Gd/Fe SL in single-photon-counting mode at the Fe L_3 edge. The rectangular intensity distribution stems from the direct soft-x-ray beam. (b) Average out-of-plane magnetization in dependence of an external magnetic field as probed by optical MOKE. (c) Magnetic SAXS intensity from (a) as a function of an external magnetic field similar to (b).

Our laser-driven approach enables a variety of resonant magnetic scattering and spectroscopy techniques in the soft-x-ray range on a laboratory scale and combines high availability with maximum flexibility in sample handling as well as environmental and excitation conditions. The temporal resolution below 10 ps is well suited to access photoexcited dynamics of, e.g., coherent magnons and phonons, de- and remagnetization processes, including domain dynamics and all-optical magnetic switching.

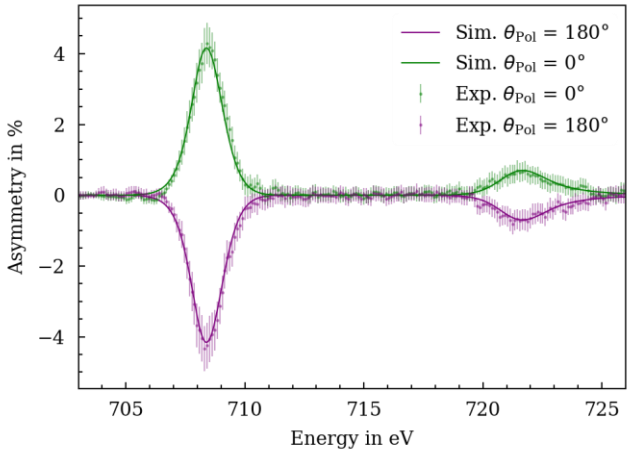


Figure 17: Magnetic asymmetry across the Fe L edges in white-light configuration. The asymmetry was recorded for two opposite polarizer magnetizations, essentially flipping the helecity of the probing light and resulting in a sign-change of the detected asymmetry.

[1] D. Schick, M. Borchert, J. Braenzel, H. Stiel, J. Tümmler, D. E. Bürgler, A. Firsov, C. von Korff Schmising, B. Pfau, and S. Eisebitt, *Laser-Driven Resonant Magnetic Soft-x-Ray Scattering for Probing Ultrafast Antiferromagnetic and Structural Dynamics*, Optica **8**, 1237 (2021).

PII-25: udkm1Dsim – a Python toolbox for simulating 1D ultrafast dynamics in condensed matter

Daniel Schick[1]
[1]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie,
Max-Born-Straße 2A, 12489 Berlin, Germany

The investigation of electronic, magnetic, and structural dynamics in solid-state physics has made great progress during the last decades due to the increasing availability of ultrashort electron and light pulses in a broad spectral range from THz to hard X-rays at large-scale facilities as well as in the laboratory. One of the major goals of these experiments is to follow the coupling of different degrees of freedom on the relevant time and length scales. In order to understand and interpret such experimental data, scientists rely on a pool of simulations for modeling and fitting, which are available as software toolkits or as published formalisms. The implementation of these formalisms or the usage and adaption of available external software packages are very time-consuming and each piece of software covers only a very limited aspect of real time-resolved experiments. To that end, the need for a generic, modular, and open-source toolbox that allows for combining different functionalities is obvious.

The *udkm1Dsim* toolbox [1] allows for creating arbitrary one-dimensional (1D) structures made of crystalline and/or amorphous layers, including stoichiometric mixtures, typically on the nanometer length scale. These 1D structures hold all relevant material information such as structural, elastic, thermal, magnetic, and optical parameters. The toolbox allows for calculating thermal, structural, and magnetic dynamics on these 1D structures utilizing an *N*-temperature model (NTM) and multi-layer absorption formalism, a linear masses-and-springs model, as well as an interface for user-defined magnetization dynamics, respectively. Different types of light-scattering theories can be applied to retrieve the static as well as the transient response from these sample structures due to the above-mentioned dynamics, similar to real pump-probe experiments. Currently, kinematical and dynamical X-ray theories, which can also include polarization-dependent magnetic scattering, are supported. With that, the generally non-linear dependence of the actual observable (scattered light intensity) and the physical quantity of interest (temperature, strain, magnetization, ...) can be revealed. This includes also methods to apply

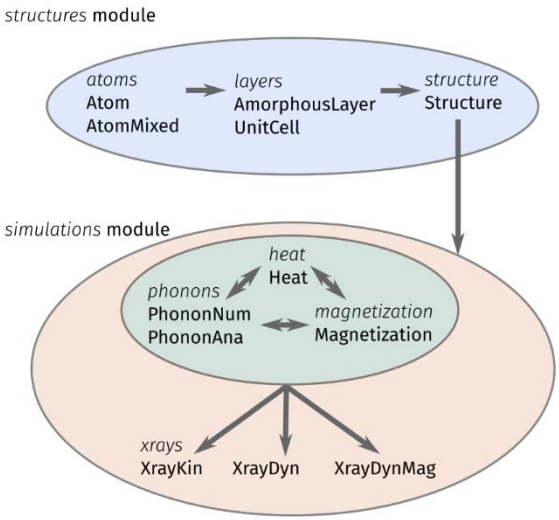


Figure 18: Current structure of the udkm1Dsim simulation toolbox. It consists of a structure module for building 1D samples and a simulation module to carry out time-resolved simulations of heat, phonon, and magnetization dynamics, which can be directly plugged into light scattering formalisms such as dynamical magnetic X-ray scattering.

realistic instrumental broadening to the simulated results for better comparison with experimental data.

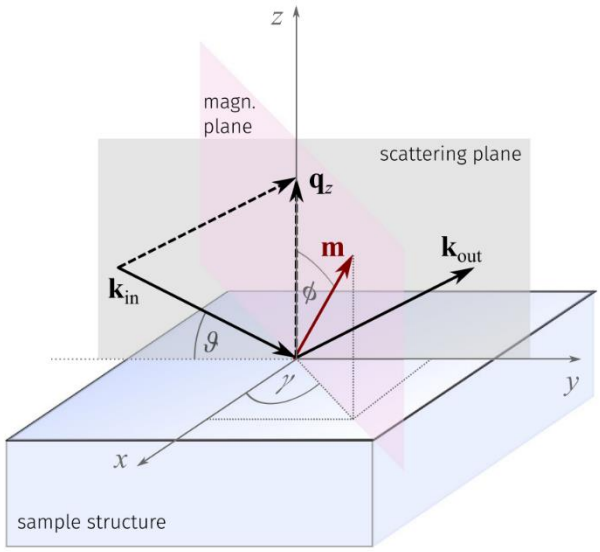


Figure 2: Experimental scheme of the *udkm1Dsim* toolbox. The co-planar scattering plane contains the scattering vector $q_z = k_{out} - k_{in}$. The magnetization *m* of the individual atoms can be defined in 3D by an amplitude and the corresponding angles γ and φ.

The udkm1Dsim is freely available at *github.com/dschick/udkm1Dsim* including full version control, issue-, and feature-tracking, as well as project management capabilities in order to allow for better collaboration between users and developers. This also includes automatic code validation and unit testing, as well as source-code-based generation of the documentation at *udkm1Dsim.readthedocs.org* as part of the continuous integration (CI) concept.

[1] D. Schick, *Udkm1Dsim – a Python Toolbox for Simulating 1D Ultrafast Dynamics in Condensed Matter*, Comput. Phys. Commun. **266**, 108031 (2021).

PII-26: Scattering and Dephasing Effects in Ferromagnetic Model Systems

Kai Leckron[1] and H. C. Schneider[1]

[1] Department of Physics and Research Center OPTIMAS, TU Kaiserslautern

Spin relaxation dynamics in semiconductors have been studied for decades. Two of the commonly used concepts for explaining the observed relaxation times are the Dyakonov-Perel (precessional dynamics around effective k-dependent internal fields) and Elliott-Yafet (EY; "spin-flip") mechanisms [1]. In particular, the concept of EY spin-flips due to electron-phonon scattering has also been applied to magnetization dynamics in ferromagnetic metals as a microscopic picture of how the spin angular momentum is transferred to the lattice on ultrafast timescales [2]. We have recently argued by analyzing electron-phonon scattering dynamics in ferromagnets that spin dephasing (and not individual spin-flip scattering events) is the microscopic process underlying this "Elliott-Yafet" like dynamics in spin-split bands.

This contribution gives an overview of the influence of electron-phonon scattering on an ultrashort time scale in ferromagnetic model band structures and ferromagnetic DFT band structure. It also addresses the question how one can include electron-electron scattering in realistic band structures with limited computational effort. To this end we present strategies to solve the electronic dynamics including electron-electron Boltzmann scattering integrals in a completely density-conserving way on arbitrary k-grids. We also discuss a generalized relaxation-time ansatz [4], which reduces the numerical complexity enormously and can be integrated into transport equations.

[1] I. Žutić, J. Fabian and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).

[2] B. Koopmans et al., Phys. Rev. Lett. **95**, 267207 (2005).

[3] K. Leckron and H. C. Schneider, Phys. Rev. B **96**, 140408 (2018).

[4] C. Scholl et al., Phys. Rev. B **99**, 224421 (2019).

PII-27: All-optical switching of magnetically hard CoPt and $L1_0$-FePt in contact with a Gd-layer

J. Seyd[1], J. Hintermayr[2], M. Albrecht[1], B. Koopmans[2]
[1]Institute of Physics, University of Augsburg, 86159 Augsburg, Germany
[2]Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

All-optical switching (AOS) by single femtosecond laser pulses promises to be an ultrafast and energy-efficient alternative to conventional writing in magnetic recording using magnetic fields. $L1_0$-FePt is a magnetic material with high perpendicular magnetic anisotropy (PMA), which makes it an interesting candidate for future ultrahigh-density magnetic recording applications like heat-assisted magnetic recording (HAMR), and for which helicity-dependent multi-shot AOS has already been confirmed [1].
Thermally-induced single-shot AOS is not only possible in ferrimagnetic alloys with a compensation temperature near room temperature, but also in synthetic ferrimagnets consisting of a ferromagnetic (multi-)layer in contact with a Gd layer, as shown by the example of Co and Co/Ni [2].
These results suggest the possibility of reproducing the same kind of switching in other magnetic thin films, which in the case of $L1_0$-FePt would circumvent the problem of writing the magnetically hard material in magnetic recording applications. Thus one would be able to combine the advantages mentioned above, namely achieving a high-density magnetic storage medium that can be switched on the ps timescale.
We show and compare the most recent results on the thermally-induced AOS behaviour of thin CoPt and $L1_0$-FePt films in contact with a Gd layer.

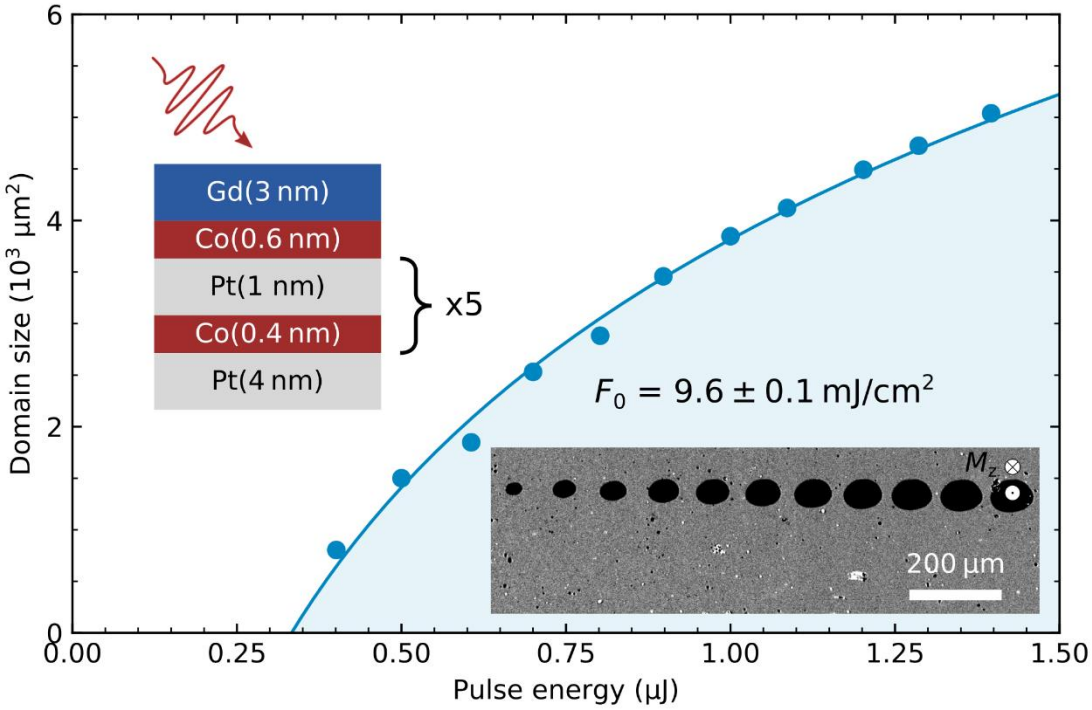


Figure 19: Size of the domains in Pt/[Co/Pt]$_5$/Co/Gd switched by single laser pulses of varying pulse energy. Insets show a schematic of the sample stack and a Kerr microscopy image of areas irradiated with 30 fs laser pulses.

References:
[1] R. John et al., Scientific Reports 7, 4114 (2017)
[2] M. Beens et al., Physical Review B 100, 220409(R) (2019)

PII-28: Ultrafast Magnetization Dynamics in [CoFeB/Pd] Multilayers Down to the Few-cycle Regime

A. S. Silva[1], T. Ferreira[1], S. P. Sá[1], S. A. Bunyaev [1], G. N. Kakazei[1], M. Canhota[1], M. Miranda[1], C. Garcia[2], I. J. Sola[3], D. Navas[4] and H. Crespo[1]

[1]Institute of Physics for Advanced Materials, Nanotechnology and Photonics (IFIMUP)/Dep. de Fisica e Astronomia, Faculdade de Ciências, Universidade do Porto, 4169-007 Porto, Portugal

[2] Dep. de Física y Centro Científico Tecnológico de Valparaíso-CCTVal, Universidad Técnica Federico Santa María, 2390123 Valparaíso, Chile.

