INTERNATIONAL WORKSHOP BRILLOUIN AND MICROWAVE SPECTROSCOPY
OF MAGNETIC MICRO- AND NANOSTRUCTURES

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Brillouin and Microwave
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of Magnetic Micro-
and Nanostructures

BOOK OF ABSTRACTS

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САРАТОВСКИЙ ГОСУДАРСТВЕННЫЙ
ТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ
ИМЕНИ ГАГАРИНА Ю.А.

АЛМАЗ

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Conference Program

August 3, 2014 (Sunday)

8:00 – 12:00 meeting of the participants in Saratov City and excursion tour

12:00 transfer to the Conference venue (sanatorium “Volzhskie Daly”)

13:30 Registration

14:00 lunchtime

16:00 opening ceremony of International Workshop “Brilmics 2014” (Conference Hall 1)

16:20 – 17:00 lectureHillebrands B. “Condensation of Mixed Magnon-Phonon States
in Gas of Pumped Magnons”

17:00 -- 17:40lecture Demokritov S.O. “BLS study of spin dynamics driven by spin currents”

18:00 –19:00 dinner

19:00 Welcome Party

August 4, 2014 (Monday) (Conference Hall 2)

8:00 – 9:00 Breakfast

9:00 – 9:40 lecture Ogrin F. “FDTD-LLG: Time-domain solutions for magnetic metamaterials”

9:40 –10:00Nikitov S.A. “Autonomous and Non-Autonomous Dynamics of Spin Hall Auto-Oscillators“

10:00 – 10:20 Fetisov Yu.K. “Nonlinear magnetoelectric effects in composite ferromagnetic-piezoelectric structures”

10:20 – 10:40 Mikhailovskiy R. “Terahertz Spectroscopy of Ultrafast Spin Dynamics”

10:40 – 11:20 Coffee break

11:20 – 11:40 Lokk E. “On the Angular Width of the Wave Beam in Anisotropic Media and Structures (In Terms of Spin Waves)”

11:40 – 12:00Ovchinnikov S. “FE/SI Nanostructures: MBE Growth and Properties”

12:00 – 12:20 Grishin S.V. ”Generation of dissipative parametric bright solitons in active ring resonators with multiresonant ferromagnetic and vacuum elements”

12:20 – 12:40 Morozova M.A. “Tunable band gaps in magnonic crystal with line-defect”

12:40 – 13:00 Kalyabin D.V. “Edge magnons in magnonic crystals”

13:00 – 15:00 lunch time

15:00 – 15:20 Grigoryeva N.Yu. “Localization Properties and Magnetic Field Tuning of Spin-Wave States in Micro- and Nanosized Ferromagnetic Waveguides”

15:20 – 15:40 Rinkevich A.B. “Complex Refraction Coefficient of Magnetic Nanocomposites on the Waves of Millimeter Waveband”

15:40 – 16:00 Rinkevich A.B. “Spatial Distributions of Electromagnetic Field in a Conductive Layer Under the Magnetic and Spin Wave Resonance Conditions”

17:30 – 18:30 dinner

18:30 Excursion tour (Volga river)

August 5, 2014 (Tuesday) (Conference Hall 2)

8:00 – 9:00 breakfast

9:00 – 9:40 lecture Krawczyk M. “Periodic and Aperiodic One-Dimensional Structures for Magnonics”

9:40 – 10:20 lecture Kruglyak V. “Breaking the symmetry of spin wave excitation in magnetic thin films and microstructures”

10:20 – 10:40 Filimomov Yu.A. “Spin wave spectroscopy in yttrium iron garnet thin film structures with micro-sized antennas”

10:40 – 11:20 Coffee break

11:20 – 12:00 lecture Stashkevich A.A. “Brillouin Scattering by Spin Wave Modes Localized on Ultra Thin Magnetic Nanowires: Magnonic and Photonic Properties”

12:00 – 12:40 lecture Aliev F. “Spin waves along topological domain walls”

12:40 – 13:00 Vysotskyi S.L. “Spin wave resonances in microstructured ferrite films”

13:00 – 15:00 lunch time

15:00 – 15:20 lecture Gieniusz R. “Quasioptic Effects of Magnetoostatic Waves in Structured Yttrium Garnet Films”

15:20 – 15:40 Meyer T. “Control of the Effective Damping in Heusler/Pt Microstructures via Spin-Transfer Torque”

15:40 -- 16:00 Sakharov V. “Kerr microscopy investigation of cobalt 2D periodic structure on Permalloy film”

16:00 – 18:30 Poster session

19:30 Banquet

August 6, 2014 (Wednesday)

10:00 – transfer to Saratov City

11:00 – 13:00 visit of the Laboratory of Metamaterials (Saratov State University)

13:00 Conference Close

Poster session

Timoshenko P. “Diffraction of Magnetostatic Waves by Surface Cavities on a Ferromagnetic Film”

Pavlov E. “Bistability in a nonlinear Fabry-Perot MSSW resonator based on magnonic cryslal with structural defect”

Tikhonov V.V. “Temperature stabilization of spin wave ferrite devices”

Litvinenko A. “The excitation of exchange spin waves on boundary of the multilayer ferrite structure”

Sheshukova S.E. “Spatio-temporal dynamics of spin waves in ferrite periodic irregular waveguides”

Sadovnikov A.V. “Discrete diffraction in coupled YIG arrays”

Romanenko D.V. “Temporal dissipative solitons in a ferromagnetic film active ring resonator at three-wave interactions”

Sharaevskaya A.Yu. “Features of formation band gaps in structures based on magnon crystals”

Beginin E.N. “A comparative study of Fe_3O_4 nanocomposite coating by means of FMR and BLS”

Bublikov K.V. “Finite Element Method for layered YIG-Ferroelectric waveguide”

Urmancheev R.M. “Analytical Theory of Spin Wave Propagation in Periodic Structures”

Churbanov A.M. “Spin-Wave Propagation in Metallized Magnetic Films”

Sadovnikov A.V. “Spin wave propagation in coupled and irregular YIG structures”

Klimov A. “Ferromagnetic resonance and magnetoelastic demodulation in thin active films with an uniaxial anisotropy”

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MAGNETIC TUNNEL JUNCTION SPIN TORQUE OSCILLATORS

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Microwave oscillators based on magneto-resistive devices are of current interest due to their frequency tunability at high frequencies, small dimensions (<100nm) and easy integration above standard CMOS circuit. This is of interest for realizing integrated microwave components. These Spin torque nano-oscillators (STNOs) can be realized in different geometries, nanocontacts and nanopillars, and for different configurations, such homogeneous in-plane magnetized or vortex type free layers combined with in-plane or out-of plane magnetized polarizing layer. Independent of the configuration, the nanofabrication process is the same.

One of the challenges for STNO integration is to enhance the output power and to decrease the linewidth of the microwave emission peak. For this, a high degree of control of the nanofabrication process and of the texture of the MgO barrier and the magnetic layers is required. In particular STNO operation requires a high tunnel magnetoresistance (large output power) combined with an ultra-low resistance x area (RA) product necessary to obtain steady state oscillations. Low RA – high TMR MgO magnetic tunnel junctions (MTJ) were deposited by sputtering at the International Iberian Nanotechnology Laboratory (INL) using a Timaris sputtering tool and at LETI using an ion beam sputtering tool from SPTS.

Here we present the different steps of the nanofabrication process that we are optimizing in order to achieve the required specifications and the static and dynamic characterization of the devices. The static characterization to determine the MTJ degradation and with this the breakdown voltage is done by measuring the resistance vs. applied magnetic field curves, R(H), at different current values. This allows extracting the parallel and antiparallel resistance, TMR and voltage values as a function of the applied current. From these results we can obtain the degradation voltage as the saturation of the voltage-current characteristics, which for the given devices is around 400-500mV. These results are important to define the measurement conditions in dynamic experiments where the current to induce the steady state oscillations needs to be below the degradation threshold in order to perform the microwave measurement safely without degrading the device. The results altogether provide a feedback to improve the material and the nanofabrication process, especially the MgO deposition conditions, with the aim to reduce pinhole formation inside the barrier during deposition, annealing or upon applying a current and to increase the barrier degradation threshold.

In order to test device stability under DC current for microwave generation, we have measured the dynamic properties in the antiparallel state such as the frequency, generated power and linewidth as a function of current I and field H. As a final test of device robustness, we also performed synchronisation experiments to an external rf current source.

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SPIN WAVE RESONANCES IN MICROSTRUCTURED FERRITE FILM

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Formation of resonance-like features in transmission coefficient $S_{21}(f)$ of magnetostatic surface waves (MSSW) [1] propagating in yttrium iron garnet (YIG) film with microstructured surface was studied. The surface structure was ion-etched in the form of array of grooves ~1 μm in depth and ~5 μm in width with period Λ~9 μm. The obtained sample was placed on the exciting and receiving microstrip antennas with the width w=50 μm spaced by 4 mm and could be rotated at angle α between groove’s axis and bias magnetic field $\vec{H}_0$ directed along antennas. Note that observation of Bragg resonances in $S_{21}(f)$ dependence could not be expected because microstrip antenna couldn’t effectively excite MSSW wavelength λ (λ_{min}~2w) short enough to satisfy Bragg condition 2Λ = nλ (n=1, 2,…). MSSW propagation characteristics were measured both in continuous and pulse regimes for different values of angle α. In comparison with starting YIG film $S_{21}(f)$ dependence of the studied sample could include (depending on α) narrow frequency regions of MSSW losses down to -60 dB close to long wavelength MSSW boundary (Fig.1) or broadband stop band (Fig.2) or dipole-exchange waves’ resonances (Fig.3). The origins of mentioned features are discussed using results of micromagnetic simulation of internal magnetic field inside the sample depending on α.

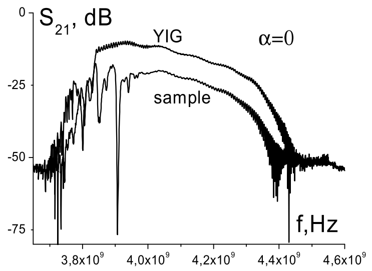

Fig1. $S_{21}(f)$ dependencies for YIG and the sample, H=680 Oe, α=0

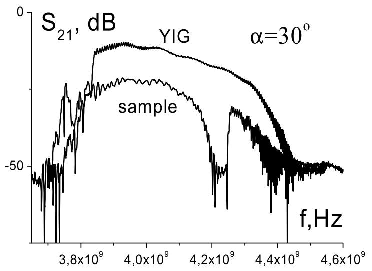

Fig2. $S_{21}(f)$ dependencies for YIG and the sample, H=680 Oe, α=30°

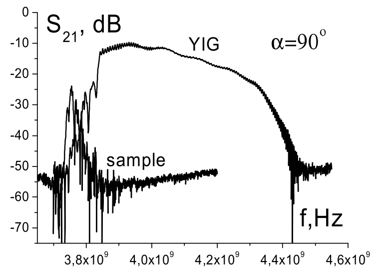

Fig2. $S_{21}(f)$ dependencies for YIG and the sample, H=680 Oe, α=90°

Support by the RFBR (Grants No. 14-07-900001_Bel_a, 13-07-12421-ofi_m, 13-07-00941-a, 14-07-00896-a,) and by the Grant of the Government of the Russian Federation for supporting scientific research projects supervised by leading scientists at Russian institutions of higher education (Contract No. 11.G34.31.0030) is acknowledged.

[1] A.G. Gurevich, G.A. Melkov Magnetization Oscillations and Waves, Fizmatlit, Moscow, (1994) [in Russian].

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BRILLOUIN SCATTERING BY SPIN WAVE MODES LOCALIZED ON ULTRA THIN MAGNETIC NANOWIRES: MAGNONIC AND PHOTONIC PROPERTIES

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Self-assembled nanowires of ferromagnetic metals embedded in a dielectric matrix are interesting both for applications and fundamental science. Suffice it to mention ultra-dense magnetic recording media and metamaterials, including recently discovered artificial hyperbolic media.

Contrary to mainstream research in this domain, relying on ferromagnetic structures elaborated by means of a technology, today already conventional, based on electro deposition of metals in a porous alumina matrix [1], we have made use of a novel one. More specifically, it consists in co-deposition, by laser ablation, of the cylinders (Co) and the matrix ($Ce0_2$), taking advantage of the natural segregation and of the columnar growth [2]. This alternative way allows fabricating really ultrathin wires with a diameter as small as 2 – 6 nm, which is entirely impossible if the conventional technology is employed (typical diameter varies from 20 nm to 200 nm). The purpose of this paper is the Brillouin Light Scattering (BLS) study of spin-wave (SW) modes (thermal magnons) of 5nm wide Co nano-wires.

