Adam Mickiewicz University in Poznań
Polish Academy of Sciences

MagIC 2017

Magnetism, Interactions and Complexity: a multifunctional aspects of spin wave dynamics

Poznań/Trzebaw, Poland, 2–7 July 2017

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im. Adama Mickiewicza
w Poznaniu

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Workshop MagIC 2017
Magnetism, Interactions and Complexity:
a multifunctional aspects of spin wave dynamics
Poznań/Trzebaw, Poland
2–7 July 2017
Book of abstracts

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Technical edition using LaTeX: Anna Krzyżewska

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Venue and excursion

The Opening

(Sunday, July 2)

Faculty of Physics
Adam Mickiewicz
University in Poznań
ul. Umultowska 85,
61-614 Poznań

Photo: Rafał Wojtyniak

How to get there?

[1] **From the airport**
http://www.airport-poznan.com.pl/en/for-passengers/arrival/transfer-to-city
By bus/tram: A 59 to 'Rondo Kaponiera' → T 12, 14, 15, 16 to os. Sobieskiego → by walk (or A 98). Time*: 50-60 min. Cost: 4.60 + 3.00 (+3.00) PLN.
By taxi: Faculty of Physics, Umultowska 85. Time*: 20-30 min. Cost: 40-50 PLN.

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By bus/tram: by walk to the tram stop 'Dworzec Zachodni' or 'Most Dworcowy' → T 12, 14, 15, 16 to os. Sobieskiego → by walk (or A 98). Time*: 20-25 min. Cost: 3.00 (+3.00) PLN.
By taxi: Faculty of Physics, Umultowska 85. Time*: 20-25 min. Cost: 30-40 PLN.

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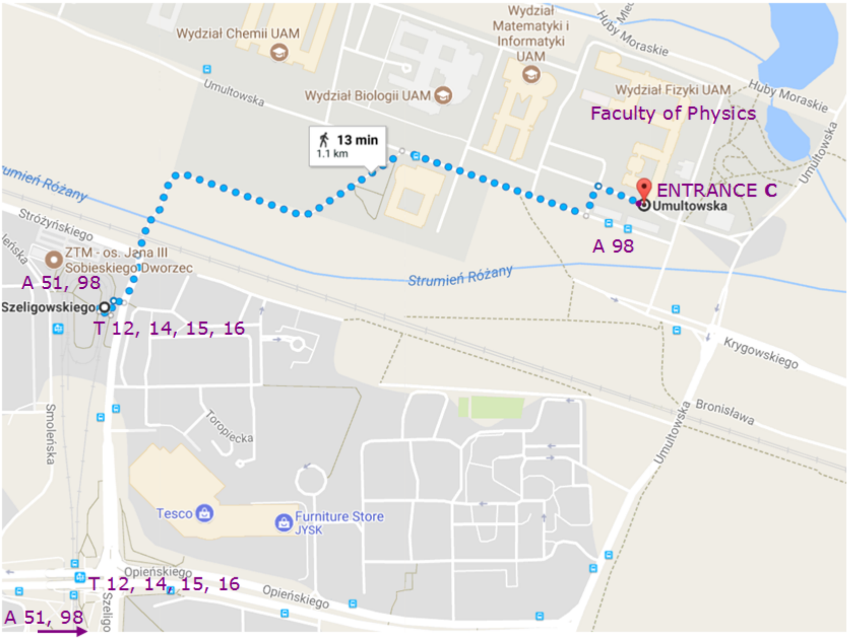
By bus/tram: T 12, 14, 15, 16 to os. Sobieskiego → by walk (or A 98). Time*: 20-25 min. Cost: 3.00 (+3.00) PLN.
By taxi: Faculty of Physics, Umultowska 85. Time*: 20-25 min. Cost: 30-40 PLN.

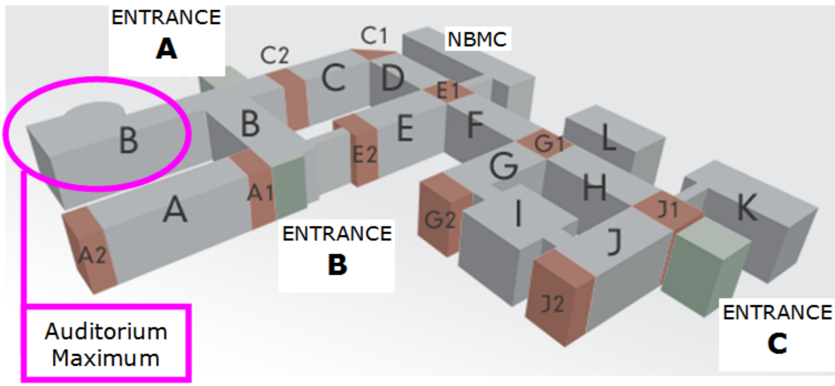
*with no traffic jams :-)



https://www.google.com/maps/@52.4644106,16.9247479,16z?hl=en

Faculty map

(Registration and Opening Lecture - Auditorium Maximum)



Workshop venue

Hotel Delicjusz
Trzebaw, ul. Poznańska 1
62-060 Stęszew
http://delicjusz.pl

Traveling from/to the airport

Please find link to jakdojade.pl – service where You can plan Your journey through Poznań.

Taxi – close to main entrance of *Poznań Ławica Airport* you can find taxi stop or call for example Taxi Poznań (tel. 61 8 222 222), Gold Taxi (tel. 61 196 60).
Costs about 100 PLN.

Excursion

Rogalin /near Poznań – palace, museum, park, old oaks.

https://en.wikipedia.org/wiki/Rogalin, http://rogalin.mnp.art.pl/

Dinner: restaurant 'Pod Dębami'

https://www.google.pl/maps/@52.2345013,16.929323,16

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Abstracts

Invited lectures

NANOMAGNONICS: FROM METALS TO INSULATORS

D. Gründler[1]

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KEY WORDS: spin waves, magnonics, magnonic crystal, chiral magnet, skyrmion

Collective spin excitations in magnetically ordered materials have gained a broad interest in recent years. Here spin waves (magnons) in magnetic nanostructures have formed a particular focus as they allow one to transmit and process microwave signals at the nanoscale. For a long time, ferromagnetic metals were exploited to prototype nanomagnonic waveguides and magnonic crystals which provide an unprecedented control over spin-wave band structures [1]. To harvest the advantages and low-energy consumption which a magnonics-based technology could offer materials of low spin-wave damping are required however. Correspondingly, magnetic insulators become important in the research field. We will review and discuss recent advances based on ferromagnetic insulators with and without Dzyaloshinsky-Moriya interaction that allow one to tailor spin-wave properties at the nanoscale via chiral spin structures [2] or nanostructuring (Fig.).

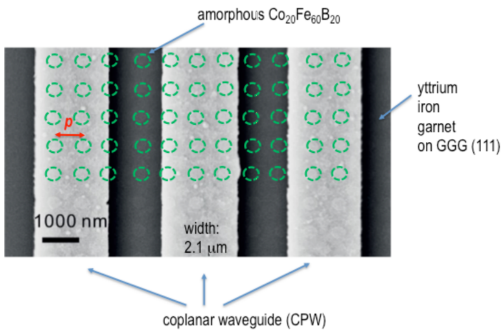

Fig. 1: Thin film of insulating ferromagnetic yttrium iron garnet (YIG) with an integrated array of ferromagnetic disks nanopatterned from CoFeB (period $p = 800$ nm, highlighted by dashed circles). The coplanar waveguide allows one to excite exchange-dominated spin waves propagating through YIG [3]

We acknowledge support by the DFG via Nanosystems Intiative Munich, project GR1640/5-2 and the Transregio TRR80 "From electronic correlations to functionality" (project F7). The Swiss National Science foundation (SNSF) funds magnonics research on skyrmion-hosting materials via the sinergia network "Nanoskyrmionics" (grant CRSII5-171003).

References:

[1] A.V. Chumak, A.A. Serga, B. Hillebrands, Magnonic crystals for data processing, J. Phys. D: Appl. Phys. **50**, 244001 (2017)

[2] M. Garst, J. Waizner, D. Grundler, Collective spin excitations of helices and magnetic skyrmions: review and perspectives of magnonics in non-centrosymmetric magnets, J. Phys. D: Appl. Phys., in press (2017), **https://doi.org/10.1088/1361-6463/aa7573**

[3] Haiming Yu et al., Approaching soft X-ray wavelengths in nanomagnet-based microwave technology, Nature Commun. **7**, 11255 (2016)

THz CONTROL OF SPINS WITH LIGHT

M. Münzenberg[1]

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Corresponding author: muenzenberg@physik.uni-greifswald.de

KEY WORDS: ultrafast magnetism, THz spintonics

I will discuss some of the knobs to tune dynamics at ultrafast time scales, where a control of spins and spin dynamics is possible by light [1]. The dynamics of the spin response depends on the energy transfer from the laser excited electrons to the spins within the first femtoseconds. This determines the speed of the ultrafast demagnetization: if the electrons are driven to a strong excitation density, a second slower process is found, a signature of the intrinsic ferromagnetic electron correlations in a ferromagnet. A special material of interest for magnetic storage development is FePt. The electron temperature shoots to higher values above the Curie temperature, a precondition for all-optical writing by light using magnetic quenching [2]. Not only magnetic nanoparticles can be reversibly written. Also vortex, antivortex networks can be written in standard thin Fe films [3].

On the other side, due to the non-equilibrium electron distribution in layered nanoscale spintronic devices, also ultrafast spin currents are generated and contribute to the laser driven spin dynamics. Layers of a noble metals like Pt, Au or transition metals like W, Ta, Ru can convert ultrafast laser-driven spin currents via the ultrafast spin-Hall effect into a charge current burst [4]. This opens a way towards novel THz spintronic devices: optimizing thicknesses and layers, we can realize efficient metallic THz spintronic emitters of ultra-broadband terahertz radiation [5], and sets the stage of first applications in the field of ultrafast magnetism.

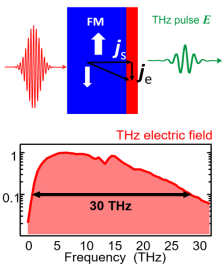

Fig. 2: Spintronic THz emitter based on ultrafast laser excited spin current bunches, driving the inverse spin Hall effect (ISHE) and subsequent THz emission

References:

[1] J. Walowski and M. Münzenberg, J. Appl. Phys. **120**, 140901 (2016).

[2] J. Mendil, P. C. Nieves, O. Chubykalo-Fesenko, J. Walowski, M. Münzenberg, T. Santos, S. Pisana, Sci. Rep. **4** 3980 (2014), R. John, et al. arXiv:1606.08723.

[3] T. Eggebrecht, M. Möller, J. G. Gatzmann, N. Rubiano da Silva, A. Feist, U. Martens, H. Ulrichs, M. Münzenberg, C. Ropers, S. Schäfer, Phys. Rev. Lett. **118**, 097203 (2017).

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[5] T. Seifert, S. Jaiswal, U. Martens, J. Hannegan, L. Braun, P. Maldonado, F. Freimuth, A. Kronenberg, J. Henrizi, I. Radu, E. Beaurepaire, Y. Mokrousov, P.M. Oppeneer, M. Jourdan, G. Jakob, D. Turchinovich, L.M. Hayden, M. Wolf, M. Münzenberg, M. Kläui, T. Kampfrath, Nature Photonics **10**, 483–488 (2016)

TIME-RESOLVED X-RAY IMAGING WITH HERALDO

F. Y. Ogrin[1], N. Bukin[1], E. Burgos-Parra[1], C. McKeever[1], G. Beutier[2], N. Jaouen[3], H. Popescu[3], F. Yakhou[4], G. van der Laan[5]

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KEY WORDS: x-ray holography, time-resolved imaging, magnetization dynamic

The magnetisation dynamics of the vortex core and Landau pattern of magnetic thin-film elements has been studied using holography with extended reference autocorrelation by linear differential operator (HERALDO) [1,2]. Here we present the first time-resolved x-ray measurements using this technique and investigate the structure and dynamics of the domain walls after excitation with nanosecond pulsed magnetic fields [3]. It is shown that the average magnetisation of the domain walls has a perpendicular component that can change dynamically depending on the parameters of the pulsed excitation. In particular, we demonstrate the formation of bloch-point excitations, which are generated in the domain walls and can propagate inside them during the cyclic motion of the vortex core. Based on numerical simulations we also show that, besides the core, there are four singularities formed at the corners of the pattern. The polarisation of these singularities has a direct relation to the vortex core, and can be switched dynamically by the wave bullets excited with a magnetic pulse of specific parameters. The subsequent dynamics of the Landau pattern is dependent on the particular configuration of the polarisations of the core and the singularities.

References:

[1] Duckworth, T. A. et al., Magnetic imaging by x-ray holography using extended references, Optics Express 19, 16223–16228 (2011)

[2] Duckworth, T. A. et al., Holographic imaging of interlayer coupling in Co/Pt/NiFe.,New J. Phys. 15, 023045 (2013)

[3] Bukin, N. et al., Time-resolved imaging of magnetic vortex dynamics using holography with extended reference autocorrelation by linear differential operator, Sci. Rep. 6, 36307 (2016)

UNCONVENTIONAL LITHOGRAPHY – THE TOOLS FOR THE FABRICATION OF ARRAYS WITH TUNABLE MAGNETIC PROPERTIES

M. Krupiński[1], D. Mitin[2], A. Zarzycki[1], R. Bali[3], Y. Zabila[1], A. Maximenko[1], A. Szkudlarek[4], K. Potzger[3], M. Albrecht[2], M. Marszalek[1]

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KEY WORDS: nanosphere lithography, anodization, direct laser interference patterning, antidot arrays, magnetic dot lattices, perpendicular magnetic anisotropy

Recently, there has been growing interest in the fabrication, characterization, and modeling of patterned magnetic thin films due to their potential applications in the field of magnetic storage, sensors, radio frequency components, information processing, and magnonic crystals. This specific interest is primarily due to the possibility of controlling the magnetic properties by introducing in ferromagnetic material artificial defects such as antidots, dots or nonmagnetic inclusions arranged in ordered or disordered arrays. In particular, the hysteresis properties of such systems can be easily tailored by shape, size, and distance between the nanostructures as well as by arrays order and their symmetry.

The lecture will focus on the magnetic properties and switching behaviour of well-ordered magnetic arrays of dots, antidots and triangles consisting of Co/Pd [1] and FeAl thin films. The patterning effect as well as the influence of period and size on domain shape and domain wall behaviour will be discussed. Different unconventional patterning approaches [2] leading to creation of the arrays will be also introduced.

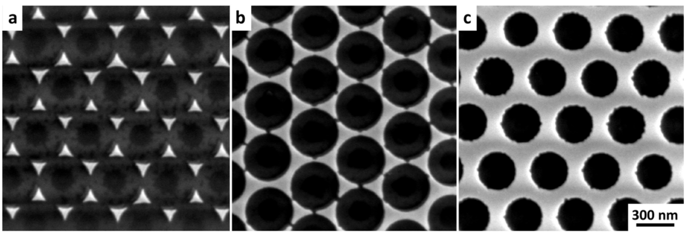

Fig. 3: Scanning electron image of Co/Pd arrays with period of 438 nm. Coverage of the sample surface with magnetic material changes and amounts to (a) 7%, (b) 16% and (c) 55%, resulting in different morphology from separated magnetic islands (a) to arrays of antidots (c)

References:

[1] M. Krupinski et al., Nanotechnology, **28** (2017) 085302

[2] M. Krupinski et al., Nanotechnology, **28** (2017) 194003

NANO-SCALED MAGNON TRANSISTOR

A. Chumak[1], Q. Wang[1], P.Pirro[1], B. Heinz[1], M. Kewenig[1], T. Brächer[1]

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KEY WORDS: magnonics, spin-wave logic

With the fast growth in the volume of information being processed, researchers are charged with the primary task of finding new ways for fast and efficient processing and transfer of data. Spin excitations – spin waves and their quanta magnons – open up a very promising branch of high-speed and low-power information processing [1]. The realization of single-chip allmagnon information systems demands for the development of circuits in which magnon currents can be manipulated by magnons themselves. In Ref. [2] we presented and tested experimentally a proof-of-concept magnon transistor. The density of magnons flowing from the transistor's source to its drain could be decreased three orders of magnitude by the injection of magnons into the transistor's gate. The operational principle of the transistor is based on a nonlinear four-magnon scattering process. We have shown that the transistor can be used directly for designing logic gates in all-magnon circuits and enables the amplification of signals coded into the magnon density using an additional interferometer structure. A maximum gain factor of 1.8 was predicted for this device [2].

