4th International Workshop on Magnonics

From Fundamentals to Applications

Magnonics

Seeon, Germany

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Contributed Talks

Monday, 03.08.2015

09:00	**Confined systems** *B. Kalinikos* *T. Ono* *R. Arias* *R. Gieniusz*
10:40	Coffee break
11:10	**Spin-torque I** *S. Urazhdin* *V.E. Demidov* *O. Gladii*
12:30	Lunch
14:00	**Spin-torque II** *I. Krivorotov* *G. de Loubens* *C.A. Ross*
15:30	Poster Session
18:30	Dinner

High-Frequency phenomena in artificial multiferroics: Physics and applications

Boris Kalinikos

Saint Petersburg Electrotechnical University, 197376, Saint Petersburg, Russia

One of the modern areas in physics and technology comprises fundamental investigations and engineering applications of multiferroic materials. Artificial multiferroics in a form of multi-layered heterostructures, such as weakly-magnetic-anisotropy yttrium iron garnet films or highly-magnetic-anisotropy barium hexaferrite films combined with barium strontium titanate films, demonstrate effects that are attractive for various applications. In the paper the physical properties of planar multiferroic hetero-materials, as well as their usage in creating linear and nonlinear high-frequency signal processing devices will be discussed. A special attention will be given to utilization of multiferroic devices in microwave photonics systems. As the examples, tunable gigahertz and terahertz oscillators will be considered.

Magnetic domain wall dynamics under Dzyaloshinskii-Moriya interaction

Teruo Ono

Institute for Chemical Research, Kyoto University, Uji, 611-0011, Japan

It has been recently found domain motion (DW) is induced by spin injection via spin Hall effect. In this spin Hall torque induced DW motion, a chiral DW stabilized by the Dzyaloshinskii-Moriya interaction is essential. In this presentation, I will present systematic investigation on the current-induced DW motion by changing thickness of magnetic layer and discuss the contribution of adiabatic spin transfer torque and spin Hall torque. I will also show a simple method for the quantitative evaluation of the Dzyaloshinskii-Moriya interaction by field-induced DW motion.

This work was partly supported by a Grant-in-Aid for Scientific Research (S) from JSPS and by R&D Project for ICT Key Technology to Realize Future Society of MEXT.

Magnetostatic modes in ferromagnetic samples with inhomogeneous internal fields

Rodrigo Arias

Universidad de Chile

Magnetostatic modes in ferromagnetic samples are very well characterised and understood in samples with uniform internal magnetic fields. More recently interest has shifted to the study of magnetization modes in ferromagnetic samples with inhomogeneous internal fields. The present work shows that under the magnetostatic approximation and for samples of arbitrary shape and/or arbitrary inhomogeneous internal magnetic fields the modes can be classified as elliptic or hyperbolic, and their associated frequency spectrum can be delimited. This results from the analysis of the character of the second order partial differential equation for the magnetostatic potential under these general conditions. In general, a sample with an inhomogeneous internal field and at a given frequency, may have regions of elliptic and hyperbolic character separated by a boundary. In the elliptic regions the magnetostatic modes have a smooth monotonic character (generally decaying form the surfaces (a "tunneling" behavior)) and in hyperbolic regions an oscillatory wave-like character. A simple local criterion distinguishes hyperbolic from elliptic regions: the sign of a susceptibility parameter. This study shows that one may control to some extent magnetostatic modes via external fields or geometry.

Spin wave excitations in periodic arrays of wave-like Py structures.

N. Tahir[1], R. Gieniusz[1], A. Maziewski[1], P. Mazalski[1], M. Zelent[2], P. Gruszecki[2], M. Krawczyk[2], T. Wojciechowski[3], J. Ding[4], and A. O. Adeyeye[4]

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Periodic arrays of wave-like $Ni_{80}Fe_{20}$ structures of 10 and 30 nm thickness were analyzed by: longitudinal magneto-optical Kerr (LMOKE) measurements and both X-band FMR and BLS spectroscopies. For magnetic field orientation along easy axis (determined by LMOKE), we observed several resonance modes at low field (high frequency), while in the case of hard axis orientation several modes are also observed at high field (low frequency) regime. Dispersion characteristics (from BLS) show several resonance modes for both magnetic field orientations. The peak near the 14 GHz with the highest intensity is connected to the Damon-Eshbach-like spin waves mode. We attribute these modes to the inhomogeneous internal demagnetizing field, being different in the wider and narrower parts of the wave-like structure.

This work is supported by Foundation for Polish Science within the Team Programme co-financed by the EU European Regional Development Fund, OPIE 2007-2013.

Magnetic nanooscillators operated by pure spin currents

Sergei Urazhdin

Emory University, Atlanta, GA 30322, USA

I will describe two types of spin current-driven magnetic nanooscillators that we have recently experimentally demonstrated, one is based on the spin Hall effect, another on the nonlocal spin injection. I will show that the oscillation is generally facilitated by the nonlinear effects that result in the transformation of the local dynamical magnetic spectrum of the magnetic system under the influence of spin current. I will describe two experimentally observed different scenarios: nonlinear self-localization of the oscillation mode (spin-wave bullet), and localization of the oscillation in an effective magnetic potential well created by the effects of spin current.

Spin-transfer torque for advanced magnonics

Vladislav E. Demidov

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I discuss recent experiments on utilization of spin-transfer torque for excitation and amplification of propagating spin waves in microscopic magnonic guiding structures. In particular, I present a novel approach to the integration of spin-torque nano-oscillators with magnonic waveguides based on the utilization of the dipolar fields of magnetic nano-patterns. The approach enables good spectral matching and efficient transmission of spin waves excited by the spin-polarized electric current. I also show that the spin-transfer torque exerted by pure spin currents generated due to the spin-Hall effect can be used to reduce propagation losses and enhance the excitation efficiency of propagating spin waves.

Spin wave propagation and spin polarized electron transport in single crystal iron films

O. Gladii, D. Halley, Y. Henry & M. Bailleul

Institut de Physique et Chimie des Matériaux de Strasbourg, UMR7504 CNRS-Université de Strasbourg, 67034 Strasbourg, France

Up to now, research in magnonics has concentrated on a few materials containing iron (Permalloy, CoFeB, YIG). Despite the promising properties of ***pure*** iron, such as low damping factor, high saturation magnetization and well-defined magneto-crystalline anisotropy, there is no study of spin wave propagation in this material. To fill this gap, we studied 10-20 nm thick Fe(100)/MgO films with the Propagating Spin Wave Spectroscopy Technique. As expected, we obtain signals with much stronger amplitude, higher frequency and lower attenuation as compared to Permalloy. More surprisingly, a spin polarization as high as 75% is deduced from current induced Doppler shift measurements at room temperature, in contradiction with early predictions of the two-current model in the phonon dominated regime. This makes pure iron a very promising candidate for spin wave and spin current based applications.

Nanowire spin torque oscillator driven by spin orbit torques

Ilya Krivorotov

University of California at Irvine

Spin torque applied to a nanoscale ferromagnet can excite self-oscillations of its magnetization. In contrast, spin torque uniformly applied to an extended ferromagnetic film does not produce the self-oscillations but reduces its saturation magnetization. I will describe the effect of spin torque on a system of intermediate dimensionality – a ferromagnetic nanowire. We observe coherent self-oscillations of magnetization in a NiFe/Pt bilayer nanowire serving as the active region of a spin torque oscillator driven by spin orbit torques. Geometric confinement of spin wave spectrum in the nanowire geometry leads to partial suppression of nonlinear spin wave scattering and thereby enables the self-oscillatory dynamics.

Full Control of the Spin-Wave Damping in a Magnetic Insulator Using Spin-Orbit Torque

Grégoire de Loubens

CEA Saclay, France

Using a magnetic resonance force microscope (MRFM), we provide direct evidence that the ferromagnetic resonance linewidth in a YIG(20nm)|Pt(7nm) disk of 5 μm in diameter changes with the dc current in the Pt layer. The observed effect has the symmetry of the spin Hall effect, and the linewidth can be reduced or enhanced linearly by a factor five, depending on the polarity of the dc current and the orientation of the in-plane bias magnetic field. Compensating completely the damping of the fundamental mode in this sample requires a current density of ~ 3.10^{11} A/m^2, in agreement with theoretical predictions. At this critical threshold, the MRFM detects a small change of spontaneous magnetization, a behavior coherent with the onset of an auto-oscillation regime. This is confirmed by direct electrical detection of auto-oscillations in similar samples using spectral analysis.

Growth, Magnetism and Optical Properties of Iron Garnet films

C.A. Ross

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Iron garnets have low damping, high magnetooptical figure of merit and high resistivity in bulk, making them attractive for studies and applications in magnetization dynamics, spin pumping, magnetooptical isolators. However, obtaining thin films with bulk-like properties is challenging, particularly in the case of polycrystalline films grown on non-garnet substrates. We describe the growth by pulsed laser deposition and properties of YIG and CeYIG single crystal films on GGG or YAG and polycrystalline films on silicon, silica or silicon nitride, including strategies for obtaining well crystallized CeYIG using YIG seed layers, and illustrate their applications to proximity effects in topological insulators, spin wave propagation, and integrated optical isolators based on ring resonators.

Tuesday, 04.08.2015

09:00	**Spin-torque III** *R.K. Dumas* *S.M. Mohseni* *S. Kasai* *N. Sato*
10:40	Coffee break
11:10	**Multiferroics** *E.Y. Tsymbal* H. *Kurebayashi*
12:15	Lunch
13:00	**Excursion**

Recent advances in magnetic nano-scale oscillators

Randy K. Dumas

Department of Physics, University of Gothenburg, Gothenburg, Sweden

In this talk I will present a comprehensive review of the most recent advances in both nano-contact spin torque oscillators (NC-STOs) [1] and spin Hall nano-oscillators (SHNOs) [2]. The first half of the talk will focus on the critical role played by the current induced Oersted field [3] on synchronization. By purposefully taking advantage of the asymmetric spin wave propagation inherent to NC-STOs not only is a new synchronization mechanism demonstrated, but also a simple array geometry that can greatly increase the number of oscillators that can be synchronized. The second half of the talk will focus on the magnetodynamical properties of SHNOs under tilted applied magnetic fields. Ultra-low linewidth, high frequency, and multi-mode generation regimes will be discussed.

Support from The Swedish Research Council (VR), The Swedish Foundation for Strategic Research (SSF), and the Knut and Alice Wallenberg Foundation is gratefully acknowledged.

[1] T.J. Silva and W.H. Rippard., J. Magn. Magn. Mater. **320**, 1260 (2008).

[2] V.E. Demidov, *et al.*, Nature Mater. **11**, 1028 (2012).

[3] R. K. Dumas, *et al.*, Phys. Rev. Lett. **110**, 257202 (2013).

Magnetic Droplet Nucleation, Collapse and Instability

Seyed Majid Mohseni

Faculty of Physics, Shahid Beheshti University, Evin, Tehran, Iran

Magnetic droplets are robust dissipative solitons that can be observed in zero damping perpendicular magnetic anisotropy (PMA) layers. Such a non-topological nano-object can be formed in a PMA thin magnetic layer while a spin-transfer torque compensates locally the natural damping of the thin magnetic layer in orthogonal nano-contact spin torque oscillators. In this talk, we will show progressive studies and developments for magnetic droplet. Here, we will discuss in details the effect of current and magnetic field on droplet nucleation and collapse. Additionally, the effect of tilted applied magnetic field on the droplet instability will be reported and discussed.