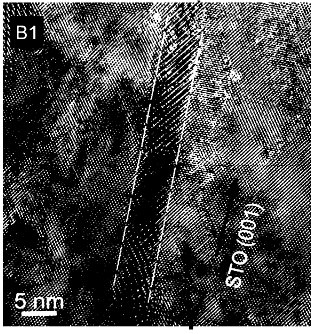

Fig.1. HRTEM image of a Co wire

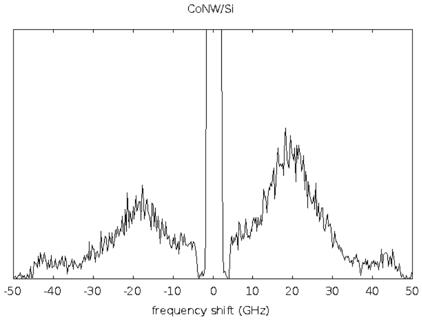

Fig.2. Typical BLS spectrum with inverted Stokes/anti-Stokes pattern

We would like to call one's attention to the double-uniqueness of these structures. Being of low concentration (around 4%), magnetically, they can be regarded as ensemble of independent spin-wave modes localized on individual wires, which allows their analytical description. Optically, metallo-magnetic inclusions are quasi-transparent, their radius being comfortably inferior to the optical skin depth (15 – 20 nm). One of the major features observed is the inversion of the Stokes/anti-Stokes asymmetry (see Fig.2: typically, the down-shifted Stokes BLS line is higher than the up-shifted anti-Stokes one). We show that it is caused by a corresponding inversion of the direction of the rotation of the elliptically polarized incident optical wave. The latter is equivalent to an inversion of the sign of the angle of refraction, a.k.a. « negative » refraction. In other words, magneto-optically, the wire medium behaves as an artificial material with a negative refractive index.

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CONTROL OF THE EFFECTIVE DAMPING IN HEUSLER/Pt MICROSTRUCTURES VIA SPIN-TRANSFER TORQUE

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We present the control of the effective spin-wave damping by the spin-transfer torque exerted by a pure spin current injected into Heusler compound microstructures [1]. Here, the pure spin current is generated by a DC current in a Pt layer on top of the magnetic layer via the spin-Hall effect [2]. By changing the current density and the direction of the DC current in the Pt layer, the generated pure spin current can be manipulated. Via the spin-transfer torque, this pure spin current can act on the magnetization in the magnetic layer and decrease or even compensate the Gilbert damping [3]. The damping is a very crucial parameter for any magnetization dynamics and the possibility to control this parameter, i.e. to further reduce the damping, gives access to novel nonlinear phenomena [4]. Especially, the cobalt-based Heusler compounds used in this work provide a large spin-wave propagation length and an already very low Gilbert damping [5]. Thus, the threshold for all spin-torque driven phenomena is comparably low and only small current densities in the Pt layer are needed. A possible way to investigate the change of the damping in a microstructure depending on the applied DC current is to determine the threshold power for parallel parametric amplification of spin waves [6]. The presented results were obtained using Brillouin light scattering microscopy [7]. Brillouin light scattering is the inelastic scattering of photons on magnons, the quanta of spin waves. By investigating the frequency and the intensity of the inelastically scattered light, the frequency and the intensity of the spin waves can be obtained. Using a microfocussed laser allows for a spatial resolution of about 400 nm. The results show a strong influence of the pure spin current on the effective damping in the magnetic layer. They show the feasibility of using a DC current in a Pt layer to control the effective damping in an adjacent Heusler layer. Thus, this is very interesting for possible applications using spin waves or for the investigation of nonlinear effects especially in Heusler compounds. The presented results were obtained in the framework of the Japanese-German Research Unit “Advanced spintronic materials and transport phenomena (ASPIMATT)”, funded by JST and DFG.

[1] V. E. Demidov, *et al.*, Nature materials **11**, 1028 (2012).
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[4] T. Sebastian, *et al.*, PRL **110**, 067201 (2013).
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[6] V.E. Demidov, *et.al.*, Nature communications **5**, 3179 (2014).
[7] V. E. Demidov, *et al.*, APL **85**, 2866 (2004).

FE/SI NANOSTRUCTURES: MBE GROWTH AND PROPERTIES

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Magnetic silicides are formed in the interface of Fe/Si heterostructure that are perspective material for spintronics. Multiphase composition of the interface usually decreases the spin tunneling from ferromagnetic to semiconductor layer. Here we discuss the formation of Fe silicides and report the properties of epitaxial single crystalline films Fe3Si (magnetic) and FeSi2 (nonmagnetic). Samples have been grown by thermal evaporation in the ultrahigh vacuum MBE machine with *in situ* control of its thickness, structural and magnetic properties. Optical and magnetooptical measurements *in situ* have been carried out with original home-made magnetoellipsometry devices for single wavelength and spectral measurement of the ellipsometry and Kerr effect

To study Fe –Si phases by Moessbauer spectroscopy we have grown isotope enriches multilayers Si/(^{56}Fe/^{57}Fe/Si)$_3$SiO2/Si samples with different interfaces: ^{57}Fe on Si and Si on ^{57}Fe [1] Combination of the volume Moessbauer data with the surface sensitive XMCD measurements allows us the estimate the space non uniform interface as a non-magnetic FeSi with thickness 0.2nm and magnetic interface with thickness 1.2nm. Magnetic interface is a solid solution of Fe3Si and Fe with increasing Fe concentration with the layer depth [2]. The single crystalline Fe3Si film gas been grown epitaxially on the Si(111) substrate with the 7x7 reconstruction. Its structure and magnetic properties are given in [3]. The optical spectra in visible range has been measured by spectral ellipsometry, both real and imaginary components of the diagonal component of the dielectric permeability tensor has been obtained [4]. The characteristic peaks in the spectra are in a qualitative agreement with the *ab initio* DFT-GGA band calculation.

This work has been supported by Presidium of RAS program 24.34.

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[2].M.S.Platunov etal., Pis’ma v ZhETF, 99, N.12 (2014).
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[4] I.A.Tarasov etal., Pis’ma v ZhETF, 99, N.10, 651 (2014).

STRUCTURE OF A SURFACE SPIN WAVE MAGNETIC INDUCTION IN FREE FERRITE FILM

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The structure of microwave magnetic induction **b** of surface spin wave is investigated. Calculations, based on Maxwell's equations, show that the vector lines of magnetic induction represent vortexes localized near both surfaces of the ferrite film (Fig. 1a), while the vector lines of the magnetic field, calculated earlier [1, 2] don’t form a vortex structure (Fig. 1b). Calculations were carried out for the next parameters: H_0 = 300 Oe, $4\pi M_0$ = 1750 Gs, ε = 15, s = 10 μm, k = 1000 cm^{-1}, $\lambda = 2\pi/k$, f = 3167 MHz. It should be noted that inside the ferrite film the vectors **b** and **h** are directed oppositely in general, while **b** and **h** fields structures coincide in vacuum half-spaces surrounding ferrite film (see Fig. 1). It is also evidently, that in accordance with Maxwell's equations magnetic induction vortexes must create a microwave electric field **e**$_z$: the upper-left and lower-right vortices in Fig. 1a create the field **e**$_z$, directed along *z* axis (in accordance with right-hand screw rule), and the lower-left and upper-right vortices in Fig. 1a create the field **e**$_z$, directed opposite to *z* axis (*z*-axis is directed from the reader to the plane of Fig.1). Mention must be made that, calculations of microwave magnetic induction structure agree with obtained previously calculations of the microwave electric field structure for spin wave. In particular, it was found in [3, 4], that dependence of electric field amplitude **e**$_z$ has two maxima along *x* axis (normal to the film plane): maxima are localized on the film surfaces, one of them is higher than the other and their signs are opposite. The resulting vector lines structure confirms the fundamental relationship (arising from Maxwell's equations) between microwave electric field and microwave magnetic induction of the surface spin wave.

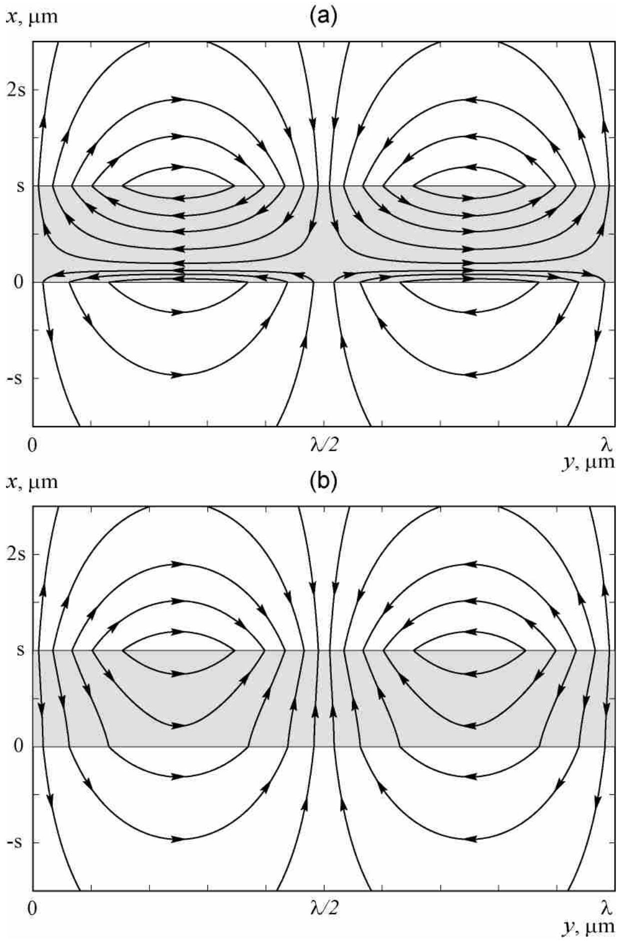

Fig. 1. Microwave magnetic induction **b** (a) and magnetic field **h** (b) structures for spin wave, propagated along *y* axis in tangentially magnetized ferrite film with thickness *s*. Magnetic bias field **H**$_0$ is parallel to *z* axis.

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NONLINEAR PHASE SHIFT AND DAMPING OF MICROWAVE SPIN-ELECTROMAGNETIC WAVES IN INFINITE MULTIFERROICS

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In recent years a strong interest to new composite and structured magnetic materials has been renewed [1, 2]. The one class of such materials is multiferroics which combine both electric and magnetic wave nonlinearities. The envelope solitons of spin-electromagnetic waves (SEWs) in infinite multiferroic medium had been studied in [3]. A nonlinear microwave phase shifter based on a planar multiferroic composite was described in [4]. In this work we report for the first time a theoretical investigation of nonlinear damping of the high power SEWs propagating in longitudinally magnetized infinite multiferroic medium. The study was carried out in several stages. In the first stage, the nonlinear dispersion characteristics were numerically simulated and analyzed employing nonlinear dispersion equation derived in the work [3]. In the second stage, the SEW propagation in a stable nonlinear regime was simulated numerically. The stable nonlinear regime is due to nonlinear four-wave process in which no enrichment of the spectrum of the microwave signal carried by SEWs takes place. Calculation of nonlinear damping and nonlinear phase shift was based on the nonlinear evolutional Ginzburg-Landau equation similar to that reported in [5].

The calculation was carried out for parameters corresponding to two media: yttrium iron garnet (YIG) [6] and Al-substituted barium ferrite $BaAl_2Fe_{10}O_{19}$ [7]. Fig.1 shows typical simulation results for $BaAl_2Fe_{10}O_{19}$. They were calculated for bias magnetic field H=1000 Oe, dielectric permittivity $\varepsilon=19$, initial amplitude of SEW $|u|=0.5$, and wave number $k=7550\ m^{-1}$. For these parameters SEW carrier frequency was 74.223 GHz. It is clear that the presence of nonlinear damping leads to a strong decrease in the amplitude and to the saturation of the nonlinear phase shift of SEW. It was found that the nonlinear effects become pronounced during SEW propagation if nonlinear damping coefficients exceed the following values: $\upsilon_1=10^8$ and $\upsilon_2=10^9$. For the described parameters the saturation value of nonlinear phase shift is -3.324 rad.

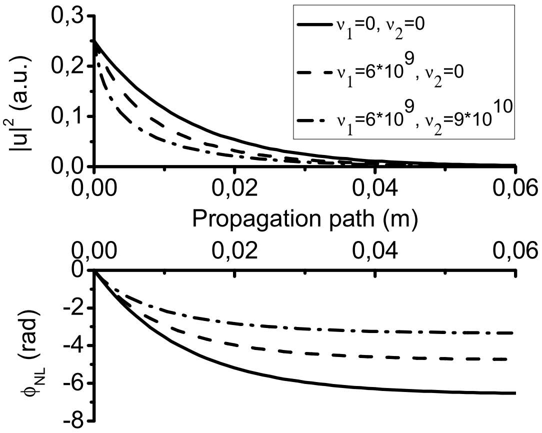

Fig. 1. Squared amplitude and nonlinear phase shift as a function of propagation path.

