University of Białystok

Faculty of Physics

Doctoral thesis

Vladimir Bessonov

Magnetization dynamics in patterned thin films

Supervisors: dr hab. Marek Kisielewski, prof. UwB

Co-supervisior: dr Ryszard Gieniusz

Białystok, 2014

Author’s statement:

I declare that I am aware of criminal liability for false statement of this doctoral thesis. I prepare this thesis myself and used only literature mentioned in this thesis.

Supervisor’s statement:

This doctoral thesis is ready to be read by reviewers.

Thankfulness

- to Andrzej Maziewski, for the possibility to work in a great science lab. Thank you for your patience and support. Thank you for learning the basics of scientific work and answers to my many questions

- to Ryszard Gieniusz, Urszula Guzowska, and Nadeem Tahir for an interesting collaboration and help in this thesis. I am very pleased to work together with you in the same group and interesting discussing that arise in the process. Thanks to learn me of physics of magnetic oscilations

- to Marek Kisielewski for his invaluable helping and fruitful discussion to work on this thesis

-to laboratory of Physics of Magnetism: Maria Tekielak, Andrzej Stupakiewicz, Iosif Sveklo, Wojciech Dobrogowski, Piotr Mazalski, Zbigniew Kurant, Jan Kisielewski, Sergii Parchenko for what never refused help when it was needed

- to Yurij Sukhorukov for help and support

- to my family, my wife Valentina and daughter Arina, patience and understanding. For a calm attitude to my late return from the university. For the comfort of home needed for productive work.

Supported by: Team SYMPHONY project of the FNP, co-financed by the EU from ERDF, OPIE 2007–2013.

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Plan of the doctoral thesis

List of publications

The doctoral thesis based to discussing by following papers, published in scientific journals:

I. "Resonant frequency multiplication in microscopic magnetic dots." V.E. Demidov, H. Ulrichs, S. Urazhdin, S.O. Demokritov, V. Bessonov, R. Gieniusz, A. Maziewski. Applied Physics Letters, volume 99, issue 1, pp. 012505 (3), (2011).

II. "Single antidot as a passive way to create caustic spin-wave beams in yttrium iron garnet film." R. Gieniusz, H. Ulrichs, V.B. Bessonov, U. Guzowska, A.I. Stognij, A. Maziewski. Applied Physics Letters, volume 102, issue 10, pp. 102409 (4), (2013)

III. "An antidot array as an edge for total non-reflection of spin waves in yttrium iron garnet films". R. Gieniusz, V. D. Bessonov, U. Guzowska, A. I. Stognii, A. Maziewski. Applied Physics Letters, volume 104, issue 8, pp. 082412 (5), (2014)

Papers not included in the thesis

IV. "Giant magnetorefractive effect in $La_{0.7}Ca_{0.3}MnO_3$ films." A.B. Granovskii, Yu.P. Sukhorukov, A.V. Telegin, V.D. Bessonov, E.A. Gan'shina, A.R. Kaul', I.E. Korsakov, O.Yu. Gorbenko, J. Gonzalez. Journal of Experimental and Theoretical Physics, volume 112, issue 1, pp 77-86, (2011)

V. "Magnetorefractive effect in manganites with a colossal magnetoresistance in the visible spectral region." Yu.P. Sukhorukov, A.V. Telegin, A.B. Granovsky, E.A. Gan'shina, A. Zhukov, J. Gonzalez, G. Herranz, J.M. Caicedo, A.N. Yurasov, V.D. Bessonov, A.R. Kaul', O.Yu. Gorbenko, I.E. Korsakov. Journal of Experimental and Theoretical Physics, volume 114, issue 1, pp141-149, (2012)

VI. "Magnetic and magneto-optical studies of silver doped manganite film." V.D. Bessonov, R. Gieniusz, M. Tekielak, A. Maziewski, Yu.P.Sukhorukov, A.R. Kaul', E.A. Gan'shina. The European Physical Journal B, volume 86, issue 5, pp 213(5) (2013)

VII. „Magnetorefractive effect in the $La_{1-x}K_xMnO_3$ thin films grown by MOCVD." Yu.P. Sukhorukov, A.V. Telegin, V.D. Bessonov, E.A. Gan'shina, A.R. Kaul', I.E. Korsakov, N.S. Perov, L.Yu. Fetisov, A.N. Yurasov Journal of Magnetism and Magnetic Materials, volume 367, pp. 53-59 (2014)

