Are magnetic waves attractive?

The research on spin waves in periodic nanostructures

Projektbericht

Magnetic systems are interesting both in terms of research and applications. They exhibit various physical phenomena related to the dynamics of magnetization (spin waves) and the transport of magnetic moments (spin transport) driven by electromagnetic fields or temperature. These effects depend strongly on the geometry of the system and can be tailored by the adjustment of structural parameters.

Magnonics is a rapidly developing field of science and technology which uses spin waves in magnetic systems for information transmission and processing. Magnonic devices can overcome some fundamental barriers limiting the development of electronic or photonic systems. Electronic systems do not work efficiently on nanoscale due to thermal losses when operating at high frequencies. On the other hand, photonic systems operating at very high frequencies cannot be miniaturized to nanoscale because of relatively large value of wavelength for light. Information processing based one spin waves can be performed using very small devices (of the order of a few tens of nm) operating at high frequency rates (of the order of tens of GHz), avoiding the bottlenecks for the development of electronic and photonic sytems. The properties of spin waves in nanostructures are also very important subjects of scientific research. The peculiarity of this kind of waves is based on two factors. The first is the possibility of tailoring (or tuning) the spin wave dynamics by changing the static magnetization resulting from the particular geometry of the system (or from the application of external bias). The second one is the complex origin of magnetic interaction resulting from the competition between short range exchange interaction (of quantum nature) and long range dipolar interaction (of classical nature). As a result, the properties of spin waves are essentially different when the sizes of the systems are changed from tens of nanometers to single micrometers.

These effects were investigated in the fellow-project: *Localized spin waves in periodic nanostructures*. The studies were concentrated on the structures of confined geometries like wires or layers where the periodicity was introduced by the repetition of the wires or by pattering the layer. The spin wave dynamic formally described by the dependence of the wave frequency on wavelength (called wave dispersion relation). For periodically modulated magnetic structures (called magnonic crystals), the dispersion relation is splitted into frequency bands allowing the propagation of spin waves. The frequency bands are separated by frequency gaps where only lo-

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Kurzvita

Jarosław W. Kłos studierte Physik an der Adam-Mickiewicz-Universität in Poznań, Polen, wo er seine Dissertation 2004 vorbereitete und sich auch 2014 habilitierte. Seine Habilitation untersucht die photovoltaische Zelle in Form einer Halbleiter-Übergitter-Struktur. Er absolvierte ein PhD-Fellowship an der Linköpings Universitet in Schweden (2008-2009) und nahm zahlreiche Forschungsaufenthalte in Kiew und Donetsk wahr. Seit 8 Jahren arbeitet er an Spinwellen in magnetischen Nanostrukturen in Poznań. 2018 erhielt er eine Professur an der Adam-Mickiewicz-Universität in Poznań.

Fellow-Projekt

»Localized spin waves in periodic nanostructures

Magnetic moments can rotate in precessional motion around the direction of a static magnetic field if they are pushed away from their equilibrium position (e.g. by application of a radio frequency field, or by thermal excitation). In a magnetic medium, due to the interaction between magnetic moments, the waves of coherently precessing magnetic moments can propagate over large distances, compared to their wavelength. These waves (called spin waves) can transmit energy and information, similarly like other waves of different nature (e.g. electromagnetic waves or acoustic waves). Typical frequencies of spin waves (less than one GHz to hundreds of GHz) and their wavelengths (hundreds to tens of nanometers) allow the design of miniaturized devices (called magnonic devices) operating on high frequency signals at nanometer scale. Thus, systems which use spin waves for processing and transmitting information can fill the gap between electronics and photonics.

In the fellow project, periodically patterned magnetic materials were considered. Such magnonic structures allow the observation of effects which are absent in homogeneous magnetic media: (1) tailoring the effective material parameters by structural changes, (2) induction of the frequency gaps supporting the localization of spin waves at specific frequencies. These features make our studies more advanced compared to the investigation of the magnonic systems based on uniform materials.

calized spin wave modes can be observed. The research conducted in the framework of the fellow-project consisted of the following topics:

1. remagnetization in the array of ferromagnetic nanowires with periodic and quasiperiodic order,
2. spin wave modes in a cylindrical nanowire in the crossover dipolar-exchange regime,
3. magnons in a quasicrystal: propagation, localization, and extinction of spin waves in Fibonacci structures,
4. driving magnetization dynamics in an on-demand magnonic crystal by magneto-elastic interaction.