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SPIN TORQUE DRIVEN EXCITATIONS OF COUPLED MAGNETIC LAYERS

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Spin momentum transfer is an efficient means to drive the magnetization of magneto-resistive nanostructures into large amplitude auto-oscillations. These auto-oscillations have in the past been analyzed mainly in an independent free layer picture, where interactions with other magnetic layers of the magneto-resistive stack have been neglected. However, many experimental observations cannot be explained in this independent free layer model. For instance in standard in-plane magnetized spin valve structures gaps and kinks have been observed in the frequency-field excitation spectra, see Fig. 1. In this presentation we demonstrate that these features arise from the interaction between the free layer and the polarizer that is in form of a synthetic ferrimagnet. This is done by comparing experiments to macrospin simulations where the different interactions such as interlayer exchange interaction RKKY, dipolar interactions H_{dip} and mutual spin transfer torque MSTT can be investigated separately. This example demonstrates some of the basic features of the non-linear dynamics of coupled magnetic layers. Another example of a coupled system is a self-polarized synthetic antiferromagnet where two magnetic layers are coupled via interlayer exchange interaction and mutual spin torque. These studies will provide a better understanding of real-world spin torque oscillators (STO) and will provide a guide to exploit these coupling mechanisms for improved microwave properties. For instance, a reduction of the emission linewidth due to coupling has been shown recently[1,2].

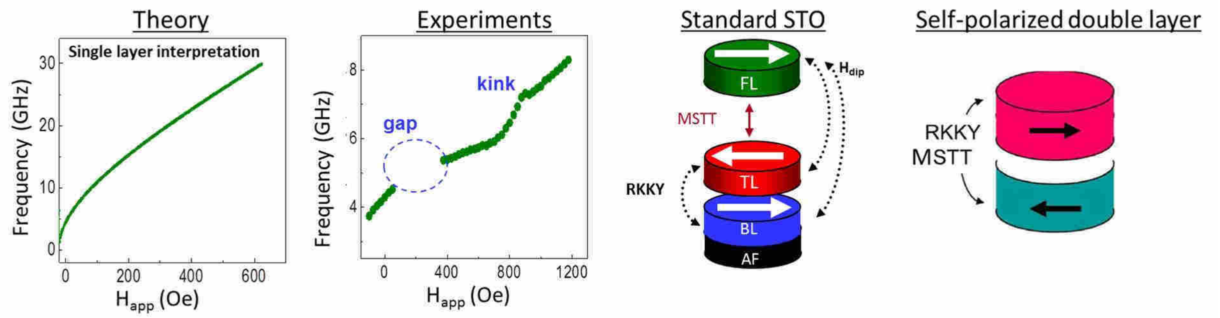

Fig.1 : Comparison of the frequency – field dependence in a single layer interpretation (theory) and experiment of a standard spin torque oscillator (STO). Schematics of a standard STO and of a self-polarized double structure, indicating the different interactions between the layers (dipolar H_{dip}, interlayer exchange coupling RKKY and mutual spin torque MSTT).

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BREAKING THE SYMMETRY OF SPIN WAVE EXCITATION IN MAGNETIC THIN FILMS AND MICROSTRUCTURES

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Investigations of symmetry breaking phenomena inherent to spin waves in continuous and structured magnetic samples form one of emerging hot spots in magnonics research. The unidirectional emission of spin waves due to the chiral magnetic precession in a nanowire placed above a continuous magnonic waveguide was observed in micromagnetic simulations of Au et al [1]. Chiral spin wave edge modes circulating around finite samples of either uniform magnetic material with Dzyaloshinskii-Moriya exchange interaction or periodically nonuniform material (“magnonic crystal”) were predicted analytically by Zhang et al [2] and Shindou et al [3] respectively. Such symmetry-breaking phenomena are predicted to form a new class of magnonic devices of high applied potential [1-4].

Here, we will report two types of experiments in which asymmetry of spin wave emission was observed. Firstly, we will describe the time resolved scanning Kerr microscopy (TRSKM) imaging of propagation of spin waves excited in a Permalloy network by cw microwave magnetic field at previously identified resonant frequencies of the network’s constituents. Depending on the orientation of the bias magnetic field, the different elements of the network can serve as either magnonic antenna or waveguides in terms of their roles in spin wave generation and propagation. The orientation of the bias magnetic field controls fine features of the spin wave excitation, with particular angles giving rise to unidirectional excitation of spin waves.

Secondly, we will use the time resolved optically pumped scanning optical microscopy (TROPSOM) imaging to demonstrate that femtosecond optical pulses focused to a diffraction limited spot by a high quality microscope objective are able to excite spin waves at specific locations on the surface of a thin Permalloy film [5]. The phase symmetry of the optically excited spin waves is found to be determined by the angle formed by the magnetization with the film plane. In particular, the optical excitation of an in-plane magnetized thin magnetic film is expected to result in excitation of anti-symmetric phase profiles relative to the direction of the magnetization.

The research leading to these results has received funding from the EC's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n°247556 (NoWaPhen).

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TEMPERATURE STABILIZATION OF SPIN WAVE FERRITE DEVICES

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The main advantage of MSW devices is the planar technology, diminutiveness and controllability by a magnetic field in a wide range of frequencies [1,2]. In spite of the evident advantages, the practical applications of the proposed devices were impeded by the problem of the frequency thermostabilization. In this work [3], we study the possibilities of self-compensation of the frequency’s temperature drift in spin-wave ferrite devices using reversible thermal demagnetization of permanent magnets. The normal magnetization of the YIG film are considered. The YIG film resonator was used for thermal stabilization. For a normal magnetization of isotropic YIG films, the film’s frequency of a fundamental mode is approximately equal to the lower frequency of the MSW spectrum:

$$f(T) \approx \gamma\left[H_0(T) - 4\pi M_0(T)\right]$$

Condition for the temperature stabilization of the resonator frequency can be presented as

$$\frac{\partial H_0(T)}{\partial T} = 4\pi M_0 \alpha_F ,$$

where M_0 is the saturation magnetization and α_F is the temperature coefficient of demagnetization for the YIG film. By application of different types of rare-earth magnets, a stabilization system was tuned to the desired thermostabilized frequency. Fig.1a shows the magnetization system for YIG film. Fig.1b demonstrates the experimental temperature dependence of the frequency for the oscillator based on the normal magnetized YIG film.

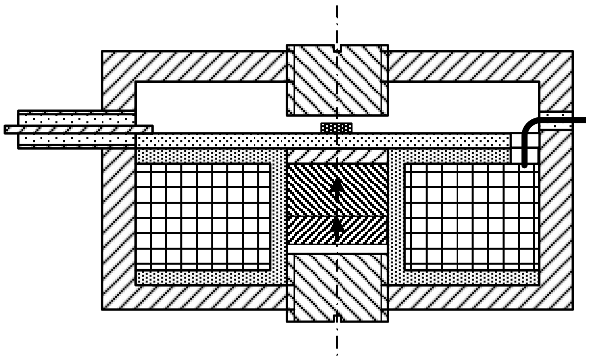

Fig1a. The thermal stabilization system.

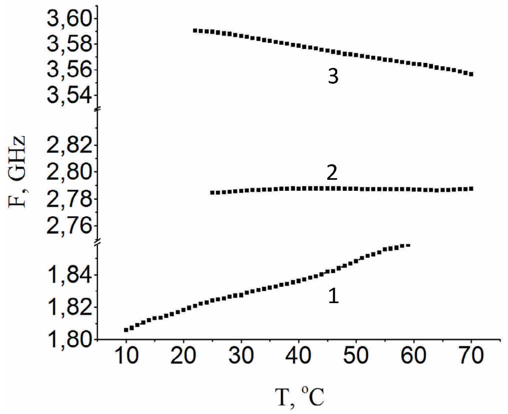

Fig1b. Experimental results for the frequency of the YIG-tuned oscillator. The central frequency: 1 – 1.82GHz; 2 – 2.78 GHz; 3 – 3.59 GHz.

The proposed system provides increased thermal stability without using of complicated thermostat systems. This system can be widely used for planar spin-wave microwave devices.

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MICROWAVE PHASE SHIFTERS BASED ON THIN-FILM MULTIFERROICS

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Rapidly growing interest to the artificial multiferroic structures is driven by a possibility to use them for various applications, in particular, to create frequency agile microwave devices. A distinctive feature of the multiferroic materials is dual electric and magnetic tunability of their physical properties (see e.g. [1-3]). One way to create the multiferroic materials is to use multilayer composed of ferrite and ferroelectric films. In such a case the multiferroic properties are due to hybrid nature of the eigen-wave excitations named spin-electromagnetic waves (SEWs). They are formed as a result of electrodynamics coupling between the spin waves localized mainly in the ferrite layer and the electromagnetic waves propagating mostly in the ferroelectric layer [2]. Electric tuning of the SEW spectrum is possible due to a dependence of dielectric permittivity from bias electric field whereas magnetic tuning is provided by a dependence of magnetic permeability from bias magnetic field.

This work reports for the first time the experimental and theoretical investigations of spin-electromagnetic waves propagating in a thin-film multiferroic phase shifter composed on a slot-line. In contrast to earlier work, the spin-electromagnetic wave (SEW) in the present device is originated from electrodynamics coupling of the electromagnetic wave localized mainly in the slot-line with the spin wave excited mostly in the ferrite film. For theoretical analysis of SEWs in such a kind of structures a theory of their eigen-wave spectrum was developed. Spectrum of SEWs in the investigated structures was calculated and analysed. The range of electric and magnetic tunability of dispersion characteristic was investigated.

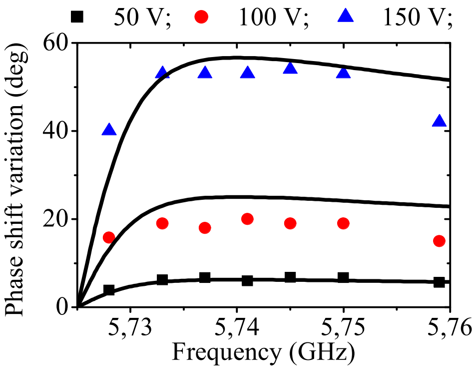

Fig. 1. Comparison of the experimental and the theoretical results.

To carry out the experiments, we fabricated multiferroic phase shifter composed by a slot-line waveguide with a ferroelectric film 2 μm thick and a single-crystal yttrium iron garnet film of thickness 13.6 μm. The performance characteristics of the phase shifter were measured. The device pass-band was 5.711-5.950 GHz. The minimum insertion loss of −20 dB was observed at 5.8 GHz. The electric field induced phase shift depended on the signal frequency. The maximum value of the phase shift variation of 54° was obtained for 30 kV/cm applied across the slot at the frequencies around 5.74 GHz.

This work was supported in part by the Russian Foundation for Basic Research, the Ministry of Education and Science of Russia, and by the grant of the National Research University of Information Technologies, Mechanics and Optics.

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DIFFRACTION OF MAGNETOSTATIC WAVES BY SURFACE CAVITIES ON A FERROMAGNETIC FILM

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The study of diffraction of magnetostatic waves (MSW) by periodic inhomogeneity of the ferromagnetic film surface magnetized at an arbitrary angle is up-to-date. The periodic structures has to be able to control the wave propagation, reflect waves with low losses, scatter waves, etc. It can develop miniature-integrated devices with unique properties for microwave signal processing [1, 2].

Let us consider infinite plane-parallel ferromagnetic film of thickness d magnetized to saturation. Vector H of the bias field placed in plane XOZ at an angle θ to the film surface. The shape of the surface inhomogeneity placed in plane YOZ is described by the equation:

$$x(y,z)=\varepsilon d f(y,z),\ \varepsilon=h/d,\ |\varepsilon f(y,z)|<<1,$$

where parameter ε is a small real number and h is the depth of the cavity. The above condition are necessary for the method of boundary perturbations [2-4] used in the study. In this case, it assume that magnetic potential Ψ depends on small parameter ε:

$$\Psi(x,y,z)=\sum_{n=0}^{\infty}\Psi_n(x,y,z)\varepsilon^n$$

Since ε is a small parameter, functions Ψ_n, $n > 0$, correspond to the n^{th} approximation of the scattered wave. Zero-order approximation Ψ_0 describes the incident wave. In the method, the surface cavities are replaced by the distribution of equivalent secondary sources on the unperturbed film surface $x(y,z)=0$. The density m of the equivalent double layer of magnetic dipoles oriented perpendicularly to the film surface can be obtained by conditions for the tangential components of the magnetic film on the surface $x=0$. The magnetic-charge surface density η can be determined by continuity conditions of the normal component of the magnetic induction. The expressions m and η are used for obtaining potentials of secondary sources φ_s [5]. It is used in the time-averaged energy flux density of MSWs [2, 6], which are used as the parameter characterizing the MSW reflection from cavities:

$$\vec{P}=-\frac{\omega}{8\pi}\mathrm{Re}\left(i\vec{\mu}\varphi_S^*\nabla\varphi_S\right),\quad \varphi_S=\varphi_\eta+\varphi_m$$

The numerical results of MSW diffraction by periodic shallow surface cavities on the ferromagnetic film magnetized at an arbitrary angle is presented in the report.

