International Symposium

Spin Waves 2007

Saint Petersburg, Russia, June 16-21, 2007

Symposium Program
Abstracts

Ioffe Physico-Technical Institute RAS

Overview

Since the sixties the Symposium on Spin Waves was held biannually in St. Petersburg providing opportunity for discussion of the last advances in fundamental research of dynamical behaviour of spins in ferromagnetic, ferrimagnetic, and antiferromagnetic materials. This year the Symposium will highlight the modern problems of spin dynamics with a special emphasis being paid to novel trends in magnetism. The Symposium will mostly consist of invited lectures, contributed talks, and posters.

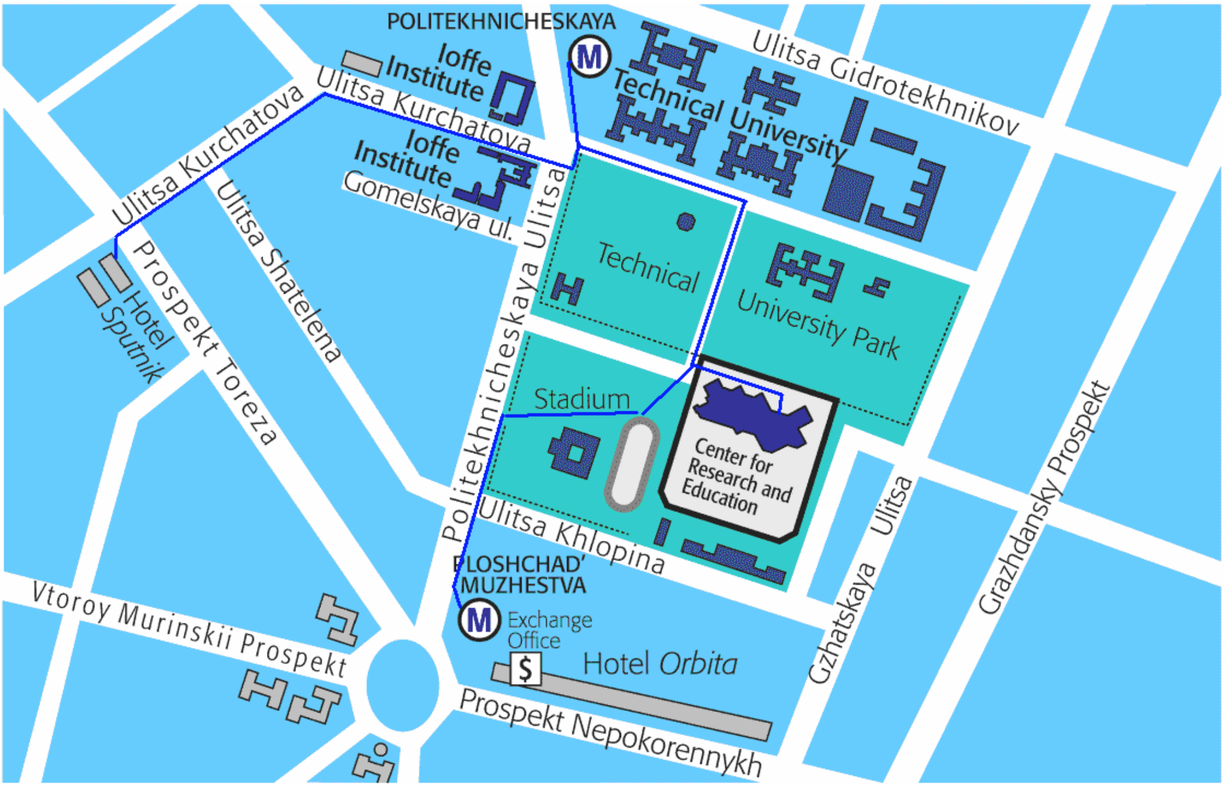
Program Topics

- Ultrafast laser-induced spin dynamics
- Current-induced spin dynamics
- X-ray probe of magnetism
- Spin dynamics in multiferroics, electromagnons
- Other new topics in magnetic dynamics

Location

Center for Research and Education, the Russian Academy of Sciences
Khlopina str. 8/3

Ioffe Physico-Technical Institute, the Russian Academy of Sciences
Polytekhnicheskaya str. 26



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Symposium Program

Sunday, June 17

10:00 – 10:10	***Opening Address*** S. A. Nikitov, R. V. Pisarev, Th. Rasing	
Novel trends in Spin Dynamics		
10:10 – 10.50	J.-Y. Bigot (Invited)	*Ultrafast magneto-optical Kerr microscope*
10:50 – 11:30	R. Chantrell (Invited)	*Atomistic and macrospin models of ultrafast magnetization reversal* **p. 9**
11:30 – 12:00	***Coffee break***	
Laser-induced Spin Dynamics I		
12:00 – 12:20	B. B. Krichevtsov	*Magnetization dynamics in Fe/Cr thin films induced by ultrashort optical pulses* **p. 10**
12:20 – 12:40	A. Kirilyuk	*Laser-induced spin dynamics across compensation points of GdFeCo ferrimagnet* **p. 11**
12:40 – 13:00	A. Melnikov	*On the nature of laser-induced ultrafast coherent lattice and spin dynamics at surfaces of rare-earth metals* **p. 12**
13:00 – 14:00	***Lunch***	
Spin-torque and Spintronics		
14:00 – 14:40	S. O. Demokritov (Invited)	*Spin-wave radiation by spin-wave nanocontacts* **p. 13**
14:40 – 15:00	D.Houssameddine	*Spin-torque oscillator using a perpendicular polarizer and a planar free layer* **p. 14**
15:00 – 15:20	I. Firastrau	*Micromagnetic investigation of the current induced magnetization oscillations for a perpendicular polarizer-planar free layer structure* **p. 15**
15:20 – 15:40	P. E. Zilberman	*Magnetization waves in ferromagnetic junctions under high spin-injection level* **p. 16**
15:40 – 16:10	***Coffee break***	
2D Magnetic Structures and Magnonics		
16.10 – 16.50	S. A. Nikitov (Invited)	*Eigen spin-waves excitations in 2D magnonic crystals* **p. 17**
16.50 – 17.10	M. V. Logunov	*Dynamic formation of two-dimensional lattices of magnetic domains with Pab2 symmetry* **p. 18**
17.10 – 17.30	S. L. Vysotsky	*Nonlinear surface magnetostatic waves in 2D magnonic crystals* **p. 19**
17.30 – 19.00	***Get-together party***	

Monday, June 18

Laser-induced Spin Dynamics II		
9:00 – 9:40	J. Hohlfeld (Invited)	*Ultrafast dynamics in magnetic recording media*
9:40 – 10:20	A. V. Kimel (Invited)	*Femtosecond opto-magnetism* **p. 20**
10:20 – 10:40	D. A. Mazurenko	*Dynamics of spin and orbital melting in* YVO_3 **p. 21**

10:40 – 11:00	C. Stamm	*Ultrafast spin dynamics probed by femtosecond X-ray spectroscopy* **p. 22**
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Spin Dynamics in Antiferromagnetic Materials		
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11:40 – 12:00	A.M.Kalashnikova	*Impulsive generation of the coherent magnons by the linearly-polarized light* **p. 24**
12:00 – 12:20	A. V. Andrienko	*Nonlinear radiation damping of parametric magnons and phonons in antiferromagnets* **p. 25**
12:20 – 12:40	A. Pankrats	*Antiferromagnetic resonance and magnetic anisotropy in $YFe_3(BO_3)_4$, $GdFe_3(BO_3)_4$ and $Y_xGd_{1-x}Fe_3(BO_3)_4$ crystals* **p. 26**
12:40 – 13:00	P. A. Usachev	*Ultrafast non-thermodynamic pathway for a magnetic first-order phase transition in $HoFeO_3$* **p. 27**
13:00 – 14:00	***Lunch***	
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14:20 – 14:40	A. A. Stashkevich	*High-intensity Brillouin light scattering by coherent spin waves excited in a permalloy film* **p. 29**
14:40 – 15:00	R. Marcelli	*Transient processes influence on magnetostatic waves soliton propagation in ferrite films* **p. 30**
15:00 – 15:20	A. B. Drovosekov	*Magnetic resonance in Fe/Cr discontinuous multilayers* **p. 31**
15:20 – 15:50	***Coffee break***	
15:20 – 15:40	R. Morgunov	*Spin-solitons and frustrations in molecular magnets based on Mn and Cr complexes* **p. 32**
15:40 – 16:00	G. S. Patrin	*Magnetic resonance investigations of interlayer coupling in NiFe/Bi/NiFe trilayer films* **p. 33**
16:00 – 16:20	D. I. Kholin	*Temperature dependence of interlayer coupling in Fe/Cr/Fe trilayers* **p. 34**
16:20 – 16:40	L. N. Butko	*Spectrum of coupled spin and electromagnetic waves propagating in a periodic magnetic* **p. 35**
16:40 – 19:00	***INTAS meeting***	

Tuesday, June 19

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9:00 – 9:40	P. M. Oppeneer (Invited)	*Computational theory of spin waves, linear magnetic dichroism and the inverse Faraday effect* **p. 36**
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10:20 – 11:00	J. Goulon (Invited)	*Element-selective X-ray detected magnetic resonance* **p. 38**
11:00 – 11:20	A. Rogalev	*Hard X-ray magnetic circular dichroism: instrumentation and applications* **p. 39**
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13:00 – 14:00	***Lunch***	
14:00 – 21:00	***Social event and dinner***	

Wednesday, June 20

Spin liquids, frustrated magnets and non-collinear magnets		
9:00 – 9:40	A. I. Smirnov (Invited)	*Low-frequency spin dynamics of spin-liquid magnets* **p. 40**
9:40 – 10:20	I. A. Zaliznyak (Invited)	*Spin conservation and quasiparticle decays in a quantum spin liquid* **p. 41**
10:20 – 10:40	V. N. Glazkov	*Single ion anisotropy, transverse magnetization and magnetic phase diagram of the frustrated gadolinium pyrochlore* **p. 42**
10:40 – 11:00	S. V. Maleyev	*Cubic helimagnets with Dzyaloshinskii-Moriya interaction: spin-waves and magnetic field behaviour* **p. 43**
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Multiferroics and Electromagnons		
11:30 – 12:10	A. A. Mukhin (Invited)	*Electromagnons in manganese multiferroics with modulated magnetic structure* **p. 44**
12:10 – 12:30	A.V.Syromyatnikov	*Nonfrustrated magnetoelectric with incommensurate magnetic order in magnetic field* **p. 45**
12:30 – 12:50	V. A. Sanina	*Magnetic and magnetoelectric (ME) dynamics in* RMn_2O_5 *(R = Gd, Eu,and Er)* **p. 46**
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14:40 – 15:00	L. V. Lutsev	*Spin waves in silicon dioxide films with cobalt nanoparticles on gallium arsenide* **p. 49**
15:00 – 15:20	O. N. Laletin	*Magnetoelastic ground state and waves in ferromagnet – nonmagnetic dielectric multilayer structure* **p. 50**
15:20 – 15:40	N. I. Polushkin	*Collective spin excitations in lateral magnetic superlattices: long-wavelength limit* **p. 51**
15:40 – 16:10	***Coffee break***	
16:10 – 16:30	O.Bolsunovskaya	*Magnetic properties and excitations of a two-sublattice magnetic system with an incommensurate phase* **p. 52**
16:30 – 16:50	V. N. Nazarov	*Localized nonlinear oscillations in a ferromagnet in a magnetic field* **p. 53**
16:50 – 17:10	I. V. Bychkov	*Coupled waves spectrum of a ferromagnetic at the account of permanent-magnet interaction* **p. 54**
17:10 – 17:25	***Closure remarks***	

Posters

Abstracts

ATOMISTIC AND MACROSPIN MODELS OF ULTRAFAST REVERSAL

D Hinzke[1], N. Kazantseva[1], U Nowak[1], R Chantrell[1*] and O Chubykalo-Fesenko[2]

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With magnetic materials becoming increasingly nanostructured, there is a developing need for models of magnetisation processes that go beyond the normal micromagnetic approach, so as to include the additional physical phenomena associated with finite size systems. This need is made more pressing by the fact that ultra-high density information storage may require Heat Assisted Magnetic Recording (HAMR), which involves heating beyond the Curie temperature, and it is known that micromagnetics is not capable of dealing with phase transitions without introducing some atomic level information. Atomistic models are currently under development and have already given important insight, for example into the properties of FePt [1]; an important candidate for ultra-high density recording media. We will introduce the physical problem in the context of the approach to ultra-high density recording, going on to describe the current state of development of atomistic models. The basis of atomistic models will then be outlined. Essentially this consists of the use of a Heisenberg effective spin model and the Langevin dynamic approach (the LLG equation augmented by a random field to include the effects of temperature) to describe the time evolution of the ensemble of coupled spins. The model enables representation of the temperature dependent magnetic properties and complete magnetic excitation spectrum. This is important because it allows the magnetic phase transition to occur at a realistic Curie temperature. The model will then be applied to studies of fast laser heating of magnetic materials. In particular it will be demonstrated that the magnetisation vanishes in a timescale of picoseconds, whereas the recovery of the magnetisation can take of the order of 1ns because of the necessity for the magnetisation to grow from a large number of small nuclei, which leads to strong frustration effects. Simulations of the heat assisted magnetisation reversal process in FePt will be presented, demonstrating a new reversal mechanism involving the destruction and recovery of the magnetisation into the reverse direction. The timescale of the recovery is an important factor in relation to the heat-assisted recording process.