Comments to the doctoral thesis:

I. Introduction

In recent years large efforts have been made for the search for new carriers for transmitting information in solid state electronics, due to the fact that standard carriers such as electrons do not meet the needs of the modern world. Magnons can act as ones of these particles. Magnons are the quanta of collective excitation of the electrons' spin system – spin waves and were first predicted by F. Bloch in 1929 [1]. From that time, they have been the subject of intensive studies interesting from both the points of fundamental physics and application, because spin waves allow both to transport and to process of spin information without moving of electrons.

Magnons operate at high frequencies, such as GHz and THz, which is important from the point of view of the velocity of information transmission and processing. Magnons – quasiparticles are therefore transferred without the Joule heating. Magnons can be easily controlled by small external magnetic fields.

In this regard, a number of questions concerning the physics of the behavior of spin waves in various materials and structures and the creation of patterned structures with predetermined properties – magnonic crystal, seem to be extremely important. Spin waves, just like light and phonons, have the nature and subject to such effects as reflection, refraction, diffraction, and interference. However, the behavior of these processes may differ significantly from the optical counter parts. Thus, the interaction of spin waves with patterned structures can give new effects, which are important for both fundamental physics and applications.

Excitation and propagation of magnetic oscillations in patterned structures is one of the main topics of research in recent years [2, 3]. However, most of the works related to the magnonic crystal is focused on the study of the band structure in the passband [3-6]. However, the knowledge of only the band structure is not enough to create a variety of devices based on the magnon. This work is devoted to the study of new effects associated with the conversion of energy of magnetic oscillations in new types of waves, which is the most promising type of research.

Magnetic oscillation in magnetic ordered state can be described by the Landau-Lifshitz equation (with neglected losses):

$$\frac{d\mathbf{M}}{dt} = \gamma[\mathbf{M} \times \mathbf{H}] \tag{1}$$

(where **M** – vector of magnetization, **H** – vector of magnetic field, *t* – time, γ – giromagnetic ratio [7]).

Together with Maxwell's equations and boundary conditions, it is possible to describe the process of propagation of magnetostatic spin waves (MSW). In tangential magnetization slab propagation one can in general describe by the following equation [8]:

$$\left(k_y^2 + k_z^2\right) + 2\mu\sqrt{\left(k_y^2 + k_z^2\right)\left(\frac{k_y^2}{\mu} + k_z^2\right)} \cdot \coth\left(d\sqrt{\frac{k_y^2}{\mu} + k_z^2}\right) + \mu^2\left(\frac{k_y^2}{\mu} + k_z^2\right) - \mu_a^2 k_z^2 = 0 \tag{2}$$

Where *d* is the thickness of film; μ, μ_a – components of the tensor of magnetic permeability:

$$\hat{\mu} = \begin{pmatrix} \mu & -i\mu_a & 0 \\ i\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$\mu = 1 + \frac{\omega_M \omega_H}{\omega_H^2 - \omega^2} \tag{4}$$

$$\mu_a = \frac{\omega_M \omega}{\omega_H^2 - \omega^2} \tag{5}$$

where $\omega_M = 4\pi M_s \gamma$; $\omega_H = \gamma H$; $\omega = 2\pi f$; M_s – magnetization saturation; γ – giromagnetic ratio; ω – angular frequency, *f* – frequency, *y*-direction is parallel to the thickness of film, an external magnetic field is applied along *z*-direction, k_i – means a component of the wave vector.

In the case of yttrium iron garned (YIG) (one of the most commonly used material in MSW study) we can neglect both the exchange interaction [9] and the magnetic anisotropy [10, 11] without distorting of physical view [12].

Equation (2) gives the surface of anisotropic dispersion $\omega = F(k_x, k_y)$, characteristic only for MSW. Analysis of this equation is rather complicated and it is possible to obtain a solution only for some simplest cases. In the case of modification of the boundary conditions, this equation becomes more complicated (for example [13]) and the analytical solution becomes impossible. The interaction of a MSW is possiblewith either a single defect of a magnetic crystal (like e.g. antidot) or many defects (e.g. line or array of antidots) in the whole patterned sample. The separation of these contributions is an important task for understanding the interaction of complex structure MSW.