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INJECTION LOCKING AT 2f OF SPIN TORQUE OSCILLATORS UNDER INFLUENCE OF NOISE

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A spin polarized current passing through a magnetic multilayered nanosystem can drive its magnetization into large amplitude periodic oscillations[1,2], when the spin polarized current is large enough to compensate the natural damping. These spin transfer driven magnetization oscillations are promising for several applications for current controlled microwave oscillators. Nevertheless, one of the main issues that remains to be addressed for these spin transfer torque oscillators (STOs) is their relative large linewidth. One possibility to reduce the linewidth is to couple either different layers within an oscillator, or to couple several oscillators. As a first step to understand the conditions for synchronization of several oscillators by their own emitted rf current, we studied the synchronization of an STO to a microwave power source, with known spectral specifications. Here we focus on standard in-plane magnetized oscillators (in-plane polarizer and in-plane free layer), for which an in-plane precession (IPP) mode is stabilized.

The injection locking of such an in-plane magnetized STO to an external microwave current at two times the generated frequency (2f) was demonstrated both numerically and by experiments[3]. However, the linewidth in the locked regime was reduced only by a factor of ten. This raises the question on the role of external noise and the conditions to achieve a true phase-locking. In order to address this question we investigate the phase noise and the transient behavior to the locked state for the synchronization at 2f.

The numerical analysis of the phase noise in the synchronized state predicts a crossover of a $1/f^2$ dependence for frequency locking to a $1/f^0$ for phase locking by increasing the microwave current. This crossover indicates a truly phase locked state. Experimentally we find for MTJ nanopillars that while a complete synchronization is achieved in the frequency, the system is not in a truly phase locked regime. While it is possible to reduce the phase noise by synchronization only a $1/f^2$ phase noise dependence was observed.

In order to understand the effects of thermal fluctuations in the synchronized state, we developed an analytical model for the IPP mode, for f and 2f synchronization, which reveals clearly that synchronization at 2f occurs only for non-isochronous oscillators. As in a previous existing model[4] at f, it was found that at 2f, the phase approaches its locked state exponentially and oscillating. However, the threshold of microwave current between a pure exponential approach to an oscillatory approach is different for synchronization at f and 2f. The correlation between the transient behavior and the phase noise diagrams will be discussed.

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SPIN WAVES ALONG TOPOLOGICAL DOMAIN WALLS

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We present an investigation of the magnetization dynamics along topological domain walls in circular Permalloy (Py) dots in double magnetic vortex (DV) states [1] and in triangular Py dots [2] by means of broadband ferromagnetic resonance and micromagnetic simulations. In the metastable DV configuration in circular dots we have observed a new type of quasi 1D spin waves excited along the domain walls (Fig.1a) connecting the vortices and edge half-antivortices [1]. We demonstrate experimentally and via simulations that the DMV state could be stabilized not only via defects (as in thinner dots [1]) but also through dipolar coupling between domain walls forming DMV state in two vertically situated multilayer Py/Cu/Py dots pillars.

We have also investigated the dynamic magnetic response of Py micron-size equilateral triangles in the GHz range as a function of applied field [2]. Several eigenmodes of magnetization were observed as a function of field, and visualized with micromagnetic simulations, corresponding to damped propagating waves generated at the vertices of the triangles, that create standing waves along its boundaries (Fig.1b,c). The abrupt magnetization reversal for this shape of triangles influences the measured spectra. Different field orientations give raise to different magnetic states (saturation in the corresponding directions), with different types of eigenmodes. Our findings provide insight into dynamics of magnetic elements with topologically pinned domain walls.

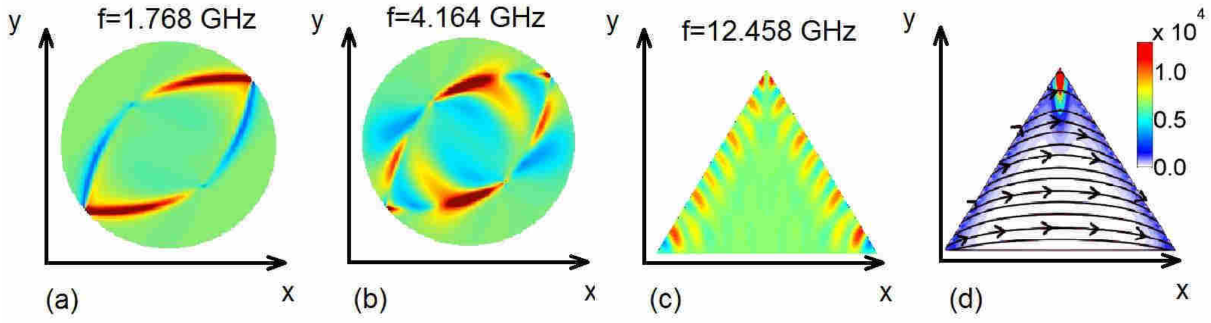

Fig1. (a) and (b) Spin waves (Winter magnons), dynamic magnetization component in x direction in a double vortex state circular dot for two eigenfrequencies, (c) Buckle state in a triangular dot, (d) Exchange energy density (colors, in J/m^3) and magnetization (arrows).

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PERIODIC AND APERIODIC ONE-DIMENSIONAL STRUCTURES FOR MAGNONICS

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Magnonic crystals provide an opportunity for tuning dispersion relation of low and high frequency spin waves exceeding capabilities of thin ferromagnetic films or stripes. With periodic structurization of the ferromagnetic film the magnonic band gaps can be opened – thus guiding and localization of spin waves can be explored [1]. Although the magnonic band gaps have already been demonstrated in one-dimensional magnonic crystals few years ago, the detailed properties need to be further investigated. We will show results of our recent studies regarding one dimensional magnonic crystals. Besides filtering properties of band gaps, the changes in the dispersion relation of spin waves will be exploited to mold the propagation of spin waves, to design the metamaterial properties of magnonic crystals [2], to tune nonreciprocity of the dispersion relation and elucidate opportunities for compensation of deficiencies in the fabricated structure [3].

The additional properties are accessible when aperiodic modulation of magnetic properties is introduced. The thin film magnonic quasiperiodic structures in crossover of dipolar and exchange regime are almost unexplored yet, thus the presented dispersion relation and mode profiles will give a new insight into the magnonic field. We have calculated magnonic band structure for magnonic Fibonacci quasicrystals composed of Co and Py wires and compared them with the properties of respective magnonic crystals. We show that spin waves in quasiperiodic sequence of ferromagnetic wires of nanometer width and thickness have plenty new properties, which are also relevant for technological applications. Among others this is possibility to design the band structure with multiple magnonic band gaps and multiple localized modes that have significant responds on the uniform rf field. This gives opportunity for developing planar metamterials for microwaves applications.

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SPATIAL DISTRIBUTIONS OF ELECTROMAGNETIC FIELD IN A CONDUCTIVE LAYER UNDER THE MAGNETIC AND SPIN WAVE RESONANCE CONDITIONS

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The problem of transmission of electromagnetic wave through a thin conductive ferromagnetic layer is considered here with the assumption that its thickness is less than skin depth. It is supposed that the conductive film is sputtered on a dielectric substrate.

Considering all possible spin wave types, which can exist in a ferromagnetic conductive medium [1,2], namely, electromagnetic-like (EL), Larmor (L) and anti-Larmor (AL) spin waves, we obtain the equations set. Solving it, we find the transmission and reflection coefficients as well as the complex amplitudes of the forward and backward propagating partial waves. The analysis has been fulfilled considering the exchange effects, surface spin pinning conditions and finite conductivity of layer [3].

The results obtained give us the possibility to compare the contribution of each spin wave mode to the total electromagnetic field within a conductive layer. We get the spatial distributions of all the components describing the electromagnetic field: the magnetic and electric field vectors as well as the magnetization vector.

In Fig. 1 we present an example of appropriate calculation corresponding to the component of magnetic field vector which is normal to the wave vector directed along the z-axis. The spatial distributions for EL, L and AL waves depending on the z/d ratio, where d is the thickness of the layer, are presented here.

The work was supported by the Program of Ural Branch of Russian Academy of Sciences, project NSh-1540.2.2014, Grant from Russian Ministry of Science and Education within p220 Program.

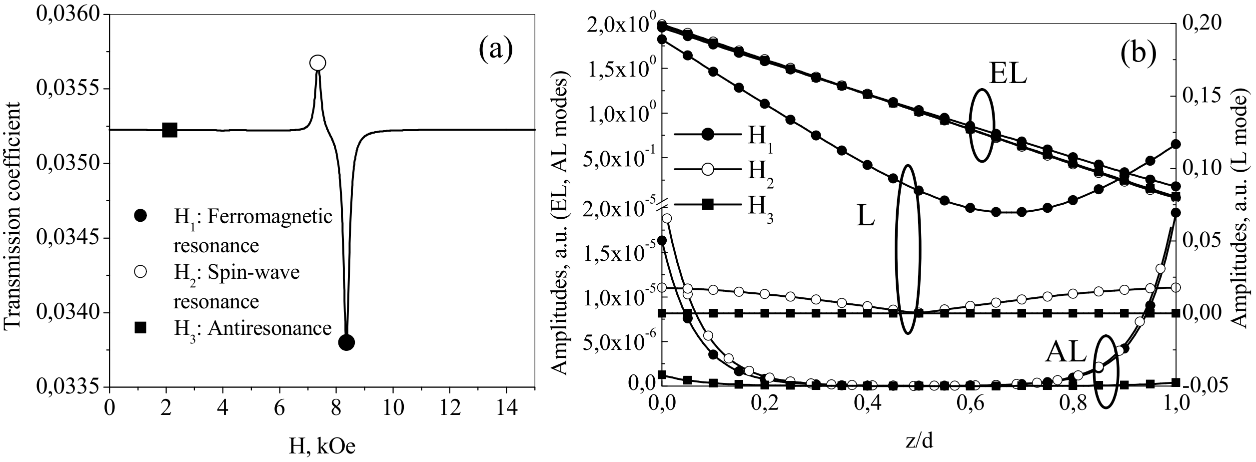

Fig1. Transmission coefficient (a) and spatial distributions of the component of magnetic field vector for EL, L and AL waves (b).

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AUTONOMOUS AND NON-AUTONOMOUS DYNAMICS OF SPIN HALL AUTO-OSCILLATORS

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With the advent of pure-spin-current sources, spin-based electronic (spintronic) devices no longer require electric charge transfer, opening new possibilities for both conducting and insulating spintronic systems. Here we demonstrate the generation of single-mode coherent auto-oscillations in a spin-Hall auto-oscillator (SHO) that combines local driving by a pure spin current with enhanced spin-wave radiation losses (see Fig.1)[1]. Counter-intuitively, the presence of radiation losses enables excitation of a single mode auto-oscillation and suppresses the nonlinear processes that prevent auto-oscillation by redistributing the energy between different modes. Our devices exhibit auto-oscillations at moderate current densities, at a microwave frequency tunable over a wide range. These findings suggest a new route for the implementation of nanoscale microwave sources for next generation integrated electronics.

We also report the study of the effects of external microwave signals on SHO [2]. Our results show that SHO can be efficiently injection-locked by applying a microwave signal at approximately twice the frequency of the auto-oscillation, which opens additional possibilities for the development of novel spintronic devices. We find that the observed injection-locking process exhibits an apparent threshold (see Fig.2 (a)) determined by the magnetic fluctuations pumped above their thermal level by the bias spin current. Phase-locking is also significantly influenced by the nonlinear self-localized nature of the auto-oscillatory mode excited by the bias spin current.

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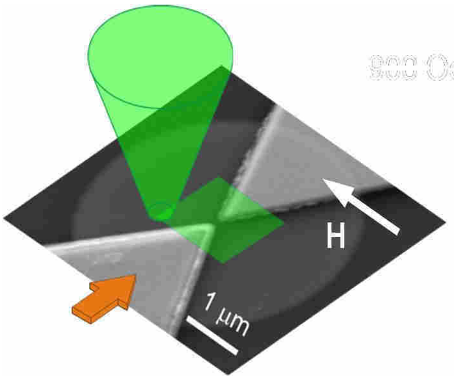

Fig.1 Brillouin light scattering (BLS) measurement set-up for a spin-Hall auto-oscillator (SHO) consisting of a Permalloy disk, platinum film and two triangular golden electrodes. Yellow arrow show the direction of the bias current, while the green cone shows the BLS probe light beam.

