3rd International Advanced School on Magnonics 2018

National Technical University of Ukraine
"Igor Sikorsky Kyiv Politechnic Institute"
and
Adam Mickiewicz University, Poznań

Kyiv, Ukraine, 17–21 September 2018

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3rd International Advanced
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Kyiv, Ukraine
17–21 September 2018
Book of abstracts

Edited by: Maciej Krawczyk, Andrii Chumak, Mateusz Zelent

Technical edition using LaTeX: Anna Krzyżewska

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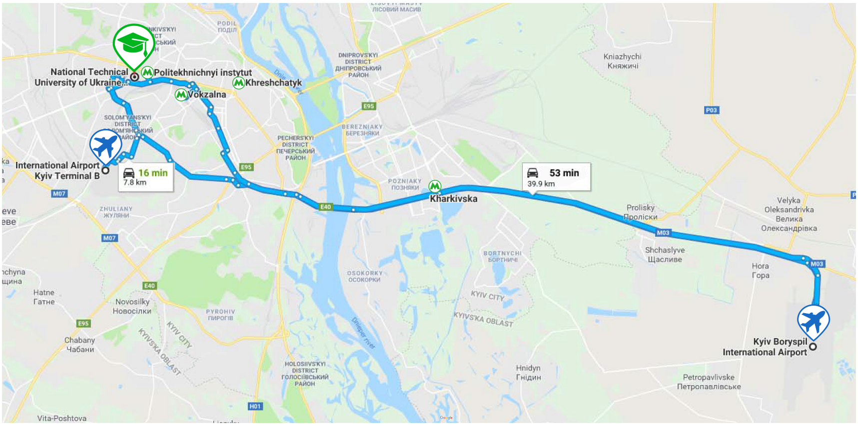
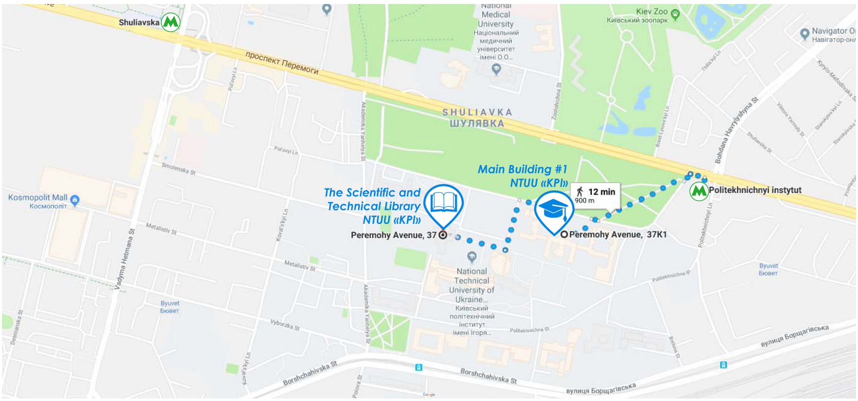
- **IEEE Magnetics Society**
- **Graduate School Materials Science in Mainz**,
- **Deutsche Forschungsgemeinschaft (DFG) Transregional Collaborative Research Center (SFB/TRR)** 173 "Spin+X – Spin in its collective environment".

Venue

Campus KPI

Conference will take place in the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (NTUU "KPI"): http://kpi.ua/en





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Honored Guests
at the IASM'2018

HONORED GUESTS AT THE THIRD INTERNATIONAL ADVANCED SCHOOL ON MAGNONICS

Prof. Dr. Viktor G. Baryakhtar

Viktor Grygorovych Baryakhtar graduated from Kharkiv State University with honors in 1953. In 1959 he obtained PhD degree and in 1965 Doctor of Sciences degree from Kharkiv Institute of Physics and Technology. In 1972 he was elected a an associate member of Academy of Sciences of Ukraine and in 1978 a full member.

Professor Baryakhtar started his scientific career in 1954 as a research scientist at Kharkiv Institute of Physics and Technology. From 1973-82 he occupied the position of Deputy Director of Donetsk Institute of Physics and Technology of the Ukraine's Academy of Sciences of. In 1985 he became the Director of Institute of Metal Physics Academy of Sciences of Ukraine in Kyiv, a post which he occupied until 1989. In 1994- 98 Prof. Baryakhtar was the first Vice-President of National Academy of Sciences (NAS) of Ukraine and he remained in this position until 1998. From 1995 until 2016 he was the Director of Institute of Magnetism NAS of Ukraine.

Viktor Baryakhtar is an outstanding Ukrainian scientist in the field of Physics, who obtained top level results which were apparent on the world stage in the theory of magnetism, superconductivity, mechanical properties of solids, nonlinear phenomena, and kinetics of solitons. Together with his colleagues, Prof. Baryakhtar created the theory of magnetoelastic waves in magnetic materials, developed the microscopic theory of magnetization relaxation in ferromagnets, predicted the isostructural phase transition in the lattices of cylindrical magnetic domains. VG Baryakhtar formulated a new vision of domain structure as an inhomogeneous state of polarized media, which allowed from a unified position used for the description of the properties of magnets, ferroelectrics and superconductors in the process of phase transformations. He was one of the first who to have investigated the nonlinear properties of magnets and introduced the term "soliton" in magnetism. Professor Baryakhtar is the author and co-author of more than 500 scientific papers and 16 monographs on physics. He is a co-author (together with A.I. Ahiiezer and S.V. Peletminskyi) of the famous book "Spin Waves" that was translated into English and serves as indisputable reference in the area of magnetization dynamics to many generations of scientists.

Scientific achievements of Prof. Baryakhtar were awarded with Vladymyr Vernadskiy Gold Medal and four personal Prizes from NAS of Ukraine, three State Prizes of Ukraine in the area of Science and Technology and several international prizes. He is a holder of numerous awards from the Government of the Ukraine, including being named a Hero of the Ukraine (Order of the State), the highest state award bestowed upon individuals.

HONORED GUESTS AT THE THIRD INTERNATIONAL ADVANCED SCHOOL ON MAGNONICS

Prof. Dr. Gennadii A. Melkov

Professor Gennadii graduated from the Department of Quantum Radiophysics of Taras Shevchenko Kiev University in 1962 and, in the same year, joined the faculty as a junior researcher. In 1967 he defended his PhD thesis and ten years later he obtained his Doctor of Science Degree from the Institute of Low Temperatures in Kharkiv (Ukraine, former USSR). Since 1979, he has held the post of Professor in the Department of Quantum Radiophysics at Kiev University.

Between 1992 and 2002, Prof. Melkov was a Dean of the Faculty of Radiophysics, and between 1998 and 2004, headed Taras Shevchenko's Department of Cryogenic- and Microelectronics. He participated in the foundation and was the first Chairman of the Foundation for Fundamental Research of the Ukrainian State Committee for Science and Technologies, was the Chairman of the Scientific Council on the defense of doctoral theses, and a member of the Professional Council for Natural Sciences of the Ukrainian Ministry of Education.

From an early stage in his career, Gennadii Melkov had been recognized to possess a rare and exceptional combination of talents: those of a pioneering experimentalist, a gifted theoretician, and an inspiring teacher. His main research interests are in the study of the nonlinear properties of magnetic solids at microwave frequencies. Among the effects which he has discovered and investigated in microwave ferrites are: multi-quantum absorption and radiation, kinetic instability of spin waves, the fine structure of nonlinear susceptibility, size effects in the parametric excitation of magnons, wave-front reversal of spin waves in magnetic films, and room temperature Bose-Einstein condensation of magnons. Prof. Melkov is the author of well over 350 articles and several books, one of which "Magnetization Oscillations and Waves" has long been considered a gold-standard reference text.

In 1999 he was awarded the title of Honored Scientist of Ukraine and, in 2005 he won the Ukrainian Academy of Sciences Ivan Pulyui Award in recognition of his series of works on wavefront reversal and phase conjugation of spin waves and oscillations.

Abstracts

Invited lectures

Magnonic Basics

TREATING SPIN WAVES AS WAVES: YOUR ENTREE POINT TO MAGNONICS

V. V. Kruglyak

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KEY WORDS: magnonics, spin waves, dispersion, graded magnonic index, Schlömann, Fano

There is one aspect of magnonics that is both ubiquitous and often underrated: magnonics is the study not only of spin but also (and most importantly) of waves. These waves have an extremely rich and peculiar dispersion, which is nonlinear, anisotropic and non-reciprocal. This dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, including both the internal magnetic field and magnetisation, so that spin waves are rarely observed to propagate in uniform media. Thus, spin waves represent a real treat for a wave physicist. In this talk, starting from the general topic and fundamentals of magnonics, we will discuss and provide demonstrations of exciting new physics and technological opportunities associated with the unique properties of spin waves. In particular, the graded magnonic index and spin wave Fano resonances will be highlighted as the next big thing in magnonics research.

The research leading to these results has received funding from the Engineering and Physical Sciences Research Council of the United Kingdom (Project No. EP/L019876/1) and from the European Union's Horizon 2020 research and innovation program under Marie Skłodowska- Curie Grant Agreement No. 644348 (MagIC).

ABOUT MAGNONS, PHONONS, AND PHOTONS IN YTTRIUM IRON GARNETS

G. E. W. Bauer

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KEY WORDS: magnons, phonons, photons, yttrium iron garnet, spintronics

Yttrium iron garnet (YIG) is an electrically insulating ferrimagnetic with high magnetic, acoustic and optical quality, which makes it very suitable for fundamental studies of magnetism. Of great interest is the interaction of the elementary excitations of the magnetic order, i.e. the spin waves and their quanta (magnons) with those of the underlying atoms, i.e., the lattice waves or phonons. The magnetization also interacts with the electromagnetic waves or photons with frequencies from GHz to PHz. The interaction of magnon with other wave fields can be modulated by cavities and plasmonic resonances.

I will introduce the basic physics of magnons, phonons, and photons in thin films and spheres of YIG and their interactions, illustrated by recent experimental and theoretical results.

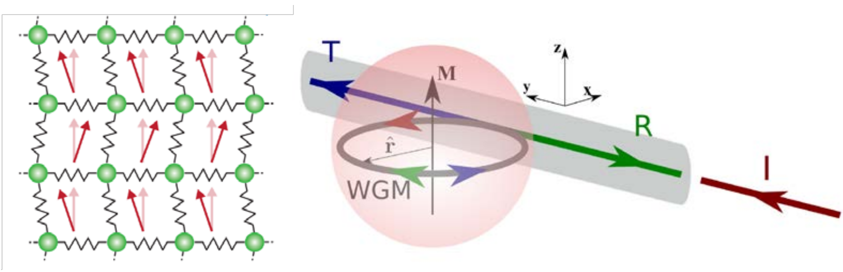

Fig. 1 : (Left) Snapshot of coupled magnon-phonon interaction [1]. (Right) Schematic of Brillouin light scattering by magnons in a magnetic sphere by a proximity optic fiber that excites whispering gallery modes (WGMs) in the sphere [2]

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TRANSDUCERS AND LOGIC GATES FOR COMPUTING WITH SPIN WAVES

F. Ciubotaru[1], G. Talmelli[1,2], F. Vanderveken[1,2], D. Tierno[1,2], I. P. Radu[1], T. Devolder[3], C. Adelmann[1]

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KEY WORDS: spin waves, spin orbit torque, magnetoelectric effect, logic gates

Spin waves in magnetic waveguides with sub-micron wavelengths have been proposed as data carriers in future information processing systems [1,2]. The information can be encoded in either the amplitude or the phase of the wave, while the logic operation is based on the interference of spin waves, which is a keystone for the realization of logic gates. In particular, spin wave based majority gates promise significant power and area reduction per computing throughput with respect to conventional CMOS [2,3]. Recently, a first macroscopic demonstrator device has been reported [4].

To render spin wave majority gates competitive with CMOS, the device has to be scaled to small dimensions and the transduction efficiency between electrical and spin wave domains has to be improved. Conventionally, spin waves are excited and detected using inductive antennas with low power efficiency. To improve the efficiency, we have developed spin waves transducers based on spin-orbit torques [5] as well as the magnetoelectric effect [6]. We will experimentally demonstrate spin wave excitation by spin-orbit torque antennas and discuss the relative influence of spin-orbit torques and Oersted fields in an analytic model for spin wave excitation.

We show by micromagnetic simulations that spin waves can be generated by magnetoelectric effect in three situations, namely (i) for canted strains with respect to the magnetization direction, (ii) using shear strain, and (iii) in scaled waveguides (e.g. with submicron widths) where the magnetization has a non-uniform distribution because of the demagnetizing field. Both the influence of the strain direction (out of plane vs. in plane) as well as the waveguide width is discussed.

Furthermore, we demonstrate the spin wave interference in micron-sized ferromagnetic waveguides using a sequential "in-line" layout of input and output antennas. Microwave currents with the same frequency were applied to two or three inputs simultaneously and the output signal was studied as a function of the input frequency, magnetic bias field, and relative phase difference between the input signals. Controlling independently the phase (0 or π) and amplitude of the spin wave generated by each input we demonstrate the tuning of the interference pattern at the output allowing for the realization of logic gates.

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DZYALOSHINSKII-MORIYA INTERACTION IN MAGNETIC MULTILAYERS

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KEY WORDS: Dzyaloshinskii-Moriya Interaction, Spin waves, Brillouin Light Scattering Spectroscopy

The Dzyaloshinskii-Moriya interaction (DMI) is of large interest. It can give rise to chiral spin-chains, chiral domain walls and skyrmions. Interfacial DMI can be described by a three-site exchange mechanism, where the coupling between two spins in the ferromagnet is mediated by an atom in the material with large spin-orbit coupling. The DMI causes a non-reciprocal frequency- shift for Damon-Eshbach spin-waves. The sign of the frequency-shift depends on the polarity of the magnetization and the propagation direction of the spin-waves. We use spin-waves as a probe of the DMI. The DMI induced frequency-shift is determined by Brillouin Light scattering spectroscopy for both field polarities. In order to gain deeper insight into the underlying physics of the interfacial DMI, we prepared different multilayer systems with DMI: We found that for a $Ni_{80}Fe_{20}(x)/Pt$ sample series with x ranging from 1 nm to 13 nm the symmetric Heisenberg exchange and the DMI both show the almost identical thickness dependence [1]. This was originally predicted for magnetic oxides and for metallic spin-glasses. With another sample series we studied the effect of oxidation of the ferromagnet on DMI. We found clear indication that interfacial oxide gives rise to DMI. This was also predicted by recent density functional calculations (DFT) [2]. Finally, we addressed the importance of the in-plane symmetry of the crystal lattice. So far, most of the experimental work on interfacial DMI has been done on highly symmetric systems, for which the DMI is isotropic. We prepared by molecular beam epitaxy the Pt(110)/Fe system, which has C_{2V} symmetry. Our measurements show a two-fold symmetry for the DMI, see Fig. 1.

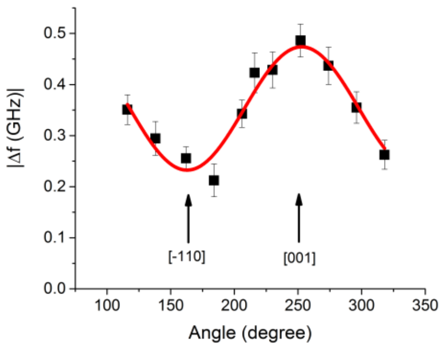

Fig. 1 : Angular dependence of the DMI induced frequency shift

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VOLTAGE-CONTROLLED MAGNONICS

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KEY WORDS: spin wave, voltage-controlled magnetic anisotropy, magnetoelectric effects

Electric field control of magnetization of ferromagnets via magnetoelectric effects attracts a lot of attention as it makes possible the development of novel magnetic devices with ultra low power consumption. In particular, it could allow energy-efficient excitation and processing of spin-wave signals in ferromagnetic films and nanowires.

In this talk we give an overview of magnetoelectric effects and their possibility to be applied in magnonic devices. Special attention is paid to the recently discovered effect of the voltage-controlled magnetic anisotropy (VCMA) in ferromagnetic metal – dielectric heterostructures, as it is one of the most promising for the applications at nanoscale. In particular, it is shown, that a microwave electric field signal of a certain frequency applied to a nanoscale VCMA gate can parametrically excite half-frequency spin waves, propagating from the gate (see Fig. 1). It is also shown that a similar microwave electric field signal applied to a "control" VCMA gate, situated along the propagation path of the excited half-frequency spin wave, can effectively parametrically amplify the propagating spin wave, if the initial wave amplitude is sufficiently small, or can stabilize the amplitude of the propagating wave, if the initial wave amplitude is sufficiently large. In addition, we discuss the effect of the interfacial Dzyaloshinskii- Moriya interaction (IDMI) on the parametric amplification of spin waves, and demonstrate that IDMI can be used for the improvement of the operational characteristics of the spin-wave signal processing devices based on the VCMA effect.

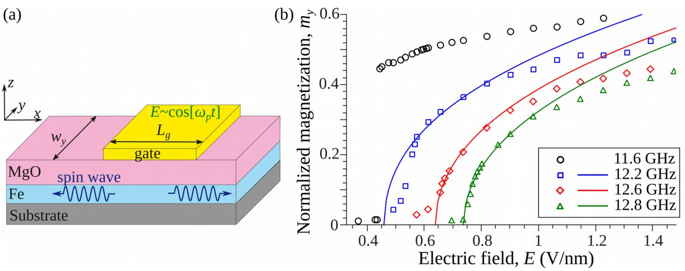

Fig. 1 : (a) – A generic sketch of a VCMA-based spin-wave excitation and processing device – ferromagnetic metal - dielectric bilayer with a local metal gate, to which voltage signal is applied. (b) – Amplitude of excited spin waves by microwave electric field of different frequency, lines – theory, dots – micromagnetic simulations; Fe(1 nm)/MgO bilayer , $w_y = 20$ nm, $L_g = 100$ nm (data from [*Phys. Rev. Appl.* **7**, 064023 (2017)])

MAGNETIC SKYRMIONS STABILIZED BY LONG-RANGE INTERACTIONS

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KEY WORDS: skyrmions, RKKY interaction, graphene

Magnetic skyrmions are topological spin textures with potential applications in future spintronic devices, but their stability is generally dependent on a subtle interplay of weak interactions. Here, we propose a novel mechanism of stabilizing skyrmions in a magnetic monolayer by placing the system on a conducting substrate (normal metal or graphene) which makes the spins interact via the long-range Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange.

We show that a proper treatment of the long-range nature of the RKKY interaction leads to a qualitatively different stabilization scenario compared to previous studies, where solitons were stabilized by the frustrated exchange coupling (leading to terms with the fourth power of the magnetization gradients) or by the Dzyaloshinskii-Moriya interaction (described by terms linear in the magnetization gradients). It is shown that for a metallic substrate skyrmions can be stabilized against the radial collapse by fine-tuning the Fermi surface parameters, while for a graphene substrate the stabilization occurs naturally in several geometries with a lattice-matching of graphene and magnetic layer [1].

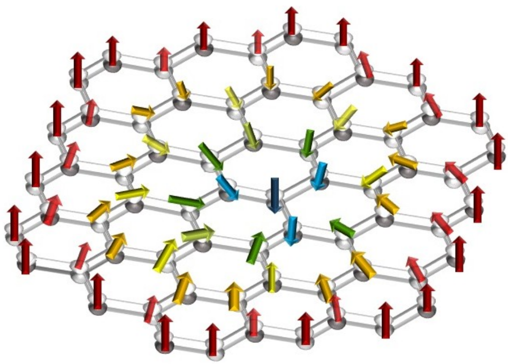

Fig. 1 : Skyrmion in a magnetic monolayer on top of a lattice-matched graphene substrate (schematic view)

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X-RAY MICROSCOPIC OBSERVATION OF SPIN WAVES IN MAGNONIC NANOSTRUCTURES

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KEY WORDS: XMCD, X-ray Microscopy

Manipulation of spin waves, the so called field of magnonics, has gained significant scientific interest in the past years [1-4]. For that purpose nano-structured materials with locally alternating magnetic properties are utilized. By structuring on the length scale of the exchange and dipole interactions the dispersion properties of spin waves can be engineered [2-4]. These nanostructures have great potential for technological applications in data processing and storage, and spintronics [3,4]. However, the spin wave behaviour is not only altered on the nano-scale, but it can be directly imaged by advanced x-ray microscopy with magnetic contrast (MAXYMUS@BESSY) with a spatial and temporal resolution of 18 nm and 35 ps respectively. Thus, emergent spin wave phenomena can be directly observed in real space on a scale beyond the capabilities of conventional BLS or MOKE measurements.

I demonstrate this powerful technique based on several magnonic structures: one of them is an antidot lattice based magnonic crystal with spin wave modes ranging from 250 MHz up to 8 GHz in the rich spin wave band structure of the magnonic crystal were imaged. Both propagating and localised modes are observed. Hybridization of modes with different localization within the ADL, as predicted in micromagnetic simulations, is experimentally confirmed. Furthermore, the mechanism behind the tailorable band structure and the selective transmission or damping is visualized. Based on this understanding a spin wave filter, tuning propagation lengths from 0.5 to >10 µm, is constructed and imaged in operation.

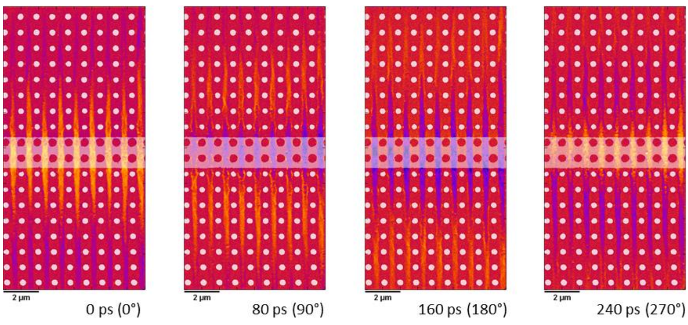

Fig. 1 : Dynamic X-ray micrographs with magnetic contrast (XMCD) at different time steps of a movie showing the propagation of a spin wave mode in an antidot lattice. The spin wave can only propagate between antidots. The applied external bias field allows propagation over 10 µm from the excitation source. The positions of the stripline and the antidots are indicated as white overlays

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Magnonic Basics

NON-LINEAR AND PARAMETRIC SPIN-WAVE PHENOMENA

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KEY WORDS: spin waves, parametric processes, nonlinear dynamics, solitons, bullets, phase conjugation, reversal of momentum relaxation, kinetic instability

It is possible to say that the modern non-linear wave physics originated in the field of microwave magnetism without it being a strong overstatement. The first nonlinear phenomena caused by processes of parametric excitation of spin waves were observed by Bloembergen and Damon still in 1952 [1]. Shortly after, the first theory of parametric excitations in solids was developed by Suhl, who investigated the parametric excitation of plane spin waves by uniform mode of magnetization [2]. Only later such processes were discovered in plasma physics (decay instability) and nonlinear optics (induced scattering).

My lecture is about nonlinear effects in connection with the parametric interaction of spin waves in magnetically ordered materials. The general principles of parametric and nonlinear spin wave dynamics in ferro- and ferrimagnets [3,4] will be presented. They will be illustrated by the number of original results from the dynamics of one- and two-dimensional spin wave solitons [5], and the phase-conjugation, amplification and restoration of spin-wave signals [5,6] obtained in experiments with single-crystal Yttrium Iron Garnet [7] films. Finally, the kinetic instability process [4] will be introduced and discussed in connection with parametric instability and Bose-Einstein condensation of magnons [8].

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ROOM-TEMPERATURE BOSE-EINSTEIN MAGNON CONDENSATES AND SUPERCURRENTS

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KEY WORDS: Bose-Einstein condensation, magnon supercurrent, magnetic insulator

Finding new ways for fast and efficient processing and transfer of data is one the most challenging tasks nowadays. Elementary spin excitations - magnons (spin wave quanta) – open up a very promising direction of high-speed and low-power information processing. Magnons are bosons, and thus they are able to form spontaneously a spatially extended, coherent ground state, a Bose-Einstein condensate (BEC), which can be established even at room temperature in magnetic insulators (single-crystal films of yttrium iron garnet, YIG) [1,2].

An extraordinary challenge is the use of this macroscopic quantum phenomenon for the information transfer and processing. Recently, we have succeeded to create magnon supercurrents by introducing a spatial phase gradient into a BEC wave function [3]. It has been found that local heating of a magnetic sample leads to the excessive BEC decay caused by outflow of condensed magnons from the hot sample spot.