Field and spin Hall excitation of spin wave in antidot lattices

Shinya Kasai[1)], Hiroshi Tsukahara[2)], Shigeyuki Hirayama[1), 3)], Seiji Mitani[1), 3)], Chiharu Mitsumata[1)]

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3) *Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577, Japan*

We demonstrate experimental and numerical study for the magnetization dynamics in anti-dot lattice consisting of crossed wire arrays by using spin current-induced ferromagnetic resonance (ST-FMR). Each wire consists of Permalloy (5 nm) / Pt (5 nm) bilayer thin film, and the width and period of the wire arrays are 100 nm and 500 nm, respectively. ST-FMR spectrum under RF currents shows clear two peaks due to the difference of effective field in each wire. Detailed analysis for experimental results and micromagnetics simulation strongly suggest~~s~~ the excitation of characteristic spin wave intermediated by the magnetization dynamics at the cross point.

Spin torque modulation on backward volume spin waves

N. Sato [1] and K. Sekiguchi [1, 2]

[1] *Department of Physics, Keio University, Japan*
[2] *JST-PRESTO, Japan*

A spin transfer torque (STT) can modulate the spin wave characteristics: frequency and amplitude. To investigate an effect of STT on backward volume spin waves (MSBVW), we excited MSBVW in a ferromagnetic metal wire, and injected a dc current into the wire. The signal of MSBVW was measured by a vector network analyzer. In the case that a current density reached to be 5×10^{10} A/m^2, we detected a gigantic frequency shift of 80 MHz. The frequency shift was reversed its sense by changing the direction of the dc current. This means the frequency shift was caused by not the Joule heating but STT. The STT on MSBVW appears to be stronger than that on forward volume spin waves reported by V. Vlaminck and M. Bailleul [1], revealing the possibility of efficient electrical control of the spin wave propagation.

Reference
[1] V. Vlaminck and M. Bailleul, Science **322**, 410 (2008).

Controlling Magnetism and Spin Transport by Electric Fields

Evgeny Y. Tsymbal

Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska, USA

Since the seminal discoveries of giant magnetoresistance in magnetic multilayers and tunneling magnetoresistance in magnetic tunnel junctions, the exploration of spin-dependent electronic transport has provided a promising avenue for applications in data storage and processing. Devices based on the electron spin typically require the application of magnetic fields or spin torques generated by large currents, consuming power and producing heat, hence limiting the application of such devices. To avoid the need for large currents, there have been recent efforts toward manipulating magnetization by the application of electric fields. Such magnetoelectric effects can be induced at the surfaces and interfaces of ferromagnetic metals affecting both the interface magnetization and the interface magnetocrystalline anisotropy. Ferroelectric materials are especially helpful in this regard because they possess a spontaneous electrical polarization which, when reversed by an electric field, can induce a large magnetoelectric response at the interface with a magnetic metal. This talk will overview our recent research efforts in this field and will discuss underlying physical principles associated with magnetoelectric interfaces and the effect of ferroelectricity on magnetism and spin transport.

Magnonics using spin textures in momentum space

Hidekazu Kurebayashi

UCL, UK

The spin-orbit interaction, that couples the motion and spin of electrons, allows us to manipulate electron spins by an electric current. When a material lacks an inversion centre, the spin-orbit interaction causes a preferential spin direction for each electronic state, as a whole, forming spin textures in momentum space. These spin textures are a fascinating playground to discover new spin excitation/detection methods, as well as to find new materials tailored for developing a spintronic/magnonic technology. In this talk, I will present our recent progresses on detecting spin textures by spin dynamics and magnonic charge pumping using spin textures.

Wednesday, 05.08.2015

09:00	**DMI** *M. Kostylev* *Y. Zhou* *T. Devolder* *H. Körner*
10:40	Coffee break
11:10	**Magnonic crystals** *A. Barman* *D. Grundler* *G. Gubbiotti*
12:30	Lunch
14:00	**SW-manipulation** *A.V. Chumak* *A. Khitun* *S. Mändl*
15:20	Coffee break
15:50	**Quantum effects** *A.D. Karenowska* *A.N. Slavin* *V. Tiberkevich*
18:30	Dinner

Application of spin waves and ferromagnetic resonances in sensing substances and particles, magnetic material characterisation, quantum information processing and microwave meta-materials

M. Kostylev

School of Physics, the University of Western Australia, Crawley, Australia

In my talk I will overview some results obtained in our research group which demonstrate potential of application of microwave magnetisation dynamics outside the conventional area of scope of magnonic community. These are detection of magnetic nanoparticles for bio-sensing using standing spin wave resonances in magnonic crystals, sensing of hydrogen gas with ferromagnetic resonance of palladium/cobalt bilayer films, and potential applications of dynamics of coupled photon-magnon modes in YIG/electromagnetic-wave coupled resonators (cavities and split-ring resonators) in Quantum Information and microwave meta-materials.

Dynamical magnetic skyrmions

Zhou Yan

University of Hong Kong

Spin transfer torque affords magnetic nanodevices the potential to act as memory, computing, and microwave elements operating at ultra-low currents and at a low energy cost. Spin transfer torque is not only effective in manipulating well-known magnetic structures, such as domain walls and vortices, but can also nucleate previously unattainable nano-magnetic objects, such as magnetic droplets and skyrmions. While the droplet and the skyrmion are both solitons, the former is inherently dynamic and non-topological, whereas the latter is static but topologically protected.

In this talk, we show that it is possible to combine the properties of non-topological magnetic droplet soliton and topologically protected skyrmions into a novel dynamical skyrmion, which adds additional degrees of freedom, and functionality, to both droplet and skyrmion based applications. Unlike static skyrmions, the dynamical skyrmion can be nucleated and sustained without Dzyaloshinskii-Moriya interaction (DMI) or dipole-dipole interaction (DDI), and is a generic soliton solution independent of STT and damping once nucleated. In the presence of large DMI, the dynamical skyrmion experiences strong breathing with particular promise for skyrmion-based memory and microwave applications.

Interfacial Dzyaloshinskii-Moriya interaction in perpendicularly-magnetized Pt/Co/AlO$_x$ ultrathin films measured by Brillouin light spectroscopy

Mohamed Belmeguenai[1], Jean-Paul Adam[2], Yves Roussigné[1], Sylvain Eimer[2], Thibaut Devolder[2], Joo-Von Kim[2], Salim Mourad Cherif[1], Andrey Stashkevich[1], André Thiaville[3]

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3) Laboratoire de Physique des Solides, UMR CNRS 8502, Université Paris-Sud, 91405 Orsay, France

In ultrathin magnetic films, it has recently been realized that the Dzyaloshinskii-Moriya interaction (DMI) can play an important role in systems showing perpendicular magnetic anisotropy (PMA). We proposed a method based on Brillouin light spectroscopy to measure the strength of this interaction in Pt/Co/AlO$_x$/Pt ultrathin films with PMA. We measure the spin waves for various Co thicknesses (0.6-1.2nm) in the Damon-Eshbach geometry, for wavevectors ranging to 20 μm^{-1} and for strong in-plane fields that drag the magnetization in the sample plane. The measurements reveal a pronounced nonreciprocal spin wave propagation, which increases with decreasing Co thicknesses. This nonreciprocity is attributed to an interfacial DMI, which is significantly stronger than asymmetries resulting from surface anisotropies for such modes. Our results are consistent with an interfacial DMI constant D_s = -1.7 pJ/m, which favors left-handed chiral spin structures.

Asymmetric spin wave dispersion due to interfacial Dzyaloshinskii-Moriya interaction

H. S. Körner[1], J. Stigloher[1], H. G. Bauer[1], H. Hata[2], T. Taniguchi[2], T. Moriyama[2], T. Ono[2], and C. H. Back[1]

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We investigate the effect of the interfacial Dzyaloshinskii-Moriya interaction (DMI) on the propagation of magnetostatic spin waves in the Damon-Eshbach geometry in micrometer-sized Pt/Co/Py/MgO stripes by means of time-resolved scanning Kerr microscopy. Imaging the travelling spin waves while sweeping the excitation frequency allows us to directly access their dispersion $k(\omega)$.

The DMI present at the Pt/Co interface is manifested in an asymmetry in the spin wave dispersion for opposite directions of the external magnetic field for a fixed propagation direction. It reverses sign upon reversal of the propagation direction. From the differences in the group velocities for the various combinations of propagation direction and equilibrium magnetization direction we deduce the value of the DMI constant of our system. It is in the same range as the values reported by other groups for similar layer stacks (e.g. Pt/Py or Pt/Co/Ni) and similar thicknesses.

All-Optical and Spin-torque Induced Spin Dynamics in Two-Dimensional Magnonic Crystals and Ferromagnetic/Nonmagnetic Bilayers

Anjan Barman

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Magnonics is an emerging research topic with huge potential applications and for this to become a viable and sustainable technology it is important to study excitation, manipulation and detection of spin waves in various periodic magnetic nanostructures. Here, we present two different methods of excitation and detection of spin waves in ferromagnetic thin films and nanostructures. An all-optical excitation and detection of spin waves in artificial two-dimensional ferromagnetic nanostructures will be presented by time-resolved MOKE microscope.[1] Tunability of collective spin wave spectrum and damping behaviour by varying the physical and material parameters of the magnonic crystals and bias magnetic field will be discussed.[2-4] Further, spin Hall-spin torque induced excitation of ferromagnetic resonance, modulation of damping and its optical detection has been employed in ferromagnetic/nonmagnetic bilayer thin films and spin Hall angle of the nonmagnetic layer has been estimated.[5]

1. A. Barman and A. Haldar, *Solid State Physics* **65**, 1-108 (2014)
2. B. Rana et al., *ACS Nano*, **5**, 9559 (2011)
3. R. Mandal et al., *ACS Nano* **6**, 3397 (2012)
4. S. Saha et al., *Adv. Funct. Mater.* **23**, 2378 (2013)
5. A. Ganguly et al., *Appl. Phys. Lett.* **105**, 112409 (2014).

Oxide nanomagnonics

D. Grundler[1,2]

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Collective spin excitations in magnets have been argued to advance today's data handling in computationally demanding tasks via parallel processing in cellular networks [1]. At the same time magnonic crystals, i.e., periodically modulated magnetic materials with artificially tailored spin-wave band structures would allow for advanced spin-wave (magnon) control. However, magnonic devices realized so far from conductive ferromagnets such as permalloy suffer from the relatively short damping length. Insulating magnetic oxides might help to improve the situation.
Here we report on spin excitations in insulating ferri- and helimagnetic oxides, i.e., thin films of yttrium iron garnet (YIG) and bulk Cu_2OSeO_3. We used broadband spin-wave spectroscopy based on coplanar waveguides and a vector network analyzer operated up to 26.5 GHz. For YIG we found that 20-nm-thick films offer a macroscopic damping length of up to almost the mm length scale at room temperature [2]. Based on this material, we show how to excite short-wavelength spin waves by making use of the grating coupler effect and periodically modulating the magnetic properties. As a cubic chiral helimagnet with space group $P2_13$, Cu_2OSeO_3 supports a Skyrmion lattice at low temperatures that provides periodically modulated magnetic properties by itself. The lattice constant is on the order of a few 10 nm. Using cryogenic spectroscopy we have studied the collective spin excitations throughout the complete magnetic phase diagram and found a universal behavior of the collective spin excitations when comparing Cu_2OSeO_3 with other chiral helimagnets [3,4]. By modifying the shape of such materials we show how to vary the eigenfrequencies and spectral weights of the modes. Once stabilized in thin films at room temperature, the Skyrmion lattice might provide novel perspectives for spintronics and nanomagnonics [4,5].
The results were obtained in cooperation with A. Anane, A. Bauer, H. Berger, R. Bernard, P. Bortolotti, F. Brandl, V. Cros, O. d'Allivy Kelly, M. Garst, F. Heimbach, R. Huber, F. Lisiecki, C. Pfleiderer, Haiming Yu, T. Schwarze, I. Stasinopoulos, J. Waizner, and S. Weichselbaumer. Financial support by the German Cluster of Excellence 'Nanosystems Initiative Munich (NIM)', the DFG via project GR1640/5 in the priority programme SPP1538 and via TRR80 is gratefully acknowledged.
[1] A. Khitun et al., J. Phys. D: Appl. Phys. **43**, 264005 (2010).
[2] Haiming Yu et al., Scientific Reports **4**, 6848 (2014)
[3] Y. Onose et al., Phys. Rev. Lett. **109**, 037603 (2012)
[4] T. Schwarze et al., submitted
[5] A. Fert et al., Nature Nano. **8**, 152 (2013)

Universal dependence of the spin wave band structure on the geometrical characteristics of two-dimensional magnonic crystals

S. Tacchi[1,*], P. Gruszecki,[2] M. Madami,[3] G. Carlotti,[3] J. W. Kłos,[2] M. Krawczyk,[2] A. Adeyeye, [4] and G. Gubbiotti[1]

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We investigate the spin waves band structure of two-dimensional magnonic crystals consisting of permalloy square antidot lattices with different geometrical parameters. We show that the frequency of the most intense spin-wave modes, measured by Brillouin light scattering, exhibits a universal dependence on the aspect ratio (thickness over width) of the effective nanowire enclosed between adjacent rows of holes. A similar dependence also applies to both the frequency position and the width of the main band gap of the fundamental (dispersive) mode at the edge of the first Brillouin zone. These experimental findings are successfully explained by calculations based on the plane-wave method. Therefore, a unified vision of the spin-waves characteristics in two-dimensional antidot lattices is provided, paving the way to the design of tailored nanoscale devices, such as tunable magnonic filters and phase-shifters, with predicted functionalities. A new method for measuring angle-resolved band structure in antidot lattice is also presented and discussed.