Finally we will review the progress in linking atomistic and micromagnetic models in a step toward creating macroscopic models of magnetic materials at temperatures approaching the Curie temperature. This is important as regards the understanding of macroscopic reversal process cannot realistically be achieved with atomistic models. Our previous work has shown [2] that the (macrospin) Landau-Lifshitz-Bloch (LLB) equation describes the physics of high temperature processes better than the LLG equation. Here we show that the LLB equation gives a reasonable description of the heat assisted reversal process for a single grain, but fails to predict the correct timescale for recovery of the magnetisation due to the frustration effects observed in the atomistic simultations. Possible solutions to this problem will be discussed.

References

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MAGNETIZATION DYNAMICS IN Fe/Cr THIN FILMS INDUCED BY ULTRA-SHORT OPTICAL PULSES

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The magnetization dynamics of single-crystalline Fe(001) thin films has been studied by an all-optical time-resolved pump-probe technique. The films were grown on GaAs(001) substrates by MBE, with an Ag(1500 Å)/Fe(10 Å) buffer layer being predeposited before the Fe(100 Å) film growth in order to provide better epitaxy. To protect the structure from oxidation it was covered by a Cr(10 Å) cap layer. The polarization plane rotation of the probe beam has been measured as a function of time delay between pump and probe pulses. The probe beam was focused into a 50 μm diameter spot in the center of the area illuminated by the pump beam.

The films are characterized by an in-plane four-fold magnetic anisotropy that was confirmed by studying hysteresis loops measured using the longitudinal magneto-optical Kerr effect (LMOKE). Hysteresis loops for **H** along the easy axis exhibit a rectangular shape with a coercive force H_c ~ 10 Oe. Along other directions the magnetization reversal also involves significant magnetization rotation processes. The considerable asymmetry of the LMOKE hysteresis loops is explained by an additional contribution to the polarization plane rotation of quadratic in magnetization terms in the dielectric susceptibility tensor.

In contrast to previous all-optical studies of metallic systems [1-3], we have chosen a particular experimental geometry with the external magnetic field being applied in the plane of the film. This configuration allows us to investigate the amplitude, frequency and damping of magnetization precession as a function of both the orientation and magnitude of the in-plane magnetic field. We observed long-lived (~1ns) probe beam polarization oscillations initiated by the ultrafast (~0,15 ps) optical pulse excitation (λ = 800 nm, f = 1 kHz, average pump power ~ 15 mW). The oscillations are associated with the temporal variation of the magnetization component M_z normal to the film surface. The phase of the oscillations is independent of the polarization state of the pump beam giving evidence for a predominantly thermal origin of the excitation. The amplitude of the oscillations considerably depends on the in-plane orientation and magnitude of the magnetic field. The maximum efficiency of the excitation is obtained at a magnetic field of ~0.5 kOe, which is slightly deflected from the hard axis ~4°. Angle and field variations of the oscillation frequency are well described by an expression for a uniform precession mode known from the theory of ferromagnetic resonance (FMR) based on the Landau-Lifschitz-Gilbert equation. Our analysis indicates that the precession amplitude is determined by the production of the uniform mode frequency ω and an in-plane tilting of the effective magnetic field $\Delta\psi$ directly caused by the pumping light beam. The damping of magnetization oscillation shows a nonlinear character as function of frequency indicating the contribution of two-magnon scattering mechanism at the interfaces.

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LASER-INDUCED SPIN DYNAMICS ACROSS COMPENSATION POINTS IN FERRIMAGNETIC GdFeCo

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The study of ultrafast magnetization dynamics has gained considerable momentum in the last decade. This is stimulated on the one hand by the ever growing demands to increase the speed of writing and retrieving magnetically stored information, and on the other, by the development of femtosecond laser sources. The latter allow excitation of magnetic systems at time scales much shorter than fundamental quantities such as spin precession or spin-lattice relaxation times. Recent experimental studies have revealed many exciting results such as the quenching of ferromagnetism at subpicosecond time scales [1], generation of coherent spin waves [2], or reorientation of antiferromagnetic spins [3].

Rare earth–3*d* transition metal (RE-TM) ferromagnetic compounds are widely used materials for magneto-optical recording. Depending on their composition, RE-TM ferrimagnets can exhibit a magnetization compensation temperature T_M where the magnetizations of the RE and TM sublattices cancel each other, and similarly an angular momentum compensation temperature T_A where the net angular momentum of the sublattices vanishes. The theory of ferromagnetic resonance predicts a strong temperature dependence of the dynamic behavior in such systems. In particular, the frequency of the homogeneous spin precession as well as the Gilbert damping parameter α is expected to diverge at the temperature T_A. However, so far there are no experimental results to substantiate these claims. Experimental confirmation of these theoretical predictions is however important for magnetic recording and magnetic random access memory, since the combination of a high frequency and large damping of the spin precession would provide ultrafast and ringing-free magnetization reversal via precessional motion. More interestingly, the absence of the angular momentum around T_A would allow an ultrafast precessional reversal of magnetic order [4].

Here we report the study of ultrafast laser-induced spin dynamics in the RE-TM ferromagnetic alloy GdFeCo across the magnetization and the angular momentum compensation points, using an all-optical pump-probe technique. It is demonstrated experimentally that both Gilbert damping and spin precession frequency increase significantly when the temperature of the sample approaches the point of angular momentum compensation [5]. These results indicate thus the crucial role of the angular momentum compensation for controlling the fast magnetization switching process. Moreover, our approach also allowed us to observe the exchange resonance mode: as it softens near T_A it is found to dominate the ordinary ferromagnetic resonance.

Crossing of T_A leads to ultrafast switching of magnetic system (<1ps) in the applied external field and a subsequent relaxation (>1ps) trough a metastable opposite magnetic state. Beside its technological importance, we believe that the observation reported here will help the understanding of the processes underlying the interaction of light with the magnetic system.

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ON THE NATURE OF LASER-INDUCED ULTRAFAST COHERENT LATTICE AND SPIN DYNAMICS AT SURFACES OF RARE-EARTH METALS

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Coherent electron, lattice, and spin dynamics was for the first time observed at *Gd*(0001) surface by means of time-resolved magneto-induced second harmonic (SH) generation [1]. Well-known surface sensitivity of SH is of special importance in case of *Gd* due to strong resonant enhancement in d_z^2-like surface state [2]. Electric field of SH from the probe pulse can be split into two components E_{even} and E_{odd}, even and odd with respect to reversal of magnetization M. E_{even} does not depend on M reflecting electron and lattice dynamics excited by the pump laser pulse while E_{odd} is proportional to M and mostly sensitive to the spin dynamics. E_{even} possesses an abrupt 20-30% drop down, which vanishes with reduce of the photon energy [3] and is attributed to the heating of electrons by pump pulse, followed by gradual evolution on a couple of picosecond time scale coursed by electron-lattice thermalization. E_{odd} shows 40-60% drop down to a constant level independently of photon the energy, reflecting an ultrafast loss of spin polarization of valence electrons in surface region.

On top of this behaviour, we observe exponentially dumped oscillations at 3 THz frequency in both SH components. Since this frequency nearly matches the eigen frequency of longitudinal phonon mode along the normal to surface in the vicinity of Γ point and close to the frequency of magnon mode with the same wavevector, we attribute these oscillations to displacive optical excitation of a coherent coupled phonon-magnon mode at the Gd surface. We suggest a mechanism of this phenomenon based on laser-induced surface charge redistribution modifying the lattice potential for the topmost ion layer and displacively initiating vibrations at the phonon frequency resonantly coupled to the magnon component [1].

This talk is aimed to go further on in the development of physical picture of this phenomenon, basing on results of temperature-dependent SHG studies and comparison of coherent dynamics in *Gd* and *Tb*, where the eigen frequency of magnon mode is considerably smaller than that of the phonon mode. The same level of amplitude A of oscillations in E_{even} in *Gd* and *Tb*, shows that the resonant character of phonon-magnon coupling is not important for the excitation of phonon mode. Moreover, the excitation of lattice vibration in general does not require the spin component and is possible at temperatures significantly exceeding the Curie temperature T_C. On the other hand, the spin ordering plays an important role in the phonon excitation owing to the strong decrease of A when the temperature increases up to T_C. Also the phonon decay rate decreases with the increase of temperature around T_C indicating an important role of magnon component and significant contribution of the electron-magnon scattering to the damping of coherent mode. Pump fluence dependence of the coherent dynamics in *Gd* shows the dominating role of hot electrons in this damping.

Combined laser-pump synchrotron-probe experiments in *Gd* allow us to probe directly the dynamics of spin ordering in *f*-shell with 50ps time resolution and shed a light to the mechanism of laser-induced demagnetization. Spin polarization of valence electrons can not be destroyed completely even for the sample temperature close to T_C since it is partially recovered by the spin transfer from *f*-shell. That course in ~20% loss of spin ordering of *f* electrons in spite of the fact that the transient lattice temperature significantly exceeds T_C, which means that *f*-spin-lattice interaction time is larger that spot cooling taking ~200ps.

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SPIN-WAVE RADIATION BY SPIN-VALVE NANOCONTACTS

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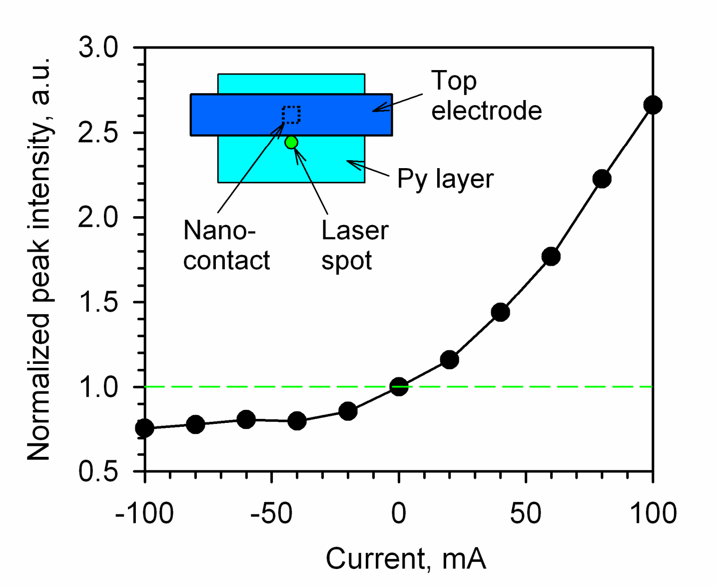
After the theoretical prediction [1] and the direct experimental observation [2] of spin-wave excitation by a spin-polarized electric current flowing through multilayered nano-pillars this phenomenon has attracted enormous attention due to its potential for nanometre-scale microwave oscillators to be used in future integrated microelectronic devices.
Using spatially resolved micro-focus Brillouin light scattering technique with spatial resolution of 250 nm we have studied radiation of spin waves by a spin-valve nano-contact into a continuous underlying magnetic film. The investigated elements have lateral dimensions in the micrometer or sub-micrometer scale and consist of a 10 nm thick $Co_{80}Fe_{20}$ and a 5 nm thick $Ni_{81}Fe_{19}$ layer separated by a 4 nm thick Cu spacer layer. It is found, that the elements radiate spin waves at frequencies corresponding to their laterally quantized spin-wave eigenmodes. Two-dimensional distributions of intensities of spin waves radiated by different eigenmodes are recorded outside the element. It is shown, that the radiation patterns consist of several rays intersecting each other and forming spots where the amplitude of variable magnetization locally increases [3].

The influence of a DC spin-polarized current on the spin-wave radiation process has been investigated as well. We show that the radiation process is strongly affected by spin-polarized direct electric current crossing the magnetic layers. The Figure shows the local spin-wave intensity at a given point as a function of the DC current. The spin-wave intensity was measured by placing the probing laser spot onto the open part of the Py film in the vicinity of the spin-valve nano-contact as shown in the inset. As seen from the Figure, the transmission of a positive electric current leads to a strong increase of the spin-wave intensity more than by a factor of two for the current rising up to 100 mA. As a negative current is applied the intensity starts gradually to decrease [4]. These results are a clear manifestation of the fact, that the effective damping of spin waves can be governed by a spin-polarized DC-current.



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SPIN TORQUE OSCILLATOR USING A PERPENDICULAR POLARIZER AND A PLANAR FREE LAYER

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Spin electronics materials have recently been considered for radio frequency applications by exploiting the concept of transfer of spin angular momentum between a spin polarized electrical current and the magnetization of a nanostructure. This angular momentum transfer is equivalent to a (spin) torque exerted on the local magnetization and which counteracts the damping torque. As a result it is possible to stabilise steady state oscillations of the magnetisation on trajectories that are in many situations close to constant energy trajectories defined only by the system energy. For an in-plane magnetised thin film with uniaxial anisotropy, two types of constant energy trajectories exist which are commonly called in-plane (IP) precession, where the magnetisation oscillates around the in-plane easy axis, and out of plane (OP) precession where the magnetisation oscillates around the out of plane energy maximum.