Here we use micromagnetic simulations to propose a conceptually different approach for the realization of a magnon transistor. In this device, a three- rather than four-magnon scattering process is utilized for the manipulation of one magnon current by another. Gate magnons of frequency 9.8 GHz are injected into the transistor's gate. The source magnons of almost twice smaller frequency of 4.4 GHz are injected in the transistor's source and propagate towards the gate. When the source magnons reach the gate region, they interact with the gate magnons boosting a three-magnon scattering process in which one gate magnon scatters into one new source magnon and into one idle magnon of frequency 5.4 GHz. As a result, the number of the source magnons at the drain is increased and the transistor acts as an amplifier of magnon signals. Our studies have shown that the source magnon's density at the transistor's drain can be enhanced 6.3 times in the presence of the gate magnons.

Our studies show that this type of magnonic transistor can be used for amplification of magnonic currents as well as for performing logic operations in future all-magnon magnonic circuits.

Financial support by the ERC Starting Grant "MagnonCircuits" is gratefully acknowledged.

References:

[1] A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, Magnon spintronics, Nat. Phys. **11** (2015) 453- 461

[2] A. V. Chumak, A. A. Serga, and B. Hillebrands, Magnon transistor for all-magnon data processing, Nat. Commun. **5** (2014) 4700

UBIQUITOUS GRADED MAGNONIC INDEX: FRIEND OR FOE?

F. B. Mushenok[1], R. Dost[2], C. S. Davies[1], S. V. Chertopalov[3], V. D. Poimanov[3], D. A. Allwoo[2], B. J. Inkson[2], V. Kruglyak[1]

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KEY WORDS: spin waves, magnonics, patterned magnetic structures

Even the most general definitions of magnonics leave a lot of freedom for interpretation and scientific discussion of directions of the field's further development. Thus, we have recently seen a number of review papers with emphasis on different aspects of spin wave research and technology. There is however an aspect of magnonics that has been both ubiquitous and somewhat underrated so far: magnonics is the study not only of spin but also (and most importantly) of waves, which have an extremely rich and peculiar dispersion. The spin wave 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. Inspired by and feeding from other fields of wave physics, such as quantum mechanics and transformation optics, we have recently formulated the concept of graded-index magnonics [1] as a unifying theme focusing on general aspects of spin wave excitation and propagation in media with continuously non-uniform properties. In this talk, we will discuss and provide demonstrations (see e.g. the figure) of exciting new physics as well as technological issues and opportunities associated with the graded magnonic index, highlighting the theme as the "next big thing" in magnonics research.

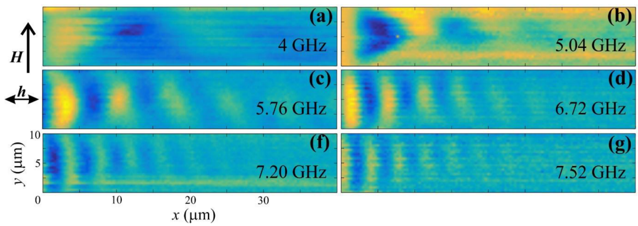

Fig. 4: The spin wave excitation from graded magnonic index in patterned magnetic structure is demonstrated with help of time resolved Kerr images of a Permalloy stripe driven by microwave field h at indicated frequency values. The bias magnetic field H has value of 200 Oe

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1, EP/L020696 and EP/P505526/1) and from the EU's Horizon 2020 research and innovation program under Marie Skłodowska-Curie GA No. 644348 (MagIC).

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MICROMAGNETIC SIMULATIONS: NANO-MAGNETISM BEST FRIENDS

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KEY WORDS: micromagnetic simulations, magnonics, spintronics

Nano-scale magnetization dynamics enables next generation storage [1], computing [2] and microwave technologies [3]. However, its intrinsic nonlinearity, non-uniformity, and presence of long-range magnetic interactions significantly complicate any analytical treatment of the technology-relevant problems, such as collective and self-sustained magnetization dynamics. So their properties are best revealed by micromagnetic simulations. In fact, for about two decades they are accompanying and frequently drive high impact research in the fields of magnonics and spintronics. The emergence of the GPU-accelerating computing allowed for large-scale micromagnetic simulations on commodity hardware and made computational magnetism accessible for virtually any research group in the world.

In my lecture, I will talk about the history of micromagnetic simulations and the most prominent problems they allowed to solve. Then, with the emphasize on the emerging problems of spintronics, I will demonstrate how to get started with systematic micromagnetic simulations, efficiently use the mumax3 code [4], perform spectral analysis of massive datasets and bridge the gap between the full-scale simulations and analytical theories.

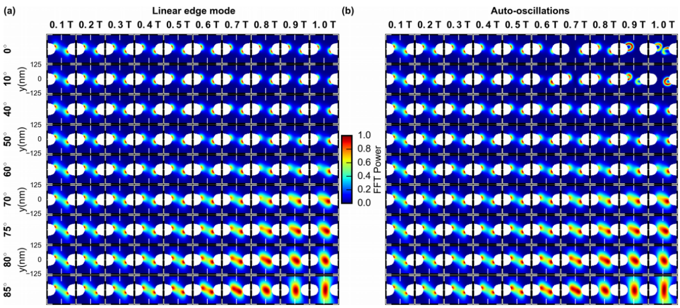

Fig. 5: Spatial profiles of (a) linear and (b) self-sustained magnetization dynamics of constrictionbased spin Hall nano-oscillator simulated using the mumax3 code on the in-house built 110 TFLOPS cluster [5]

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MAGNETIC EXCITATIONS IN PATTERNED FILMS STUDIED BY BRILLOUIN LIGHT SCATTERING TECHNIQUE

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KEY WORDS: magnonic cristals, spin waves, Brillouin scattering

Review of magnetic excitations experimental techniques studies will be focused on Brillouin Light Scattering (BLS) spectroscopy with time and space resolution. Selected results of magnetic excitation investigated in patterned both laterally yttrium iron garnet (YIG) films and in depth FeAl layers (ion irradiated) will be reported. Different spin waves (SW) "optical" effect such as reflection, refraction, focusing and diffraction [1,2] on micrometers thickness YIG films will be discussed. We shall show that adjusting the ion energy in FeAl layers can be used as a lever to manipulate the behavior of spin waves [3]. The application of quasi optical effects in patterned garnet film for switching of the spin waves will be discussed, see Fig.

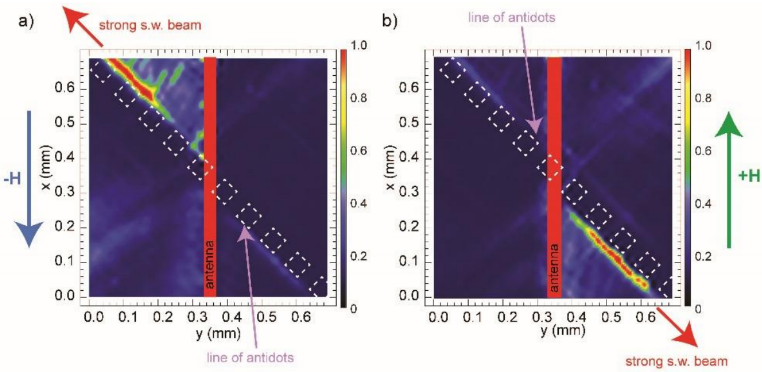

Fig. 6: The strong spin waves beam formation combined with changing of the SW propagation direction. Twodimensional mapping of the SW amplitude (detected with the BLS spectrometer) registered for a) –H and b) +H. The spin waves are generated by the microwave antenna (red vertical bar). Square holes (50 µm size) in YIG film with period a=100 µm created the antidots line marked by crosshatch

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EVOLUTION OF DAMPING AND RESONANCE FIELD-SHIFT IN FINEMET/Pt THIN FILM BILAYERS

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KEY WORDS: ferromagnetic resonance, spin pumping, damping magnetic proximity effect

Evolution of FMR spectra in Al doped (7 at. %) Finemet thin films with the mean thickness $\langle d_F \rangle = 9, 15, 20, 30$ and 40 nm, respectively, covered by Pt wedge layers (0 to 7 nm) is studied. Vector network analyzer ferromagnetic resonance (VNA-FMR) is applied for measurements of FMR absorption spectra for various positions along wedge-shaped bilayers. The Finemet films with the effective magnetization M_{eff} of $770 - 800$ G, and the Gilbert damping of $4 - 5 \times 10^{-3}$, comparable to that of CoFeB, reveal a low inhomogeneous broadening ΔH_0 of only $2 - 4$ Oe. This makes Finemet/Pt bilayers suitable to search for subtle effects accompanied by spin pumping. The dependencies of damping on d_{Pt} are carefully analyzed by taking into account thickness profiles of Finemet films and discontinuous microstructure of Pt for $d_{Pt} < 1.5$ nm. The inhomogeneous broadening ΔH_0 scales roughly with discontinuous Pt topography. The experimental data yield the values of $g_{eff}^{\uparrow\downarrow} = 30$ nm^{-2}, the spin-diffusion length $\lambda = 1.5$ nm, comparable to those obtained for Permalloy/Pt or CoFeB/Pt bilayers.

The most characteristic new feature seen in the Finemet/Pt structures is that the changes in the Gilbert damping α vs. d_{Pt} due to spin pumping are accompanied by a clear negative resonance field shift δH_r which tends to saturation for $d_{Pt} > 2 - 3$ nm. We find that both changes in $\delta\alpha$ and δH_r have a linear dependence on $1/d_F$. Therefore, δH_r has interface origin like an increase in damping $\delta\alpha$ due to spin pumping. Moreover, we provide experimental evidences that the negative resonance field shift δH_r mainly results from an increase in M_{eff} and, in scant account, on variations in g-factor. We attribute this effect to the presence of induced moments in Pt via the magnetic proximity effect. The experimental data are discussed in the framework of recent theories on spin pumping.

We acknowledge support from Project NANOSPIN PSPB-045/2010 under a grant from Switzerland through the Swiss Contribution to the enlarged European Union and from the project "Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE)" Contract No. 644348 with the European Commission, as part of the Horizon2020 Programme.

SPIN WAVES IN YIG-BASED METASTRUCTURES

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KEY WORDS: spin waves, YIG films, subwavelength periodic structures

Periodic magnetic structures – magnonic crystals – allow to control the spin wave (SW) spectrum that can be used for microwave signal processing. The main feature of SW's propagation in magnonic crystals (MC) is formation of the forbidden band gaps in their spectra which appear at Bragg resonance frequencies f_B corresponding to the condition $\lambda(f_B) = 2\Lambda/n$, where Λ is the period of the structure, λ is the SW's wavelength, $n = 1, 2, \ldots$ In the case when subwavelength condition $\lambda \gg \Lambda$ is fulfilled the MC can be considered as a metastructure. So far the case when the subwavelength condition $\lambda \gg \Lambda$ is fulfilled was poorly studied and only theoretically [1]. In this work we present results of investigations of SW's propagation in magnetic metastructures based on micrometer thick yttrium iron garnet (YIG) films.

Most attention paid to the experimental results on the magnetostatic surface wave (MSSW) propagation in YIG films with "leaky" and "resonant" metasurfaces (MS). The first type of MS represented itself the grooves with subwavelength period etched in the YIG film surface and the second one – the plane YIG film with the subwavelength periodic array of micron-sized magnetic stripes placed on its surface. Such structures demonstrated effects of MSSW filtration and formation of anomalous regions in its dispersion.

In the case of the YIG film with "leaky" MS such effects were explained as the resonant interaction of the MSSW with the leaky exchange modes that appeared due to demagnetization fields created by the surface periodic structure. The filtering effects and dispersion of MSSW in the film with 1D- "leaky" MS was studied as a function of the angle between the directions of the magnetic field and the grooves. It was shown that anomalous regions are formed in the MSSW dispersion and their number and width are minimal for the bias field applied along the grooves and maximal for the fields perpendicular to grooves axis (Laue geometry).

MSSW propagation in YIG film with "resonant MS" accompanied by the appearance of resonance features in the transmission characteristics and dispersions and could be considered as a result of the resonant interaction of two magnetostatic SWs propagating in two plane YIG films. One of them is the actual thick YIG film and the other one is the effective thin YIG film that is equivalent to the YIG microstripe array. An influence of SW parametric instability (both first and second order) on SW propagation in YIG-based metastructures is also discussed.

This work was supported by RFBR (Grant Nos. 16-57-00153, 16-02-01073, 17-07-01452) and Belarusian Republican Foundation for Fundamental Research (Grant No. F16R-086).

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OPTICAL PHENOMENA IN PHOTONIC-MAGNONIC CRYSTALS

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The photonic-magnonic crystals (PMCs) are complex multifunctional one-dimensional systems which combine properties of magnonic and photonic crystals (PCs) and possess the band gaps (PBGs) in GHz and PHz regimes for spin waves and light, respectively [1-3]. In this presentation we report about the optical phenomena in PMCs which are bi-periodic structures $[C(A/B)^N]^M C$ with the equidistant magnetic layers C spaced by dielectric PCs $(A/B)^N$. We focus on investigation on the transmittivity spectra, Faraday rotation and Goos-Hänchen effect of the light passing through the finite size PMCs.

The transmittivity spectra of the PMCs contain the inside-PBG bands of complex structure [1-3]. We sowed the increase of Goos-Hänchen shift and Faraday rotation at the frequencies of inside-PBG modes and enhancement of the shift peaks due to the linear magneto-electric effect in the magnetic layers of the system for the case of s- (p-) polarized transmitted beam produced by p- (s-) polarized incident beam. The magneto-electric coupling in the magnetic layers results in significant increase of the positive maxima of the polarization plane rotation angles of s-polarized incident light and decreases the negative ones, whereas the Faraday rotation of p-polarized light almost doesn't change in presence of the magneto-electric interaction.

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ELASTIC ACTIVATION OF LOCALIZED SPIN WAVE MODES IN A TRANSIENT MAGNONIC CRYSTAL

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KEY WORDS: magnonics, spin wave localization, magnetoelastics

In this talk I will describe our experimental efforts to apply ultrafast optical techniques to study magnetoelasticity, the interaction between coherent structural deformations and material magnetization [1]. We utilize the ultrafast optical transient grating (TG) technique, where a spatially tailored optical pulse impulsively generates narrowband acoustic waves, which propagate along the surface of the sample and resonantly drive magnetization dynamics via inverse magnetostriction. The experimental approach allows us to monitor the elastic and magnetic dynamics simultaneously and provides a unique, real-time view of their coupling.

I will describe the basics of ultrafast magnetoelastics including optical geometries and experimental results in the linear magnetoelastic regime before presenting more recent results where we include an understanding of the effects of the spatially modulated magnetization profile. Modulations in the material magnetic properties, such as saturated magnetization or anisotropy, behave as an optically configurable magnonic crystal, capable of localizing spin wave modes in different regions of the sample. The localized spin wave modes are then resonantly driven by the underlying elastic waves present in the system. Taken in combination, the elastic actuation of magnonic modes heralds the emergence of elasto-magnonics, where user defined spatially localized spin wave modes can be driven by structural deformations of materials.