Here, I show that non-local probing of the magnon BEC provides direct evidence of long-distance supercurrent transport. By utilizing space-, time- and wavevector-resolved Brillouin light scattering (BLS) spectroscopy the propagation of a supercurrent pulse is detected on an undisturbed background of the slowly decaying magnon BEC. This pulse can be understood as a (nonlinear) second sound of magnon BEC travelling with a constant velocity over a millimeter-long distance. The discovery of the room-temperature magnon supercurrent transport opens door to studies of magnonic macroscopic quantum transport phenomena as a novel approach in the field of information processing.

At the same time, the miniaturization of supercurrent-based magnonic devices constitutes an extraordinary challenge for their future applications. Conventionally, the conditions for the formation of the BEC are created in macroscopic YIG samples by powerful microwave parametric pumping. Here, a fundamentally new approach is presented. Fast DC-current pulses applied to YIG/Pt microstructures result in a strong heating. Consequently, this leads to an increased number of magnons, distributed over the whole spectrum. Once the current is switched off the system cools down rapidly. This results in a strong increase of the magnon density at the bottom of the spectrum, leading to the formation of magnon BEC observed by BLS microscopy. Our experiments show, that the BEC formation depends on the magnon temperature and the timescale of the cooling process.

The work is supported by ERC Starting Grant 678309 MagnonCircuits, ERC Advanced Grant 694709 SuperMagnonics, EU-FET Grant 612759 InSpin, and DFG Grant DU 1427/2-1.

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HYDRODYNAMICS AND TOPOLOGICAL SPIN CURRENTS IN AMORPHOUS MAGNETS

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Coherent spin transport mediated by topologically stable textures, offers promising perspectives for the design of energetically efficient devices for applications in spintronics. In contrast to spinor condensates and He-3, however, collective spin transport in solid state is limited by parasitic anisotropies rooted in relativistic interactions and spatial inhomogeneities. Here, we propose that structural disorder in amorphous materials can average out the effect of these undesired couplings. To illustrate this, we construct a hydrodynamic description of spin dynamics in insulating amorphous magnets, where the currents are defined in terms of coherent rotations of a noncollinear texture. Our theory includes dissipation and nonequilibrium torques at the interface with metallic reservoirs. This framework allows us to determine different regimes of coherent dynamics and their salient features in nonlocal magneto-transport measurements.

TOPOLOGICAL SPIN TEXTURES: STABILITY AND DYNAMICS

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KEY WORDS: skyrmions, antiskyrmions, Dzyaloshinskii-Moriya interaction, antiferromagnets

Skyrmions are topologically protected spin textures, which can be used in spintronic devices for information storage and processing. Ferromagnetic skyrmions attracted a lot of attention because they are small in size, better than domain walls at avoiding pinning sites, and can be moved very fast by current in ferromagnet/heavy-metal bilayers due to spin-orbit torques [1,2].

Meanwhile, the ferromagnetic skyrmions also have certain disadvantages to employ them in spintronic devices, such as the presence of stray fields and transverse to current dynamics. To avoid these unwanted effects, we propose a novel topological object: the antiferromagnetic skyrmion. This topological texture has no stray fields and its dynamics are faster compared to its ferromagnetic analogue [3]. More importantly, I will show that due to unusual topology it experiences no skyrmion Hall effect, and thus is a better candidate for spintronic applications [4]. Then I will discuss the lifetimes of antiferromagnetic skyrmions at finite temperatures [5].

Lastly, I will talk about antiskyrmions – unusual anisotropic topological objects, which have been recently observed in the systems with anisotropic Dzyaloshinskii-Moriya interaction. I will explain their lifetimes and current-driven dynamics based on the spin transformation between skyrmion and antiskyrmion. Furthermore, I will make predictions for the antiskyrmion existence and properties in antiferromagnets.

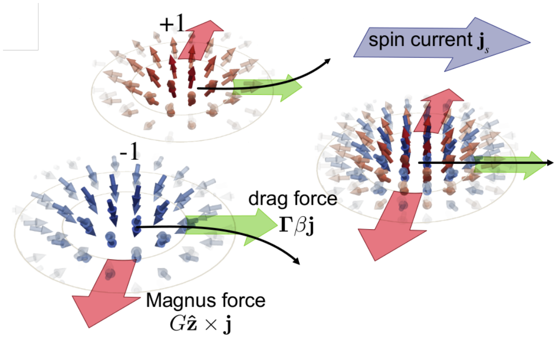

Fig. 1 : The generalized forces acting on antiferromagnetic skyrmion

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VERTICAL CONTROL OF THE SPIN WAVE BAND STRUCTURE IN 1D AND 2D MAGNONIC CRYSTALS

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Magnonic crystals (MCs) are materials with periodically modulated magnetic properties where the spin waves (SWs) band structure consists of intervals of allowed SW frequencies and forbidden gaps in which there are no allowed magnonic states.

In the recent past, most of the studies have been focused on planar nanostructures where the magnetic constituents have the same thickness, while, to the best of our knowledge, there are no reports of SW band structure in 3D MCs. This is mainly due to the difficulties associated with the fabrication of thickness modulated nano-elements by conventional nanofabrication techniques which require multilevel exposure process and alignment between successive fabrications steps.

Very recently, we proposed a new class of MCs constituted by closely packed thickness-modulated nanowires. We show that this kind of structures support the propagation of collective SWs in the periodicity direction, thus demonstrating that layering structure and in-plane modulation are very effective for controlling the characteristics of the magnonic band [1].

Another possible approach to achieve a vertical control of the spin wave band structure is to have either an array of layered magnetic elements or an array of ferromagnetic dots deposited on top of a continuous ferromagnetic film. I will review the properties of the spin wave band structure, studied by wavevector-resolved Brillouin light scattering, in dense arrays of Py/Cu/Py nanowires [2] and 2D array of elliptical Py/Pt nanodots arranged into dense chains over the surface of a 20 nm thick Py continuous unpatterned film [3]. Particular emphasis is given to the reconfigurable dynamic response of these systems.

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CURVATURE–INDUCED EFFECTS IN NANOMAGNETS

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The interplay between geometry and topology is of fundamental importance throughout many disciplines. In this respect, the investigation of physical effects governing the responses of curved magnetic nanoobjects to electric and magnetic fields is of strong fundamental interest but is also technologically appealing. Owing to intense theoretical and experimental efforts, the topic of magnetism in curved geometries has evolved in an independent research field of modern magnetism with many exciting theoretical predictions and strong application potential.

This talk focuses on the peculiarities emerging from geometrically curved magnetic objects, including two-dimensional bent wires, three-dimensional helices, three-dimensional curved shells, e.g. spherical or tubular and Möbius bands. During the talk we will discuss two groups of curvature-induced effects in nanomagnets: (i) magnetochiral effects unite the phenomena of curvature-induced chiral symmetry breaking and (ii) topologically induced magnetization patterning which appears in curvilinear magnets, where orientation of the effective anisotropy axis is determined by the geometry.

ULTRAFAST SPIN DYNAMICS IN FERROMAGNETIC/NONMAGNETIC THIN FILM HETEROSTRUCTURES

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KEY WORDS: ultrafast spin dynamics, thin film heterostructures, spin-orbit effects

Ferromagnetic/nonmagnetic (FM/NM) thin film heterostructures show a range of important properties such as perpendicular magnetic anisotropy, spin pumping, spin transfer torque, spin Hall effect, Rashba effect and interfacial Dzyaloshinskii-Moriya interaction. The above properties are generally controlled by the interface and they have huge potential applications in new generation spintronic and magnonic devices.

Here, we present the investigation of time- and wave-vector-resolved ultrafast spin dynamics in ferromagnet (Co, $Ni_{81}Fe_{19}$, CoFeB)/ nonmagnet (Pd, Pt, Au, W, Ta, TaO_x, SiO_2) heterostructures induced by optical, thermal and spin-orbit-torque excitation using time-resolved magneto-optical Kerr microscope and Brillouin light scattering spectroscopy [1]. We present correlation between ultrafast demagnetization, perpendicular anisotropy and damping in Co/Pd multilayers [2]. We demonstrate an energy efficient spin-wave propagation and magnonic bandgap formation by controlling domains in Co/Pd multilayers [3]. Further we introduce a new method to investigate spin Hall angle (SHA) and spin pumping in FM/NM bilayers [4] and show a giant SHA in β-W [5]. Finally we investigate the interfacial Dzyaloshinskii-Moriya interaction (IDMI) using Brillouin light scattering and show pure IDMI in NM(W, Ta, graphene)/FM(CoFeB, NiFe)/SiO_2, TaO_x) heterostructures [6-7]. The effects of variation of thicknesses of FM and NM layers are also discussed.

The author gratefully acknowledges financial assistance from Department of Science and Technology, Department of Information Technology and S. N. Bose National Centre for Basic Sciences.

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Magnonic Basics

BASICS OF MAGNON SPINTRONICS

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KEY WORDS: spin-waves, spintronics, spin to charge-conversion, spin-orbit torques

In this lecture, an introduction into the field of magnon spintronics, i.e., the cross-section between magnonics and spintronics, will be given. Possible ways to couple spin-waves and charge currents will be discussed and general concepts like the spin transfer torque and the spin pumping effect will be introduced. A particular focus will lie on the more-and-more established spin-orbitronique schemes to interact with spin waves. These schemes, of which a prominent example is the inverse Spin Hall effect, rely on the conversion of a spin-current into a charge-current via spin-orbit interaction. The physical origin of this conversion mechanism will be discussed and it will be highlight how it can be used for spin-wave excitation and detection alike.

MAGNONIC TRANSPORT WITH ANTIFERROMAGNETS

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Spintronics has as the long-term goal to use spins, the intrinsic angular momentum of electrons, as an alternative to the electron charge in the development of beyond-Moore, low-dissipation information devices. Recent progress demonstrated the long-distance transport of spin signals across ferromagnetic insulators [1], providing a route towards signal transmission without Joule heating. Inherently, antiferromagnetically ordered materials are the most ubiquitous class of magnetic materials and reveal crucial advantages over ferromagnetic systems. In contrast to the latter, antiferromagnets exhibit no net magnetic moment, which renders them stable and impervious to external fields. In addition, the effective operation at THz frequencies is enabled [2].

While fundamentally the properties of antiferromagnets bode well for spin transport and magnonics devices, accessing and controlling their properties is a challenging task. In this lecture, I will introduce the dynamics of antiferromagnets, and show that the magnon and spin-transport properties strongly depends on the antiferromagnetic symmetry [3-5].

I will then first show how one can detect electrically the antiferromagnetic order [6] and its dynamics. Second I will show that thermal magnonic spin currents can be transported in an antiferromagnet [7]. Finally, I will present some of our recent results [8] on the long-distance propagation of spin currents in the prototypical insulating antiferromagnet hematite (α-Fe_2O_3) [9], the most common antiferromagnetic iron oxide. Exploiting the spin Hall effect for spin injection [4], one can control the spin current flow through the interfacial spin-bias and by tuning the antiferromagnetic resonance frequency with an external magnetic field. This simple antiferromagnetic insulator is shown to convey spin information parallel to the compensated moment **n** (Néel order) or to the field induced magnetisation **m** over distances exceeding tens of micrometers [8]. This newly-observed mechanism transports spin as efficiently as the best-suited ferromagnets [1]. Hence, these results pave the way to ultra-fast, low-power antiferromagnet-insulator-based spin-logic devices.

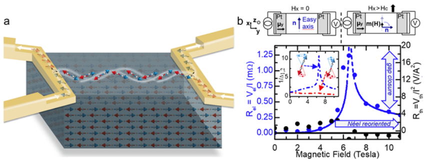

Fig. 1 : (a) **Spin transport schematic in an insulating antiferromagnet**. Two Platinum (Pt) wires on an insulating easy axis antiferromagnet. The spin-Hall effect in the left wire generates a spin-accumulation μ at the Pt/antiferromagnet interface breaking the antiferromagnetic symmetry. Transferring angular momentum to the antiferromagnet, this excites magnons which diffuse to the right wire, where the generated spin-current is detected by the inverse spin-Hall effect. (b) **Experiments in α-Fe_2O_3 with a magnetic applied along the easy-axis**. The non-local signal R_{el} (blue) is zero at small fields, exhibits a sharp peak at the spin-flop field $\mathbf{H}_c$, is finite above, and matches a theoretical model based on the lowest magnon gap Δ (inset: the inverse gap of one mode is reduced at $\mathbf{H}_c$, whilst the other is enhanced). The thermal signal R_{th} remains low (black)

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MAGNETIZATION DAMPING AND SPIN-TRANSPORT ACROSS INTERFACES IN FERROMAGNETIC THIN-FILMS AND MULTI-LAYERED SYSTEMS

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KEY WORDS: ferromagnetic damping, thin-films, spin-mixing conductance, spin-transport

There are many exciting areas of research linked to interfacial effects in ferromagnetic/non- magnetic (FM/NM) thin-film systems, such as interface spin-orbit interactions (SOI), spin-currents from the spin Hall effect (SHE), spin-orbit torques (SOT), interfacial Dzyaloshinskii-Moriya interaction and proximity-induced-magnetization of non-magnetic metals. Damping in these systems can yield new insights into interfacial effects via spin-pumping into non-magnetic layers.

Here details of damping in thin-films and multilayers are reviewed with a focus on interfacial damping effects [1], followed by a discussion of spin-transport across interfaces in FM/NM systems that can be extracted from ferromagnetic damping. Damping gives details about the spin- transport from changes of the spin-mixing conductance (see Fig. 1), which is discussed in terms of the effects of non-magnetic layer thickness [2], interfacial structure modification [3], interfacial crystal structure [4], and the spin-diffusion length and spin-flip probability [5].

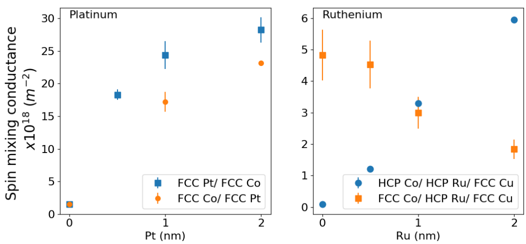

Fig. 1 : Examples of spin-mixing conductance for different Co/NM interface crystal structures and thickness

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ALL-OPTICAL SWITCHING OF MAGNETIZATION: MECHANISMS AND TIME SCALES

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KEY WORDS: magnetization dynamics, all-optical switching, photo-magnetic anisotropy

The incessant increase in the amount of digital data greatly boosts the demand for faster, smaller, and energy-effective data-recording technologies. One viable possibility is the all-optical approach, which allows to control the magnetization of a medium using fs laser pulses only [1].

First of all, it has been demonstrated that the magnetization of ferrimagnetic RE-TM alloys and multilayers can be reversed by single fs laser pulses, without any applied magnetic field [2]. This switching is found to follow a very non-trivial pathway, that crucially depends on the dynamic balance of net angular momentum, set by the two opposite sublattices. The switching is of a toggle nature, where every next laser pulse switches the magnetization to the opposite direction.

Recently it has been shown, moreover, that the ferromagnetic Co/Pt and FePt layers can also be switched optically, with the unambiguous dependence on the light helicity [3]. However, even under the optimal pulse parameters, the observed effect is multi-pulse in nature. It is shown that the magnetic switching proceeds via thermally-induced stochastic nucleation of reversed domains followed by a helicity-dependent deterministic growth [4].

Most exciting, very recently an all-optical switching was demonstrated in transparent films of a magnetic dielectric [5]. A single linearly polarized fs laser pulse resonantly pumps specific $d - d$ transitions in the dopant cobalt ions, creating strong transient magnetocrystalline anisotropy. By selecting the polarization of the laser pulse, one could deterministically steer the net magnetization in the garnet. This mechanism outperforms existing alternatives in terms of the speed of the write–read magnetic recording event (less than 20 ps) and the unprecedentedly low heat load.

Moreover, yet another mechanism of laser-induced switching was found in magnetic garnets in the presence of strong in-plane magnetic field [6]. This mechanism is based on an ultrafast heating of the lattice resulting in a rapid change of magneto-crystalline anisotropy. In this talk various switching mechanisms will be considered and compared, with the goal to provide a clear picture of the processes accompanying the reversal at these ultrafast time scales.

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ANTIFERROMAGNETIC SPIN DYNAMICS. APPLICATION TO ULTRAFAST SPINTRONICS

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KEY WORDS: antiferromagnets, ferrimagnets, spin current, magnetic solitons

Spin dynamics is usually associated with magnetic materials with high density of spin angular momentum **s** or, respectively, magnetization $\mathbf{M} = -g\mu_B\mathbf{s}$, where g is Lange factor and μ_B is the Bohr magneton. It is natural to call such dynamics "ferromagnetic". It is worth noting that ferromagnetic spin dynamics is realized not only for "pure" ferromagnets, like iron or nickel, but also for standard ferrimagnets with significantly different sublattice spin densities $\mathbf{s}_\alpha$, like yttrium iron garnet. Ferromagnetic spin dynamics can be described by familiar Landau-Lifshitz equation for the total spin density $\mathbf{s} = \sum_\alpha \mathbf{s}_\alpha$. The characteristic resonance frequency for this dynamics $\omega_{FM} = \gamma H_r$, $\gamma = g\mu_B/\hbar$, is determined by relativistic effective field H_r . The value of ω_{FM} does not exceed dozens of gigahertz.

For "pure" antiferromagnets (AFM) total spin density equals to zero in the ground state, and so-called Neel vector **l**, proportional to the difference of sublattice spin densities, plays the role of the main dynamical variable. The antiferromagnetic spin dynamics is characterized by the exchange enhancement of all dynamic parameters [1]. In particular, spin resonance frequency $\omega_{AFM} = \gamma\sqrt{H_{ex}H_r}$, where H_{ex} is the exchange field; ω_{AFM} enters the terahertz region. This type of spin dynamics can be described by the so-called sigma-model equation, the closed equation for the Neel vector **l**. It is important to note that these features of antiferromagnetic spin dynamics are valid not only for "pure" AFMs, but for any magnets with small value of the total spin density **s**, like canted AFMs [2] or even ferrimagnets in the vicinity of the compensation point of the angular momentum, i.e., at $|\mathbf{s}|/|\mathbf{l}| < \sqrt{H_r/H_{ex}} \ll 1$, see [3,4]. Many typical ferrimagnets have different Lange factors of sublattices, and the value of magnetization can be non-small in this point, what can be useful for spintronic applications [5]. In this talk, main aspects of antiferromagnetic spin dynamics and their application for the terahertz spintronics and magnonics will be discussed.

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SPIN TRANSPORT VIA MAGNONS AND SPIN CALORIC EFFECTS IN ANTIFERROMAGNETS

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KEY WORDS: antiferromagnet, magnon, spin, caloritronics

Magnon currents which transfer spin can be used for manipulation of states in the magnetic insulators. In this presentation we consider different ways to create spin-polarised magnon currents in antiferromagnets and corresponding effects.

We analyse the magnon spectra of an antiferromagnet in the presence of the external magnetic field and/or spin current (see Fig. 1) and calculate the magnon (spin) Seebeck coefficients as a function of the density and polarization of the external spin polarized current. Basing on the properties of the magnon spectra we predict the spin Peltier effect and describe the magnon (spin) Seebeck effect supported by the spin current. We show that the Peltier and the magnon (spin) Seebeck effects can induce motion of the antiferromagnetic domain walls. We compare the driving forces induced by the thermal and non-thermal mechanisms in the presence of the external spin- polarized current. Combination of the predicted caloritronic and spintronic effects can be used for the effective switching between the different antiferromagnetic states in experiment-friendly geometry.

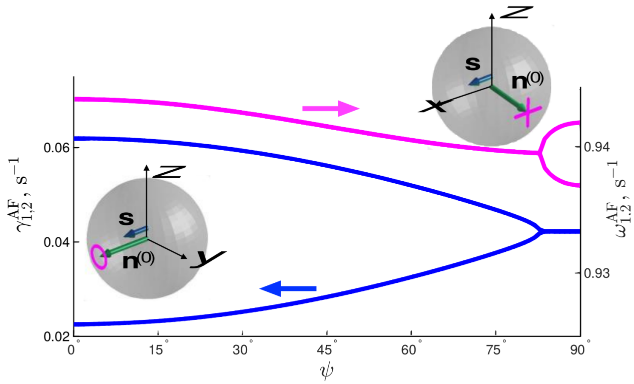

Fig. 1 : Angular dependence of the frequencies (right axis) and damping coefficients (left axis) of the spin wave eigen modes in the presence of current

SKYRMION AND SPIN WAVE DYNAMICS IN ULTRATHIN FILMS WITH DZYALOSHINSKII- MORIYA INTERACTION

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KEY WORDS: DMI, spin wave, skyrmion, skyrmion dynamics

The spin excitations in ultrathin films and nanodots with Dzyaloshinskii-Moriya Interaction (DMI) were under investigation. At first, the influence of the DMI on spin wave propagation in single domain state was studied in magnonic crystal and stripes [1], especially the effect of nonreciprocity induced by DMI was focus. Next, the skyrmion stability influenced by the dipolar interaction in multilayer nanodisks was evaluated [2] (Fig. 1). In particular, the influence of the nanodisk boundaries and nonuniformities in multilayer structures on the skyrmion stabilization was studied. Further, the spin excitations in various nonuniform magnetization states in nanodots were characterized and their spectrum compared. Specifically, mapping of the dynamical modes in vortex and skyrmion states was calculated [3] helping to better understand the dynamics present in skyrmion state. The classification of the low frequency gyrotropic mode and the high frequency spin wave excitation was analogically showed. The higher order azimuthal spin waves were studied in details, showing lift of degeneracy and change in systematics of the energy levels [4]. Further, the influence of the nanodot shape (with non-circular symmetry) was studied and possibility of different mode excitation with uniform field evaluated. The results contribute to understanding of the skyrmion dynamics and control of the skyrmion stability in confined geometries.

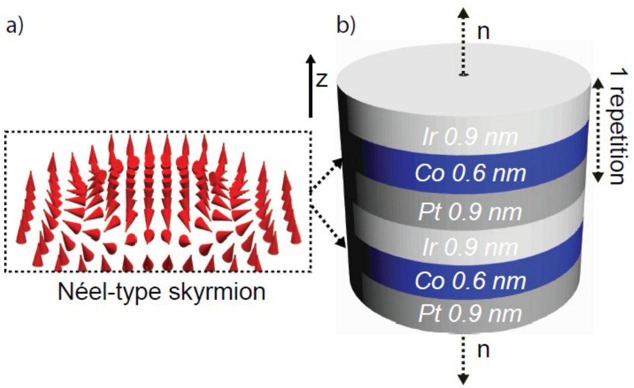

Fig. 1 : a) Skyrmion state in the circular dot (Néel-type skyrmion). b) Sketch of the multilayer nanodot based on dipolarly coupled ultrathin Co layers with varied number of repeats, n, of the Ir/Co/Pt unit cell

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MODELING OF TEMPERATURE-INDUCED MAGNETIZATION DYNAMICS

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KEY WORDS: ultrafast magnetization dynamics, atomistic simulations, Langevin dynamics simulations

A large number of recent important applications involve magnetization dynamics at high temperatures. Its correct accounting constitutes one of the important aspects of material modeling methodology and is relied on the correct account for thermally-induced spin waves. Langevin dynamics simulations on atomistic level correctly reproduce the spinwave spectra and the spectral density. In the multiscale picture, [1] they allow the evaluation of the scaling of the macroscopic anisotropy or the exchange stiffness [2] on temperature-dependent magnetization. Modeling of thermal spinwave spectrum in systems with the Dzyaloshinkii-Moriya interactions (DMI) have also provided us the thermal dependence of the macroscopic DMI parameter.

Furthermore, the prominent example of the success of the Langevin dynamics atomistic simulations is in the modeling of the ultrafast laser-induced magnetization dynamics, for example in disordered ferrimagnetic FeCoGd [3] or TbFe [4] alloys. We show that thermal spin waves are the key factor for excitations of ferromagnetic and antiferromagnetic modes which result in the energy transfer between them, finally leading to the magnetization switching [5]. We will also discuss conditions for reliable and efficient thermal switching in these alloys.