From an applications point of view it will be of interest to excite OP precessions with a small out of plane magnetization component at the threshold current and in zero field. Such OP precessions will lead to a larger output signal than IP precessions that are usually excited in ‘planar’ spin valve structures that use an in-plane magnetised polarizer and free layer. In contrast to this, we will present here a spin torque oscillator that combines an out of plane magnetised polarizer with an in-plane magnetized free layer [1]. Using static and dynamic transport measurements, we will show that OP precessions are induced at the threshold current for moderate current densities of $9x10^6$ A/cm. These OP precessions manifest themselves as discrete steps in the resistance-field transfer curves whose field range increases as a function of current. The experimental current-field state diagram as well as the frequency vs. current and applied bias field is well explained by macrospin and micromagnetic simulations.

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MICROMAGNETIC INVESTIGATION OF THE CURRENT INDUCED MAGNETIZATION OSCILLATIONS FOR A PERPENDICULAR POLARISER-PLANAR FREE LAYER STRUCTURE

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The possibility of inducing large angle steady state oscillations in a magnetic thin film element by the transfer of spin angular momentum has been widely discussed by theoreticians and experimentalists. Recently, it has been shown experimentally that in nanostructures using a perpendicular polarizer (with out-of-plane magnetization, F1 in the Fig. 1) out-of-plane (OP) steady state precessions of the free layer (F2) magnetisation can been excited at the threshold current and in the absence of an external magnetic field [1]. Experimentally, the observation of such OP precessions requires an in-plane magnetised analyzer (F3) to monitor the magnetisation motion of the planar free layer. In order to compare the experimental results to theory we have studied the dynamics in the free layer by solving the Landau-Lifschitz-Gilbert equation enhanced by the spintorque term in the frame of the Slonzcewski [2] model. In our simulations we have taken into account only the perpendicularly polarized electrons coming from F1. While the experimental current-field state diagram is in good qualitative agreement with the simulated one using a macrospin approximation, differences occur when comparing the oscillation frequencies as a function of applied current density J. In the macrospin approximation the oscillation frequency increases monotonously with increasing current density. However, the experiments reveal two frequency branches: a first branch at small J, with increasing frequency for increasing J, and a second branch, at larger J, with decreasing frequency. This behaviour is well explained through micromagnetic simulations which take into account the spatial distribution of the magnetization inside the layer. Indeed, at low current density, the magnetic moments rotate almost uniformly and the system responds approximately like a macrospin, with a frequency that increases linearly with current. In contrast, for large J, a non-homogenous magnetisation configuration with two vortex-like regions forms. These regions are characterised by an important out-of plane magnetization component Mz. In order to minimize the large out-of-plane demagnetization field created in these zones, the magnetization in the rest of the element will stay close to the plane, so that the mean Mz component decreases when the current density increases. Consequently the frequency decreases with increasing J as in the experiment. Finally, the effects of the Oersted field and of the dipolar stray field generated by the perpendicular polariser and the planar analyzer were also investigated. We have shown that the dipolar field diminishes the oscillation frequency while the Oersted field does not seem to influence these oscillations.

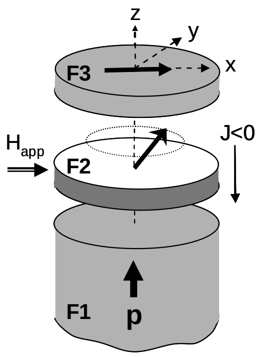

Fig.1. Oscillator geometry

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MAGNETIZATION WAVES IN FERROMAGNETIC JUNCTIONS UNDER HIGH SPIN-INJECTION LEVEL

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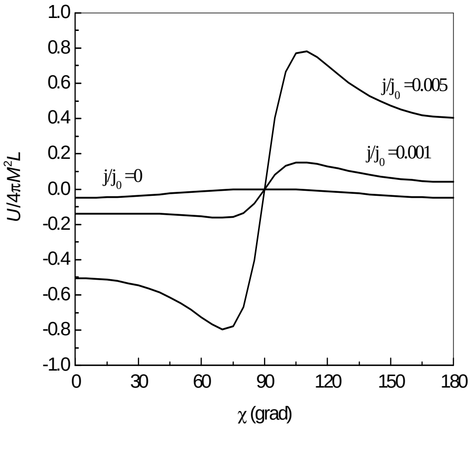
Matching conditions for spin resistances are found at the interfaces of a magnetic junction. These conditions provide high current driven spin injection level. Essence of the conditions consists in creating effective injection at input interface and suppressing the injection at the output one. These conditions combined with parallel magnetization orientation leads to orders of magnitude lowering of instability threshold. Contrary to this, stability preserves completely for antiparallel magnetization orientation and for any direct current magnitude. However, new effect of population inversion of spin subbands is predicted in the situation.

Perpendicular electric current creates a non-equilibrium spin injection in the structure of contacting thin ferromagnetic layers (ferromagnetic junction). We calculate net spin polarization of the junction for very high level of the injection when non-equilibrium spin density is comparable with the equilibrium one. Spin resistances are introduced for each layer of the three layered junction, namely, Z_1, Z_2, Z_3, where $Z_i = \rho_i l_i/(1-Q_i)$, ρ_i - specific resistance, l_i - average spin relaxation length and Q_i - spin polarization degree of current for the layer of number $"i"=1,2,3$. As it is shown, the conditions $Z_1 >> Z_2$ and $Z_3 >> Z_1$ provide the most high injection level at a given current density j in the forward direction $1 \to 2$, the first condition providing strong spin injection into the layer 2 and the second condition providing lock of spins in the layer 2.

If the conditions are fulfilled, the junction demonstrates some interesting new properties. First of all the injection suppresses completely the so called spin-transfer torque. Then the situation becomes different depending on parallel or antiparallel is the mutual magnetization orientation of neighbouring ferromagnetic layers. The proper junction magnetization waves become unstable at current density exceeding some threshold value for parallel orientation. It is significant to note that this threshold appears many orders of magnitude lower than it is in the commonly used low injection regime. For example, the threshold may reach $j_{th} \sim 10^5$ A/sm^2 instead of an ordinary value $j_{th} \sim 10^7$ A/sm^2.

In contrast to this, lattice magnetization waves become stable at any current for antiparallel magnetization orientation of neighbour ferromagnetic layers. This may be seen from the figure where magnetic energy U versus angle χ between the magnetizations is shown, M and L are correspondingly magnetization and thickness of the working layer 2. There exist two energy minima at zero current, that is parallel and antiparallel configurations both are stable. Minimum at $\chi = 0$ disappears with current increasing and only minimum at $\chi = 180^0$ remains. It means the only antiparallel configuration remains stable. It is interesting to note some new stable orientation appears at the angle near 67^0. We may conclude the direct current leads to switching of the magnetization vector from $\chi = 0$ to $\chi \approx 67^0$. Stable configuration at $\chi = 180^0$ is remarkable due to some other interesting effect, namely, negative spin temperature and a possibility of laser effect in the range of terahertz frequencies.



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EIGEN SPIN-WAVES EXCITATIONS IN 2D MAGNONIC CRYSTALS

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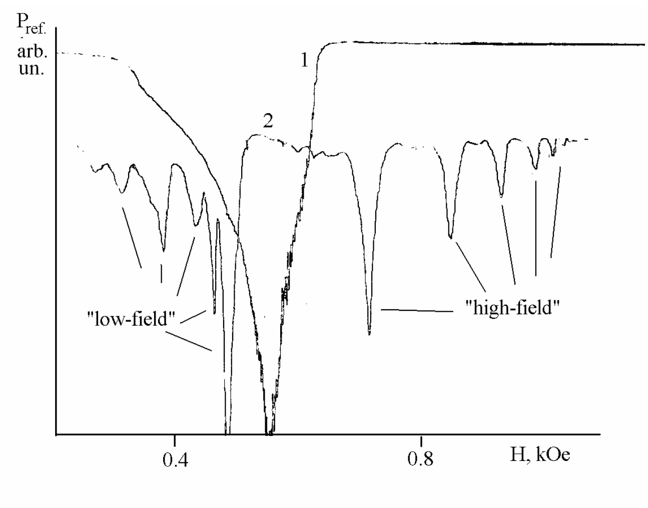
In recent years microwave properties of 2D magnonic crystal (MC) based on yttrium-iron garnet (YIG) films are intensively investigated. MC can be maid by etching of 2D periodic array of holes on the film's surface; the etching depth can take up the different part of film's thickness [1,2]. The influence of this periodic structure on the magnetostatic surface waves (MSSW) propagating was investigated in [1,2] while properties of 2D MC itself has received low attention. Here we report the results of experimentally investigation of eigen spin-wave excitation spectra of 2D MC consist of rhombic and square arrays of 4-4,5 μm depth holes based on 5 μm YIG film [1].

The figure demonstrates dependencies of power P_{ref} reflected from a microstrip transducer placed onto both the YIG film (curve 1) and rhombic MC surface (curve 2) on bias tangentially directed magnetic field H_0 at f=3,5 GHz. One can see that the curve 2 includes two sets of absorption peaks: "low-field" and "high-field" one. We have investigated the dependence of intensity of both sets of absorption peaks on the angle φ between the array's axis and wave vector. It was found that low-field" peaks can be observed at any value of φ without significant changes and can be attributed as spin-wave excitations of hole itself. In contrast "high-field" peaks was observed at φ values in the vicinity of $0^o \pm n\pi/3$ (0^o corresponds to array's axis) and transformed to broadband excitation region at other φ values so they were associated with the excitation determined by the array's symmetry. The transformation of curve 2 depending on φ is discussed. Note that investigation of square array MC with the analogous parameters demonstrates similar "low-field" peaks and different character of "high-field" peaks that is attributed as a result of distinction of holes' cross section for different arrays.



It should be noted that in 2D MC with respectively shallow holes (1-2 μm in 16 μm thickness YIG film [2]) weak "high-field" peaks were also observed. In this structure we have observed the interaction of MC excitation with backward volume magnetostatic waves.

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DYNAMIC FORMATION OF TWO-DIMENSIONAL LATTICES OF MAGNETIC DOMAINS WITH *Pab*2 SYMMETRY

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The self-organizing of the distribution of magnetization vector can result in formation of the ordered domain structures as two-dimensional lattices of domains [1-3] under action of a variable magnetic field in thin magnetic films with a punch-through labyrinth domain structure. Two-dimensional lattices consist of dumbbell-like, elliptic, and bubble magnetic domains and can be considered as a set of flat geometrical figures. The greatest variety of domain structures probably in low coercive films with easy-axis magnetic anisotropy that is normal to the surface of the film. An iron garnets film is a material with small dissipation of spin waves and the aforesaid domain structure.

In the present work, we report the results of experimental study of the dynamic formation of two-dimensional magnetic domain lattices with *Pab*2 (as "parquet") symmetry in harmonic and pulsing magnetic field. Our experiments showed that such lattices can have different directions of alignment of domain system relatively to the basic direction in the film plane. Presence of two mutually perpendicular primary directions in the arrangement of the domains testifies to influence of orthorhombic components of magnetic anisotropy on two-dimensional lattice formation from initial labyrinth domain structure. Controlled influence of magnetic field with taking into account parameters of magnetic anisotropy allows to carry out controlled formation of two-dimensional domain configurations with the set direction in the plane of magnetic film.

Thus, the possibilities of formation of two-dimensional magnetic domain lattices with various symmetry, “turning” of lattices relatively to the basic direction in the film plane under the external magnetic field, and little dissipation of spin waves in garnet films are showing on perspectives of theirs application as a base of magneto-photonic crystals [4].

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NONLINEAR SURFACE MAGNETOSTATIC WAVES IN 2D MAGNONIC CRYSTALS

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Recently the investigation of magnetostatic waves' propagation in 2D magnonic crystals was reported [1]. The magnonic crystals (MC) are microwave analog of widely known photon crystals used in optical (visible) range [2]. MC can be fabricated, for example, by forming of 2D periodic structure on yttrium-iron garnet (YIG) film's surface. Particularly, in [3] 2D MC obtained by etching of 16 μm thickness YIG film to provide square and rhombic arrays (lattice constant $\Lambda \approx 40\,мкм$) of 1-2 μm depth holes with 32 μm diameter were investigated. For the case of propagating magnetostatic surface waves (MSSW) two types of forbidden frequency band were found in wave's spectra. It was shown that the first band (B_1) is determined by Bragg resonances in 2D array and depends on both symmetry and period of the array. The second type band (B_2) arises as a result of spin pinning (during etching process) in some surface region leads in turn to increasing of efficiency of hybridization of MSSW with exchange spin waves (so-called "radiation losses"). Note that MSSW' power P used in [1,3] was low enough to neglect well-known nonlinear effects (parametric and modulation instability of MSSW) observed at $P>P_{th}$, where P_{th} is a threshold parametric instability power. The paper reports the results of experimental investigation of parametric instability of MSSW propagating in 2D-magnonic crystal described in [3].