[3] Laser Applications and Photonics group, Applied Physics Department, University of Salamanca, E-37008 Salamanca, Spain.

[4] Instituto de Ciencia de Materiales de Madrid, ICMM-CSIC, 28049 Madrid, Spain.centered

Since the first demonstration of the possibility of manipulating the magnetization using femtosecond (fs) laser pulses performed by Beaurepaire et al. in 1996 [1], time-resolved pump-probe measurements based on the magneto-optical effects have provided an invaluable tool for the study of ultrafast magnetic dynamics in many relevant systems [2]. Although rapid advances in ultrafast optical methods have allowed the temporal resolution to be gradually improved, the measurements are routinely performed with few tens of fs. However, achieving an even higher temporal resolution is very important for studying ultrafast processes in matter, such as the spin-orbit coupling, the exchange interaction and the structural anisotropy of the materials, among others. With this in mind, we have developed a unique, compact and versatile time-resolved magneto-optical (TR-MO) system to study ultrafast magnetodynamic processes. Our setup uses state-of-the-art ultrafast optical methods to deliver few-cycle, sub-5-fs, carrier-envelope phase (CEP) stable pump and probe laser pulses at the sample position, permitting the observation of ultrafast magnetization dynamics at unprecedented temporal resolutions in the optical range. The few-cycle regime is also highly promising for the direct excitation and observation of coherent ultrafast magnetodynamic behaviour [3]. Using our TR-MO system, we have performed magnetization dynamics measurements of [CoFeB/Pd] multilayer ultrathin films in different temporal regimes, where we were able to track down processes such as precessional motion [4] and ultrafast demagnetization (Figure 1).

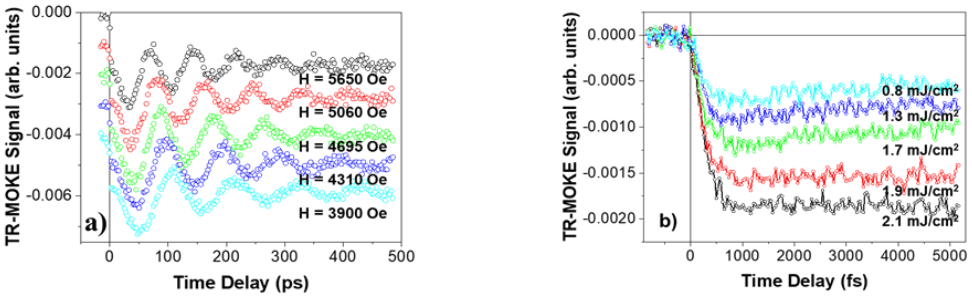


Figure 1: TR-MOKE measurements on the [CoFeB (3 Å) / Pd (10 Å)]5 multilayer thin films (a) with different applied magnetic fields and (b) ultrafast demagnetization curves for different laser fluences.

References:

[1] E. Beaurepaire *et al., Phys. Rev. Lett.* **76**, 4250 (1996).

[2] A. Kirilyuk *et al., Rev. Mod. Phys.* **82**, 2731 (2010); J. Y. Bigot and M. Vomir, *Ann. Phys.* **525**, 2 (2013).

[3] J.-Y. Bigot *et al., Nature Physics* **5**, 515 (2009); F. Siegrist *et al., Nature* **571**, 240 (2019).

[4] A. S. Silva *et al., Sci. Rep.* **11**, 43 (2021)

Acknowledgments: Fundação para a Ciência e a Tecnologia e COMPETE 2020 (FEDER) (POCI-01-0145-FEDER-031302, PTDC/FIS-OTI/32213/2017, UIDB/04968/2021, UIDP/04968/2021); Programa Operacional Temático Factores de Competitividade (NORTE-01-0145-FEDER-022096).

PII-29: Development of ultrafast soft X-ray magnetic holography at SwissFEL

B.V. Sorokin[1], K. Schnorr[1], J. Raabe[1] and S. Finizio[1]

[1]Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

X-ray imaging techniques have enabled a significant advancement in the understanding of the physics driving magnetic systems, thanks to the possibility of combining element sensitive imaging, sensitivity to the magnetic and antiferromagnetic ordering through contrast mechanisms such as X-ray magnetic circular (XMCD) and linear (XLD) dichroism, and high spatial and temporal resolutions. Up to now, most of the X-ray imaging research on spintronics has concentrated on ferromagnetic materials where both the geometric dimensions and characteristic timescales are accessible with synchrotron-based microscopes. However, the constant push towards the investigation of faster processes occurring at smaller length scales is now encouraging the development of novel time-resolved X-ray imaging techniques able to accommodate such requirements.

For X-ray imaging at the ultrafast timescales, free-electron lasers become a necessity. Here, we present an ongoing project devoted to the development of time-resolved magnetic imaging at the ultrafast timescales at the Maloja endstation of the soft X-ray Athos beamline of SwissFEL (PSI, Switzerland). The setup will be based on X-ray holographic imaging [1], which is a lensless coherent diffractive imaging technique where the interference pattern between the X-ray beam crossing the sample and a set of defined references is recorded on a 2D detector, allowing for the recovery of both the amplitude and phase information of the sample by performing a Fourier transform of the recorded interference pattern. Since X-ray holography is an intrinsically drift free technique and a full-field microscopy technique, it is particularly well-suited for free-electron lasers, where shot-to-shot variations render scanning microscopy techniques unsuitable [2, 3].

The recently commissioned Athos beamline of SwissFEL, with its 16 Apple-X undulators, is currently the only soft X-ray free electron laser source (250 to 1800 eV, covering all of the relevant edges of the magnetic elements) with a fully controllable X-ray polarisation. XMCD and XLD then can be used as contrast mechanisms for both ferromagnetic and antiferromagnetic samples. Moreover, both electrical and optical excitation schemes will be available for the time-resolved pump-probe experiments. First beam on the holography endstation is expected in November 2022.

References

[1] Eisebitt, S. et al. Lensless imaging of magnetic nanostructures by X-ray spectro-holography, *Nature* **432**, 885 (2004).

[2] Wang, T. et al. Femtosecond single-shot imaging of nanoscale ferromagnetic order in Co/Pd multilayers using resonant X-ray holography, *Phys. Rev. Lett.* **108**, 267403 (2012).

[3] von Korff Schmising, C. et al. Imaging Ultrafast Demagnetization Dynamics after a Spatially Localized Optical Excitation, *Phys. Rev. Lett.* **112**, 217203 (2014).

PII-30: Ultrafast magnetization dynamics in 2d ferromagnets

N. Stetzuhn[1,2], F. Steinbach[1], M. Borchert[1], C. von Korff Schmising[1], K. I. Bolotin[2], S. Eisebitt[1,3]
[1] Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy
[2] Department of Physics, Freie Universität Berlin
[3] Institut für Optik und Atomare Physik, Technische Universität Berlin

Two-dimensional ferromagnets are one of the latest additions to the family of 2d materials, with CrI_3 being the first material to have shown ferromagnetic order down to the monolayer limit in 2017 [1]. Since then, the number of 2d ferromagnets has steadily grown to include materials such as $CrCl_3$, Fe_3GeTe_2 and $FePS_3$ [2]. One challenge working with these 2d magnets is their lack of environmental stability as well as the cryogenic Curie and Néel temperatures which so far limit their use in real-life devices. Promising candidates to overcome the latter issue are Fe_3GeTe_2 (F3GT) and Fe_5GeTe_2 (F5GT) who already have relatively high Curie temperatures ranging from 200 K to almost room temperature, depending on iron content. Recently, it has been shown that by doping F5GT with nickel, the Curie temperature can be further increased to up to 478 K. In this work, we study the magnetic response of F3GT and F5GT to an ultrafast laser pulse using time-resolved MOKE microscopy. Additionally, we will present first results using magnetic circular dichroism measurements in the extreme ultraviolet (XUV) spectral range to study the element-specific responses using a two-color emission of the free electron laser FERMI, Trieste in Italy.
In first experiments, we conducted spatially and temporally resolved measurements in a MOKE microscopy setup [4]. At low temperatures between 100 and approx. 150 K, we observe a demagnetization time τ_1 in F3GT below our temporal resolution of ~400 fs, as well as a slower component τ_2 of a few picoseconds. The remagnetization takes several nanoseconds and exceeds our measurement window. The high spatial resolution of the time resolved microscope allows us to correlate spatial coordinates with different excitation fluences given by the Gaussian shape of the pump pulse, leading to a full fluence dependence within a single measurement. In figure 1, delay curves extracted from concentric rings around the fluence maximum are shown as an example. Additionally, the ultrafast response of exfoliated FGT flakes with different number of atomic layers is encoded in a single snapshot.
With element-specific measurements using XUV photons tuned to the Fe $M_{2,3}$-edge as well as to the Te $N_{4,5}$ edge, we plan to investigate the role of optical intersite spin transfer (OISTR) recently predicted for F3GT [5]. These measurements are also expected to shed light on the remarkable observation of ultrafast optical doping, leading to light induced ferromagnetism at room temperature [6].
This work presents the stepping-stone for further ultrafast studies using complex 2d heterostructures with well-defined interfaces and tuneable properties like, e.g., strain.

References:
[1] Huang, B., Clark, G., Navarro-Moratalla, E. *et al.* Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit. *Nature* **546,** 270–273 (2017)
[2] Huang, B., McGuire, M.A., May, A.F. *et al.* Emergent phenomena and proximity effects in two-dimensional magnets and heterostructures. *Nat. Mater.* **19,** 1276–1289 (2020)
[3] Xiang Chen et al. arXiv:2203.00125
[4] F. Steinbach, D. Schick, C. von Korff Schmising, K. Yao, M. Borchert, W. D. Engel, and S. Eisebitt, Wide-field magneto-optical microscope to access quantitative magnetization dynamics with femtosecond temporal and sub-micrometer spatial resolution, *J. Appl. Phys.* **130**, 083905 (2021)

[5] Junjie He, Shuo Li, Arkamita Bandyopadhyay, and Thomas Frauenheim, Unravelling Photoinduced Interlayer Spin Transfer Dynamics in Two-Dimensional Nonmagnetic-Ferromagnetic van der Waals Heterostructures. *Nano Letters* **2021 21** (7), 3237-3244
[6] Liu et al., Light-tunable ferromagnetism in atomically-thin Fe3GeTe2 driven by femtosecond laser pulse, *Phys. Rev. Lett.,* **125**, 267205 (2020).

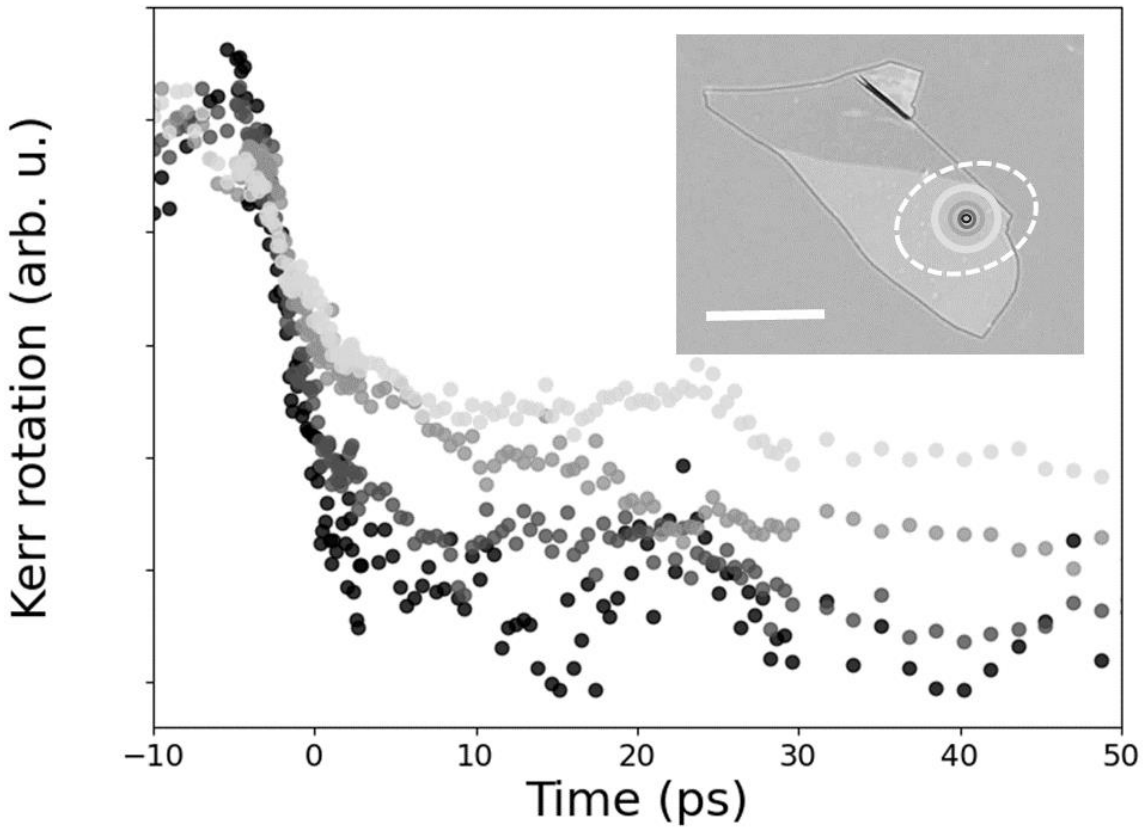


Figure 1: Ultrafast demagnetization curves measured on F3GT at 130 K using a 1030 nm pump and a 515 nm probe laser in a Kerr microscope. The color scale from dark to light grey corresponds to regions of high to low fluence. The curves was extracted from the microscope image in concentric rings around the center of the pump laser spot marked by the dashed line in the inset image. Each curve corresponds to the region bordered on the outside by the circle marked by the same color and on the inside by the following concentric circle. The scale bar corresponds to 10 μm.