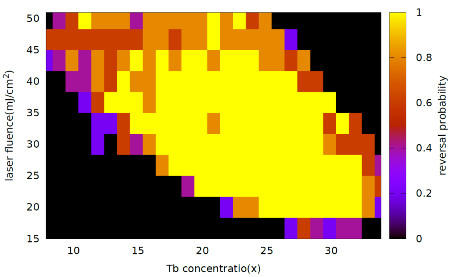

Fig. 1 : Modeling results for the switching probability in TbCo disordered alloy with 50 fs laser pulse

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FORMATION OF SKYRMIONS IN SOFT MAGNETIC FILMS

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KEY WORDS: magnetic nanostructures, magnetic skyrmions, dipolr strate fields

Magnetic skyrmions, topologically nontrivial magnetization configurations, attracted much attention recently as promising for applications in information recording, signal processing and microwave devices. Commonly, magnetic skyrmions are stabilized in non-centrosymmetric B20 bulk crystals and ultrathin magnetic films with out-of -plane magnetic anisotropy by chiral bulk or interfacial Dzyaloshinskii-Moriya interaction (DMI), respectively. Here we demonstrate that artificial magnetic skyrmions can exist in a soft ferromagnetic film without any DMI, coupled to a hard magnetic antidot matrix by exchange and dipolar interactions. Neel skyrmions, either isolated or arranged in 2D array having a high packing density can be stabilized using an antidot as small as 40 nm in diameter (for soft magnetic film made of Permalloy, see Fig. 1). Depending on the material and geometry parameters, one can achieve at remanence either the formation of the stable Neel solitons (skyrmions or their non-topological counterpart), or curled solitons with a complex magnetization distribution, being an intermediate between the Neel and Bloch skyrmions. The formation of the curled solitons is a result of competing demagnetization energy and Zeeman energy in the stray field created by antidot matrix. The curled skyrmions are realized in the case of relatively thin hard layer and large antidot diameter, while smaller antidots and thicker hard layers support the formation of the Neel skyrmions.

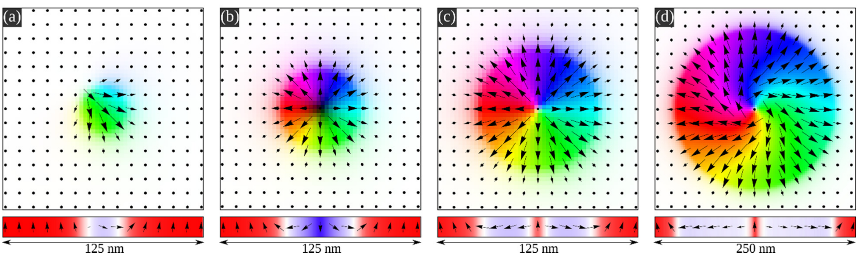

Fig. 1 : Magnetization configurations in the soft layer. The possible remanent states of Permalloy film in zero bias field: top – in-plane view, bottom – x-z central cross-section. (a) single domain state (antidot diameter 30 nm), (b) Neel skyrmion (50 nm), (c) Neel non-topological soliton (75 nm), (d) curled non-topological soliton (200 nm). Py film thickness is 3 nm, hard layer thickness is 20 nm

MAGNON TRANSPORT IN SPIN TEXTURES

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One of the grand challenges in cutting edge quantum and condensed matter physics is to harness the spin degree of electrons for information technologies. While spintronics, based on charge transport by spin polarized electrons, made its leap in data storage by providing extremely sensitive detectors in magnetic hard-drives, it turned out to be challenging to transport spin information without great losses. With magnonics a visionary concept inspired researchers worldwide: Utilize magnons - the collective excitation quanta of the spin system in magnetically ordered materials - as carriers for information. Magnons are waves of the electrons' spin precessional motion. They propagate without charge transport and its associated Ohmic losses, paving the way for a substantial reduction of energy consumption in computers.

While macroscopic prototypes of magnonic logic gates have been demonstrated, the full potential of magnonics lies in the combination of magnons with nano-sized spin textures. Both magnons and spin textures share a common ground set by the interplay of dipolar, spin-orbit and exchange energies rendering them perfect interaction partners. Magnons are fast, sensitive to the spins' directions and easily driven far from equilibrium. Spin textures are robust, non-volatile and still reprogrammable on ultrashort timescales. The vast possibilities offered by combining this toolset of magnetic phenomena, add value to both magnonics and the fundamental understanding of complex spin textures.

I will give an introduction about magnon propagation and manipulation in microstructures with noncollinear spin textures, in particular magnons propagating in nano channels formed by magnetic domain walls. Furthermore, I will address how magnons can be excited in domain wall channels by pure spin currents originating from the spin Hall effect.

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GENERATION OF MICROWAVE AND THz-FREQUENCY ELECTROMAGNETIC SIGNALS IN SPINTRONIC NANOSTRUCTURES

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KEY WORDS: THz-frequency signal, microwave signal, signal generation, spin-torque nano- oscillator, spin Hall oscillator

Since the discovery of the spin-transfer torque and the spin Hall effects tens of years have passed. During this time the mentioned effects were thoroughly investigated and novel nano-scale magnetic oscillators, the so-called spin-torque nano-oscillators (STNOs) and spin Hall oscillators (SHOs), were developed and their properties were studied. Now these oscillators are considered as promising base elements for energy-efficient modern and future nano-scale electronics.

In this paper the basic principles of the operation of ac signal sources based on STNOs and SHOs are formulated, and the most successful models and schematics of such devices and key experiments are considered. A special emphasis on the problem of efficient and reliable generation of THz-frequency electromagnetic signals in antiferromagnetic nanostructures – an important and not yet solved problem in antiferromagnetic spintronics – has been made.

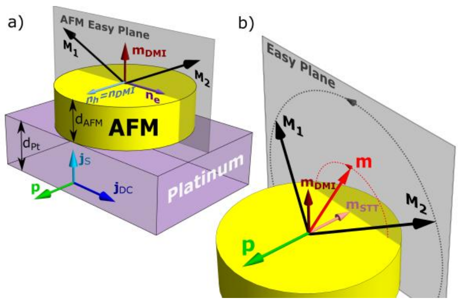

Fig. 1 : a) Schematics of SHO based on a canted antiferromagnet and b) current-driven magnetization dynamics in a canted antiferromagnet. Adapted from Ref. 1

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HARTMAN EFFECT FOR SPIN WAVES IN EXCHANGE REGIME

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KEY WORDS: spin waves, Hartman effect, exchange interaction, tunneling

Hartman effect for spin waves tunnelling through a barrier in a thin magnetic film is considered theoretically. The barrier is assumed to be created by a locally increased magnetic anisotropy field. The considerations are focused on a nanoscale system operating in the exchange-dominated regime. We derive the formula for group delay τ_{gr} of spin wave package and show that τ_{gr} saturates with increasing barrier width, which is a signature of the Hartman effect predicted earlier for photonic and electronic systems [1,2]. In our calculations we consider the general boundary exchange conditions which take into account different strength of exchange coupling between the barrier and its surrounding. As a system suitable for experimental observation of the Hartman effect we propose a CoFeB layer with perpendicular magnetic anisotropy induced by a MgO overlayer.

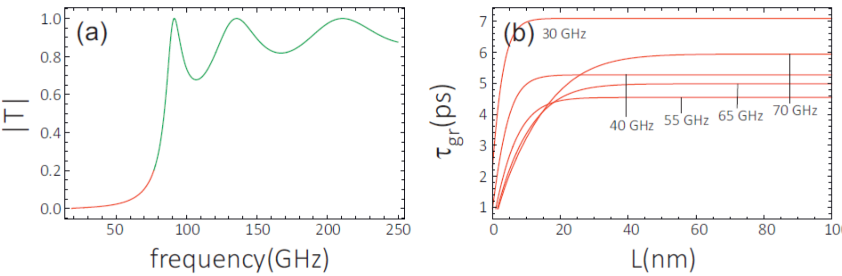

Fig. 1 : (a) Modulus of the transmissivity $|T|$ for the CoFeB layer of thickness 1.3 nm (and 1.0 nm) in the matrix (and the barrier) region, respectively. We assumed the width of the barrier $L = 30$ nm and the thickness of the interface between the matrix and the barrier as 4 nm. (b) The saturation of the group delay τ_{gr} in the tunneling regime

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DARK MAGNON: AN ENTANGLEMENT WAVE IN MAGNETIC F-ELECTRON METAL

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KEY WORDS: quantum magnetism, neutron scattering, spin chains, f-electron systems

A plethora of quantum states and excitations in atomic condensed matter emerge at low energy from the combination of electronic interactions that act on much higher energy scales. They are usually described by effective low-energy theories, which map the system's physical manifold on an auxiliary quantum space, sharing much in common with theories of particle physics. In the 4f-electron metal Yb_2Pt_2Pb, the emergent quantum dynamics of large, 4f-orbital-dominated Yb magnetic moments are described by the theory of fractional spinon excitations on spin-1/2 chains. Neutron scattering measurements reveal a broad continuum of magnetic excitations (Fig. 1) that can be described by multi-spinon states of an effective spin-1/2 XXZ Hamiltonian [1].

Here, we present new neutron scattering experiments, which reveal another enigmatic excitation, a dark (or hidden) magnon quasiparticle in this material. It appears in the ferromagnetic phase induced by magnetic field, which causes confinement of fractional spin-1/2 spinons into spin-1 wave-like magnon quasiparticles. Although complete understanding of the dark magnon interaction with the embedding conduction electrons remains a challenge [2], our results reveal an emergent quantum system where theories with both bright and dark excitation sectors can be studied in experiment. We thus uncover mechanisms of illuminating the emergent hidden physics that can help in understanding both the debated hidden order phenomenon in the 5f-electron system URu_2Si_2 and perhaps even the mysterious dark matter of particle physics.

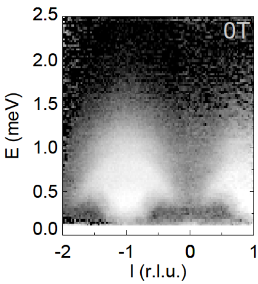

Fig. 1 : Spinon continuum in Yb_2Pt_2Pb. The dispersion of the spectrum of magnetic excitations along the chain (c-axis) direction in reciprocal space of Yb_2Pt_2Pb measured by neutron scattering at zero field and T = 0.060(5) K. The intensity has been averaged along the perpendicular lattice directions

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QUANTUM-IMPURITY RELAXOMETRY OF MAGNETIC DYNAMICS

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KEY WORDS: NV centers, magnetization dynamics, antiferromagnetic domain-walls

Prototypes of quantum impurities (QI), such as NV centers in diamond, have been recently growing in popularity due to their minimally invasive and high-resolution magnetic field sensing. In this work, we focus on quantum-impurity relaxometry as a method to probe collective excitations in magnetic insulators.

We develop a general framework that relates the experimentally-measurable quantum- impurity relaxation times to the properties of a magnetic system via the noise emitted by the latter. We suggest that, even when the quantum-impurity frequency lies within the spin-waves gap, quantum-impurity relaxometry can be effectively deployed to detect signatures of the coherent spin dynamics, such as magnon condensation, both in ferromagnetic and antiferromagnetic systems, as well as open prospects to nonintrusively probe spin-wave transport regimes in magnetic insulators.

Furthermore, we show that magnetic textures such as antiferromagnetic domain-walls, whose detection in conventional magnetometry experiments is challenging, can be imaged via quantum-impurity relaxometry.

Finally, we put forward a proposal for coupling distant quantum impurities via such topological defect.

MAGNETIC AND MAGNETORESONANCE PROPERTIES OF MAGNETIC SHAPE MEMORY ALLOYS EPITAXIAL FILMS

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KEY WORDS: magnetic resonance, magnetic shape memory alloys, epitaxial films, twin structure

Quite sophisticated physical and chemical methods like nanolithography, surface templates, block chemistry, etc. are usually used to produce periodic or quasiperiodic nanostructures. But here we will focus on the films deposited by conventional magnetron sputtering method demonstrating rare examples of nanomesh surface self-patterning and formation mesoscale periodic structures. These films have well defined crystalline and magnetic structure. They show unusual magnetic properties to be considered as systems interesting for possible smart nanoscale applications.

This presentation is devoted to the study of magnetic and resonance properties of thin epitaxial films of ferromagnetic shape memory alloys (FSMA). Main attention will be paid to the influence of films thickness and mesoscale twin structure on magnetic parameters of NiMnGa alloys films. It will be shown that the elastic interaction between film and substrate determines the microstructure of FSMA films resulting to the dramatic change of their magnetic parameters. This interaction suppresses the martensitic transformation for thin films while for the thick films it leads to formation of periodic twin structure. The size of twins increases with the films thickness increasing. Some new possible applications of FSMA films such as magnonic and photonic crystals fabrication will be discussed. The resent results on the observation of giant magnetoresistance in epitaxial films in a wide temperature range will be shown.

Natural selforganized morphology being formed by the elongated bar-like shaped crystals will be demonstrated for epitaxial Ni-Mn-Ga thin films deposited on MgO (001) substrate and will be discussed in terms of surface stress relaxation. Modification of magnetic properties in periodic nanotwin structures in the case of ferromagnetic and antiferromagnetic exchange on twin boundaries will be demonstrated for epitaxial Ni-Mn-Ga and Ni-Mn-Sn films.

3D ANALYTICAL MODEL OF SKYRMIONS AND SKYRMION-LIKE STRUCTURES IN A TWO-SUBLATTICE ANTIFERROMAGNET WITH DZYALOSHINSKII-MORIYA INTERACTION

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KEY WORDS: magnons, antiferromagnetic spintronics

Today antiferromagnetic spintronics is a rapidly developing new field of research of antiferromagnetic materials as elements in spintronic devices. Antiferromagnets represent perspective materials for spintronic generators where THz-frequencies can be reached enabling ultrafast information processing in comparison with ferromagnets [1].

There are two most popular candidates as information carries for the next generation memory devices in antiferromagnets – antiferromagnetic domain walls and antiferromagnetic skyrmions. The skyrmions represent stable nanoscale magnetization nonuniformities in ferro- and antiferromagnets [2, 3]. Usually the skyrmions are topologically protected and the stability of skyrmions is supplied by the Dzyaloshinskii-Moriya interaction [3], which is more commonly found in antiferromagnets than in ferromagnets [4].

In this talk, the analytical model is proposed for description of skyrmions and skyrmion- like magnetic structures in a two-sublattice antiferromagnet with uniaxial magnetic anisotropy and Dzyaloshinskii-Moriya interaction. "Relativistic contraction" of skyrmion size in the direction of motion is demonstrated for "subcritical" case when the skyrmion velocity is less than spin wave velocity in antiferromagnet. Lorentz-like "supercritical" transformation are found for sizes of skyrmion-like magnetic structures moving with velocity greater than spin wave velocity in antiferromagnet.

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Abstracts
Posters

LOW-FIELD MICROWAVE ABSOPTION AND ITS CORELATION WITH MAGNETIZATION IN Ni-Mn-Sn HEUSLER ALLOY FILMS

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KEY WORDS: ferromagnetic resonance (FMR), Heusler alloys, LFMA, ESR spectroscopy

Ferromagnetic as resonance (FMR) is associated with the resonance absorption of microwaves by ferromagnetic materials at an appropriate magnetic field. Analysis of FMR signal gives information about effective magnetization, effective magnetic anisotropy, damping constant, spin splitting g factor, magnetic inhomogeneity etc. of a material. Recently, a new non resonant microwave absorption phenomenon at low or zero magnetic field called low-field microwave absorption (LFMA) has been observed in some materials. Unlike the resonant FMR absorption, Non resonant LFMA shows a hysteresis behavior between in the spectrum recorded during increasing and decreasing magnetic field. LFMA has been observed in high temperature superconductors [1], amorphous ribbons [2], glass coated micro wires [3], ferrite nanoparticles [4], magnetic thin film [5], etc. Though several interpretations and explanations have been proposed for the origin of LFMA signal, it is still not properly understood and the absence of LFMA various materials is unexplained. In this paper, we report for the first time, the detection of LFMA signal in polycrystalline Ni-Mn-Sn thin films deposited on Si substrates. This discovery of LFMA in Heusler alloys films offers an opportunity to explore the properties of LFMA and its universality in Heusler alloys films LFMA measurements were performed on the films at from temperature at 9.44 GHz using an ESR spectrometer. LFMA spectra were recorded with different orientations film plane with respect to applied field direction (Θ_H) staring from 0° to 90°. The LFMA hysteresis characteristics could be correlated with the isothermal magnetization ($M - H$) loop characteristics recorded for different film orientation in static magnetic measurements (cf. Fig. 1). When magnetic elements such as Fe, Co were substituted in Ni-Mn-Sn film, both LFMA signal as well as the M-H loop properties of the quaternary films varied in a correlated manner with substitution, signifying a strong dependence of LFMA on the magnetization process in these films. Apart from establishing LFMA in ternary and quaternary Ni-Mn-Sn Heusler alloy films, this study also points out that Ni-Mn-Sn thin films on Si substrate are potential candidates for fabricating low magnetic field sensors in microwave frequency range.

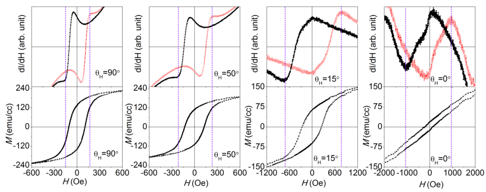

Fig. 1 : LFMA and M-H loops of Ni-Mn-Sn film for different film orientations to applied magnetic field

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SPINWAVE HARMONIC COMB GENERATION BY ULTRAFAST LASER PULSES WITH A HIGH REPETITION RATE IN THIN MAGNETIC FILMS

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KEY WORDS: spin wave, magnonics, Brillouin light scattering, ultrafast demagnetization

The discovery of ultrafast demagnetization by ultrashort laser pulses in 1996 [1], triggered interest in optical manipulation and detection of the magnetization at nanometer scale as a rout for the development of new technologies. It is by focusing an ultrashort laser pulse on a thin magnetic sample possible to either write a magnetic domain or launch a propagative spinwave (SW) [2].

Typically, SWs are injected in nanostructures by electrical current, RF antennas or laser pulses. Optical characterization of SWs has been primarily based on either Magneto-Optical Kerr Effect (MOKE) [3] or Brillouin Light Scattering (BLS) [4]. So far, all optical studies on ultrafast demagnetization have been carried out using MOKE microscopy. The main advantage of instead using BLS in such experiments is the direct access to the frequency domain information, which provides a deeper insight to the phenomenon under investigation. Here we proposed a new method to fully optically create, manipulate and characterize SWs in magnetic structures at the nanoscale.

We report the excitation of SWs in a thin film magnetic sample by means of a high repetition femtosecond laser. The new technique offers strong advantages over other methods, with its sensitivity to all spin waves excited in the thin film. The laser spot on the sample forms a sub- micron magnon source with specific and narrow equally spaced frequencies which directly depend on the laser characteristics irrespective of the sample magnetization and the applied external field. The SW comb generated by this method propagates several microns away from the laser spot. We show that this technique may be used to locally enhance SW's which frequencies resonate with a harmonic of the repetition rate of the excitation laser. By using a BLS microscope, we could frequency and spatially resolve the phenomena down to sub-micron and sub-GHz resolution.

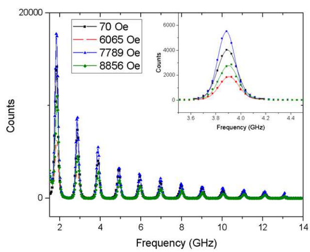

Fig. 1 : Excitation spectrum of Yttrium Iron Garnet (YIG) by a 1 GHz repetition rate femtosecond laser

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PHOTOMAGNONIC CAVITIES FOR ENHANCED MODULATION OF LIGHT BY SPIN WAVES: A QUASISTATIC APPROACH

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KEY WORDS: photon-magnon interaction, photomagnonic cavities, multimagnon processes

The inherently week interaction of visible and near-infrared light with magnetization waves can be significantly enhanced in the so-called photomagnonic or optomagnonic cavities [1,2] opening the way for ultrafast and energy-efficient spin-based information processing miniaturized devices. Photomagnonic cavities confine long-lifetime photons and magnons in the same ultra-small region of space thus increasing their mutual interaction. In this presentation we review some planar and spherical photomagnonic micro/nano-cavities, as those shown in the Figure. Notably, due to the large frequency mismatch between the optical (200 $\sim$ 400 THz) and spin (1 $\sim$ 100 GHz) waves involved, a quasistatic approximation can be applied for an accurate description of the dynamical evolution of the photomagnonic interaction.

Our results predict the occurrence of strong photon-magnon interaction in such appropriately designed cavities, which is manifested as a large dynamical optical frequency shift driven by multi-magnon absorption and emission processes by a photon. The quasistatic approach allows for a clear and transparent interpretation of the underlying physical mechanisms in all the aforementioned cases.

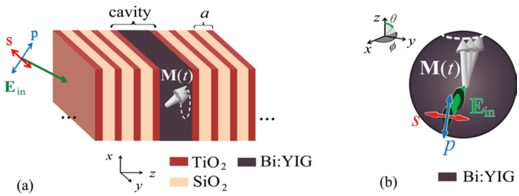

Fig. 1 : (a) A planar photomagnonic cavity, formed by a trilayer TiO_2 /Bi:YIG/TiO_2 sandwiched between two SiO_2/TiO_2 multilayer Bragg mirrors. A perpendicular standing spin wave is excited in the dielectric magnetic defect. (b) A spherical photomagnonic cavity, in which a uniform precession spin wave is excited

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POWER-DEPENDENT OPERATION REGIMES OF A SPIN-TORQUE MICROWAVE DETECTOR

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KEY WORDS: spin-torque microwave detector, operation regime, microwave power

Spin-torque microwave detector (STMD) is a spintronic device generating output dc voltage under the action of input microwave power and having volt-watt sensitivity that exceed the sensitivity of a Schottky diode, which makes STMD to be promising microwave signal detector for various applications. Basic operation principles [1] of an STMD and its possible applications are well known [2]. However, to date a resonance quadratic regime of STMD operation is analyzed thoroughly, while other several possible operation regimes are unexplored. Here we consider several operation regimes of an STMD, which could be observed at different level of input microwave power subjected to the device.

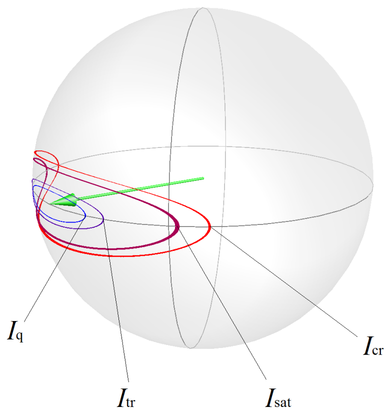

Fig. 1 : Typical trajectories of magnetization precession realized at different operation regimes of an STMD. I_q, I_{tr} and I_{sat} are the input microwave currents corresponding to the appearance of quadratic, transient, and linear regimes, respectively. I_{cr} corresponds to the transition from in-plane magnetization precession to chaotic dynamics or out-of-plane precession. Green arrow marks initial magnetization direction

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INVESTIGATION OF MAGNONS AND PHONONS IN CoFeB/Au MULTILAYER STRUCTURES BY HIGH RESOLUTION BRILLOUIN SPECTROSCOPY

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Experiments with multilayered CoFeB materials are of particular interest owing to their numerous number of applications in spintronics and magnonics. We determine the dispersion relation of thermal magnons and phonons which exist in multilayered sample using Brillouin light scattering (BLS) spectroscopy in CoFeB/Au multilayer deposited on silicon substrate with Ti and Au layers. In the backward scattering geometry, the dispersion relations of magnons and phonons are determined for different values of the magnetic field. Two kinds of surface phonons are observed: Rayleigh and Sezawa waves. The dispersion branches of phonons and magnons are intersect each other. A hybridization of the dispersive relation of spin wave and surface acoustic waves is observed. The finite element method (FEM) is used for interpretation of the experimental results.

This work was supported by National Science Centre of Poland Grant No. UMO- 2016/21/B/ST3/00452 and the EU's Horizon 2020 Research and Innovation Program under Marie Sklodowska-Curie Grant Agreement No. 644348 (MagIC).

SPIN-WAVE PHASE INVERTER UPON A SINGLE NANOGROOVE

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KEY WORDS: spin waves, phase shift, focused electron beam-induced deposition (FEBID)

Featuring low dissipation, spin waves are seen as prospective data carriers in future signal processing systems [1]. In these, information can be encoded in the spin wave phase, as already demonstrated in several prototype spin-wave logic gates [2]. Recently, phase shifts of up to almost π have been observed for spin waves in a one-dimensional magnonic crystal with a single magnetic defect [3].

Here, we investigate by all-electrical spectroscopy phase shifts in spin waves propagating through a nanogroove in 45 nm-thick Co-Fe waveguides. The 1x3 μm^2 waveguides are fabricated by focused electron beam induced deposition (FEBID) [4]. The defects are 120 nm-wide nanogrooves milled by focused ion beam milling across the waveguides. Increasing the nanogroove depth from 0 to 35 nm and the in-plane bias magnetic field strength from 0 to 2.3 kOe, we have been able to continuously invert the spin-wave phase shift from 0 to π without a significant suppression of the spin-wave transmission. Our findings are relevant for a fine tuning of the spin-wave phase in magnonic circuits.