The measurements were done using MSSW delay line where amplitude-frequency response characteristics and dependencies of output power (P_{out}) on the input power (P_{in}) were investigated at frequency range 2 - 4 GHz at P_{in}<60 mW. MSSW power P was defined as $P=P_{ref}(H_0^*)-P_{ref}(H_0)$, where $P_{ref}(H_0)$ and $P_{ref}(H_0^*)$ are values of power reflected from the input transducer of delay line at bias magnetic field correspond to exciting of MSSW and impossibility of MSSW exciting, respectively. P_{th} value was defined as the one corresponding to the deviation of $P_{out}(P_{in})$ dependence from the linear law.

The results of investigation of nonlinear MSSW in 2D magnonic crystals are the following:

- the threshold parametric instability power values provides parametric (three-magnon) instability development in 2D MC are more than two times greater compared to the analogous values for the starting YIG film. This can be related to increasing of relaxation velocity of spin waves because of dissipation on the 2D array microirregularities;
- at frequencies adjacent to forbidden frequency band B_2 parametric instability process wasn't observed while increasing P_{in} up to 60 mW;
- at the experimental conditions the parametric process doesn't destroy the forbidden frequency zone B_1 in MSSW spectra;
- mentioned properties were found quite similar for both investigated types of arrays.

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FEMTOSECOND OPTO-MAGNETISM

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The demand for the ever-increasing speed of information storage and manipulation has triggered an intense search for ways to control the magnetization of a medium by means other than magnetic fields. The control of magnetism by light is one of the promising approaches to this problem, because such methods may access timescales of a picosecond or less [1].

Can light directly and nonthermally magnetize a medium? A circularly polarized photon carries angular momentum. If it would be possible, using this angular momentum, to affect spins of electrons directly, this would result in ultrafast laser control of magnetism, since right- and left-handed circularly polarized light-waves should affect spins as magnetic fields of opposite sign.

Recently, our group observed for the first time ultrafast and nonthermal effects of light on magnetization [2-6]. We demonstrated that circularly polarized femtosecond laser pulses can excite and coherently control the spins in magnets. Moreover, the effect of this ultrashort optical pulse on a magnetic system was found to be equivalent to the effect of an equally short magnetic field pulse with strengths up to 1 T. Therefore, in contrast to the well-known magneto-optical Faraday effect, where the polarization of light is affected by magnetism, these experiments demonstrate the feasibility of the inverse, *opto-magnetic,* phenomenon: polarized light affects magnetism via the inverse Faraday effect.

We will show that the mechanism of opto-magnetic excitation does neither require annihilation of a photon nor loss of its angular momentum. Instead, the energy transfer from the light to the magnetic system takes place via the mechanism of stimulated Raman scattering [5]. Using this opto-magnetic phenomenon one may selectively excite different modes of magnetic resonance, realize quantum control of magnons, trigger magnetic phase transitions and switch spins on a subpicosecond time-scale. Our findings open new insights into the understanding of ultrafast magnetic excitation and, regarding recent progress in the development of compact ultrafast lasers, may provide new prospects for applications of ultrafast opto-magnetic phenomena in magnetic storage and information processing technology.

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DYNAMICS OF SPIN AND ORBITAL MELTING IN YVO_3

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Dynamics of phase transitions induced by light is an important and rapidly growing area of modern science. The interest to this subject is not only limited by general physics aspects but also motivated by applications in multimedia technologies.

Yttrium vanadate (YVO_3) gives an excellent opportunity to study various magnetic and orbital phase transitions in the same crystal. At T_c = 77 K it undergoes a first-order phase transition from antiferromagnetic to a *c*-axis ferromagnetic state, which is accompanied by a sudden lattice expansion along the *b*-axis, and a contraction along the *a*- and *c*-axes. The antiferromagnetic order in the *ab*-plane survives up to the Néel temperature, T_N = 116 K, above which YVO_3 is paramagnetic. Apart from the spin ordering, YVO_3 possesses an orbital ordering transition, which appears below a structural transition at T_{OO} = 196 K. This transition is accompanied by a lattice distortion that gradually appears below T_{OO} and causes substantial changes in the dielectric function of YVO_3. In the present studies we analyze the dynamics of optically induced phase transitions of YVO_3 by monitoring the evolution of the transient reflectivity.

We discuss the observed power and temperature dependence of the transient reflectivity of YVO_3 in terms of ultrafast melting of the spin and orbital order that takes place on a picosecond time scale. In contrast, the first-order phase transition associated with the orbital reordering is expected to be much slower and has not been observed on a picosecond timescale.

ULTRAFAST SPIN DYNAMICS
PROBED BY FEMTOSECOND X-RAY SPECTROSCOPY

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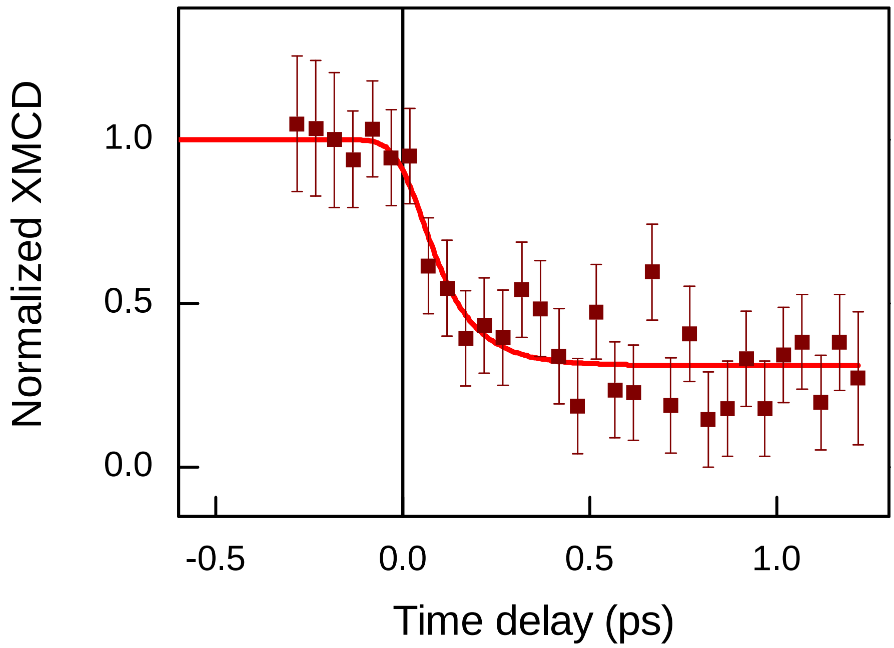
Ultrafast demagnetization of ferromagnetic thin films has been studied extensively by means of magneto-optical Kerr effect (MOKE) [1]. Here we demonstrate a new method, combining fs laser excitation with x-ray spectroscopy, probing the dynamic response of the magnetic moments by means of x-ray magnetic circular dichroism (XMCD). Its main advantage is the possibility to directly determine spin and orbital angular moments through sum rules. The true challenge is to achieve fs time resolution required to observe ultrafast processes.

Using a standard Synchrotron source, the x-ray pulse length is typically 50 ps long. The Femtoslicing source at BESSY however is capable of generating x-ray pulses of just ~100 fs duration and with selectable polarization [2]. The accessible x-ray energies allow for x-ray absorption measurements of the 3d transition and rare-earth elements (L and M edges, respectively), covering the important ferromagnetic elements Fe, Co, Ni, and Gd.

In a fs laser pump – fs x-ray probe experiment we observed the temporal evolution of the magnetic moments in a 15 nm thick Ni film. The dichroic signal at the Ni L_3 edge was found to vanish with a time constant of 120 fs (see figure). Applying sum rules we conclude that fs laser excitation is causing an ultrafast quenching of spin moments, thus unambiguously proving by XMCD the demagnetization on the sub-ps time scale.



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NONLINEAR SPIN DYNAMICS FOR ANTIFERROMAGNETS AND NON-HEISENBERG MAGNETS

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The scope of this talk is to discuss up-to day understanding of the description of dynamics of spin systems under an action of high-intensity and fast pulse pumping, for example, produced by sub-picosecond laser pulses. Such pulses can produce non-linear spin dynamics, as well as irreversible processes, like phase transitions. The transitions can be order-disorder type or re-orientation transitions, including transitions without change of the underlying magnetic order (ferromagnetic (FM) or antiferromagnetic (AFM)), or with more substantial reconstruction of the ground state, like FM-AFM transition. Non-dipolar phases, like spin nematic state with zero expectation values for spins of all sublattices, are also of interest. First order magnetic transitions are developed through the motion and reconstruction of the topological defects present in the system, like domain walls (DW), vortices and AFM disclinations. Depending of the nature of the phenomena, different levels of theory can be adequate.

The simplest way is to take into account the dipolar degrees of freedom which corresponds with expectation value of spin for $\alpha-$th sublattice, $\vec{m}_\alpha = \left\langle \vec{S}_\alpha \right\rangle$. For FM with one sublattice the dynamical equation for $\vec{m}$ is nothing but familiar Landau-Lifshitz equations. For The case of AFM is more interesting for applications. For two-sublattice AFM with use of natural combinations $\vec{m} = (\vec{m}_1 + \vec{m}_2)/2, \vec{l} = (\vec{m}_1 - \vec{m}_2)/2$ the condition $|\vec{m}| << |\vec{l}| \approx 1$ leads to anisotropic sigma-model equations for $\vec{l}$ vector only. The Lagrangian of sigma-model includes inertial term proportional to $(\partial\vec{l}/\partial t)^2$, and the dynamics of AFM is common to that for "massive arrow". As a response on ultra-short pulse of magnetic field, the inertial dynamics is present after end of the pulse. This effect is obviously absent for FM's. For DWs this mechanism leads to pulse field induced DW motion even without direct interaction of $\vec{l}$ vector and magnetic field $\vec{H}(t)$, caused by Dzyaloshinskii-Moriya interaction. In the last case, the "driving force" for DW is proportional to $d\vec{H}/dt$. The time integral of the force of this origin is zero, but it can trigger the depinning of DW from defects. The common effects appears for AFM disclinations and vortices.

Nearly FM-AFM phase transition the effective exchange interaction of sublattices becomes "soft" and the condition $|\vec{m}| << |\vec{l}|$ is obviously failed. For this case, sigma-model is not adequate more. The effective Lagrangian includes both components of $\vec{m}$ and $\vec{l}$, their gradients and terms linear on their time derivatives, but no inertial terms. For this model, some types of topological solitons, like AFM vortices and DW's for vector $\vec{l}$, with ferromagnetic core (in the core region, $\vec{l} << \vec{m}$), are present. There are some peculiarities for dynamics of such defects, for example, AFM vortices and Bloch lines in DW's are subject to gyroforce, common to that for FM's and absent for "usual" AFMs treated within sigma-model approach.

Beyond the dipolar approximations described above, we construct phenomenological equations describing collective semiclassical dynamics a set of quadrupole variables (biquadratic combinations of the component of the spin operators) coupled with dipolar (magnon) variables and learned non-linear dynamics within this approach.

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IMPULSIVE GENERATION OF THE COHERENT MAGNONS BY THE LINEARLY-POLARIZED LIGHT

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In recent years the ultrafast manipulation of the magnetic state of matter by femtosecond laser pulses has emerged as one of the most intriguing issues of magnetism, spintronics, information processing and magnetic recording [1]. The ultrafast magnetization reorientation requires fast and efficient channels for the angular momentum transfer between external stimuli, spins, orbitals and phonons [1-3]. However, it was argued in [2] that the direct transfer of the momentum from photons to spins is not sufficient for magnetization reorientation and, therefore, the feasibility of the all-optical control and switching of magnetization is opened to question now.

Using the magneto-optical pump-probe technique we show that in an easy-plane weak ferromagnetic $FeBO_3$ the *linearly-polarized* 150 fs laser pulses *carrying no angular momentum* excite the coherent spin precession (Fig.1). It is in contrast to the previously reported experimental observations in the rare-earth orthoferrites [4], where circularly-polarized laser pulses were shown to excite spin precession with the phase being set by the photon angular momentum.

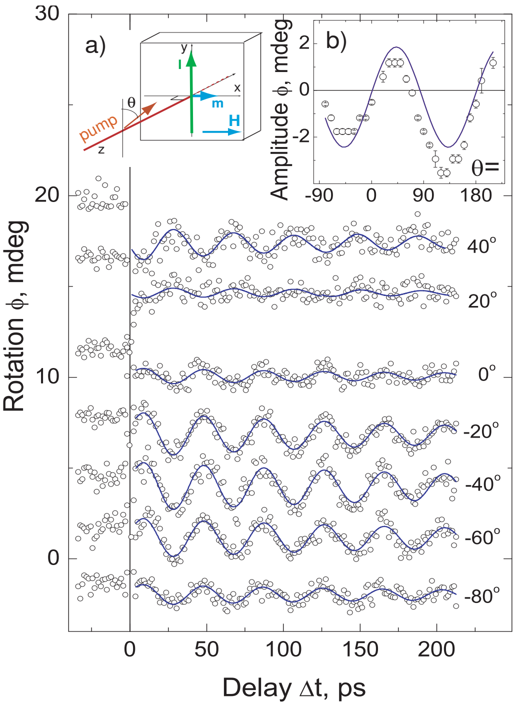

Fig. 1 The excited spin precession as a function of the pump-probe time delay measured at different orientation of the linearly polarized pump pulses as shown in (a). (b) Amplitude of the oscillations as a function of the pump polarization.