PII-31: Magnetisation switching via THz phonons induced by optical pulses

M. Strungaru[1], M. O. A. Ellis[2], S. Ruta[3], R. F. L. Evans[1], R. W Chantrell[1] and O. Chubykalo-Fesenko[4]

[1]University of York, York, UK
[2]University of Sheffield, Sheffield, UK
[3]Sheffield Hallam University, Sheffield, UK
[4]Instituto de Ciencia de Materiales de Madrid, Madrid, Spain

The interaction of magnetic materials with fs laser pulses has shown multiple fundamental effects that culminate in the ability to switch the magnetisation by means of purely optical excitation [1]. The current understanding of these processes employs a thermal description, where the optical pulse is absorbed by the electron sub-system and creates a non-equilibrium distribution that leads to a fast demagnetisation of the spin system and a further relaxation with the lattice. Thermomagnetic switching increases the temperature of potential devices which is not optimal over a device's lifetime, hence non-thermal control of the magnetisation, that can be applied to a large range of magnetic materials (including insulators), needs to be found. There are several mechanisms that could lead to a magnetic response in insulating magnetic systems, such as the inverse Faraday effect, induced magnetic anisotropy, phonon excitation etc. Controlling spins by the optical excitation of phonons has been demonstrated in some materials both experimentally [2,3] and theoretically, showing even the possibility of switching the magnetic order parameter in this way [4].

In this work, we investigate the possibility of non-thermal magnetisation control via THz phonons, which can represent a main optical reversal mechanism in insulators. By employing a unified model of molecular and atomistic spin dynamics, called spin-lattice dynamics (SLD)[5,6], we are able to follow the magnetisation dynamics under phonon excitation at THz frequencies. The transfer of energy and angular momentum between the lattice and spin system is realised by the pseudo-dipolar coupling [7], which arises from the quantum mechanical spin-orbit interaction to act as a local induced anisotropy, and can be parameterised from magneto-elastic experiments[6]. There are two main mechanisms in which strongly pumped phonons in the THz regime can modulate the magnetisation: via the exchange interaction and via the anisotropy and in reality there is a combination of both elements, which is present in SLD modelling. For simplicity, the exchange and lattice parameters have been considered the ones for bcc Fe, since this is a very well-studied material in the spin-lattice dynamics community[5,6]. However, the Gilbert spin damping is neglected (so the system can be treated as an insulator), the relaxation of magnetization happening only via phonon

thermalisation [6].

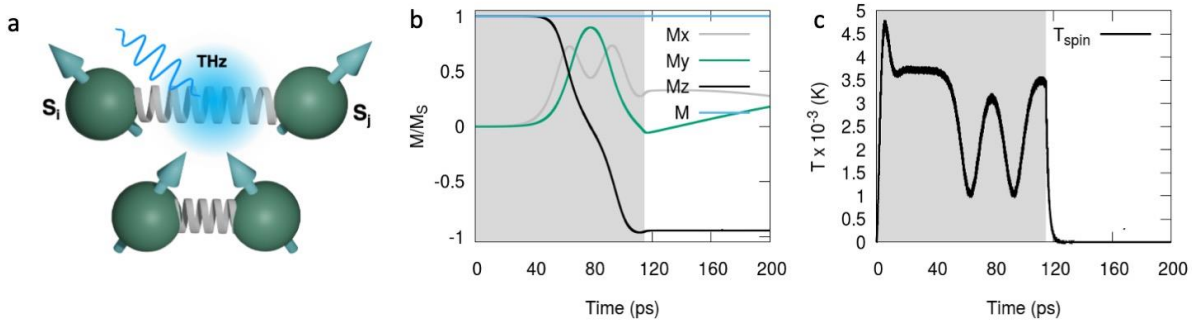


Figure 1: 20 Low-dissipation switching via THz phonons. a) Illustration of excitation of phonons at THz frequencies which via spin-lattice coupling an control the magnetic order. b) Magnetisation dynamics during the application (grey region) and after a THz pulse. The frequency of the pulse width used in the calculations is 8.3THz, the pulse being applied for 115 ps. The evolution of Mz shows a switched state after the application of the pulse, with no change in the total magnetisation. c) Change in the spin temperature during switching via THz phonons. The increase in temperature is in the order of mK, showing a low dissipation process.

Fig. 1 illustrates magnetisation switching via THz phonons within an SLD model of a magnetic insulator. Panel b shows the magnetisation switching when a square pulse of 115ps width and 8.3 THz has been used. The phonons can be excited at different points around the Brillouin zone, in Fig.1 the lattice being excited at the P point in the Brillouin zone corresponding to the phase factor (π/a, π/a, π/a). After the application of the THz pulse, the magnetisation remains in a switched state. During the application of the THz pulse, we observe that the spin temperature is increased in the mK regime (panel c), corresponding to the change in the magnetisation observed in panel b, however no additional heating is developed in the system – hence the non-dissipative nature of the process. In the case shown in Fig. 1, the switching appears via the development of an in-plane magnetoelastic field leading to a full precessional switching of the system. However, by changing the phonon spectra (which in simulations is obtained by employing a different mechanical potential) it is possible to observe complex phonon mode decaying and switching phase diagrams. We observe that the switching via THz phonons is dependent on multiple factors; such as the available phonon and magnon modes frequencies, the density of states of the phonons which can promote more efficient coupling of the phonons to the THz excitation and the spectral properties of the spin-lattice coupling term, which is able to increase the efficiency of this process. This work demonstrates the viability of ultrafast magnetisation control without direct heating from the fs laser.

References:

[1] TA Ostler et al., Nature Communications, 3(1):1–6, 2012.
[2] JW Kim, Mircea Vomir, and Jean Yves Bigot, Physical Review Letters, 109(16):1–5, 2012.
[3] AV Scherbakov et al., Physical Review Letters, 105(11):1–4, 2010.
[4] O Kovalenko et al., Physical Review Letters, 110(26):1–5, 2013.
[5] PW Ma et al., Physical Review B, 78(2):024434, 2008.
[6] M Strungaru et al., Phys. Rev. B 103, 024429, 2021.
[7] JH Van Vleck, Physical Review, 52(11):1178–1198, 1937.

PII-32: Broadband, ultrafast magneto-optics of layered ferromagnet $Cr_2Ge_2Te_6$

E. Sutcliffe[1], X. Sun[2], I. Verzhbitskiy[2], G.Eda[2], J. O. Johansson[2]
[1]EaStCHEM, School of Chemistry, The University of Edinburgh
[2]Department of Physics, National University of Singapore

$Cr_2Ge_2Te_6$ (CGT) is a two-dimensional ferromagnetic material and is predicted to have rich magneto-optic properties [1], which makes it an ideal candidate for studying ultrafast magnetisation effects. However, while groups have observed ultrafast magnetisation dynamics in the material [2,3], no-one has measured ultrafast changes to its spectral properties, yet this can provide valuable insights into the processes occurring within the material. Here we describe a pump-probe spectrometer designed to simultaneously measure broadband changes in transmission and polarisation [4]. A magnetic field of up to 0.4 mT is applied across the sample, and some of the probe is used as a reference to enable shot-by-shot referencing at 1kHz. The change in transmission of a circularly polarised white-light probe pulse through the sample upon reversal of this field gives the change in ellipticity caused by the sample. Through this scheme, we can measure ellipticity changes as small as 0.5 mdeg, and can also measure rotation to similar precision with a small change to the setup. Samples consisting of exfoliated crystals of CGT (~10^3 μm^2) on a transparent substrate were excited by an 800 nm pump pulse of 70fs duration. Transient transmission and ellipticity spectra were measured up to a nanosecond for several fluences (0.1 - 0.5 $mJcm^{-2}$) and temperatures (20 - 82 K). Analysis of the resulting spectra revealed type II magnetisation dynamics and substantial dichroic bleaching.

References:

1. Yimei Fang, Shunqing Wu, Zi Zhong Zhu, and Guang Yu Guo. *Large magneto-optical effects and magnetic anisotropy energy in two-dimensional $Cr_2Ge_2Te_6$*. Phys. Rev. B, 98(12):125416, 2018.
2. Tao Sun, Chun Zhou, Zhongzhu Jiang, Xiaoming Li, Kang Qiu, Ruichun Xiao, Caixing Liu, Zongwei Ma, Xuan Luo, Yuping Sun, and Zhigao Sheng. *Ultra-long spin relaxation in two-dimensional ferromagnet $Cr_2Ge_2Te_6$ flake*. Applied Physics Letters, 116(22):223103, 2020.
3. Tongyao Zhang, Yuansen Chen, Yanxu Li, Zhichao Guo, Zhi Wang, Zheng Han, Wei He, and Jing Zhang. *Laser-induced magnetization dynamics in a van der waals ferromagnetic cr2ge2te6 nanoflake.* Applied Physics Letters, 116(22):223103, 2020.
4. Jake Sutcliffe and J. Olof Johansson. *A femtosecond magnetic circular dichroism spectrometer.* Review of Scientific Instruments, 92(11):113001, 2021.

PII-33: Ultrafast spin dynamics in magneto-photonic crystals

D.A. Sylgacheva[1,2,3], V.A. Ozerov[1,4], M.A. Kozhaev[1], A.N. Kalish[1,2], and V.I. Belotelov[1,2,3]
[1]Russian Quantum Center, Skolkovo, Moscow, Russia
[2]Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia
[3]Vernadsky Crimean Federal University, Simferopol, Russia
[4]Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Russia

It was demonstrated in the first decade of the century that circularly polarized femtosecond laser pulses can trigger fast coherent spin dynamics in a magnetic medium via the ultrafast inverse Faraday effect (IFE) [1]. IFE is described by a pulse of effective magnetic field that appears inside a magnetic medium during the propagation of a laser pulse. If the induced effective magnetic field is not co-directed with the spins, it launches spin dynamics and spin waves, particularly [2]. So far, the main progress in ultrafast laser excitation of spin dynamics via opto-magnetic effects has been achieved for homogeneous films and bulk crystals. However, the nanophotonic approach (in particular, magneto-photonic crystals) offers new benefits that they allow 3D localization of light by tailoring different optical modes which is very advantageous for opto-magnonic applications since allows to engineer spin dynamics patterns and control the spin waves.

In our work we consider two different types magnetophotonic crystals (MPC): (i) the microcavity MPC having nonmagnetic Bragg mirrors and magnetic cavity layer and (ii) the all-garnet MPC having magnetic layers in both cavity and Bragg mirrors. We demonstrate the Inverse Faraday effect induced by fs-laser pulses inside MPCs. Theoretically and experimentally, it is shown that non-uniform distribution of the femtosecond optical power within the microcavity MPC induce the effective field of the inverse Faraday effect also spatially non-uniform inside the magnetic cavity. It results in excitation of perpendicular standing spin waves (PSSWs). PSSWs whose wavevector is closest to the wavevector characterizing distribution of the inverse Faraday effect field are excited most efficiently. Consequently, a key advantage of this approach is a selectivity of the PSSW excitation which allows to launch PSSWs of required orders. In case of the all-garnet MPC containing magnetic layers not only in the nanocavity but also in the Bragg mirrors surrounding the cavity the spin dynamics is excited not only in the nanocavity but in different parts of the structure which are spatially tunable by modifying the pump laser wavelength. The optical impact on the spins caused by the inverse Faraday effect and spectrum of this effect are found to correlate mostly to the direct Faraday effect.

Thus, we introduce a new concept for extending spatial and spectral tunability of the opto-magnetic excitation of spin waves. We believe that our study represents a significant step forward and the results pave the way to the ultrafast optical control of magnetization dynamics at a sub-wavelength scale that is vital for modern magneto-photonics and magnonics.

This work was financially supported by the Russian Ministry of Education and Science, Megagrant project N 075-15-2019-1934.

Reference

[1] A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, and T. Rasing, ‘‘Ultrafast non-thermal control of magnetization by instantaneous photomagnetic pulses,’’ Nature, vol. 435, pp. 655−657, 2005.
[2] T. Satoh, Y. Terui, R. Moriya, et al., ‘‘Directional control of spin-wave emission by spatially shaped light,’’ Nat. Photonics, vol. 6, pp. 662−666, 2012.
[3] V. A. Ozerov, D. A. Sylgacheva, M. A. Kozhaev, et al., ‘‘One-dimensional optomagnonic microcavities for selective excitation of perpendicular standing spin waves,’’ J. Magn. Magn Mater., vol. 543, p. 168167, 2022.
[4] M. A. Kozhaev, A. I. Chernov, D. A. Sylgacheva, et al., ‘‘Giant peak of the Inverse Faraday effect in the band gap of magnetophotonic microcavity,’’ Sci. Rep., vol. 8, pp. 1−7, 2018.
[5] D.A. Sylgacheva, N.E. Khokhlov, P.I. Gerevenkov, et al., ‘‘Spatially selective excitation of spin dynamics in magneto-photonic crystals by spectrally tunable ultrashort laser pulses,’’ Nanophotonics in press, 2022.