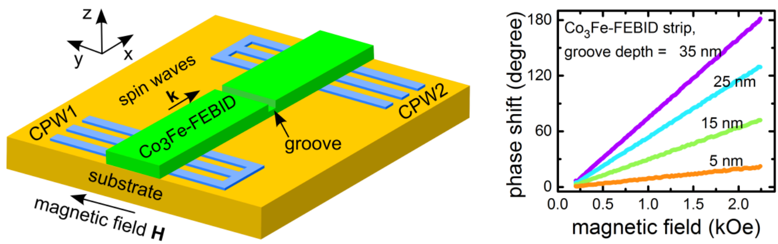

Fig. 1 : Left: Experimental geometry. A Co-Fe waveguide is deposited by FEBID between two microwave antennae (CPW1 and CPW2) which are used for excitation and detection of transmitted spin waves. A nanogroove milled by FIB in the middle of the waveguide introduces a phase shift in spin waves passing trough it. Right: Experimentally measured phase shifts as a function magnetic field for a series of groove depths, as indicated

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BOUNDARY CONDITIONS AT AN ANTIFERROMAGNET/FERROMAGNET INTERFACE OF FINITE THICKNESS. PROPAGATION OF SPIN WAVE THROUGH THIS INTERFACE

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KEY WORDS: antiferromagnet, ferromagnet, interface, boundary conditions, spin wave

Abridged general form of the boundary conditions at an interface between antiferromagnet (AFM) and ferromagnet (FM) have been obtained in the continuous medium approximation similarly to the approach in [1,2] taking into account the fact that the interface is a composite material with finite thickness δ which is much less than the length of the spin wave λ_{sw}. Three order parameters have been considered inside an interface of finite thickness with magnetizations of both sublattices $\mathbf{M}_1$ and $\mathbf{M}_2$ of AFM, and magnetization $\mathbf{M}$ of FM (see Fig. 1(a)). Using these boundary conditions, the excitation of a surface evanescent spin wave has been considered in FM when spin wave in AFM falls onto this interface as shown in Fig. 1(b). The uniform and nonuniform exchange between all order parameters have been taken into account in the interface energy as the coordinate dependencies of the magnetic parameters characterizing two-sublattice AFM, FM, and the interface region on the y coordinate in the energy as shown in Fig. 1(c). The coefficients and the phases of transmission and reflection of spin wave through the AFM/FM interface have been derived in general case.

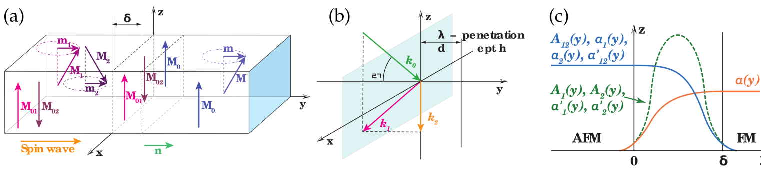

Fig. 1 : a) The model shows the schematic image of the system consisting of two-sublattice AFM, interface of finite thickness between AFM/FM and FM, and magnetizations in each layer with the small perturbations of order parameters relative to the ground state; b) Schematic illustration of the excitation of a surface evanescent spin wave in FM when spin wave in AFM falls onto this interface, where the incident wave vector is $\mathbf{k}_0$, the reflected wave vector is $\mathbf{k}_1$ and the transmitted wave vector is $\mathbf{k}_2$, and θ is angle between the wave vector of incident wave and y-axis; c) Schematic assumption of the coordinate dependence of the magnetic parameters characterizing two-sublattice AFM, FM, and the interface region on the y coordinate

This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie GA No. 644348 (MagIC).

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SPIN WAVE DAMPING NONRECIPROCITY IN SPIRAL FERROMAGNETS

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KEY WORDS: dissipative function, dispersion law, long-periodic magnetic structures, spin wave damping

Within the general phenomenological description of the relaxation phenomena in magnetic materials, a dissipative function is constructed for crystals of different symmetry with magnetochiral nonreciprocity. It is shown that the existence of a chiral-direction in the magnetic structure leads not only to an "energy" nonreciprocity but manifests itself in a different damping of volume spin waves with a given but opposite wave vector directions (see Fig. 1).

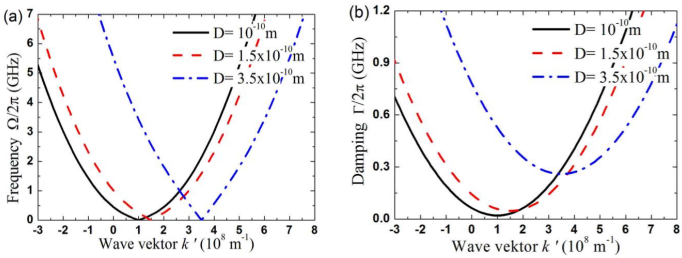

Fig. 1 : Dispersion of spin wave frequency (a) and spin wave damping (b) in the exchange-relativistic spirals. The dispersion curves were computed for the various values of the DM interaction

The dynamic magnetochiral nonreciprocity is determined by the competition of different magnetic exchange-relativistic and exchange-exchange interactions. This feature of magnetization dynamics in magnetochiral structures is sufficiently general and robust against the detailed magnon scattering mechanisms. In particular, this causes a finite damping even for the Goldstone mode (see Fig. 1(b)).

The "damping" nonreciprocity of the magnetic dynamic in magnetochiral magnets should be taken into account modeling the spin waves dynamics in such systems. We expect the present results may have practical applications in the field of magnonics. In particular, this specific of spin waves paves a route for the design of efficient spin wave diodes based on the crystallographic symmetry and long-periodic magnetic structures.

The work was funded through the projects No. 0117U000433 provided by NAS of Ukraine and No. 0117U004340 provided by MES of Ukraine. We are grateful for the support of the research from the European Union's Horizon 2020 research and innovation program under Marie Sk odowska-Curie GA No. 644348 (MagIC).

1D MAGNONIC QUASICRYSTALS: SPIN WAVES PROPAGATION AND REPROGRAMMABILITY

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KEY WORDS: Fibonacci quasicrystals, spin waves, scanning transmission X-ray microscopy

In this work, we investigate one-dimensional magnonic quasicrystals consisting of dipolarly coupled permalloy (Py – $Ni_{80}Fe_{20}$) nanowires (NWs) of two widths, arranged using the Fibonacci inflation rule [1]. Propagating spin waves (SWs), excited by a coplanar waveguide, are imaged using scanning transmission X-ray microscopy (STXM). Modes from the 1st and 2nd band are observed as well as band gap between them. Reprogrammability of this system is also demonstrated, by changing the magnetic configuration between the ferromagnetic (FO) and antiferromagnetic (AFO) order. For selected frequencies, SWs propagating across the structure are excited only for one of the magnetization configuration, indicating the presence of the band gap for the other (Fig. 1(b)). That means that by switching between the FO and AFO, it is possible to reprogram the dispersion (Fig. 1) and control the transmission of the SWs.

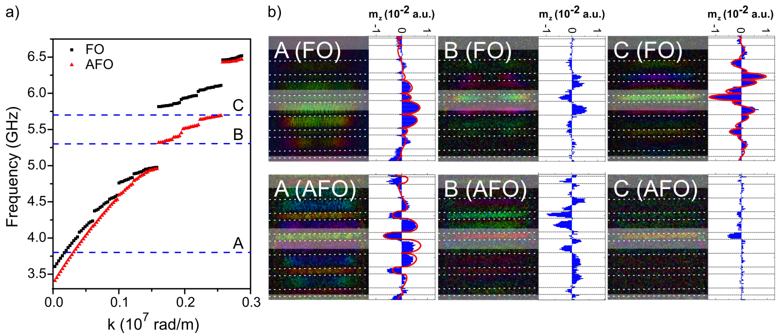

Fig. 1 : (a) The simulated SWs dispersion for the Fibonacci structure with FO and AFO. (b) Amplitude (color)-phase (brightness) STXM images for different excitation frequencies (A-C) in FO and AFO. Excitation profiles are plotted on the right side of the images (blue bars) and compared with simulated profiles (red lines)

The study has received funding from: EU H2020-MSCA-RISE GA No. 644348 (MagIC); J. R. from the Adam Mickiewicz University Foundation and from the NCN - UMO-2017/24/T/ST3/00173.

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ANOMALOUS NONLINEARITY OF THE MAGNONIC EDGE MODE

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KEY WORDS: magnonic edge mode, nonlinear dynamics, spintronics

In extended geometries, the nonlinearity of magneto-dynamics is typically described by a single constant [1]. Its positive and negative values indicate repulsion and attraction of magnons, respectively. In thin magnetic films with easy-plane magnetic anisotropy, the attraction is typically achieved for the in-plane magnetization. If the sufficient stimulus is provided, e.g., via application of spin transfer torque, this interaction gives to rise to the self-localized magnetic solitons, such as spin wave bullets. In contrast, for oblique magnetization above a so-called critical angle, the repulsion of magnons only allows for propagating modes. Here we demonstrate analytically and via micromagnetic simulations that such description is not adequate for the magnonic edge modes, which naturally appear in confined magnetic systems [2]. We demonstrate that the confinement potential of such modes is nonlinear and its contribution makes nonlinearity of the edge modes either negative, positive or non-monotonically dependent on their amplitude. Furthermore, the sign of the nonlinearity could be tuned by the aspect ratio of the structure. Our results shed light on the non-monotonic frequency vs. current dependence that was recently observed in constriction spin Hall nano-oscillators [3].

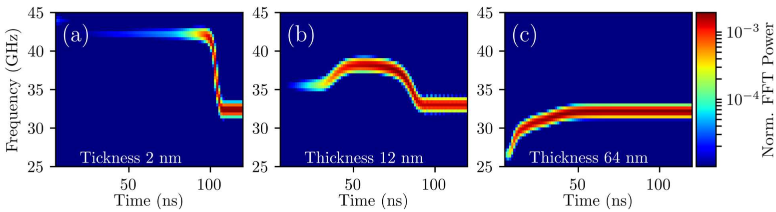

Fig. 1 : Simulated spectrograms of the auto-oscillating magnonic edge mode showing (a) negative, (b) non-monotonous and (c) positive nonlinear frequency shifts depending on the thickness of the in-plane magnetized, semi-infinite Permalloy film

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MAGNETOMECHANICAL EFFECTS IN ELASTIC FILMS WITH MAGNETIC APPLICATIONS

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KEY WORDS: elastomers, magnetic strips, flexural deformation

Highly elastic polymers (elastomers) are easily deformed under the influence of external influences. Their Young's modulus can be tens of kilopascals and they can experience elastic deformations comparable to the sample dimensions. Of particular interest is the study of the deformation of elastomers under the influence of magnetic forces. For example, in magnetically active elastomers (MAEs) containing ferromagnetic particles (micro- or nanometer-sized), a giant magnetostriction, shape memory effect and an anomalous magnetic field dependence for the shear modulus can be observed due to the high-elastic matrix. Due to the fact that in MAE the magnetic interaction forces between magnetized ferromagnetic particles can significantly deform the elastomer matrix.

We studied the effect of flexural deformation of elastic films in the magnetic field with a surface application in the form of plane-parallel magnetic stripes, which structure is shown schematically in Fig. 1. The magnetization vector of the strips M lies in the plane of the film, when magnetizing by a field lying in the plane of the film. There are magnetic attraction forces between magnetized strips, which lead to elastic compression of the film surface and, accordingly, to flexural deformation of the film.

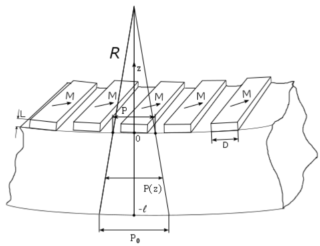

Fig. 1 : Scheme of the arrangement of magnetic strips and bending deformation in an elastic film

Solving the problem of minimizing the sum of the magnetostatic energy of the interaction between the strips and the elastic deformation energy in the film in an analytical form we determined the curvature radius of the flexural deformation of the film. The obtained expression for the inverse radius of curvature has next form:

$$\frac{1}{R} = \frac{1}{P_0}\frac{3M^2\sin^2\chi}{E}\left(\frac{L}{l}\right)^2\left[1-\frac{\pi D}{P_0}\text{ctg}\left(\frac{\pi D}{P_0}\right)\right],$$

where P_0- the period of the structure in undeformed state; $M-$ the saturation magnetization of the material, $E-$ the Young's modulus of the film material, $\chi-$ the magnetic field orientation angle in the film plane (reckon from the direction of the magnetic stripes), $R-$ the radius of curvature of the deformed film, $l-$ the thickness of the film, L, $D-$ the thickness and width of the magnetic stripes.

PROPAGATION OF SPIN WAVES IN MAGNONIC CRYSTALS

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KEY WORDS: magnonic crystals, spin waves, Brillouin light scattering

The interest in artificial magnetic media like magnonic crystals visibly increases during the recent years in view of their application for information processing at microwave frequencies [1]. The main features of these crystals are the presence of bandgaps in the spin-wave spectra. The bandgaps are formed due to the Bragg reflections on the artificially created periodic structures. Therefore, it is possible to influence the properties of the crystals using different designs of these structures within a magnetic material. Recently, potential of edge- and width-modulated waveguiding structures for creation of macro- and micro-sized magnonic crystals was demonstrated [2-5]. At the same time, the exact band structure and peculiarities of spin-wave dynamics in such waveguides are not clarified yet.

We studied spin-wave propagation in longitudinally magnetized width-modulated yttrium- iron-garnet (YIG) waveguides by means of both Brillouin light scattering and microwave spectroscopies. The waveguides were produced by chemical etching of a YIG film of 8.5 μm- thickness. Short pulses (30 ns) of backward volume magnetostatic spin waves (BVMSW) were excited, close to the ferromagnetic resonance frequency and their propagation was visualized and measured, both in pass and rejection frequency bands. The influence of spin-wave caustic formation [6] on crystal properties is revealed and discussed.

Financial support by the DFG (B01 project within SFB/TRR 173 "Spin+X" and the project DE 639) as well as by DAAD grant 57213643 is gratefully acknowledged.

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FANO-RESONANCE BASED NANOSCALE SPIN-WAVE TRANSDUCER, VALVE AND PHASE SHIFTER IN DAMON-ESHBACH GEOMETRY

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KEY WORDS: Fano resonance, Damon-Eshbach, spin waves, nanoscale, logic device

The promise of creation of spin-wave based logic devices rests on our ability to excite spin waves with nanoscale wavelength and then to control their amplitude and / or phase, all on the nanoscale. Au et al demonstrated that a magnetic nanoelement formed above a longitudinally magnetised magnonic waveguide can act as an efficient spin-wave transducer, valve and phase shifter, each reprogrammable through switching the magnetisation in the element [1,2]. Here, we use micromagnetic simulations to extend the concept of Au et al to the case of the magnonic waveguide magnetised parallel to its width, i.e. Damon-Eshbach geometry for spin-wave propagation. This system demonstrates the ability to control the propagation of spin waves along the waveguide via magneto-dipolar coupling to the overlaid magnetic nanoelement [1,2]. Depending upon the direction of the magnetisation of the nanoelement and waveguide by the bias magnetic field, the spin waves either can be transmitted, phase-shifted or reflected in a controlled manner. Our observations are explained in terms of the coupling of the discrete spectrum of precessional modes of the nanoelement to the continuum of the waveguide, which is a typical example of a Fano resonance. This is interpretation is supported by frequency dependent micromagnetic simulations that yield the characteristic Fano-like lineshapes for the reflection and transmission coefficients of spin waves in the waveguide.

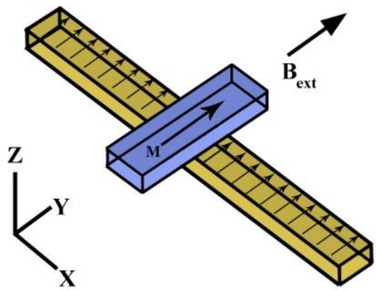

Fig. 1 : Schematic of the arrangement of Permalloy antenna on top of Permalloy waveguide. Here M denotes the direction of magnetisation and B the biasing field

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MAGNONIC SPECTRA OF ANTIFERROMAGNETIC SKYRMION CRYSTALS

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KEY WORDS: magnonics, skyrmion, antiferromagnetic, spin wave

Magnetic skyrmions are particle-like, topological stable, nanoscale spin configurations with integer topological numbers which have been recently found in extended lattices of bulk non- centrosymmetric magnetic materials as well as in the ultrathin film with the presence of interfacial Dzyaloshinskii-Moriya interaction (DMI).[1, 2] The static and dynamic properties of magnetic skyrmions show high promise for the future spintronic memory and logic application with the main fundamental limitations of the skyrmion Hall effect. [1] Recently, it has been shown that this issue could be solved by using antiferromagnetic skyrmion [3,4], opening a path for a more competitive skyrmion based racetrack memory.

Here, we firstly investigate how to stabilize skyrmions use tunnelling interlayer coupling in synthetic antiferromagnets (SAF) of the Co/Ru/Co trilayer type. To stabilize a SAF skyrmion, the DMI in the top and the bottom ferromagnet should have an opposite sign. By periodical arrangement of these SAF skyrmion, a novel type of magnonic crystal can be realized. We further study the magnonic bandstructure of spin wave in such a kind of antiferromagnetic skyrmion based magnonic crystal. The calculated magnonic spectra exhibit allowed frequency bands and forbidden frequency bandgaps analogous to that of conventional magnonic crystals and ferromagnetic skyrmion based magnonic crystals [6]. Therefore, it is possible to tailor the spin-wave spectra of SAF skyrmion systems into a band-like organization that displays a segregation of allowed and forbidden bands. Our results provide a natural link between two steadily growing fields of antiferromagnetic spintronics: skyrmionics and magnonics.

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INTERFERENCE OF FORWARD VOLUME SPIN WAVES USING YTTRIUM IRON GARNETS

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KEY WORDS: spin wave waveguide, yttrium iron garnet, forward volume spin wave

Spin wave logic gates are being developed rapidly because of their interesting features including wave functionalities and low dissipation operation [1,2]. In this study, we demonstrated a three port spin wave device using the forward volume mode which was selected because of its high in-plane uniformity. Fig. 1(a) shows the top view of a fabricated device. A 50 nm thick yttrium iron garnet (YIG) was patterned into a 100 µm by 400 µm region using phosphoric acid etching. The edges of the YIG waveguide were covered by 90 nm thick gold film to absorb spin waves. This absorber suppresses reflected spin waves, providing robust interference even though forward volume spin waves usually suffer from noise based on reflected waves and/or standing waves. Clear interference of forward volume spin waves was obtained and analyzed using the integral form of Maxwell's equations based on three-dimensional objects similar to the experimental setup.

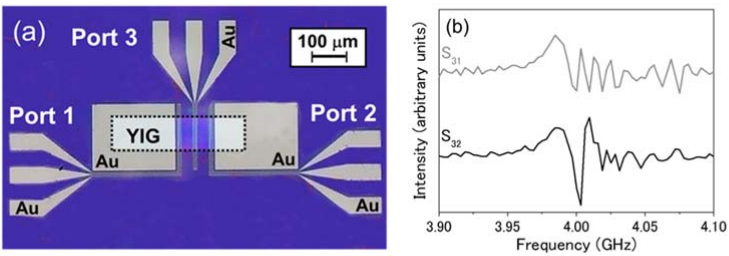

Fig. 1 : (a) Fabricated three port spin wave interferometer using 50 nm thick YIG film. Width of YIG waveguide was about 100 µm. (b) Transmission spectra of spin waves

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STRIPE DOMAINS NUCLEATION THROUGH SPIN WAVES SOFT MODES IN THIN FILMS WITH PERPENDICULAR MAGNETIC ANISOTROPY

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KEY WORDS: spin wave, soft mode, stripe domain

We present a study of the spin wave dynamics in thin films with perpendicular magnetic anisotropy. In particular, we analyze the spin wave propagation in samples with a stripe domain structure as function of the applied magnetic field. Some works suggest that the stripe nucleation process upon reduction of an external in-plane magnetic field could be related with the occurrence of a soft spin wave mode with a non-zero wave vector [1,2].

In practice, we compare data obtained from two numerical methods, usual micromagnetic simulations performed with the MuMax3 program on the one hand, and a propagating spin-wave normal mode analysis based on the dynamic matrix approach [3] (SWIIM) on the other hand.

Starting from saturation and decreasing the in-plane external magnetic field $\mathbf{H}_0$, we find that the Damon-Eshbach (DE) spin-wave mode ($\mathbf{k} \perp \mathbf{M}$) of lowest frequency softens progressively. We have found that the soft modes explain quite well the characteristics of the stripe patterns like period and nucleation field. In this frame, the nucleation field will be the one that allows the existence of a soft mode, while the period can be determined by looking at the wave vector of this soft mode.

An illustration of this behavior is shown at the Fig. 1, which presents the dispersion relation for a 50 nm Co HCP (0001) thin film at different applied fields. It shows that when $\mu_0 H = 538$ mT, it is possible to excite a mode with $k = 64$ rad/µm and $f \sim 0$ GHz, allowing the nucleation of stripes with period $p = 2\pi/k = 98$ nm.

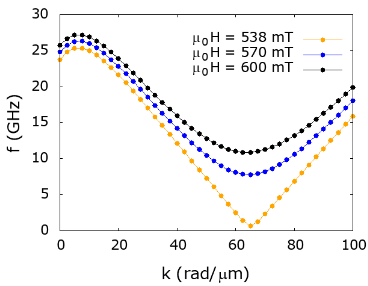

Fig. 1 : Dispersion relations of the Damon-Eshbach spin-wave mode in a 50 nm thick Co (0001) film, for decreasing values of the external magnetic field. When $\mu_0 H_0 = 538$ mT, a soft mode with zero frequency appears and the stripe domains are nucleated

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SCANNING TRANSMISSION X-RAY MICROSCOPY OF SPIN WAVES IN PERMALLOY

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KEY WORDS: scanning transmission x-ray microscopy, spin waves, x-ray magnetic circular dichroism

Within the last years moors law is slowly approaching its limits. The size reduction of transistors gets continuously more difficult, the smaller they become. Modern transistors are so small (7 nm architecture, 5 nm planed) that quantum effects will start to have a critical influence on the circuit if their size is further decreased. That means that new smart solutions for data processing are necessary to maintain a steady increase of computing power.

One possible approach for "smarter" data processing are magnetic devices such as racetrack memories or magnetic gates. Due to the wave nature of magnons information cannot only be encoded in amplitude, but also in phase [1]. However, the scaling of magnetic devices into the sub µm region is always accompanied by problems such as the resolution and scalability of the production process, or even more fundamental, the observation of the desired effect.

Fortunately, scanning transmission x-ray microscopy (STXM) is able to resolve magnetic structures well below 100 nm using x-ray magnetic circular dichroism [2] (XMCD). The MAXYMUS microscope at BESSY routinely achieves resolutions down to 15 nm. This enables direct observation of objects of magnitudes, interesting for technical application in time domain and real space.

A quickly recovering avalanche photodiode and a fast sorting algorithm allows for an acquisition of a dynamic spin wave video within 5 minutes. A spin wave video in real space yields information about the amplitude and the phase at the same time. With 5 µm Fourier analysis a "dynamic picture" of the measurement. Here we show a demonstration of the method, therefore, we measured a 50 nm think permalloy sample in Demon-Eshbach geometry. The result is shown in Fig. 1. The color represents the relative phase of each pixel, the amplitude is encoded in brightness. The total area displayed is 40 x 5 µm^2 with a resolution of 200 nm. Furthermore, the measured videos can also be filtered in k-Space, which not only allows a smooth representation of the spin wave video but also the separation of different modes in real space.

STXM gives massive new opportunities for the observation of nano magnetic structures such as spin waves, skyrmions, domainwalls, demagnetizing fields, or magnetization reversal processes. With resolutions down to 15 nm in space and 5 ps in time, there is an almost endless amount of opportunities to investigate magnetic structures and their dynamic behavior.

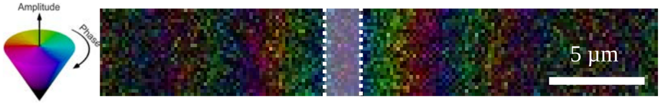

Fig. 1 : Dynamic illustration of a spin wave. Color encodes relative phase, such a spin wave movie brightness encodes amplitude. Dashed white lines denote the position of the stripline. can be extracted from Area = $40 \times 5\ \mu m^2$, Resolution = 200 nm

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MICROMAGNETIC STUDY OF A REFLECTION OF A SURFACE MAGNETOSTATIC WAVE

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KEY WORDS: spin waves

We consider a reflection of a surface magnetostatic wave incident on the edge of an abruptly terminated magnetic film. This work has been inspired by experimental results [1]. We show, by means of micromagnetic simulations, that the dynamic dipolar magnetic field associated with the reflected spin wave is non-uniform near the film's edge (see Fig. 1(a)). Moreover, the ellipticity and the area of spin wave precession change in that region. Those nonuniformities emerge in the existence of a non-zero phase shift of the reflected waves with respect to the incident ones. The value of the phase shift depends on the external magnetic field and spin waves frequency. We associate the existence of these effects with the presence of the radiated fields at the edge of the film.