We show that phenomenologically the impulsive action of the linearly polarized light on a spin system can be understood as an action of impulsive magnetic fields and this effect can be sizable only in magnetically ordered media. In the case of the multi-sublattice magnetic medium these fields influence not only the ferromagnetic but also the antiferromagnetic order parameters.

We propose the theoretical model that proves the impulsive stimulated Raman scattering to be a mechanism of the light excitation of the spin precession. We show that the efficiency of this process is determined by the intrinsic properties of the media such as magnetic structure and magneto-optical properties. It is these properties that define whether the circularly or linearly polarized laser pulses will be efficient for the spin precession excitation. The direct transfer of the angular momentum from photons to spins is absent in this process.

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NONLINEAR RADIATION DAMPING OF PARAMETRIC MAGNONS AND PHONONS IN ANTIFERROMAGNETS

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The parametric resonance of nuclear magnons [1] and quasiphonons [2] under a microwave magnetic field was studied in antiferromagnets $CsMnF_3$ and $FeBO_3$ respectively. Parametric waves were excited in single crystals by a method of parallel pumping at a frequencies $\omega_p/2\pi$ =1.1-1.2 GHz. The threshold of parametric excitation was determined from the sharp feature arises on the MW pulse transmitted through resonator. Above the excitation threshold (i.e., for $h>h_c$), a dynamic order is established in the system, which is characterized by two parameters: the number N_k of parametric pairs of magnons (or quasiphonons) and their phase with respect to the pumping field. This nonequilibrium Bose condensate (NBC) of a macroscopic number of generated pairs represents a forced oscillation of the medium at the frequency of the external field.

Immediately after switching off a pumping pulse, the electromagnetic radiation from the NBC was observed. It is well-known that the power of a microwave signal transmitted through a resonator is proportional to the number of photons in the resonator. In the absence of the NBC, after switching off the oscillator, this signal monotonically decreases with a characteristic decay time of photons of about 0.1 μs, which is determined by the quality factor of the resonator Q. If the pumping power is substantially greater than the threshold power, then, after switching off the pumping field, one can observe radiation from the sample behind the trailing edge of the pulse. Presence of this radiation demonstrates existence of the radiating mechanism of parametric wave attenuation. As frequency of radiation is approximately equal to frequency of the MW pumping it means, that radiation is caused by the coalescence of two quasiparticles of a parametric pair to create a photon with a frequency close to ω_p ($m + m \rightarrow ph$), i.e., by the reverse process of pumping. Inasmuch as all parametric pairs in the NBC have the same phase, this radiation is coherent and has large amplitude.

In [3] was shown that the process $m + m \rightarrow ph$ gives rise to positive nonlinear damping of parametric pairs in the combined resonator–sample system. The coefficient of the nonlinear radiation damping is given by [2] $\gamma_{rad} = 2\pi \cdot QV_k^2/v_R$, where V_k is the magnetic moment of parametric pair, v_R is the volume of the resonator. It is obvious that the emission of photons due to this process is hard to detect under switched on pumping because a counterflow of photons from the sample to the resonator merely reduces the microwave power absorbed by the sample. However, this radiation can be detected after the termination of the pumping pulse.

The time dependencies of the radiation signal were measured. Experimental data were described using the formula $dN_k/dt = -2\gamma(N_k)N_k$, where $\gamma(N_k) = \gamma_0+\gamma_{nl}N_k$ is whole damping of parametric waves, γ_0 and γ_{nl} – parameters of linear and nonlinear damping. Comparison of the experimental data with the theory shown, that nonlinear damping of parametric magnons and quasiphonons consists of two parts: 1. nonlinear radiation damping, caused by resonator–sample interaction; 2. self nonlinear damping, caused by inherent magnetic nonlinearity of crystals.

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ANTIFERROMAGNETIC RESONANCE AND MAGNETIC ANISOTROPY IN $YFe_3(BO_3)_4$, $GdFe_3(BO_3)_4$ AND $Y_xGd_{1-x}Fe_3(BO_3)_4$ SINGLE CRYSTALS

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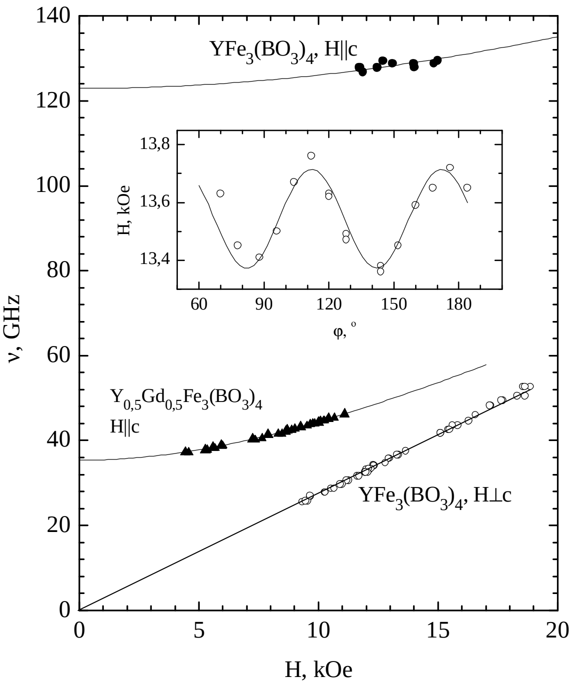
The magnetic structures of rhombohedral crystals $RFe_3(BO_3)_4$ with R^{3+} - rare earth ion are formed due to the competition of contributions to magnetic anisotropy of Fe^{3+} and R^{3+} subsystems. The magnetic structure and phase diagrams of $GdFe_3(BO_3)_4$ showing multiferroic properties are studied by antiferromagnetic resonance (AFMR) method [1]. To separate the contributions of Fe^{3+} and Gd^{3+} ions in this crystal we investigated the AFMR and magnetic anisotropy in $YFe_3(BO_3)_4$ single crystal having the only Fe^{3+} magnetic subsystem.



The frequency-field dependences of AFMR in $YFe_3(BO_3)_4$ at T=4.2 K for two orientations of magnetic field are shown in Figure. The low-frequency AFMR branch at H⊥c is linear with very small energy gap due to the weak anisotropy in a basal plane (see the insert of Figure). It confirms a conclusion [1] about the "easy plane" type of magnetic anisotropy for Fe^{3+} subsystem in $GdFe_3(BO_3)_4$. Taking into account the exchange field H_E=700 kOe found from magnetization at T=4.2 K and the energy gap of the high-frequency AFMR branch in $YFe_3(BO_3)_4$ at H||c (see Figure) we calculated the effective field of magnetic anisotropy for Fe^{3+} system which temperature dependence is well described by Brillouin function for S=5/2.

This dependence allows to separate the contributions of Fe^{3+} and Gd^{3+} ions to total magnetic anisotropy of $GdFe_3(BO_3)_4$. It was found that these contributions are close on absolute value, but have opposite signs: -1.44 kOe and 1.52 kOe at T=4.2 K for Fe^{3+} and Gd^{3+}, accordingly. Because of the distinction of there temperature dependences the total anisotropy changes a sign at T=10 K giving rise to spontaneous spin-reorientation transition between "easy plane" and "easy axis" magnetic states.

Partial diamagnetic substitution of Gd^{3+} ions for Y^{3+} ions decreases the contribution of rare earth subsystem to anisotropy. As a result the magnetic state of $Y_{0.5}Gd_{0.5}Fe_3(BO_3)_4$ single crystal remains "easy plane" down to T=4.2 K, however the energy gap for high-frequency AFMR branch falls essentially in comparison with $YFe_3(BO_3)_4$ (see Figure). The distinction of temperature dependences of Fe^{3+} and Gd^{3+} ions contributions explains unusual temperature behaviour of magnetic anisotropy and energy gap in this crystal with decreasing at low temperatures.

The work was supported by RFBR, grant 06-02-16255.

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ULTRAFAST NON-THERMODYNAMIC PATHWAY FOR A MAGNETIC FIRST-ORDER PHASE TRANSITION IN $HoFeO_3$

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The dynamic response of magnetically ordered materials to femtosecond laser excitation has been intensively studied over the last 10 years [1-5]. Among these, the studies of magnetic first-order phase transitions are scarce. Moreover, in all these cases the observed phase transformations were the result of ultrafast laser heating [3]. However, it has been recently demonstrated that besides heating, a 100 fs circularly polarized laser pulse may act on spins as a similarly short magnetic field pulse up to 1 T [4]. In magnetically ordered materials such a strong field is a stimulus that on itself can efficiently induce a first-order phase transition. In contrast to heat-driven phase transitions, magnetic-field-driven transitions are not associated with an increase of entropy and thus expected to have different kinetics.

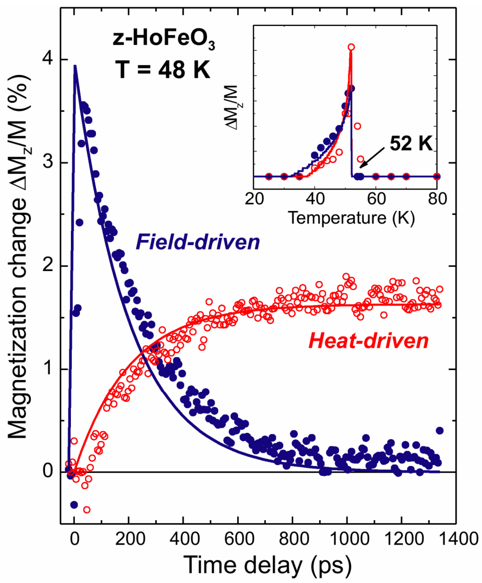

Fig. 1 Ultrafast kinetics of the first order phase transition from Γ_{12} to Γ_{24} driven by laser heating (open circles) and laser-generated magnetic field (solid circles). Inset shows temperature dependencies of the efficiencies of the phase transition from Γ_{12} to Γ_{24}. Lines show calculated efficiencies of the phase transitions.

We investigate the difference in kinetics of first-order magnetic phase transition in $HoFeO_3$ induced by magnetic field and heating pulses and demonstrate that a laser-generated effective magnetic field of 100 fs provides a novel and ultrafast pathway for the first order magnetic phase transition. The transition occurs within 3 ps, which is about two orders of magnitude faster than via laser-induced heating. In contrast to the slow thermodynamic scenario, a 100 fs magnetic field pulse brings the spins into a strongly nonequilibrium state, so that the following relaxation from this state results in an ultrafast phase transformation.

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SPIN-MODULATED QUASI-1D ANTIFERROMAGNET $LiCuVO_4$

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The quasi-one dimensionality (1D) of the spin system in $LiCuVO_4$ is provided by the magnetic ions of Cu^{2+} ($3d^9$ configuration, S=1/2). Lithium and copper ions share the octahedral sites in the orthorhombically distorted spinel structure in that way that the copper ions are arranged along chains separated by the nonmagnetic ions of lithium, vanadium and oxygen. The temperature dependence of the magnetic susceptibility exhibits a broad maximum at around T=28 K, typical for low-dimensional antiferromagnets, and a sharp anomaly at T=2.3 K, which is associated with the establishing of three dimensional (3D) magnetic order. Elastic neutron diffraction experiments B.J. Gibson et al. [Physica B **350**, 253 (2004)] on single crystals of $LiCuVO_4$ revealed that the 3D ordered phase exhibits an incommensurate, noncollinear magnetic structure. According to that work, the wave vector of this magnetic structure is directed along the copper chains $\mathbf{k}_{ic} \parallel \mathbf{b}$ and the value of the ordered magnetic moments of the Cu^{2+} ions amounts to $0.31\mu_B$, lying within the ab-planes.
In the present work, antiferromagnetic resonance (AFMR) and nuclear magnetic resonance (NMR) on the nuclei of nonmagnetic ions ^7Li and ^{51}V were studied for temperatures within this magnetically ordered phase. Additionally, the AFMR experiment is extended towards elevated temperatures T<30 K where 3D order already is absent, but spin correlations along copper chains are well developed. Our studies reveal a spin reorientational transition at a magnetic field H_{c1} ~25 kOe applied within the crystallographical ab-plane in addition to the recently observed one at H_{c2} ~75 kOe [M.G. Banks et al., cond-mat/0608554 (2006)].

Spectra of the antiferromagnetic resonance (AFMR) along low-frequency branches can be described in the frame of a macroscopic theory of exchange-rigid planar magnetic structures. These data allow to obtain the anisotropy of the exchange interaction together with a constant of the uniaxial anisotropy. Spectra of ^7Li nuclear magnetic resonance (NMR) show that, within the magnetically ordered phase of $LiCuVO_4$ in the low-field range $H<H_{c1}$, a planar spiral spin structure is realized with the spins lying in the ab-plane in agreement with neutron scattering studies of B.J. Gibson et al. [Physica B **350**, 253 (2004)]. Based on NMR spectra simulations, the transition at H_{c1} can well be described as a spin-flop transition, where the spin plane of the magnetically ordered structure rotates to be perpendicular to the direction of the applied magnetic field. For $H>H_{c2}$ ~75 kOe, our NMR spectra simulations show that the magnetically ordered structure exhibits a modulation of the spin projections along the direction of the applied magnetic field H.