PII-34: Nonequilibrium sub–10 nm spin-wave soliton formation in FePt nanoparticles

Diego Turenne[1], A. Yaroslavtsev[1,2], X. Wang[1], V.Unikandanuni[3], I. Vaskivskyi[4], M. Schneider[5], E. Jal[6], R. Carley[2], G. Mercurio[2], R. Gort[2], N. Agarwal[2], B. Van Kuiken[2], L. Mercadier[2], J. Schlappa[2], L. Le Guyader[2], N. Gerasimova[2], M. Teichmann[2], D. Lomidze[2], A. Castoldi[7,8], D. Potorochin[2,9,10], D. Mukkattukavil[1], J. Brock[11], N. Zhou Hagström[3], A. H. Reid[12], X. Shen[12], X. Wang[12], P. Maldonado[1], Y. Kvashnin[1], K. Carva[13], J. Wang[14], Y. K. Takahashi[14], E. E. Fullerton[11], S. Eisebitt[5,15], P. M. Oppeneer[1], S. Molodtsov[2,10], A. Scherz[2], S. Bonetti[3,16], E. Iacocca[17,18], H. A. Dürr[1]

[1]Department of Physics and Astronomy, Uppsala University, 751 20 Uppsala, Sweden
[2]European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
[3]Department of Physics, Stockholm University, 106 91 Stockholm, Sweden
[4]Complex Matter Department, Jožef Stefan Institute, Ljubljana, Slovenia
[5]Max-Born-Institut, Berlin, Germany
[6]Sorbonne Université, CNRS, Laboratoire de Chimie Physique-Matière et Rayonnement, 75005 Paris, France
[7]Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano, Italy
[8]Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy
[9]Deutsches Elektronen-Synchrotron 22607 Hamburg, Germany
[10]Institute of Experimental Physics, Technische Universität Bergakademie Freiberg, 09599 Freiberg, Germany
[11]Center for Memory and Recording Research, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0401, USA
[12]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[13]Faculty of Mathematics and Physics, Department of Condensed Matter Physics, Charles University, Ke Karlovu 5, 121 16 Prague, Czech Republic
[14]Magnet Materials Unit, National Institute for Materials Science, Tsukuba 305-0047, Japan
[15]Institut für Optik und Atomare Physik, Technische Universität Berlin, Berlin, Germany
[16]Department of Molecular Sciences and Nanosystems, Ca' Foscari University of Venice, 30172 Venice, Italy
[17]Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle upon Tyne NE1 8ST, UK
[18]Center for Magnetism and Magnetic Materials, University of Colorado Colorado Springs, Colorado Springs CO 80918, USA

Magnetic nanoparticles such as FePt in the $L1_0$ phase are a medium being used for laser assisted magnetic storage due to their high magneto-crystalline anisotropy also strongly couples the atomic lattice to the spin lattice.

In our recently published paper [1] we have shown an alternative method of generating spin wave solitons and with it, a record small sub-10 nm size.

Magnetic droplet solitons are dynamical magnetic textures that may form in materials with perpendicular magnetic anisotropy due to the condensation of spin-waves in highly non-equilibrium conditions [2,3].

Up to now, access to spin wave solitons has been granted through spin torque devices, where the dampening can be offset by an injected spin polarized current [2,3].

Instead of using a contact, a highly nonlinear magnetic oscillations can be driven with a single fs laser pulse and then observed with x-rays in a pump-probe setup as shown in Fig. 1-A. The pulse also drives oscillations in the lattice, which interacts with the magnetic mode, a sketch of this can be seen in Fig.1-B, and experimental results in Fig.1-C. The oscillations are

characteristic of interaction with a confined magnetic mode shown in Fig.1-D. The observed magnetic mode has a record size below 10nm and a high precession frequency close to the THz range.

These results place FePt as a candidate platform to study non-equilibrium magnetism in the sub 10 nm scale which has implications for the future of magnetic information storage, communication and processing.

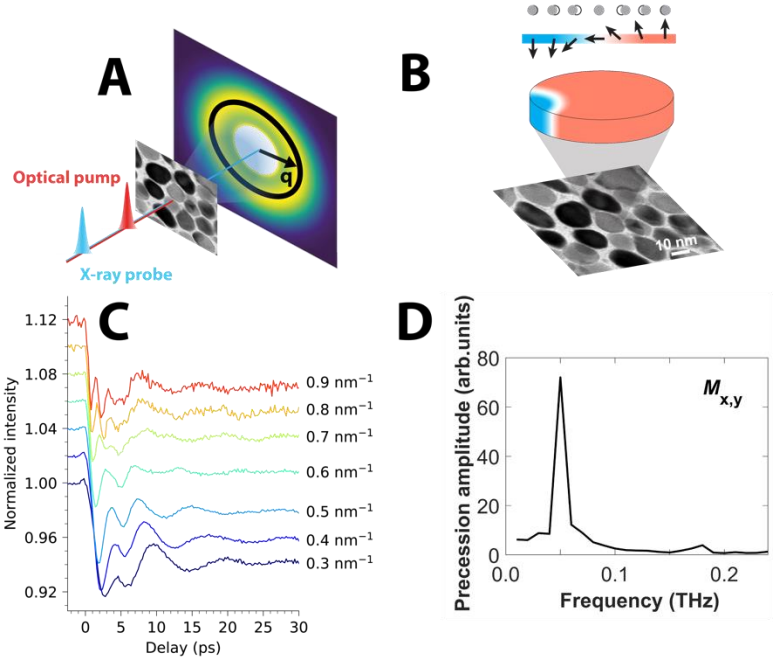


Figure 1: (**A**) Bottom panel: TEM image of granular FePt sample. Middle panel: the magnetization distribution over a single FePt grain: the red, spin-up area corresponds to the "normal" particle, while the blue, spin-down area corresponds to the spin wave soliton. Top panel: the magnetization (colors and arrows) and atomic displacements (open and gray circles) due to the magneto-elastic coupling. (**B**) In-plane magnetization precession frequency calculated for a single nanoparticle with MuMax3. (**C**) Experimental setup used with the transfer wavevector **q** defined as shown. (**D**) Experimental results, at least two frequencies with different dispersion are seen at every q vector. the curves are offset on the y axis for readability.

References:

[1] D. Turenne et al., Nonequilibrium sub–10 nm spin-wave soliton formation in FePt nanoparticles. Sci. Adv. **8**, eabn0523 (2022)

[2] Ferran Macià and Andrew D. Kent, Magnetic droplet solitons. J. Appl. Phys. **128**, 100901 (2020)

[3] M. A. Hoefer, T. J. Silva, M. W. Keller, Theory for a dissipative droplet soliton excited by a spin torque nanocontact. Phys. Rev. B **82**, 054432 (2010)

PII-35: Tuning magnetic and spin-orbitronics properties in synthetic ferrimagnetics

S. Valoti[1,2], H. Damas[1], A. Anadon[1], H. Ren[2], S. Petit-Watelot[1], S. Mangin[1], M. Hehn[1], A. D. Kent[2] and J-C. Rojas-Sánchez[1]

[1]Université de Lorraine, CNRS, Institute Jean Lamour, F-54000 Nancy, France

[2]Center for Quantum Phenomena , Department of Physics, New York University, NY 10003, USA

Ferrimagnetic alloys based on transition metals and rare earths, RE-TM, have recently positioned themselves in the field of spintronics and spin-orbitronics [1-7]. RE-TM alloys show interesting properties: their magnetization and anisotropy can be tuned by changing composition and/or temperature and they can easily be integrated in other heterostructures while keeping strong Perpendicular Magnetic Anisotropy (PMA) [3]. Moreover, amorphous GdFeCo has recently been shown to have bulk Dzyaloshinskii Moriya interactions (DMI) [4] and interfacial DMI has been found in CoGd [5]. It has also been demonstrated that when a current is applied there is a self-torque in the presence of good spin-sink [6], and that they can also be good spin-current generators [6,7]. Another interesting type of heterostructure to study would be (RE/TM) synthetic ferrimagnetic [8] materials and more specifically (RE/TM)n multilayers where n represents the number of repetitions.

In this work we present experimental results of the magnetic properties, such as magnetic compensation temperature (T_M) which correspond to the temperature at which the net magnetization is zero, and spintronic properties, such as spin-orbit torque in Pt/(Co/Gd)n/X/Al multilayers. We report the evolution of T_M with the number of repetitions for n=1 and 2, as well as with the thickness of the Gd layer. Furthermore, we study these properties for different X layers, X=Pt, Ta and Al.

This work was partially supported by European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement Nº 101007825 ULTIMATE-1. Devices in the present studied were patterned at IJL's MiNaLor cleanroom which is partially funded by Region Grand Est trough RANGE project. Research at NYU was supported by NSF-DMR-2105114.

[1] J. Finley & L. Liu, Appl. Phys. Lett. 116, 110501 (2020)
[2] S. K. Kim et al., Nat. Materials 21, 24 (2022).
[3] T. Pham et al., Phys. Rev. Appl. 9, 064032 (2018)
[4] D. H. Kim et al., Nat. Materials 18, 685 (2019)
[5] Y. Quessab et al., Sc. Rep. 10, 7447 (2020)
[6] D. Céspedes-Berrocal et al., Advanced Materials 33, 2007047 (2021)
[7] H. Damas et al., Phys. Status Solidi RRL, 2200035 (2022)
[8] M. Martini et al. Phys. Rev. Applied 17, 044056 (2022)

PII-36: Energy efficient single pulse switching of $[Co/Gd/Pt]_N$ nanodisks using surface lattice resonances

M. Vergès[1], S. Perumbilavil[2], J. Hohlfeld[1], F. Freire-Fernández[3], Y. LeGuen[1,2], G. Malinowski[1], D. Lacour[1], M. Hehn[1], S. van Dijken[2], S. Mangin[1]

[1]Université de Lorraine, Institut Jean Lamour, UMR CNRS 7198, Nancy 54011, France
[2]Department of Applied Physics, Aalto University School of Science, P.O. Box 15100, FI-00076 Aalto, Finland
[3]Department of Materials Science and Engineering and Department of Chemistry, Northwestern University, Evanston, Illinois 60208, United States

Plasmonic surface lattice resonances, visible in periodic arrays of nanodisks, arise from radiative coupling between the localized surface plasmon resonance[1-3] of individual particles and diffracted orders[4]. Here, we study the impact of these optical modes on the magneto-optical properties[5,6] and energy absorption efficiency[7] of $[Co/Gd/Pt]_N$ nanodisks by measuring the response of different arrays to optical excitations as function of the light wavelength, the disk diameter, and the array period. We demonstrate that surface lattice resonances allow All-Optical single pulse switching[8,9] of the nanodisks using much less energy than for the thin film, with an energy absorption enhanced by more than 400 %. Besides, these optical modes enhanced the magneto-optical Faraday effect by more than a 2 000 %. The influence of the disk diameter and array period on the amplitude, width and position of the resonances is in qualitative agreement with theoretical calculations and opens the way to design magnetic metasurfaces for all-optical magnetic recording whose energy efficiency and magneto-optical read-back sensitivity are optimized for any given light wavelength.

[1] Liu, T.-M., *et al.* Nanoscale Confinement of All-Optical Magnetic switching in TbFeCo – Competition with Nanoscale Heterogeneity. Nanoletters, 15:6862 – 6868, 2015.
[2] Savoini, M., *et al.* Highly efficient all-optical switching of magnetization in GdFeCo microstructures by interference-enhanced absorption of light. Physical Review B, 86:140404, 2012.
[3] Cheng, F., *et al.* All-Optical Manipulation of Magnetization in Ferromagnetic Thin Films Enhanced by Plasmonic Resonances. Nanoletters. 20:6437 – 6443, 2020.
[4] Kataja, M., *et al.* Surface lattice resonances and magneto-optical response in magnetic nanoparticle arrays. Nature Communications, 6:1 – 8, 2015.
[5] Freire-Fernández, F., *et al.* Surface-plasmon-polariton driven narrow-linewidth magneto-optics in Ni nanodisk arrays. Nanophotonics, 9:113 – 121, 2019.
[6] Freire-Fernández, F., *et al.* Magnetoplasmonic properties of perpendicularly magnetized $[Co/Pt]_N$ nanodots. Physical Review B, 101:054416, 2020.
[7] Kataja, M., *et al.* Plasmon-induced demagnetization and magnetic switching in nickel nanoparticle arrays. Applied Physics Letters, 112:072406, 2018.
[8] Radu, I., *et al.* Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins. Nature, 472:205 – 208, 2011.
[9] Lalieu, M. L. M., *et al.* Deterministic all-optical switching of synthetic ferrimagnets using single femtoseccond laser pulses. Physical Review B, 96:220411, 2017.

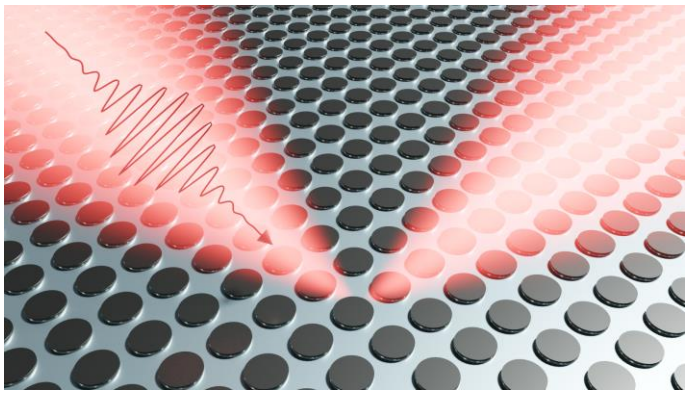


Figure 1: Magnetic $[Co/Gd/Pt]_N$ metasurface.

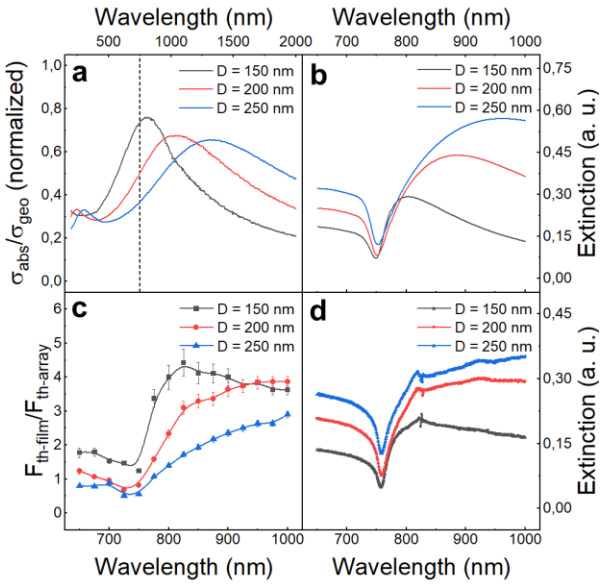


Figure 2: a) Normalized absorption efficiency for single $[Co/Gd/Pt]_2$ disks, showing localized surface plasmon resonance. b) Calculated extinction for metasurfaces with P = 500 nm and different nanodisk diameters. c) Ratio of the AOS threshold fluence measured on the film and metasurfaces with P = 500 nm and different nanodisk diameters. d) Optical extinction spectra of the same metasurfaces as in b) and c).