II. The aim of this dissertation

The main aim of this dissertation is to study the interaction of magnetostatic oscillations with patterned structures prepared on the basis of both permalloy and YIG in the form of magnetic single dot, single antidot, and line of antidots. The study will be performed for different sizes of dots (in the range of micrometer) and antidots (in the range of tens of micrometer) and different distances between antidots (in the range from 40 to 180 micrometers). The following experimental conditions will be varied: the power of microwave excitation, the value of an external magnetic field and direction of the field in respect to the line of antidots. The experimentally obtained results will be explained by both analytical models and numerical calculation, as well as by iso-frequency dependences.

III. Experimental technique and samples

3.1 General information about Brillouin Light Scattering

Magnetic excitations that can interact with visible photons are present in magnetic solids. Because the energy spectra of these excitations are dependent on intrinsic material properties and are dramatically affected by nanostructuring the materials, they provide a powerful tool for magnetic characterization of magnetic thin films. Brillouin light scattering (BLS) is an optical probe capable of detecting and determining the frequency of these excitations with high sensitivity. Photons with energy $\hbar\omega_L$ and momentum q_L interact with quanta of spin waves $(\hbar\omega, q)$, which are magnons. Although most incident photons scatter elastically, a very small fraction undergo inelastic scattering. In these inelastic events, photons may create phonons or magnons with energy $\hbar(\omega_L - \omega)$ and wavevector $\hbar(q_L - q)$ or absorb collective excitations with energy $\hbar(\omega_L + \omega)$ and wavevector $\hbar(q_L + q)$ see figure below. Thus scattered photons are frequency shifted by an amount corresponding to the excitation energy of the phonon or spin wave. For magnetic characterization, the spin wave excitations are the ones of interest and are selected by preparing the polarization of the incoming light beam appropriately. By determining the dependence of the spin wave frequency and intensity on the external magnetic field and film thickness, the spin wave spectrum is directly probed, yielding valuable information on the magnetic ordering of the films, as well as their uniformity and anisotropies [14].

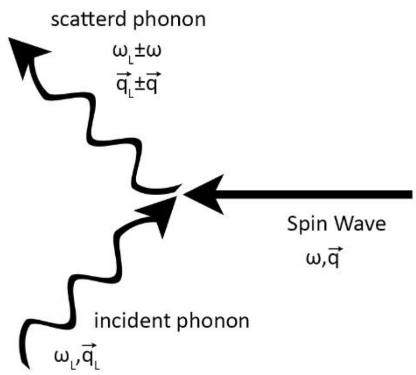

Figure 1. Scheme of scatter’s process on phonons or magnons.

Because of the relatively small number of inelastically scattered photons and the closeness of the spin-wave modes to the primary laser line, the requirements on the performance of the optical system are extreme, especially for detecting spin waves in films only a few monolayers thick. The spin-wave frequencies can be as small as a few GHz, so the light source must have a line width of, at most, 20 MHz.

3.2 Brillouin light scattering setup

As a method for studying these processes, the Brillouin light scattering spectroscopy has been selected. BLS has the ability to detect the intensity of spin waves in a localized region of the sample’s surface. Therefore, one may visualize the process of interaction of MSW with patterned structures with high both spatial and temporal resolutions. Currently BLS is one of the most modern methods of investigation of the dynamic of magnetization.