[1] S. Tacchi et al, *Sci. Rep.* **5**, 10367; doi: 10.1038/srep10367 (2015)

Spin pumping and spin transfer torque in YIG/Pt bilayers

Andrii V. Chumak

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The effects of spin pumping (SP) and spin transfer torque (STT) are of large importance for modern magnonics since they allow for the detection, damping compensation and excitation of magnons with spin-polarized electric currents. The spin-polarized currents, in turn, can be interconverted into conventional charge currents using spin Hall effect (SHE). In my talk, I will discuss first the progress in the detection of magnons in the form of the inverse SHE voltage in yttrium-iron garnet (YIG) Platinum (Pt) bilayers. Special attention will be devoted to the spin pinning conditions at the YIG/Pt interface. Afterwards, I will present experimental results on the STT-based damping compensation in YIG due to the current sent through the Pt layer. Brillouin light scattering spectroscopy was used in order to measure damping in YIG via the threshold of parametric instability. Contribution of the STT to different magnon modes are discussed.

Magnonic Holographic Memory for Data Storage and Information Processing

Alexander Khitun

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Magnonic Holographic Memory (MHM) is a novel device exploiting spin wave interference similar to the operation of optical holographic devices. In this talk, we will describe the principle of operation of MHM, and present experimental data on the first working prototypes. In general, MHM devices comprise a magnetic matrix and spin wave generating/detecting elements placed on the edges. The matrix consists of a grid of magnetic waveguides connected via cross junctions. Memory elements are incorporated within the junction while the read-in and read-out is accomplished by the spin waves propagating through the waveguides. We present experimental data on the 2-bit magnonic holographic memory built on the double cross YIG structure with micro-magnets placed on the top of each cross. It appears possible to recognize the state of each magnet via the interference pattern produced by the spin waves. We also present experimental data demonstrating the possibility of pattern recognition by the prototype eight-terminal device. Input information is encoded in the phases of the spin waves generated on the edges of the magnonic matrix, while the output corresponds to the amplitude of the inductive voltage produced by the interfering spin waves on the other side of the matrix. Experimental data collected for several magnonic matrixes show the unique output signatures in which maxima and minima correspond to specific input phase patterns. All experiments are done at room temperature. Potentially, magnonic holographic devices may provide a higher storage density compare to optical counterparts due to a shorter wavelength and compatibility with conventional electronic devices. According to the estimates, magnonic holographic devices may also provide data processing rates higher than 1×10^{18} bits/cm^2/s while consuming 0.15mW. Technological challenges and fundamental physical limits of this approach are also discussed.

Spin-wave modes and grating coupler effect in a bicomponent magnetic periodic lattice

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Recently the so called magnonic grating coupler (MGC) effect was observed for bicomponent periodic lattices consisting of e.g. a two-dimensional array of Py nanodisks partly embedded in a CoFeB thin film. [Yu13] It was shown that the nanodisk array provoked backfolding of the spin- wave dispersion relation. We present broadband spin-wave spectroscopy, micromagnetic simulations and Brillouin light scattering (BLS) performed on a 60 nm thick bicomponent MGC with an inverted material composition to optimize the backfolding effect. The CoFeB nanodisks were arranged on a square lattice (lattice constant of 700 nm). In the experiments a series of spin-wave resonances was resolved that we attributed to MGC modes radiated in up to 14 different spatial directions. Comparing micromagnetic simulations, spectroscopy and micro-focus BLS data we report on our microscopic insight gained about the MGC. The work was funded by the Cluster of Excellence Nanosystems Initiative Munich and in the SPP 1538 via GR1640/5.

[Yu13] H. Yu, G. Duerr, R. Huber, M. Bahr, T. Schwarze, F. Brandl, D. Grundler, Omnidirectional spin-wave nanograting coupler, Nature Communications 4, 2702 (2013)

Towards quantum magnonics.

Karenowska A.D

Oxford University

Over the last decade, the fields of spin-wave dynamics and magnonics have contributed a great deal to our understanding of fundamental magnetism. To date however, experiments have predominantly focused on the study of room-temperature systems within classical limits. In this talk we shall discuss experiments at millikelvin temperatures in which we are able to measure systems of propagating spin waves at the single magnon level. Our results allow us to project that coupling of propagating spin-wave excitations to quantum circuits is achievable, enabling quantum-level studies of magnon systems and potentially opening doors to novel hybrid quantum measurement and information processing devices.

Coherent excitation of a magnonic second sound

A.N. Slavin

Oakland University

When the density of the gas of quasiparticles increases to the extent that the characterisic time of the four-particle nonlinear interactions conserving the linear momentum and the number of quasiparticles is substantilly smaller than the quariparticale lifetime determined by the three-particle processes describing the flow of quasiparticles out of the quasiparticle gas, the thermalization of the quasi-particle gas to a dynamical quasi-equilibrium state and the following Bose-Einstein condensation (BEC) of quasiparticles become possible. The classical Boltzmann theory applied to the quasi-equilibrium thermalized gas of quasiparticles predicts the existance in this gas of dissipative waves of quasiparticle density or "quasiparticle second sound" characterized by the different relaxation rates of the quasiparticle energy and linear momentum.

It is demonstrated that such a quasiparticle second sound can be coherently excited in a dense gas of parametrically pumped magnons existing in a ferrite film at room temperature. The discovered “magnonic second sound” shows a linear dispersion at low wavenumbers, while at larger wavenumbers the dispersion becomes almost quadratic. The magnonic sound is dissipative in a sense that the real and imaginary parts of its wavenumber are comparable, and the rate of the magnon energy relaxation, obtained from the sound dispersion, goes through a pronounced maximum when the magnon gas undergoes the BEC transition with the further increase of the magnon density.

Interaction of Bose – Einstein condensate of magnons with acoustic waves

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We demonstrate theoretically that magnons in a Bose – Einstein condensate (BEC) existing in yttrium-iron-garnet films can efficiently excite acoustic waves (phonons) through a magneto-elastic interaction. The strong coupling between BEC and phonons takes place when the bias magnetic field is chosen in such a way that the dispersion law of the acoustic waves crosses the minimum of the dispersion law of backward volume spin waves in the film. Thus, a band gap opens, due to the hybridization of spin and acoustic waves. Our theoretical estimations show that the value of this band gap, which characterizes the magnitude of interaction between the phonons and BEC, can reach ~50MHz for realistic experimental parameters, and is sufficient for the effective excitation of an acoustic wave. We demonstrate also, that such an effective excitation of the acoustic waves by BEC of magnons can lead to the mutual synchronization of two spatially separated magnon BECs.

Thursday, 06.08.2015

09:00	**Spin-torque IV** *U. Ebels* *Y. Tserkovnyak* *K. Kondou*
10:30	Coffee break
11:10	**Spin waves and spin current** *K. Schultheiss* *T. Silva*
12:30	Lunch

Influence of interlayer coupling on spin torque driven excitations in nanopillar structures

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Spin torque driven auto-oscillations of nanopillar spin valve or tunnel junction structures are described in most models by considering the oscillations of the free layer only, neglecting coupling (such as dipolar or via spin momentum transfer) to the polarizing layer. However to understand excitation spectra of real devices, these interactions need to be taken into account. Here we summarize our recent experimental, simulation and analytical studies on the influence of coupling on the microwave emission properties such as the non–linear frequency shift with current or the linewidth. Different configurations are considered: a synthetic ferrimagnet without and with an external polarizer and the coupling of the free layer to a synthetic antiferromagnetic polarizer. These studies will be important to understand experimental results and to define configurations of improved microwave performances.

Interfacial Spin and Heat Transfer between Metals and Magnetic Insulators

Tserkovnyak Yaroslav

UCLA

We study the role of thermal magnons in the spin and heat transport across a normal-metal/insulating-ferromagnet interface, which is beyond an elastic electronic spin transfer. Using an interfacial exchange Hamiltonian, which couples spins of itinerant and localized orbitals, we calculate spin and energy currents for an arbitrary interfacial temperature difference and misalignment of spin accumulation in the normal metal relative to the ferromagnetic order. The magnonic contribution to spin current leads to a temperature-dependent torque on the magnetic order parameter; reciprocally, the coherent precession of the magnetization pumps spin current into the normal metal, the magnitude of which is affected by the presence of thermal magnons.

Experimental detection of charge to spin conversion in (Bi1-xSbx)2Te3 by means of spin torque ferromagnetic resonance

Kouta Kondou

RIKEN, Japan

By applying spectral analysis based on spin-torque ferromagnetic resonance (ST-FMR) to (Bi1-xSbx)2Te3 (BST)/Cu/NiFe tri-layer films, we succeeded in determining the charge to spin conversion efficiency of a 3D topological insulator BST of which Fermi level was varied by tuning the Sb composition. This analyses enable us to separate the surface state contribution from the bulk contribution. We found the sign of the conversion efficiency changed when the carrier in the topological insulator becomes p-type from n-type.

Guiding spin waves with locally generated Oersted fields

K. Vogt, F.Y. Fradin, J.E. Pearson, T. Sebastian, S.D. Bader, B. Hillebrands, A. Hoffmann, and H. Schultheiss

Spin waves carry angular momentum and can be used to transport spin information over distances much larger than the spin diffusion length of metals. However, the anisotropic dispersion relation of spin waves in thin magnetic films hampers the development of complex, two-dimensional structures that allow for directional changes of the spin-wave propagation path. To overcome this challenge, we designed waveguides that enable the generation of locally rotating magnetic fields via electric current pulses. Using Brillouin light scattering microscopy, the propagation in curved waveguides and the switching in spin-wave multiplexers was investigated, directly demonstrating the advantages over global magnetic fields.

Non-local damping and its dependence on both magnon dispersion and sample structure.

Tom Silva

NIST, Boulder, Colorado, USA

We initially reported on the observation of strong non-local damping for the case of localized magnon modes in nanostructures in 2013 [PRL 110, 117201]. We used a novel magneto-optic method to unambiguously measure the damping in individual nanostructures patterned from 10 nm films down to 100 nm in diameter. Subsequent reports of damping for perpendicular standing spin waves (PSSWs) in thicker, continuous films reveal a much weaker effect [arXiv 1401.6467]. I will present FMR data for PSSWs obtained in our lab that confirms the absence of a strong non-local damping in such a system. The strong electromagnetic coupling between the sample and waveguide transducer when thick films are measured complicates the accurate extraction of damping for PSSW measurements. After correcting for this coupling, the damping is independent of magnon dispersion. Concurrently, magneto-optic measurements for nanostructures patterned from films of varying thickness indicate that the non-local damping is inversely correlated with film thickness. We conclude that the mode-dependent damping we observe in nanomagnets is interfacial in nature.