The phase change of the reflected waves exists for both normally and obliquely incident magnetostatic spin waves. Furthermore, the phase change for obliquely incident spin waves depends on the angle of incidence. Therefore, we expect that for the magnetostatic spin waves can exist Goos-Hänchen effect, i.e., a lateral shift along the interface between the incident and reflected beam spots, what is opposite to Ref. [2], where Yasumoto and Oishi have shown in the simplified analytical calculations, that there is no Goos-Hänchen shift for magnetostatic waves. We show that including evanescent radiated waves in the area surrounded the film edge in the theoretical approach allows removing discrepancy between the micromagnetic simulations and analytical model.

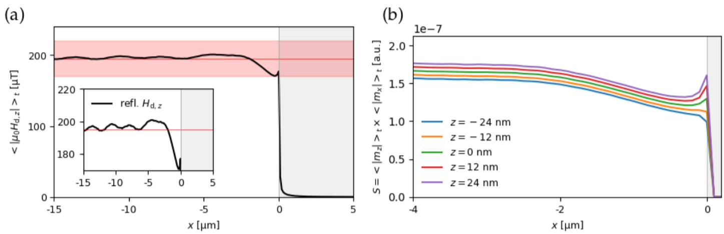

Fig. 1 : (a) Out-of-plane component of the reflected dipolar magnetic field (related to the surface mode and the scattered modes) for the stripe with the edge located at $x = 0$. The inset presents the zoomed-in region highlighted by a semi-transparent red in the main figure. (b) Precession area of the reflected magnetization for different values of the z coordinate (across film's thickness)

Acknowledgments: This work was supported by grant EU's Horizon 2020 MSCA RISE programme GA No. 644348 (MagIC).

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PHASE SHIFT OF SPIN WAVES TRAVELING THROUGH THE INTERFACE WITH ASYMMETRICAL PROPERTIES

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KEY WORDS: spin waves, phase shift, broken spatial inversion symmetry

Last years the study of phase shifters (PS) of spin waves (SW) attach much attention of researchers for development the logic devices encoding information in the phaseof travelling SW packets and utilizing them for data processing [1]. The system consisting of two semi-infinite ferromagnetic medias separated by an interface is considered. Between those medias we assume boundary conditions with broken spatial inversion symmetry (BSIS) [2]. The dependence of PS between the transmitted and incident SW on the interlayer exchange coupling is obtained and analyzed for different value of parameter BSIS (Fig. 1). The new possibility to introduce a controlled PS of the propagating SWs is in transmission through interface with BSIS.

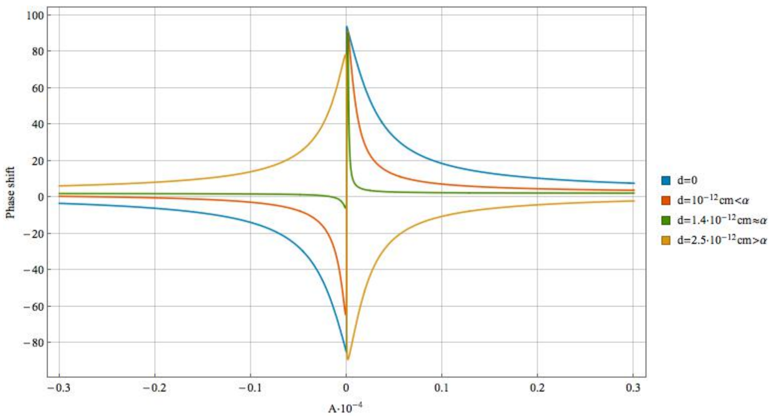

Fig. 1 : The dependence of PS between the transmitted and incident SW on the interlayer exchange coupling for different parameter BSIS d

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 644348 (Magic).

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MAGNETIC PROPERTIES OF NiFeCuMo ALLOYS FOR THERMALLY DRIVEN SPIN DEVICES

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KEY WORDS: NiFeCuMo, Mumetall, alloy, magnetic properties, spin transport

Permalloy layers are ideal for application in modern sensors and spintronic devices [1,2]. Alloys based on NiFe compositions are very perspective, low cost and they can be treated as an alternative solution to spintronic devices based on YIG. The first observation of Spin Seebeck Effect was made with the use on NiFe layers [3]. However activating magnetic field strongly depend on thickness and processing of an active ferromagnetic layer in NiFe-based spintronic devices.

In the study commercially available NiFeCuMo samples (Mumetall Vacuumschmelze) were used as sheets, rings, sputtering targets and thin films. Investigated samples are shown in Fig. 1. The alloy with nominal composition $Ni_{76}Fe_{14}Cu_5Mo_7$ was used for further processing.

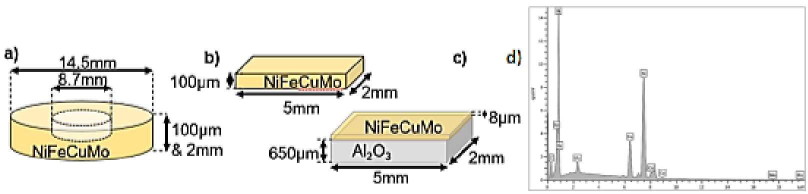

Fig. 1 : Investigated samples: NiFeCuMo ring structure (a), NiFeCuMo plate sample (b), NiFeCuMo film on Al_2O_3 (c), the EDS spectrum of the NiFeCuMo (d)

Magnetic polarization J, coercive field H_c, hysteresis loops $J(H)$ and initial magnetization curves $J(H)$ were measured in order to verify the influence of processing and thickness of samples on magnetic properties. The magnetic properties of the samples were measured in a closed samples with a magnetizing and pickup coils systems and with the usage ofvibrating magnetometer.

Nominal magnetic parameters of NiFeCuMo alloy cannot be directly applied for estimation of magnetizing field. Sputtered thin films and thin plates require 1000 times higher activating magnetic field than nominal one. Therefore magnetic field should exceed 10 mT to activate spin transport in the sample and overcome coercive field.

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CHARACTERIZATION OF INDIVIDUAL SUB-100 NM YIG STRUCTURES USING BRILLOUIN LIGHT SCATTERING MICROSCOPY

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KEY WORDS: Yttrium-Iron-Garnet, nanofabrication, magnon lifetime

Spin waves and their quanta, magnons, open up a promising branch of high-speed and low- power information processing [1]. Several important milestones were achieved recently in the realization of magnonic data processing devices. Nevertheless, the developed prototypes still have millimeter or micrometer sizes [2]. Thus, the fabrication of magnonic structures of lateral sizes down to a few tens of nanometers represents one of the main challenges in the field of magnonics. A material of special interest is Yttrium-Iron-Garnet (YIG) since it provides the highest known magnon lifetime. The recent revolutionary progress in the growth of high-quality YIG films with nanometer thickness [3] allows for the fabrication of nano-sized magnonic YIG conduits and paves the way for the realization of nanoscale magnonic computing systems.

Spin-wave conduits with widths down to 50 nm (Fig. 1) were investigated by means of Brillouin Light Scattering (BLS) Spectroscopy. The conduits were fabricated from a plain YIG film grown by liquid phase epitaxy [3] using electron beam lithography and subsequent ion milling. In order to measure the spin-wave lifetime, magnetization dynamics were excited via a macroscopic stripline by applying pulsed microwave currents. By employing time-resolved micro- focused BLS spectroscopy, the decay of the magnetization dynamics was measured after the excitation pulse was switched off and the magnon lifetime was extracted. The experimental results show that the magnon lifetime in the fabricated sub-100nm structures is comparable to the value of the initial plain film and still exceeds other state of the art magnonic materials like Permalloy.

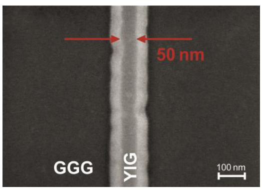

Fig. 1 : Scanning electron microscopy image of a 50 nm wide YIG waveguide

This research has been supported by ERC Starting Grant 678309 MagnonCircuits and DFG Grant DU 1427/2-1.

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TRANSITION BETWEEN MAGNON SCATTERING PROCESSES IN THE TIME DOMAIN

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KEY WORDS: time resolved µBLS, nonlinear magnons, vortex

Experimental results of time resolved µBLS measurements on a Permalloy disk with a diameter of 5 µm are presented. With the sample being in vortex state it is possible to excite nonlinear processes such as three- and four-magnon scattering [1] by applying a homogenous out-of- plane AC field with sufficiently large amplitudes.

When passing the linear regime additional spin wave frequencies besides the directly excited radial modes were detected. Results of time resolved measurements show that these pumping conditions cause cascades of different types of magnon-magnon interaction. By using different excitation powers it is shown that the delay time between three- and four-magnon scattering can be tuned.

Further, we show first results of realizing parametric amplification [2] via nonlinear scattering by applying two initial microwave signals to the same structure.

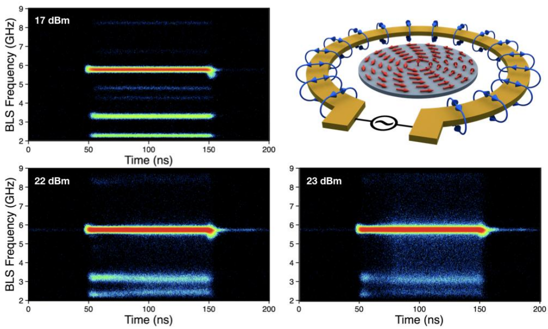

Fig. 1 : Time resolved BLS measurements for different excitation powers at 5.9 GHz show the transition from three- to four-magnon scattering depending on the applied microwave power. Upper right: Schematic of the structure under investigation. Out-of-plane fields were generated by applying microwave currents to an omega-shaped Au-loop around the disk. The vortex configuration of the magnetic system is indicated by red arrows

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GROWTH AND CHARACTERIZATION OF YIG FOR SPIN WAVE EXCITATION USING COPLANAR WAVEGUIDES

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KEY WORDS: spin wave, yttrium iron garnet, forward volume spin wave, epitaxial growth

Spin wave (SW) integrated circuit (IC) attracts many interests as a novel information processing device because of its Joule-heat-free feature [1]. So far, we demonstrated a four-port logic gate based on wave functionalities of forward volume (FV) SWs propagating in ∼10 µm thick yttrium iron garnet (YIG) films [2]. To transform this device into chip scale, YIG and SW excitation antennas need to be miniaturized. In this study, single crystalline YIG films with various thicknesses were grown onto (111) oriented gadolinium gallium garnet (GGG) substrate using pulsed laser deposition (PLD). The YIG showed clear x-ray diffraction peak (Fig. 1(a)), bulk-like magnetization, and atomically flat surface. Two coplanar waveguides (CPWs) with 16 µm distance were prepared onto the YIG using lithography. The width and gap of the CPW were both 2.5 µm. Obtained SW spectroscopy showed the clear propagation of FV SW. Fig. 1(b) is obtained SW spectroscopy, showing clear FV SW. However, the intensity of SW was low, probably because of impedance mismatches among probes, CPWs, and YIG film. This was analyzed using full-wave analysis based on three dimensional model. As a next step, we fabricate such a matched CPW onto YIG films and demonstrate SW IC.

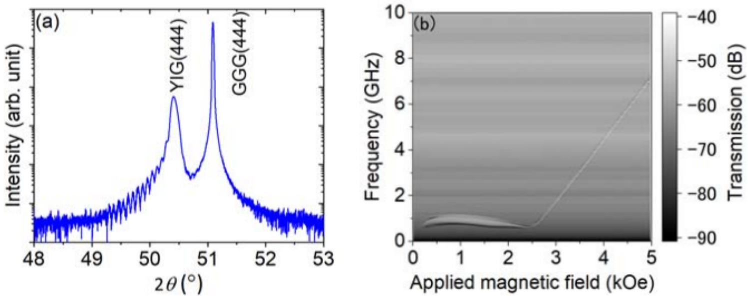

Fig. 1 : (a) X-ray rocking curve of 119 nm thick YIG. (b) SW spectroscopy between 16 µm distant CPWs. The magnetic field was applied perpendicular to the film

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ELECTRONIC SPIN RESONANCE IN OYSTER MUSHROOM *PLEUROTUS OSTREATUS*, GROWN ON A SUBSTRATE WITH THE ADDITION OF MAGNETITE

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KEY WORDS: electronic spin resonance, biosorbent, nanoparticles

It is known that oyster mushroom is a good sorbent of ions of heavy metals and other pollutants [1,2], but today there is a problem of extraction of spent biosorbent. Therefore, it is important to obtain a magnetically controlled biosorbent, which can be isolated in the high-speed regime using magnetic separators.

In this work, to impart to the biosorbent of magnetically controlled properties the oyster mushroom, *Pleurotus ostreatus* was grown on a substrate of wheat straw, 1 ml of a solution of 0.1 and 1 mg/ml magnetite nanoparticles was injected into the fungal growth sites for 5 days. Before magnetoresonance (ESR) experiments, samples of fungi were dried to constant weight at 105°C and ground using a laboratory mill. The ESR measurements of oyster mushroom Pleurotus ostreatus were carried out at $T = 300$ K in the frequency band 9-12 GHz [3]. Based on the experimental data, the resonance frequency-field dependence has been obtaiined (Fig. 1). The effective magnetization for Pleurotus ostreatus $M_{eff} = 37$ Gs has been calculated using the traditional procedure [3].

The ESR linewidth for these samples is 1 kOe, that is much larger than the linewidth for single-crystal magnetite. This fact indicates that the structure is a typical superparamagnet.

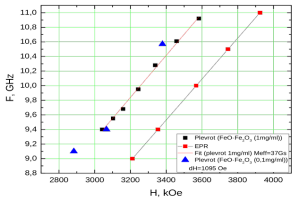

Fig. 1 : The frequency-field dependence for oyster mushrooms *Pleurotus ostreatus* (substrate with addition of magnetite nanoparticles of the: 1 mg/ml concentration – black square; 0.1 mg/ml – blue triangle

The study shows that the studied specimens of oyster mussel *Pleurotus ostreatus*, grown on a substrate with the addition of magnetite, exhibit the magnetic resonance properties of the superparamagnet. It is shown that the change in the concentration of magnetite nanoparticles from 0.1 to 1 mg/ml does not affect the value of M_{eff}. This means that the type of magnetic ordering in the structure being studied is determined by the properties of a single nanoparticle conglomerate, and not by the interaction between them. For commercial purposes, the results obtained can be used to reduce the cost of extraction of spent biomass of fungi from food and wastewater.

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REALIZATION OF A MICRO-SCALED SPIN-WAVE MAJORITY GATE

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KEY WORDS: magnonics, spin wave, data processing, sample fabrication

Spin-wave logic devices offer large advantages compared to modern CMOS-based elements. An example for such a logic element is the majority gate 1 , in which the logical output is given by the majority of the logical inputs. Furthermore, a spin-wave majority gate is suitable for the construction of all-magnonic circuits.

The operation of a macroscopic spin-wave majority gate made from a 5.4 µm-thick yttrium iron garnet (YIG) film is already proven – the output phase of the signal was defined by the majority of the input phases [2].

The miniaturization of the device is naturally the next step and the functionality of a micro- scaled spin-wave majority gate has already been investigated by numerical methods [3].

We will show spin-wave dynamics in microstructured YIG waveguides and microstructured combiner areas. In addition, we will present the fabrication and investigation of a micro-scaled spin-wave majority gate device made from a 70 nm thick YIG film.

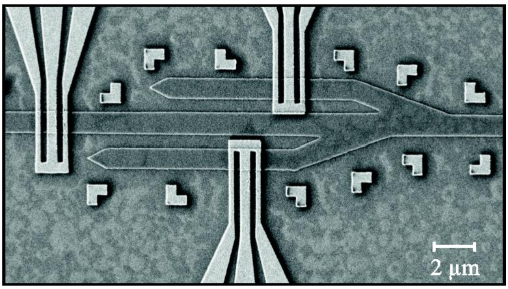

Fig. 1 : SEM picture of a microstructured spin-wave majority gate with three input antennas

This research has been supported by: DFG SFB/TRR 173 Spin+X, Project B01, ERC Starting Grant 678309 MagnonCircuit, and DFG (DU 1427/2-1).

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LOGIC DEVICES BASED ON ANTIFERROMAGNETIC GENERATORS OF ULTRA-SHORT PULSES

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KEY WORDS: antiferromagnetic spintronics, spin-Hall nano-oscillators, neuro-inspired computing

We demonstrate analytically and numerically, that a thin film of an anisotropic antiferromagnetic (AFM) material, being driven by an external spin-transfer torque signal [1-3], can be used for the generation of ultra-short "Dirac-delta-like" spikes. The duration of the generated spikes is several picoseconds for typical AFM materials, and is determined by the magnetic anisotropy and the effective damping of the AFM material. The generated output signal can consist of a single spike or a discrete group of spikes ("bursting"), which depends on the repetition (clock) rate, amplitude and shape of the external control signal. The spike generation occurs only when the amplitude of the control signal exceeds a certain threshold, similar to the action of a biological neuron in response to an external stimulus.

We modeled numerically simple circuits based on a small number of such antiferromagnetic artificial "neurons" and show, that they could perform different operations of Boolean logic, particularly AND, OR, Majority gates, and more complex functions like a Q-gate, Full-adder or a dynamic memory loop with a variable clock frequency of the pulsed signals circulating in the loop. Wherein, the designed logical circuits demonstrate high stability in respect to the deviation of the signal shape, including dispersion blur. The obtained simulation results show that the proposed antiferromagnetic artificial "neurons" could become base elements of the future ultra-fast neuromorphic computers and signal processing systems.

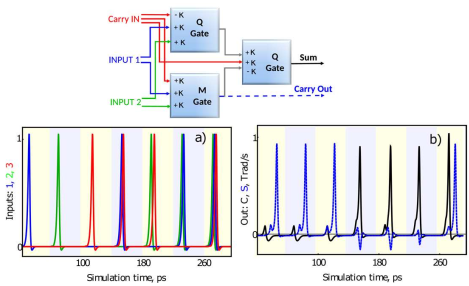

Fig. 1 : Scheme: a) input and b) output normalized signals of a Full-adder based on three AFM "neurons"

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SPIN DYNAMICS IN CoFeB/Ta/CoFeB SPIN VALVES

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KEY WORDS: Ferromagnetic Resonance, spin, spin valves, magnetic anisotropy

In magnetic CoFeB multilayers reorientation magnetic moments of the ferromagnetic layers can be achieved due to antiferromagnetic interlayer coupling [1,2].

In MgO/CoFeB/MgO/Ta and MgO/CoFeB/Ta/CoFeB/MgO/Ta spin valve the orientation dependences of ferromagnetic resonance (FMR) have been analyzed. Intense asymmetrical line was observed, the position of which depends on angle θ and corresponds to the signal from the sample (Fig. 1(a)).

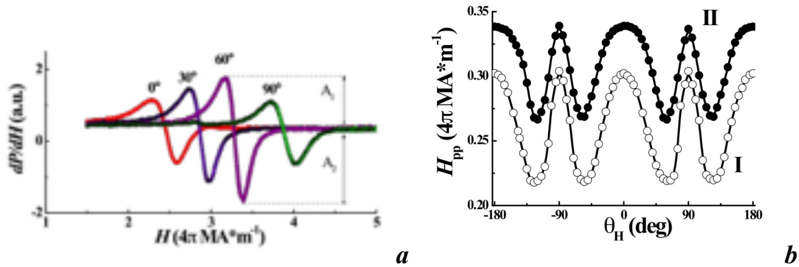

Fig. 1 : FMR spectra for CoFeB/Ta/CoFeB spin valves (a) in four orientations θ of the magnetic field H relative of the normal to the plane of the sample and the angular dependences of the resonant field H_{RES} and linewidth H_{PP} (b)

The damping factor of spin precession 0.034 exceeds the 0.004 – 0.027 range convenient for applications CoFeB in spintronics. The FMR lineshape (Fig. 1(b)) can be explained by contribution of ferromagnetic resonance Lorenz line and non resonant contribution to microwave cavity Q-factor provided by inverse spin Hall effect (ISHE) due to change of the sample conductivity.

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EXCITATIONS IN CURVATURE-INDUCED ONE-DIMENSIONAL MAGNONIC CRYSTAL

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KEY WORDS: ferromagnetic nanowire, magnonic crystal, magnetization, spin-wave, magnons

Artificial periodic structures known as metamaterials are a subject of intensive study in different fields of physics due to their advantages for control of wave propagation. In magnetism, the concept of periodic nanopatterned metamaterials is encapsulated in magnonic crystals, artificial structures with periodic distribution of the constituent materials or periodic modulation of magnetic parameters [1].They are promising for controlling and manipulating the magnon currents [2], for all-magnon data processing and used for the realization of logic operations [3].

Here we propose a concept of geometry-induced magnonic crystals using a periodically bended ferromagnetic nanowire, see Fig. 1(a). We consider a planar wave-shaped nanowire with an anisotropy of easy-tangential type. We analyze a static magnetization distribution and magnon dynamics using the recently developed approach [4] for arbitrary shaped wires describing the sample in terms of the spatially inhomogeneous distribution of curvature of amplitude κ_0. It results in two geometry-driven effective interactions: the Dzyaloshinskii-Moriya one and additional anisotropy. They lead to an in-plane deviation of the magnetization from the strictly tangential distribution. Analytically and using spin-lattice simulations we calculate the ground state of magnetization in a wide range of curvatures. As the curvature radius is reduced, the quasi-tangential ground state asymptotically approaches an easy-plane state.

The periodic structure of the ground state of the magnetization plays a role of periodic potential for magnon excitations. We analytically analyze the spin-wave spectrum in the case of small curvature using the Floquet technique and found the band gap order of κ_0^3. The magnon spectrum structure is calculated numerically in a wide range of curvatures, see Fig. 1(b).

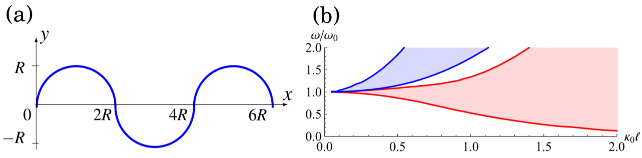

Fig. 1 : Curved ferromagnetic wire: (a) Schematic of the periodically bended wire with curvature radius $R = 1/\kappa_0$ and curvature κ_0. (b) The first two zones of the magnon spectrum of the magnonic crystal; ω is the frequency, $\omega_0 = 2\gamma_0 K_{eff}/M_s$, γ_0 is the gyromagnetic ratio, K_{eff} is the the constant of the effective easy-tangential anisotropy, M_s is the saturation magnetization, l is the magnetic length

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TEMPORAL EVOLUTION OF MAGNON SCATTERING PROCESSES IN A MAGNETIC VORTEX

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KEY WORDS: vortices, nonlinear magnons, 3-magnon scattering, BLS, micromagnetic simulation

When driven with a high-amplitude external field, magnons show nonlinear behavior. Above a certain threshold, they can take part in 3-magnon scattering processes which obey certain selection rules for the modes involved. In particular, for magnetic nano disks in the vortex state, this leads to a delicate nonlinear response. Due to the threshold behavior, 3-magnon scattering shows a strong dependence on the intensity of the scattering partners. This, in return, leads to an inherent driving power dependence and thus an effect on the time-scales of the nonlinear processes. The focus of this research is to shed light on this matter from an experimental as well as from a theoretical view.

CONTROL OF MAGNON SUPERCURRENTS BY MAGNON DENSITY

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KEY WORDS: Brillouin light scattering spectroscopy, magnonics, Bose-Einstein condensation

A room-temperature magnon Bose-Einstein condensate (BEC) can be created by parametric microwave pumping in a tangentially magnetized yttrium-iron-garnet (YIG) film. We study the condensate by means of time-resolved Brillouin light scattering spectroscopy (BLS). By heating the sample, a spatially variation of the saturation magnetization is induced, which leads to a change of the magnon frequencies across the heated film. Because the magnon condensate is coherent across the entire heated area, a spatial varying phase shift is imprinted into its wave function. The spatial phase gradient generates a magnon supercurrent flowing out of the probing point. The earlier evidence of these supercurrents was obtained by an observation of the different relaxation behaviors of the magnon BEC under different heating conditions. Here, we are using the one- dimensional supercurrent transport as a measure of the coherency of the system. The dependence of the supercurrent formation on the magnon density is investigated.