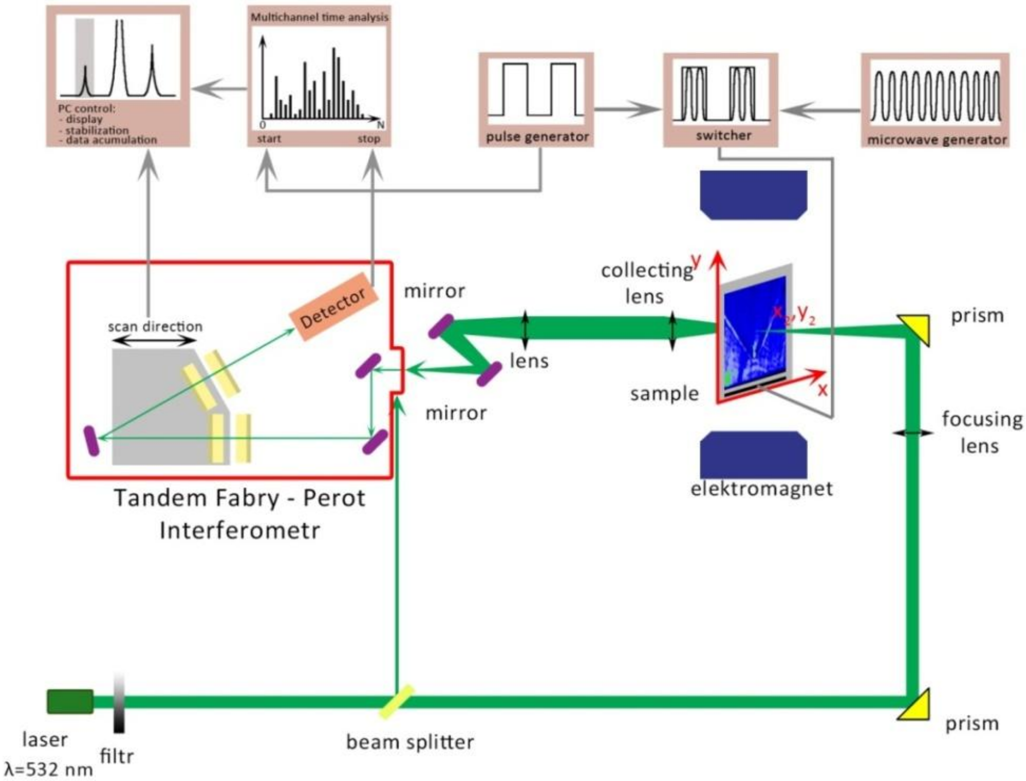

Figure 2. Scheme of setup for Brillouin light scattering spectroscopy.

Spectra of Brillouin light scattering have been studied using the setup made by the JRS Scientific Instruments company,including two three-pass tandem Fabry-Perot interferometers [15] (Figure. 2). The radiation source is the monochromatic single-mode solid-state laser Spectra- Physics, operating at the wavelength λ = 532 nm and thepower of W = 300 mW. The power of laser light is attenuated by a neutral filter down to 10 mW, in the aim to avoid a deformation of the sample by the thermal radiation. The setup can be operated in one of the following modes: forward, backward and quasi-inverse scattering at different angles of orientation of the sample. The light is focused on a sample using a lens of the focal length of F = 35 mm. Scattered light is collected by lenses and gets to the Fabry-Perot interferometer. An external magnet field of maximum value of H = 12,5 kOe can be applied parallel to the film surface and perpendicularly to the incident light. The separation of contributions of phonon and magnon occurs with the polarizer, which allows to measure the signal coming from magnons only. [16].

Fabry-Perot interferometer allows to resolve the wave vectors in the range from 0 to 2.4×10^4 cm^{-1} with high sensitivity - the contrast is as high as $1:10^{10}$.

MSW is excited by a stripline antenna connected to the microwave (MW) current generator .It is possible to modulate the microwave current by the pulse generator . The same pulse generator gives the command to start the measuring of the signal. This synchronization allows to obtain the temporal resolution up to 1 ns.

Measured intensity of light is proportional to the average square of the dynamic magnetization $<m_z^2>$ [14]. Thus, the fixed time of signal acquisition of scatter light can judge the intensity of MSW at different points. A special system of step engines allows to shiftthe sample in two directions in the surface of the sample . Thus it is possible to visualize the process of propagation MSW in the sample with a spatial resolution down to 40 microns.

3.3 Microfocusing BLS

It is possibleto install a special microscopic objective focusing the light beam to the diameter of 250 nm, i.e. near the diffraction limit. This allows to considerably increase the spatial resolution of the apparatus. For such high resolution, a thermal drift of the sample can significantly affect the results. To compensate the drift, a special system has been used. The movement to the sample is carried out using piezo table. The monitoring of the position of the sample is carried out by a diode lamp illuminator. The separation of the laser and diode light is performed by polarizers [17].