All research was performed in strong collaboration with my colleagues form Poznań, from the Adam Mickiewicz University and the Institute of Molecular Physics at the Polish Academy of Sciences. The studies concerning the remagnetization of arrays of nanowires and the research on optically induced magnonic crystals consists of both experimental and theoretical results and were done in collaboration with the group of Professor Markus Münzenberg from the University of Greifswald and with the group of Professor Ranan Tobey from University of Groningen. The experimental and theoretical investigation of spin wave localizations in quasiperiodic sequences of wires were done together with the group of Professor Gisela Schütz from the Max Planck Institute for Intelligent Systems in Stuttgart. The other studies are purely theoretical works done together with the groups of Professor Igor L. Lyubchanskii and Professor Andriy N. Kuchko, originating from Donetsk.

Remagnetization in the array of ferromagnetic nanowires with periodic and quasiperiodic order

Long ferromagnetic wires are characterized by strong shape anisotropy. For weak external magnetic fields the static magnetization is oriented along the axis of the wire, pointing in one of two opposite directions. If the external magnetic field is oriented along the wire and antiparallel to the orientation of magnetization it must exceed some threshold value in order to reverse the direction of the magnetization. In other words, the dependence of magnetization with respect to the field exhibits the hysteresis-like behavior. The width of this hysteresis loop is larger for narrower wires characterized by stronger shape anisotropy. We investigated how the dipolar coupling in periodic or quasiperiodic (Fibonacci) sequences of wide and narrow wires (made of premalloy) affects the magnetization switching. The numerical studies (done in Greifswald in collaboration with Aleksandr Makarov) were performed with the aid of Monte Carlo simulations for macrospin models. We showed that the dipolar interactions between nanowires forming one ribbon can be controlled by changing the distance between neighboring ribbons. Moreover, we found that the quasiperiodic order can influence the hysteresis loop by introducing additional tiny switching steps when the dipolar interactions are sufficiently strong.

These studies allow us to understand the mechanism for switchings of the magnetization configuration in periodic or quasiperiodic sequences of nanowires - being a specific kind of magnonic (quasi)crystals. The discussed mechanism can be further used to control the spectrum of spin waves in these complex structures.