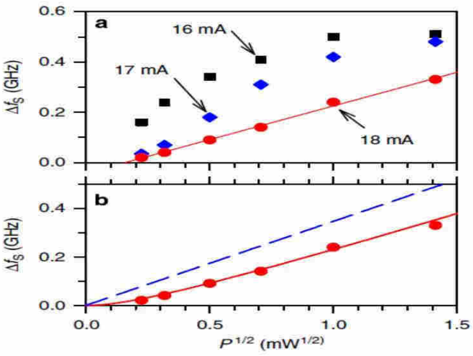

Fig.2 Frequency band of injection-locking in a parametrically driven SHO as a function of the amplitude of the microwave injection signal : (a) data measured at different values of the bias current; (b) theory without noise (dashed blue line) and theory with noise (solid red line) for bias current of 18 mA.

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FDTD-LLG: TIME-DOMAIN SOLUTIONS FOR MAGNETIC METAMATERIALS

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Magnetic metamaterials (MM) have been under increasing attention in recent years because of the possibility of new electromagnetic applications utilising the magnetic effects offered by magnetic materials and applied magnetic fields. In contrast to ‘conventional’ electromagnetic metamaterial (EM), in which RF permeability is modified by structuring or specific geometry of the elements (e.g. in split-ring resonators, [1]) , MMs take advantage of the dynamic effects of the intrinsic magnetic moments. The magnetisation dynamics naturally has a great flexibility in controlling its characteristics, thus providing a wide range of RF properties [2,3].

Although conventional EM has been extensively explored, including a variety of numerical tools, (such as HFSS, COMSOL), MMs are generally more complex as the exact solutions in the frequency domain require the frequency dependent permeability, which has to be known before the simulations can be applied. Given that the permeability generally depends on the structure of the material, the solutions are normally found in an approximate form.

Here we demonstrate a numerical model which combines a 3D Finite-Difference-Time-Domain (FDTD) model, providing the solutions of Maxwell equations, with a standard algorithm of Landau-Lifshits-Gilbert equations. The latter is solved directly, using iterative techniques, allowing to find the solutions without linearizing the LLG. As examples of solutions we demonstrate some ‘classical’ analytical solutions [4] verified by the model and also discuss the results of the simulation of experimental systems and structures where such model can be useful to identify response of the system. In particular, we demonstrate an effect of magnetically induced transparency in a system of coupled oscillators.

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EFFECT OF DAMPING ON THE DISPERSION CHARACTERISTICS OF SURFACE MAGNETOSTATIC WAVES

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The attenuation of magnetostatic surface waves (SMSW), propagating at an arbitrary angle to the bias field on the plane of the ferrite film, was investigated. Decaying plane waves in the form $A\mathrm{e}^{i(\mathbf{kr}-\omega t)-\mathbf{qr}}$ were considered, where the frequency ω depends on the parameters of the film, on the bias field and on 2D wave vector **k**, **r** – 2D radius vector on the *yz* plane of the film. Bias field vector is directed along the axis *z*. Directions of phase and group velocities of these waves are different, so they are called non-collinear. As is known [1], the attenuation of the ferrite medium can be considered by formally adding the imaginary term $i\alpha\omega/\gamma$ to the value of the bias field in the dispersion equation for MSSW [2], where α - attenuation coefficient , γ - gyromagnetic ratio. Vector **q** describes the attenuation of the wave in the minimal losses direction, which is calculated directly from the dispersion equation for SMSW. Characteristic dependences of the normalized vector magnitude |**q**| and its angle ψ_q from the angle φ of the phase velocity are shown in Fig. 1 and 2. The angles are measured from the axis *y*. Fig. 3 shows the isofrequency curves of SMSW. In all figures, the dashed line shows the graphs for the film with the small attenuation factor α, and the solid line – for the film with the large one.

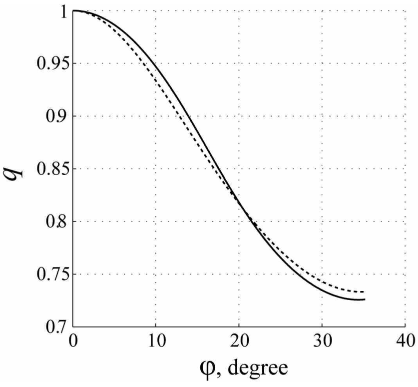

Fig. 1. Dependence of the attenuation coefficient |**q**| from the angle φ of the phase velocity.

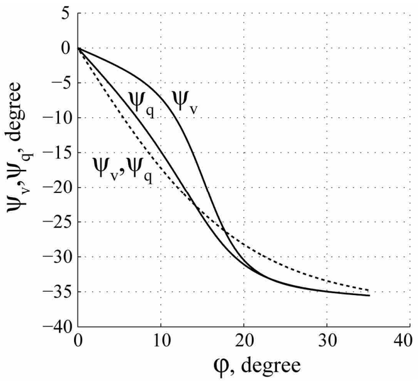

Fig. 2. Dependences of the angle ψ_q of the decay vector **q** and the angle ψ_v of group velocity vector from the angle φ of the phase velocity.

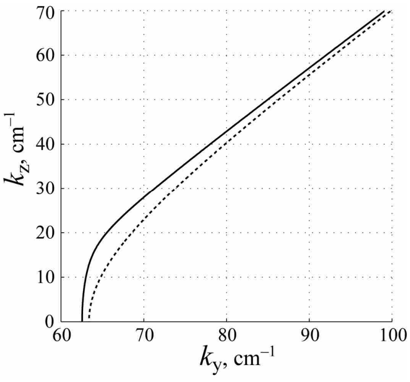

Fig. 3. Isofrequency curves showing possible values of the wave vector **k** at a given frequency ω.

In low attenuation films the vector **q** is directed along the group velocity (Fig. 2). With increasing of the attenuation these vectors cease to be parallel, isofrequency curves become deformed (Fig. 3).

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COMPLEX REFRACTION COEFFICIENT OF MAGNETIC NANOCOMPOSITES ON THE WAVES OF MILLIMETER WAVEBAND

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Investigation of extraordinary electromagnetic properties of magnetic nanocomposites becomes a fashionable topic at present times. Owing to possibility to vary the properties under the influence of magnetic field they have attract essential interest [1-3]. Microwave resonant phenomena are studied in this paper for the nanocomposite containing magnetic nanoparticles embedded into the dielectric matrix that is a latticed package of submicron SiO_2 spheres. The opal matrices with the following nanoparticles are under study: 1) metals Co, Ni, Fe; 2) ferrites: splinel $Ni_{0.5}Zn_{0.5}Fe_2O_4$, garnet $Nd_3Fe_5O_{12}$; 3) spinel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ + metallic Ag, spinel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ + metallic Co. Magnetic resonance is studied in the nanocomposites via its action on the reflection and transmission coefficients.

The refraction coefficient $n = n' - in''$ is a complex value. As long as the effective magnetic permeability is not a true material constant, it is necessary to consider the refraction coefficient only as a parameter characterizing heterogeneity of electromagnetic field inside the studied media. If one examines the refraction coefficient on the submicron scale but discusses the submicron volume does not including any ferromagnetic particle, the refraction coefficient will found to be qualitatively similar to the macroscopic coefficient. Let us further analyze the submicron volume including at least one ferromagnetic particle. The dependences of the real and imaginary parts of microscopic refraction coefficients are shown in Fig.1. The real part of the refraction coefficient was found to be positive, and the nanocomposite is not a double left handed media. Nonetheless, the refractive index of the nanocomposite is unusual, it can be less than unity.

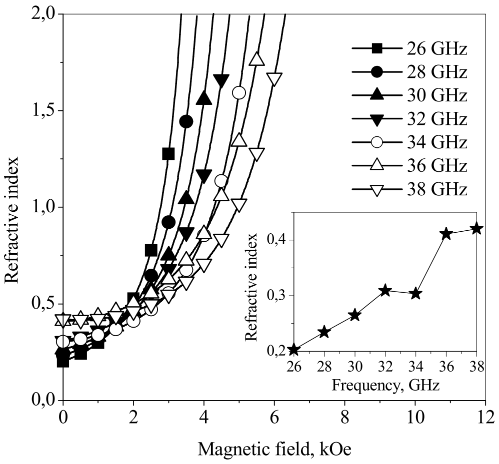

Fig1. Refractive index calculated for submicron scale for the nanocomposite containing Co nanoparticles.

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Localization properties and magnetic field tuning of spin-wave states in micro- and nanosized ferromagnetic waveguides

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Steady interest in the investigation of spin waves propagated in ferromagnetic nanorods and microstructured magnonic systems is concerned with their perspective application in logic elements and signal processing devices at microwave and subterahertz frequencies. In the last few years a set of experimental studies report about new interesting effects in confined ferromagnetic structures [1-4]. However, some authors pointed out that not all observed effects and dependences can be described in the frames of commonly used analytical approach and even micromagnetic simulation doesn’t give proper results. This statement mostly concerned with so-called localized spin-wave modes, which exist in magnetic wells near lateral boundaries of the confined ferromagnetic structures. These localized spin-wave modes are well observed in transversely magnetized narrow ferromagnetic waveguides made of permalloy or YIG (yttrium-iron garnet) [2,4].

Here, on the base of previously elaborated theory [5], we present a consistent theoretical investigation of the behaviour of localized spin-wave modes in narrow ferromagnetic waveguide with rectangular cross section. The role of demagnetizing field in the formation of spin-wave spectrum in finite-width magnonic structures is pointed out. The dependence of the frequency of volume and localized spin-wave modes on bias magnetic field is described numerically. The study is carried out for two types of ferromagnetic waveguides: nanosized permalloy waveguide and microsized yttrium-iron garnet waveguide. The behaviour of localized modes reported in the experimental work [2] is theoretically described. The relation between the magnetic tunability of spin-wave spectrum and the material and size parameters of the structure is established. The required conditions for existance of localized spin-wave modes are deduced.

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TERAHERTZ SPECTROSCOPY OF ULTRAFAST SPIN DYNAMICS

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In my talk I will demonstrate that terahertz emission spectroscopy represents a unique tool allowing to obtain crucial information about ultrafast spin dynamics not accessible by any other methods applied so far. In this technique one detects the electro-magnetic radiation at THz frequencies emitted from the sample subjected to the ultrafast laser pulses. Using the THz emission arising from the optical illumination of the rare-earth orthoferrites as an example, I will introduce the difference in selection rules for optical and terahertz probes of the magnetization dynamics thereby showing how they complement each other.

I will demonstrate both experimentally and theoretically that the ratio between the antisymmetric and symmetric exchange components can be manipulated via ultrafast, sub-picosecond laser excitation of iron oxides which represent a very broad class of magnetic insulators. The resulting coherent spin oscillations lead to THz emission and from its strength we estimate that a sub-picosecond laser pulse with a moderate fluence of ~ 1 mJ/cm^2 acts as a pulsed magnetic field of 0.01 Tesla that corresponds to the change of the exchange energy of over 10 nJ.

Finally, I will discuss our recent results upon the ultrafast dynamics in copper oxide CuO, a close relative of the high-T_C cuprate superconductors, which is known for remarkable magnetic properties. The THz emission generated in CuO reveals a novel mechanism of the optical control of spins in this material. It also indicates the presence of the multiferroic order in the incommensurate phase. Understanding of the light-induced dynamics in CuO may pave new ways to manipulate competing order parameters in multiferroic materials and superconducting cuprates.

MAGNETIC DROPLET SOLITONS IN ORTHOGONAL-SPIN VALVE NANOWIRES

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Recently, it was demonstrated that nano-contact spin torque oscillators (NC-STOs) containing a free layer with a perpendicular magnetic anisotropy (PMA) can form a dynamic state of nearly reversed magnetization underneath the nanocontact, a so-called droplet [1, 2]. Micromagnetic simulations have since demonstrated that the droplets can transform into other soliton modes in confined geometries such as nanowires (NW) [3]. In this work, nanowire devices with NC diameters between 70 and 90 nm and widths down to 160 nm were fabricated on $\mathrm{Ta(5)/Cu(15)/Ta(5)/Co(8)/Cu(8)/Co(0.3)/[Ni(0.9)/Co(0.4)]_{x4}/Cu(3)/Pd(3)}$ spin valves (thicknesses in nm); scanning electron microscopy (SEM) images of the devices are shown in Fig1(a).