3.4 Samples

Study of the properties of magnetic oscillation should be carried out on materials characterized by a low value of the damping parameter of magnet subsystem. Thus, the following samples have been chosen: permalloy $Ni_{80}Fe_{20}$ (Py), as it is the best material for study of magnetic oscillation among metallic system [3] and yttrium iron garned $Y_3Fe_5O_{12}$ (YIG), as it is the best material in general because of the smallest damping of magnetic oscillation [12].These materials are well-studied, which greatly simplifies the analysis of the data. The aim of the study is not to find a new property of solidstate, butto investigate the interaction of MSW with patterned structures of micro- and nano- sizes. In this case it is possible to consider the properties obtained in the theory of continuous media.

IV. Theoretical modeling

4.1 Analytical solution

A propagation of magnetic oscillation in solid state just like all problems of electrodynamics, can be found by solving the Maxwell equations [18]:

$$\begin{aligned} \mathrm{rot}\,\mathbf{H} &= 0 \\ \mathrm{rot}\,\mathbf{B} &= 0 \end{aligned} \qquad (6)$$

where **H** and **B** are vectors of the magnetic field intensity, magnetic field induction, respectively.

Let us assume that the material is electrically isotropic, thus the tensor $\hat{\varepsilon}$ is reduced to scalar ε. In the case of YIG, we can neglect exchange interaction [9, 12].

By dividing the **H** into constant and time-dependence components [7], one comes to:

$$\mathbf{H} = \mathbf{H_0} + \mathbf{h}(\mathbf{r}, t) \qquad (7)$$

To solve of problem of magnetic oscillation one needs the Landau-Lifshicz equation (1) of motion of magnetization [7] (with neglected losses).

Solution of eq. (6), (7), and (1) for the tangentially magnetized plane gives [8]:

$$k_z^2 = -\left(k_x^2 + \frac{k_y^2}{\mu}\right) \qquad (8)$$

Taking into account the boundary conditions for dielectric medium outside magnetic plane:

$$k_{zy}^2 = k_x^2 + k_y^2 \qquad (9)$$

one can obtain the equation (2) which describes the propagation of MSW in a tangentially magnetized sample [8].

In the case of magnetostatic surface spin waves or Damon-Esbach (MSSW), there isan additional condition for solving the eq. (1):

$$\mu \geq 0; \quad \frac{k_x^2}{\mu} + k_y^2 = \frac{1}{\mu}\cot^2\varphi + 1 \geq 0 \qquad (10)$$

and then one can find the solution that Damon-Eshbach waves can propagate in the following φ range: $90^0 \leq \varphi < \varphi_c$ [19], where φ_c is the critical angle of propagation of MSSW:

$$\varphi_c = \arctan\sqrt{\frac{H}{4\pi M_s}} \qquad (11)$$

In the case of backward volume magnetostatic spin waves (BVMSW) there isan additional condition for solving theeq. (2) [8]:

$$\mu < 0; \quad \frac{k_x^2}{\mu} + k_y^2 = \frac{1}{\mu}\cot^2\varphi + 1 < 0 \qquad (12)$$

The anisotropy of propagation of MSW significantly changes the reflection low in comparison with the light reflection in optics. For MSW, the projections of the incident and reflected wave vectors on the mirror plane are conserved [20]:

$$k_{in}\cos(\varphi_{in} - \Theta) = k_{ref}\cos(\Theta - \varphi_{ref}) \qquad (13)$$

where subscript *in* and *ref* means incident and reflection, respectively; Θ – angle between the the mirror plane and the direction of an external magnetic field. We assume that there is no conversion of the MSSW to other type of waves.

By solving the eq. (13) and eq. (2) we obtain the reflection equationfor MSW:

$$\frac{\cot\varphi_{in} + \cot\Theta}{\sqrt{\frac{1}{\mu}\cot^2\varphi_{in} + 1}}\operatorname{arctanh}\frac{2\sqrt{\mu(\cot^2\varphi_{in} + \mu)(\cot^2\varphi_{in} + 1)}}{(1 + \mu^2 - \mu_a^2) + (1 + \mu)\cot^2\varphi_i}$$
$$= \frac{\cot\varphi_{ref} + \cot\Theta}{\sqrt{\frac{1}{\mu}\cot^2\varphi_{ref} + 1}}\operatorname{arctanh}\frac{2\sqrt{\mu(\cot^2\varphi_{ref} + \mu)(\cot^2\varphi_{ref} + 1)}}{(1 + \mu^2 - \mu_a^2) + (1 + \mu)\cot^2\varphi_{ref}} \qquad (14)$$