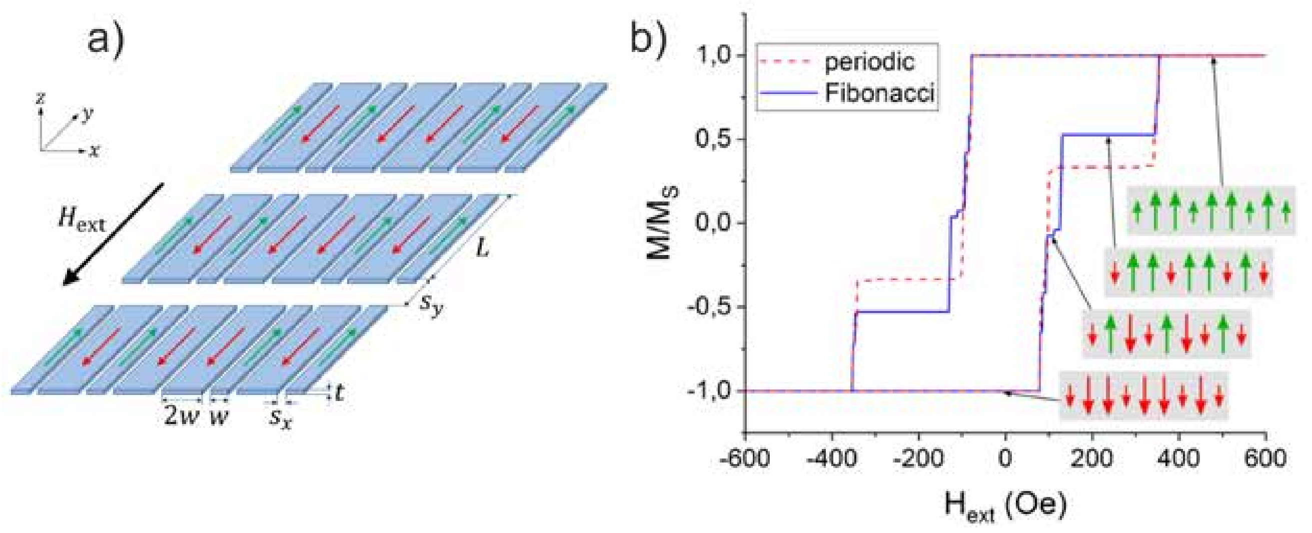

Fig. 1: Magnetization reconfiguration in the sequences of two kinds of flat nanowires made of Py, differing in width, ordered quasiperiodically - in Fibonacci sequence or periodically. In experimental studies the sequences are arranged in the ribbons (a). The simulated hysteresis loops (b) for Fibonacci and periodic sequences have additional steps (corresponding to metastable configurations) which result from the dipolar interaction between nanowires.

Spin wave modes in a cylindrical nanowire in crossover dipolar-exchange regime

Individual magnonic wires seem to be simple magnetic structures but their spin wave spectrum is quite complex. We calculated (analytically and numerically) the spin wave dispersion relation for a cylindrical nanowire magnetized along its axis, taking into account both dipolar and exchange interactions. The significant part of numerical studies was done by a Ph.D. student from Poznań (Justyna Rychły) during her one month visit in Greifswald. The dipolar or exchange character of particular spin wave modes was identified by the calculation of their exchange and dipolar energy. In the rich spectrum of eigenmodes, we were able to find the dipolar-dominated modes (characterized by large negative values of the group velocity at small wave numbers) and the exchange modes (of positive group velocity). The dispersion branches of the modes which have positive and negative slopes (different signs of group velocities) cross or anti-cross each other. The anticrossing occurs when the modes have the same symmetry of magnetostatic potential.

The research on spin wave dynamics in cylindrical magnetic nanowires extends our knowledge of the interplay of dipolar and exchange interactions in this elementary magonic structure.