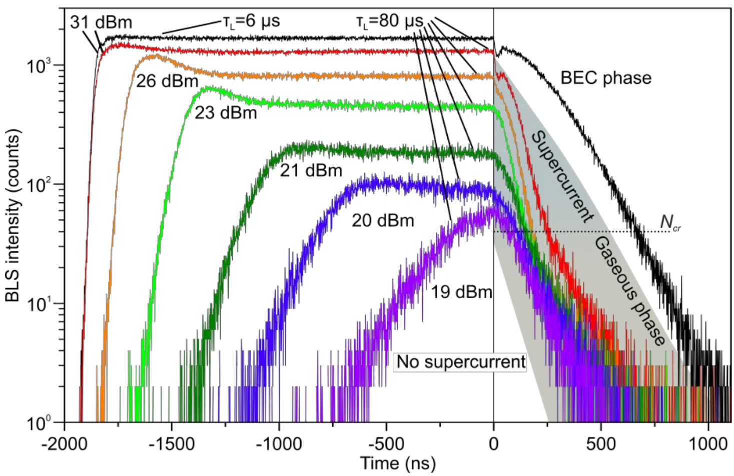

Fig. 1 : The top waveform corresponds to the case of a weakly heated YIG sample and, therefore, is not affected by a supercurrent magnon outflow. This also means, that a distinction between the BEC and gaseous phases isn't possible. In all other cases the non-uniform heating of the YIG sample creates a magnon supercurrent and, therefore, a higher decay rate of the magnons in the BEC phase is observed. This effective decay rate falls with the pumping power. Below a critical magnon density, which characterizes the transition from the coherent BEC phase to the incoherent gaseous magnon phase, the decay rate is the same for all cases

LONGITUDINAL MAGNETIZATION DYNAMICS IN THE HEISENBERG ANTIFERROMAGNET

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KEY WORDS: longitudinal magnetization dynamics, the Heisenberg antiferromagnet

In spite of the fact that dynamical properties of magnets have been extensively studied over the past years, the longitudinal magnetization dynamics is still much less understood than transverse one even in the equilibrium state of a system. Dynamical properties of an antiferromagnet essentially differ from those of ferromagnet and ferrimagnet because of the magnetic order nature. In particular, the longitudinal dynamics for an antiferromagnet has not been still investigated theoretically in such details as a ferromagnet or a ferrimagnet.

In this report, within a spin Green functions diagrammatic approach, we consider the longitudinal magnetization dynamics for antiferromagnetic dielectrics. It is shown that, in general, there are two virtual processes that determine the longitudinal energy spectrum and the longitudinal susceptibility: (i) absorption of one transverse magnon and excitation of another one, and (ii) two transverse magnon excitation/absorption. The first channel is controlled by the thermal occupation factor of magnons. This makes the spin waves with wave vector k 0 to be dominant ones. The frequency of this longitudinal spin excitations lies energetically below the transverse spin wave frequency at the same temperature and wave vector. The frequency of the second longitudinal spin excitations lies energetically above the transverse spin wave frequency. This channel remains in force even in the absence of thermal excitations. The overall scattering weight of the simultaneous creation/annihilation of two magnons is proportional to the zero-point longitudinal quantum fluctuations in the ground state.

We hope that understanding of the longitudinal magnetization dynamics features in the equilibrium state is to be a reference point for a theory that uncover the physical mechanisms underlies ultrafast demagnetization after femtosecond laser pulses.

This work is partly supported by the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie (project No. 644348).

TOWARDS ANALYTICAL THEORY OF EDGE SPIN WAVE MODES IN IN-PLANE MAGNETISED MAGNETIC NANO-ELEMENTS

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KEY WORDS: spin waves, magnonics, edge modes, confinement

It is widely known that the spin wave dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, the latter including both the internal magnetic field and magnetisation. In fact, spin waves are rarely observed to propagate in uniform media. Inspired by and feeding from other fields of wave physics, we have recently formulated the concept of graded-index magnonics as a unifying theme focusing on general aspects of spin wave excitation and propagation in media with continuously non-uniform properties – the graded magnonic index. Davies et al. suggested the graded profile of the so called local ferromagnetic resonance (FMR) frequency as a powerful tool by which to predict the character of spin wave emission in patterned magnetic structures excited by a uniform microwave magnetic field [1]. Here, we have tested the ability of the local FMR frequency concept to aid interpretation of the spin wave normal modes in square nanomagnets with nonuniform ground states [2]. We have found that, while offering some insights into the frequency of the quasi-uniform spin wave modes, the concept fails to predict or describe the edge spin wave modes confined in the demagnetised regions of the nanoelements. To describe the latter modes, we have developed an analytical theory based on that proposed by Bailleul et al. [3] and adopting exact solutions presented by Downing [4]. The predictions of our theory for the frequency and profile of the edge modes compare favourably with the results of dynamic micromagnetic simulations for the same static micromagnetic configurations.

The research leading to these results has received funding from the Engineering and Physical Sciences Research Council of the United Kingdom Project No. EP/L019876/1 and from the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie Grant Agreement No. 644348 (MagIC).

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COLLECTIVE MODES OF A BUBBLE DOMAIN LATTICE TRAPPED WITHIN A LATTICE OF ANTIDOTS

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KEY WORDS: micromagnetic simulation, bubble domains, magnonic crystal, antidot

Magnonic crystals, (MCs) are periodically patterned magnetic media which can be utilised to control the propagation of spin waves, for instance by opening band gaps in the dispersion via Bragg reflection. They are considered a key component in future magnonic information technologies. Recent research is focussed on increasing the functionality of MCs and we investigate the utility of the collective modes of a bubble domain lattice, stabilised and confined within an array of antidots (Fig. 1).

We use micromagnetic simulations to calculate the band structure and mode profiles of collective excitations and observe that the width of bands formed from different modes of an isolated bubble domain decreases dramatically as the mode number increases, with only the band associated with the m=0 "breathing" mode showing a significant group velocity. The decaying group velocity of higher order modes curtails their use for the transport of information.

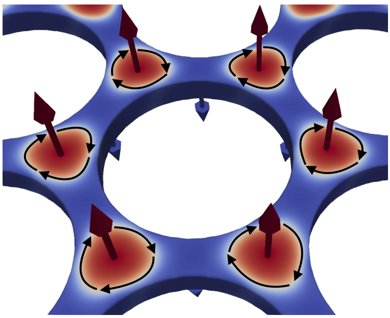

Fig. 1 : The bubble domain lattice. The red and blue colour intensities scale with the out-of-plane component of the magnetisation. The arrows show the magnetisation's orientations and circulation directions within domains and domain walls, respectively

This research has received funding from the Engineering and Physical Sciences Research Council of the United Kingdom, via the center for Doctoral Training in Metamaterials XM2, and from the European Union's Horizon 2020 Marie Skłodowska-Curie project No. 644348 (MagIC).

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INELASTIC SPIN WAVE SCATTERING BY DOMAIN WALL OSCILLATIONS IN THIN MAGNETIC FILM

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Spin wave (SW) propagation in inhomogeneously magnetized magnetic films, magnetic stripes and artificial magnetic periodic nanostructures (magnonic crystals) is the subject of intensive theoretical and experimental investigations because of promising applications of such magnetic structures in spintronic and magnonic devices [1]. Usually, the propagation of SW through static and/or pinned domains [2] and SW emission by oscillating domain wall (DW) [3] is studied. However, it is well known that some flexure oscillations of the domain wall shape exist in DW and they can be represented as specific SW localized at the DW plane [4]. The DW oscillation modes can interact with SWs resulting in an inelastic scattering of SWs by the DW modes or excitations of the DW modes by SWs. These inelastic scattering processes are characterized by three magnetic excitation modes interaction [5].

In this communication, we consider the scattering of SWs by DW oscillations in magnetic film with a single Bloch DW. We investigate an angular dependence of the scattered SW modulated by the DW oscillations and present a numerical estimation of expected effect.

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NON-UNIFORM SOFTENING OF SPIN WAVES IN TWO-DIMENSIONAL MAGNONIC CRYSTALS AS A TOOL FOR A REVERSIBLE TUNING OF OMNIDIRECTIONAL BAND GAPS

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KEY WORDS: magnonic crystals, magnonic gaps, spin waves

The change of the external magnetic field at low fields leads to the non-uniform shift of spin waves (SWs) frequencies [1,2]. The non-uniformity refers to two different effects: different shift for different modes and/or k-dependent shift within the single mode. In this work, we study the mechanisms of both types of non-uniform shift in two-dimensional (2D) magnonic crystals (MCs). We address these features to the growing influence of the demagnetizing field combined with the spin wave profile of the mode. We show that the non-uniform mode softening can be utilized to the reversible control of band gaps just by changing of the external magnetic field magnitude. We propose 2D MCs, with the structure feasible for the experimental realization with the current technology, for which the SW spectrum exhibits omnidirectional band gaps with a different sensitivity of the gap width to the external field magnitude.

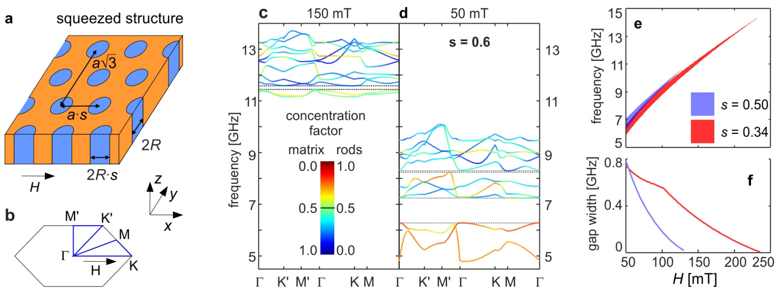

Fig. 1 : (a) 2D MC based on the hexagonal lattice squeezed in the direction of the external field H by the structure ratio s. (b) The FBZ for the squeezed structure. (c, d) Spin wave spectra for Co/Py 2D MCs over the high symmetry path in the FBZ for $s = 0.6$ and two values of H. Line colors depict concentration factor according to the color scale shown in the inset. Dotted horizontal lines represent bounds of the complete magnonic gaps. (e) Omnidirectional gaps vs. H for two values of s. (f) The dependence of the gap width on H for both gaps shown in (e)

Financial support: the EU's Horizon 2020 RISE GA No. 644348 (MagIC), the Polish Ministry of Science and Higher Education resources for science in 2017-2019 granted for the realization of an international co-financed project (W28/H2020/2017), and the National Science Centre of Poland under grant No. UMO-2016/21/B/ST3/00452.

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SPIN WAVE DYNAMICS IN ARTIFICIAL ANTI-SPIN-ICE SYSTEMS

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KEY WORDS: anti spin ice, spin-wave spectrum, band gaps

Reversed structures of artificial spin-ice, where elongated holes (antidots) are arranged into a square array, are referred to as anti squared spin-ice (ASSI). Using the Brillouin light scattering spectroscopy and the plane wave method, we investigate the spin wave (SW) propagation perpendicular to the applied field direction for two 20 nm thick Permalloy nanostructures with single and double elliptical antidots. For the SW propagation along the principal antidot lattice axis, the spectrum consists of flat bands separated by several frequency gaps which are the effect of the SW amplitude confinement in regions between antidots. For 45° propagation straight and narrow propagation channels are formed, leading to broadening of bands and closing of gaps. In this case, extra band gaps occur due to the additional periodicity along this direction. The width and the position of these gaps depend on the presence of single or double antidots. In this context, we discuss possibilities for the tuning of SW spectra in ASSI structures [1].

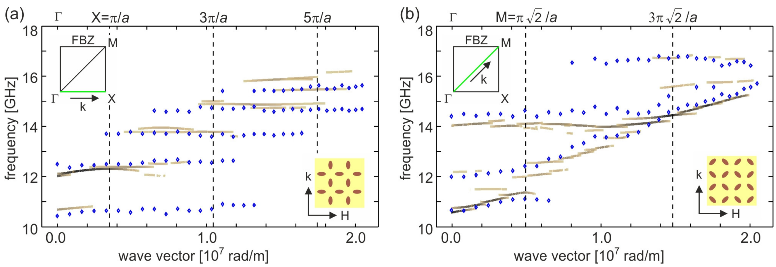

Fig. 1 : Frequency dispersion for the ASSI along the direction shown in the insets for (a) $\phi = 0^\circ$ and (b) $\phi = 45^\circ$, where ϕ is the angle between the external field H and the crystallographic axis of the ASSI. Brown lines mark BLS intensity calculated by means of PWM (darker color means higher intensity) and blue diamonds represent experimental data. Borders of the successive Brillouin zones are drawn as vertical dashed lines

Financial support: the EU's Horizon 2020 RISE GA No. 644348 (MagIC), the National Science Centre of Poland under grant No. UMO-2016/21/B/ST3/00452, and the Ministry of Education Singapore under research Project No. R-263-000-C61-112. A.O.A. is a member of Singapore Spintronics Consortium (SG-SPIN).

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ESTIMATION OF THE EXCHANGE STIFFNESS CONSTANT BY USING BACKSCATTERING MAGNON MODE

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KEY WORDS: exchange stiffness, spin wave, surface spin wave, backscattered magnon mode

Brillouin light scattering (BLS) measurements were performed in the backscattering geometry on a Bi-substituted rare earth iron garnet as shown in Fig. 1(a). Fig. 1(b) shows the observed two different peaks, one attributed to a surface spin wave in the dipole-exchange regime. The other is referred to as a backscattering magnon (BSM) [1] mode, because the incident light in this case is scattered backward by exchange-dominated spin wave inside the material.

The fitting using the dispersion of spin waves enables us to obtain the exchange stiffness constant as a fitting parameter. In the poster, we propose a method to estimate the exchange stiffness constant from the frequency of the backscattering magnon mode. The obtained value is comparable with the previously reported values for $Y_3Fe_5O_{12}$ [2] which has the same structure as our sample.

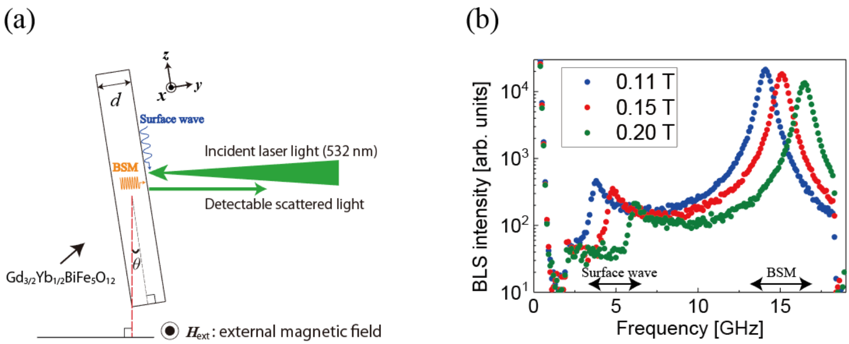

Fig. 1 : (a) The experimental geometry. Surface wave and BSM scatters the incident light backward. (b) The observed BLS signals when the external field is 0.11, 0.15, 0.20 T. Two different signals were found to be the surface wave and BSM, respectively.

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ULTRA-HIGH MAGNETISATION DYNAMICS IN HOLLOW FERROMAGNETIC PARTICLES

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KEY WORDS: magnetisation dynamics hollow nanomagnet chiral symmetry breaking

Three-dimensional (3D) magnetic nanostructures have attracted significant interest in recent years, stemming from advances in the synthesis and characterization of magnetic samples of the nano- and micrometer size range [1,2]. Curvature in nanomagnets brings about an effective exchange-driven anisotropy and an effective Dzyaloshinskii-Moriya interaction (DMI) [3] giving rise to chiral magnetic structures and handedness in the magnetisation. Recently, it has been shown that domain walls with an axial configuration in nanotubes can beat the Walker limit due to a break in the chiral symmetry resulting from the curved surface [4].

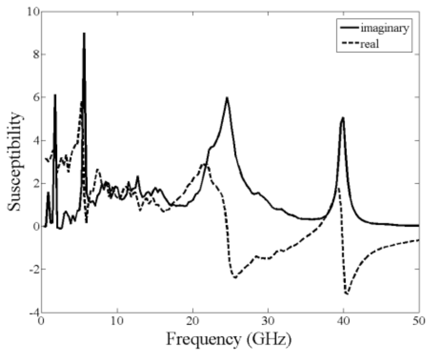

Fig. 1 : Dynamic susceptibility of a ferromagnetic nanotube with outer radius 400 nm and $R_1 / R_2 = 0.3$, where R_1 and R_2 are the inner and outer radii, respectively

Here, we investigate the role of chiral effects in the high-frequency dynamic susceptibility of hollow nanomagnets (nanotubes, shells and toroids) (see Fig. 1). We show that intensive resonances can be excited up to frequencies of 40-45 GHz in all of these particles (in the absence of an external DC field), in addition to broad resonances across the 20-30 GHz frequency band.

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ULTRA-LOW LOSSES YIG MAGNONIC CRYSTAL

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KEY WORDS: magnonic crystal, YIG, propagating spin-wave spectroscopy

Here we report on a S-parameter characterization of a series of 23 nm-thick YIG magnonic crystals (MC) using propagating spin wave spectroscopy. The MC is obtained by etching 150nm-wide, periodically spaced grooves. Thickness modulation is expected to improve the filtering efficiency and insertion losses compared to width-modulated MC [1]. The studied system (inset Fig. 1) is composed of 50 parallel 2.5 µm-wide wave-guides designed on a PLD-grown YIG film. The 150 nm wide periodic grooves, orthogonal to the waveguides principal axis, corresponds to a Bragg k-vector of 1 μm^{-1}, the depth of the grooves is incremented from 0 to 23 nm in 6 successive steps.

The spectrum of mutual inductance due to the propagation of Damon-Eshbach spin waves is recorded over a frequency range between 0.5 and 2.5 GHz, at various magnetic fields. A first measure of this spectra is performed on the waveguide without grooves and is found to be in a good agreement with theoretical expectations for magnetic fields up to 20 mT. Within the same field range, we then measure the mutual inductance after etching, for the same magnonic crystals, having now grooves depth greater than 5 nm. An example of successful filtering at 1.4 GHz obtained for a field $\mu_0 H = 11.5$ mT is shown in Fig. 1. A 15 MHz transmission gap is observed corresponding to a decrease by a factor of 5 of the spin wave intensity at 30 µm from the antenna when compared to the reference waveguide. Importantly, we also find that the transmission outside the frequency gap is weakly affected by the presence of the periodic grooves, even when we fully etch our waveguides.

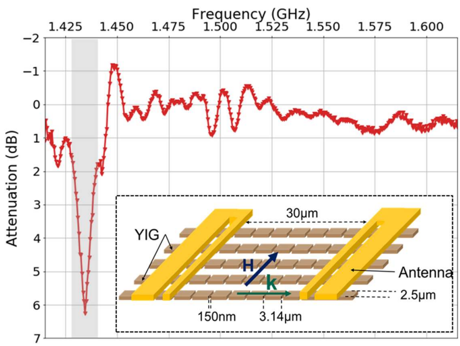

Fig. 1 : Spectrum of the attenuation of the spin-waves-induced mutual inductance for a MC with 8 nm grooves compared to the reference, showing a 15 MHz gap (shaded area) for an applied field of 115 Oe. Inset: Sketch of the studied system

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DEVELOPMENT OF MAGNETIC VORTEX-BASED TRANSISTOR AND LOGIC CIRCUIT

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KEY WORDS: magnetic vortex transistor, vortex core gyration, antivortex soliton, logic operation, micromagnetic simulation

Ferromagnetic micro- and nanodiscs with a spin-vortex ground state shows interesting dynamics leading towards its applications in various spintronics devices. Here, we have numerically demonstrated enhanced amplification of the gain in a magnetic vortex transistor (MVT) [1] achieved by introducing geometrical asymmetry in a three vortex sequence. The asymmetric MVT [2] is constructed by optimizing the inter-vortex separations (S1 = 10 nm, S2 = 100 nm) of $Ni_{80}Fe_{20}$ disks (200 nm diameter and 40 nm thickness, polarity combination 1,-1,-1) placed in a row (see Fig. 1). After excitation of the dynamics of input vortex, a cascade of antivortex solitons travels through the dynamic stray field in different trajectories. This offers significant amplification of core gyration amplitude (28.28 dB in terms of energy spectral density) at the output vortex [2]. This transistor unit is further used for a successful fan-out operation, which provides nearly equal gains in two output branches of an integrated network.

Exploiting the asymmetric nature of the energy transfer mechanism by antivortex solitons, we have shown successful fan-in operation. A tri-state buffer gate with fan-in of two AMVTs can be formed. The loss (0) and gain (1) of energy at the output vortex can be controlled only by manipulating the polarities of the middle vortices in four different combinations as (1,-1), (-1,-1), (-1, 1) and (1, 1) placed at input branches. This gate can be used as a "switch" to the logic circuit and it has technological importance for energy transfer to large scale vortex networks. With the rapid advancement of memory devices we hope that our findings will accelerate the development of all-magnetic computation.

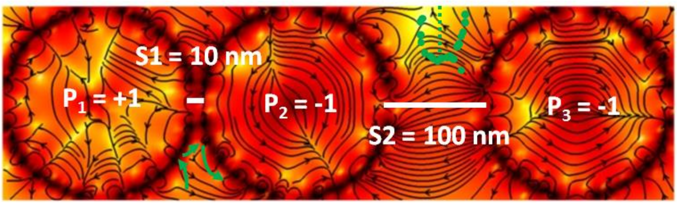

Fig. 1 : Strayfield distributions for asymmetric MVT. The green dots/lines represent the trajectories of the antivortex solitons

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SPINWAVES EXCITATION BY SPATIALLY AND TEMPORALLY SHAPED FS-LASER PULSES IN NiFe THIN FILMS STUDIED USING BRILLOUIN LIGHT SCATTERING MICROSCOPY

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KEY WORDS: magnetization dynamics, high rep-rate laser pulses and spin waves

Optical manipulation of the magnetization of magnetic thin films is a promising route towards ultrafast magnetic switching and information transfer from light to spin waves (SWs). Very recently it has been shown that propagating SWs can be excited and quantified using an all-optical pump-probe method [1]. However, to excite high amplitude sustained SWs, a train of light pulses with very short time interval is needed. So far, there is very little literature addressing the SWs excited by highly repetitive train of light pulses [2]. Optical pump-probe measurements have been primarily based on Magneto-Optical Kerr Effect (MOKE) microscopy. Instead, here we report on the effect of a high repetition-rate train of ultrashort optical pulses on the SW spectrum of magnetic thin films. Using the μ-focused Brillouin light scattering (BLS) technique to investigate the optically excited spin dynamics have much higher sensitivity and provide detailed information on both coherent and non-coherent excitations of the SWs. Where, in addition to the μ-BLS green laser (532 nm), we incorporate femtosecond laser pulses of 800 nm and high repetition rate of 1 GHz as a pump.

We show that for a thin magnetic film, such as NiFe, a substantial enhancement of the thermal SW amplitudes can be observed at frequencies that coincide with the harmonics of the repetition rate of the laser pulses (see Fig. 1).

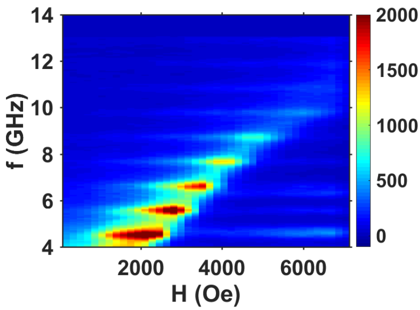

Fig. 1 : Intensity map of BLS signal at different applied field values on NiFe thin film sample

Our results clearly indicate that it is possible to excite SWs of high amplitudes using a high-repetition-rate femtosecond laser. Further spatial and temporal modulation of the pump laser is investigated to study the tunability of the spin waves in thin magnetic films.

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UNCONVENTIONAL SPIN CURRENTS IN MAGNETIC FILMS

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KEY WORDS: spin wave, spin-wave energy, spin-wave angular momentum, spin current, magnetic film, Brillouin light scattering spectroscopy, dipole-exchange spin-wave spectrum

A flow of the spin angular momentum, referred to as a spin current [1], can be carried either by spin-polarized free electrons or by magnons, the quanta of a moving collective oscillation of localized electron spins – a spin wave. Traditionally, it is assumed that a spin wave in a free magnetic film transfers energy and angular momentum only along its propagation direction [2]. In this work, we show that in an obliquely magnetized film the transverse profiles of in-plane-propagating dipole- exchange spin waves are only quasi-standing and, thus, allow for the transport of spin angular momentum along the film normal, although they abstain from a net transport of energy. This finding are proved using the Brillouin light scattering spectroscopy as an experimental technique and Slavin-Kalinikos' theory of dipole-exchange spin-wave spectra [3] as a theoretical model. Thus, our results demonstrate that the transport of spin-wave energy and spin angular momentum can be decoupled, and a transverse spin current can be realized in obliquely magnetized films of different thicknesses.