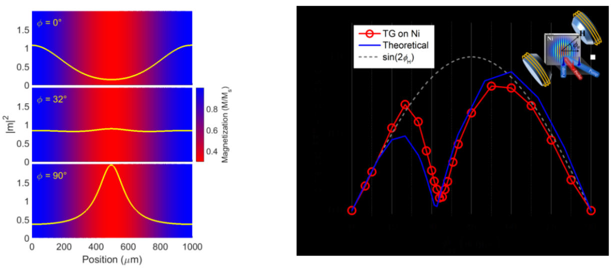

Fig. 7: (left) Spin wave modes in a sinusoidally varying magnetization profile. (right) The magnetoelastic excitation cross section of the spin wave modes is suppressed in a wide angular range around 30degrees, which is well represented in a calculation based on the Plane Wave Method for calculating the spin wave localization

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A NEW CLASS OF SELF-SIMILAR SOLUTIONS OF THE LANDAU-LIFSHITZ EQUATION FOR A SPIN WAVE IN A TWO-SUBLATTICE ANTIFERROMAGNET

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KEY WORDS: spin wave, antiferromagnet, self-similar solution

In the paper, spin waves in a uniaxial two-sublattice antiferromagnet are investigated. A new class of self-similar solutions of the Landau-Lifshitz equation is obtained and, therefore, a new type of spin waves is described. Different types of solution are obtained for the cases when the spin wave speed v exceeds the characteristic speed c defined by the antiferromagnet parameters and when $v < c$ (for $v = c$, no solutions of the described type are possible). Examples of solutions of the found class are presented. New type of solution admits both linear and non-linear spin waves, including solitons. Space transformations used for finding of the above-mentioned solutions are mathematically analogous to the relativistic space transformations, with the abovementioned characteristic speed playing role of the speed of light.

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

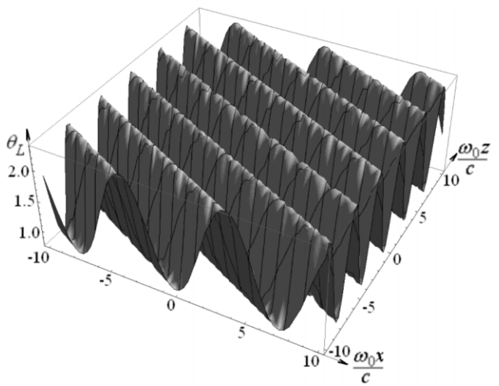

Fig. 8: Dependence of the azimuthal angle for the antiferromagnetic vector θ_L on the dimensionless coordinates for an example for the described spin waves class for the time $t = c/\omega_0 v$. Here x, z are the Cartesian coordinates, c is the above-mentioned speed defined by the antiferromagnet parameters and ω_0 is the wave frequency

MAGNETIC SKYRMIONS IN PATTERNED FILMS: STABILITY AND DYNAMICS

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KEY WORDS: magnetic skyrmions, nanodots, magnetic films, topological charges, spin waves

Magnetic skyrmion is a kind of topological soliton, a non-trivial magnetization texture on the nanoscale. Skyrmions can be manipulated by spin polarized currents of extremely low density in comparison with the densities used in traditional spintronics [1]. Recently stabilization of the individual skyrmions was experimentally demonstrated at room temperature in Co/Pt, Co/Pd and Ir/Co/Pt ultrathin multilayer structures, including magnetic dots. To achieve efficient manipulation of the nanosized spin textures and realize skyrmion-based new brand spintronic devices, it is essential to understand skyrmion dynamics in confined geometries.

In this talk I focus on skyrmion stability and excitations in ultrathin cylindrical magnetic dots. The skyrmion can be stabilized at room temperature due to interplay of the isotropic exchange, interface Dzyaloshinskii-Moriya (DMI), perpendicular magnetic anisotropy and magnetostatic interaction [2]. The chiral DMI induced on the interfaces with ultrathin ferromagnetic layers ($0.5 - 1$ nm) is crucial for the skyrmion stabilization. We consider Bloch- and Neel- skyrmions (see Fig.). The calculated spin wave eigenfunctions/eigenfrequencies are classified according to number of nodes of the dynamical magnetization in the radial and azimuthal directions [3]. The low-frequency skyrmion gyrotropic modes are in sub-GHz frequency range [4] and can be exploited in spin-torque nano-oscillators. The excitation frequencies are represented as functions of the skyrmion equilibrium radius, dot radius and the dot magnetic parameters. Recent experiments on magnetic skyrmion stabilization and dynamics in nanodots will be discussed.

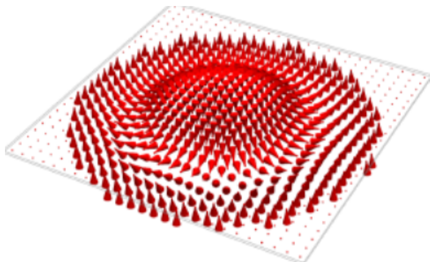

Fig. 9: The magnetization texture of the Neel skyrmion in thin circular dot [5]

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

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KEY WORDS: Dzyaloshinskii-Moriya interaction, nonreciprocal spin wave, skyrmion, skyrmion dynamics, spin excitation over skyrmion state

The spin excitations in ultrathin films and nanodots with Dzyaloshinskii-Moriya interaction (DMI) were under investigation. At first, influence of the DMI on propagation in single domain (SD) state was studied in magnonic crystals and stripes [1]. The effect of nonreciprocity induced by DMI was described. The stability of nonuniform magnetization states was evaluated in nanodisks, where influence of the presence of nanodisk boundaries and nonuniformities in multilayer structures was considered. Further, the spin excitations in nonuniform states in nanodots were analyzed, specifically, mapping of dynamical modes in vortex and skyrmion states of Bloch and Néel type was calculated [2] to understand the dynamics present in skyrmion state. The classification of low frequency gyrotropic modes and high frequency spin wave excitations was analogically showed. Further, influence of the nanodot shape (non-circular symmetry) on spin wave dynamics was studied and possibility of different mode excitations with uniform microwave magnetic field evaluated. The results point out at the possible spin wave excitations in Skyrmion Lattices (SkL), where non-circular potentials are spontaneously formed. Next, the spin dynamic in the array of nanodots was under investigation and possible coupling of skyrmion modes analyzed, see Figure [3].

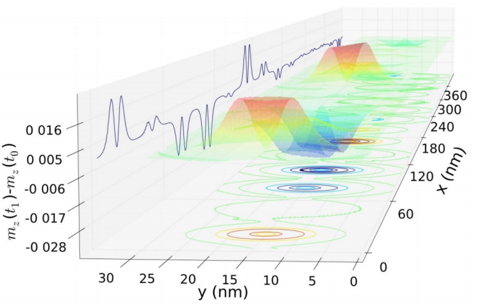

Fig. 10: A collective spin excitation in an array of nanodisks: breathing skyrmion mode

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SPIN-WAVE EXCITATION SPECTRA OF THICK MAGNETIC CIRCULAR DOT IN VORTEX STATE

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KEY WORDS: spin waves, magnetization dynamics, ferromagnetic resonance

Magnetic vortex state excitations in relatively thick cylindrical $Ni_{80}Fe_{20}$ dots with radius of 150 nm and thicknesses varying from 20 to 100 nm were investigated experimentally and micromagnetically. Multiple spin excitation modes were detected using broadband ferromagnetic resonance spectroscopy in the frequency range 0.1-20 GHz in the absence of external magnetic field. The remarkable similarity between experimental and simulated microwave absorption spectra was found, allowing to consider micromagnetic simulations as a reliable tool to study in details intensity profiles of the observed modes and their evolution with time.

The spin-wave exitation spectra of thin (30 nm and below) circular ferromagnetic dot consists of uniform gyrotropic mode G_0 and doublets of azimuthal modes (± 1 modes) with different radial indices, among which uniform along radial coordinate modes are the lowest and the most intensive. With further thickness increase the situation is getting more complicated. First, higher order gyrotropic modes G_1, G_2 (flexure oscillations of the vortex core string with $n = 1, 2$ nodes along the dot thickness, see Fig.) become noticeable [1] and their relative intensities grow with thickness [2]. Second, at higher frequencies new modes having curled structure at surfaces and radial nodes at dot central plane appear [3]. Such complex structure of modes is a consequence of increasing thickness nonuniformity of effective field in thick dots. These "curled" modes become the lowest ones in azimuthal modes spectrum for $t > 50$ nm, and, in contrast with common uniform along dot thickness modes, have a significant difference in the intensity between clockwise (cw) and counterclockwise (ccw) modes of the same type.

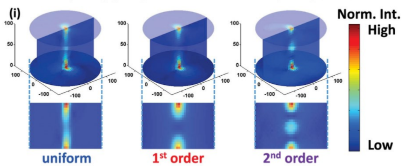

Fig. 11: Dynamical magnetization distributions of $n = 0, 1, 2$ vortex eigenmodes

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ELECTRICALLY DRIVEN MAGNETIC DYNAMICS

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KEY WORDS: spin waves, magnetization dynamics, ferromagnetic resonance

One of key issues in current spintronics/magnonics is all-electrical control of magnetic (spin) states, and electrically driven magnetic dynamics. This can be achieved by several different methods. Some of the possibilities of electrically driven magnetic dynamics will be briefly discussed in the context of recent theoretical and experimental achievements. This includes spin wave excitation in magneto-electric crystals, where a dynamical electric field can excite spin waves owing to magneto-electric interactions. Another possibility of electrical excitation of magnetic dynamics is due to spin transfer torque and/or spin-orbit torque exerted on a magnetic moment when a current flows through the system. The former torque appears due to absorption of spin current, while the latter torque is a result of current-induced polarization of electrons in the presence of spin-orbit interaction. Both these methods require either charge current or spin current. A pure spin current can be generated for instance due to spin Hall effect in heavy metals (strong spin-orbit coupling). An interesting option appears when magnetic system is on an insulating piezoelectric substrate. Magnetic dynamics can be then excited by a dynamical electric field without accompanying electric current.

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LOCAL INJECTION OF PURE SPIN CURRENT GENERATES ELECTRIC CURRENT VORTICES

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KEY WORDS: pure spin current, spin diffusion length, Johnson-Silsbee voltage

We show that local injection of pure spin current can produce electric currents running inside an electrically disconnected device with ferromagnetic and normal metal parts.1 These currents are circular, run along closed loops inside the device, and are powered by the outside source responsible for spin injection.

Pure spin current injection is always assumed to be special because electric and spin currents are dissociated in such an experiment. Generation of circular currents violates this assumption, and may lead to important consequences. For example, in the non-local voltage measurements of Johnson-Silsbee type circular currents change measured voltages by an amount that has the same order of magnitude as voltages in zero-current situation.

Another surprising consequence of the loop current generation is the enhancement of spin diffusion length along the normal metal - ferromagnet interface. For an infinitely thick ferromagnetic overlayer spin diffusion length becomes infinite, and spin decay follows a power law.

More generally, electric current vortices at the interface between two conducting materials shall be expected whenever electric current is coupled to another driven diffusive current by linear relationships with material-dependent Onsager crosscoefficients.

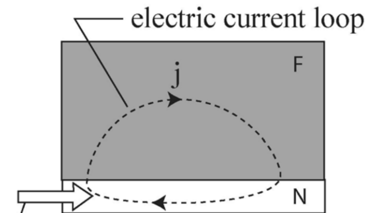

Fig. 12: Pure spin current injected into the normal part of the F/N bilayer

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MAGNETIC VORTEX LATTICE

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KEY WORDS: magnetic vortices, reversal behavior, exchange bias

Magnetic nanostructures have attracted large interest due to their unique properties. In this regard, as the size of a magnetic structure is reduced, the multi-domain state becomes energetically unfavorable and either a single domain or an inhomogeneous magnetization configuration is formed. In particular, for soft ferromagnetic disks in the micron size range a so called vortex state is favored, where the magnetization is forming an in-plane flux closure structure to minimize the magnetostatic energy. In addition, in the center, a vortex core occurs where the magnetization is pointing perpendicular to the disk plane as a result of minimizing the exchange energy. In our study, a two dimensional vortex lattice was prepared by magnetic permalloy (Py) film deposition onto self-assembled densely packed particle arrays forming magnetic cap structures. Strong coupling is induced by deposition of thick Py films, where neighboring caps will be interconnected at the contact areas, resulting in direct magnetic exchange coupling [1]. Here, we report on the influence of magnetic coupling on the reversal behavior and the in-plane circulation orientation of neighboring caps, which can lead to frustration in a hexagonal cap array. Moreover, exchange biased Py/CoO vortex structures studying magnetization reversal, cooling field dependence, and training will be discussed [2].

In a further study, the vortex cores were investigated by an in-field scanning magnetoresistive microscope (SMRM). This device uses a state-of-the-art magnetic recording head of a hard disk drive and individual vortex cores can be investigated and their lateral displacement when an in-plane field is applied can be evaluated. In addition, this tool allows applying a magnetic field pulse to individual vortices. A successful sequential switching process of individual vortex cores is obtained, where vortices with core polarization “down” (dark) were reversed to the opposite direction “up”, revealing bright contrast after the switching event [3]. This study is accompanied by micromagnetic simulations, revealing that the reversal processes are dominated by strong suppression of spin waves excitations using a local field pulse [4].

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SPIN WAVES IN MAGNONIC NANOSTRUCTURES

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KEY WORDS: X-ray Microscopy, XMCD, magnonic crystals, spin wave focusing

Magnonic crystals are nanostructured metamaterials with periodically alternating magnetic properties, similar to photonic crystals, which have gained significant scientific interest in the past years [1-4]. A periodic variation is achieved by creating holes in a magnetic host material to form a so-called antidot lattice (ADL). The introduction of the artificial ADL allows to alternate the spin wave dispersion in the material and to form a spin wave guide or filter [2,3]. Additionally, these antidots act as scattering centers for spin waves and can be used to form magnonic devices based on spin wave interference [4].

As the spin wave propagation in nanoscaled magnonic structures cannot be visualized by time resolved Kerr microscopy, typical investigations use all electrical spin wave spectroscopy or Brillouin light scattering and are unable to directly image the propagation of spin waves in nanometer sized magnonic crystals. Here, we present results from advanced time resolved x-ray microscopy (MAXYMUS@BESSY) with magnetic contrast. Spin wave modes ranging from 250 MHz up to 8 GHz in the rich spin wave band structure of ADL based magnonic crystals 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.

Additionally, we present an interference based Fresnel lens that is based on an antidot structure in permalloy. The spin wave propagation is then imaged by time-resolved x-ray microscopy to observe the interference that leads to the formation of a focal spot in a wide frequency range (2 – 10 GHz). In the focal spot the spin waves are confined to less than 800 nm within a uniform film. The intensity is increased by more than 20% above the emission intensity. Thus, the lens is overcompensating the damping. Furthermore, the focal spot can be moved in a 6x6 μm^2 area by changing the applied magnetic bias field.

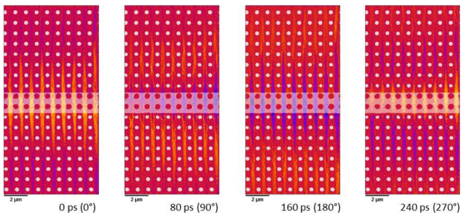

Fig. 13: Dynamic X-ray micrographs with magnetic contrast (XMCD) at different time steps of a movie showing the propagation of a spin wave mode in an antidot lattice. The spin wave can only propagate between antidots. The applied external bias field allows propagation over 10 μm from the excitation source. The positions of the stripline and the antidots are indicated as white overlays

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TOWARD THREE-DIMENSIONAL MAGNONIC CRYSTALS

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

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 thicknessmodulated nanowires fabricated by the self-aligned shadow deposition technique. We have shown that this kind of structures support the propagation of collective SWs in the periodicity direction, thus demonstrated that layering along the third dimension is very effective for controlling the characteristics of the magnonic band [1]. More in details, a blue shift in frequency of the lowest frequency modes has been observed for thickness-modulated Permalloy (Py) NWs when compared to a reference planar array of Py NWs. Later, the investigation has been extended to the case of bi-layered Fe/Py NWs having either rectangular or L-shaped cross-section (upper layer of a half width with respect to the bottom one), for 10 nm thick Py layer and Fe thickness in the range between 0 and 20 nm [2,3]. Remarkably, it was found that the magnonic band structure was significantly altered by the combination of the two layers and by the thickness of the Fe layer.