Posters

Tunable permalloy-based films for magnonic devices

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To optimize the performance of magnonic devices, it is necessary to have a means to control the saturation magnetization (M_s), the magnetic damping (α) and the exchange stiffness (A) of the constituent magnetic materials.

Here we use broadband ferromagnetic resonance (FMR) together with ab initio calculations to study the magnetodynamic properties of $Py_{100-x}M_x$ films (x=0-30), where M is Pt, Au and Ag. The magnetic and magnetodynamic properties show significantly different dependencies on the concentration of the different elements. Thus, co-alloying with Pt, Ag and Au defines a parameter space where M_s, α and A can be varied independently within certain limits. As a proof-of-principle demonstration, we designed a new set of five co-alloyed ternary films, $Py_{100-x-y}Pt_xAg_y$, where the magnetization was held constant, A showed a modest decrease, while α, on the other hand, was tuned a factor of four in a highly predictive manner.

This work was supported by VR, SSF, and the Knut and Alice Wallenberg.

Spatially resolved oscillation modes of the Spin Hall Nano-Oscillators

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The recent demonstration of so called Spin hall Nano-Oscillators (SHNOs)[1,2] driven by pure spin currents has greatly increased the versatility of spin transfer torque (STT) driven devices. In SHNOs the auto-oscillations are driven by a laterally injected spin current in between two low-resistance needles, as a consequence, SHNOs allow for simultaneous measurement and characterization of their magnetization dynamics via wide range of different techniques ranging from electrical measurement to optical techniques such as micro-focused scanning Brillouin Light Scattering (u-BLS).

What is not yet clear is the nature and interplay mechanism of the multimode operation at room temperature[2]. In order to study this in depth a sample SHNO is prepared of Py(5nm)/Pt(6nm) bilayer.

Here we spatially resolved via u-BLS two different oscillation modes, a self-localised solitonic bullet mode and a localized linear mode. Micromagnetic simulations, using Mumax3[3], shed additional light on both modes.

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2. Liu, R. H., Lim, W. L. & Urazhdin, S. *Phys. Rev. Lett.* **110,** 147601 (2013).
3. Vansteenkiste, A. *et al. AIP Adv.* **4,** 107133 (2014).

Modulation of the spectral characteristics in a NC-STO by spin waves in a nearby ferromagnetic insulator

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The emergence of the ferromagnetic insulator YIG in spintronic devices is promising due to its ultra-low damping. However, spin torque driven auto-oscillations in YIG have been elusive. Conversely, nano-contact spin torque oscillators (NC-STO) can readily produce localized and propagating spin waves in metallic $Ni_{80}Fe_{20}$. In this work, we fabricated a conventional NC-STO on top of a YIG film in order to study the modulation of the spectral characteristics in the NC-STO. We performed the measurements at an external field angle and magnitude where the intrinsic frequencies of the YIG and $Ni_{80}Fe_{20}$ films coincide. By passing dc current through the NC-STO auto-oscillations are generated in the $Ni_{80}Fe_{20}$ and oscillations in the YIG are driven by an external microwave source simultaneously. At the coincidence frequency, the spectral properties in the NC-STO exhibit a higher power and lower linewidth as compared to the spectrum away from the coincidence condition. This observation will open new perspectives for utilizing YIG in spintronic and magnonic applications.

Spin-wave frequency non-reciprocity in permalloy thin films

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Propagating spin-waves can now be used as a powerful spectroscopic probe of magnetic interactions (adiabatic and non-adiabatic spin-transfer torques, Dzyaloshinskii-Moriya interaction). For such studies, it is essential to measure and interpret the frequency non-reciprocity, i.e. the change of frequency occurring when the spin-wave propagation direction is reversed. In this work, we investigate the frequency non-reciprocity of MagnetoStatic Surface Waves in 6-40nm thick permalloy films for which the top/bottom symmetry is broken.

Frequency non-reciprocities ranging from 2 to 50 MHz have been measured by propagating spin-wave spectroscopy for wave vectors in the range 1.5-7.8 rad/µm. These values were reproduced using both micromagnetic simulations and an approximate dipole-exchange analytical model, accounting for a 0.2 mJ/m2 difference of the surface anisotropies between the top and bottom film surfaces. This shows that spin wave measurements give access to ferromagnetic film asymmetries with high accuracy, which opens new perspectives for advanced magnetic characterization.

Magnetization dynamics of CoFeB magnetic tunnel junctions bottom electrode with different buffer layers

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We present spin-dynamics measurements on multilayers: buffer/ $2Co_{40}Fe_{40}B_{20}$/ 2MgO /5Ta with the following buffer layers (a) 5Ta / 30CuN / 5Ta, (b) 5Ta, (c) 5Ta / 10Ru / 5Ta (thicknesses in nm). The buffer layers characterized with different crystallographic texture and surface roughness. The lowest damping coefficient derived from the ferromagnetic resonance was measured for the sample with the lowest in-plane uniaxial anisotropy and the smoothest buffer (b), where $\alpha = 5.1\cdot10^{-3}\pm2\cdot10^{-4}$. For buffer (a) damping coefficient was higher due to the roughness induced by columnar texture of CuN with (111) and (200) crystallographic orientations, $\alpha = 5.7\cdot10^{-3}\pm2\cdot10^{-4}$. While for buffer (c) damping coefficient $\alpha = 10.7\cdot10^{-3}\pm3\cdot10^{-4}$ was the highest due to the roughness and high (001) texture of Ru. The spin–wave dispersion relations of investigated samples will be also discussed.

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Spin-torque ferromagnetic resonance in YIG/Pt nanowires

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We use epitaxial (30nm)YIG/GGG(111) films grown by sputter deposition and caped with Pt. By means of electron beam lithography and ion milling we fabricate nanowires with widths in the range of 90-250nm. We observe two contributions to magnetoresistance: One arising from the spin Hall magnetoresistance (SMR) of 0.01% and another from the inverse spin Hall effect (iSHE) in conjunction with spin Seebeck effect (SSE). Utilizing the SMR, we measure spin-torque ferromagnetic resonance (ST-FMR) in the temperature range of 4.2-295K and observe a thermal training effect. The FMR spectra reveal a set of spin-wave modes, which we compare with the results of our micromagnetic simulations. Using DC bias current, a spin current can be injected into YIG causing anti-damping, resulting in FMR linewidths below 1 MHz. Our results elucidate the complex behavior of magnetization dynamics and spin current injection in nano-patterned YIG/Pt systems.

Polarization rotation of microwaves in ferromagnets subjected to spin torque

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It is well known [1] that microwaves propagating through a ferromagnetic material experience a resonance increase of polarization rotation (Faraday effect) near the ferromagnetic resonance frequency. For the same reason the polarization of reflected waves is also increased (Kerr effect). Here we study how these effects are modified in the presence of spin torques acting on magnetization.

Acknowledgments: Supported by the NSF CAREER grant DMR-0847159

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Switching diagram and two-step switching induced by spin Hall effect in a perpendicular magnetic layer

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In a ferromagnet/heavy-metal bilayer device with strong spin Hall effect, an in-plane current excites magnetic dynamics through spin-torque transfer. Using the methods of Refs. [1,2] we analyze bilayers with a perpendicularly magnetized ferromagnet and calculate three-dimensional phase diagrams describing switching due to application of external magnetic field at a fixed current [3]. For fields applied in the plane formed by the film normal vector and the current direction, we find the location of the additional equilibria created by the spin torque and give analytic expressions for two different destabilization boundaries. We further discuss the nature of switching at each boundary and qualitatively describe the magnetic state evolution. By analyzing the phase portraits of the system we give the condition at which switching from "up" to "down" state proceeds through this intermediate state. Using numeric simulations we analyze the switching time and compare it to that of a spin valve with a perpendicular polarizer.

Acknowledgments: Supported by the NSF CAREER grant DMR-0847159

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The total non-reflection of spin waves in thin garnet films

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The phenomenon of total non-reflection of the spin wave was detected for the first time in yttrium iron garnet film patterned by line of antidots. This phenomenon is related to wave arisen at the critical angle between the reflective boundary of the medium and an external magnetic field. The edge wave propagates along the reflective boundary while the reflected waves are absent for all possible incidence angles of the spin wave. A high-intensity beam of spin waves moving along the line of antidots was observed at the critical angle between the line of antidots and magnetic field. The isofrequency curves can provide a tool for clear interpretation of the obtained experimental data.

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Spin Wave Spectroscopy on Topological Defects in Artificial Spin Ice Lattices

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Topological defects (TDs) in ferromagnetic (FM) artificial spin ice (ASI) structures — often considered in the form of magnetic monopoles separated by a so-called Dirac string—have been studied mainly in quasistatic regime [1-3]. Recently, magnetodynamic experiments have been suggested to generate and manipulate such TDs (for example, via ferromagnetic resonance (FMR)); at the same time ASIs are interesting for magnonics [4,5].

We have fabricated periodic FM ASI structures and performed both broadband spectroscopy in the GHz frequency regime and micromagnetic simulations. The interconnected Permalloy nanobars (810 nm long, 110 nm wide, 25 nm thick) were arranged on kagome and square lattices using nanofabrication techniques. Our FMR data show systematic and reproducible resonant modes in the switching regime of ASIs; furthermore, field-dependent amplitudes may be directly related to the population of TDs [4]. Our experiments might be seen as a first step towards utilization of TDs for future magnonic devices [4,5].

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Spin wave excitation by a resonant microwave-to-spin-wave transducer

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The operational principles of many magnonic (and more generally, wave-based) logic devices are based on the interference of multiple spin waves. The ability to excite multiple coherent spin waves is therefore crucial for the perceived magnonic technology. One way to excite multiple coherent spin waves was proposed and experimentally verified in Ref. 1. The aim of this report is to model both analytically and numerically the system studied experimentally in Ref. 1. The micromagnetic OOMMF simulations of the “waveguide-transducer” system from Ref. 1 yield a good agreement with the measurements from Ref. 1. The analytical model is developed assuming a transducer of elliptical cross-section. Then, the relative coupling strength of the transducer's stray field to the dipole-exchange spin waves in the waveguide is calculated for different excitation frequencies. Finally, we analyse the dependence of the spin-wave excitation efficiency upon the transducer's size and cross-section aspect ratio.

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Spin wave observation in an antidot array obtained by self-assembly

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Magnetic spin waves (SWs) have been induced and detected in a Permalloy (Py) thin film nanostructured by the self-assembly of nanospheres [1]. A colloidal solution of water monodispersed polystyrene nanospheres has been spinned in a two-dimensional monolayer array in close packed configuration. After a reduction in size of the nanospheres in Ar plasma, the array acts as a mask for Py sputtering deposition. The removal of the nanospheres creates an antidot structure with holes having 400 nm diameter, and 800 nm center-to-center distance. We generated and detected SWs in Damon-Eschbach configuration by two antennas realized on the same sample by electron beam lithography. The SWs were observed by connecting the antennas to the two ports of a vector network analyzer that generates a continuous wave excitation and allows the measure of scattering parameters. Alternatively, we excited the SWs by connecting the input antenna to a voltage step generator, and the SW propagation was observed by the measure of the induced voltage at the output antenna. In addition, micromagnetic simulations were performed under the harmonic regime by assuming the induced spin waves as perturbations of the ground state. The numerical analysis, taking into account the statistical distribution of defects, is in good agreement with the experimental data.