PII-37: Laser-induced ultrafast demagnetization and perpendicular magnetic anisotropy reduction in a $Co_{88}Tb_{12}$ thin film with stripe domains

M. Hennes[1], A. Merhe[1], X. Liu[1], V. Chardonnet[1], E. Jal[1], G. Malinowski[2], M. Hehn[2], F. Capotondi[3] ,E. Pedersoli[3], J. Lüning[1] and B. Vodungbo[1]

[1]Sorbonne Universite, CNRS, Laboratoire de Chimie Physique—Matière et Rayonnement, LCPMR, 75005 Paris, France

[2]Institut Jean Lamour, CNRS, Université de Lorraine, 54000 Nancy, France

[3]FERMI, Elettra-Sincrotrone Trieste, 34149 Basovizza, Trieste, Italy

Since its discovery by Beaurepaire and coworkers in 1996 [1], the phenomenon of laser induced ultrafast demagnetization has attracted world-wide attention and created an entirely new research field in magnetism named femtomagnetism [2]. Following 25 years of ongoing experimental and theoretical research, the underlying mechanisms of the rapid decrease of the magnetization of a ferromagnetic film on the femtosecond time scale after a femtosecond optical excitation remains intensively debated. The scientific challenge to explain this magnetization dynamics with its associated energy and angular momentum transfer between the electron/spin system and the crystalline lattice occurring on a sub-picosecond time scale is at the base of this strong interest.

Here we will describe a time resolved X-ray resonnant magnetic scattering (TR-XRMS) experiment on amorphous $Co_{88}Tb_{12}$ thin films with magnetic stripe domains conducted at the free-electron laser FERMI. Although several femtomagnetism studies have already been performed on ferrimagnetic Co-Tb [3], a material system of great tech- nological relevance for future all optical magnetic data storage [4], experiments describing the evolution of magnetic domain structures in rare earth–transition metal alloys following an ultrashort optical pulse are still scarce. Recently, Fan et al. performed a TR-XRMS study on $Co_{88}Tb_{12}$ samples using a tabletop high harmonics source but their analysis remained limited to the first magnetic diffraction order at the N edge of Tb (155 eV) [5].

In the present work [6], we complement their findings using different probe beam energies and deepen the analysis by using an experimental setup that allows us to record the first and third magnetic diffraction order simultaneously. With this, we are able to explicitly monitor the pump-induced evolution of the periodic magnetic structure, i.e., the change of domain size and domain wall width with the highest accuracy up to 120 ps.

We show that the average domain wall width starts to increase after about 5 ps with a time constant of a few picoseconds and remains higher for at least 120 ps. With the support of static magnetometry measurements, we argue that his increase is due to a decrease of the perpendicular anisotropy constant of our thin films. Our results thus reveal the time scale on which the magnetic domain structure is affected by a change of the magnetic anisotropy.

References:

[1] E. Beaurepaire *et al.*, Phys. Rev. Lett. **76**, 4250 (1996).
[2] A. Kirilyuk *et al.*, Rev. Mod. Phys. **82**, 2731 (2010).
[3] V. López-Flores *et al.*, Phys. Rev. B **87**, 214412 (2013).
[4] M. S. El Hadri *et al.*, Phys. Rev. B **94**, 064419 (2016).
[5] G. Fan *et al.*, Optica **9**, 399 (2022).
[6] M. Hennes *et al.*, Phys. Rev. B **102**, 174437 (2020).

PII-38: All-optical switching on the nanometer scale excited and probed with femtosecond extreme ultraviolet pulses

K. Yao, F. Steinbach, M. Borchert, D. Schick, D. Engel,F. Bencivenga,R. Mincigrucci, L Foglia, E. Pedersoli, D. De Angelis, M. Pancaldi, B. Wehinger, F. Capotondi, C. Masciovecchio, S. Eisebitt and C. von Korff Schmising

[1] Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, 12489 Berlin, Germany
[2]Elettra Sincrotrone Trieste S.C.p.A34149 Basovizza (TS), Italy
[3]Department of Molecular Sciences and Nanosystems, Ca' Foscari University of Venice, 30172 Venezia Mestre, Italy
[4]Institut für Optik und Atomare Physik, Technische Universität Berlin, 10623 Berlin, Germany

Ultrafast control of magnetization on the nanometer length scale, in particular all-optical switching (AOS), is key to putting ultrafast magnetism on the path towards future technological applications. Here, we present results on nanoscale magnetization dynamics in GdFe employing transient magnetic grating spectroscopy in the extreme ultraviolet (XUV) spectral range at the free-electron laser facility FERMI [1,2]. By examining the simultaneously recorded first and second diffraction orders and performing all-optical reference measurements in real space, we demonstrate the ultrafast emergence of all-optical switching on the nanometer length scale [3]. Furthermore, we will discuss recent data with increased spatial resolution down to a 17 nm grating period.

We excite a ferrimagnetic Ta(3 nm)/$Gd_{24}Fe_{76}$(20 nm)/Ta(3 nm) sample by interfering two coherent XUV pulses and generating a transient magnetic grating (TMG) with a period of 87 nm. We probe the spatial evolution of the TMG by diffracting a time-delayed, third XUV pulse tuned to the Gd *N*-edge at 150 eV (cf. Fig. 1e) and simultaneously record the first and second diffraction orders (Fig. 1f, g). Due to the characteristic and strongly nonlinear fluence dependence of AOS, the magnetization reversal is accompanied by a changing shape of the TMG profile, with a line-to-space ratio different from the initial sinusoidal excitation pattern (Fig. 1a). As the intensity of the second and *forbidden* diffraction order is particularly sensitive to such symmetry changes, we can conclusively demonstrate the emergence of AOS in reciprocal space. To corroborate our conclusions, we performed additional measurements on the same sample using a wide-field magneto-optical microscope in the visible spectral range (Fig. 1b) and directly image in real space how the periodic excitation evolves into a pattern with switched magnetization regions (Fig. 1c). A Fourier analysis yields the corresponding signal in reciprocal space (Fig. 1d) and serves as a reference to verify the results of the diffraction experiment [3].

We also present new results from very recent transient grating experiments with periodicities down to 17 nm, where ultrafast lateral transport processes equilibrate the excitation gradients within only a few picoseconds, expected to define a fundamental spatial limit for AOS.

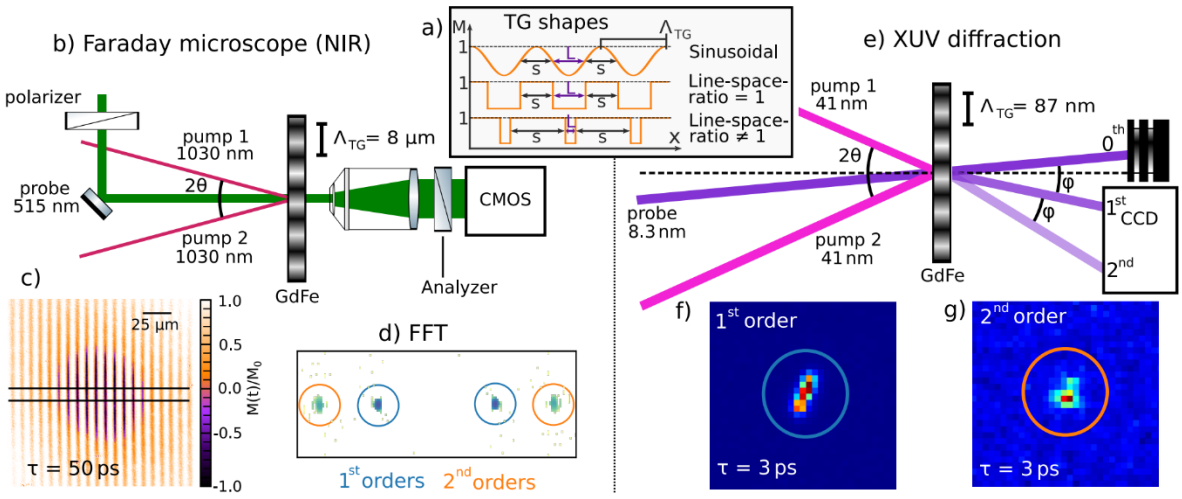


Figure 1: (a) Schematic examples of transient magnetic grating shapes with different line (l) and space (s) widths: sinusoidal, described by only the first Fourier component in reciprocal space; equal line and space width (line–space ratio = 1) with suppression of even Fourier components; unequal line and space widths (line–space ratio ≠ 1), exhibiting the first, second, and higher Fourier components. (b) Widefield, magneto-optical microscope probes the evolving magnetization pattern via the Faraday effect. (c) Real-space image depicting the TMG at a delay of τ = 50 ps with corresponding (d) Fourier transform. (e) Diffraction experiment at the free-electron laser (FEL) facilities FERMI in Trieste, Italy. The interference of two XUV pump pulses generates a TMG with a periodicity of Λ_{TMG} = 87 nm. The first (f) and second (g) order diffractions of a time-delayed, resonant XUV probe pulse at 8.3 nm (150 eV) are simultaneously recorded by a CCD camera. Adapted from [3].

References:

[1] F. Bencivenga et al., *Nanoscale transient gratings excited and probed by extreme ultraviolet femtosecond pulses,* Science Advances 5 (2019). https://doi.org/10.1126/sciadv.aaw5805

[2] D. Ksenzov et al., *Nanoscale Transient Magnetization Gratings Created and Probed by Femtosecond Extreme Ultraviolet Pulses*, Nano Lett. **21**, 2905 (2021). https://doi.org/10.1021/acs.nanolett.0c05083

[3] K. Yao et al., *All-Optical Switching on the Nanometer Scale Excited and Probed with Femtosecond Extreme Ultraviolet Pulses*, Nano Letters, online (2022). https://doi.org/10.1021/acs.nanolett.2c01060

PII-39: Theory of THz-Driven Rare-Earth Dynamics in $RFeO_3$

M.R. Vovk[1], E.V. Ezerskaya[2], R.V. Mikhaylovskiy[1]
[1]Department of Physics, Lancaster University, Bailrigg, Lancaster LA1 4YW, United Kingdom
[2]Department of Physics, V. N. Karazin Kharkiv National University, Svobody Sq. 4, Kharkiv 61022, Ukraine

One of the most intriguing issues of modern data storage technologies is the creation of devices that allow information recording in an ultrafast way and with minimal energy losses. From the theory of magnetism, we know that the existence of the exchange interaction between neighboring spins is responsible for creating a long-range magnetic ordering. Therefore, one of the possible realizations of ultrafast recording could be the switching of the exchange between the spins with subsequent writing in the form of a standard "0,1" binary code.

In this regard, the Rare Earth Orthoferrites (REO) compounds can be promising recording media due to their intrinsic properties like a strong exchange interaction between 3*d* iron and 4*f* rare-earth magnetic ions. As has been shown recently in [1,2] by using ultrashort intense coherent THz radiation (See Fig.1 a) one can modify REO *f-d* exchange and induce a strongly nonlinear regime of spin dynamics with subsequent switching of the magnetic order. In this way, theoretical description of nonlinear dynamics behaviour of coupled 4*f* rare-earth ions orbitals and 3*d* Iron ions spins has become an important subject to investigate.

However, to the present moment, only the role of Iron spins dynamics has been well understood, but the rare-earth subsystem's role has remained largely unexplored. Here, based on the theoretical formalism proposed in [3], we derive and calculate the response of the rare-earth orbitals to the strong THz excitation. Thus by using mean-field theory approximation, we have got a thermodynamic potential of the system which we used to obtain the set of equations of motion to describe the dynamics of rare-earth subsystem. Then by solving them numerically, we were able to model the behaviour of coupled rare-earth and Iron subsystems (See Fig.1b).

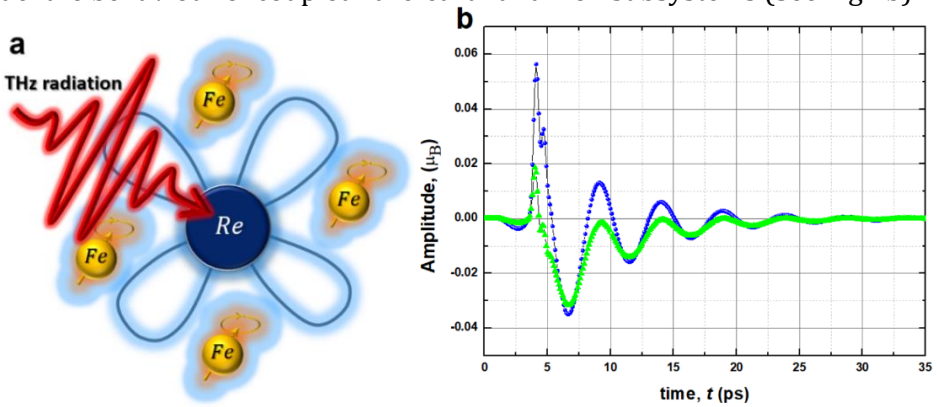


Fig.1 (a, b). Panel a shows the general idea of how strong THz radiation excites heavy Rare Earth ions and therefore modulates the *f-d* exchange interaction with Iron ions. Panel b shows calculated dynamics of rare-earth magnetic moment components μ_x and μ_y driven by realistic waveform of the THz pulse.