For MSSW there is an interesting case when $\varphi_r \le \varphi_c$. In this case, a new wave arises, propagating along the mirror plane called **the total non-reflection wave**. The intensity of this wave strongly decreases in the direction normal to the mirror plane [8]. The real solution of the eq. (14) does not dependent on the direction of the incident wave φ_{in}. But using the asymptotic solutionfor eq. (2) taken from the Ref. [20] we can find the following formula for the critical, angle Θ_{crit}, for which one can observe the total non-reflection waves:

$$\Theta_{crit} = \frac{\pi}{2} - \arcsin\left(\frac{\omega - \sqrt{\omega^2 - \omega_H^2 - \omega_H\omega_M}}{\omega_H + \omega_M}\right) \qquad (15)$$

4.2 Micromagnetic simulation

Micromagnetic simulations have been performed using the software The Object Oriented MicroMagnetic Framework (OOMMF) [21].

This program uses a phenomenological approach to a magnetic material. One should set the value of saturation magnetization, the exchange interaction constant and the Gilbert damping parameter. Additionally, one can set other parameters, such as the type the magnetic anisotropy and anisotropy constants, conductivity, and so on. A simulated sample is modelled as a matrix of rectangular cells with dimensions and shape set by the user. Magnetization is homogeneous inside a cell. The cell size should be smaller than the exchange length. The interaction between cells is calculated using the Landau-Lifshitz-Gilbert equation. But in the case of YIG, mainly the dipole waves are excited, thus it is possible to set the cell's size much smaller than wavelength, but larger than the exchange length. Numbers of cells is limited only by the computer's memory. An external magnetic field is given by the Zeeman energy term.

The dynamics of the magnetization is calculated in few steps. In the first step the equilibrium state for a fixed external magnetic field is calculated. The determination of the equilibrium state takes place on the base of finding of the minimum of the total energy. In the second step a magnetic bias field is applied in one part of the sampleonly in the aim to model an excitation antenna. In the aim to exclude the reflection of MSW from the edge of the simulated sample one can either use periodic boundaries conditions or increase Gilbert damping parameter near the edge of the sample.

V. Published papers

5.1 The first publication

"Resonant frequency multiplication in microscopic magnetic dots." V.E. Demidov, H. Ulrichs, S. Urazhdin, S.O. Demokritov, V. Bessonov, R. Gieniusz, A. Maziewski.Applied Physics Letters, volume 99, Issue 1,pp 012505 (3) (2011).

The process of excitation and hybridization of different modes in magnetic dots and waveguides were investigated in the paper [22]. The eigen modes in this structures, caused by the dipole-dipole interaction, were excited as a central mode while the exchange interaction were responsible for the edge mode [23]. Also in the paper [24] the possibility of excitation of standing waves due to reflection from the sample boundaries, have been shown.

In the first paper, we show that dynamic nonlinearity in microscopic Permalloy structures can be used for efficient frequency multiplication. The elliptical dots had the lateral dimensions of 1 by 0.5 μm and the thickness of 10 nm and were prepared bye-beam lithography on top of 1 μmwide microwave transmission line used for the excitation of magnetization dynamics. We demonstrate that the nonlinearity of magnetic system that emerge at large excitation powers results in the generation of the dynamic magnetization harmonics at twice and three times excited signal frequency. We study the spatial and the spectral properties of the response of the BLS signal to the microwave excitation. We show that the process of second harmonic generation involves the anti-symmetry of the spatial distribution with respect to the initial oscillation directly excited by the microwave field. In contrast, the triple- frequency harmonics preserves the symmetry of the dynamic magnetization with respect to the initial oscillation. The latter process is particularly efficient, which makes it promising for technical applications.