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Auto-oscillations induced by direct spin hall effect in ultra-thin YIG microdisks for active magnonics devices.

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Spin Transfer torques induced high frequency dynamics has been up to now mainly studied in magnetic metallic materials as the spin current acting on the magnetization flows together with the charge current. Spin Hall Effect (SHE) allows to release this constrain as the spin current flows normally to the charge current opening the field of spin torques to insulating magnetic materials. We have fabricated magnetic microdisks (1 to 4 μm in diameter) from a $Y_3Fe_5O_{12}$ (YIG) (20nm)\Pt (7nm) bilayer. The bare pulsed laser deposited YIG film has a Gilbert damping of α=4.8.10^{-4} and an extrinsic linewidth lower than 1 Oe.

In this study, we demonstrate that spin wave modes can be excited by simply injecting a dc current in the top Pt layer. The threshold current density for the onset of the auto-oscillations is ~ a few 10^{11} A.m^{-2}. Our results pave the way toward SHE based active magnonics.

Low linewidth spin Hall nano-oscillators in oblique magnetic fields

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Spin Hall nano-oscillators (SHNOs) [1] hold great promise as versatile and compact microwave devices particularly suited for magnonics applications. The spin torque in these devices is supplied by a transverse pure spin current, which is generated by the spin Hall effect (SHE) [2] in an adjacent non-magnetic heavy metal [3]. Studies of the microwave emission in SHNOs have been so far limited to cases where the magnetization is oriented in the film plane [1, 4], leading to the observation of self-localized spin wave bullets [5]. Here we study the SHNO characteristics with *out-of-plane* applied fields, *i.e.*, ≥70° w.r.t the film plane. This results in a self-localized bullet, clearly observable in our electrical measurements at room temperature, which is also stable over a wide range of applied fields with frequencies between 2-15 GHz. More interestingly, the minimum spectral linewidth is found to be only 1.9 MHz, which is significantly smaller than what has been previously reported for similar SHNOs at cryogenic temperatures [4].

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Multiferroic structure for electrical field switched magnetoresistive memory

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Promising ways to develop the magnetoresistive memory switched by an electric field are the memory based on the multiferroic structure with exchange interaction between the ferromagnetic layer and multiferroic $BiFeO_3$ layer, as well as the memory based on the elastic interaction between the ferromagnetic layer and the layer of ferroelectric–ferroelastic, in which the magnetization direction of the ferromagnetic layer is determined by the deformation of the electrosensitive layer in the absence of electric field. Possible interaction mechanism between these layers is the interaction due to the elastic deformations transferred from one layer to another. If the reorientation occurs between two equilibrium positions existing in the absence of the interaction with the electrosensitive layer (two easy axes in the layer plane caused by the crystalline symmetry), there is the lower limit of about 100 nm for the bit size because of the occurrence of the superparamagnetic threshold.

Skyrmion racetrack memories and beyond

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Skyrmions are topologically protected magnetic solitons behaving like particles. They are nucleated in out-of-plane materials where the Dzyaloshinskii–Moriya interaction (DMI) arises. According to the type of DMI (Interfacial or Bulk), two kinds of skyrmions can be stabilized (Néel or Bloch).

Recently, the use skyrmions as information carriers in racetrack memories has been proposed. So far, such memory architecture can code the information bit in magnetic regions separated by domain walls, which can be moved by means of the spin-transfer-torque (STT), or, more efficiently, via the spin-Hall effect (SHE).

Here, we show that a skyrmion racetrack memory can be obtained in four scenarios, by combining the skyrmion type (Néel and Bloch) and the motion source (STT and SHE), highlighting that the Néel skyrmion motion driven by the SHE is a promising strategy to design a racetrack memory. Further technological applications of skyrmions beyond the racetrack memory will be shown.

Thermally stabilized magnonic sensors using yttrium iron garnet

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Spin waves can be used to enable extremely sensitive magnetic-field sensors by introducing nano/micro-scaled artificial periodic structures to control the spectral shape of the spin wave propagation. Experimentally a high magnetic field sensitivity, ~38 pT/Hz, was demonstrated in structures made from yttrium iron garnet (YIG) patterned with copper stripes, but the thermal instability of the magnetic properties of YIG precluded the use of the structure as a practical spin wave field sensor device. To solve this issue, we used a spin wave differential circuit (SWDC) comprising two YIG films magnetized in opposite directions. The temperature sensitivity was suppressed, and the thermal stability of the phase of the spin wave was –0.0095° K^{-1}, which is three orders of magnitude better than a simple YIG-based sensor, ~20° K^{-1}. These results constitute an important milestone of the development of magnetic field sensors based on spin waves propagating in YIG.

Influence of gradual change of the refractive index and surface anisotropy on the spin wave beam reflection from the edge of thin ferromagnetic film

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We provide an analysis of the spin wave (SWs) beam reflection from the edge of the thin ferromagnetic film, which is magnetized perpendicularly to the edge. We focus on the magnetic properties at the film edge and their contribution to the Goos-Hänchen (GH) effect and SWs bending. We found considerable influence of the surface magnetic anisotropy at the film edge and non-uniform internal magnetic field in the vicinity of the film edge on the reflection of the SW beam. In our study we used micromagnetic simulations supported by the analytical models. We show that the lateral shift between reflected and incident spin wave beam's spots (i.e., GH shift) is particularly sensitive to the magnitude of the surface magnetic anisotropy.

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Design of coplanar waveguides to excite spin waves beam.

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Here, we show theoretical analysis of the spin wave (SWs) excitation using RF magnetic field generated by coplanar waveguide (CPW) transducers, which can be used to excite SWs in form of the beams with low divergence. We show, that by varying the profile of the classical CPW along its axis, we can mold the envelope of the generated SW. We provide a qualitative description of our idea and validate it in numerical simulations (electromagnetic simulations and micromagnetic simulations). Our analysis shows that slight modification of the CPW geometry enables to excite SWs in form of one (or multiple) beam(s) synchronized in phase with a customizable waist width.

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Giant dynamical mass of magnetic vortices and skyrmions in ferromagnetic nanodots

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The magnetization dynamics of topological solitons (vortices, skyrmions etc.) in the patterned magnetic nanostructures attract considerable attention due to possible applications in spintronics and magnonics. So far, the vast majority of the vortex and skyrmion dynamics studies were focused on thin dots or layers with a thickness 5–50 nm. Thickness dependence of the dynamic magnetization was neglected and only uniform across the thickness spin excitation modes were observed.

In the present paper magnetic topological soliton excitations in relatively thick (50-100 nm) cylindrical permalloy dots are calculated and compared to the excitation modes detected using broadband ferromagnetic resonance [1]. The observed modes are interpreted as flexure oscillations of the vortex core string with n = 0,1,2… nodes along the dot thickness. The frequency of the lowest vortex gyrotropic (n = 0) mode cannot be explained without introducing an inertia (mass) term to the vortex equation of motion. The mass is anomalously large and reflects moving vortex interaction with azimuthal spin waves. A possible mechanism of the giant bubble-skyrmion mass formation in CoB/Pt dots [2] is discussed.

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Tuning the spin wave frequency spectra in flux closed magnetic structures by simultaneous excitations of the vortex gyromode and magneto-static spin waves

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In nano-sized ferromagnetic disks recent experiments and micromagnetic simulations of simultaneous excitations of both, the gyromode and spin wave modes, demonstrate a significant reduction of the vortex core (VC) switching threshold[1]. Using micromagnetic simulations H.G. Bauer et al.[2] have shown that two frequency excitation below the switching-threshold results in a frequency splitting of the lowest spin wave modes.

Here we report on an experimental verification of this prediction by VNA-FMR and TR-MOKE measurements of the frequency spectrum of the azimuthal spin waves when the sub-GHz gyromode is excited simultaneously in $Ni_{80}Fe_{20}$ disks with a diameter of 1.6 μm. Without excitation of the gyromode, the first two magnetostatic spin wave modes ($n = 1$, $m = \pm 1$) are observed at about 5 GHz and 6.5 GHz. After additional simultaneous excitation at the gyromode eigenfrequency (about 250 MHz) we observe a decrease and shifting of the lower frequency spin wave absorption peak with increasing gyro-excitation amplitude as predicted by micromagnetic simulations[2].

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Propagating Spin wave eigenmodes determined by a dynamical matrix approach

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We develop a new finite-difference approach for determining the propagating spin wave eigenmodes in magnetic thin films and stripes. The linearized Landau-Lifshitz equation that describes the magnetization dynamics around an equilibrium configuration is discretized and written in the form of an eigenvalue equation. Then the corresponding dynamical matrix is diagonalized, which yields the spin-wave eigenmodes and the associated frequencies. Our model takes into account both short range exchange interactions and long range dipole-dipole interactions. The latter are evaluated through the calculation of dynamical demagnetizing factors, which depend not only on the geometry and relative positions of the magnetic cells, as usual (static) demagnetizing factors do, but also on the wave vector of the propagating spin waves. We apply our numerical approach to study the profile of magnetostatic surface spin wave modes through the thickness of extended films and the channeling of spin waves along magnetic textures such as domain walls in magnetic stripes.

Parametric Amplification of Spin Waves by Acoustic Waves

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The parametric amplification of spin waves in yttrium iron garnet (YIG) films by acoustic waves of twice the frequency was observed. Understanding such parametric magnon-phonon processes has taken on new importance in light of recent experiments on spin caloritronics [1] and acoustic pumping of spin currents [2]. Acoustic parametric amplification of spin waves may also provide a convenient, integrated approach to extending the distance that information can be transmitted in spin-wave buses proposed for spin-based computation.

Spin wave packets (1.23 GHz, 60 ns bursts) were generated in a 13 μm thick YIG film on a gadolinium gallium garnet (GGG) substrate via a microstrip antenna driven by a signal generator. An appropriate dc bias field was applied in the film plane to allow propagation of backward volume spin waves at this frequency. The spin wave packets were detected at a second, identical antenna after propagating 8 mm through the YIG. In the intervening space, standing acoustic waves of twice the frequency (2.46 GHz) were established by means of a piezoelectric ZnO thin-film transducer patterned on the opposite side of the GGG substrate.

It was observed that the amplitude of the detected spin wave packet increased when the acoustic signal was applied and the amplification became larger with increased amplitude of the acoustic wave. Further, the transit time of the burst from the transmitting to receiving antenna became smaller as the acoustic amplitude increased. The effects resemble those observed in parametric amplification of spin wave solitons by electromagnetic fields [3] and may be explained [4] in terms of an effective ac magnetic field caused by the acoustic wave through magnetoelastic coupling in the YIG.

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Demonstration of XNOR gate using interference of magnetostatic forward volume waves propagating in yttrium iron garnet

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The interference of spin waves is expected to enable computation without charge transportation, which holds promise for the realization of low-loss logic devices. Spin wave interference in Ni-Fe waveguides with three-port antennas has been demonstrated using MSSW (magnetostatic surface wave) [1]. To develop integrated spin wave circuits, use of a spin wave mode without anisotropy in the film plane and a waveguide with low damping is preferable. In this study, we demonstrated three-port spin wave interference with a perpendicularly magnetized YIG (yttrium iron garnet) waveguide to verify the suitability of MSFVW (magnetostatic forward volume wave) propagating in the low- damping spin waveguide. The spin waveguide consisted of 16 pm thick bulk-like YIG with low magnetic damping (linewidth of AH = 0.8 Oe). A micro-strip antenna for spin wave detection was sandwiched by two input micro-strip antennas with a 5 mm gap. Continuous waves at a frequency of 4 GHz were supplied to the input antennas to inject spin waves toward the detection antenna. The output signal of the detection antenna was maximized for the in-phase condition and minimized for the out-of-phase condition. An extremely high isolation value of -25 dB between in-phase “1” and out-of-phase “0” conditions was obtained even after propagation over a distance of 5 mm, which indicates the potential of YIG waveguides to include a spin wave modulator such as a magnonic crystal to control the phase of injected spin waves.