HIGH-INTENSITY BRILLOUIN LIGHT SCATTERING BY COHERENT SPIN WAVES EXCITED IN A PERMALLOY FILM

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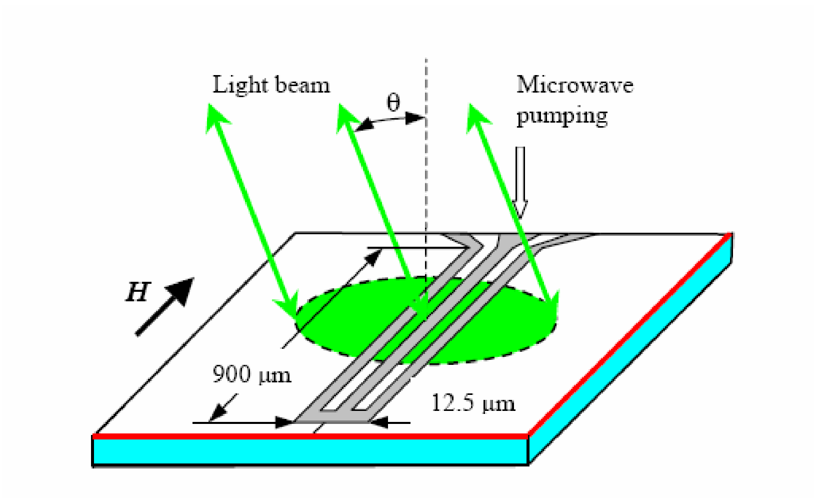
In the present paper it has been experimentally shown, that application of the proposed "active" BLS approach allowing dramatic improvement of the performance of Brillouin light scattering technique, provides access to important information on the physics of spin-wave modes unattainable by conventional "passive" BLS [1]. The "active" BLS relies on resonant excitation of coherent spin waves, in a finite range of wave-numbers, by a coplanar antenna due to an intense and highly inhomogeneous microwave field created by such structure (see Fig.1). While in "passive" BLS frequency resolution is to be sacrificed to improve on sensitivity, it is not the case in the "active" BLS. In the proposed technique the desired spin-wave mode can be selectively excited with required amplitude and frequency. For this reason, it has proved effective for detection of hybrid spin wave resonances in a thick permalloy film characterized by a very complex and ramified spectra of spin-wave modes [2]. In particular, the analysis of the amplitude, shape and frequency position of Stokes and anti-Stokes lines in the BLS spectra, for non-zero angles of the light incidence, demonstrated the presence of a strong hybridization of standing spin-wave resonances with propagating spin waves due to partial non-symmetric pinning on the film surfaces. At the same time, direct optical probing has shown that the excited hybrid spin-wave modes are localized strictly in the vicinity of the microwave antenna.



With only 2 mW of microwave power used in our work, the BLS intensity has been increased 3 orders of magnitude, with respect to the light scattering by thermal magnons. Further improvement, at least by 2 orders of magnitude, is possible via better optical beam focusing and utilization of more powerful microwave source. The combination of the intrinsic flexibility, characteristic of the conventional BLS, with significantly improved sensitivity makes the proposed microwave assisted "active" BLS technique promising for studies of dynamic magnetic properties of ferromagnetic nano-structures.

This work was partially supported by the ACI "NANODYNE" and RT network DYNAMICS, HPRN-CT-2002-00289, as well as the ANR

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TRANSIENT PROCESSES INFLUENCE ON MAGNETOSTATIC WAVES SOLITON PROPAGATION IN FERRITE FILMS

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For characterising of the magnetostatic wave (MSW) soliton-like pulses propagating in ferrite films the output pulse peak amplitude $\varphi_{\max}(\varphi_0)$ and width $W(\varphi_0)$ at the halfheight dependencies on the rectangular input pulse amplitude φ_0 and duration T_0 are typically used [1,2]. So far an influence on this parameters of the so-called transient processes, correspondent to an interference of the solitonic and non-solitonic parts of the MSW pulse and dispersive disturbances of the rectangular input pulse haven't been discussed. The main goal of this work to analyse some possible effects of transient processes on MSW solitons in garnet films.

Note, that MSW pulse propagation distance x in real experiments is of the order of the nonlinear L_n and dispersive L_d lengths. In this case ($x < (5-20)L_d$) [3], for pulses with initial shape different from the hyperbolic-secant solutions and amplitude φ_0 within the range $\varphi_{th}^{n} < \varphi_0 < \varphi_{th}^{n+1}$, where φ_{th}^{n} is the thresholds of the input amplitude for n^{th}-soliton formation, one can expect the damping oscillations of the $\varphi_{\max}$ and W parameters of pulse while its propagating along the film due to interference of solitonic and non-solitonic parts. One can expect also, that at distances $x \le L_d$ the behaviour of the input rectangular pulse will be similar to the wave beam diffraction on the slot in the Fresnel zone and pulse shape will be strongly depends on the interference of the main part of the pulse, propagating with group velocity, and precursors.

The influence of the non-solitonic part of the pulse was investigated on the basis of nonlinear Shrodinger equation (NSE) with parameters correspondent to experiment [4]. It is shown, that peak amplitude $\varphi_{\max}(x)$ oscillates as pulse propagates along the film with FMR linewidth $\Delta H = 0.1$ Oe and demonstrates non-monotonous behaviour or only levelling-off $\varphi_{\max}(\varphi_0)$ dependencies for films with $\Delta H = 0.35$ Oe that were reported in a number of experiments on solitons in ferrite films [1,2]. It is shown also, that independently on the input amplitudes the pulse evolution can be divided at same distance $x = L_c \approx 0.44 L_d$ onto two regions: "compression" ($x < L_c$), where *W* arrives its minimum value and "spreading" ($x > L_c$). Pulse width increasing for $x > L_c$ is due to dispersion effects, while pulse power decreases due to dissipation and at some distance the balance between nonlinearity and dispersion is broken. The position of the minima in *W(x)* dependencies practically independent on input power. At distance $x = L_c$ pulse width at the halfheight is minimal (about 60% of initial width) while amplitude is maximal (1.33φ_0). This "*compression*" effect easy to observe experimentally, if one fixed the distance x between MSW's input and output transducers and by changing input pulse duration T_0 receive the fulfilment of the condition $L_c \approx 0.44 L_d$. Note, that from experimental dependence $W(T_0)$, measured at some distance x, it is easy to calculate the dispersion coefficient of the MSSW $\nu = \partial^2 k / \partial \omega^2$ if one takes in to account the relations $x = L_c(T_0^c)$, $L_c = 0.44 L_d$, $L_d = T_0^2/(8\nu)$.

The work was supported by RFBR grants 06-07-89341 and 05-02-17361.

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MAGNETIC RESONANCE IN Fe/Cr DISCONTINUOUS MULTILAYERS

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Magnetic Fe/Cr superlattices with extremely thin (t_{Fe}<10Å) iron layers were investigated by ferromagnetic resonance (FMR) technique. The aim of the work was to study the evolution of resonance properties of the system as ferromagnetic layers become discontinuous.

Multilayer structures $[Fe(t_{Fe})/Cr(t_{Cr})]_n$ were prepared by MBE technique on MgO(100) substrates. Two sets of samples with t_{Cr}=20Å and t_{Cr}=10Å and different values of t_{Fe} in the 2 – 15 Å interval were investigated. The chosen values of the chromium spacer thickness corresponded to extremums of RKKY interlayer exchange in Fe/Cr multilayers: ferromagnetic for t_{Cr}=20Å and antiferromagnetic for t_{Cr}=10Å [1]. The number of layers *n* for each sample was of the order of 50.

Static magnetization measurements for the obtained structures indicated a presence of some critical thickness of iron layers t_{Fe}~3Å below which the samples exhibited superpara-magnetic properties [2]. The structures with t_{Fe}>3Å behaved like regular superlattices.

To study FMR in our samples, we used a home-made spectrometer with a possibility to measure resonance spectra in 4 – 400 K temperature interval and 7 – 38 GHz frequency range in magnetic fields up to 10 kOe.

Samples with t_{Fe}>3Å showed resonance properties typical for regular superlattices with ferromagnetic or antiferromagnetic coupling for t_{Cr}=20Å and t_{Cr}=10Å respectively. Several absorption lines associated with non-homogeneous resonance modes were observed in samples with t_{Cr}=10Å, which is usual for antiferromagnetically coupled superlattices [3]. Depending on the magnetic field direction in the film plane, a four-fold anisotropy of the spectra was observed.

Structures with very thin iron layers (t_{Fe}<3Å) demonstrated a single absorption line with a linear $\omega(H)$ dependence typical for paramagnets and no evidence of any in-plane anisotropy. This effect was independent on chromium spacer thickness.

A transition between two types of behaviour occurred near t_{Fe}~3Å [4]. At high temperatures the samples with t_{Fe}~3Å and both t_{Cr}=10Å and t_{Cr}=20Å showed similar isotropic paramagnetic-like spectra with linear $\omega(H)$ dependence. At low temperature these samples demonstrated four-fold in-plane anisotropy typical for superlattices with relatively thick iron layers. Corresponding $\omega(H)$ dependencies can be good approximated by formulas for regular multilayers with ferro- or antiferromagnetic interlayer coupling for t_{Cr}=10Å and t_{Cr}=20Å respectively [2].

As a conclusion, the investigated epitaxial structures Fe/Cr demonstrate a strong change in resonance magnetic properties as the iron layer thickness diminishes. The observed behaviour confirms the cluster structure of ferromagnetic layers below t_{Fe}~3Å.

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SPIN-SOLITONS AND FRUSTRATIONS IN MOLECULAR MAGNETS BASED ON Mn AND Cr COMPLEXES

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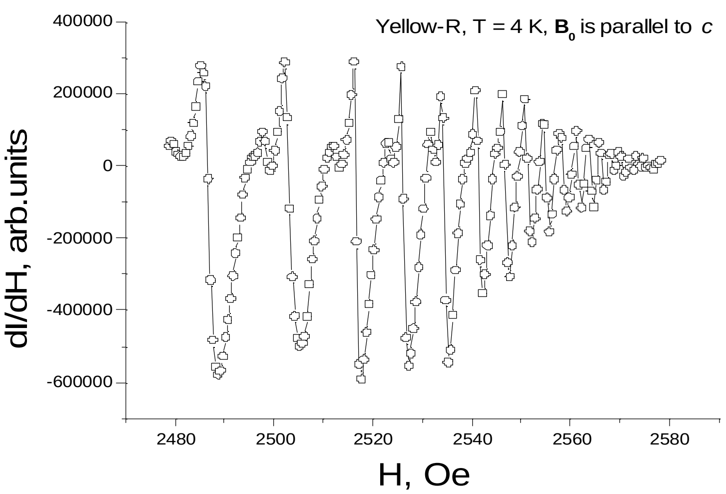
A new type of the electron spin resonance, the spin soliton resonance, has been observed in the bulk of [Mn{(R/S)-pn}]2[Mn{(R/S)-pn}2(H2O)] [Cr(CN)6]2, as well as [Cr(CN)6][Mn(S)-pnH-(H2O)]H2O crystals. The possibility of its observation in the crystals indicates the existence of the new type of magnetic excitations, which are bulk analogues of the spin wave resonance and spin solitons in thin films according to the phenomenological criteria. In contrast to thin films, the physical nature of the spin solitons in chiral magnetic materials is associated with the presence of the Dzyaloshinskii–Moriya interaction.



Since, the spin frustrations might be a reason of chirality, we have studied also materials with three angle lattice giving opportunity for the frustrations. Main idea of these experiments was to detect spin frustrations by changes performed in conductive organic layers alternating with magnetic ones. For this purpose two new cation-radical salts BEDT-$TTF_2[CuMn(dca)_4]$ and BEDT-$TTF_2[Mn(dca)_3]$ were synthesized and their magnetic properties were studied. Field dependence of magnetization in the second salt is typical for weakly frustrated antiferromagnet. Temperature dependence of magnetic susceptibility of the second salt indicates magnetic phase transition at about 25 K. Thus, this transition leads to spin frustrated state. We observed remarkable correlations between ESR parameters of BEDT-TTF and $Mn(dca)_3$ subsystems during magnetic phase transition to spin frustrated state. Thus, dynamical (spin solitons) and static (spin frustrations) magnetic states were observed in molecular magnet based on transition metal complexes with pseudohaloid ligands for the first time.