References

[1] S. Baierl, et al. Nature Photonics 10, 715 (2016).
[2] S. Schlauderer, et al. Nature 569, 383 (2019).
[3] A. M. Balbashov, et al. Sov. Phys. JETP 68, 629–638 (1989).

PII-40: Spin-dependent carrier dynamics in antiferromagnetic model systems

Marius Weber[1], K. Leckron[1], B. Rethfeld[1], B. Stadtmüller[1,2] and H. C. Schneider[1]

[1] Department of Physics and Research Center OPTIMAS, TU Kaiserslautern
[2] Institute of Physics, Johannes Gutenberg University Mainz

The Elliot-Yafet mechanism for the relaxation of an electronic spin polarization was originally developed for the case of electron-phonon scattering in Kramers degenerate bands in semiconductors and metals, where spin hot-spots may play an important role[1]. For the case of magnetization dynamics in ferromagnetic metals one often also employs the concept of Elliott-Yafet spin-flip scattering as a microscopic picture of how the spin angular momentum is transferred to the lattice on ultrafast timescales [2]. We have recently shown using a microscopic calculation of the k-resolved spin-density matrix for a *ferromagnetic* model system that this picture is not rigorously correct as precessional dynamics around internal spin-orbit and exchange fields together with a spin-independent scattering mechanism (such as electron-phonon scattering) play a central role [3].

Here, we use the microscopic approach of [3] to calculate the electronic dynamics in antiferromagnetic model systems, such as the minimal model discussed in [4]. Its band structure is anisotropic (see Fig. 1) with two twofold degenerate bands and pronounced spin mixing. We numerically study the spin-resolved electronic dynamics for different scenarios of spin-polarized anisotropic excitation, such as spin injection and k-selective spin flips, as shown in Fig. 1.

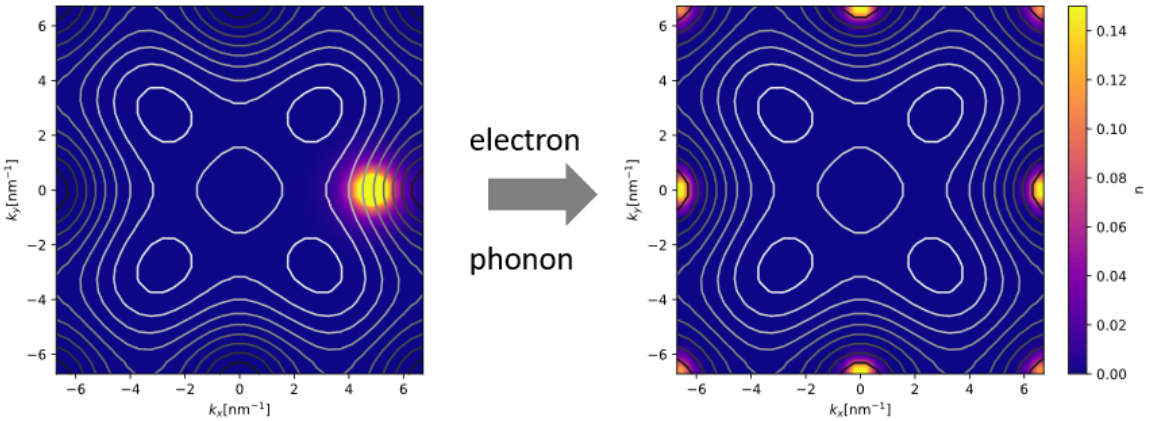


Figure 1: Contour plot (black: low energy, white: high energy) of the band structure and the k-resolved occupation number n as color map in the background. Excitation is assumed to occur via spin polarized carrier injection in one upper band (left) and quasi equilibrium after electron phonon mediated carrier relaxation.

[1] J. Fabian and S. Das Sarma, Phys. Rev. Lett. 81, 5624 (1998).
[2] B. Koopmans et al., Phys. Rev. Lett. 95, 267207 (2005)
[3] K. Leckron et al.; Phys. Rev. B **96**, 140408 (2017).
[4] L. Šmejkal et al.; phys. Stat. sol. RRL **11**, 1700044 (2017).

PII-41: Differentiating mechanisms that drive ultrafast magnetization dynamics in Nickel

F.-C. Weber [1], J. Jarecki [1], M. Deb [1], W. Engel[2], A. von Reppert[1], and M. Bargheer[1,3]
[1]Institute of Physics and Astronomy, University of Potsdam
[2]Max-Born-Insitut, Berlin, Germany
[3]Helmholtz-Zentru, Berlin, Germany

We study the ultrafast response of the magnetization in two different Nickel (Ni) films upon optical excitation. The samples differ by the thickness of their Ni layer, which is 20 and 200 nm, respectively. By measuring the different magnetization precession under various angles of the external magnetic field for the two samples, we distinguish the acousto-magnetic excitation mechanism from mechanisms relying on thermal energy transfer.

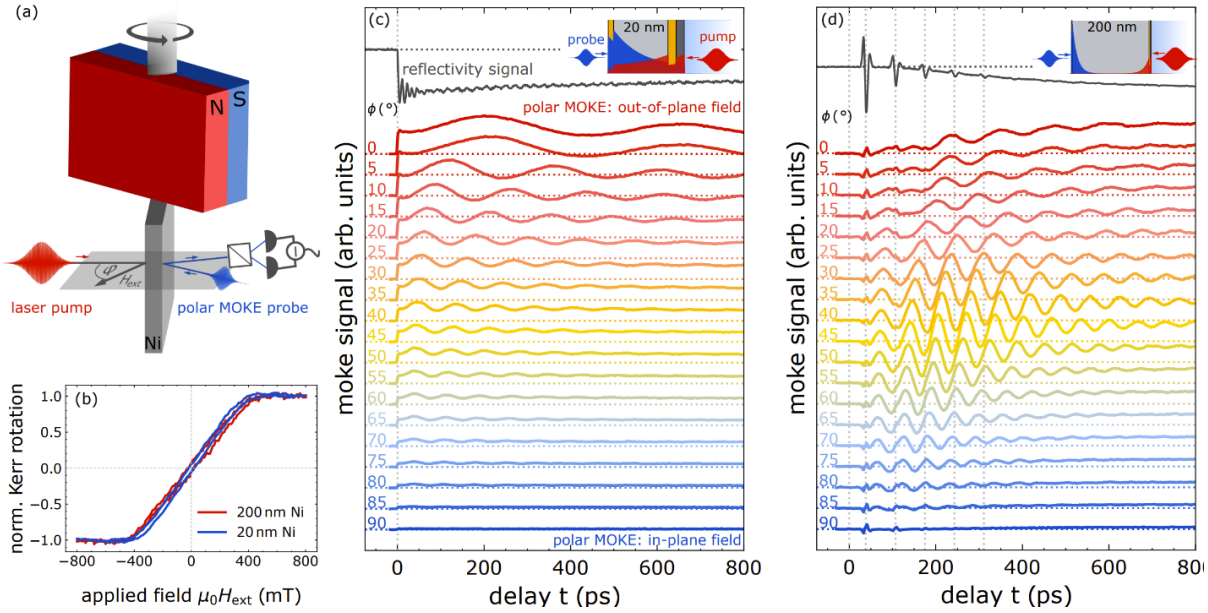


Figure 1: **Principle of the trMOKE experiment:** (a) schematic sketch of the polar MOKE setup using a permanent rotatable magnet that yields an external field of $\mu_0 H_{ext} \approx 350$ mT at the probed sample position. (b) out-of-plane field hysteresis of both Nickel samples. (c,d) representative all-optical pump-probe data set that depicts the time-resolved reflectivity change (grey) and the Kerr rotation for different angles ϕ of the external field relative to the surface normal for the 20 and 200 nm Nickel sample.

We use the polar time-resolved magneto-optical Kerr effect (trMOKE), where the out-of-plane magnetization is probed by a 400 nm femtosecond light pulse as a function of the external field angle Φ, which is set by a rotatable permanent magnet (Fig. 1 (a)).
A representative data set depicting the magnetization response of both samples upon photo-excitation of the Ni film from the substrate side is shown in Fig. 1 (c,d). This backside-pumping geometry makes sure that the probed surface of the 200 nm Ni film does not receive optical or electronic excitation. This is revealed by the optical reflectivity trace (gray) in Figure 1(d), which clearly shows the multiple arrival of the bipolar strain pulse at the surface upon reflection from the film interfaces and a slow

heating on a sub-nanosecond timescale. In contrast the 20 nm Ni film is fully excited and shows an according ultrafast response of the reflectivity signal (Fig. 1c).
While the frequency and amplitude of the magnetization precession varies according to the effective magnetic field in both samples, Fig. 1(c,d) clearly show that the maximum amplitude is observed around $\Phi = 45°$ for the thick film, whereas the 20 nm sample shows the highest precession amplitude at $\Phi = 0°$. We suggest that in the latter case, the ultrafast demagnetization is the dominant factor for modifying the effective magnetic field. The magnetoacoustic mechanism is not effective in the thin film, because every 9 ps the strain changes sign as Ni film is breathing acoustically. For the thick film, in contrast, the demagnetization is much slower than the precession frequency. However, the strain pulses optically generated at the Ni/substrate interface multiply excite the precessional motion at the probed Ni surface. For $\Phi = 45°$ the precession frequency is resonant with the multiple acousto-magnetic kick of the precession. For the thick film the front-side pump and front-side probe geometry confirms these interpretations.

PII-42: Indirect optical manipulation of the antiferromagnetic order of insulating NiO by ultrafast interfacial energy transfer

Stephan Wust,[1] C. Seibel,[1] H. Meer,[2] P. Herrgen,[1] C. Schmitt,[2] L. Baldrati,[2] R. Ramos,[3,4] T. Kikkawa,[5] E. Saitoh,[5,6,7,8] O. Gomonay,[2] J. Sinova,[2,8] Y. Mokrousov,[2,9] H.C. Schneider,[1] M. Kläui,[2] B. Rethfeld,[1] B. Stadtmüller,[1,2] and M. Aeschlimann[1]

[1]Departement of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[2]Institute of Physics, Johannes Gutenberg-University Mainz, 55099 Mainz, Germany
[3]CIQUS, Departamento de Química-Física, Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[4]WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[5]Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan
[6]Institute for AI and Beyond, The University of Tokyo, Tokyo 113-8656, Japan
[7]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
[8]Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 162 00 Praha 6, Czech Republic
[9]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Antiferromagnets are promising candidates for improved future spintronic devices in terms of robustness and speed. Here, we report the ultrafast, (sub)picosecond reduction of the antiferromagnetic order of the insulating NiO thin film in a Pt/NiO bilayer. This reduction of the antiferromagnetic order is not present in pure NiO thin films after a strong optical excitation. This ultrafast phenomenon is attributed to an ultrafast and highly efficient energy transfer from the optically excited electron system of the Pt layer into the NiO spin system. We propose that this energy transfer is mediated by a stochastic exchange scattering of hot Pt electrons at the Pt/NiO interface [1].

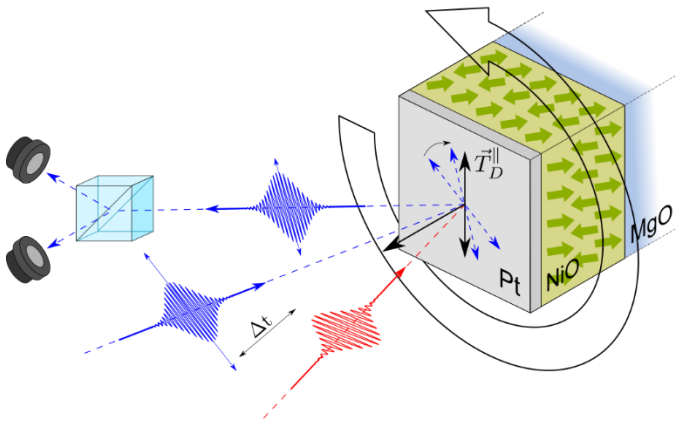


Figure 1: Schematic illustration of the experimental approach to record the magnetic response of NiO by is magneto-optical birefringence (MOBF) signal. Adapted from [1].

References:

[1] S. Wust, C. Seibel, H. Meer, P. Herrgen, C. Schmitt, L. Baldrati, R. Ramos, T. Kikkawa, E. Saitoh, O. Gomonay, J. Sinova, Y. Mokrousov, H.C. Schneider, M. Kläui, B. Rethfeld, B. Stadtmüller, and M. Aeschlimann, arXiv preprint arXiv:2205.02686 (2022)

PII-43: Coupling-strength dependent switching of ferrimagnetic multilayers

Y. Xu[1,2], D. Wei[1], S. Mangin[2]

[1] State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China.
[2] Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, 54506 Vandoeuvre-lés-Nancy, France

The interplay between electrical current and magnetization plays a major role in much of aspects of modern technologies. Among a variety of novel physical effects, spin-orbit torque (SOT) has been extensively accepted as an optimal current-induced switching mechanism of nanomagnets, which enables the features of ultra-fast reversal and low-energy consumption in the next-generation spin memory/logic devices.

In this work, we explore the SOT switching mechanism in the ferrimagnetic alloy of Co-Tb, which has exotic properties like ultrafast all-optical switching[1] and high-speed magnetic domain-wall motion[2]. By tailoring the coupling strength of the rare-earth and transition-metal moments, we observed quite different switching behaviors.

For the study, we deposited several samples consisting of the sandwich structure of Ta(3 nm)/Co-Tb(6 nm)/Pt(3 nm), the Ta and Pt layers serve as the spin current source via the spin Hall effect, the middle Co-Tb layers are engineered into alloy and multilayers which show different anomalous Hall loops as depicted in Fig.1 (a). For all the Co-Tb layers, the relative chemical concentrations of Co and Tb atoms, and the layer thickness are the same, the only changed parameter is the repetitive number of the $[Co/Tb]_N$ multilayers. By doing so, we manage to tune the bulk perpendicular magnetic anisotropy (PMA), and the bulk Dzyaloshinskii–Moriya interaction (DMI). Figure 1(b) shows the SOT switching loops as functions of current pulse strength under an in-plane assistant field of 500 Oe. As the repetitive number increases, the switching loops attain more and more intermediate states which may infer a multi-level or relative slower switching process.