5.2 The second publication

"Single antidot as a passive way to create caustic spin-wave beams in yttrium iron garnet film." R. Gieniusz, H. Ulrichs, V.B. Bessonov, U. Guzowska, A.I. Stognij, A. Maziewski. Applied Physics Letters, Volume 102, Issue 10, pp102409 (4) (2013)

An experimental implementationof an active spinwave quasipoint excitation source as a waveguide terminated by an infinite film, was presented for backward volume magnetostatic spin waves in the paper [25]. But the realization ofan active spin-wave point source inside an infinite film alone is not easy to accomplish. Here, we show that this demand can also be fulfilled by a single antidotas a passive way to create caustic spin-wave beamsin yttrium iron garnet films, and israther simple to create.

Second publication reviews the diffraction of surface magnetostatic spin waves on an isolated local antidot in a thin garnet film. The magnetostatic spin waves were excited by anmicrowave magnetic field generated by a 50 μm wide microstrip antenna located near the array of the antidots on the garnet film. The carrier wave length of the excited spin waves was comparable to the diameter of the antidot. The Brillouin light scattering spectroscopy with high spatial and temporal resolution, allowing two-dimensional visualization of the spin waves propagation was employed to the study of diffraction patterns of spin waves around an antidot.

The diffraction patterns were investigated as a function of the excitation frequency, the strength of the static magnetic field and as a function of the in-plane angle between the antenna and the magnetic field. The diffraction patterns showed a structure with semicaustic beams directions. These directions were experimentally investigated as a function of the excitation frequency. To explain experimental results, numerical calculations of diffraction patterns were performed by applying spin wave theory for thin films and Huygens principle.

These theoretical calculations are in good agreement with our experimental findings. The micromagnetic simulation of the spin wave propagating in the patterned film was also performed.

5.3 The third publication

“An antidot array as an edge for total non-reflection of spin waves in yttrium iron garnet films”. R. Gieniusz, V. D. Bessonov, U. Guzowska, A. I. Stognii, A. Maziewski Applied Physics Letters, volume 104, issue 8, pp. 082412 (5), (2014)

MSSW diffraction processes on an array of antidots have been studied before and have been easily described by a superposition of diffraction on a single antidot [26]. The similar effects for backward volume waves was considered theoretically using micromagnetic simulation in the work [4].

In the this paper, we consider the interaction of propagating MSSW with a line of antidots. The samples under study were single crystalline YIG films with a thickness of $t = 4.5$ μm, which were epitaxially grown along the (111) crystallographic axis. The arrays of antidots were chemically etched, with 67 μm diameters or widths, and with either round or square shapes. It was shown that the line of antidots can be used as an edge to produce the phenomenon of total non-reflection of the spin wave in YIG film. At the critical angle between the line of antidotsand the magnetic field, we observe a high-intensity beam of spin waves moving along the line of antidotes and we do not observe the reflected waves. From the BLS measurements we obtained that the transverse intensity profiles for moving beams along the line of antidotes and along the edge of the YIG sample are almost equal. We show that by changing the periods of the antidots arrays, it is possible to generate either continuous or periodic spin wave beams. The results of the OOMMF simulations are consistent with the experimental results, while the isofrequency curves provide a tool for clear interpretation of the experimental data.

VI. Conclusions

The most important achievement of my dissertation, are the following:

1. The examination of the phenomenon of nonlinear frequency multiplication in submicrometer-sized-Permalloy-elliptical dots at large excitation power. The use of an unique experimental system, namely the micro-focus Brillouin light scattering spectroscopy, to the detection of the dynamic magnetization. The observation that the characteristics of resonant enhancement are dependent on the spatial symmetry of the dynamical mode and are different for the double- and the triple-frequency harmonics. The demonstration that the resonant frequency tripling is particularly efficient and the suggestion of a route for the implementation of nanoscale frequency multipliers for integrated microwave technology.
2. The observation of spin waves scattering from the single antidot as a passive way to the creation of the caustic spin wave beams in yttrium garnet films. Characterization of the properties of the diffraction beams depending of the frequency, the direction of the incident waves and the properties of the external magnetic field. The proposition of a numerical calculations of diffraction patterns based on Huygens's principle. The application of the magnetostatic spin wave theory for thin films and demonstration of a good agreement between the experimental and theoretical data. Proving that for microwave devices, the passive antidot offers a convenient way to realize functionalities based on the focusing effect and that it is rather simple to create in comparison with active spin-wave point sources.
3. The proposition and experimental demonstration of the total non-reflection of spin waves by an antidots array. Showing that a highly intense beam of spin waves propagates along these antidots at the critical angle Θ_{crit}, which was measured between the line of antidots and the direction of magnetic field. The observation that by changing the periods of the antidot arrays, itis possible to generate either continuous or periodic spin wavebeams. Showing that the results of the OOMMF simulations are consistent with the experimental results and the isofrequency dependences provide a good tool for the clear interpretation of the experimental data.