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Synchronization of spin-Hall nano-oscillator arrays

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Recently it has been demonstrated experimentally [1] how spin-Hall nano-oscillators can be fabricated in a simple nanoconstriction geometry. The flexibility of this geometry should open up the possibility to construct larger arrays of synchronized oscillators.

In this contribution we show micromagnetic simulations of nano-oscillators in this new kind of geometry, which give additional insights in the details of excited auto-oscillation modes. Similar to the experiment we find one single auto-oscillation mode for lower currents. Above a certain threshold current a transition to chaotic oscillation takes place.

Furthermore we analyze the synchronization dynamics of a nano-oscillator array based on multiple nanoconstrictions in a row. Even for large arrays in a certain range of parameters the oscillators can be globally synchronized in-phase. However the transition to chaos, which hinders the synchronization, shows a strong dependence on the number of the oscillators and the exact geometrical layout of the system.

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Stoner excitations by inelastic spin-polarized electron scattering - revisited -

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In magnets Stoner excitations are related to magnons like electron-hole pairs to plasmons in a semiconductor. Stoner excitations can be seen in spin-polarized electron energy loss spectroscopy (SPEELS) as demonstrated 30 years ago /1/. Based on general considerations /2/ and theory /3/ one should expect the energy loss spectrum to be richly structured in intensity and asymmetry as a function of energy and angle. The spectra should show features on the scale of one eV, should depend on the primary energy on a similar scale, and should respond to angular variations of a few degrees. However, in experiments with metallic ferromagnets, unanimously, these features were not observed. This remained a puzzle from the beginning.

During the last few years, I developed an improved SPEELS apparatus including a multichannel energy analyzer and a multichannel spin detector. The gain in intensity was sacrificed for better angular resolution and, indeed, all the expected features have been found. We know now that the crucial parameter is momentum resolution, rather than just energy resolution. I found that at least a resolution of 0.1 A^{-1} is needed. I will show new data on Fe on Ir(100) in comparison with literature data of similar systems.

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Spin-wave logics with isotropic forward volume magneto-static waves

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We propose the utilization of isotropic forward volume magneto-static spin waves (FVMSW) in modern wave-based logic devices and suggest a concrete design for a spin-wave majority gate operating with these waves. We demonstrate by numerical simulations that the proposed out-of-plane magnetized majority gate overcomes the limitations of anisotropic in-plane magnetized majority gates due to the high spin-wave transmission through the gate, which enables a reduced energy consumption of these devices. Moreover, the functionality of the out-of-plane majority gate is increased due to the lack of parasitic generation of short-wavelength exchange spin waves. Additionally, the utilization of FVMSW is presented in two dimensional waveguide crossings which can be utilized to build complex spin-wave networks such as spin-wave based full adders or holographic memory devices.

Spatial filtering effect in magnonic crystals

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The magnonic crystals (MC)s, as a counterparts of photonic crystals, can be used to mold the propagation of spin waves (SW)s. We considered 2D planar, bicomponent MC with in plane external magnetic field saturating the sample. One can observe two sources of anisotropy in SW propagation: (i) related to orientation of SW propagation with respect to the direction of the magnetic field – long wavelength (metamaterial's) regime, (ii) anisotropy induced by lattice of MC related to presence of the magnonic band structure, for SWs of wavelengths compatible (or smaller) to lattice constant. We investigated the effect of spatial filtering which blocks the transmission of SWs in specific ranges of refraction angles. The isofrequecy lines were used to identify the magnonic bands and the intervals of frequencies suitable to gain this effect.

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Application of magnonic crystals: The determination of the exchange stiffness in ultrathin magnetic films using ferromagnetic resonance.

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In ultrathin films of below 20 nm thickness, it is hardly possible to determine the exchange constant $\boldsymbol{A}$, since perpendicular standing spin waves (PSSWs) are shifted up to inaccessibly high energies. In this work, a method is presented to analytically determine the exchange stiffness constant $\boldsymbol{D} = 2\boldsymbol{A}/\boldsymbol{M}_S$ using ferromagnetic resonance (FMR). Standard FMR measurements, however, are not influenced by the value of $\boldsymbol{D}$, since no exchange energy is involved in uniform precession. To overcome this problem, a coupling mechanism, such as two-magnon scattering (TMS), can be employed to couple exchange dominated in-plane spin waves, with the uniform mode.

In this approach, lateral surface patterning was carried out to artificially induce TMS. Subsequent FMR measurements give access to the spin wave spectra of backward volume modes and thus, to the exchange stiffness constant $\boldsymbol{D}$.

Control of the spin-wave relaxation in a magnetic insulator of macroscopic dimensions via spin-transfer torque

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It was shown recently that in micro-structured YIG/Pt disks the spin-wave damping can be controlled via the spin Hall effect (SHE) and spin-transfer torque (STT). However, one main advantage of the SHE-STT-based damping compensation is its applicability to macroscopic systems.

Here, we present experimental studies of the SHE-STT-based spin-wave relaxation control in a YIG(100 nm)/Pt(10 nm) film with dimensions 4x2 mm². The change of the relaxation frequency with the applied dc current was determined from investigations of the parallel parametric instability. For this purpose, parametrically excited spin waves were detected by BLS spectroscopy that allowed for the determination of the threshold values of the pumping magnetic field.

We found that the relaxation frequency changes linearly with the dc current and can be tuned by ±7.5% for a current density of $5 \cdot 10^{10}$ A/m^2. The sign of the relaxation variation changes with the current direction and the field polarity.

Propagating spin waves excited by spin-transfer torque in nanocontact oscillators: a combined electrical and optical study

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Nanocontact spin-torque oscillators are devices in which the generation of propagating spin waves can be sustained by spin transfer torque. In the present work, we perform combined electrical and optical measurements in a single experimental setup to systematically investigate the excitation of spin waves by a nanocontact spin torque oscillator and their propagation in a $Ni_{80}Fe_{20}$ extended layer. By using microfocused Brillouin light scattering we observe an anisotropic emission of spin waves, due to the broken symmetry imposed by the inhomogeneous Oersted field generated by the injected current. In particular, spin waves propagate on the side of the nanocontact where the Oersted field and the in-plane component of the applied magnetic field are antiparallel, while propagation is inhibited on the opposite side. Moreover, propagating spin waves are efficiently excited only in a limited range of wavelengths comparable with the nanocontact diameter. This frequency range obeys the dispersion relation for exchange-dominated spin waves in the far field, as confirmed by micromagnetic simulations of similar devices.

Spin-wave modes and grating coupler effect in a bicomponent magnetic periodic lattice

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Recently the so called magnonic grating coupler (MGC) effect was observed for bicomponent periodic lattices consisting of e.g. a two-dimensional array of Py nanodisks partly embedded in a CoFeB thin film. [Yu13] It was shown that the nanodisk array provoked backfolding of the spin- wave dispersion relation. We present broadband spin-wave spectroscopy, micromagnetic simulations and Brillouin light scattering (BLS) performed on a 60 nm thick bicomponent MGC with an inverted material composition to optimize the backfolding effect. The CoFeB nanodisks were arranged on a square lattice (lattice constant of 700 nm). In the experiments a series of spin-wave resonances was resolved that we attributed to MGC modes radiated in up to 14 different spatial directions. Comparing micromagnetic simulations, spectroscopy and micro-focus BLS data we report on our microscopic insight gained about the MGC. The work was funded by the Cluster of Excellence Nanosystems Initiative Munich and in the SPP 1538 via GR1640/5.

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Spin-wave modes in magnonic crystal waveguides and inverted waveguides.

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This work contributes to the understanding of spin waves behavior excited on periodically structured magnetic thin films. The examined sample consist of 50 nm CoFeB continuous film, where a square lattice of 1 μm antidots (3.5 μm lattice constant) has been produced. We determine the spin-wave spectra of two kind of different structures. First, a magnonic waveguide is realized by introducing 3-5 defect lines in the crystal structure. Second, a set of inverted waveguides consisting of n by 40 unit cells, where n=2, 4..,20 was produced.

Spin-wave modes have been excited and observed optically using a pulsed (40 fs) 800nm laser. Magnetization oscillations are detected using time resolved magneto-optical Kerr effect. We observe that a Damon-Eshbach mode is supported on inverted waveguides of more than n=6 rows. This mode can also be detected on defect lines (waveguides) of as large as 5 rows of antidots.

Room temperature observation of individual skyrmions in asymmetric magnetic multilayers

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In the last couple of years, interests for magnetic skyrmions has been growing a lot because their unique properties should be interesting for the development of novel high density and low power spintronics nano-devices for information storage and/or logic. However, up to now, magnetic skyrmions were mostly observed either in B20 crystals or in single Fe monolayers at low temperature. In this work, we propose a new approach, designing cobalt-based multilayered thin films where the Co layer is sandwiched between two heavy metals, providing additive interfacial Dzyaloshinskii-Moriya interactions, which reach about 2 mJ/m^2 in the case of the Ir|Co|Pt multilayers. Using a magnetization-sensitive scanning x-ray transmission microscopy technique, we image magnetic bubble-like domains in these multilayers. The study of their behavior in magnetic field allows us to conclude that they are actually magnetic skyrmions stabilized by the Dzyaloshinskii-Moriya interaction. This discovery of stable skyrmions at room temperature in a technologically relevant material opens the way for device applications in a near future. Our room temperature observation of isolated skyrmionic spin textures that are stabilized in magnetic multilayers by a strong interfacial chiral interaction represents the main achievement of this work.

Laser driven magnonics

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Spin-waves can be generated on different length scales using femtosecond laser pulses. At the same time the temperature gradient can be used to modify the spin-wave dispersion of dipolar and exchange spin-wave modes. I will discuss a few aspects of the laser driven spin-waves in confined anti-dot lattices. Their generation in stripes and notch samples gives us insights how a magnonic mode is established in small size magnonic crystals and at crystal interfaces. In addition the temperature gradients generated by lasers on nanosecond time scales will be discussed.

Berry curvature and Hall effect for dipole-exchange magnons

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Berry curvature is a quantity defined for any types of waves labeled by a Bloch wavevector, and characterizes a differential-geometric structure of waves in a uniform or periodic medium. In previous works we calculated the Berry curvature for magnetostatic waves, and found that only for magnetostatic forward volume-wave modes, the Berry curvature is nonzero. In the present work we include the exchange coupling to this setup to see how the Berry curvature is affected. The exchange coupling gives rise to anticrossing in the spin-wave branches of forward volume-wave modes, and at such anticrossing the Berry curvature is found to be enhanced. This Berry curvature leads to Hall effect of magnons. For example, as a result of the magnon Hall effect, a magnon wavepacket is porposed to undergo a transverse shift at a refraction or reflection at interfaces and boundaries of the system.

Qualitative analysis of voltage modulation of propagating spin waves in Fe

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Spin waves are useful system to study the magnetism in thin-film ferromagnets, such as the Dzyaloshinskii-Moriya interaction. [1] Recently we have investigated the voltage controlled magnetism in Au/Fe/MgO artificial multilayer using spin waves with micro-antennae methods, and found that the resonant magnetic field of the magnetostatic surface spin waves can be controlled by the voltage-induced magnetic anisotropy change. [2] In this paper, we report the Fe-thickness dependence of the voltage effect. The multilayer consists of Au(50 nm)/Fe(7-21 nm)/MgO(10 nm) was prepared by molecular beam epitaxy methods. The spin-wave properties were characterized using vector network analyzer. We found that signal-to-noise ratio in voltage modulated signals increases as the Fe thickness increases. This indicates that spin-wave measurements with thicker ferromagnetic film offer highly sensitive characterization methods for voltage controlled magnetism.