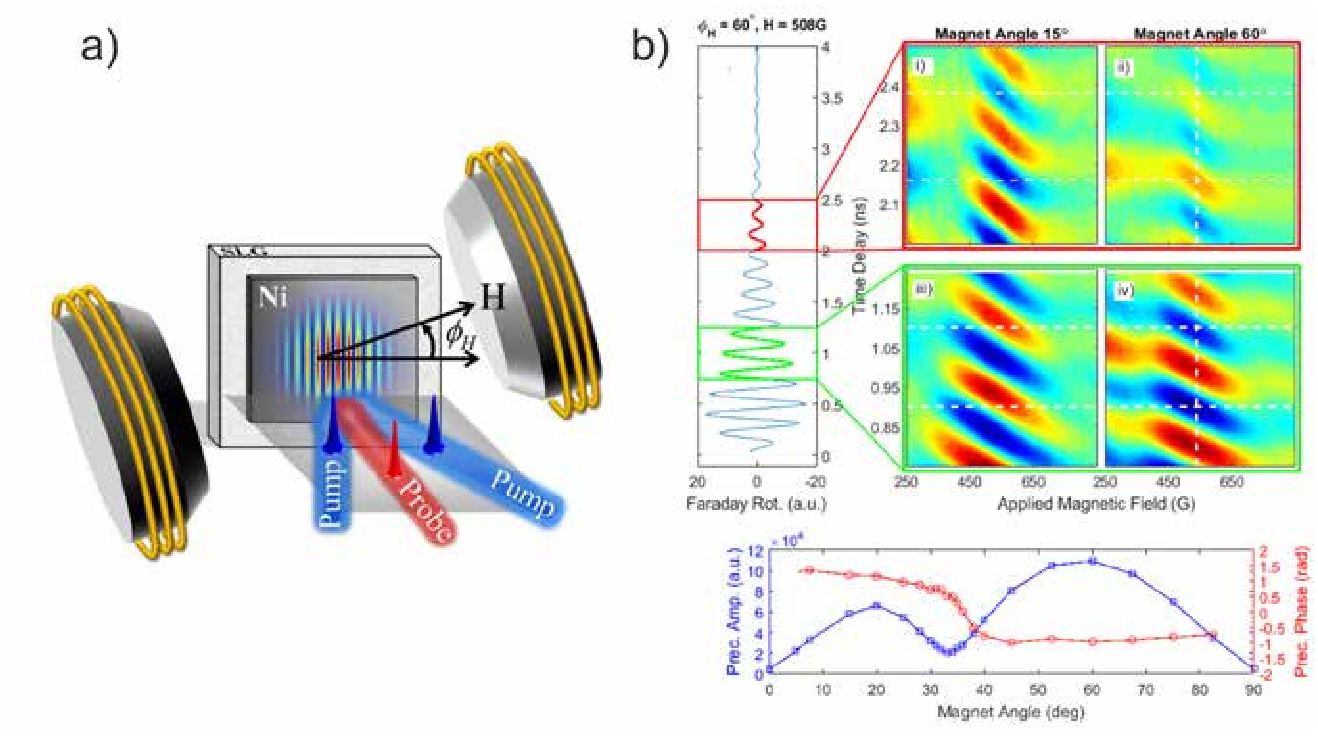

Fig. 2: Spin wave excitation in magnonic crystal optically induced in homogeneous Ni layer (a). The amplitude and phase of the spin wave precession shows the unusual angular dependence on the direction of the magnetic field (b) which is not observed in flat magnetic landscapes and can be explained when the localization of spin wave modes in the induced magnetic pattern is taken into account.

Magnons in a quasicrystal: propagation, localization, and extinction of spin waves in Fibonacci structures

Magnonic quasicrystals exceed the possibilities of spin waves manipulation offered by regular magnonic crystals because of their more complex spin wave spectra with fractal characteristics. In our studies we reported on the direct X-ray microscopic observation of propagating spin waves in a magnonic quasicrystal consisting of dipolarly coupled permalloy nanowires arranged in a one-dimensional Fibonacci sequence (done in the BESSY II synchrotron radiation facility in Berlin). Spin waves from the first and second band as well as evanescent waves from the band gap between them were imaged. Moreover, the additional mini-band gaps in the spectrum were demonstrated, directly indicating an influence of the quasiperiodicity of the system. The experimental results were interpreted using numerical calculations. We deduced a simple model to estimate the frequency position of the magnonic gaps in quasiperiodic structures.

We have shown experimentally that spin wave propagation in quasi-crystals is not restricted to the long wavelength limit, for which the structure can be considered as an effective medium, but also occurs at higher frequencies, for which the structure's long-range quasiperiodic order is critical.

Driving magnetization dynamics in an on-demand magnonic crystal by magneto-elastic interaction

The interfering beams of ultrafast laser pulses can generate the periodic pattern which varies in time. We projected this pattern on the surface of a magnetic layer to heat it locally and to induce the lateral modulation in the magnetization profile of an otherwise uniformly magnetized system. The large temperature gradient, which varies in time, produces the dynamic strain in the magnetic layer. This strain can drive the spin waves when the magnetic material shows magnetostrictive properties. We investigated the spin waves induced by this kind of elastic excitation in thin layers of Ni and CeFeB. The latter material is a basic magnetic material used in the group of Professor Münzenberg for magnonic studies (the sample was prepared by Ulrike Martens from Greifswald).

We found an unusual dependence of the magnetoelastic coupling as the externally applied magnetic field is angle- and field-tuned relative to the wave vector of the magnetization modulation, which can be explained by the emergence of spatially inhomogeneous spin wave modes. In this regard, the spatial light interference methodology can be seen as a user-configurable, temporally-windowed, on-demand magnonic crystal which allows control and selectivity of the spatial distribution of spin waves. Calculations of spin waves, based on the plane wave method, allowed to identify the spatial distribution and associated energy scales of each excitation. These studies open the door to a number of excitation methodologies beyond the well-known techniques. (The mentioned numerical calculations were done by a Ph. D. student from Poznań – Szymon Mieszczak who discussed his results during a one-week visit in Greifswald.)