Another possible approach to realize 3D MCs, is to have an array of ferromagnetic dots deposited on top of a continuous ferromagnetic film. We will present some preliminary results for this kind of structures and discuss the relevant aspects of the spin wave propagation.

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IMPRINTED NON-COLLINEAR SPIN TEXTURES

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Chiral magnetic spin textures, such as vortices, chiral bubbles, Skyrmions and chiral Neel walls, are topologically non-trivial solitary objects with fundamentally intriguing properties and potential applications as magnetic storage and logic devices. However, neither configuration is a ground state in conventional extended magnetic films. Vortices are stabilized in soft-magnetic nano- and micro patterns and as thermally excited states in extended films. Chiral bubbles, Neel walls and Skyrmions typically nucleate in systems with inversion symmetry breaking due to an emergent vector spin exchange, known as Dzyaloshinskii-Moriya interaction (DMI).

In this talk, I will present an alternate route to design imprinted non-collinear spin textures by vertically stacking patterned magnetic films with distinct properties and interlayer exchange coupling. I will address recent theoretical and experimental works covering both static and dynamic aspects. Tailoring the strength of interlayer exchange coupling allows to tune the directionality of modifications and may serve as a tool to probe DMI and topology detecting e.g. the gyration frequency.

FABRICATION OF NANOSTRUCTURES FOR MAGNONIC AND SPINTRONIC APPLICATIONS

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KEY WORDS: electron beam lithography, focus ion beam, maskless photolithography

Magnonics and spintronics are now highly developed areas in physics that open possibilities to fabricate new magnetic devices allowing for operation with spin/magnon in nanoscale. This approach is highly important for a new type of ultra-fast magnetic memories [1] and for new concepts in information technology [2]. An important aspect of this research and consequent future applications is a fabrication of magnetic active elements, which have to be combined with the architecture of whole device integrated with conventional electronic elements. In many cases, it is required that the individual elements of a structure have to be made in the submicron scale, which means that patterning of thin films with thicknesses in the nanometer range need to be performed using the electron beam lithography (EBL) or the focused ion beam (FIB). Combining these methods with maskless photolithography (MPL), which can be done in the areas of 6-inch wafers, open the way to fabricate complete devices for magnonic and spintronic applications.

In this talk, the technology of manufacturing of magnetic structures in the submicron scale will be presented using the infrastructure of the Wielkopolska Center for Advanced Technologies and the Institute of Molecular Physics, Polish Academy of Sciences. I will focus on technological aspects of nano- and microstructure patterning using EBL, FIB, and MPL techniques. Based on the fabrication of the Ni80Fe20 kagome lattice and the one-dimensional magnonic crystals in the form of periodic and quasiperiodic $Ni_{80}Fe_{20}$ stripes using EBL and liftoff technique the preparation difficulties will be discussed. Additionally, propagation of the spin waves in CoFeB/NiO system and Yttrium Iron Garnet thin film will be shown using Vector Network Analyzer and two coplanar waveguides (CPWs) made by MPL.

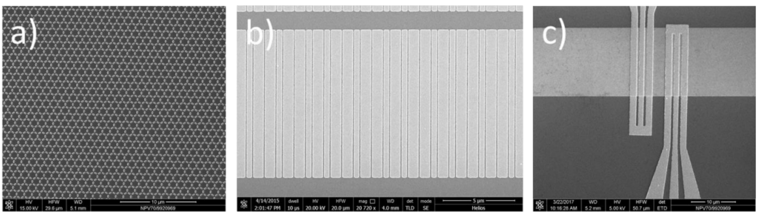

Fig. 14: Scanning electron microscopy images of: a) $Ni_{80}Fe_{20}$ kagome lattice, b) quasiperiodic $Ni_{80}Fe_{20}$ stripes and c) CoFeB/NiO microstripe with deposited CPWs

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SPIN WAVE DYNAMICS IN PLANAR MAGNONIC CRYSTALS AND QUASICRYSTALS

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KEY WORDS: spin waves, magnonic crystals, plane wave method, micromagnetic simulations

Magnonic crystals and quasicrystals are the structures where the magnetic properties change periodically and qusiperiodically in space, respectively. This kind of long range order leads to the appearance of forbidden frequency gaps in the spectrum of magnetic excitations – spin waves. In magnonics, similarly like for other sorts of systems (e.g. photonic systems), the geometry of the structure and the material composition are the main factors responsible for shaping the properties of wave excitations and determining their spectrum. However, the magnonic systems have a few unique features which make them particularly interesting. (i) There are two magnetic interactions of different kind: long range dipolar interaction and short range exchange interaction. They change differently when the sizes of the system are scaled up or down and therefore the spin wave spectrum cannot be scaled with sizes of the structure. (ii) Spin wave propagation for film geometry is strongly anisotropic in dipolar regime with respect to the direction of the external magnetic field, even for homogeneouslayer. This introduces the additional source of the anisotropy which is purely related to periodicity or quasiperiodicity. (iii) The patterning of the film is responsible for the existence of inhomogeneous distribution of static demagnetizing field which, additionally to the spatial distribution of material parameters, affect the spin wave spectrum. The demagnetizing field, and thus the spin wave dynamics can be controlled by the change of the direction of external field.

We are going to discuss the mentioned features of planar magnonic crystals and quasicrystals by presenting the results of numerical calculations performed with the aid of plane wave method and micromagnetic simulations, supplemented with some experimental results.

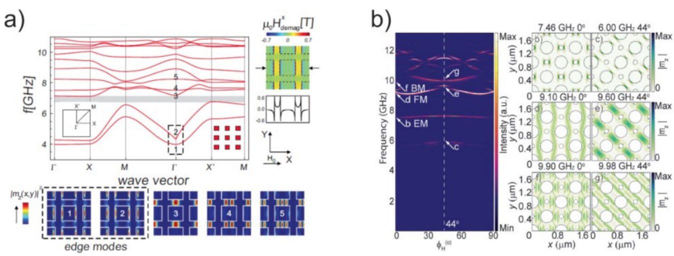

Fig. 15: Spin wave spectrum and profiles for (a) bi-component magnonic crystal [1] and (b) magnonic antidote lattice [2] calculated with the aid of plane wage method and micromagnetic simulations, respectively

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Abstracts
Short talks

THEORY OF LINEAR SPIN WAVE EMISSION FROM A BLOCH DOMAIN WALL

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KEY WORDS: domain walls, spin waves, theory

The generation of small wavelength spin waves for future magnonic technologies will require nanometre-sized spin wave sources. Recent work has shown that pinned domain walls can generate spin waves when excited by a microwave external field [1,2,3,4] or spin-polarised current [5], even with wavelengths down to tens of nanometres. These results would benefit from a quantitative, theoretical explanation of the underpinning physics. Here, we use analytical theory to demonstrate and explain the emission of exchange spin waves from a Bloch domain wall driven by a uniform microwave magnetic field directed perpendicular to the plane of the wall. Crucially, we find that the spin wave emission (Fig.) is the result of a linear process, meaning that the spin wave frequency matches that of the excitation field. Furthermore, we explore the peculiar characteristics of the Pöschl-Teller potential well, which naturally represents the graded magnonic index due to the Bloch domain wall in the Schrödinger-like linearized Landau-Lifshitz equation. This potential is known to allow 100% transmission of incident waves at any frequency, for certain parameters of the potential. We find that the domain wall is naturally sized not only to exhibit this property, but also to maximize its spin wave emission.

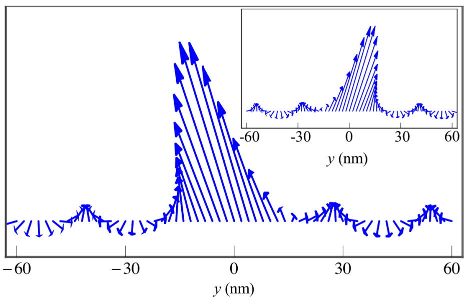

Fig. 16: Projection onto the x-y plane of the magnetization vectors for the Bloch domain wall is shown for phase = 0 and (inset) phase = π

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SPIN WAVE BEAM PROPAGATION THROUGH MEDIA WITH THE GRADED REFRACTIVE INDEX

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KEY WORDS: spin wave beams, graded-index magnonics

One of approaches for efficient wave guiding is use of media with a gradually modulated refractive index (graded index media). Using iso-frequency dispersion contours analysis supported by micromagnetic simulations, we study the spin wave beam propagation in thin ferromagnetic films with gradually modulated refractive index introduced by means of spatially nonuniform static internal magnetic field. The influence of the refractive index modulation on the direction of the spin wave beam propagation is discussed, in particular we show a mirage effect for spin waves. The acquired knowledge we use to study the influence of the refractive index variation near the edges of narrow ferromagnetic stripes on the spin waves propagation, especially on the dispersion of the spin wave pulses. Such systems can be considered as the magnonic graded-index waveguides with the prospects for applications which will be discussed.

Acknowledgements: This work was supported by grants: NSC Poland UMO-2012/07/E/ST3/00538 and EU's Horizon2020 MSCA RISE programme GA No. 644348(MagIC).

SPIN WAVE FOCUSING IN THIN MAGNETIC FILMS WITH ELECTRIC FIELD CONTROLLED NONRECIPROCITY

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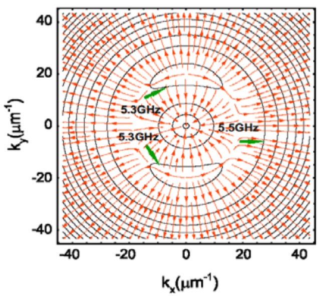
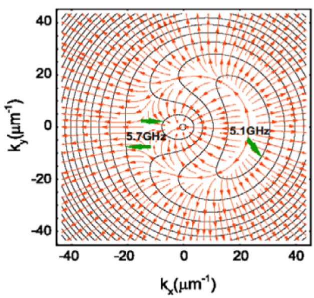
KEY WORDS: spin waves, power flow, nonreciprocity, backward waves

External electric field can modify the strength of the spin-orbit interaction between spins of ions in magnetic crystals. This influence results in a spin wave frequency shift, which is linear in both the applied electric field **E** and the wave vector of spin waves **k**. Thus, in addition to an ellipticity of the precession, the external electric field results in nonreciprocity of spin wave propagation, i.e. $\omega(\mathbf{k}, \mathbf{E}) \neq \omega(-\mathbf{k}, \mathbf{E})$, and in noncollinearity the group velocity v_g and the wave vector **k**. We apply these findings to examine theoretically how the dipole-exchange spin wave nonreciprocity can be tuned by the electric field and how the spin wave power flow is affected by the external electric field in ultrathin ferromagnets. The spin wave focusing pattern is obtained from the slowness surfaces (isofrequency curves in *k*-space) by finding the normal, i.e. v_g , to the slowness surface and then evaluating the curvature at each point of the curves. The v_g indicates the direction of the energy flow. When the curvature is zero, one finds the so-called caustics beams: for waves with different wave vectors **k** the group velocity has the same direction and, formally, in such directions the power flow diverges. The figure shows isofrequency curves with the frequency step of 0.2 GHz and corresponding group velocity v_g directions for dipole-exchange spin waves in $Y_3Fe_5O_{12}$ thin film at (a) $E = 0$ and (b) $E = 2 \cdot 10^7$ V/m. Thus, we demonstrate that the combination of the dipole-dipole interaction and field-induced nonreciprocity of spin wave propagation can result in unidirectional caustic beams of dipole-exchange spin waves. Our findings open a novel important avenue for spin wave manipulation and development of electrically tunable magnonic devices.



(a)



(b)

Fig. 17: Spin waves lowness surfaces and group velocity directions at (a) $E = 0$ and (b) $E = 2 \cdot 10^7$ V/m

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FORCED MAGNETIC OSCILLATIONS AND EXCITATION OF BULK SPIN WAVES BY ACOUSTIC WAVE AT THE PLANE DEFECT OF A FERROMAGNET

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KEY WORDS: spin wave, acoustic wave, ferromagnet, elastic energy

Surface acoustic waves are extensively investigated in seismology, bio-sensing and phononics. Recently much attention is focused on the coupling of spin waves with other degrees of freedom in the solid state, e.g. on coupling with acoustic waves [1-3]. In this work we considered analytically and numerically the influence of externally excited Kosevich wave to the dynamics of magnetization at the interface between two ferromagnets. We obtained the solution for the magnetic oscillations forced by the acoustic wave. Next, we performed numerical simulations for the case of cobalt in the exchange regime to present those oscillations. Moreover, we present numerical results for the resonant excitation of bulk spin waves by the interface Kosevich wave - in and out of the regime of the phase matching.

We acknowledge the financial assistance from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 644348 (MagIC).

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STATIC AND DYNAMIC PROPERTIES OF 1D QUASIPERIODIC MAGNONIC STRUCTURES

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KEY WORDS: magnonic crystals, quasiperiodic, Fibonacci

In this work we report on fabrication of one-dimensional quasiperiodic magnonic structures consisted of $Ni_{80}Fe_{20}$ nanowires (NWs) arranged using Fibonacci inflation rule [1] and their static and dynamic properties. An influence of stripes arrangement and distance between NWs arrays on magnetization switching behavior was investigated in static measurements using magneto-optical Kerr effect. For Fibonacci structures preferences of magnetization switching dependent on types of neighboring stripes were observed and also changing of strength of magnetostatic interactions between stripes for different gaps between arrays was seen. Magnetic dynamic properties were investigated using ferromagnetic resonance with vector network analyzer and scanning x-ray microscopy with x-ray circular dichroism contrast, enabling imaging of SWs propagation for both quasiperiodic and reference periodic structures. Gradual variation of the phase along the SWs motion direction was visible which indicates propagating character of the SWs in the structure. Significant jumps of the phase value between wide and narrow nanowires were also observed and were recognized as out-of-phase oscillations in both type of nanowires. It may suggest that the optical modes were excited. The outcomes of numerical calculations were used for the interpretation of the experimental results.

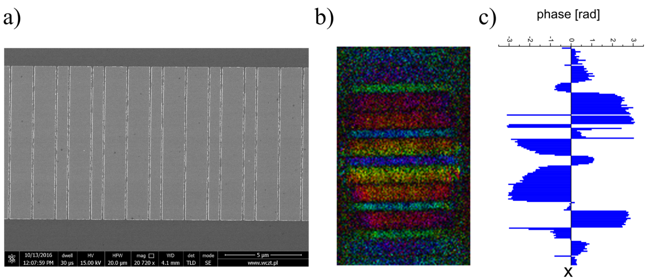

Fig. 18: (a) SEM images of the quasiperiodic Py structure, (b) STXM image of magnetic excitation in the structure and (c) corresponding phase plot

The study has received funding from European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie GA No644348 (MagIC).

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SPIN WAVE STANDING MODES IN BICOMPONENT MAGNONIC CRYSTALS AND QUASICRYSTALS

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KEY WORDS: spin waves, magnonic crystals, magnonic quasicrystals, localized states

Magnonic crystals are artificial structures, composed of periodically arranged ferromagnetic elements (layers, wires, dots), in which the spin wave dynamics can be tailored by adjusting the structural and material parameters. We considered the spin wave standing modes in one-dimensional planar magnonic crystals of finite thickness, terminated in symmetry points of unit cells. The profiles of magnetization for these modes can be distributed in oscillating way (for the frequencies of bands regions) or can be localized at the defects/surfaces (for the bandgaps frequencies ranges) evanescing into the bulk of the structure. These kinds of localized modes are called surface states. We study here two types of surface states referred to as the Shockley and Tamm states (which is the terminology used in electronic crystals). Shockley states appear due to the breaking of the magnonic crystal exactly at the symmetry point of the symmetric unit cell, while Tamm states appear due to the presence of an additional perturbation [1].