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Micromagnetic study of magnetization dynamics activated by spin transfer torque in circular nanopillars: evolution from the linear to the non-linear regime

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We present a micromagnetic study of the transition from the linear oscillation regime towards the non-linear one, induced by Spin Transfer Torque, in circular Permalloy nanopillars having a diameter of either 100 nm or 300 nm. Both in-plane and out-of-plane externally applied fields are considered. Emphasis is given to the effect of the Oersted field generated by the injected current on both the frequency and the spatial symmetry of the excitations. In the out-of-plane case, the main effect of the increasing current is to enhance the angle of magnetization precession and lift the modes frequencies. In the in-plane case, instead, the transition to the non-linear regime is also accompanied by a qualitative evolution of the spatial profile of the modes: those localized at the dot edges, that dominate the low-amplitude dynamics, tend to delocalize and occupy the whole dot extension as the current increases and the non-linear regime is attained.

Magnonic diodes and transistors

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Every logical gate can be decomposed in a combination of diodes and transistors. For that purpose, we have first studied the dynamics of atomic moments and the magnon dispersion curves of a 1D magnonic crystal composed of alternating layers of permalloy and cobalt.

In order to simulate a magnonic diode, we excited a magnon at a specific frequency with an external magnetic pulse. The diode is made of two ferromagnets with different exchange parameters, anisotropy constants and Dzyaloshinskii-Moriya interaction.

Regarding the transistor, we sandwiched a magnonic crystal between two ferromagnets. We excited several magnons in one side of the sample applying a gaussian site and time-dependent magnetic pulse. Moreover, we applied a static external magnetic field only to the magnonic crystal and depending on the value of the static field, we tuned the number of magnons that arrived to the other side of the sample.

Programmable magnonic crystal by voltage-controlled perpendicular magnetic anisotropy

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In this work, we numerically and analytically investigate the voltage-controlled spin wave propagations in a narrow waveguide with periodically manipulated perpendicular magnetic anisotropy induced by voltage. The voltage induces periodic magnetization distribution in the waveguide. We observe that the dispersion curve of spin wave is manipulated by voltage and form band gaps at the Brillouin zone. The band gaps is switched “on” and “off” by voltage. Furthermore, the center frequencies of the band gaps are adjusted by different periodic magnetization structures induced by voltage. We finally design programmable magnonic waveguide crystals.

Excitation of magnetization dynamics in thin CoFeB films by electric field

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We study precessional magnetization dynamics in thin CoFeB film [CoFeB(1.4nm)/MgO(2nm)/CoFeB(3nm)] excited by modulating perpendicular interfacial magnetic anisotropy of CoFeB/MgO by RF electric field. Experimental results show that electric field (***E***) excitation consumes much lower power compared to other known methods. The excitation amplitude strongly depends upon the inclination angle of the magnetization and the magnitude of ***E***. The excitation amplitude shows its minima when the magnetization is either in-plane or out-of-plane of the film. The amplitude also show a quadratic dependence on ***E***, whereas cone angle of precession is proportional to ***E***. Experimental results show that the cone angle of precession can be up to few degrees probably due to the non-uniform spin precession, while macrospin calculations show that it could be up to few tens of degrees for uniform precession. Micromagnetic simulation study reveals that the spin-wave with defined wavelength can also be excited by electric field.

Microwave Giant magnetoresistive effect in Co/Cu Multilayers

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Giant microwave magnetoresistive effect is investigated in the glass/Fe(50Å)/[Co(15 Å)/Cu(t)]$_{10}$/Cr(20 Å) multilayered nanostructures with thickness of copper layers from 8 Å to 27 Å. Measurements of frequency and magnetic field dependences of transmission and reflection coefficients have been carried out in frequency range from 26 to 38 GHz. The magnetization curves have been measured as well as giant magnetoresistive effect (GMR). It is established that giant microwave magnetoresistive effect (μ-GMR) has the shape of magnetic field dependency quite similar to that for GMR measured at DC. The magnitude of μ-GMR is less that the magnitude of GMR. It has been established experimentally that μ-GMR is frequency-dependent and the magnitude of the microwave effect increases if frequency rises. This frequency dependence is linked with the fact that total metal thickness is small and the inequality $\mathrm{th}(1+i)d/\delta >> 2Z_m/Z$, that is necessary for frequency independent μ-GMR, is not valid here. *d* is the total metal thickness of the nanostructure, δ is the skin depth, Z_m is the impedance of the metal of nanostructure, *Z* is the impedance of free space. Comparison in sign and the shape of magnetic field variations in transmission and reflection of the wave is carried out. The microwave results are compared to the magnetoresistive data and the results of magnetic measurements.

Micrometer scale spin-wave interferometer

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We realized a micrometer scale the spin-wave interferometer consisting of two parallel separated $Co_{20}Fe_{60}B_{20}$ spin-wave waveguides. Spin-waves are excited by one excitation antenna. After propagating over a distance of 20 μm, spin-wave in each ferromagnetic waveguide generates inductively an electrical voltage in the detection antenna where theses electrical voltages interfere. A dc current flowing through the normal metal underneath one spin-wave waveguide generates an Oersted field and Joule heating inside the corresponding spin-wave waveguide which modify the propagating spin-wave wave vector. Therefore a phase delay is developed between the spin waves in the two spin-wave waveguides at the receiving antenna. Thus the interferences are controlled by changing propagation conditions in one of the waveguides. We further discuss the influence of both Oersted field and Joule heating effects and the optimum conditions for totally destructive interferences arising from spin waves propagation.

O. Rousseau et al. *Realization of a micrometer scale spin-wave interferometer* accepted in Scientific Reports.

Brillouin light scattering study of laterally coupled multiferroic waveguides

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Modern progress in the investigation of the multilayered structures composed of ferrite and ferroelectric materials (multiferroics) lead to miniaturize passive microwave components [1]. A number of linear and nonlinear devices (microwave phase shifters, filters, delay lines and resonators) can be fabricated using the multiferroic structures (see e.g., [2,3]). The characteristics of such devices can be tuned using both the static magnetic and electric fields over a wide frequency range [4].

In this work we report the experimental and numerical investigations of spin-electromagnetic waves propagating in finite-width multiferroic waveguide. Numerical simulation was provided by the developped finite-element method (FEM) of electromagnetic eigenspectrum calculation. Experimental study of eigenmodes of laterally confined multiferroic was performed by using space-resolved Brillouin light scattering (BLS) spectroscopy [5]. We show that the spatial distribution of magnetization of the width-modes in laterally confined multiferroic structure changes due to the electrodynamic coupling between the spin waves (SW) localized mainly in the finite-width ferrite layer and the electromagnetic waves propagating in the ferroelectric layer. The transformation of eigenmodes spatial distribution was demonstrated with the modes decomposition analysis. In particular, transformation of spatial distribution of third width-mode leads to the localization of SW intensity in the center of finite-width waveguide.

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Temperature-dependent FORC diagrams of template-assisted CoNi nanowire arrays

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We will present recent results of our study of CoNi binary alloy nanowire arrays fabricated with alumina template –assisted electrodeposition. CoNi nanowires are very interesting magnetic systems for spintronic and magnonic applications, because they give a possibility to tune the effective magnetic anisotropy through the variation of material composition. Since nanowires can contain of different crystal phases (hcp, fcc or mixture hcp+fcc [1]), an investigation of interrelation between crystal structure and magnetic properties is an important and difficult task, which can be successfully solved using not only hysteresis loop measurements, but also involving the first order reversal curve (FORC) method [2]. FORC analysis is very powerful tool for studying of binary or multicomponent nanostructures coupled by the magnetostatic interaction. We will display FORC diagrams in dependence on the nanowire content and will demonstrate their temperature-dependent evolution down to 77 K. Quantitative evaluation of the effective magnetic anisotropy and distribution of the coercivity and interaction field will be explained within models for highly interacting systems. We will define magnetization reversal mechanisms, matching the angle dependence of coercivity for arrays with different Co and Ni content, comparing theoretical calculations with experimental data.

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Spin-wave excitation in YIG-Pt bilayers

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The decrease in the damping of spin waves propagating in a single-crystal yttrium iron garnet (YIG) film covered with a current conducting Pt layer has already been reported. However, the absolute spin-wave attenuation in such a structure is much stronger in comparison with a free YIG film. We have found that the spin-wave amplitude decreases due to the electromagnetic shielding of microwave Oersted magnetic fields induced around input and output microstrip antennas. The shielding effect turns to be strong even if the thickness of the Pt layer (2.5 nm-10 nm) is significantly smaller than the skin depth. By placing the Pt layer near the ground plane of the microstrip antennas, we have reduced the shielding effect and achieved, thus, a drastic (up to 100 times) increase in the excitation efficiency of the Damon-Eshbach surface spin wave.

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Ferromagnetic resonance modes of nanomagnetic logic elements

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Nanomagnetic logic (NML) built from nano-scale magnets has attracted extensive interest as an alternative for digital circuits. The dynamic properties of NML element are relevant to understand the maximum operation speed and to investigate, e.g., microwave-assisted programming schemes. In this work we study the precessional dynamics of NML elements composed of individual rectangular magnets, lengthwise-coupled magnet pairs and driver-input magnet pairs by vector network analyzer ferromagnetic resonance (VNA-FMR) and Landau-Lifshitz-Gilbert (LLG) micromagnetic simulations. In FMR experiments we observe a center resonance mode for all samples and edge modes for arrays with individual rectangular magnets and lengthwise-coupled magnet pairs. In the simulations distinct edge modes not visible in the experiments are revealed. Based on these numerical investigations we propose a new addressing scheme to switch a specific element of the driver-input magnet pair based on resonant excitation of the unique edge-mode resonance.

The work was co-funded within EMRP JRP EXL04 by EURAMET and the EU. The Notre Dame group was supported in part by an NSF/SRC Nanoelectronics Beyond 2020 (NEB) grant.

Micromagnetic simulation of tunable magnonic filters consisting of mono- and bi-component nanostructured films

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We propose the realization of tunable magnonic filters based on the exploitation of spin waves propagating across either arrays of Permalloy antidot lattices or bi-component arrays where the antidots are filled with a second magnetic material (e.g. Cobalt). The andidot lattice has circular hole with diameters D=50nm, thickness d=10nm and variable periodicity in the range between 100 and 400 nm. The micromagnetic simulations are performed using the open source GPU-accelerated code MuMax3, for different lattices geometries and considering both the backward and the Damon-Eshbach configurations. It is shown that the main features of the frequency-dependent transmission coefficient of each array can be interpreted through a careful analysis of the characteristics of the spin wave eigenmodes of the corresponding magnonic crystal, with emphasis given to both the dispersive character and the spatial profile of the most prominent modes.

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Snell's law for spin waves

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Snell's law is well known in optics. It describes the refraction of light at the transition between two media with different dispersions. As its origin is the wave-nature of light it should also be applicable to spin waves.

We achieve this transition by a thickness step: Spin waves excited in a 60 nm thick Permalloy film by a microwave antenna propagate into a 30 nm thick film. Their wave vector amplitude is adjusted by the magnitude of the external magnetic field.

Utilizing time-resolved scanning Kerr microscopy we can directly track the wave fronts and therefore deduce the changes in the angle of propagation and in the wave vector amplitude at the transition to the thinner film. By measuring the refraction for varying incident angles, we determine Snell's law for spin waves. It deviates from Snell's law in optics since the spin wave dispersion is anisotropic, i.e. it strongly depends on the angle between propagation and field direction.