The outlined program of the research conducted during the fellowship comprised: the studies of static configurations of magnonic (quasi)crystals composed of the sequences of nanowires, the investigation of spin wave dynamics in a single cylindrical nanowire and in magnonic quasicrystals composed of flat nanowires, and additionally the research on one-dimensional magnonic crystals induced on-demand by optical means in a uniform magnetic layer. One of the most important problems studied in this research was the impact of the geometry of (quasi)periodic magnetic structures and the external magnetic field on the spin wave localization. The presented result will be supplemented in the future by the results of on-going research about magnonic surface states.

Additional studies and popularization

Except of this quite consistent studies, some additional research, slightly out of the main scope of the presented research, was also performed. I would like to mention: (1) the theoretical prediction of the Hartman effect for spin waves in exchange regime and (2) the measurements and numerical simulation of electromagnetic microwave surface states in periodic microstripes.

The first work reports on the counterintuitive effect related to the tunneling of a (spin) wave package through the (magnetic anisotropy field) barrier. We predicted the saturation of the group delay for tunneling spin waves with increasing width of the barrier, known earlier for electromagnetic waves as the Hartman effect. We also proposed the planar magnonic structure in which the Hartman effect can be potentially observed. We chose the system based on low damping materials for spin waves - CoFeB, covered by a MgO layer which induces the strong magnetic anisotropy at the interface with CoFeB.

The latter work concerns numerical and experimental studies of a peculiar kind of one-dimensional photonic crystal (periodic microstrip) operating in GHz frequency range – typical for spin waves. Contrary to spin waves, the electromagnetic waves of this frequency are extended in spaces and the sizes of the periodic microstrip are practically macroscopic. We found the surface modes localized at the terminations of the microstrip.

The conducted research was also popularized by giving the public lecture dedicated to pupils entitled: *Co łączy magnes na lodówce z laserem - czyli układy Halbacha?* (eng. *Halbach arrays – what do the fridge magnet and the laser have in common?*) and by writing a popular article for Przegląd Elektrotechniczny in (eng. Electrotechnical Review) about the future electronics based on memristors entitled *Rozwiązania techniczne i zasady funkcjonowania memrystorów* (eng. *Operating principles and technical implementation of memristors).*

Am Kolleg entstandene Veröffentlichungen

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3. F. Lisiecki, J. Rychły, P. Kuświk, H. Głowiński, J.W. Kłos, F. Groß, I. Bykova, M. Weigand, M. Zelent, E. Goering, G. Schütz, M. Krawczyk, F. Stobiecki, J. Dubowik, J. Gräfe, *Magnons in a Quasicrystal: Propagation, Localization and Extinction of Spin Waves in Fibonacci Structures.*
4. F. Lisiecki, J. Rychły, P. Kuświk, H. Głowiński, J.W. Kłos, F. Groß, I. Bykova, M. Weigand, M. Zelent, E.J. Goering, G. Schütz, G. Gubbiotti, M. Krawczyk, F. Stobiecki, J. Dubowik, J. Gräfe, *Reprogrammability and Scalability of Magnonic Fibonacci Quasicrystals*, Phys. Rev. Applied 11, 054003 (2019)
5. C. L. Chang, S. Mieszczak, M. Zelent, V. Besse, U. Martens, R.R. Tamming, J. Janusonis, P. Graczyk, M. Münzenberg, J. W. Kłos, R.I. Tobey, *Driving magnetization dynamics in an on-demand magnonic crystal via the magneto-elastic interaction.*
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7. A. A. Girich, A. A. Kharchenko, S. I. Tarapov, S. Mieszczak, J. W. Kłos, M. Krawczyk, *Microwave surface states in periodic microstrip.* (preprint arXiv:1807.08629)
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