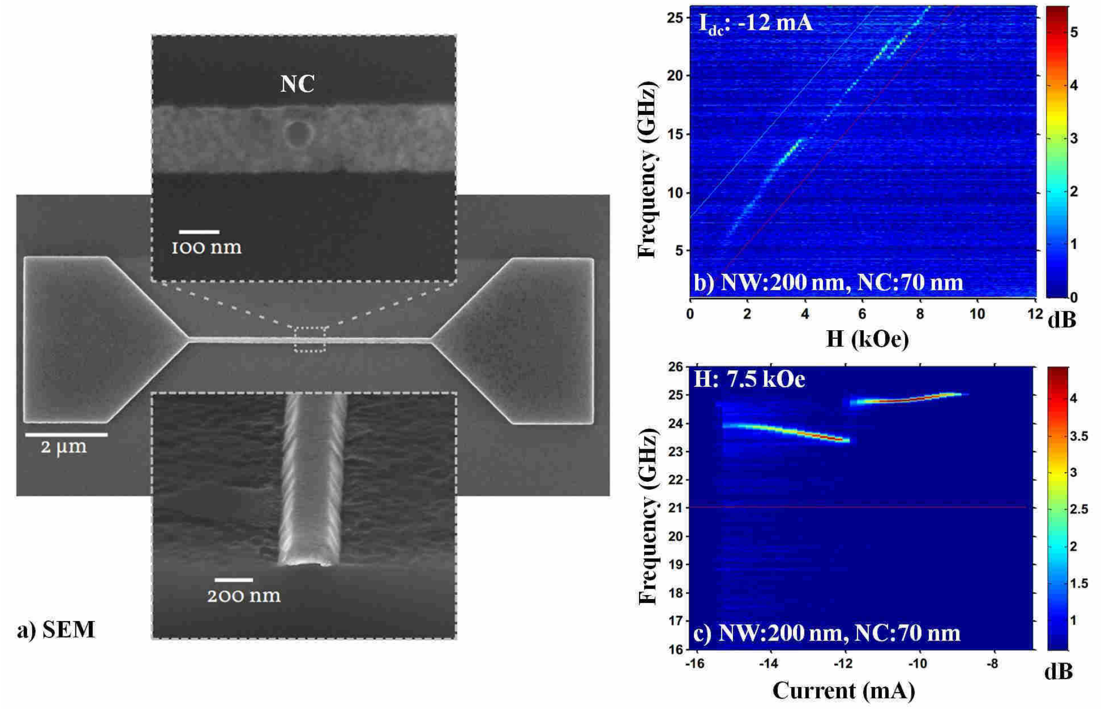

Fig1. (a) Scanning electron microscopy (SEM) images of NWs. (b), (c) Field dependency and current dependency of NWs spectra at room temperature, respectively.

Figures 1(b-c) show room temperature microwave signal generation of a droplet underneath an 80 nm NC on a 200 nm wide NW similar to the device in Fig.1(a). Fig.1(b) shows how a lower frequency droplet mode appears at about 7.5 kOe for a constant drive current of -12 mA. Fig.1(c) shows how the same lower frequency mode appears at about -12 mA in a constant field of about 7.5 kOe. Both measurements are consistent with a droplet edge mode developing in the device. In my talk I will present a full characterization of this novel droplet mode as a function of field, field angle, current, and also temperature down to 80 K.

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KERR MICROSCOPY AND FMR SPECTROSCOPY INVESTIGATION OF COBALT 2D PERIODIC STRUCTURE ON PERMALLOY FILM

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In this work the 2D periodic cobalt (Co) structure in the form of 7×7 μm squares with distance 3 μm between them and having thickness of 55 nm on a plain 15 nm Permalloy (Py) film was studied both experimentally and applying micromagnetic simulations. The structure was fabricated on cover glass substrate (0.15 mm in thickness) using magnetron sputtering, photolithography and lift-off technique.

Ferromagnetic resonance (FMR) spectra of the structure measured at different angles θ with respect to one side of cobalt square showed three main peaks (with big amplitude). Dependencies of FMR resonance fields $H_{res}(\theta)$ on θ were then used for estimation of anisotropy axis direction, values of anisotropy constant, damping parameters and magnetization. Obtained parameters were employed for micromagnetic simulations performed with object oriented micromagnetic framework (OOMMF [1]) to analyze origin of FMR peaks. According to simulations FMR response at around 0.63 kOe as expected was caused by quasiuniform precession of magnetization in Co elements, two other main peaks originated from excitations in Py film. Response at 1.19 kOe resulted from excitation of Py parts located between sides of Co elements directed along the applied field while the response at 1.09 kOe was caused by excitations in intersections of Py lines formed by Py film not covered with Co elements (see Fig. 1c). Time-resolved (TR) Kerr microscopy with 500 nm probe size was used to detect response from several points of the structure. Good agreement with simulation results was achieved (see Fig. 2).

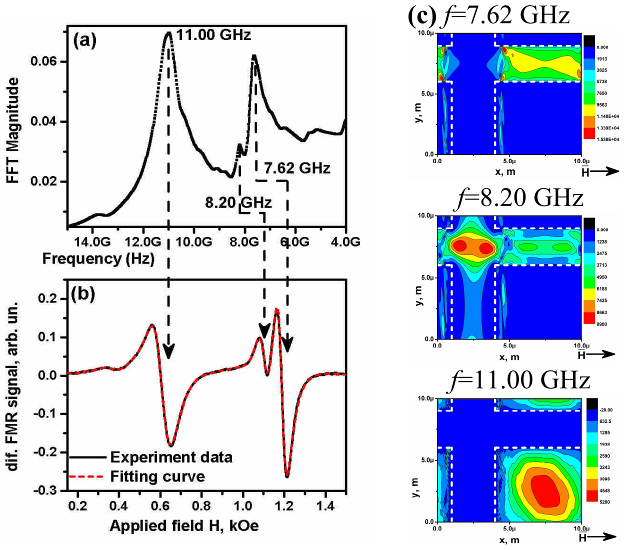

Fig 1. FFT spectra obtained in simulations with OOMMF from overall structure (a), FMR spectrum of the structure at *f*=9.8 GHz (b); FFT amplitude distribution in the sample at frequencies corresponding to main peaks (c).

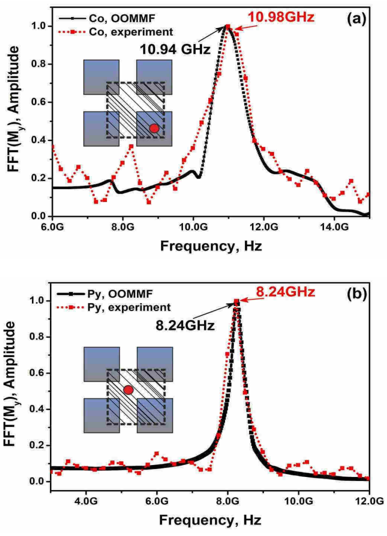

Fig. 2. FFT spectra from the experimental data (TR Kerr microscopy) and results of simulations corresponding to the spot with diameter 500nm that marked with red point on the inset.

This work was supported by RFBR grants No 13-07-00941, 13-07-12421, European Community’s 7th Framework Programme under Grand Agreement No 247556 (NoWaPhen).

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ELECTRONICALLY TUNABLE MICROWAVE NONLINEAR PHASE SHIFTERS BASED ON PLANAR MULTIFERROIC STRUCTURES

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In recent years there is a strong interest to ferrite-ferroelectric (FF) structures (see e.g. [1]. In particular, the linear properties of spin-electromagnetic waves (SEWs) propagating in FF layered structures have been studied and a number of linear ferrite-ferroelectric devices have been designed and suggested [2-6]. This work reports the first experimental results on a nonlinear FF device, namely, SEW nonlinear phase shifter. A principle of operation of the device is based on the dual control of the phase shift of the hybrid spin-electromagnetic waves propagating in the FF bilayer. The specific experiments were carried out for the phase shifter structure similar to that described in [3]. The layered structure was composed of 5.7-μm-thick single crystal yttrium iron garnet film and a 500-μm-thick barium strontium titanate slab. Two microstrip transducers separated by 8 mm were used for the excitation and detection of the SEW. A bias voltage in the range of U = 0-1000 V was applied across the BST slab. The prototype device was placed between the poles of electromagnet. The bias magnetic field in the range of H = 1100-1400 Oe was applied in-plane of the YIG film parallel to the antennae.

In the experiment, S-parameters as a function of frequency f and as a function of input microwave power Pin were measured for different H and U. The device demonstrated a dual-function performance with a nonlinear phase shift up to 250 degrees for Pin = 17 dBm and electric field induced differential phase shift up to 330 degree for U = 1000 V. The nonlinear phase shift increased with frequency whereas the differential phase shift decreased with frequency. Therefore, the nonlinear phase shift and electric field induced differential phase shift are competing characteristics for the surface SEW nonlinear phase shifters. The device could find different applications. In particular, it could be used for development of the microwave logic gates, nonlinear interferometers, and nonlinear directional couplers.

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CONDENSATION OF MIXED MAGNON-PHONON STATES IN GAS OF PUMPED MAGNONS

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A magnon gas is an excellent model system for the investigation of interacting bosonic particles. Its potential is due to the wide controllability of the magnon density as well as of the spectral properties influencing the magnon-magnon interaction. Bose-Einstein condensation can be achieved either by decreasing the temperature of boson gases or by increasing their density. The last method is especially applicable to gases of weakly interacting quasi-particles such as excitons, polaritons, photons, and magnons. When a spin system is pumped and injected magnons thermalize a Bose-Einstein condensate (BEC) can appear at the lowest energy state of the energy-momentum spectrum even at very high temperatures [1, 2]. Recent progress in the technique of Brillouin light scattering (BLS) spectroscopy allowed us to study this interesting field with increased breadth and depth. A combination of time-, space, and wavevector-resolved BLS provides us full access to the properties of magnon condensates.

We studied the magnon dynamics in an yttrium-iron-garnet film at room temperature. The total number of magnons was controlled by parametric electromagnetic pumping causing spectrally localized injection of ultra-cold (7 GHz, mK temperature range) magnons. Along with the observation of the magnon BEC at the global energy minima at 4.8 GHz and wavenumbers $\pm 3.93\times 10^4$ cm^{-1}, we detected a strong magnon density peak at nearly the same frequency but at higher wavenumbers $\pm 8\cdot 10^4$ cm^{-1}. This peak is associated with the hybridization area of a fundamental magnon mode and a transversal acoustic wave. It is remarkable that corresponding mixed magnon-phonon states still possess significant magnetic properties even below the energy minimum of the pure magnon spectrum. Consequently, they can effectively interact with the magnon gas. As a result, a virtual energy minimum appears at the bottom of the pure spin-wave spectrum. The existence of this additional minimum drastically modifies the dynamics of the parametrically driven magnon gas: the parametrically injected magnons can spontaneously condense at this spectral point. Furthermore, as opposed to the classical magnon BEC, this magnon-phonon phase has an intrinsically non-zero group velocity. It leads to a clearly visible flow of the condensed magnon-phonon phase through the pumping region.

In spite of the drastic difference of their nature both condensed phases possess very similar temporal dynamics: just after the external pump is switched off, their density dramatically jumps up. This effect corresponds with an evaporative supercooling of the parametrically populated magnon gas and evidences our previous statement that magnon temperature should be defined as a spectral non-uniform quantity [2]. Thus, we conclude that the experimental and theoretical results, obtained for a magnon system as a model system, are of general nature, and it is very probable that they apply to most, if not all quasi-particle systems undergoing Bose-Einstein condensation.

Support by the DFG within the SFB/TRR 49 is gratefully acknowledged.

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SPATIO-TEMPORAL DYNAMICS OF SPIN WAVES IN FERRITE PERIODIC IRREGULAR WAVEGUIDES

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During last decades the magnonic crystals (MCs) are actively investigated [1]. MC represents periodic magnetic structures and it can be used as elements of functional devices of spintronics and magnonics. Periodicity in MCs can be created by the modulation of various parameters of structure, for example, the width of planar waveguide. The width-modulated structures based on permalloy were studied in ref. [2-4]. Nevertheless, the investigations of multimode propagation of magnetostatic waves (MSW) in similar waveguide, fabricated from yttrium iron garnet (YIG) films, are of interest.

The structures under study was created by precise laser scribing technique from YIG film with thickness d=10 μm and saturation magnetization 1350 Gs. The transmission characteristics were measured by network analyzer at small input signal and the first two band gaps are observed. The first band gap has the width about 40 MHz and attenuation -50 dB. The second band gap with central frequency 2.608 GHz has attenuation -60 dB and wave number in this case corresponds to Bragg condition $k \sim k_B = \pi/L = 257\ \mathrm{cm}^{-1}$.

The spatial-frequency characteristics of MSW were investigated by Brillouin light scattering (BLS) technique [5]. The waveguide surface was scanned by the laser beam with diameter of 30 μm and the intensity $I(t,y,z)$ of scattered light was measured ($I(t,y,z) \sim |\mathrm{m}(t,y,z)|^2$, where $\mathrm{m}(t,y,z)$ – amplitude of MSW). The spatial distributions of intensity were obtained at different frequencies (near and inside of band gap). The intensity distributions in the cross section of the waveguide (in the narrow and wide parts of it) were measured at different frequencies. In the narrow part of the waveguide wave is localized near the center of the structure and in the wide – the maxima of intensity are observed near the waveguide edges. At the boundaries of band gap curves have maximum in the center of the waveguide, and inside of band gap – minimum. The changing of this dependence indicate a change of the modal distribution.