MAGNETIC RESONANCE INVESTIGATIONS OF INTERLAYER COUPLING IN NiFe/Bi/NiFe TRILAYER FILMS

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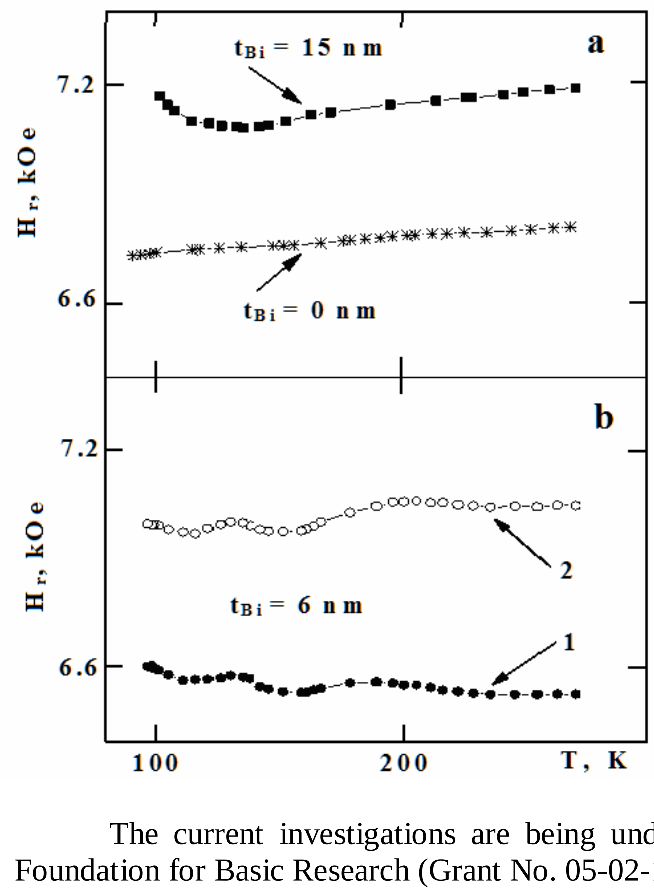
Multilayer magnetic films with a nonmetal spacer, in particular, those belonging to the system *ferromagnetic metal/semiconductor* [1], or with a *semimetal* spacer attract close attention by virtue of a great variety of effects observed in these films. When the semiconductor material is used as an interlayer, it is arose the possibility for controlling of properties of spacers and interlayer coupling (J) by means of external influence (impurities, different kind of radiation, temperature, fields, etc). Inasmuch as the electron magnetic resonance (EMR) parameters are sensitive to coupling factors that are responsible for the formation of a magnetic state, this method turns out informative to establish detail information in multilayer films [2]. Early [3], for the first time the NiFe/Bi/NiFe trilayer films were synthesized and investigated by us. Measurements of magnetic field and temperature dependences of magnetization have shown that the interlayer coupling depends on bismuth spacer thickness. The dependence of saturation magnetization of the system on semimetal thickness has been found.

In given paper the results of investigations of interlayer interactions in *permalloy/bismuth/permalloy* films via magnetic resonance method at different bismuth thickness (t_{Bi}) are represented. It was established that in the bismuth thickness interval t_{Bi} = 2 – 12 nm magnetic resonance spectrum consists of two lines, which is in agreement with antiferromagnetic interlayer coupling between magnetic layers. For control film with t_{Bi} = 0 nm and films with $t_{Bi} \geq$ 15 nm the solitary line is observed. In Fig. the temperature dependences of resonance field are shown for films cited above. Processing of the temperature dependences of resonance field revealed to determine the temperature dependences of interlayer interactions. Also the dependence J on bismuth spacer thickness is established. Mechanisms responsible for effects observed are discussed.



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TEMPERATURE DEPENDENCE OF INTERLAYER COUPLING IN Fe/Cr/Fe TRI-LAYERS

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We have studied a series of MBE-grown Fe/Cr/Fe tri-layers with wedge-type chromium spacers and different degree of interfacial roughness. The interlayer coupling was investigated as a function of spacer thickness (0-40 Å) and temperature using two experimental techniques: static Kerr magnetometry (at 77-473 K) and Mandelstam-Brillouin light scattering (at room temperature only).

Samples with rough interfaces obeyed the biquadratic exchange model [1] quite well. Coupling constants obtained from static and spin-wave measurements proved to be in agreement with each other. Samples with the smoothest interfaces, on the contrary, demonstrated a noticeable deviation from the biquadratic coupling model predictions. Most clearly it could be seen from the field dependence of the spin-wave spectrum measured in MBLS experiments. According to our in-situ STM-measurements the break-down of the biquadratic coupling model took place when the distance between monoatomic steps on the interface was comparable with the domain wall thickness in the antiferromagnetic chromium spacer. This result was previously predicted by several theoretical models [2-3].

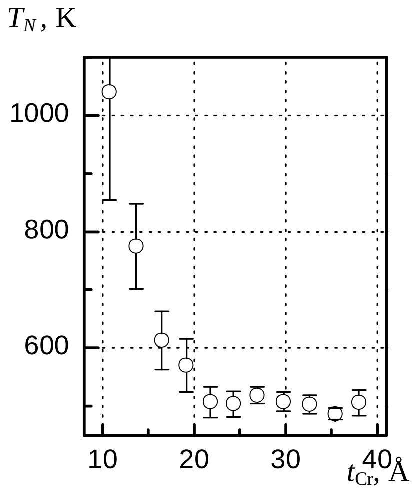

Fig. 1. Vanishing temperature of the short-period coupling oscillations as a function of spacer thickness.

The interlayer coupling in the Fe/Cr/Fe system is known to oscillate with the chromium spacer thickness having two oscillation periods: the long one (about 18 Å) and the short one (about 3 Å). We analyzed the temperature dependence of short-period bilinear coupling oscillations in our samples for different thicknesses of the chromium spacer. The oscillation amplitude defined as peak-to-peak value within each oscillation period was plotted as a function of temperature for different spacer thicknesses in the 5-40 Å interval. We supposed that the fast-oscillating coupling component was proportional to the order parameter in the antiferromagnetically ordered spacer and approximated it by the most common $\sqrt{1-T/T_N}$ temperature dependence. The extrapolated temperature T_N at which the short-period coupling vanishes is shown in fig.1 as a function of spacer thickness. This results correlate well with the magnetic phase diagram of thin chromium spacers measured by neutron scattering in Fe/Cr superlattices [4].

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SPECTRUM OF COUPLED SPIN AND ELECTROMAGNETIC WAVES PROPAGATING IN A PERIODIC MAGNETIC STRUCTURE UPON MODULATION OF ALL PARAMETERS OF LAYERS

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This work is devoted to the theoretical studying of the spectrum of coupled electromagnetic (EMW) and spin waves (SW) in a multilayer ferromagnetic (FM) upon periodic modulation of all magnetic parameters entering into the Landau-Lifshitz equation and permittivity.

For the investigation of the spectrum of coupled waves we used the method [1] which is based on the consideration of the system of Maxwell and Landau-Lifshitz equations with boundary for the electromagnetic field, the magnetization and the condition of periodicity. The solution of the system of equations with account of the expression for the free energy of a cubic FM allows us to receive the system of linearized equations for definition of the expressions of a spectrum of the coupled oscillation in FM layers.

The system of boundary conditions and the condition of periodicity (the Floquet-Bloch theorem) are

$$\begin{pmatrix} h_{x1}^{(2)} \\ h_{x2}^{(2)} \\ h_{x3}^{(2)} \end{pmatrix} = \mathbf{M} \cdot \begin{pmatrix} h_{x1}^{(1)} \\ h_{x2}^{(1)} \\ h_{x3}^{(1)} \end{pmatrix}, \begin{pmatrix} h_{x1}^{(2)} \\ h_{x2}^{(2)} \\ h_{x3}^{(2)} \end{pmatrix} = e^{-iQd} \cdot \begin{pmatrix} h_{x1}^{(1)} \\ h_{x2}^{(1)} \\ h_{x3}^{(1)} \end{pmatrix}$$

The dispersion equation of coupled waves for all system can be written as

$$\det(\mathbf{M} - e^{-iQd} \cdot \mathbf{E}) = 0 \ ,$$

Here $\mathbf{M}$ - transformation matrix, connecting amplitudes of waves of 1-st layer with similar amplitudes for an equivalent following layer, Q-Bloch wave vector, i.e. averaged on the period d wave vector of periodic structure.

A graphical method for analyzing the dependence of the propagation of coupled electromagnetic and spin waves on the depth of modulation of the material parameters is proposed. Practical application of the obtained results and the effect of dissipation on the propagation of coupled waves in the system are discussed.

From the frequency dependence of imaginary part Q follows that modulation of parameters can be fit in such a manner that at the fixed magnitude of external magnetic field H_0 our system will correspond to „quasi-homogeneous“ material. In this case the system can be considered as a multilayer magnetic without the band gap in which the parameters (as well as wave vectors in layers) is not distributed homogeneously. The deviation of magnitude of a constant external magnetic field from value H_0 lead to the disbalance of system and the appearance in a spectrum of the band gap. That allows to use the given system as functional element of the wave device strongly sensitive to a magnetic field (the switch or the filter).

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COMPUTATIONAL THEORY OF SPIN WAVES, MAGNETIC LINEAR DICHROISM AND THE INVERSE FARADAY EFFECT

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Ab initio calculations of magnon spectra have proven to be both feasible and rewarding. We briefly review the theory of the adiabatic approximation and show that it leads, for transition metals, to very good spin-wave stiffness constants and spin-wave spectra as a whole, when compared to available experimental data. In a further topic, we consider the ab initio theory of the magnetic linear dichroism. In the optical regime, the origin of the magnetic linear dichroism has been discussed for quite some time. We present ab initio calculations of this effect in the optical regime, which show 1) that the effect is small, yet of comparable size to available experimental spectra, 2) that the effect in lowest order is proportional to x^2, with x the spin-orbit strength, and 3) that a huge magneto-crystalline anisotropy should be expected for the linear dichroism. Furthermore, we consider the X-ray magnetic linear dichroism (XMLD) in the soft-X-ray regime. In this regime, the leading contribution to the XMLD stems from the small, yet existing exchange splitting of the 2p-core states. A comparison with experimental XMLD spectra convincingly proves this theoretical model. We also predict that a huge magneto-crystalline anisotropy should be present in the XMLD, a prediction that is confirmed by recent experiments. As the XMLD holds particularly potential for element-specific investigations of antiferromagnetic materials, we consider theoretical results for some of these. The inverse Faraday effect, lastly, is a magneto-optic effect which has not been explained on an ab initio level. Considerations concerning this are presented.

PROBING MAGNETISM ON THE NANOSCALE USING PHOTOEMISSION ELECTRON MICROSCOPY

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A powerful tool to investigate the magnetic properties of nanoscale systems is X-ray photoemission electron microscopy (XPEEM) employing X-ray magnetic linear dichroism (XMLD) and X-ray magnetic circular dichroism (XMCD). Using recent results of research I will explain the technique and its possibilities.

A prominent example is the directional coupling between the spins in an antiferromagnet (AFM) and those in an adjacent ferromagnet (FM), referred to as exchange bias. Employing X-ray magnetic linear dichroism (XMLD), this interface region can be studied and the orientation of individual antiferromagnetic domains can be determined. For $LaFeO_3$ thin films, we found the antiferromagnetic axes are tilted by 20° out of the surface plane and have a different sign of the x-ray magnetic linear dichroism compared to previous reports on $LaFeO_3$. Employing XMCD one can also study the coupling of the FM to the AFM. Currently, we are studying the effect of spin-reorientation in an AFM (SmFeO3) via laser induced heating onto a ferromagnetic Co layer.

Another example is the study of the magnetic properties and scaling laws of nanoparticles. Recently we have explored the feasibility of XPEEM to do x-ray magnetic circular dichroism (XMCD) spectroscopy of individual iron (Fe) particles, in a size range of 6 to 12 nm, deposited in-situ onto ultrathin (2-4 nm) Co films and have obtained the first indication of magnetic dichroic contrast signal from individual Fe particles down to 9 nm.

ELEMENT-SELECTIVE X-RAY DETECTED MAGNETIC RESONANCE

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X-ray Detected Magnetic Resonance (XDMR) is a new spectroscopy in which X-ray Magnetic Circular Dichroism (XMCD) is used to *probe* the resonant precession of the magnetization when a strong microwave *pump* field $\mathbf{h}_p$ is applied perpendicularly to the static bias field $\mathbf{H}_0$. Experimental configurations suitable to detect the weak XDMR signals will be compared [1]. XDMR is element- and edge-selective and is expected to become a unique tool to tentatively resolve the precessional dynamics of spin and orbital magnetization components in excited states with either p- or d- like symmetry [1-3]. To illustrate this presentation, we will show how the opening angle of precession (θ) of the magnetization can be determined from XDMR/XMCD measurements carried out at the iron K-edge and at the yttrium $L_{II,III}$ edges on yttrium-iron-garnet (YIG) thin films in which yttrium was optionally substituted with *diamagnetic* rare earths such as lanthanum and lutetium. Whereas XDMR signatures measured at a K-edge yield unique information on the precession of only *orbital* magnetization components, we will produce strong evidence that the XDMR signatures measured at the L-edges of yttrium or lanthanum are to be assigned to the precession of *induced* spin components. XDMR spectra were also recorded at the iron K-edge under the conditions of premature saturation of precession, *i.e.* beyond the 2nd order Suhl's instability threshold of magneto-exchange spin waves. Measurements of ΔM_Z revealed a very sharp increase of the *apparent* opening angle of precession of the orbital magnetization component very near the foldover jump. This was rather unexpected since, in a classical four-magnons scattering process, two uniform magnons are annihilated but the total number of magnons should remain unchanged. Our result appears to be consistent with the apparent increase of T_1 also observed recently by de Loubens *et al.* [4] in a conventional FMR study performed on a YIG thin film prepared in the same way.