Interatomic Exchange Interactions for Finite-Temperature Magnetism and Nonequilibrium Spin Dynamics

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We derive ab inito exchange parameters for general noncollinear magnetic configurations, in terms of a multiple scattering formalism. We show that the general exchange formula has an anisotropic like term even in the absence of spin-orbit coupling (SOC), and that this term is large, for instance, for collinear configuration in bcc Fe, whereas for fcc Ni it is quite small. To illustrate our results in practice, we calculate for bcc Fe magnon spectra obtained from configuration dependent exchange parameters, where the configurations are determined by finite-temperature effects. Our theory results in the same quantitative results as the finite-temperature neutron scattering experiments, and have been published in the Phy. Rev. Lett. **111**, 127204 (2013) To extend the non-collinear formalism we present new results when the SOC is present, and the Dzyaloshinskii-Moriya terms in the exchange tensor apprear.

Interaction of Bose – Einstein condensate of magnons with acoustic waves

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We demonstrate theoretically that magnons in a Bose – Einstein condensate (BEC) existing in yttrium-iron-garnet films can efficiently excite acoustic waves (phonons) through a magneto-elastic interaction. The strong coupling between BEC and phonons takes place when the bias magnetic field is chosen in such a way that the dispersion law of the acoustic waves crosses the minimum of the dispersion law of backward volume spin waves in the film. Thus, a band gap opens, due to the hybridization of spin and acoustic waves. Our theoretical estimations show that the value of this band gap, which characterizes the magnitude of interaction between the phonons and BEC, can reach ~50MHz for realistic experimental parameters, and is sufficient for the effective excitation of an acoustic wave. We demonstrate also, that such an effective excitation of the acoustic waves by BEC of magnons can lead to the mutual synchronization of two spatially separated magnon BECs.

Relative role of in-plane and out-of-plane spin-transfer torques on the magnetization switching of fully perpendicular magnetic tunnel junctions

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The switching process in a fully perpendicular magnetic tunnel junction (pMTJ) can be more clearly interpreted by transforming the usual Landau-Lifshitz-Gilbert-Slonczewski equation to a Landau-Lifshitz (LL) form. This substantially clarifies the interpretation of spin-transfer-torque (STT) driven reversal under the mutual action of in-plane (damping-like) and out-of-plane (field-like) STT torques. Collinear configuration of the external magnetic field, polarizer and perpendicular magnetic anisotropy existing in the considered system, allows deriving the phase boundaries of a current-field switching diagram directly from the LL equation. It allows for a simplified analysis of the relative contributions of both torques in the precession and dissipation terms of Landau-Lifshitz equation. It is demonstrated that in pMTJ structures obeying macrosin dynamics, the out-of-plane torque can change the precession frequency and even the precession direction but does not contribute significantly to the STT switching process in which the in-plane torque is still dominating. Validity of this conclusion is confirmed by macrospin simulations of the current-field switching diagrams at finite temperature under writing pulses of finite width. Finally, we apply our analysis to the description of voltage-field switching diagrams measured experimentally on fully perpendicular pMTJ pillars. The good agreement between macrospin simulations and experimental data for small pillar diameters ~40nm indicate that the magnetic behavior is macrospin at these small diameters.

Ultrafast motion of domain wall in permalloy microstripes under spin-polarized current pulses

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The switching of the magnetic state of the structures by spin-polarized current is now considered as prospective to be used in spintronics and cryoelectronics. Important questions are how fast could be this switching and what the limiting factors are. In this study, the maximum velocities of the domain walls moving under the magnetic field and under the current pulses were determined experimentally in wide temperature range, from 6 K up to 300 K.

The experiments were performed on bilayer niobium-permalloy stripes with the width of 2 and 7 µm, and thicknesses of about 100 nm of niobium sublayer and 40 nm of permalloy upper layer. The structures were fabricated by lift-off lithography after magnetron spattering on cold substrate in the presence of 600 Oe in-plane field on SiO_2 substrate. The visualization of the magnetic domain structure and domain wall motion were performed by magneto-optic visualization technique [1]. The magnetization in permalloy stripes was oriented along the stripe length. The stripes in initial state always were in the single domain state. The domain walls formed during magnetization reversal under the field were 180-degree walls of Bloch type with out-of-plane magnetization [1]. The velocity of the walls was estimated from the shift of the walls between two serial video-frames trapped by fast digital camera synchronously with the beginning and the end of the wall excited pulses.

We have observed the nonlinear response of the walls on the applied field magnitude and on the current value, the existence of threshold values of the field and current for the beginning of the wall motion, and wall velocity saturation at high enough excitations. We found the decrease of the maximum velocity values for the field stimulated motion and unexpected increase of the velocity under the current with temperature decrease, both following the power laws despite of exponential growth of the coercivity with temperature decrease [2], Fig.1. The maximum wall velocity exceeds several times the Walker limit. The wall motion under the current was accompanied by its broadening up to hundreds of micrometers leading to formation of the domain with transverse to the stripe magnetization [3].

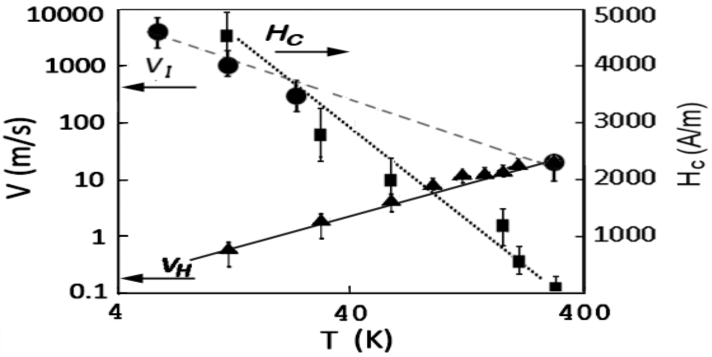

Fig.1. Temperature dependences of coercivity H_c (squares), maximum domain wall velocity moving under the magnetic field, V_H , (triangles) and under the current pulses, V_I, (circles).

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Microwave-induced spin currents in ferromagnetic-insulator|normal-metal bilayers

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We used microwaves as a simple-and-controlled heating technique to generate a thermal gradient in ferromagnetic-insulator|normal-metal systems to study static and temporal properties of the longitudinal spin Seebeck (LSSE). Experiments were conducted using a bilayer of a magnetic insulator (Yttrium Iron Garnet (YIG)), and a normal metal (Pt). The static dc measurements demonstrate that in the LSSE a spin current flows from the normal metal (hot) towards the ferrimagnet (cold), while in the spin pumping case, the flow is opposite. The temporal dynamics of the LSSE in micrometer-thick YIG films manifests the sub-microsecond timescale of the effect. The thermal magnon diffusion model leads to conclude that the timescale of the effect relies the evolution of the vertical thermal gradient in the vicinity of the ferrimagnet|normal-metal interface. From experiments, magnon diffusion lengths are estimated for different YIG|Pt systems.

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Spin-wave propagation within domain walls

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Research efforts to deploy spin waves as information carriers in micro- and nano-structured ferromagnetic materials have increased tremendously over the recent years. However, tailoring guided spin-wave propagation in two dimensions still remains a delicate challenge.

Here we demonstrate spin-wave transport inside a domain wall. For this, we perform Brillouin-Light-Scattering microscopy (hier zitat?) as well as micromagnetic simulations for thin film elements in a Landau state.

According to the simulations, we find several spin-wave modes of different energies with well distinguished wave vectors. They exhibit a positive dispersion and propagate along the domain-wall.

In the experiment, we observe the domain wall as a narrow spin-wave channel of about 100 nanometer in width. We show, that by applying external fields of a few Oersteds, this propagation channel can be shifted by several microns, combining strong confinement and reversible control of the spin-wave propagation.

Domain walls, thus, open the perspective for reprogrammable and yet nonvolatile spin-wave waveguides of nanometer width.

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Graded-index magnonics with local electrical currents

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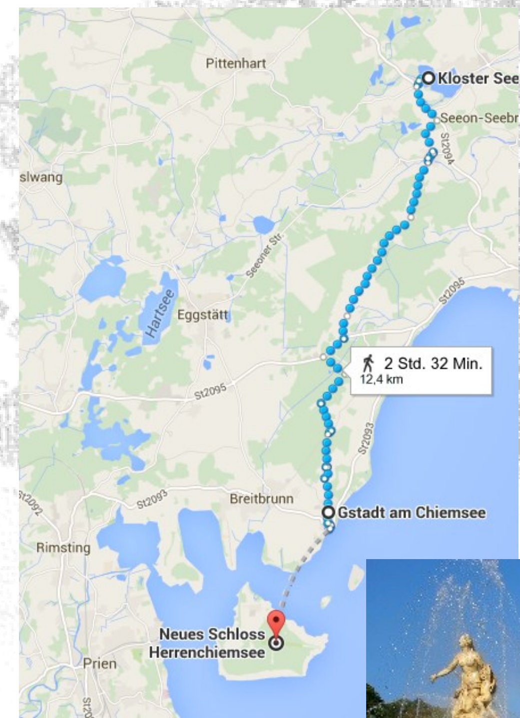
Vogt et al reported recently [1] a magnonic multiplexor consisting of a network of Permalloy waveguides, formed on a similar network of current-carrying wires. By switching the current between the different arms of a Y-shaped structure, a local bias magnetic field was introduced so as to direct spin waves through either arm. Here, we explain the results of Vogt et al fully by mapping the local spin-wave group velocity distribution within the structure, within the concept of graded-index magnonics. First, we use Comsol to solve Maxwell's equations to calculate the spatially-resolved non-uniform bias magnetic field, and then OOMMF to calculate the static magnetisation and effective field distribution across the structure. Finally, we then use the dipole-exchange dispersion relation [2] to calculate the distribution of spin-wave group velocity, which enables us not only to explain the experimental results of Vogt et al but also to predict the optimal geometry of the multiplexor.

[1] K. Vogt et al, Nat. Commun. **5**, 3727 (2014).
[2] B. A. Kalinikos and A. N. Slavin, J. Phys. C **19**, 7013 (1986).

Excursion to Schloss Herrenchiemsee

13:00	Bus departure at Seeon Abbey
14:05	Boat departure at Gstadt
15:25	Guided tour at Schloss Herrenchiemsee
17:10	Boat departure at Herrenchiemsee
17:30	Bus departure at Gstadt
18:45	Mozart in Seeon (Lambertisaal)
19:30	Conference Dinner



Sunday	Monday	Tuesday	Wednesday	Thursday
Arrival	09:00 – 10:40 *Confined systems* Kalinikos Ono Arias Gieniusz	09:00 – 10:40 *Spin-torque III* Dumas Mohseni Kasai Sato	09:00 – 10:40 *DMI* Kostylev Zhou Devolder Körner	09:00 – 10:30 *Spin-torque IV* Ebels Tserkovnyak Kondou
	10:40 – 11:10 *Coffee*	*10:40 – 11:10* *Coffee*	*10:40 – 11:10* *Coffee*	*10:30 – 11:10* *Coffee*
	11:10 – 12:30 *Spin-torque I* Urazhdin Demidov Gladii	11:10 – 12:10 *Multiferroics* Tsymbal Kurebayashi	11:10 – 12:30 *Magnonic crystals* Barman Grundler Gubbiotti	11:10 – 12:10 *Spin waves and spin current* K. Schultheiss Silva
	12:30 – 14:00 *Lunch*	*12:30 – 13:00* *Lunch*	*12:30 – 14:00* *Lunch*	*12:30 – 14:00* *Lunch*
	14:00 – 15:30 *Spin-torque II* Krivorotov De Loubens Ross	13:00 *Excursion*	14:00 – 15:20 *SW-manipulation* Chumak Khitun Mändl	***Departure***
	15:30 – 16:00 *Coffee*		*15:20 – 15:50* *Coffee*	
	16:00 – 18:00 *Poster Session*	18:45 *Mozart in Seeon*	15:50 – 17:10 *Quantum effects* Karenowska Slavin Tiberkevich	
18:30 Dinner	*18:30 Dinner*	*19:30 Conference Dinner*	*18:30 Dinner*	

Wednesday 12:30 – 12:40 Conference photo