We will also present results of our calculations regarding spin wave dynamics in magnonic quasicrystals, which are ordered but not periodic structures. Surroundings of elements, building the structure of quasicrystal are unique. These features of magnonic quasicrystals are manifested by (i) the appearance of complex system of band gaps and (ii) localization of spin waves of higher frequencies in the bulk regions of an intact system [2]. Moreover, we have investigated the lifetime of spin wave modes in magnonic crystals and magnonic quasicrystals [3].

This work was supported by grants founded by (i) the EUs Horizon2020 MSCA-RISE-2014 Marie Skłodowska-Curie Research and Innovation Staff Exchange GA No. 644348 (MagIC), (ii) National Science Centre Poland: for Sonata-Bis2 grant UMO-2012/07/E/ST3/00538 (MagnoWa).

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PARAMETRIC FREQUENCY MIXING IN THE MAGNETO-ELASTICALLY DRIVEN FMR – OSCILLATOR

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KEY WORDS: parametric excitation, spin waves, magnetoelasticity, FMR

We describe measurements of the elastically driven ferromagnetic oscillator, which exhibits sum and difference frequency conversion over a wide range of frequencies [1]. The magnetization precession is driven by two narrowband elastic waves which are generated using the ultrafast optical transient grating geometry [2]. The frequencies of the driving forces are fixed by the underlying elastic waves, which are measured simultaneously with the magnetic response. The phase velocity of elastic waves are $v_{SAW} = 3.0$ km/s and $v_{SSLW} = 5.7$ km/s, providing driving frequencies of $\nu = v_{acoustic}/\Lambda$. Along with magnetization precession at the elastic wave fundamental frequencies, we further observed precessional frequencies coincident with the sum of the driving frequencies, as well as a parametrically downconverted precessional motion. We calculate the response of a forced linear parametric oscillator and show that all sum and difference frequencies can be incorporated into this model. Numerical solutions show good qualitative agreement with experiments.

This work may provide an effective way to a fabricate a high-speed magneto-photonic device which can carry specific remote spin information on an elastic wave in the future spintronic application.

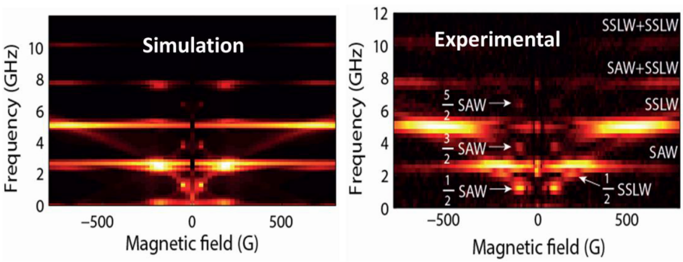

Fig. 19: This figure shows a comparison between experiment and simulation of the parametric excitation of spin waves

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SPATIAL ALTERATION OF MAGNETIC ANISOTROPY IN MULTILAYERED SYSTEMS: AN INITIAL STEP TO MAGNONIC CRYSTAL FABRICATION

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KEY WORDS: spin wave in YIG, magnon BEC, spin superfluidity

Recently it was suggested [1] that spin supercurrents analogous to supercurrents in superfluids are possible in the magnon BEC observed in yttrium-iron-garnet (YIG) magnetic films under strong external pumping. Bozhko et al. [2] declared experimental detection of spin supercurrent in a decay of the magnon condensate in YIG.

The previous analysis of spin superfluidity in YIG films was based on the widely accepted in the past spin-wave spectrum in YIG films, which was essentially revised in the present work. The new analysis properly takes into account exchange and boundary conditions on film surfaces without approximations used before.

The revised spectrum of linear spin waves has different dependence on film thickness. This led to reaccession of non-linear effects, which determine stability of the magnon BEC and possible spin superfluidity.

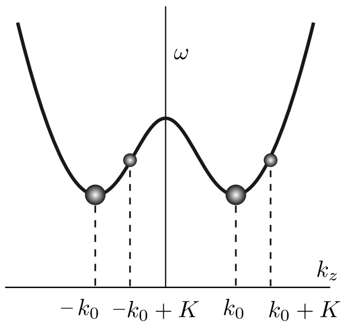

Fig. 20: The spin-wave spectrum in a YIG film. In the ground state the magnon condensate occupies two minima in the $k$space with $k_z = \pm k_0$ (large circles). In the current state two parts of the condensate are shifted to $k = \pm k_0 + K$ (small circles)

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TEMPERATURE DEPENDENT CAVITY MAGNON POLARITON SPECTROSCOPY IN YIG

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KEY WORDS: polariton, temperature dependence, coupling strength, magnon linewidth

In information technology research, spin based approaches are promising candidates for new applications such as data storage or logic. The collective excitation of a spin ensemble can result in a spin wave that is often in the microwave (GHz) regime and termed magnon. Experimentally, we interface such magnons with microwave cavities to investigate dynamics within the magnetic system. To this end, magnonic elements are strongly coupled to a photonic resonator, resulting in hybridized magnon - resonator states, i.e. cavity magnon polaritons. We have set up an experimental apparatus for the resonant coupling of spin waves in magnetic bulk or thin film systems to either inside a microwave cavity or a coplanar waveguide (CPW) in the strong coupling regime [1,2]. This enables both readout at a fixed frequency or broadband measurements employing ferromagnetic resonance (FMR) and input-output theory for temperatures from 5 K to 300 K. We present temperature dependent spectroscopic measurements of magnon - polariton states. The sample is a YIG sphere ($d = 0.5$ mm), placed in the 6.5 GHz bright mode of a double post cavity [3]. Features of the strongly coupled systems such as the coupling strength g, resonance frequency and linewidth of Kittel mode are analyzed [4] . We find a proportionality of the coupling strength of the Kittel mode to the temperature dependent saturation magnetization of our sample for high temperatures only. Below temperatures of 100 K the influence of additional higher order magnetostatic modes is considered.

As shown in Fig., the coupling strength g can be well described by the relation $g \propto \sqrt{M_S(T)}$, where to first order the saturation magnetization changes according to Bloch's $T^{3/}2$ law above 100 K. Since the total number of spins is conserved, the coupling strength of the Kittel modes decreases due to additional coupling to other magnetostatic modes for lower temperatures. Similarly, we study the temperature dependence of the magnon linewidth. Investigating the changes in the loss factors of cavity and magnon on- and off resonance, reveals a total decrease in the linewidth by an order of magnitude to 290 K.

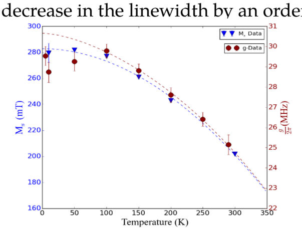

Fig. 21: Temperature dependence of the coupling strength and the saturation magnetization of the YIG sphere measured in SQUID along the (110) direction. Deviations for $T < 100$ K are attributed to the influence of simultaneous coupling to other magnetostatic modes.

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MAGNETORESISTIVE SENSORS WITH SUPERFERROMAGNETS

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Superferromagnets (SFMs), e.g., magnetic nano-crystal self-assemblies and/or arrays, represent promising candidates for Lab on a Chip systems including many laboratory tasks. Such soft magnetic systems provide an opportunity to develop new materials with characteristics far beyond traditional solids. The randomly jumping interacting moments (RJIM) model, see [1] and refs. therein, gives useful framewok for studies of SFMs. In particular, it provides a basis for developing analytical tools employed in order to specify, quantify and analyse respective magnetic structures. Such tools explore correlations of magnetic noise amplitudes and allow for quantitative definition, description and study the SFM origin, as well as self-organized criticality in the response properties. In this contribution we briefly overview some results for a sensor mode of SFM reactivity associated with spatially local external fields, i.e., a detection of magnetic particles. Favorable designs of superferromagnetic systems for sensor implications are revealed.

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TAILORING OF UNIAXIAL MAGNETIC ANISOTROPY IN PERMALLOY THIN FILMS USING SELF-ORGANIZED NANO RIPPLED TEMPLATES

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KEY WORDS: uniaxial magnetic anisotropy, nanoripples, ion beam erosion, grazing incidence small angle x-ray scattering

Controlling and manipulating of magnetic anisotropy in low dimensional systems such as ultra thin films is so important in applications like magnetic storage devices. Magnetic anisotropies of ultra thin films are inherently related to the structure and morphology of the thin films [1]. In this work we have employed nanopatterned substrates as a template to tailor uniaxial magnetic ansiotropy in Permalloy thin films deposited on it. Periodic Si ripple substrates having different value of wavelength have been prepared using oblique angle low energy ion beam erosion. Strong uniaxial magnetic anisotropy (UMA) with magnetization in a direction normal to the ripple wave vector has been observed. UMA is found to be gradually decreasing with increasing thickness of Permalloy thin films. Also thin films deposited on low value of (24 nm) ripple wavelength Si substrates are found to be exhibiting strong uniaxial magnetic anisotropy. Coercivity of the samples is also found to be increasing with increasing values of ripple wavelength. In order to correlate the structure and morphology of the substrates with observed magnetic anisotropy variation we did a detailed growth study of the films using in-situ grazing incidence small angle x ray scattering. We have found that both periodicity as well as depth of the ripples is crucial in determining the strength of UMA.

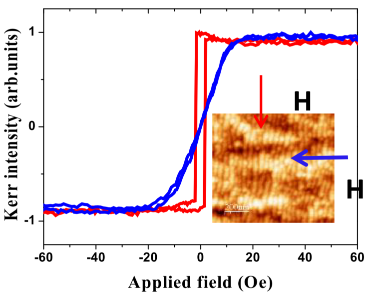

Fig. 22: MOKE hysteresis loops of Permalloy 10 nm thick film deposited on rippled Si substrate taken with applied field along (blue) and normal (red) to the ripple wavevector

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NEEL SKYRMION OBSERVATION IN Pt/Co/Au MULTILAYER NANODOTS

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KEY WORDS: skyrmion, spin waves, multilayers structrues

Neel skyrmions are of high interest due to their potential applications in a variety of spintronic devices, currently accessible in ultra-thin heavy metal/ferromagnetic bilayers and multilayers with a strong Dzyaloshinskii-Moriya interaction. Here, we report on the observation of magnetic skyrmions hysteresis behaviour, nucleated in an exchange-coupled Pt/Co/Au multilayers stacks with perpendicular magnetic anisotropy. We consider theoretically with Micromagnetic Simulations (MSs) a circular dots for different parameters like a diameter and number of repetitions. For some configurations, we notice two stable magnetic configuration of skyrmion type with significantly different diameters.

We found reversible hysteresis loops of the skyrmion radius as a function of the Interfacial Dzyaloshinskii-Moriya strength (Fig.), giving realistic opportunity to create memory cells where information bit will be coded by the skyrmion diameter. The switching would be realised with sweeping the external magnetic field or by change in the spin-polarized current. We developed a technique to compute the total energy of magnetic configuration as a function of the skyrmion diameter, allowing us to estimate the potential barrier between stable states and to explain the influence of dipolar energy contribution on bi-stable skyrmion formation in multilayer dot systems, and skyrmion formation in general.

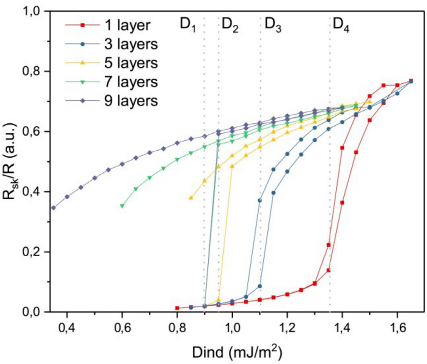

Fig. 23: Skyrmion diameter in Pt/Co/Au system as a function of the DMI parameter for different numbers of multilayers. D_{1-5} represents a starting point of skyrmion growing for different number of structure repetitions

CALCULATION OF COLLISION INTEGRAL BETWEEN MAGNONS AND PHONONS AT DIFFERENT TEMPERATURES IN FERRODIELECTRIC

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KEY WORDS: ferrodielectric, different temperatures of magnons, phonons, collision integral

A ferrodielectric (FD) at two essentially different temperatures for magnons and phonons – T_s and T_l, respectively, is theoretically considered. It is shown that a simple expression for the collision integral between magnons and phonons at $T_s \neq T_l$ can be derived. Actually, it is well known [1] that a change of the number of phonons with a given wave vector **q** caused by absorption and emission of a phonon by magnon in the unit of time can be presented as $\left(\dot{N}_g\right)_S = L_{ls}\{N, n\}$, where the right hand is the collision integral between phonons and magnons with distribution functions N and n, respectively. We have shown that for quasiequilibrium FD at two different temperatures T_s and T_l for magnons and phonons, respectively, the collision integral can be presented in relatively simple form as

$$\dot{N}(T_l, T_s) = v_{ls}\left[N_q\left(\frac{\varepsilon_q}{T_s}\right) - N_q\left(\frac{\varepsilon_q}{T_l}\right)\right],$$

where

$$v_{ls} = \frac{1}{\tau_{ls}(\omega)} = -\frac{\delta L_{ls}}{\delta N_q(\omega)},$$

(see [1]) is the frequency of phonon-magnon collisions at temperature of magnons T_s (and τ_{ls} is the corresponding relaxation time), for which we obtained the formula

$$v_{ls}(T, q) = D(T)\int_{y_0}^{\infty} dyy(x+y)\left(\frac{1}{e^y - 1} - \frac{1}{e^{x+y} - 1}\right) \equiv D(T)I_D(T),$$

where

$$D(T_s) = \frac{\theta_D^2\theta_C}{2\hbar\theta_P}\left(\frac{T_s}{\theta_C}\right)^3 \quad \text{and} \quad I_D(T_s, x, y_0) = \int_{y_0}^{\infty} dy(yx + y^2)\{[e^y - 1]^{-1} - [e^{y+x} - 1]^{-1}\}.$$

Here θ_C is the Curie temperature, θ_D is the Debye temperature, $x = \varepsilon_q/T, y = \varepsilon_k/T, y_0 = \theta_D^2/(4\theta_C T) \gg 1$, ε_q and ε_k is the energy of phonon and magnon with wave vectors values q and k, respectively, $\theta_P = Ms^2$, where M is the magnetic ion mass and s is the average sound velocity. The results presented here will allow us to study the nonlinear magnon-phonon relaxation FD films at low ($T < \theta_D$) temperatures for the cases where the temperature of "hot" magnons is substantially different from the temperature of "cold" phonons.

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SKYRMION CONFINEMENT IN MAGNONIC ANTIDOT LATTICES

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KEY WORDS: skyrmion, magnonic crystal, scanning transmission X-ray micoroscopy

Magnonic crystals are a novel type of artificial crystal formed by the periodic arrangement of magnetic nanostructures, and exchange coupled ferromagnetic antidot lattices are one of the most popular examples of magnonic crystals. Magnetic skyrmions [1] are topologically stable spin textures, generally stabilized by Dzyaloshinskii-Moriya interactions [2] that mainly arise due to the spin-orbit coupling and the lack of structural inversion symmetry. Skyrmions are a promising candidate for low dissipation magnetic information storage devices because of their small size and facile current driven motion. In addition to this, ensembles of skyrmions can also be considered as a self-organized lattice with periodically modulated magnetic properties, which could be implemented in future magnonic devices. Key challenges regarding the skyrmion lattice are to stabilize, confine and move skyrmions at room temperature by introducing magnetic topological defects in the form of magnonic crystals. The aim of the present work is to stabilize and confine the magnetic skyrmions by patterning a nanometer size antidot lattice in high perpendicular magnetic anisotropy films.