Reference

1. F. Bloch. Z. Phys. **61**, 206 (1930)
2. S. O. Demokritov, A. N. Slavin. *Magnonics. Form Fundamentals to Applications*. Springer. Heidelberg, New York, Dordrecht, London. 2013
3. M. Krawchyk, D. Grundler. J. Phys.: Conden. Matter. **26**, 123202 (2014)
4. E. K. Semenova, D. V. Berkov. J. Appl. Phys. **114**, 013905 (2013)
5. A. V. Chumak, A. A. Serga, S. Wolff, B. Hillebrands, M. P. Kostylev. Appl. Phys. Lett. **94**, 172511 (2009)
6. Yu. V. Gulyaev, S. A. Nikitov, L. V. Zhivotovskii, A. A. Klimov, Ph. Tailhades, L. Presmanes, C. Bonningue, C. S. Tsai, S. L. Vysotskii, Yu. A. Filimonov. JETP Lett. **77,** 567 (2003)
7. A. G. Gurevich, G. A. Melkov. *Magnetization Oscilations and Waves*. CRC Press. Boca Raton, New York, London, Tokyo. 1996
8. P. Kabos, V. S. Stalmachov, *MagnetostaticWaves and Their Applications*. Chapman and Hill. London. 1994
9. L. R. Walker. Phys. Rev. **105**, 390 (1956)
10. M. J. Hurben, C. E. Patton. JMMM. **139**, 263 (1995)
11. M. J. Hurben, C. E. Patton. JMMM. **163**, 39 (1996)
12. A. A. Serga, A. V. Chumak, B. Hillebrands. J. Phys. D: Appl. Phys. **43**, 264002 (2010)
13. B. A. Auld, K. B. Mehta. J. Appl. Phys. **38**, 4081 (1967)
14. M. G. Cottam, D. J. Lockwood. *Light scattering in magnetic solids*. Willey. New York. 1986
15. S.M. Lindsay, M.W. Anderson, J.R. Sandercock. Rev. Sci. Instr. **52**, 1478 (1981)
16. N. Bloembergen, S. Shapiro, P. S. Pershan, J. O. Artman. Phys. Rev. **114**, 445 (1959)
17. S. O. Demokritov, V. E. Demidov. Magn. IEEE. Trans. **44**, 6 (2008)
18. M. Born, E. Wolf. *Principles of Optics*. Cambridge University Press. Cambridge. 1998
19. R.W. Damon, J.R. Eshbach. J. Phys. Chem. Solids. **19**, 308 (1961)
20. A.V. Vashkovsky, D.G. Shahnazaryan. Radiotehnika I Elektronika (Journal of Communications Technology and Electronics). **32**, 719 (1987)
21. M. Donahue, D. G. Porter. The Object Oriented MicroMagnetic Framework. http://math.nist.gov/oommf/

22. V. E. Demidov, M. Buchmeier, K. Rott, P. Krzysteczko, J. Münchenberger, G. Reiss, S. O. Demokritov. Phys. Rev. Lett. **104**, 217203 (2010)
23. M. Grimsditch, G. K. Leaf, H. G. Kaper, D. A. Karpeev, R. E. Camley. Phys. Rev. B. **69**, 174428 (2004)
24. V. E. Demidov, U.-H. Hansen, S. O. Demokritov. Phys. Rev. Lett. **98**, 157203 (2007)
25. T. Schneider, A. A. Serga, A. Chumak, C. W. Sandweg, S. Trudel, S. Wolff, M. P. Kostylev, V. S. Tiberkevich, A. N. Slavin, B. Hillebrands. Phys. Rev. Lett. **104**, 197203 (2010)
26. S. Mansfeld, J. Topp, K. Martens, J. N. Toedt, W. Hansen, D. Heitmann, S. Mendach. Phys. Rev. Lett. **108**, 047204 (2012)

Originals of publications