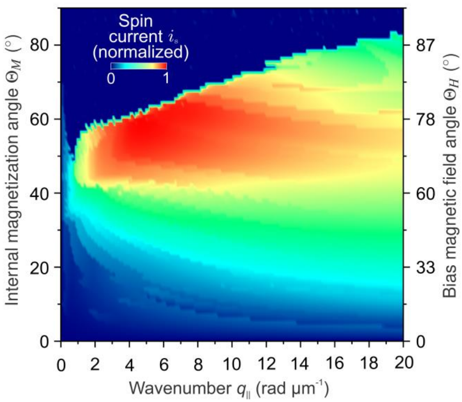

Fig. 1 : Intensity of a spin current i_S calculated as a function of the in-plane wavenumber and magnetization angle for the modes with quasi-uniform distribution across the thickness of the film

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EXCITATION AND CONFINEMENT OF SPIN WAVE MODES IN ARRAYS OF COBALT MICROSTRIPES FORMED ON A PERMALLOY UNDERLAYER

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KEY WORDS: FMR, patterned magnetic structures, spectrum

We present ferromagnetic resonance measurements and theoretical description of standing spin-wave modes in arrays of long thin film cobalt microstripes formed on thin permalloy films.

The measurements were performed at microwave frequency of 9.92 GHz while the swept bias magnetic field H was applied in the plane of the sample at various orientations relative to the symmetry axes of the stripes. The value of H was large enough to saturate both cobalt and permalloy magnetic subsystems at sufficiently large distances from the stripe edges. Up to four different spin wave modes were identified from the experiments and classified as belonging to two series, using their resonance field values and their dependence on the bias field orientation.

The first of the two series ("cobalt modes") included modes with resonance fields that had an angular dependence typical for the easy-axis shape anisotropy of magneto-dipole origin expected for long stripes. Their resonance fields increased as the bias field orientation varied from that along the stripe length to that parallel to the stripe width. The second series included "permalloy modes", which had generally higher resonance fields. The angular dependence of the resonance field of the strongest permalloy mode was the same as that of the cobalt modes. However, its lower field satellite had an opposite angular dependence, i.e. its resonance field decreased as the bias field orientation varied from that along the stripe length to that parallel to the stripe width.

The angular dependence of the permalloy modes is explained in terms of that of the stray magnetic field created by the magnetic charges formed at the edges of the cobalt stripes. The stray field increases/decreases the internal field in the permalloy film between/under the cobalt stripes.

This interpretation is corroborated by the results of micromagnetic simulations and analytical theory. The discovered modulation of the internal magnetic field induced by the stripe array in the permalloy film is also periodic, which can be exploited to create magnonic crystals without physical patterning of the magnetic film used as a medium for spin wave propagation.

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1 and EP/P505526/1) and from the EU's Horizon 2020 research and innovation program under Marie Skłodowska-Curie GA No. 644348 (MagIC).

ENHANCEMENT OF THE SPIN PUMPING EFFECT BY THE TWO- MAGNON CONFLUENCE PROCESS IN YIG-Pt BILAYERS

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KEY WORDS: ISHE, spin pumping, parallel parametric pumping, two magnon confluence

Magnon spin currents are seen as a promising alternative to electrical charge currents for the transport and processing of information. Besides magnon-based elements operating with analogous and digital data, the field of modern magnon spintronics crucially depends on the progress in developing of effective converters between the magnon subsystem and the electron- carried spin and charge currents. This task is especially challenging in a case of short-wavelength exchange magnons, which application is promising for the miniaturization of magnonic devices. In Platinum (Pt) covered magnetic insulators such as Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$) films, combined action of the inverse spin-Hall effect (ISHE) and the spin-pumping (SP) effect constitutes an important mechanism allowing for the detection of this kind of magnons: Here, we present our studies on the efficiency of spin pumping in in-plane magnetized Pt-covered YIG films of different thicknesses. In our time-resolved field-dependent measurements of the ISHE- voltage, it has been found that at the given pumping frequencies of $f_p = 14.45$ GHz and $f_p = 17.09$ GHz a clearly visible sharp voltage peak appears at bias magnetic fields of approximately 100 mT and 130 mT. These peaks can be related to the confluence of two parametrically excited magnons with frequencies $f_p/2$ and wavevectors k_p into one magnon (f_p, $2k_p$).

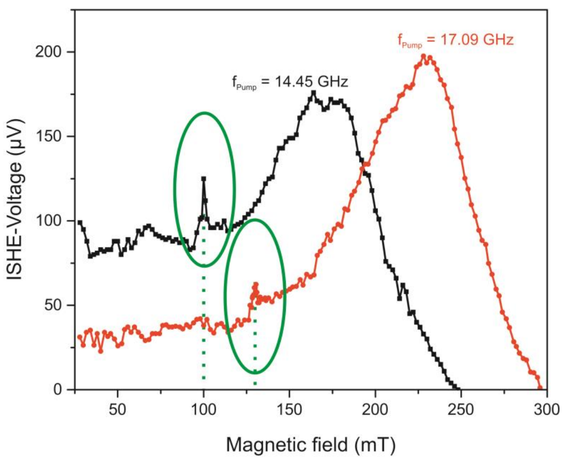

Fig. 1 : Measured inverse spin-Hall-voltage in dependence on the applied bias magnetic field. The indicated sharp enhancement of the voltage is originated to the two magnon confluence process.

EXCITATION OF DOMAIN WALLS IN UNIAXIAL ANTIFERROMAGNETS BY SPIN CURRENT

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KEY WORDS: antiferromagnetism, magnetic solitons, spintronics

It has recently been proposed to use antiferromagnets (AFM) as active layers of spin-torque nano-oscillators (STNO) due to their ability to operate at high frequencies, up to the THz range. In an AFM-based STNO the spin current induces a torque on the Neel vector. It is rather difficult to excite the auto-oscillations in the case of an easy-axis anisotropy in AFM, because a spin torque must overcome a high potential barrier created by the anisotropy field that, in turn, requires substantially high values of the electrical current density.

To overcome the above problem, STNO can be based on spin textures in the easy-axis AFM, such as domain walls (DW), located directly under the source of spin current (see Fig. 1). The use of DW has several advantages: AFM DW have a precessional solution (forbidden for ferromagnets), they are topologically stable and easy to control with an external magnetic field.

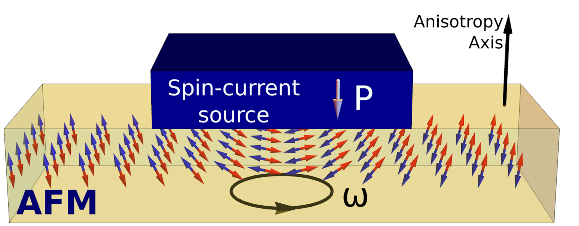

Fig. 1 : The scheme of the STNO based on the DW in AFM with easy-axis anisotropy. The spins of the antiferromagnet sublattices are shown by the blue and red arrows, while their precession under the action of STT – by a black arrowed circle

We show that the spin current, with the out-of-plane polarization excites precession of the Neel vector in such a DW. The excitation of the auto-oscillations does not have a threshold in applied current for pure uniaxial AFM. The frequency of the Neel vector precession is proportional to the driving current and, thus, is easily tunable in the range $(0..\omega_{AFMR})$, where ω_{AFMR} is the frequency of antiferromagnetic resonance, which can reach the THz range.

Spin current with the in-plane polarization creates the translational viscous motion of the DW, the velocity of which can be additionally controlled by the component with the out-of-plane polarization. Above a certain threshold the out-of-plane polarized current leads to oscillations of the domain wall around the equilibrium position.

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SPIN MEMORY LOSS IN MAGNETICALLY ORDERED Pt BY PROXIMITY EFFECT

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KEY WORDS: spin memory loss, spin pumping, interlayer exchange coupling, FMR

We report on a study of spin pumping, spin diffusion and spin-loss in magnetically ordered Pt due to proximity to a ferromagnet. By means of ferromagnetic resonance we extract a Pt thickness (d_{Pt}) dependent damping of the acoustic resonance [1] of Py | Pt(d_{Pt}) | [Py | Fe], where $0 < d_{Pt} < 2.2$ nm, see Fig. 1 below. For $d_{Pt} < 1.5$ nm there is significant ferromagnetic coupling between the two magnetic layers, Py and [Py | Fe], which is originating from proximity induced magnetization in Pt [2]. The magnetic moment of Pt is decaying exponentially on a length scale of $\varepsilon = 0.3$ nm. This structure presents a unique system in which, spin pumping, spin diffusion, spin-loss and proximity magnetization all have significant contributions to the total damping. To make a unique interpretation, we also study the damping of Py | Pt and compare it to result in Fig. 1(b). We conclude that to have self-consistent results for magnetic damping in both Py | Pt and Py | Pt | [Py | Fe] structures, spin-loss must be developing with thickness on a length scale of ~0.3 nm. Importantly, this is the same length as the decay of exchange coupling, suggesting a connection between the two mechanisms.

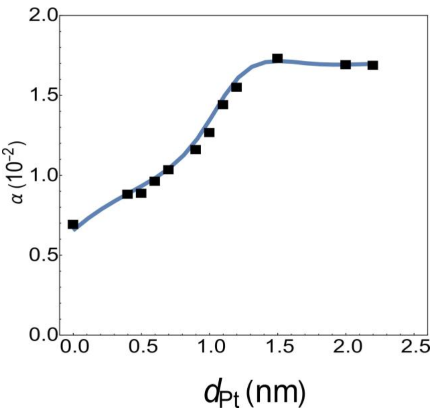

Fig. 1 : Effective damping of the acoustic mode of Py | Py(d_{Pt}) | [Py | Fe]. The solid line represents the best fitting model which includes exchange coupling, spin pumping, spin diffusion and spin-loss

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ULTRAFAST MAGNETIZATION DYNAMICS IN HIGH MAGNETIC FIELDS

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KEY WORDS: ultrafast spectroscopy, magnetic dynamics, ferrimagnets, compensation point, high magnetic fields

The idea to change properties of media with the help of light has been intriguing people for a long time. Recently it was demonstrated that the laser induced ultrafast spin dynamics in ferrimagnetic GdFeCo can be dramatically influenced by the application of high magnetic fields. It was observed that across a critical field called the spin-flop field, the material shows distinct spin dynamics. The underlying mechanism was attributed to the spin dynamics associated with the two-different magnetic sublattices. However, these measurements were sensitive only to the iron magnetic sublattice. It has already been shown that, one can element specifically probe in the visible spectral range, the laser triggered spin dynamics in the ferrimagnetic TbFeCo. In this work we therefore consider TbFeCo to study the ultrafast spin dynamics associated with the individual magnetic sublattices across the spin-flop transition.

In our experiment, TbFeCo with out-of-plane magnetic anisotropy was studied in an out-of-plane magnetic field up to 28 T. Our study reveals anomalous hysteresis loops and strong field-dependence of the laser-induced dynamics in the vicinity of the compensation point in this ferrimagnet. In particular, the experiment shows that applying fields weaker than the exchange interaction between Tb and Fe, both sublattices show fast spin dynamics ($\approx$ 200 fs), associated with laser-induced demagnetization. If the field is strong enough to trigger a spin-flop transition ($\approx$ 13 T), both the sublattices show a dramatic slowing down of the spin dynamics. Here we explain these observations as manifestations of the first and second order phase transitions in this ferrimagnet.

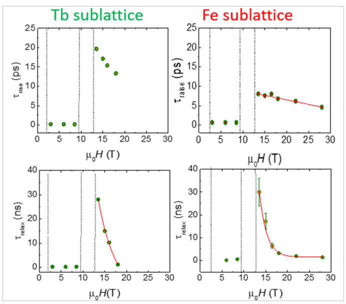

Fig. 1 : The raise time and the relaxation time of time-resolved magnetooptical Kerr effect, measure on Tb and Fe sublattices

INTER-VORTEX DISSIPATION IN FERROMAGNETS

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KEY WORDS: vortices, ferromagnets, solitons, drag

We derive viscous forces for vortices in a thin-film ferromagnet. The viscous force acting on vortex i is a linear superposition $\mathbf{F}_i = -\sum_j \hat{D}_{ij}\mathbf{V}_j$, where $\mathbf{V}_j$ is the velocity of vortex j. Due to the long-range nature of vortices, the mutual drag tensor $\hat{D}_{ij}$ is comparable in magnitude to the coefficient of self-drag D_{ii} . Two vortices with winding q_i, q_j separated by distance R_{ij} have mutual drag coefficients $D_{ij} \propto q_i q_j \ln(R_D/R_{ij})$, where R_D is the system size. This logarithmic dependence on vortex separation indicates that there may be non-trivial dissipative scaling in systems of many vortices. These results call for fundamental investigations into the spin-wave mediated long-range interactions between vortices.

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BULK SPIN WAVE SCATTERING ON A SURFACE OF SPHERICAL SPIN LENS

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KEY WORDS: exchange interaction, uniaxial anisotropy, saturation magnetization, spin wave reflection

We theoretically consider a spin dynamics process in a ferromagnetic structure having the form of spherical lens and located in infinite ferromagnetic medium that have parameters of exchange interaction, uniaxial magnetic anisotropy and saturation magnetization different from the material of a lens.

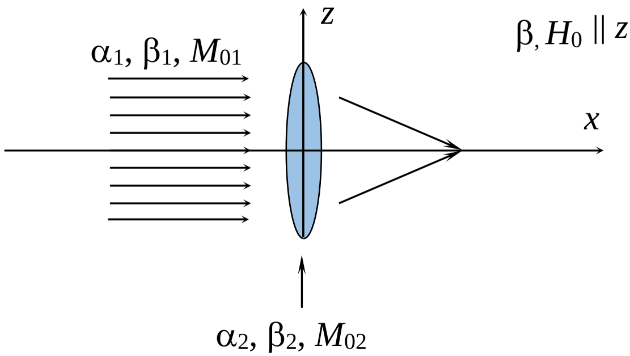

Fig. 1 : The model of spherical spin lens

In exchange mode, we find the refraction index of spin waves on boundaries of such lens as a ratio of corresponding wave numbers. Focal length of lens is also calculated.

The spin wave reflection amplitude is written on a boundary of two ferromagnetic media as a function of frequency, external permanent magnetic field and incident angle. The reflection coefficient of spin waves on a spherical surface is calculated as a ratio of angle-integrated intensity of reflected wave to intensity of incident one taking into account the radius of curvature of a spherical surface. The reflection coefficients for spherical and plane surfaces are compared for various values of frequency, external permanent magnetic field and curvature radii. System parameters ranges are found which gives essential/omissible difference between reflecting abilities of spherical and plane interfaces. The dependencies of reflection coefficients on spin wave frequency and magnetic field are also calculated. It is found the region of sharp change of reflection coefficients with frequency or magnetic field.

OPTIMIZATION OF SPINTRONIC THz EMITTERS BASED ON THE CRYSTAL STRUCTURE

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KEY WORDS: spintronic THz emitters, crystal structure

We demonstrated the generation of pulsed broadband terahertz radiation utilizing the inverse spin Hall effect in Fe/Pt bilayers on MgO substrates. The spintronic emitter provided a bandwith of up to 8 THz mainly limited by the LT-GaAS photoconductive antenna used as detector and by the pulse length of the pump laser. The THz pulse length was as short as 220 fs for a sub 100 fs pulse length of the pump laser. The metallic layers where optimized with respect to layer thickness and geometrical arrangement. The experimentally determined optimum layer thicknesses were in qualitative agreement with simulations of the spin current induced in the Fe layer. Our model takes into account the generation of spin polarization, spin diffusion and accumulation in Fe and Pt and electrical as well as optical properties of the emitters [1].

Further exploring the efficiency of THz spintronic emitters, we find significant differences in the efficiency for emitters with epitaxial and polycrystalline grown layers. Additionally, we are able to distinguish epitaxially grown bilayers of varying quality by their THz emission (see Fig. 1). These experimental results are quantified by simulations of the laser induced spin current in Pt with respect to the crystal structure of Pt.

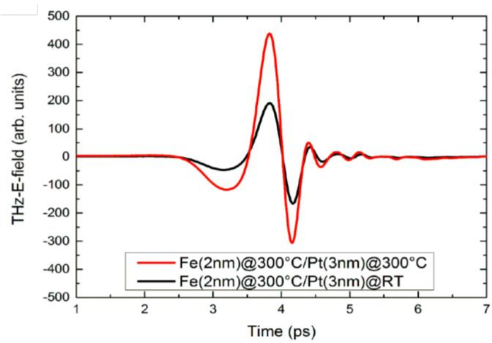

Fig. 1 : THz amplitude of epitaxially grown Fe(2nm)/Pt(3nm) emitters of different Pt quality (attained by different growth temperatures)

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BOSE-EINSTEIN CONDENSATION OF MAGNONS BY RAPID COOLING

M. Schneider[1], T. Brächer[1], V. Lauer[1], P. Pirro[1], A. A. Serga[1], B. Heinz[1,4], Q. Wang[1], D. Bozhko[1], H. Musiienko-Shmarova[1], T. Meyer[1], F. Heussner[1], S. Keller[1], B. Lägel[1], T. Löber[1], V. Tyberkevych[2], A. N. Slavin[2], C. Dubs[3], B. Hillebrands[1], A. V. Chumak[1]

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KEY WORDS: Bose-Einstein condensation, nano-structures, YIG, cooling

Recently the formation of magnon Bose-Einstein Condensates (BEC) in extended films attracted large attention [1,2]. In previous studies the conditions for the formation of the BEC are artificially created by parametric pumping [3]. Here we present a fundamentally new approach. Fast DC current pulses applied to yttrium-iron-garnet (YIG)/Pt microstructures result in a strong heating. Consequently, this leads to an increased number of magnons, distributed over the whole spectrum. Once the current is switched off, the locally heated, micro-sized system cools down rapidly. Hence, the magnon and the phonon system are driven out of equilibrium, which results in a redistribution of high frequency magnons to the bottom of the spin-wave spectrum due to four-magnon scattering processes and viscous damping. A strong increase of the magnon density at the bottom of the spectrum is observed using time-resolved Brillouin light scattering microscopy (see Fig. 1). A theoretical model is developed, which describes the redistribution of magnons. This results in an increase of the chemical potential up to the bottom of the spin-wave band. Our experiment shows that the BEC formation depends on the magnon temperature and the timescale of the cooling process.

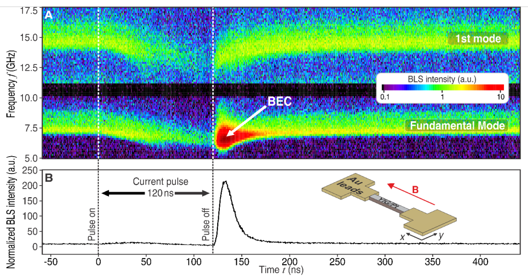

Fig. 1 : Time resolved BLS spectrum, the fundamental mode at a frequency of 7.5 GHz and the first perpendicular standing spin wave at a frequency of 15.0 GHz are shown. The dashed lines indicate the time, when the DC pulse is present. The BEC formation can be observed after the pulse is switched off

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PHONON HEAT TRANSFER IN HETEROSTRUCTURES CONTAINING LAYERS OF A NORMAL METAL, FERROMAGNETIC INSULATOR AND MASSIVE DIELECTRIC

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KEY WORDS: ferromagnetic insulator, heat transfer, phonons, magnons

We begin by discussing theoretically the nonlinear relaxation between magnons and phonons in a ferromagnetic insulator. The partial equilibrium state of magnons and phonons is described using equilibrium Bose functions with different temperatures. The heat flow from hot magnons to cold phonons connected with the Cherenkov radiation of phonons by magnons is then calculated.

After that, within the frames of the kinetic approach based on the Boltzmann equation for the phonon distribution function, the size effect in the heat transfer from heated ferromagnetic insulator plates (films) is discussed theoretically for the case when the magnonic contribution to thermal resistance ("Kapitza resistance") of the ferrodielectric-dielectric interface plays a decisive role.

We analyze also the phonon heat transfer in a heterostructure containing a layer of a normal metal (N) and a layer of a ferromagnetic insulator (F). Two realistic methods for creating a temperature gradient in such a heterostructure are considered: by heating of the N-layer by an electric current and by placing an N/F-bilayer between massive dielectrics with different temperatures. The electron temperature T_e in the N-layer and the magnon temperature T_m in the F-layer are calculated. The difference in these temperatures determines the voltage V_{ISHE} on the N-layer in the spin Seebeck effect regime. The dependence of V_{ISHE} on the bath temperature and on the thickness of the N and F layers is compared with the experiment.

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie Grant Agreement No. 644348 (MagIC).

EXITATION OF ULTRASHORT WAVELENGTHS SPIN WAVES IN MAGNETIC WAVEGUIDES VIA SPIN-CERENKOV EFFECT

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KEY WORDS: magnetic waveguides, ultrashort spin waves, spin-Cerenkov effect

Conventional methods of spin waves excitation in magnetic thin films do not allow excitation of spin waves with wavelength below some limit associated with patterning size. Parametric excitation on the other hand allows in principle excitation of any wavelength but tunability of this method is quite cumbersome task [1].

In contrast spin-Cerenkov effect allows excitation of any wide range wavelength in a film [2]. Excited spin waves wavelength can be easily tuned by changing the velocity of moving magnetic impulse in film. Excited spin waves are entirely determined by spin wave spectrum of the sample and velocity of the magnetic impulse.

We demonstrate this idea using micromagnetic modeling in a case of YIG waveguide with parameters similar to one in [3]: namely 100 nm width and 10 nm thickness. Moving magnetic pulse with $b_z = 1$ mT and speed 200 m/s excites two opposite propagating spin waves in a sample due to spin-Cerenkov effect. There wavelength are: $\lambda_1 = 740$ nm and $\lambda_2 = 40$ nm. As one can see spin-Cerenkov effect leads to the excitation of ultrashort wavelength spin waves while remaining easy tunable and effective method.

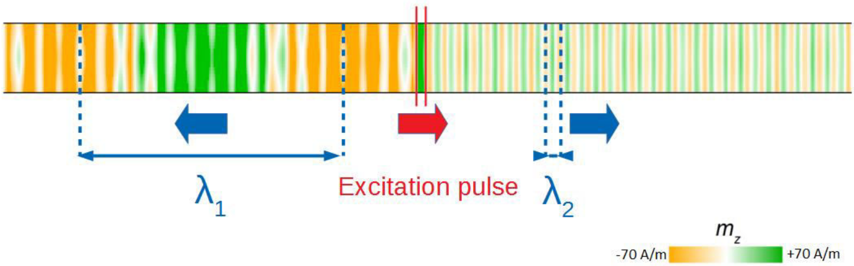

Fig. 1 : Magnetization map of a waveguide with moving excitation pulse. Two opposite propagating spin-waves with different wavelength clearly seen. External magnetic field 10 mT

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ANTIFERROMAGNETIC TUNNEL JUNCTION AS THz-FREQUENCY AC SIGNAL SOURCE

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KEY WORDS: AC power, THz-frequency signal, antiferromagnet, spin Hall oscillator

We propose a novel type of a terahertz-frequency signal source based on an antiferromagnetic tunnel junction (ATJ), where the generated ac signal is extracted through the variations of the tunneling anisotropic magnetoresistance (TAMR) of an ATJ. The signal source consists of a current-driven platinum (Pt) layer and a layer of an antiferromagnet (AFM) separated by an MgO spacer from an additional Pt electrode. A dc electric current flowing in the first Pt layer due to the spin Hall effect creates a perpendicular spin current [1], that, being injected in the AFM layer, tilts the magnetizations of the AFM sublattices, and, therefore, causes THz-frequency rotation of these magnetizations in a large internal exchange magnetic field of the AFM. This rotation, through the TAMR effect [2], causes the THz-frequency variation of the total resistance of the layered structure. Our calculations show that such a source could provide an output power exceeding 1 μW at the frequency of 0.5 THz.