Also the spatial-frequency distribution of the integrated intensity was measured. Two frequency regions with strong spatial damping of MSW are observed. The positions of these regions on the frequency axis correspond to band gaps in the transmission characteristic. The forbidden bands were formed due to the scattering of MSW on the periodic waveguide edges. The estimation of the distance along which MSW propagate with significant decay reveals the sufficient distance from the beginning of the MC to formation of rejection band. It was shown that this distance is equal to 10 period of structure.

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TEMPORAL DISSIPATIVE SOLITONS IN A FERROMAGNETIC FILM ACTIVE RING RESONATOR AT THREE-WAVE INTERACTIONS

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Dissipative solitons are the new paradigm that has been actively developing during the recent decades thanks to the new ideas about the influence of energy flows on the processes of forming structures [1]. Balance between gain and losses, as well as between the spatial dispersion and cubic nonlinearity leads to the formation of periodic sequences of dissipative bright solitons in a ferromagnetic film active ring resonator [2]. Besides four-wave processes, there are three-wave parametric decay processes of MSW in a ferromagnetic film. These processes can lead to self-generation of parametric dissipative soliton trains of different shapes [3, 4].

This paper presents the results of experimental research of spatial and temporal dynamics of dissipative parametric solitons at frequencies of both MSSW and parametrically excited SW. The Brillouin light scattering (BLS) setup is used to study the dynamics of such structures directly in a ferromagnetic film.

The investigated ring system consists of solid-state power amplifier, variable attenuator, volume resonator and delay line on MSW. The ring gain is controlled by the variable attenuator, and the volume resonator provides a frequency selection of a dominant ring mode. The time selection method provides the dynamics control of the ferromagnetic film active ring resonator. This method is based on the use of external MW pulses that applied to the input of the amplifier via a directional coupler DC.

In the autonomous regime, a chaotic sequence of dissipative solitons is self-generated at the dominant ring mode frequency f_{MSSW}=3110 MHz. These structures are formed due to the three-wave parametric decay of MSSW that is described in detail in Ref. [4]. The carrier frequency of external MW pulses is located outside the chaotic signal bandwidth, but inside the amplifier frequency band. The external MW pulses form a periodic sequence of dissipative parametric solitons from its chaotic sequence. The spatial distribution of MSSW and SW corresponds to the superposition of the odd (first and third) width modes propagating in a ferromagnetic waveguide [5]. The parametric excitation of SW is clearly observed in two areas. One of them is located near the input microstrip transducer and the other one corresponds to the local maxima of MSSW. In a time domain, dissipative solitons are formed at both MSSW frequency f_{MSSW}=3110 MHz and SW frequency f_{SW}=1556 MHz. The peak amplitude of these structures exponentially decreases with the increase of a distance value of D. The obtained experimental data are in a fair agreement with the theoretical results that describe the mechanism of the dissipative soliton formation at frequencies both MSSW and SW [4].

This work was supported by the Russian Foundation for Basic Research (Project No. 14-07-31142), and the Government of Russian Federation for support of scientific research in the Russian universities under the guidance of leading scientists (Project No.11.G34.31.0030).

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TUNABLE BAND GAPS IN MAGNONIC CRYSTAL WITH LINE-DEFECT

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At present great interest are periodic structures of micron or submicron size based on ferromagnetic films - magnonic crystals (MC) [1-4]. The presence of band gaps in the spectrum of spin waves can create based on MC tunable magnetic field devices for processing and generating signals in the microwave range [1,2]. In this case, the urgent problem of controlling the characteristics of band gaps in the spectrum of propagating waves (density, width, etc.). Introduction of defects into MC opens a number of additional features for controlling band gaps in the MC [2,3]. To date, most studies have been devoted local defects. Another type of violation of the periodicity in the MC is distributed defect (line - defect). It is a homogeneous area in MC in the direction of the spin-wave propagation, longitudinal dimension of this area is much larger than the period of structure [3].

In this report the line-defect in the MC, which is a structure in the form of yttrium iron garnet (YIG) film, loaded on a periodic system of copper strips (Cu) (Fig.1). In such one-dimensional periodic structure the band gap is preserved. Its position in the frequency spectrum depends on the size of line-defect in a direction perpendicular to the wave propagation (*D*). The experimental results on the study of this structure (Fig.2). Describes a theoretical model based on the method of coupled waves can explain the experimental results.

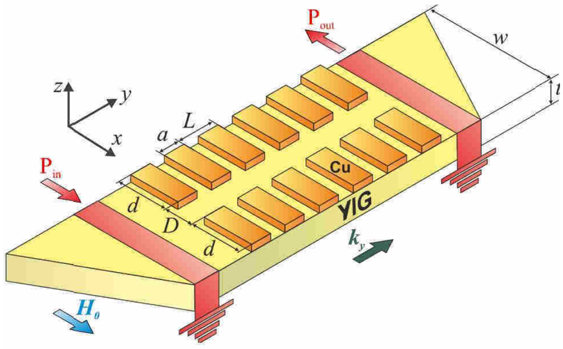

Fig. 1. Scheme of MC with line-defect. (*w*=2.2 mm, *t*=7.7 μm, *L*=0.3 mm, *a*=0.2 mm).

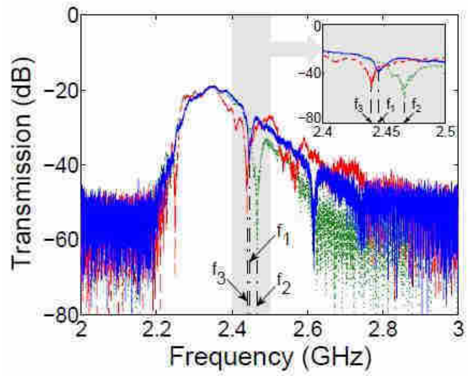

Fig. 2 The transmission response of MC without line-defect (blue curve); MC with line-defect *D*=0.2 mm (green curve), *D*=1 mm (red curve).

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MAGNETOSTATIC SPIN WAVES IN ONE-DIMENSIONAL FINITE MAGNONIC CRYSTAL

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In this work we present a method to calculate transmission and reflection coefficients of a spin wave in a finite one-dimensional magnonic crystal formed by a periodic lattice of ferromagnetic stripes. We consider a surface wave in Damon-Eshbach geometry (see Fig.1). The problem is studied in magnetostatic approximation thus taking into account only dipole-dipole interaction and leaving the exchange interaction out of the picture. Such approximation is proved to be worthwhile for relatively large wavelengths, i.e. for comparatively small wave numbers

In order to calculate said coefficients for a single interface between two ferromagnetic materials with saturation magnetizations $M_S=M_1$ and $M_S=M_2$ we use variational approach. Considering the form of magnetostatic potentials $\psi_{1,2}$ on both sides of the interface, one is able to construct a functional which would define, how well the Maxwell border conditions at the interface are satisfied. Requiring the minimization of this functional we obtain the relation between amplitude coefficients of waves on two sides of the interface. By also taking into account that power flow must remain continuous we obtain the equation set which allows us to calculate the amplitude coefficients of the magnetostatic potential on both sides of the border.

Using this method we calculate for example a magnonic crystal consisting of 20 periods, each 10mkm long with total of 200mkm, Fig. 1. We use a thin film with thickness d=100nm and magnetic materials with saturation magnetizations M_1=1750Oe and M_2=1800Oe. By doing so we show that described method can serve as another tool for studying finite 1D structures.

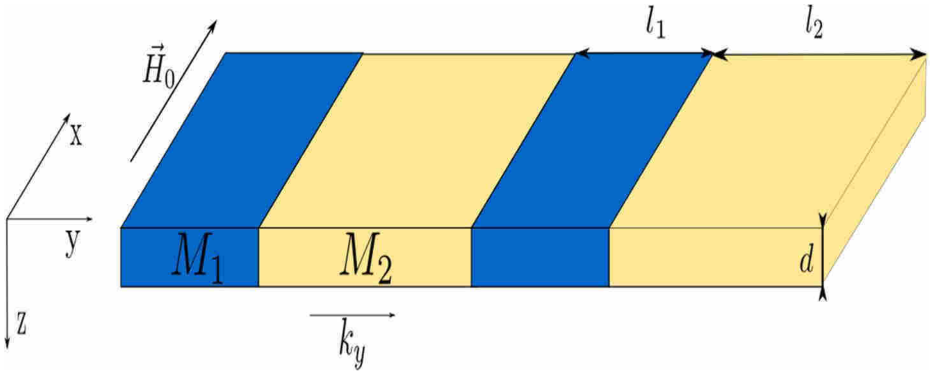

Fig1. Geometry of the problem.

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NONLINEAR WAVES IN COUPLED MAGNONIC CRYSTALS

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Magnonic crystals (MC) - periodic structures with microwave bandgap based on ferromagnetic materials. In the nonlinear case when the amplitude of the input signal to increase an effect of switching observe: periodic structure begins to pass signal at frequencies within band gap [1,2]. Coupling between two periodic structures of is an additional operating parameter. In the nonlinear case input pulse can be switched from one output port to other, depending on its input power [3].

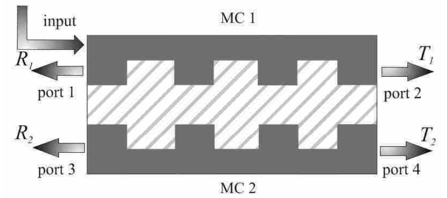
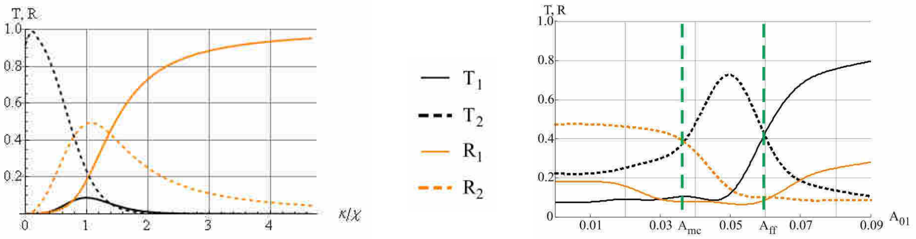


Fig. 1. Schematic illustration of structure MC-MC

Numerical investigation of transmission characteristics of structures of two coupled magnonic crystal (MC-MC) (fig. 1) was provided. The model is constructed in the form of a system of the coupled Schrodinger equations. It was shown that such structures have a number of special properties and can be the basis for the multifunctional device.

Fig. 2a shows the transmission and reflection power on ports 1-4 depending on coupling coefficients (in linear case). In region of strong coupling between MC (κ<χ) behavior of structure is similar to structure of two coupled homogenous ferromagnetic films, one may observed transfer of power from one film to the another. In region of strong coupling between counterpropagating waves (κ>χ) reflection of input power occur as well as in one MC. However, in region when these coefficients are approximately equal structure has both of the above effects.

Fig. 2b shows a transmission and reflection of MC-MC depending on amplitude of input pulse. It is seen, that input signal depending on its amplitude may exit at port 3 (at low amplitude), at port 4 (at average amplitude), at port 2 (at large amplitude of input signal). Thus, investigated structure can show effect of “double nonlinear switching”.



a) b)

Fig. 2 (a) Transmission ($T_{1,2}$) and reflection ($R_{1,2}$) power on ports 1-4 depending on (a) coupling coefficients (linear case), (b) input amplitude .

Obtained results allow us to consider the investigated layered structure MC-MC as a system that effectively operate the propagation of nonlinear pulses. This circumstance makes coupled MC unique object for apply in information processing devices of radioelectronics.

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EDGE ROTATIONAL MAGNONS IN MAGNONIC CRYSTALS

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Magnonic crystals (MCs) are counterparts to photonic [1] and phononic [2] crystals for spin waves [3]. Periodic perturbations located along the spin wave propagation path form frequency band gaps within the spin wave spectrum, which where observed [4]. Band gap formation in artificial periodic structures generally relies on two mechanisms, namely Bragg scattering and local Mie-like scattering inside inclusions. Bragg band gaps are formed if the wave-vector inside the crystal is roughly equal to one of the reciprocal lattice vectors. Local resonant band gaps may be formed if resonant scattering conditions, or Mie conditions, are fulfilled inside the inclusions. Generally, local resonant modes are tightly bounded to inclusions, being nearly monochromatic across the Brillouin zone and have zero group velocity [5]. In the present work we consider propagation of forward volume magnetostatic spin waves (FVMSW) [6] in a 2D MC. However, gyrotropic properties of the ferromagnetic medium play important role in wave scattering, producing an asymmetric helical scattered field, similar to electromagnetic waves in magneto-photonic crystals [7]. Origin of such behavior underlies in time-reversal symmetry breakage in ferromagnetic media. Thus it is expected that surface edge modes of FVMSW may appear by analogy with electromagnetic waves in magneto-photonic crystals, as well as other types of magnonic crystals. We consider a ferromagnetic film (matrix) with the thickness d and the saturation magnetization M_{s0} with embedded cylindrical inclusions of an another ferromagnetic material with the same thickness and the value of the saturation magnetisation M_{s1}. An external uniform magnetic field is applied normally to the film surface, allowing propagation of FVMSW. We show theoretically that under certain conditions in such structure appear modes with field strongly localized near inclusions. Moreover this field rotates while moving from one inclusion to another. It is also found that under certain conditions the local resonant modes may have negative group velocity, what can be used in signal processing devices.