For this purpose, circular antidots of about 200 nm diameter and an edge separation of about 1 μm have been fabricated from $[Pt(3\,nm)/Co(0.9\,nm)/Ta(4\,nm)]_{12}$ multilayer stacks with high perpendicular magnetic anisotropy using focused ion beam lithography (Fig. a). The magnetic configuration of the continuous and patterned film was investigated with scanning transmission x-ray microscopy as a function of applied out-of-plane magnetic field. For the continuous film, a worm domain structure is observed which transforms into skyrmions on application of a magnetic field (Fig. b)). A similar worm domain structure is stabilized in the magnetic antidot arrays (Fig. c). However, due to the pinning caused by the presence of antidots, a higher magnetic field was necessary to cause the collapse of the worm domains into magnetic skyrmions, which are stable over a range of a few mT. These experimental observations are important for future magnon spintronic devices based on skyrmion lattices.

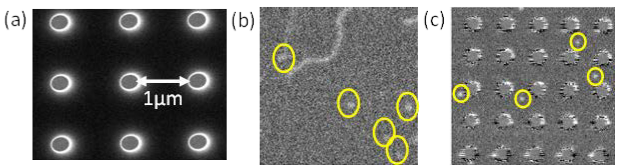

Fig. 24: (a) SEM images of antidot lattices, and STXM images of (b) skyrmions in the PMA film at 27 mT and (c) skyrmions in antidot lattice at 26 mT. The dark and bright contrast corresponds to magnetization oriented up and down, respectively

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ELECTRIC FIELD CONTROL OF MAGNETIZATION DYNAMICS AND STANDING SPIN WAVES INVESTIGATED WITH SPIN-DIODE EFFECT

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KEY WORDS: electric field controlled magnetization dynamics, spin waves, spin-diode effect

We present our recent results on modelling of spin-diode (SD) effect in spintronics devices: PMN-PT/NiFe heterostructures [1] and highly resistive magnetic tunnel junctions, controlled with electric field. We use micromagnetic approach and perform calculations in Object Oriented Micromagnetic Framework together with our custom extensions and support software. By utilizing micromagnetic simulations, we are able to get an insight into parameters and details of dynamics that are hard or impossible (as in the case of SD measurements) to obtain experimentally, standing spin waves (SSW) spatial distribution, phase and length. Experimental results are compared with micromagnetic simulations, showing good quantitative agreement for SSW resonance mode shift due to applied electric field (Fig. (a-b)), as well as field angular dependence of observed modes frequencies and amplitudes. We verify which experimentally observed modes are the SSW modes (Fig. (e-h)) and the FMR mode (Fig. (c-d)). Additionally, we discuss the influence of the distribution of the excitation current on the dynamics spatial distribution and SD output voltage.

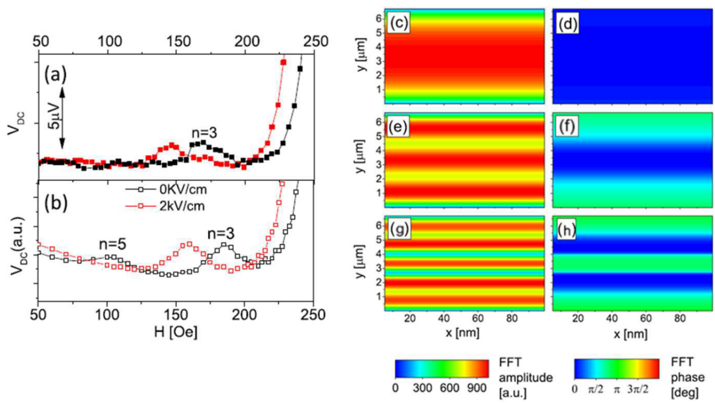

Fig. 25: (a) experimental and (b) simulated resonance modes as a function of magnetic field H for different electric fields. Spatial FFT amplitude and phase distributions corresponding to (c) and (d) FMR mode, (e) and (f) $n = 3$ SSW mode, (g) and (h) $n = 5$ standing spin wave mode

We acknowledge grant Preludium 2015/17/N/ST3/02276 from National Science Center, Poland. Numerical calculations were supported by PL-GRID infrastructure.

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FOCUSED ELECTRON BEAM-INDUCED DEPOSITION OF MAGNONIC METAMATERIALS

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KEY WORDS: focused electron beam-induced deposition, metamaterials, magnonic crystals, magnonic waveguides

Spin waves can be used as data carriers in next-generation information processing systems [1] and on-chip microwave applications. In this respect are especially promising magnonic metamaterials [2], in which the transmission of spin waves as well as the frequency and strength of spin-wave resonances are determined by the geometry and magnetization configuration of meta-atoms [3]. Practical ways to tailor properties of the building blocks are via their geometrical shaping and compositional modulation.

Focused electron beam induced deposition (FEBID) is a direct-write approach for the fabrication of 2D- and 3D-nanostructures [4]. Over the last decade FEBID has developed into a highly versatile technology for various materials research areas. These comprise superconductors, magnetic materials, multilayer structures and meta-materials in which suitable materials combinations result in a desired functionality.

In this work, we demonstrate a series of planar and 3D Co-based [5] structures fabricated by FEBID and present early results on the transmission of spin waves through them.

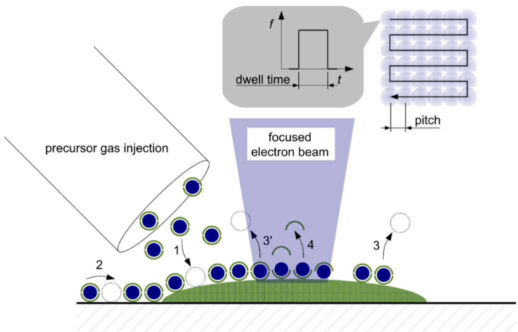

Fig. 26: Illustration of FEBID [4]. Precursor molecules are supplied by a gas-injection system and physisorb (1) on the surface. Surface diffusion (2), thermally induced desorption (3) and electron-stimulated desorption (3') take place. Within the focus of the electron beam, adsorbed molecules are dissociated followed by desorption of volatile organic ligands (4). Upper right: For pattern definition the electron beam is moved in a raster fashion over the surface and settles on each dwell point for a specified dwell time

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COUPLED SPIN MODES IN A BILAYER PERIODIC STRUCTURE

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KEY WORDS: spin wave, magnonic crystal, thin films

Coupling between modes is of great interest in all branches of wave physics, including magnonics. It is important phenomenon for developing such devices as waveguides, filters, transducers or amplifiers [1].

One way to design efficient interaction between modes is to optimize a periodic structure, the so-called magnonic crystal. With the help of the magnetostatic interaction it is possible to achieve energy transfer between two spin waveguides. On the other hand, couplings between different degrees of freedom, e.g. magnon-phonon [2] or magnon-photon [3] are also in development.

Here, we investigated coupling between spin modes propagating in a bilayer permalloy/nickel structure in Damon-Eshbach geometry. The permalloy layer is a homogeneous film, while the thickness of the nickel film is periodically modulated down to zero thickness (nickel stripes). The layers were in direct contact or the separation was introduced.

Dispersion relations of the bilayer structure have been numerically investigated. Brillouin light spectroscopy measurements of permalloy – Ni stripes were presented. The modes in permalloy/Ni bilayer possess nonreciprocal character, that is the wave numbers of the wave propagating in the opposite directions for a given frequency are different. Next, hybridizations of modes confined to a particular layer occur at the points of crossings. In case of Ni stripes typical band gaps appear for the modes propagating in a permalloy. On the other hand, co-directional and contra-directional couplings occur if the nickel is continuous periodic layer. Thus, interaction between propagating modes are present. What is also important, hybridizations of modes have nonreciprocal character.

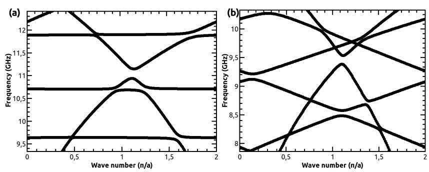

Fig. 27: Dispersion relations for (a) permalloy film – nickel stripes of the thickness of 30 nm and (b) permalloy film – nickel layer of alternating 30/15 nm thickness. Lattice constant of the structure was 490 nm. Hybridizations of permalloy mode with (a) nickel standing modes and (b) nickel propagating modes are visible

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Abstracts

Posters

THE MAGNETIZATION DISTRIBUTION IN FERROMAGNETIC THIN FILM WITH THE ANTIDOT

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KEY WORDS: single circular antidot, the magnetization distribution, magnetic field

We investigate theoretically the influence of dynamic microwave magnetic field applied to the permalloy (Py) thin film with a single circular antidot on the magnetization. The Py film is saturated by the external constant magnetic field along the direction perpendicular to the film plane. The structure is showed schematically in Fig. (a). Coordinates x and y are given in units of the radius of the antidote. Radius of the antidote $R = 100$ nm and film thickness $h = 10$ nm.

The linearized Landau-Lifshitz equation is considered in order to create an analytical model of small deviations from the equilibrium values of the magnetization and magnetic field [1]. The model shows that maximum amplitude of the magnetization component, which is perpendicular to the equilibrium orientation, is localized near the antidot edge and it decreases with increasing the distance from the edge (see Fig. (b) and (d)).We also defined the conditions of the local ferromagnetic resonances and finally, we visualized the resonance frequency dependency on the magnetic field magnitude (Fig. (c)).

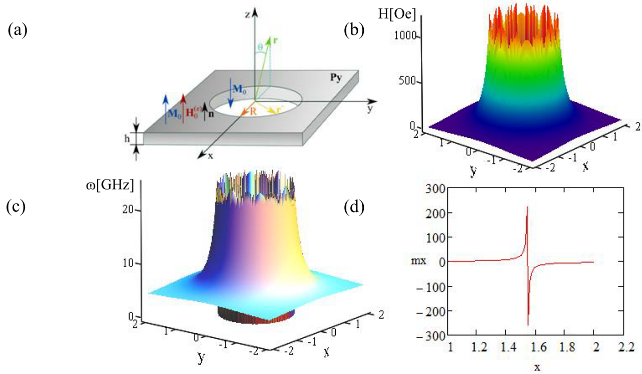

Fig. 28: Direction of magnetization M_0 and magnetic field $H_0^{(e)}$ (a); the antidot-induced magnetostatic field distribution (b); positions of the ferromagnetic resonance angular frequency around the antidot (c); the magnetization distribution around the antidot edge at frequency 6.5 GHz (d)

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MICROMAGNETIC SIMULATION OF THE SPIN WAVES PROPAGATION IN 2D YIG-BASED MAGNONIC NETWORK

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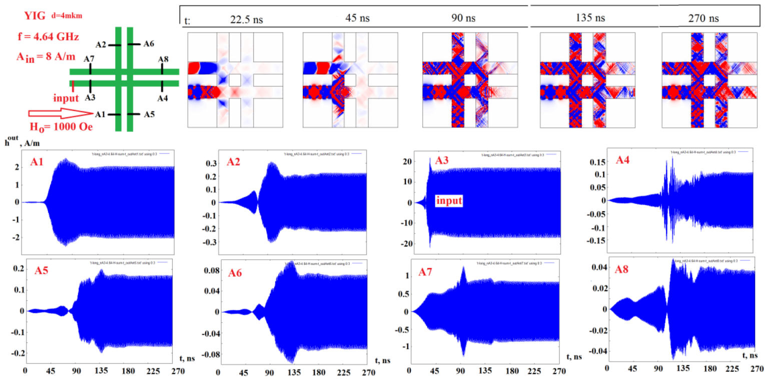
KEY WORDS: spin waves, YIG cross junction, micromagnetic simulation

Two-dimensional (2D) magnonic network based on the system of orthogonal spin waves (SW) waveguides are perspective for magnetic logic circuits engineering, which takes an advantage of magnetization as a computational variable and exploits SW's for information processing [1]. Recently [2] SW propagation in eight-terminal 2D matrix based on YIG thin film waveguides (see Figure) was experimentally studied. In this work we discuss results of micromagnetic simulation of SW propagation through such 2D matrix and compare them with the experiment [2]. In the simulation SW was excited at input antenna A3 (see Figure) at the frequency $f = 4.64$ GHz that corresponds to the central frequency of the overlapping propagation bands for the MSSW and BVMSW, propagating in mutually orthogonal waveguides. An influence of the long-range dipole fields, quantization effects, precursors as well as diffraction and reflection of the SW on time evolution of the amplitude of the transmitted signals at the different outputs are discussed.



The work of G. Dudko, A. Kozhevnikov, Y. Khivintsev and Y. Filimonov is supported by the Russian Science Foundation under grant 17-19-01673. The work of A. Khitun was supported by the Spins and Heat in Nanoscale Electronic Systems (SHINES), an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences (BES) under Award #SC0012670.

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VORTEX CORE REVERSAL IN MAGNETIC ELEMENTS WITH A LANDAU CLOSURE DOMAIN STRUCTURE

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KEY WORDS: reversal, vortex core, thin films, Landau closure domain pattern

We report a numerical study of the fast transient response of square shaped thin film magnetic micro-elements to excitation by nanosecond-long magnetic field pulses. At a critical field strength, such pulses have shown an ability to reverse the polarisation of the vortex core, domain walls and corner singularities in the elements. The critical field strength has been found to scale linearly with the film thickness. The mechanism of the observed reversal is topologically related to the winding number and Skyrmion energy of a vortex anti-vortex pair. The predicted exchange energy barrier can be observed as a peak in the numerically simulated time dependence of the exchange energy with the peak height relative to the ground state energy being considered as the energy cost of reversal. The finite mesh grid of the simulations leads to underestimation of the required energy. However, an extrapolation of the cell-size dependence of the energy to zero cell size has shown convergence towards the predicted energy value.

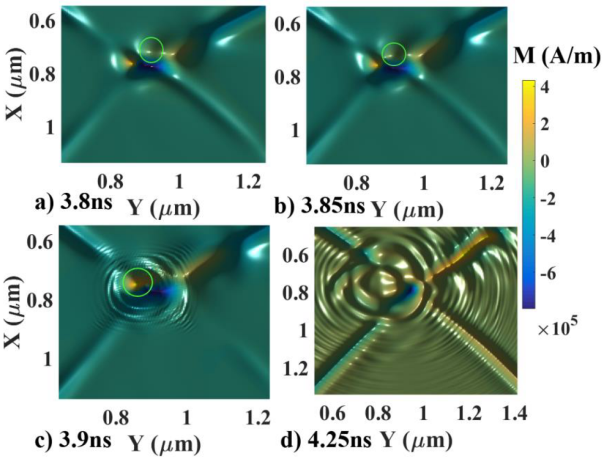

Fig. 29: Panels (a) and (b) show the generation of a Bloch point (circled), its transit towards the vortex pair and annihilation with the vortex core in (c), followed by a full reversal and spin wave emission in (d)

The research leading to these results has received funding from the EPSRC of the UK (Project No. EP/L015331/1) and from the EU's Horizon 2020 research and innovation program under Marie Skłodowska-Curie Grant Agreement No. 644348 (MagIC).

GROWTH OF YTTRIUM IRON GARNET STRUCTURED THIN FILMS FOR MAGNONIC APPLICATIONS

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KEY WORDS: Yttrium Iron Garnet, low damping materials, magnonics

Hitherto, Yttrium Iron Garnet (YIG) remains the most desirable material for magnonic applications due to the lowest achievable damping of magnetization precession which allows for spin wave propagation over hundreds of micrometers [1]. To fabricate any complex architecture of magnonic waveguides and circuits it is essential not only to grow monocrystalline thin films of YIG, but also to develop growth conditions, which ensure the compatibility with the bottom-up lithographic technique. In particular, the critical parameter is a substrate temperature during the film deposition, which is commonly set above 500°C [2] and, therefore, precludes the lift-off process. Here, we show that this issue can be overcome and the film with an ultra-low damping can be achieved after the ex situ recrystallization from an amorphous phase.

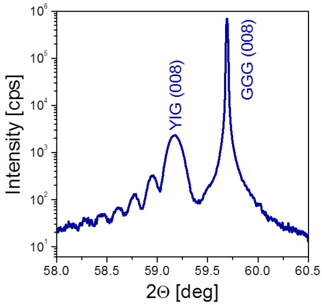

Fig. 30: A Θ˘2Θ XRD scan of the YIG film after *ex situ* annealing treatment

This research has received funding from the European Union's Horizon 2020 MSCA-RISE-2014: Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) Grant Agreement No. 644348 (MagIC).