We attribute this phenomenon to the coexistence of collective magnetization precession and domain-wall nucleation and propagation in the switching process. However, to obtain a more evident and convincing conclusion acquire further dynamical detection like depth-resolved TR-MOKE and TR-MOKE microscopy[3].

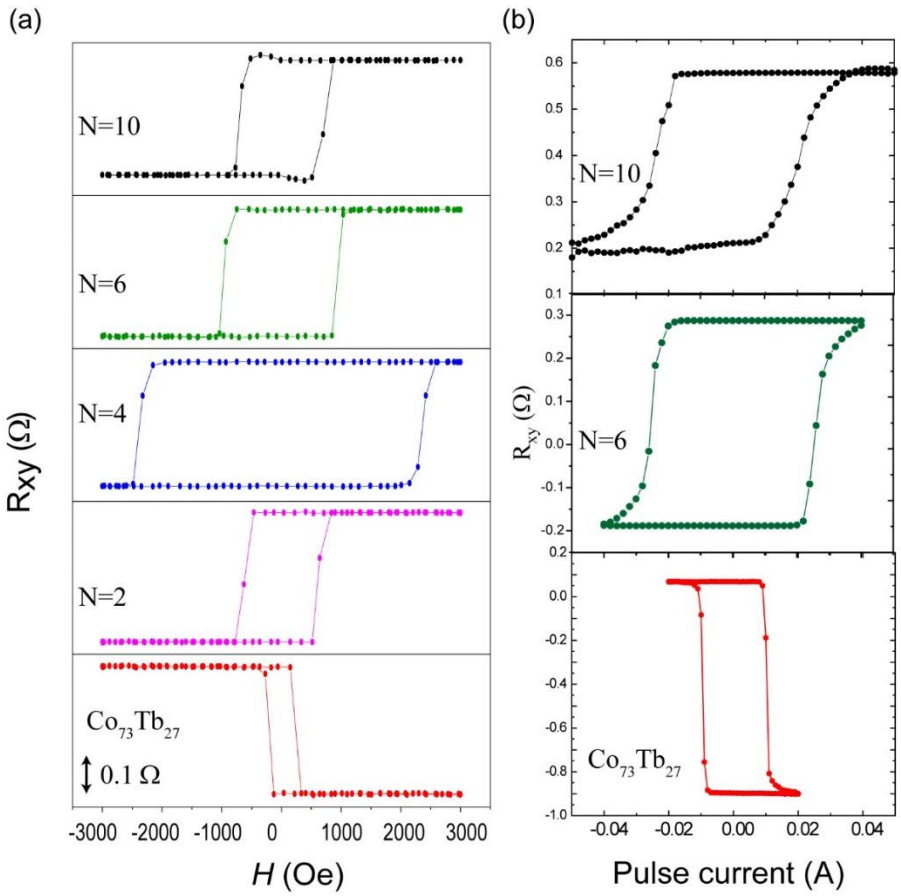


Figure 1: (a) Anomalous Hall resistance loops for samples of $Co_{73}Tb_{27}$ alloy and $[Co/Tb]_N$ multilayers with different repetitive numbers. All the Co-Tb layers have the same thickness and chemical concentration. (b) Current induced switching loops for 3 kinds of samples show different switching features.

Reference

[1] A. V. Kimel and M. Li, Nature Reviews Materials **4** (3), 189-200 (2019).

[2] K. Cai, Z. Zhu, J. M. Lee, R. Mishra, L. Ren, S. D. Pollard, P. He, G. Liang, K. L. Teo, and H. Yang, Nature Electronics 3 (1), 37-42 (2020).

[3] A. J. Schellekens, N. de Vries, J. Lucassen and B. Koopmans, Physical Review B 90 (10), 104429 (2014).

PII-44: Spin Manipulation by Giant Valley-Zeeman Spin-Orbit Field in Atom-Thick WSe_2

W. Yang[1,2], X. Wang[1] W. Yang[3], Y. Cao[1], X. Lin[1] G. Wei[1], H. Lu[1], P. Tang[1], J-C. Rojas-Sánchez[2], and W. Zhao[1]

Jean. Lamour, U. Mc21 and , D. Nancy

[1] Beihang University, China

[2] Université de Lorraine, CNRS, IJL, France

[3] University of British Columbia, Canada

The phenomenon originating from spin-orbit coupling (SOC) provides energy-efficient strategies for spin manipulation and device applications[1]. The broken inversion symmetry interface and resulting electric field induce a Rashba-type spin-orbit field (SOF), which has been demonstrated to generate spin-orbit torque for data storage applications. The low symmetry of 2D materials provides new possibilities for efficient spin manipulation[2]. In this study, we found that spin flipping can be achieved by the valley-Zeeman SOF in monolayer WSe_2 at room temperature, which manifests as a negative magnetoresistance in the vertical spin valve[3]. Quantum transmission calculations based on an effective model near the K valley of WSe_2 confirm the precessional spin transport of carriers under the giant SOF. In particular, the valley-Zeeman SOF-induced spin dynamics was demonstrated to be tunable with the layer number and stacking phase of WSe_2, which provides a novel strategy for spin manipulation and can benefit the development of ultralow-power spintronic devices. Furthermore, we will explore the magnetization manipulation with lower symmetry 2D materials like Td-WTe_2.

Reference:

[1] A. Manchon et al., NAT MATER 14, 871 (2015).

[2] H. Yuan et al., NAT PHYS 9, 563 (2013).

[3] X. Wang et al. arXiv:2205.02876, in press.

PII-45: Simulation of THz-driven magnetization dynamics near compensation point

Evgeny A. Mashkovich[1]*, Anatoly K. Zvezdin[3,4], Alexandr G. Zavyalov[5], Alexandra M. Kalashnikova[6] and Alexey V. Kimel[2]

[1]University of Cologne, Institute of Physics II; Cologne D-50937, Germany
[2]Radboud University, Institute for Molecules and Materials; Nijmegen 6525 AJ, The Netherlands
[3]Prokhorov General Physics Institute, Russian Academy of Sciences; Moscow 119991, Russia
[4]Moscow Institute of Physics & Technology; Dolgoprudnyi 141700, Russia
[5]University of Nizhny Novgorod, Nizhny Novgorod 603022, Russia
[6]Ioffe Institute, Russian Academy of Sciences; St Petersburg 194021, Russia

The control of magnetic bits in the fast and least dissipative manner is the crucial task of magnetic writing. In this regards antiferromagnets start to grow attention as they intrinsic magnetic frequency lie in a few terahertz (THz) range. Several recent experiments show possibility to trigger magnetization precession by a high-intense THz pulse [1,2]. Among magnets ferrimagnets present unique combination of antiferromagnetic spin alignment with a ferromagnetic like magneto-optical response. Interestingly, near compensation point a total magnetization moment is zero, while the magneto-optical response is determined by the residual of magneto-optical sublattices susceptibilities.

In this work we have performed simulation of magnetization dynamics of a two sublattices ferrimagnet triggered by an intense broadband terahertz pulse. The dynamics shows excitation of two magnetic modes, which frequencies cross at the compensation point. Theoretical consideration is based on symmetry and Lagrangian formalisms [3]. The comparison with experiment is done on example of an yttrium iron garnet low-symmetry film doped with non-magnetic Ga ions (Ga: YIG).

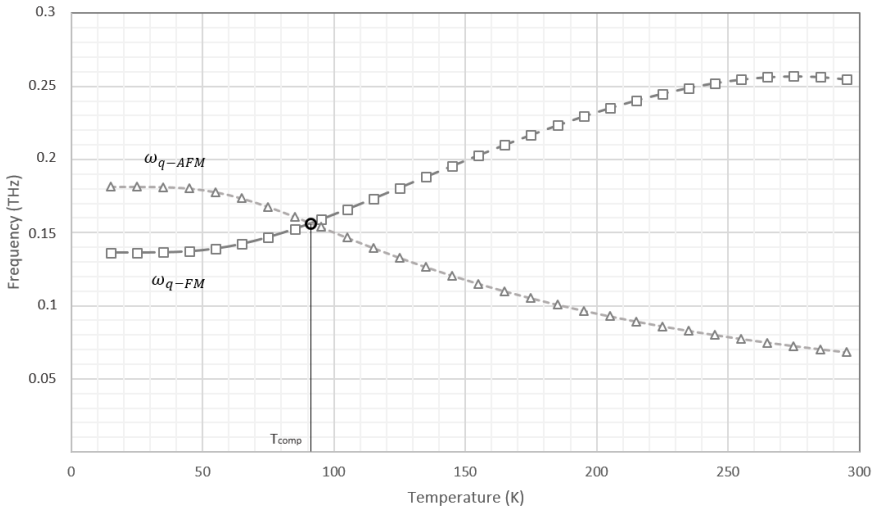


Figure 1: Frequencies of the q-FM (circles) and the q-AFM (triangles) vs temperature. Fit fictions are shown by solid lines. Here, we assume contribution from

Figure 1 shows frequencies of the quasi-antiferromagnetic (q-AFM) and the quasi-ferromagnetic (q-FM) mode in Ga: YIG film. To simulate dynamics, we consider contribution from exchange, Zeeman and anisotropy energy terms. The latter consists of in-plane, out-of-plane and canted contributions. In simulation we investigate temperature frequency behavior and ellipticity of the magnetic modes

assuming different anisotropy contributions. Note, that prevail type of anisotropy of a low-symmetry thin film can be controlled by proper doping [4]. Here, the reasonable fitting can be achieved neglecting canted anisotropy and considering equal in-plane and out-of-plane anisotropy contributions. Moreover, in this case the q-FM and the q-AFM modes are circular polarized.

Support by Ministry of Science and Higher Education of the Russian Federation (FSWR-2021-011) is acknowledged.

References

[1] T. Kampfrath *et al.*, Coherent terahertz control of antiferromagnetic spin waves. *Nat. Photonics*. **5**, 31–34 (2011).

[2] T. G. H. Blank *et al.*, THz-Scale Field-Induced Spin Dynamics in Ferrimagnetic Iron Garnets. *Phys. Rev. Lett.* **127**, 037203 (2021).

[3] M. D. Davydova, K. A. Zvezdin, A. V Kimel, A. K. Zvezdin, Ultrafast spin dynamics in ferrimagnets with compensation point. *J. Phys. Condens. Matter*. **32**, 01LT01 (2020).

[4] I. Nistor, C. Holthaus, S. Tkachuk, I. D. Mayergoyz, C. Krafft, Magnetic anisotropies in (210)-oriented bismuth substituted iron garnet thin films. *J. Appl. Phys.* **101**, 09C526 (2007).

PII-46: Terahertz and infrared excitation of ultrafast demagnetization in Co2MnAl1-xSix Heusler compounds

W.Zhang[1,2,3*], T. Blank[4], C. Guillemard[3], S. Mangin[3], S. Andrieu[3], A. Kimel[4], W. S. Zhao[1,2], G. Malinowski[3]

[1]Anhui High Reliability Chips Engineering Laboratory, Hefei Innovation Research Institute, Beihang University, Hefei 230013, China

[2]MIITKey Laboratory of Spintronics, School of Integrated Circuit Science and Engineering, Beihang University, Beijing 100191, China

[3]Université de Lorraine, CNRS, IJL, F-54000 Nancy, France

[4]Radboud University, Institute for Molecules and Materials, 6525 AJ Nijmegen, The Netherlands

Half-metallic ferromagnets (HMFs) exhibit a metallic density of states at the Fermi level for one spin channel, but an insulating band gap for the other one. As one popular kind of HMFs, Heusler compounds [5] have attracted much more attention in the past decades due to their high spin polarization as well as Curie temperature. Moreover, the Heusler alloys show high potential for ultrafast and low-energy memory applications in combination with ultrashort femtosecond laser pulse, which serves as the fastest external stimulus [1]. Despite this, fully exploiting the capabilities of Heusler compounds-based ultrafast spintronic devices will require a detailed understanding on the interaction between their magnetism and ultrashort laser pulse. In particular, no evidence has been identified for the expected spin-flip blocking effect in Heusler alloys. It challenges the current understanding of spin-flip processes underlying demagnetization at ultrafast timescale.

Here, we investigate the ultrafast demagnetization in $Co_2MnAl_{1-x}Si_x$ quaternary Heuslers induced by terahertz (THz) [2] and infrared (IR) pulses. Adjusting the alloy's composition allows tailoring the spin polarization at the Fermi level from 60 to 100 %. The pump wavelength is tuned to modify the photon energy from 1.02 eV (IR) down to 5 meV (THz). We found that the demagnetization time remains very fast (less than 1ps), even for THz pumping, indicating both intra- and interband excitations induced by THz and IR pulses plays no distinct role on the magnetization dynamics in Heusler compounds.

References

[1] C. Guillemard, W. Zhang, G. Malinowski, C. de Melo, J. Gorchon, S. Petit-Watelot, J. Ghanbaja, S. Mangin, P. Le Fèvre, F. Bertran and S. Andrieu, Adv. Mater. 32, 1908357 (2020).

[2] E. A. Mashkovich, K. A. Grishunin, H. Munekata, and A. V. Kimel, Appl. Phys. Lett. 117, 122406 (2020).