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A COMPARATIVE STUDY OF Fe_3O_4 NANOCOMPOSITE COATINGS BY MEANS OF FMR AND BLS

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Theoretical and experimental investigation of incoherent magnetic excitations in nanocomposites via BLS in order to relate characteristics of magnetic excitations spectra with materials parameters of magnetic composites and to compare them with ones obtained via FMR. The intensity of Brillouin scattered light is directly related with the spectral power density of incoherent magnetic excitations [1], which is given as

$$\left\langle m^2(\omega)\right\rangle \sim \chi^e_{12}(\omega)\chi^{e*}_{12}(\omega)+\frac{1}{2}[\chi^e_{11}(\omega)\chi^{e*}_{11}(\omega)+\chi^e_{22}(\omega)\chi^{e*}_{22}(\omega)] \qquad (1)$$

,

where $\left\langle m^2(\omega)\right\rangle$ is the average spectral density of magnetization fluctuations, $\chi^e_{11}(\omega)$, $\chi^e_{22}(\omega)$ are diagonal and $\chi^e_{12}(\omega)$ are off-diagonal elements of external magnetic susceptibility tensor $\tilde{\chi}^e(\omega)$. A comparison between resonance frequencies of coherent and incoherent magnetic excitations in the composite coating formed after 20 deposition cycles of Fe_3O_4 nanoparticles. The theoretical BLS curve figured out with the same parameters (δH_a = 0,32 kOe and M_{eff} = 0,11 kOe) as for FMR fits to the experimental BLS data in the region of external magnetic field H_0 = 2 ÷ 4 kOe. Under H_0 > 4 kOe the BLS peaks become to wide, so it is impossible to distinguish BLS peaks from FMR ones (see Fig.1) . To sum up, a comparison between the FMR and BLS resonance frequencies was performed. Although, the typical resonance frequencies of coherent magnetic excitations measured by FMR are different from the frequency maximums of incoherent magnetic excitations found out by BLS all the experimental data are fitted well by the corresponding theoretical curves calculated with the same values of magnetic crystalline anisotropy filed and effective magnetization. These results confirm BLS as a versatile tool for investigation of local material parameters in nanocomposite coatings in a wide dynamic range with a high spatial resolution under conditions the FMR technique is not suitable. This work is supported by the Government of the RF (Grant 11.G34.31.0030) and RFBR (14-02-00577).

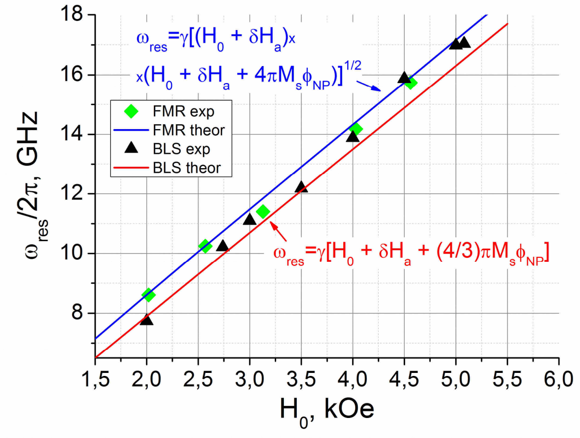

Fig. 1. FMR and BLS resonance frequency ω_{res} *vs* external resonance magnetic field H_0 in case of in-plane magnetization.

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GENERATION OF DISSIPATIVE PARAMETRIC BRIGHT SOLITONS IN ACTIVE RING RESONATORS WITH MULTIRESONANT FERROMAGNETIC AND VACUUM ELEMENTS

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This paper represents a new approach for dissipative bright soliton generation through the balance between the time dispersion and cubic nonlinearity. These temporal patterns are formed in the ferromagnetic film active ring resonators containing different multiresonant elements one of them is a magnonic quasicrystal (MQC) with Fibonacci type structure and other is a multi-cavity klystron amplifier. Cubic nonlinearity is a result of quadratic coupling between the spin waves at three-wave parametric spin-wave interactions. Two generators schemes are considered. First scheme contains the MQC which is simultaneously used both a multiresonant and nonlinear element. Second scheme contains two independent elements one of them (a klystron amplifier) is a multiresonant element and other (a homogeneous ferromagnetic film) is a nonlinear medium.

In the MQC active ring resonator, the self-generation of dissipative parametric bright solitons is observed only in two-mode regime when the time filtering technique is used (see Fig.1a). For time filtering, we exploit the external microwave pulses that are applied to the amplifier input. For explanation of the obtained experimental results, the model of two coupled (parametric and linear) oscillators is used. From the analytical solutions, it is shown that a bright soliton threshold is maximal in one-mode regime. In the ferromagnetic film active ring resonator with klystron amplifier, the dissipative parametric bright soliton generation is observed in one-mode regime at lower values of an external magnetic field (see Fig.1b).

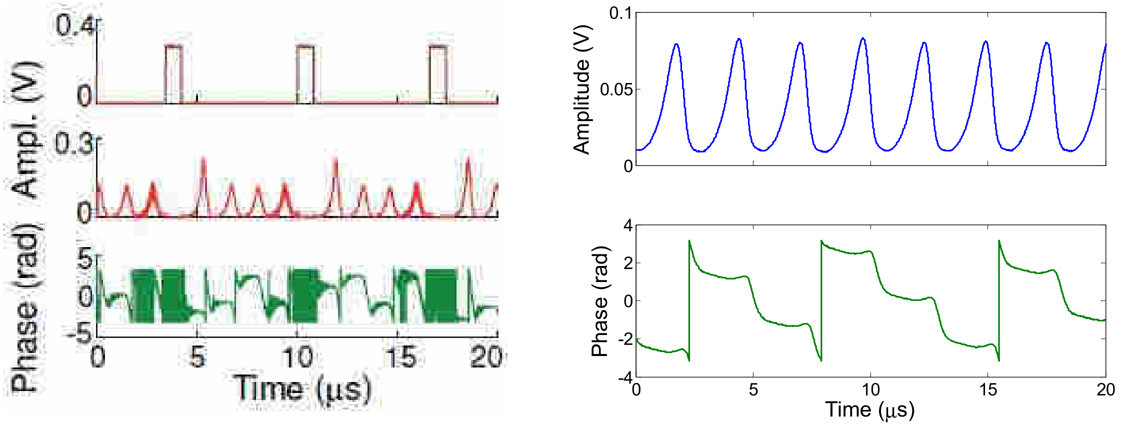

Fig1. Time diagrams measured for an active ring resonator with (a) the MQC with Fibonacci type structure and (b) the klystron amplifier. In (a), upper time diagram represents the amplitude profile of external pulses, middle and low time diagrams represent the amplitude and phase profiles of dissipative solitons, respectively. In (b), upper time diagram represents the amplitude profile of dissipative solitons and low time diagram represents its phase profile.

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DISCRETE DIFFRACTION IN COUPLED YIG ARRAYS

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The discrete diffraction phenomena was studied in optics both theoretically and experimentally by scanning tunneling optical microscopy in arrays of equally spaced identical waveguide elements [1,2]. Coupled Yttrium iron garnet (YIG) structures are of great interest nowadays due to extremely small spin-wave loss in this material and the possibility of spin-wave wave propagation control. Coupled YIG waveguides can be used as components in the tunable signal processing devices (nonlinear couplers, nonlinear switches) [3].

This report shows the results of investigation of the spatio-temporal dynamics of magnetization in the laterally coupled planar YIG waveguide array by Brillouin light scattering (BLS) spectroscopy [4]. The structure was fabricated from a sample of the YIG film thickness of 7.7 μm, grown on the basis of GaGd-garnet (GGG) thickness of 0.5 mm by laser cutting (Fig.1). The microstrip antenna with the width of 30 μm formed on the Al2O3 substrate was used for the MSSW excitation in the central waveguide (number n=0 in Fig.1). The structure was magnetized by an in-plane magnetic field of H_0=1300 Oe parallel to the microstrip antennas. The discrete diffraction of surface spin wave in a lateral coupled YIG waveguide array was demonstrated experimentally with BLS technique in planar waveguide geometry, when a single input channel with number n=0 is excited.

It was shown that the degree of system discreteness could be regulated by changing the external bias magnetic field angle. The dependence of coupling between the waveguide channels on the parameters of spin wave (wavenumber, frequency, power) makes the continuous regulation of spin wave path possible.

Nonlinear propagation, interactions between waves and generation of discrete solitons are interesting field for further studies.

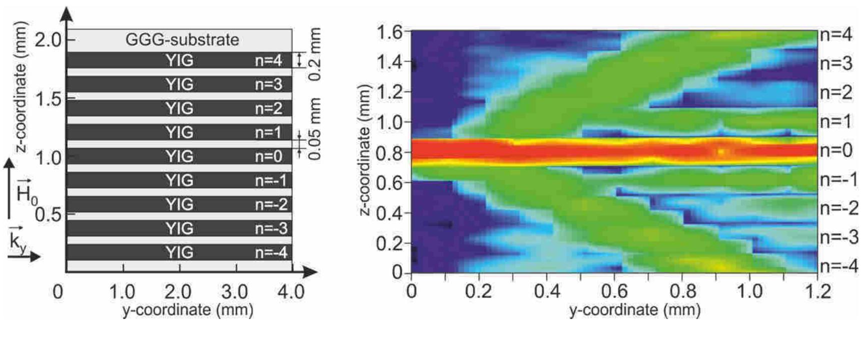

Fig. 1. Geometry of YIG waveguides array (left) and spatial distributions of $|m(y,z)|^2$ (right)

This work was supported by the Grant of RFBR (project No. 13-02-00732, 14-07-00273, 14-02-00976), the Government of RF (project No. 11.G34.31.0030).

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FEATURES OF FORMATION BAND GAPS IN STRUCTURES BASED ON MAGNON CRYSTALS

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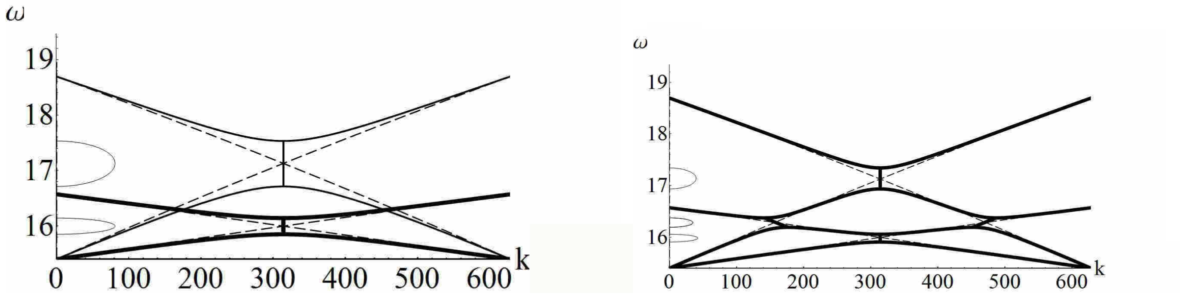
Recently, there is some interest in creation of crystals, that based on magnetic films and calls as magnon crystals (MC) [1-2]. The present work is devoted to the observation of mechanisms formation Bragg band gaps in ferromagnetic periodic structures, which are represent two coupled one-dimensional structure such as MC and MC-ferrite film when magnetostatic waves propagates in them (MSW).Using the coupled-mode approach a general model has been constructed for the first time, it describes the propagation of the forward and backward waves in such periodic structures, and the detailed analysis of behavior dispersion characteristics of MSW in the band's first Bragg resonance has made for different values of the coupling coefficient K and the periodicity parameter δd.

This structure has the distinctive feature, the dispersion curve that corresponding to the MSW in a single film is split into two curves, they describe behavior of fast and slow waves (dashed curves in Fig. 1).At frequencies of phase-matching interaction of fast forward and backward waves, as well as slow forward and backward waves should lead to the formation of two band gaps, as shown in Fig. 1a (two identical MC), in contrast to case of one MC.

Note, that this result was considered first in detail by authors in [3]. However, there are three band gaps during propagation of MSW in the structure of MC-film, it had shown by the results of the calculation (Fig. 1b). A similar result was obtained for the structure of the MC-MC with different geometric parameters, due to the asymmetry of the structures.



a) b)

Fig.1.Dispersion characteristics for fast (thin curves) and slow (thick curves) waves in different structures: a) MC-MC at $\delta d_{1,2}$= 0.5, K = 0.5; b) The MC-film is δd_1 = 0, δd_2= 0.5, K = 0.5.

Recapitulate, the possibility of effectively controlling the characteristics of the Band Gaps in various related periodic ferromagnetic structures was shown.

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