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BLS EXAMINATION OF ELECTRON-PHONON INTERACTION IN $Bi_2\ Te_3$-SEMICONDUCTOR HETEROSTRUCTURES

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KEY WORDS: topological insulator, bismuth telluride, BLS, phonon, electron, dispersion

The main aim of our work was to describe and provide an interaction between electron and phonon in semiconductor-topological insulator heterostructures. Systems $Bi_2\ Te_3$/GaAs and $Bi_2\ Te_3$/Si were prepared and examined by high resolution Brillouin Light Scattering Spectroscopy. To verify a hypothesis that Electron-Phonon Interaction (EPI) is present in such structures phonons on surface of topological insulator ($Bi_2\ Te_3$) were observed. Phonon energy (frequency) depencence on wavevector is called dispersion relation. $\omega(q)$ is nearly linear for trivial insulator or semiconductor phase. Modifications of this linearity is resulting from demended coupling of electron and surface phonon. The results of performed BLS experiments were confirmed by results of simulations.

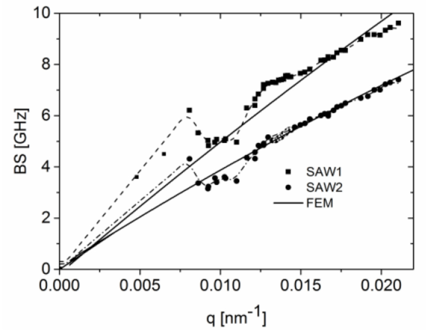

Fig. 31: Dispersion relation of two surface phonons in $Bi_2\ Te_3$. (BS- frequency of phonon, q- wavevector)

This work was supported by the National Science Centre (Grant Number: 2015/17/B/02391).

SPIN WAVE NORMAL MODES OF NONELLIPSOIDAL NANOMAGNETS WITH NONUNIFORM GROUND STATES REVISITED

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KEY WORDS: spin waves, magnonics, patterned magnetic structures

It is widely known that the spin wave dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, 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 [1] 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. Many aspects of the latter can be captured by the so called local ferromagnetic resonance (FMR) frequency, which can be defined as a frequency at which the local magnetic susceptibility peaks. Here, we apply the concept of the local FMR frequency to the interpretation of the TRSKM measurements of spin wave normal modes of square-shaped nanomagnets with nonuniform ground states from Ref. [2]. The analysis sheds new light onto the origin of the evolution of the mode spectra as a function of the applied magnetic field value. Furthermore, we will discuss how the same grade magnonic index landscape can lead to excitation of propagating spin waves near the nanoelements' edges [3,4].

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1, EP/L020696 and EP/P505526/1).

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MICROMAGNETIC AND DYNAMIC PROPERTIES OF TOPOLOGICAL MAGNONIC CRYSTALS

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KEY WORDS: magnonic crystal, domain walls

We present a numerical investigation into the collective dynamics of coupled skyrmions, vortices and skyrmion-like bubble domains confined to a hexagonal magnetic antidot lattice (Fig.). The shape and perpendicular magneto-crystalline anisotropy stabilise domains with a topological charge of unity at the 'node' regions between antidots. When varying magnetic and geometrical parameters of the antidot lattice, several other metastable states were identified and their collective dynamics were investigated. Our modelling revealed additional magnonic bands in the metamaterials' spectra, which were identified as gyrating and breathing modes of the domain and skyrmion structures. The introduction of additional bands depending on the micromagnetic ground state enables re-programmability of such magnonic metamaterials and therefore additional functionalities in data and signal processing at microwave frequencies.

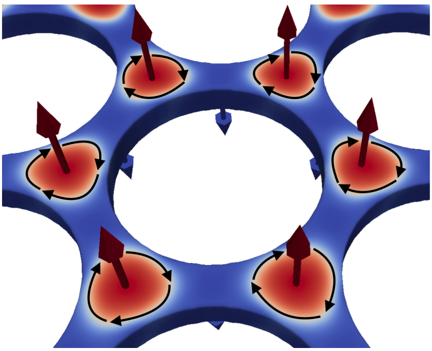

Fig. 32: The equilibrium state of skyrmion-like bubble domains in a hexagonal antidot lattice. Red/blue colour scale and arrows indicate the +z/-z components of the magnetisation, whilst the black arrows indicate the chirality of the vortex-skyrmion magnetisation configuration

This research has received funding from the EPSRC's Centre for Doctoral training in Electromagnetic metamaterials (XM^2) under EP/L014331/1, the EU's Horizon 2020 research and innovation program under MSC GA No. 644348 and from Ukrainian State Fund for Fundamental Research under project No. F71/73-2016.

CENTRE TO EDGE MODE CROSSOVER IN NONELLIPSOIDAL NANOMAGNETS REVISITED

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KEY WORDS: spin waves, magnonics, patterned magnetic structures

It is widely known that the spin wave dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, 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 [1] 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. Many aspects of the latter can be captured by the so called local ferromagnetic resonance (FMR) frequency, which can be defined as a frequency at which the local magnetic susceptibility peaks. Here, we apply the concept of the local FMR frequency to the interpretation of the size dependent crossover from the centre to edge localised spin wave normal modes of square-shaped nanomagnets observed in Ref. [2]. The analysis sheds new light onto the origin of the evolution of the mode spectra as a function of the element size under different values of the bias magnetic field. Furthermore, we will discuss how the same grade magnonic index landscape can lead to excitation of propagating spin waves near the nanoelements' edges [3,4].

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1, EP/L020696 and EP/P505526/1).

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[4] F. Mushenok, et al., Broadband conversion of microwaves into propagating spin waves in patterned magnetic structures, to be published.

SPIN-WAVE PROPAGATION THROUGH THE SYSTEM OF TWO RKKY COUPLED FERROMAGNETS

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KEY WORDS: spin waves, RKKY interaction , micromagnetic simulations

Spin-waves (SW) transmission through specifically designed metasurface represents the new possibility to introduce a controlled phase shift. The metasurface is represented as an ultrathin nonmagnetic metallic spacer separating two ferromagnets, with a thickness much less than the SW wavelength. This allows controlling the phase of the SW. The phase shift between the transmitted and incident SW can be varied in the range of $[-\pi/2; \pi/2]$ depending on the strength of the interlayer exchange coupling. In the case of the two Co films, the change of the Cu spacer thickness by one monolayer may introducing the change of the SW phase by π. For both cases of ferromagnetic (FM) and antiferromagnetic (AFM) interlayer coupling the analytical model is developed for the exchange SW propagating through the interface between two semi-infinite ferromagnetic materials. The analytical results were validated by the micromagnetic simulations (Fig.). Moreover, micromagnetic simulations show that the phase shift still exists for the SW propagating in the plane of thin films through the metasurface created between the edges of the films.

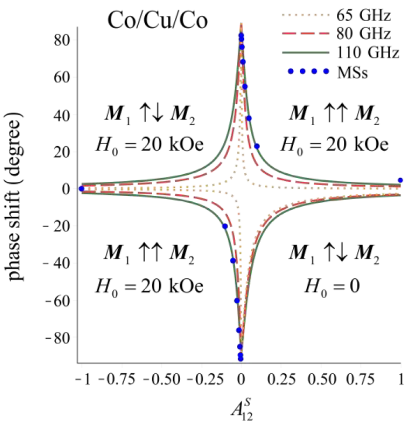

Fig. 33: The dependences of the phase shift of transmitted wave on the interlayer exchange coupling A_{12}^S for the both ground states $M_1 \uparrow\uparrow M_2$ and $M_1 \uparrow\downarrow M_2$ for the system Co/Cu/Co. The analytical results have been obtained for different frequency values: 65 GHz (orange doted lines), 80 GHz (red dashed lines) and 110 GHz (green solid lines) with (for $\phi_1 > 0$ and $\phi_1 < 0$, $A_{12}^S < 0$) and without (for $\phi_1 < 0$, $A_{12}^S > 0$) the application of external magnetic field. The MSs data is defined with the blue dots

This research has received founding from EU Horizon2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement 644348 (MagIC) and from the National Science Centre Poland grant UMO-2012/07/E/ST3/00538.

COMPLETE BAND GAP OPENING IN THE SPIN-WAVE SPECTRUM OF TWO-DIMENSIONAL BI-COMPONENT MAGNONIC CRYSTALS

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KEY WORDS: magnonic crystals, spin waves, band gap tailoring

Two dimensional (2D) magnonic crystals (MCs) with tunable band gap in the spinwave spectrum have potential applications in different types of magnonic devices, such as microwave resonators, spin-wave filters or switches, and current-controlled delay lines. To examine possibilities of the magnonic band gap opening we employ the plane-wave method (PWM) and solve linearised Landau-Lifshitz equation together with magnetostatic Maxwell equations [1]. We study spin- wave propagation in 2D bicomponent MCs of finite thickness consisting of the scattering centres of elliptical cross section distributed in ferromagnetic matrix in sites of a square or hexagonal lattice with the in-plane structure distorted (squeezed) in one direction. We show that such squeezing leads to the spin-wave spectrum very sensitive to external magnetic field which can be used to opening / closing complete magnonic gaps.

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 644348.

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SPIN WAVE EXCITATIONS OF THE INTERACTING TWO-DIMENSIONAL IN-PLANE NANO-VORTICES

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KEY WORDS: magnetic vortices, spin waves, dynamical matrix method

The aim of this work is to study spin-wave excitations in the system of interacting twodimensional nanodots in the vortex state. We use a discrete dipole model taking into account the nearest-neighbour exchange and dipolar interactions [1]. Magnetic configuration of each dot is assumed to form an in-plane vortex (circular magnetization). We examine the dependence of the frequencies and profiles of spin-wave modes vs. the dipolar-to-exchange interaction ratio, the size of the dot, and the dot separation. Special attention is paid to some particular modes, including the lowest-frequency mode, the localized modes, and the fundamental mode, an analogue of the uniform excitation. Some conclusions regarding the influence of the chirality of neighbouring vortices are provided as well.

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 644348.

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MODE LOCALIZATION IN PLANAR MAGNONIC CRYSTAL

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KEY WORDS: magnonics, Damon-Eshbach modes, Backward-Volume modes

We considered the planar one-dimensional magnonic crystal, with sin-like and step-like distribution of magnetization saturation, where external magnetic field is applied in plane with different angle with respect to periodicity. We have shown that profile of dynamic magnetization is strongly correlated with direction of external magnetic field. We found that there is an angle below which the modes of lowest frequencies are mostly localized in area of lower saturation magnetization and above which the modes are localized mostly in area with lower saturation magnetization. Furthermore, for the transient regime the profile of mode is mostly homogeneous. Responsible for such behavior is the competition between demagnetizing energy and Zeeman energy and exchange energy.

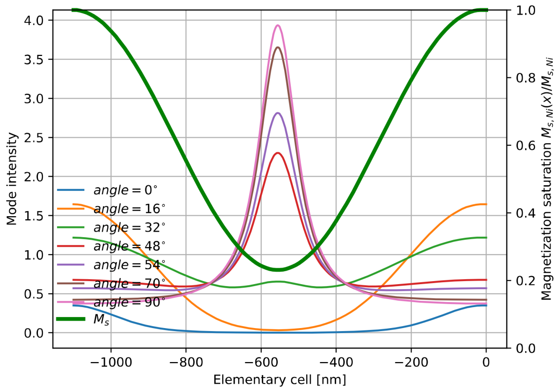

Fig. 34: The profiles of first modes for different angle between magnetic field and periodicity periodicity. Thick green line describes profile of magnetization saturation in elementary cell. Value of magnetic field is 0.05 T, size of elementary cell is 1100 nm

EXCITATION AND CONFINEMENT OF SPIN WAVE MODES IN A PATTERNED Co/Py MAGNONIC METAMATERIAL

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KEY WORDS: FMR, patterned magnetic structures, spectrum

We report on ferromagnetic resonance (FMR) characterization of magnonic metamaterials formed by Co microstripes patterned on top of continuous Permalloy films. The measured spectra contain up to four resonance peaks depending on the angle of the applied magnetic field. Using micromagnetic simulations, we assign the experimentally observed peaks to spin wave modes confined in cobalt stripes and different regions of the Permalloy film experiencing nonuniform internal field due to the stray magnetic field from the cobalt structures. The observed confinement of the spin wave modes is interpreted in terms of the local FMR frequency in Permalloy.

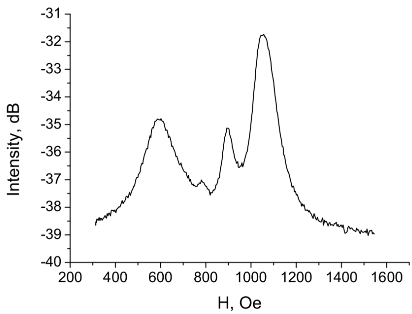

Fig. 35: The typical FMR spectrum acquired from the patterned Co/Py magnetic system

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).

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DYNAMIC CONFIGURATIONAL ANISOTROPY IN NANOMAGNETS REVISITED

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KEY WORDS: spin waves, magnonics, patterned magnetic structures

It is widely known that the spin wave dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, 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 [1] 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. Many aspects of the latter can be captured by the so called local ferromagnetic resonance (FMR) frequency, which can be defined as a frequency at which the local magnetic susceptibility peaks. Here, we apply the concept of the local FMR frequency to the interpretation of the dynamic configurational anisotropy of square-shaped nanomagnets observed in Ref. [2]. The analysis sheds new light onto the origin of the evolution of the precessional mode spectra in nanomagnets as a function of the orientation of the in-plane bias magnetic field. Furthermore, we will discuss how the same grade magnonic index landscape can lead to excitation of propagating spin waves near the nanoelements' edges [3,4].

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1, EP/L020696 and EP/P505526/1).

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[3] C. S. Davies, V. V. Kruglyak, Generation of propagating spin waves from edges of magnetic nanostructures pumped by uniform microwave magnetic field, IEEE Trans. Magn. **52**, 2300504 (2016)

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MAGNON-POLARITON EXPERIMENTS AT mK TEMPERATURES

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KEY WORDS: magnon-polariton, microwave spectroscoy, hybrid quantum system

While magnon dynamics in ferromagnetic materials have been studied for decades with respect to ferromagnetic resonances, Bose-Einstein condensation, and spintronics, there has been recent progress towards studying collective spin excitations in the quantum regime. Strongly coupled quantum hybrid systems of microwave photons and magnons (magnon-polaritons) can mediate the interaction between well-controlled superconducting quantum-circuits and magnetic materials.

An important criterion for possible applications in quantum information processing is the magnon resonance linewidth, representing the information lifetime of a quantum memory. We investigate a strongly coupled hybrid system consisting of a YIG sphere and a 3D microwave cavity. The coupling and the internal linewidths of resonator and magnon are obtained by fitting the full complex scattering parameter to the widely used input-output formalism adapted from quantum optics. We focus on temperature dependent magnon-polariton properties obtained by spectroscopic measurements at temperatures between 25 and 1600 mK. This is the first step towards exploring spin wave dynamics by coupling to a superconducting qubit. Such a hybrid system will provide quantum resolved spectroscopy and coherence measurements on intrinsic magnon states.