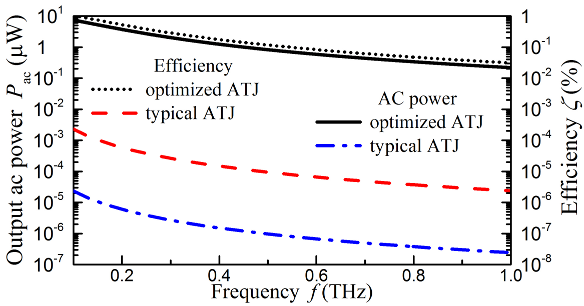

Fig. 1 : Frequency dependence of the output ac power Pac (solid and dashed lines) and the energy conversion efficiency ζ (doted and dash-dotted lines) of the THz-frequency signal source with typical and optimized parameters

This work has been supported by the President's of Ukraine grant for competitive projects (F 78), by the grants F 76 and F 83 from the State Fund for Fundamental Research of Ukraine, by the Grants Nos. EFMA- 1641989 and ECCS-1708982 from the NSF of the USA, and by the DARPA M3IC Grant under the Contract No. W911-17-C-0031, by the grants 16BF052-01 and 18BF052-01M from the Taras Shevchenko National University of Kyiv, and by the grant 7F from the National Academy of Sciences of Ukraine.

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MAGNETIZATION REVERSAL PROCESS IN THIN-FILM MAGNONIC CRYSTALS

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KEY WORDS: magnetism, hysteresis, quasicrystals, magnonic crystals, Monte Carlo

Permalloy (Py, $Ni_{80}Fe_{20}$) nanowires of two widths $w_1 = 350$ nm and $w_2 = 700$ nm separated by 100 nm with length $L = 5$ μm and thickness $t = 50$ nm arranged alternately (magnonic crystals, MCs) and according to the Fibonacci sequence (magnonic quasicrystals, MQs) into ribbons were considered. Magnetostatic interactions between stripes were investigated in dependence on the order of the stripes.

Monte Carlo simulations of magnetic dipoles with effective shape anisotropy field show complex multiphase remagnetization with multiple stable plateau phases in MQs in comparison to more simple process in MCs. Reduction of magnetostatic interactions, e.g. due to nonuniform magnetization, narrows the reversal process. Magnetostatic fields in MCs and MQs under consideration were calculated analytically. The results show that volume average magnetostatic field explain main characteristics of the hysteresis loops of MCs and MQs. The most significant features were confirmed in hysteresis loops measured with longitudinal magneto-optical Kerr effect (L-MOKE) microscope, which show reversal process with two phases. We show that the multiple ribbon structures can be well described by a single ribbon structure with reduced magnetostatic interaction.

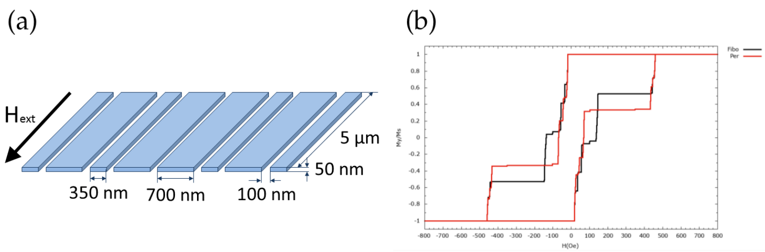

Fig. 1 : (a) Model of bi-component one-dimensional magnonic quasicrystal. (b) Hysteresis loops of MC and MQ obtained from Monte Carlo simulations with magnetostatic interaction reduced to 0.15

The research received funding from the European Union Horizon 2020 Research and Innovation Programme under Marie Sklodowska-Curie Grant Agreement No. 644348 (MagIC) and from Narodowe Centrum Nauki (NCN), Poland grant MetaSel UMO-2015/17/B/ST3/00118.

ONE-DIMENSIONAL MAGNONIC CRYSTALS WITH DZYALOSHINSKII-MORIYA INTERACTIONS

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KEY WORDS: magnonic crystals, Dzyaloshinskii-Moriya interaction, nonreciprocity, spin waves

We investigate influence of Dzyaloshinskii-Moriya interaction (DMI) on the spin wave spectra in one-dimensional magnonic crystals. They consist of 6 nm thick ferromagnetic film with 100 nm wide and 6 nm thick ferromagnetic stripes with 100 nm separation arranged on its top. The change of the magnetization configuration between thick and thin stripes, from parallel to antiparallel, and change of the DMI coefficient on the spin wave dispersion were in focus of our study.

We demonstrated with numerical calculations [1] in linear approximation, that the spin wave spectra of a corrugated thin film in Damon-Eshbach geometry shows similar nonreciprocity to a smooth thin film. However, in magnonic crystal few GHz wide bandgaps are present in the dispersion relation. In addition, a negative group velocity of the spin waves is obtained for wavenumbers near the border of the Brillouin zone, which is a result of the nonreciprocity. Interestingly, numerical analysis shows effective reducing of DMI influence on the band structure when the anti-parallel configuration of the magnetisations is assumed. Our results point at the possibility of controlling the nonreciprocity originating from DMI by the change of the magnetization texture.

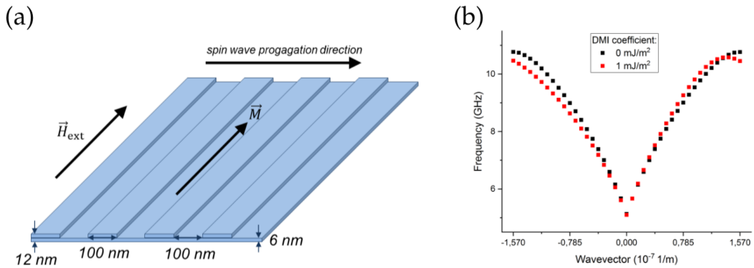

Fig. 1 : (a) Model of the magnonic crystal. (b) Dispersion relation of CoFeB thin film with and without DMI in the external magnetic field 10 mT

The research received funding from the European Union Horizon 2020 Research and Innovation Programme under Marie Sklodowska-Curie Grant Agreement No. 644348 (MagIC) and from Narodowe Centrum Nauki (NCN), Poland grant MetaSel UMO-2015/17/B/ST3/00118.

[1] Calculations with the finite element method in a frequency domain were made with the COMSOL Multiphysics®.

SYNTHESIS OF FMR SPECTRA OF PATTERNED MAGNETIC NANOSTRUCTURES FOR ACCESS CONTROL AND IDENTIFICATION SYSTEMS

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KEY WORDS: FMR spectrum synthesis, patterned magnetic nanostructures

Today the necessity of development and improvement of security systems is occurred. As one of the most promising possibilities for the development of such a systems, we suggest the design of access cards (identity cards) based on the effect of Ferromagnetic Resonance (FMR) in magnetic nanostructures and metamaterials based on them.

The development of manufacturing technologies for magnetic nanostructures makes it possible to produce both single and arrays of nanostructured elements of various shapes and combinations. It is known that for magnetic nanostructures/metamaterials the shape of the FMR spectrum depends strongly on the shape of the nanostructure and on the mutual arrangement of the elements of the array. Thus this allows to create the unique digital prints from these structures.

The contribution presents the results demonstrating the possibility of synthesizing FMR spectra (in frequency domain) with subsequent promising application for access control systems. It is shown that a pronounced dependence of the shape of the magnetization loop on the notch size is observed for a nanostructure formed by discs made of permalloy with a diameter $d < 500$ nm with a radial notch. The FMR spectra in frequency domain for the nanoparticle pattern (disks diameter 500–3000 nm) as a function of magnetic field are analyzed also.

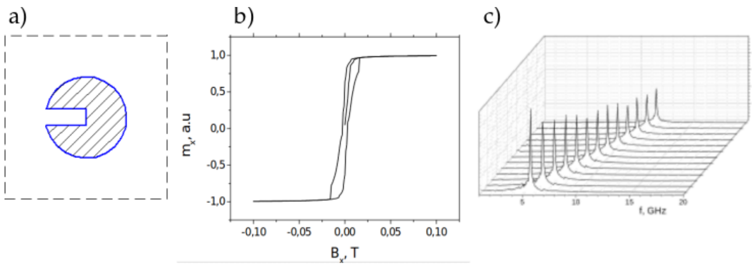

Fig. 1 : The element of nanoparticle pattern (a)); the typical magnetization loop (b)) and the synthesized FMR spectrum (magnetic field varies between 1600-200 Oe) for Py 20 nm thickness disk with diameter 3000 nm(c))

TEMPERATURE EVOLUTION OF THE OPTICAL PROPERTIES IN (Ga,Mn)As

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KEY WORDS: diluted magnetic semiconductors, low-temperature molecular-beam epitaxy, band structure, spintronic

The diluted magnetic semiconductors (DMS) developed on the basis of the complex compounds are still under deep investigation because of their advantages for future spintronic: integrated modern microelectronics with spin physics. The progress in growing technology allows obtaining the homogeneous epitaxial layers, quantum wells, quantum wires and quantum dots where the semiconducting and ferromagnetic properties are combined.

Our resent efforts are aimed at the optimization of the low-temperature molecular-beam epitaxy (LT-MBE) growth conditions to fabricate epitaxial (Ga,Mn)As layers with the lowest level of undesirable defects, such as arsenic antisites, (As_{Ga}), and Mn interstitials, (Mn_I). The 100 nm thick (Ga,Mn)As layers for this study have been prepared at approximately 230°C on semi- insulating (001) GaAs substrates with the LT-MBE growth technique, with the Mn contents ranging from 0 to 1.6%. High-resolution X-ray diffraction measurements show that the investigated LT-GaAs and (Ga,Mn)As epitaxial layers have been pseudomorphically grown on GaAs substrate under compressive misfit strain with a rather low concentration of As Ga defects – in the range of 10^{19} cm^{-3}. The micro-Raman spectroscopy is used for the analysis of coupled free hole plasmon–LO phonon related mode (CPPM) to estimate free hole concentration.

The low-temperature (LT) high-spectral-resolution optical studies of the energy gap (E_0) evolution of the (Ga,Mn)As epitaxial layers, obtained under the optimized conditions, have shown that the modification of the GaAs valence band caused by Mn incorporation occurs already for a very low Mn content, much lower than that required to support ferromagnetic spin– spin coupling in (Ga,Mn)As [1].

The combined LT magnetic, spectroscopic ellipsometry (SE) and photoreflectance (PR) studies have indicated that the paramagnetic–ferromagnetic phase transition in p-type (Ga,Mn)As takes place without imposing changes in the unitary character of the valence band with the Fermi level located therein. Comparing the evolution of the optical transitions at E_0 with those at E_1 and $E_1 + \Delta_1$ optical-transition spectral areas allows for better understanding the band structure modification in (Ga,Mn)As with increasing Mn concentration.

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CROSSOVER FROM THERMAL TO SUBTHERMAL MAGNONS SPIN CONDUCTANCE IN YIG THIN FILMS DRIVEN BY LARGE SPIN-ORBIT TORQUE

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KEY WORDS: yttrium iron garnet, spin waves, spin-orbit torque, non-linear phenomena

Generation and detection of pure spin currents circulating in magnetic materials through spin-orbit torque (SOT) has attracted recently a lot of attention, especially for future applications exploiting magnonic concepts. Among them, Yttrium Iron garnet (YIG), a magnetic insulator with very low damping, appears to be a promising material [1] since it can propagate very efficiently magnons. It has been established [2] that a pure spin current can be induced and detected between two Pt electrodes deposited few microns apart on top of YIG. Here we present a study of spin waves propagation in ultra- thin film of YIG (few nm) excited by large spin orbit torque. By injecting a high current density in Pt injector strip we are able to put our system strongly out of equilibrium and thus reach subcritical regime. We show that at such high current density, an exponential decrease of the resistivity of the YIG must be taken into account and give rise to a parasitic non-magnetic offset voltage in the detector strip which is not related to magnon propagation [3]. The main contribution of this work is an experimental evidence of a gradual spectral shift from thermal to subthermal magnon transport when a current density of $Jc = 5 \cdot 10^{11}$ A/m^2 is injected in the Pt [4]. Our results suggest that a new spin conduction channel appear in the GHz frequency range close to the damping compensation threshold. This observation is supported by microfocus Brillouin light scattering measurement.

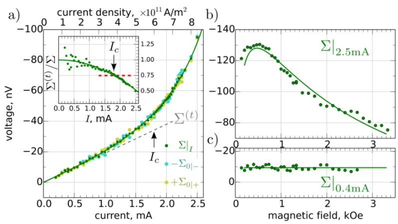

Fig. 1 : a) Non-local SOT signal (Σ) as a function of the current density apply to the magnon source strip. b) and c) Non local signal as a function of the applied magnetic field above and below Ic

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DIRECT OBSERVATION OF SUB-100 NM SPIN WAVE PROPAGATION IN MAGNONIC WAVE-GUIDES

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KEY WORDS: magnonic wave-guides, spin-waves, time-resolved STXM, dynamics

In magnonics research, capabilities of data processing mediated by spin waves are of current interest for beyond-CMOS data processing technologies, promising non-Boolean computing algorithms or majority gates substituting several tens of CMOS transistors and making this an exciting candidate for next level computing [1]. However, for magnonic logic operations, reliable spin wave guides on the nano-scale are indispensable.

Here, we use scanning transmission x-ray microscopy (MAXYMUS@BESSY II) with magnetic contrast and a spatial and temporal resolution of 18 nm and 35 ps respectively to investigate such magnonic wave-guides in real space and time domain. These were structured as 50 nm thin and < 2 µm wide Py stripes. A coplanar waveguide (Cr/Cu/Al) was deposited on top to allow RF excitation of spin waves in these structures [2]. The results are shown exemplary in Fig. 1(a) for a Py stripe under CW excitation and with an applied external field along the long axis of the wave-guide. We are able to directly observe a spin-wave with a wavelength of $\lambda_2 = 95$ nm (corresponding to $k_2 = 10.5\ \mu\text{m}^{-1}$ in Fig. 1(b)). This pushes the limit for spin-wave generation and long-range guiding below the 100 nm wavelength barrier. Additionally, we recreated a data transmission scenario by using a Burst excitation scheme. The simple wave-guides were found to be able to carry multiple modes simultaneously making this system an ideal candidate for data transmission.

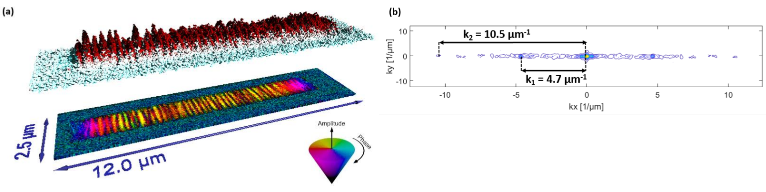

Fig. 1 : (a): Frequency image of a STXM measurement (1.4 µm Py stripe) with information on amplitude and phase represented by the colour code. Standing spin-wave structures are clearly visible within the Py stripe. The three- dimensional image emphasizes the appearance of standing spin waves. (b): K-space of the frequency image. K-vectors emerge next to the DC-peak with k-values up to 10.5 µm^{-1} revealing a spin-wave wavelength of 95 nm

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DAMPING RATES OF SPIN-WAVE MODES UNDER NONUNIFORM AND NONLOCAL DAMPING MECHANISMS

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KEY WORDS: spin wave, damping, spin diffusion, spin pumping

We present a framework for the calculation of damping rates of linear spin-wave modes in ferromagnetic films and nanostructures. The framework is based on the perturbation theory and allows to account common uniform Gilbert damping, as well as nonuniform (coordinate dependent) and nonlocal (magnetization texture dependent) Gilbert-like dissipation mechanisms. We derive a general expression for the spin-wave mode damping rate, for the calculation of which one need to know just the spin-wave mode frequency, its profile and material parameters describing a particular magnetic damping channel. The developed formalism is especially convenient for the applications with micromagnetic and other numerical simulations, allowing to calculate damping rates based on a numerical solution of a conservative spin-wave mode eigenproblem. As example applications of the developed formalism, we consider the damping of spin-wave modes of a ferromagnetic film under the spin pumping into adjacent nonmagnetic metal layer. The enhancement of the damping rate shows characteristic dependence on the magnetization angle – nonmonotonic one for all spin- wave modes, except 1 or 2 modes which transform to surface modes in in-plane fields (see Fig. 1), which may be used as an experimental evidence of the spin pumping damping mechanism.

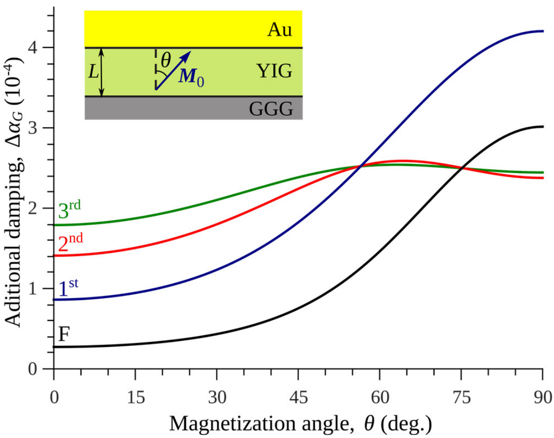

Fig. 1 : Dependence of the enhanced damping constant due to the interlayer spin pumping on magnetization angle θ. Calculations are made for 200 nm thick YIG film covered by Au in the long-wave limit. Inset shows a sketch of the considered structure

SPIN-WAVE OPTICS IN MAGNETIZATION LANDSCAPES

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KEY WORDS: spin wave beams, holography, lenses, Fourier optics

The refraction of electromagnetic waves in conventional optics as well as dipolar magnetic waves – namely spin waves – in ferrimagnetic films (several micrometers thick yttrium iron garnet) follows the well-known Snell's law [1]. To do optics with electromagnetic waves in the visible range low divergent beams are needed. In spin-wave optics, the excitation of spin-wave beams is necessary, too. Therefore, we use specially designed coplanar waveguides or microstrip antennas [2]. Microstructured induction probes are scanned over the sample in order to visualize the spin-wave propagation.

We propose to use optically-induced magnetization landscapes [3] to create the building blocks of spin-wave optics, e.g., spin-wave (graded-index) lenses, fibers, beam-splitter or diffraction gratings. Moreover, spin-wave lenses can be used to realize spin-wave Fourier optics. We compare our experimental results with micromagnetic simulations.

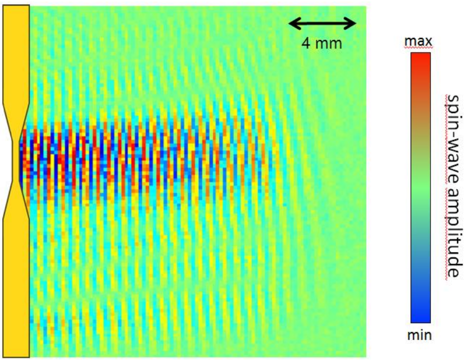

Fig. 1 : Narrowed microstrip antennas are used to excite spin-wave beams. By scanning an induction probe over the sample, a phase resolved visualization of the propagating spin wave is obtained

Financial support by DFG collaborative research center SFB/TRR 173 "Spin+X" (project B04) is gratefully acknowledged.

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GRADED INDEX LENSES FOR SPIN WAVES

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KEY WORDS: spin waves, lensing, graded magnonic index, spin wave optics

Graded index lenses have long been studied for the purpose of controlling the direction of wave propagation. In this work, we use micromagnetic modelling to demonstrate a range of graded index lenses designed for forward-volume spin waves. The refractive index for spin waves in a thin film may be defined for a particular frequency and is determined by the film thickness, magnetisation or the magnetic field. So, the graded magnonic index can be created by changing one of these parameters to match the required profile [1]. For ease of modelling, each lens is created here by modulating the saturation magnetisation in a circular region of a thin YIG-like film.

Our primary result is for a Luneburg Lens [2] (Fig. 1), which has previously been realised for both high and low frequency electromagnetic waves [3,4] and more recently for sound waves [5]. This lens could be a useful circuit component, as it is designed to focus an plane wave incident from an arbitrary direction to a point on the edge of a lens, or, conversely, convert a point source to a plane wave. We analyse the behavior of a spin wave packet as it moves through the lens, and demonstrate a significant enhancement of the wave amplitude as the wave is focused.

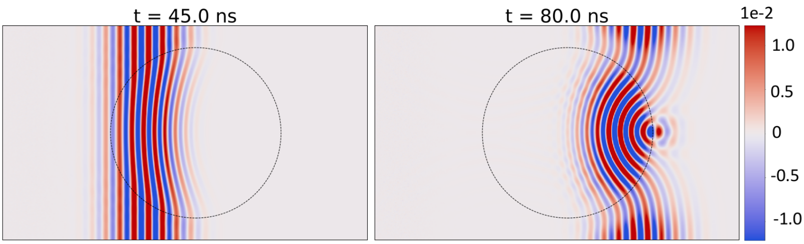

Fig. 1 : Snapshots of pulse moving through Luneburg lens (dotted outline). Normalised Mx component of magnetisation shown, and colour scale is saturated to show the pulse clearly

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THE MAGNETIZATION DISTRIBUTION IN FERROMAGNETIC THIN FILM WITH THE ANTIDOT

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KEY WORDS: spin waves, Snell's law, magnonic devices

A neotype magnetic metamaterial in the presence of spatially modulated Dzyaloshinskii- Moriya interaction is theoretically proposed and demonstrated by micromagnetic simulations [1]. By analogy to the fields of photonics, we first establish Snell's law for spin waves or magnons passing through an interface between two media with different dispersion relations due to different Dzyaloshinskii-Moriya interactions. Based on the Snell's law, we find spin waves can experience total internal reflection. The critical angle of total internal reflection is strongly dependent on the sign and strength of Dzyaloshinskii-Moriya interaction. Furthermore, spin-wave beam fiber and spin-wave lens are designed by utilizing the artificial magnetic metamaterials with inhomogeneous Dzyaloshinskii-Moriya interactions. Our findings open up a rich world of spin waves manipulation for prospective applications in magnonics.

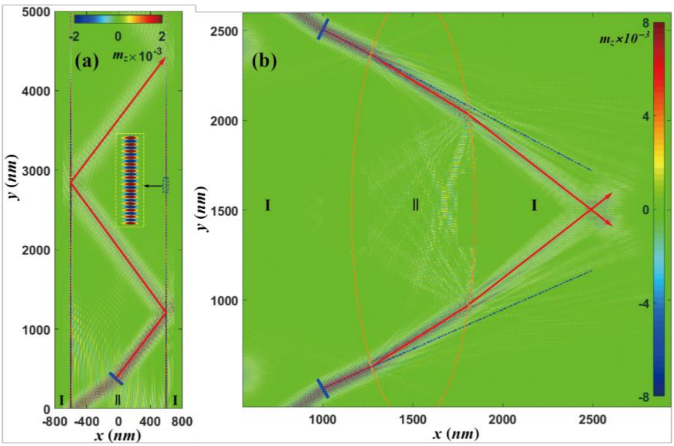

Fig. 1 : Schematic illustration of a spin-wave fiber and spin-wave lens

References:

[1] S. J. Lee, J. H. Moon, H. W. Lee, K. J. Lee, *Phys. Rev. B* **96**, 184433 (2017)

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Presenting authors

3rd International Advanced School on Magnonics'2018

	17.09.2018 Monday	18.09.2018 Tuesday	19.09.2018 Wednesday	20.09.2018 Thursday	21.09.2018 Friday
8:00-9:00	*Registration/Inauguration*	*Registration*	*Registration*	*Welcome coffee*	*Welcome coffee*
9:00-9:50	Kruglyak Volodymyr (magnonics basics)	Serga Alexander (magnonics basics)	Brächer Thomas (magnonics basics)	**Poster session**	Zaliznyak Igor
9:50-10:40	Bauer Gerrit	Hillebrands Burkard	Romain Lebrun		Flebus Benedetta
10:40-11:30	Ciubotaru Florin	Tserkovnyak Yaroslav	Atkinson Del		Golub Vladimir
11:30-12:00	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*
12:00-12:50	Nembach Hans	Tretiakov Oleg	Kirilyuk Andrei	Gomonay Olena	Gorobets Oksana
12:50-13:40	Verba Roman	Gubbiotti Gianluca	Ivanov Boris	Mruczkiewicz Michał	**Best poster awards & Closing remarks**
13:40-14:40	*Lunch*	*Lunch*	*Lunch*	*Lunch*	*Lunch*
14:40-15:30	Kolezhuk Oleksiy	Sheka Denis	**Excursion**	Chubykalo-Fesenko Oksana	
15:30-16:20	Gräfe Joachim	Barman Anjan		Kakazei Gleb	
16:20-17:10	**Poster session** & **Welcome reception**	**Honored guests session**		Schultheiss Helmut	
17:10-17:40		*Coffee break*		*Coffee break*	
17:40-18:30		**Special session** *"Science & magnonics in Ukraine and worldwide "*		Prokopenko Oleksandr	
18:30-19:00				Kłos Jarosław	
19:00			**Conference dinner**		