PII-47: Ultrafast demagnetization dynamics in Fe studied by tr-ARPES

Xinwei Zheng, Shabnam Haque, Christian Strüber, Martin Weinelt

Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany

We investigate the ultrafast demagnetization dynamics of 15 monolayer bcc Fe(110) epitaxially grown on W(110). To this end we use time- and angle-resolved photoemission spectroscopy (tr-ARPES) applying an IR pump pulse and a high-order harmonic XUV probe pulse. Tuning the XUV photon energy to 27 eV we probe the Fermi surface of Fe(110)/W(110) in the 2nd Brillouin zone. Minority and majority spin bands crossing the Fermi surface at different momentum are identified [1,2]. The valence bands close to the Fermi level show a pronounced magnetic linear dichroism (MLD), *i.e.* the difference in photoemission yield for opposite in-plane magnetization directions. In contrast to a small reduction of the exchange splitting by only 3%, the MLD signal drops by 60% within 150 fs after optical excitation. This result proves that spin-mixing dominates the ultrafast demagnetization dynamics in iron [3] as previously suggested for cobalt [4] and corroborates that magnon emission occurs on the femtosecond timescale [5]. Moreover, we find a stronger reduction of the asymmetry in the minority spin band close below the Fermi level compared to that of the majority spin band at a binding energy of 0.3 eV. This is explained by spin-wave emission which is based on angular momentum conservation driven by a spin flip of an electron with minority spin into a majority spin electron, which outweighs the opposite process of magnon absorption [5]. The spin system in Fe is out of equilibrium after laser excitation until electron, spin, and lattice subsystems equilibrate at about 1.5 ps. Both bands probed are also depleted by the pump pulse and optical induced spin transfer is unlikely the source of non-equilibrium spin dynamics [6]. We studied the pump-fluence dependence of the MLD signal and the electronic temperature extracted from the transient Fermi distribution. The increase of the electronic temperature is lower as expected from the well-known electron specific heat. This implies that a significant amount of energy is transferred into the spin system within 150 fs, which matches the rise time of the electronic temperature upon optical excitation [6]. Our findings show that the ultrafast demagnetization of Fe is driven by a non-equilibrium process with energy transfer into the spin system on the time scale of thermalization of the electron system.

References

[1] J. Schäfer et al., Phys. Rev. B **72**, 155115 (2005).
[2] J. Sánchez-Barriga el al., Phys. Rev. Lett. **103**, 267203 (2009).
[3] E. Carpene et al., Phys. Rev. B **78**, 174422 (2008).
[4] S. Eich et al., Sci. Adv. **3**, e1602094 (2017).
[5] A. B. Schmidt et al., Phys. Rev. Lett. **105**, 197401 (2010).
[6] R. Gort et al., Phys. Rev. Lett. **121**, 087206 (2018).
[7] P. Tengdin et al., Sci. Adv. **4**, eaap9744 (2018).

We acknowledge funding by the Deutsche Forschungsgemeinschaft via the SFB/TRR 227 Ultrafast Spin Dynamics, project A01.

PII-48: Light-driven propagating THz magnons in an antiferromagnet

R.A. Leenders[1], R.V. Mikhaylovskiy[1], A.V. Kimel[2], D. Afanasiev[2]

[1] Department of Physics, Lancaster University, Bailrigg, Lancaster LA1 4YW, United Kingdom

[2]Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

Magnons, waves of spin precession, have recently gained a lot of interest owing to their potential applications in data storage and information processing without Joule heating. The possibility to control magnons all-optically, combined with their low dissipations, could make magnons a future alternative to highly dissipative electric currents. Particularly, magnons in antiferromagnets are interesting due to their high resonance frequencies in the THz range, allowing for substantially faster processing times than traditionally used ferromagnets. [1]

First, we model the precession of antiferromagnetically coupled spins after excitation by an ultrashort laser pulse [2] by solving the equation of motion of antiferromagnetic spins. [3] We find that propagating wavepackets of magnons are generated by a strongly absorbed laser pulse, such that the excitation is confined in a region of tens of nanometers from the boundary. We compare the results for various excitation time-shapes, and material parameters.

Then, we model the detection of the generated wavepacket using the Magneto Optical Kerr Effect (MOKE). We derive an expression that shows that the probe pulse imposes a selectivity on the detected magnon wavevector, in the form of a Brillouin condition. [4] We find that the probe wavelength selectively probes points on the magnon dispersion, resulting in blue shifts with increasing probe photon energy in MOKE experiments (figure a).

Finally, we experimentally measure propagating magnons in the canted antiferromagnet $HoFeO_3$ by performing MOKE experiments with a variety of probe wavelengths. In addition to a peak corresponding to the antiferromagnetic resonance frequency f_0, we observe a peak at frequency f_k which depends on the wavelength of the probe. This dependence is well fitted with the magnon dispersion (figure b).

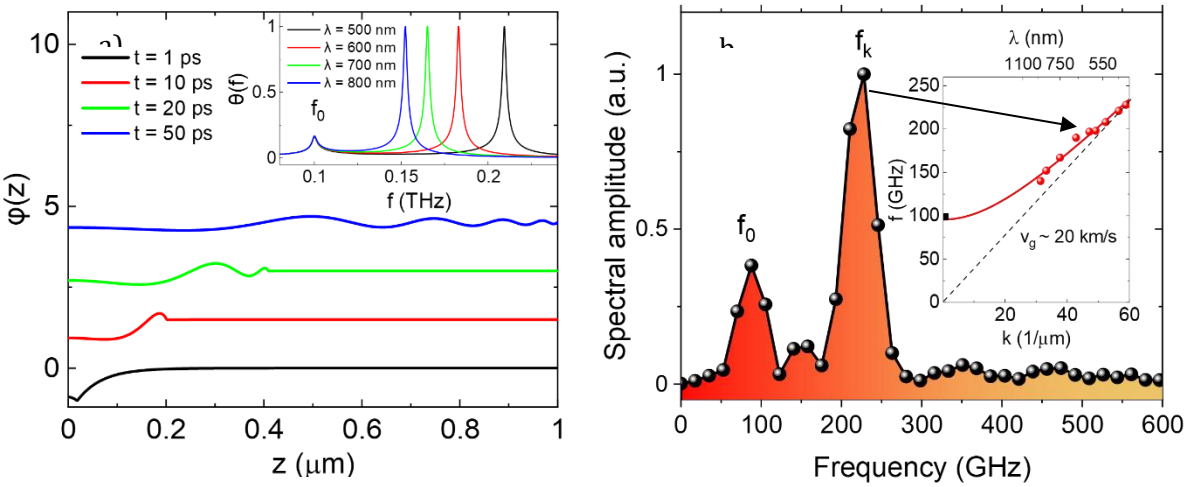


Figure 21: a) Simulation of spin deflection profile for an impulsive excitation, assuming antiferromagnetic resonance frequency f_0=100 GHz; magnon velocity limit c =20 km/s, penetration depth d=50 nm, and free spins boundary condition. The inset shows the predicted spectra in a MOKE experiment at various probe wavelengths. b)

Spectrum obtained from the MOKE experiment on $HoFeO_3$, using a 660 nm probe pulse. The inset shows the extracted frequency of the f_k mode for various probe wavelengths. The data is fitted with the magnon dispersion relation. All spectra and the spin wave profiles are normalized.

References:

1 Zakeri, K. Terahertz magnonics: Feasibility of using terahertz magnons for information processing. *Physica C* **549**, 164-170, doi:10.1016/j.physc.2018.02.035 (2018).

2 Kimel, A. V. *et al.* Ultrafast non-thermal control of magnetization by instantaneous photomagnetic pulses. *Nature* **435**, 655-657, doi:10.1038/nature03564 (2005).

3 Zvezdin, A. K. Dynamics of Domain-Walls in Weak Ferromagnets. *Jetp Lett+* **29**, 553-557 (1979).

4 Hortensius, J. R. *et al.* Coherent spin-wave transport in an antiferromagnet. *Nat Phys* **17**, 1001-+, doi:10.1038/s41567-021-01290-4 (2021).

PII-49: All-optical spin injection in silicon investigated by element specific time-resolved Kerr effect

Simone Laterza,[1, 2] Antonio Caretta,[1] Richa Bhardwaj,[1] Roberto Flammini,[3] Paolo Moras,[4] Matteo Jugovac,[4] Piu Rajak,[5] Mahabul Islam,[5] Regina Ciancio,[5] Valentina Bonanni,[1] Barbara Casarin,[2] Alberto Simoncig,[1] Marco Zangrando,[1, 5] Primoz Rebernik Ribic,[1] Giuseppe Penco,[1] Giovanni De Ninno,[1] Luca Giannessi,[1] Alexander Demidovich,[1] Miltcho Danailov,[1] Fulvio Parmigiani,[1, 6] and Marco Malvestuto[1, 5]

[1]Elettra Sincrotrone Trieste S.C.p.A. Strada Statale 14 - km 163.5 in AREA Science Park 34149 Basovizza,
Trieste, Italy
[2]Department of Physics, University of Trieste, Via A. Valerio 2, 34127 Trieste, Italy
[3]Istituto di Struttura della Materia-CNR (ISM-CNR), Via del Fosso del Cavaliere 100, 00133, Roma, Italy
[4]Istituto di Struttura della Materia-CNR (ISM-CNR), SS 14 km 163.5, I-34149, Trieste, Italy
[5]Istituto Officina dei Materiali (CNR-IOM), SS 14 km 163.5, I-34149, Trieste, Italy
Corresponding author: marco.malvestuto@elettra.eu

Nowadays, spin-based electronics (spintronics) has been compared favourably to conventional electronics because of the lower switching energy and the higher switching speed [1, 2]. The main reasons being that spin currents are suggested to flow nearly dissipationless [3, 4], while spin coherence time is larger than the charge confinement lifetime [5]. In particular, this applies to the injection of the superdiffusive spin currents (SCs) through some metal/metal interfaces [6, 7]. SCs are generated inside ferromagnetic metals by means of ultrashort infrared (IR) pulses [8, 9] where a spin-preserving out-of-equilibrium hot electron distribution is created [6]. SCs have been reported in Ni/Au, Ni/Fe and Ni/Co-Pt multilayers [10-12]. Besides, spin currents in the form of propagating magnons triggered by ultrafast optical pulses, have been observed for NiO [13], CoO [14] and ZnO [15]. Conversely, the spin injection into some technologically relevant semiconductors is still an open question. Silicon, by allowing long lived spin currents because of the small spin-orbit interaction, the reduced nuclear spin and the crystal inversion symmetry, is a good candidate for these studies [4, 16, 17].

Understanding how a spin current flows across metal-semiconductor interfaces at pico- and femtosecond timescales is of paramount importance. However, the possibility to directly access the propagation of spin currents, within such time scales, has been hampered by the simultaneous lack of both ultrafast element specific magnetic sensitive probes and tailored well-built and characterized metal-semiconductor interfaces.

Here, we report about a novel ultrafast time resolved resonant magneto-optical Kerr effect experiment (TR-RMOKE) [20] at Si L2;3 and Ni M2;3 absorption edges. Thanks to the element selectivity of the TR-RMOKE spectroscopy, performed at an externally seeded and tunable free electron laser and to a state-of-the-art fabrication and characterization of the Ni/Si interface, we can decouple the magneto-dynamical response of the Si support from the Ni overlayer.

References

1 D. D. Awschalom and M. E. Flatt, Nature Physics 3, 153 (2007).
2 K. L. Wang, J. G. Alzate, and P. K. Amiri, Journal of Physics D: Applied Physics 46, 074003 (2013).
3 S. Murakami, N. Nagaosa, and S.-C. Zhang, Science 301, 1348 (2003), cond-mat/0308167.
4 I. uti, J. Fabian, and S. D. Sarma, Reviews of Modern Physics 76, 323 (2004), cond-mat/0405528.
5 B. Huang, D. J. Monsma, and I. Appelbaum, Physical Review Letters 99, 177209 (2007), 0706.0866.
6 M. Battiato, K. Carva, and P. M. Oppeneer, Physical Review Letters 105, 027203 (2010), 1106.2117.
7 A. Eschenlohr, M. Battiato, P. Maldonado, N. Pontius, T. Kachel, K. Holldack, R. Mitzner, A. Fhlisch, P. M. Oppeneer, and C. Stamm, Nature Materials 12, 332 (2013).
8 M. Battiato and K. Held, Physical Review Letters 116, 196601 (2016), 1604.05882.

9 M. Battiato, Journal of Physics: Condensed Matter 29, 174001 (2017), 1803.09083.
10 D. Rudolf, C. La-O-Vorakiat, M. Battiato, R. Adam, J. M. Shaw, E. Turgut, P. Maldonado, S. Mathias, P. Grychtol, H. T. Nembach, T. J. Silva, M. Aeschlimann, H. C. Kapteyn, M. M. Murnane, C. M. Schneider, and P. M. Oppeneer, Nature Communications 3, 1037 (2012).
11 T. Kampfrath, M. Battiato, P. Maldonado, G. Eilers, J. Ntzold, S. Mhrlein, V. Zbarsky, F. Freimuth, Y. Mokrousov, S. Blgel, M. Wolf, I. Radu, P. M. Oppeneer, and M. Mnzenberg, Nature Nanotechnology 8, 256 (2013).
12 T. Seifert, S. Jaiswal, U. Martens, J. Hannegan, L. Braun, P. Maldonado, F. Freimuth, A. Kronenberg,
J. Henrizi, I. Radu, E. Beaurepaire, Y. Mokrousov, P. M. Oppeneer, M. Jourdan, G. Jakob, D. Turchi novich, L. M. Hayden, M. Wolf, M. Mnzenberg, M. Klui, and T. Kampfrath, Nature Photonics 10, 483 (2016), 1510.03729.
13 K. Lee, D.-K. Lee, D. Yang, R. Mishra, D.-J. Kim, S. Liu, Q. Xiong, S. K. Kim, K.-J. Lee, and H. Yang, Nature Nanotechnology 16, 1337 (2021).
14 Y. Sasaki, G. Li, T. Moriyama, T. Ono, R. V. Mikhaylovskiy, A. V. Kimel, and S. Mizukami, Applied Physics Letters 117, 192403 (2020).
15 M. Althammer, E.-M. Karrer-Mller, S. T. B. Goennenwein, M. Opel, and R. Gross, Applied Physics Letters 101, 082404 (2012), 1205.3666.