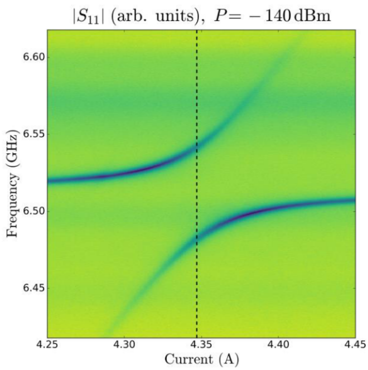

Fig. 36: Spectroscopic measurement of strongly coupled magnon-polariton hybrid system at 25 mK temperature

MAGNETIZATION DYNAMICS IN SQUARE THIN FILM MAGNETIC MICROELEMENTS REVISITED

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KEY WORDS: spin waves, magnonics, patterned magnetic structures

It is widely known that the spin wave dispersion is very sensitive to the sample's magnetic properties and micromagnetic state, 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 [1] 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. Many aspects of the latter can be captured by the so called local ferromagnetic resonance (FMR) frequency, which can be defined as a frequency at which the local magnetic susceptibility peaks. Here, we apply the concept of the local FMR frequency to the interpretation of the time resolved scanning Kerr microscopy (TRSKM) measurements of the magnetisation dynamics in a square-shaped magnetic element from Ref. [2]. The analysis sheds new light onto the origin of the evolution of the precessional mode spectra in the sample as a function of the strength and orientation of the in-plane bias magnetic field. Furthermore, we will discuss how the same grade magnonic index landscape can lead to excitation of propagating spin waves near the elements' edges under excitation by a high frequency uniform microwave magnetic field [3,4].

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[4] F. Mushenok, et al, Broadband conversion of microwaves into propagating spin waves in patterned magnetic structures, to be published

The research leading to these results has received funding from the EPSRC of the UK (Project Nos. EP/L019876/1, EP/L020696 and EP/P505526/1).

SCATTERING OF SPIN WAVES ON A SPIN LENS WITH INHOMOGENEOUS BOUNDARIES

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KEY WORDS: spin wave lens, exchange interaction, uniaxial anisotropy, spin wave refraction, spin wave reflection

We theoretically consider a spin dynamics process in a ferromagnetic structure having the form of lens and located between two homogeneous half-infinite ferromagnetic media, which have different parameters of exchange interaction, uniaxial magnetic anisotropy and saturation magnetization. Homogeneous material of a lens has magnetic parameters different from half- infinite parts.

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

To estimate transparency of thin spin lens, we calculate its reflection coefficient using corresponding method of quantum mechanics taking into account inhomogeneous boundary conditions [1]. Study of reflection coefficient's dependencies on spin wave frequency, external permanent magnetic field and medium's magnetic parameters shows the opportunity to operate lens transparency in a wide range by changing, for example, only value of external permanent magnetic field, so that almost perfect transparency is replaced with total reflection, and such structure is becoming a mirror instead of lens.

Note, that similar lens can be constructed just as lens-form inhomogeneity in a homogeneous medium, but availability of a part of third type with different magnetic parameters behind the lens gives an additional possibility to choose the point of sharp change of spin wave reflection coefficient.

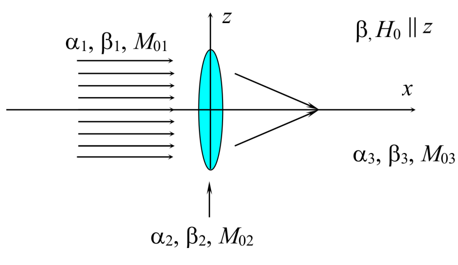

Fig. 37: Spin wave transmission scheme through a spin lens

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MAGNETOSTATIC INTERACTION IN AN ARRAY OF Py STRIPES WITH PERIODIC AND FIBONACCI ORDER

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We have investigated experimentally and theoretically magnetostatic interaction between permalloy (Py, $Ni_{80}Fe_{20}$) thin stripes of the finite length ($L = 5$ or 10 μm) in dependence on the order of the stripes. The stripes of the two widths $w_1 = 350$ nm and $w_2 = 700$ nm with the $t = 30$ nm and 50 nm thickness and the separation between stripes fixed to 100 nm arranged in a periodic order [bi-component one dimensional (1D) magnonic crystals, MCs] and according with the Fibonacci sequence (magnonic 1D quasicrystals, MQs) ribbons were considered (Fig. a, b). In the measured hysteresis loops with longitudinal magneto-optical Kerr effect (LMOKE) microscope we clearly identified two steps reversal process in both structures, related to the different shape anisotropies of the wide (w_2) and narrow (w_1) stripes (Fig. c).

We have analytically calculated magnetostatic stray and demagnetizing fields for the MCs and MQs under consideration to test hypothesis, that the order of the stripes via magnetostatic coupling can influence the magnetization reversal process. We showed, that an increase of the separation between the ribbons stretches switching field distribution of the MCs and MQs. On the other hand, an increase of the stripe thickness (from 30 to 50 nm) significantly articulates characteristic plateau derived from antiferromagnetic configuration proving the dominate role of the magnetostatic coupling between stripes in the reversal of the magnetization. However, the definite answer for the research hypothesis has not yet been found. We present the results of calculations for further discussion (Fig. d).

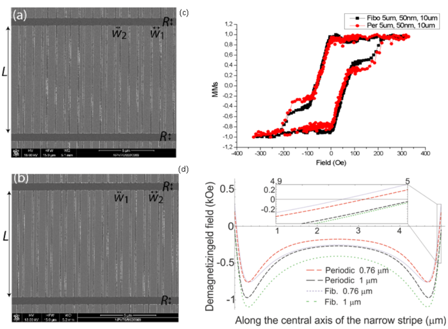

Fig. 38: (a) and (b) SEM images of the Py MQs and MCs fabricated using electron-beam lithography and lift-off technique. (c) Hysteresis loop measured in MCs and MQs. (d) The internal magnetostatic field in the narrow stripe in MC and MQ with the antiferromagnetic orientation of the magnetization between narrow and wide stripes and two separations between the ribbons

The study has received funding from European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie GA 644348 and National Science Centre of Poland project UMO-2212/07/E/ST3/00538.

DETECTION OF SPIN-WAVE EXCITATIONS VIA NERNST EFFECT

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KEY WORDS: magnonics, anomalous Nernst effect, spin-waves, ferromagnetic resonance

Characterization of magnetodynamic properties of nanomagnets and nanostructured magnetic materials requires methods appropriate for probing the typical timescales of these systems, i.e. in the sub-nanosecond range. The lack of appropriate time-domain characterization techniques is linked to the limits of current electronics. Other possible approach is to use the frequency domain characterization in GHz range. The most common frequency domain characterization technique is the ferromagnetic resonance (FMR) measurement. From FMR spectra it is possible to extract valuable information about the system: the saturation magnetization, damping parameter, magnetic anisotropy etc. The detection of the specific resonances is typically done using microwave cavity FMR (mc-FMR), other approaches use either a Vector Network Analyzer (VNA-FMR) [1] or optical detection [2].

The method we utilize for detection of spin-wave excitations aims for the simplification of the characterization experiment. We employ the thermoelectric detection of spin-waves in magnetic stripes via anomalous Nernst effect [3]. The method is based on the heat generation inside a magnetic film due to the relaxation of spin-waves to the lattice. The dissipation of spin-wave energy heats the magnetic stripe and creates a temperature gradient towards the substrate (perpendicular to the surface). This leads to generation of an electric field perpendicular to both the temperature gradient and the magnetization direction. The voltage is usually in the µV range hence it can be measured with common laboratory equipment. The probed volume can be much smaller than in the case of mc-FMR, allowing characterization of micron-sized objects. Despite its simplicity, this method yields very interesting results and can be used for characterization of magnonic waveguides, magnonic metamaterials, spin-wave emitters and other spin-wave devices.

The excitation of spin-waves is done via coplanar waveguide (CPW). A typical spin-wave spectrum measured using our approach is shown in Fig. In our case we used a permalloy stripe 100-nm-thick, 20-µm-wide and 2-mm-long. The CPW used for excitation was on top of a structure in the center of the magnetic stripe to rule out any other contributions other than the Nernst voltage because the spin-waves are attenuated before reaching the contacts for DC voltage measurement.

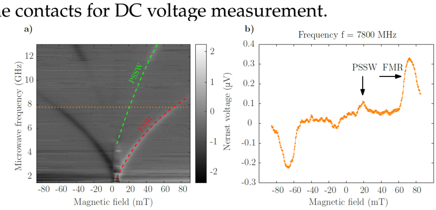

Fig. 39: Grey scale plot for the Nernst voltage corresponding to the spin-wave resonances for different magnetic fields and different excitation frequencies. The red curve (marked FMR) corresponds to the ferromagnetic resonance (Kittel) mode and the green curve (marked PSSW) corresponds to perpendicular standing spin-wave mode in the magnetic stripe. b) Line profile of the image a) at the frequency of 7.8 GHz reveals the S-N ratio

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NUMERICAL MODELLING OF THERMAL TRANSPORT AND MAGNETISATION DYNAMICS IN THIN FILMS OF PERMALLOY IRRADIATED BY ULTRASHORT OPTICAL PULSES

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KEY WORDS: heat diffusion equation, Comsol, micromagnetics

Further progress in solid state physics and technology rests on our ability to push limits of investigations to phenomena occurring on ultrashort time and ultrasmall length scales. This is also true in femtomagnetism – the study of spin-related phenomena triggered by ultrashort optical pulses. In metals, a significant proportion of the optical pulse energy is absorbed as heat. If the pulse is ultrashort and tightly focused, the resulting temperature distribution is both transient and non-uniform, which may trigger various regimes of the magnetisation dynamics and relaxation through the reduction of the length of the magnetisation vector.

In this presentation, we will report on numerical modelling of the thermal transport and magnetisation dynamics induced in thin films of permalloy by femtosecond optical pulses, specifically addressing experimental results reported in Refs. [1,2]. The modelling of the thermal transport reveals that the optically induced temperature distribution contains two contributions: a stationary profile due to incomplete heat dissipation between subsequent optical pulses and a transient increase that disappears prior to arrival of the next pulse. Both contributions are converted into associated distributions of the reduced saturation magnetisation. Approximating the transient temperature increase in micromagnetic simulations as instantaneous, we study conditions that lead to optical excitation of propagating spin waves and those confined by the graded magnonic index landscape due to the stationary temperature profile.

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).

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SPIN-WAVE PINNING CONDITIONS IN NANOSCALE WAVEGUIDES

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KEY WORDS: magnons, pinning conditions, effective width, magnonics

Spin waves and their quanta, magnons, feature frequencies in the GHz to THz range and wavelengths in the micrometer to nanometer range. They are envisioned for the design of a next generation of data processing devices where information is carried by magnons instead of electrons [1]. The recent progress in fabrication technology led to the development of nanoscale proof of concept spin-wave waveguides where magnons carry, process or store information [2]. However, with the reduction of the element size the spatial non-uniformity of internal dipolar fields in the spin-wave waveguides becomes comparable to the exchange length. This results in a change of the spin pinning conditions at waveguide edges, which are now determined both by the exchange and the dipole interactions and depend on the waveguide aspect ratio (thickness/width). Modified spin pinning at the boundary changes the spin-wave dispersions and mode profiles in nanoscale structures in comparison to micro- and macro-structures.

In this work, the spin pinning conditions of spin waves in nanoscale waveguides are studied by experiments, micromagnetic simulations, and analytic theory. Spin-wave spectra were measured in 100 nm-thick Yttrium Iron Garnet (YIG) waveguides of width down to 200 nm using Brillouin Light Scattering (BLS) spectroscopy. The developed theory accounts for the boundary conditions arising from the dipole as well as the exchange interaction and its findings are compared to the results of the experiments and simulations. For a quantitative description of the pinning conditions, an "effective width" of the spin-wave waveguide w_{eff} is introduced which is larger than the geometric width of waveguide w. The pinning parameter P is defined by the ratio $(w_{eff} - w)/w_{eff}$ and its dependence on the aspect ratio of the waveguide is studied. It is shown that an increase in the aspect ratio results in the reduction of the dipolar pinning at the edges of the waveguides and in a corresponding increase of the effective waveguide width. Consequently, the pinning parameter increases from zero (fully pinned) for aspect ratios close to zero to one (fully unpinned) for aspect ratios close to one. Therefore, mode profiles and their frequencies in pinned micro-wide YIG waveguides differ drastically from the mode profiles in unpinned 200 nm wide waveguide.

Financial support by the ERC Starting Grant "MagnonCircuits" is gratefully acknowledged and by the Deutsche Forschungsgemeinschaft (DU 1427/2-1) is gratefully acknowledged.

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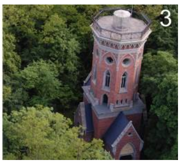
Presenting authors

Tourist attractions close to Trzebaw

(1) – location of Delicjusz Hotel

Trip A – Museum of Agriculture (2) in Szreniawa and scenic view point (3)



How to get there?

one stop by train heading to Poznań
(from Trzebaw-Rosnówko station (1) to Szreniawa station)

Opening hours

(3) – museum

Thu-Fri: 9:00 – 17:00
Sat-Sun: 10:00 – 18:00

(2) – tower

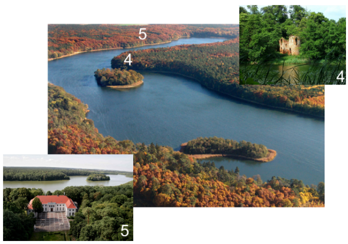
Thu-Sun: 10:00 – 10:30, 12:00 – 12:30, 14:00 – 14:30, 16:00 – 16:30, 17:30 – 18:00

Tickets

12 PLN (museum) + 3 PLN (tower)

http://www.muzeum-szreniawa.pl

Trip B – Trip to National Park of Wielkopolska:
(4) –- ruins of the castle of Klaudyna Potocka
(5) –- Museum of National Park



Path's length

$\sim$ 17 km (3.5-4h on foot, 1h by bike) – violet dashed line on the map

Opening hours

(5) - museum

Mo-Fri: 7:00 – 15:00
Sun: 10:00 – 17:00

Tickets

6 PLN

http://www.wielkopolskipn.pl

	Sunday, July 2	Monday, July 3	Tuesday, July 4	Wednesday, July 5	Thursday, July 6	Friday, July 7	
9:00 - 9:30		**M. Münzenberg**	**R. Gieniusz**	**K. Guslienko**	**J. Gräfe**	**P. Kuświk**	9:00 - 9:30
9:30 - 10:00							9:30 - 10:00
10:00 - 10:30		**F. Ogrin**	**J. Dubowik**	**M. Mruczkiewicz**	**G. Gubbiotti**	**J. W. Kłos**	10:00 - 10:30
10:30 - 11:00		**M. Krupiński**	**Y. Filimonov**	**G. Kakazei**	**R. Streubel**	**Workshop Closing**	10:30 - 11:00
11:00 - 11:30		**Coffee break**	**Coffee break**	**Coffee break**			11:00 - 11:30
11:30 - 12:00		**A. Chumak**	**I. Lyubchanskii**	**J. Barnaś**			11:30 - 12:00
12:00 - 12:30					**Lunch**	**Lunch**	12:00 - 12:30
12:30 - 13:00		**V. Kruglyak**	**R. Tobey**	**Y. Bazaliy**			12:30 - 13:00
13:00 - 13:30		**M. Dvornik**	**O. Gorobets**	**M. Albrecht**			13:00 - 13:30
13:30 - 14:00					**Excursion with dinner**	**Transportation to Poznań**	13:30 - 14:00
14:00 - 14:30		**Lunch**	**Lunch**	**Lunch**			14:00 - 14:30
14:30 - 15:00							14:30 - 15:00
15:00 - 15:30	**Registration 15:00 - 18:00**						15:00 - 15:30
15:30 - 16:00		**Short talks 01-06**	**Short talks 07-12**	**Short talks 13-17**			15:30 - 16:00
16:00 - 16:30	**Workshop Opening**						16:00 - 16:30
16:30 - 17:00	**Opening Lecture: D. Gründler**						16:30 - 17:00
17:00 - 17:30				**Refreshments**			17:00 - 17:30
17:30 - 18:00		**Refreshments**	**Refreshments**				17:30 - 18:00
18:00 - 18:30	**Welcome Party**	**Poster sesion 17:30 - 19:00**		**Concert 17:30 - 18:45**			18:00 - 18:30
18:30 - 19:00			**Grill party**				18:30 - 19:00
19:00 - 19:30		**Dinner**		**Dinner**			19:00 - 19:30
19:30 - 20:00							19:30 - 20:00
20:00 - …	**Transportation to Trzebaw**						20:00 - …