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HARD X-RAY MAGNETIC CIRCULAR DICHROISM: INSTRUMENTATION AND APPLICATIONS

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Recent developments in the synchrotron radiation instrumentation have made possible the production of high flux of hard X-ray photons (2 - 15 keV) with flexible polarization [1]. Magnetic circular dichroism (MCD), the difference in the absorption or reflection of magnetic samples using left- and right-handed circularly polarized light has been widely exploited in the visible and soft X-ray spectral regions to provide useful information on the electronic and magnetic properties of magnetically ordered systems [2].

This talk reviews the recent advances in magnetic circular dichroism experiments in the hard X-ray energy range which covers K-edges of transition metals, L-edges of rare-earths, L-edges of 4d and 5d metals and M-edges of actinides. After giving a short introduction to the principles of X-ray MCD spectroscopy, I shall focus on the experimental aspects and the main strengths of this technique. These are quantitative determination of the element and orbital selective magnetic moments and their anisotropies using magneto-optical sum rules [3]. Hard X-ray MCD measurements performed at the ESRF beamline ID12 on a wide variety of magnetic systems, including intermetallics, ferromagnetic semiconductors, paramagnetic insulators and magnetic multilayers will be presented to demonstrate the application of this technique to magnetism research.

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LOW-FREQUENCY SPIN DYNAMICS OF SPIN-LIQUID MAGNETS

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We describe examples of magnetic dielectric crystals with antiferromagnetic exchange, exhibiting no magnetic ordering till the temperatures far below Curie-Weiss temperature. By the absence of the magnetic ordering we mean a zero average spin projection for magnetic ions, this kind of magnetic ground state is known as a spin liquid state, or as a collective paramagnet.

The examples of the spin liquids are presented by Haldane magnets (S=1 spin chains), dimer nets, some of the frustrated systems, etc. The Haldane magnets and dimer nets exhibit an energy gap between the singlet ground state and triplet magnetic excitations. This energy gap makes a spin liquid state stable with respect to weak perturbations like interchain exchange or anisotropic interactions.

Nevertheless, in an applied magnetic field the energy of a spin sublevel of a triplet excitation is reduced and may be vanished at a critical field. As a result, the magnetically ordered state appears at this critical point via a quantum phase transition.

We describe the experimental investigation of the vanishing of the energy gap at the critical magnetic field by the ESR methods in the Haldane-like magnet $PbNi_2V_2O_8$ and in the dimer system $TlCuCl_3$. In low fields, far from the critical point, the energy levels of the collective triplet excitations are completely equivalent to the spin sublevels of isolated S=1 magnetic ions in the crystal field. However, in the vicinity of the critical point, the spectrum of triplet excitations is strongly affected by the 3D correlations and, at some field orientations demonstrates a distortion of the frequency-field dependence [1,2,3].

In the frustrated system $Gd_2Ti_2O_7$, the classical ground state is strongly degenerated in the exchange approximation. This degeneration is associated with a macroscopic number of soft magnetic modes, which result in the residual entropy and absence of spin ordering at low temperatures. We test these soft modes in the thermodynamic experiment with adiabatic demagnetization [4] and by means of an ESR experiment [5].

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SPIN CONSERVATION AND QUASIPARTICLE DECAYS IN A QUANTUM SPIN LIQUID

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Magnetic properties of many-electron condensed matter systems arise from cooperative quantum behaviour of atomic spins which is usually understood in terms of magnons, elementary quanta of magnetic excitation. Magnon quasiparticles are fundamental carriers of energy and momentum in spin systems, much like the phonons are in solids and liquids. However, an interesting failure of the quasiparticle description occurs in quantum Bose liquids, such as the superfluid helium. Like unstable elementary particles, quasiparticles cannot survive beyond a threshold where certain decay channels become allowed by conservation laws – their spectrum terminates at this threshold. This regime of quasiparticle failure was observed in helium-4 at temperatures close to absolute zero where it forms quantum Bose-liquid. More recently, neutron scattering experiments have shown that similar failure regime leading to magnon spectrum termination can also occur in a quantum magnet and, by implication, in other systems with Bose-quasiparticles [1]. Here we have measured spin excitations in a two dimensional (2D) quantum-magnet, piperazinium hexachlorodicuprate (PHCC) in which spin-1/2 copper ions form a non-magnetic quantum spin liquid (QSL), in magnetic field, and find remarkable differences with the zero-field picture. Unlike phonons in superfluid helium, magnons in a quantum spin liquid also carry spin quantum number, and therefore their decays are subject to spin conservation. Hence, a threshold momentum beyond which magnon merges with the appropriate two-quasiparticle continuum and becomes unstable, is field independent. Moreover, at energies below decay threshold magnons whose decays are not allowed by spin conservation happily co-exist with two-magnon continuum.

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SINGLE ION ANISOTROPY, TRANSVERSE MAGNETIZATION AND MAGNETIC PHASE DIAGRAM OF THE FRUSTRATED GADOLINIUM PYROCHLORE

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Heisenberg exchange interaction $H=\Sigma J\mathbf{S}_i\mathbf{S}_j$ usually align neighbouring spins to be parallel (J<0) or antiparallel (J>0). Three- dimensional magnets order at temperature $T\sim\theta\sim J$ (here θ is a Curie-Weiss temperature). Specific geometry of the exchange bonds (e.g., antiferromagnet on a triangular lattice) can result in the frustration of the exchange interaction, when a static structure cannot simultaneously minimize all pair interactions on the lattice. Pyrochlore lattice formed by the corner-sharing tetrahedra is an example of a strongly frustrated lattice. Classical antiferromagnet on a pyrochlore lattice demonstrates disordered and macroscopically degenerated ground state. Thus, in the exchange approximation, it should remain in the disordered spin-liquid state down to zero temperature. Degeneration of the ground state could be lifted by the weak relativistic interactions, further neighbour exchange interactions or fluctuations effects. Subtle interplay of these factors could lead to the formation of the unusual magnetic structures.

Gadolinium compound $Gd_2Ti_2O_7$ provides an example of an antiferromagnet on a pyrochlore lattice: magnetic ions Gd^{3+} (S=7/2, L=0) forms a network of corner-sharing tetrahedra, Curie-Weiss temperature θ is about 10K. It remains disordered down to 1K then a two-step phase transition occurs. The *H–T* phase diagram of Gd2Ti2O7 evidence two-phase transitions induced by an external field at $\mu_0 H_{c1}$ ~3T and $\mu_0 H_{c2}$ ~6T. The magnetic properties of this compound were taking into account Heisenberg exchange interaction and dipolar coupling only. This model could explain certain properties of the ordered phases, however the structure of the magnetic phases and the nature of the phase transitions still remains an enigma.

We have performed an ESR study of the isostructural magnetically diluted samples $(Y_{0.995}Gd_{0.005})_2Ti_2O_7$. We have found that Gd^{3+} ions in $Gd_2Ti_2O_7$ are affected by single ion anisotropy of easy-axis type with local anisotropy axes directed along the 111-like directions. The anisotropy constant (neglected in the earlier models) appears to be comparable with the exchange integral value: $D\approx0.75J$. Analysis of the magnetization process of the classical pyrochlore with the easy plane anisotropy reveals that a transverse magnetization should appear above some critical field at T = 0. We have performed a detailed transverse magnetization study of the $Gd_2Ti_2O_7$ single crystals. These measurements result in the refinement of the Gd2Ti2O7 phase diagram. A transverse magnetization of about 0.003Msat was observed in the low-temperature ordered phases in the temperature range 100mK-1K. This is a direct evidence for the loss of the cubic symmetry in some of the ordered phases. This observation is of importance for the deciphering of the low-temperature ordered structures of gadolinium titanate and for the better understanding of its phase diagram.

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CUBIC HELIMAGNETS WITH DZYALOSHINSKII-MORIYA INTERACTION: SPIN-WAVES AND MAGNETIC FIELD BEHAVIOR

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During decades the cubic helimagnets (MnSi etc.) with the Dzyaloshinskii-Moriya interaction (DMI) attracted a lot of attention due to their unusual magnetic properties and sets of the phase transitions in magnetic field and under applied pressure ([1-3] and references therein). The DMI is responsible for the helical structure of these compounds. Violating the total spin conservation law this interaction must play the crucial role in the spin dynamics as well.

In our work we follow the Bak-Jensen model [4] and consider the hierarchy of interactions: the ferromagnetic exchange, the DMI, the non-isotropic exchange, and the cubic anisotropy accompanied by the Zeeman energy. Below we list our principal theoretical results and their experimental confirmation [5-8].

1) The classical energy depends on the field component $H_{\|}$ along the helix wave-vector **k.** The critical field for the transition to the ferromagnetic state is given by: $H_{C2} = Ak^2$, where A is the spin-wave stiffness for $q >> k$ in agreement with the experimental data for MnSi [6].

2) The DMI leads to the umklapp interaction connecting spin-waves with momentums **q** and $\mathbf{q} \pm \mathbf{k}$ and gives rise to the spin-wave anisotropy: excitations with **q** along and perpendicular to **k** have energies Akq and $3Aq^2/8$, respectively.

3) The field perpendicular to **k** gives a quantum contribution to the ground-state energy mixing spin-waves with **q** = 0 and $\pm\mathbf{k}$. Their amplitudes become classical variables (Bose condensation) and the ground-state energy is given by

$$E_G = -\frac{H_{\|}^2}{H_{C2}} - \frac{H_{\perp}^2\Delta^2}{4H_{C2}(\Delta^2 - H_{\perp}^2/2)} + L(\hat{k})$$

where Δ is the spin-wave gap and L is a cubic invariant responsible for the **k** orientation with respect to the cubic axes. If $H_{\perp} > \Delta\sqrt{2}$ the system is unstable and **k** rotates toward the field in agreement with the neutron scattering data [7], which demonstrated also that $\Delta \approx 0.1T \approx H_{C2}/6$.

4) There are two contributions to Δ^2: the spin-wave interaction and the cubic anisotropy. At $\mathbf{H} = 0$ the former survives only but with as the field increases two contributions compete. For MnSi at $\mathbf{H} \| [1,1,1]$ we have $\Delta^2 < 0$ at $H > H_{C1} \approx 0.5 H_{C2}$ and spin-wave spectrum becomes unstable. In this case a partially disordered chiral state appears instead of the long-range helical structure [7,8]. The system becomes ferromagnetic at $H > H_{C2}$.

In summary, we present the microscopic low-T theory of non-centre-symmetric cubic helimagnets, which is confirmed by the experiment.

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ELECTROMAGNONS IN MANGANESE MULTIFERROICS WITH MODULATED MAGNETIC STRUCTURE

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Recently interesting multiferroic properties exhibiting a strong interplay between ferroelectricity and modulated (sinusoidal or cycloidal) spin structures were observed in some pure and substituted orthorhombic manganites $RMnO_3$ (R = Gd, Tb, Dy) [1,2] and $Eu_{1-x}Y_xMnO_3$ [3,4] with frustrated exchange interactions controlled by rare-earth ionic radius. We have revealed in these multiferroics fundamentally new spin excitations: electro-active magnons, or electromagnons, i. e. spin waves, which can be excited by ac electric fields. Using a submillimeter backward-wave-oscillator quasioptical technique (3-35 cm^{-1}) we have observed in transmission spectra and extracted dielectric $\varepsilon^*(\omega)$ spectra of $GdMnO_3$, $TbMnO_3$ [5] and $Eu_{1-x}Y_xMnO_3$ strong wide absorption lines at frequencies 20-25 cm^{-1} identified as the electromagnons. The electro-active origin of the observed modes was determined by independence of their excitation conditions on a polarization of ac magnetic field **h** and strong dependence on the polarization of ac-electric one **e**: the modes were observed for **e**||a-axis. The contribution of the electromagnons to the dielectric function $\Delta\varepsilon_a$ amounts up to ~2. These excitations were observed both in paraelectric sinusoidal and ferroelectric cycloidal phases in the studied multiferroics. Besides electromagnons, usual antiferromagnetic resonance (AFMR) modes excited by ac magnetic field, were also observed. The AFMR modes are more broadened in the modulated phases compare to a canted antiferromagnetic state however their resonance frequency values remain similar (~ 20 cm^{-1} at T~4.2 K).

In external magnetic fields H||c-axis the incommensurate modulated structures can be suppressed due to a transition to the usual canted state and the electromagnons are wiped out, thereby inducing considerable changes in the index of refraction from dc up to THz frequencies. These transitions are accompanied by a transfer of the corresponding spectral weight to the lowest lattice vibration ($GdMnO_3$), demonstrating the strong coupling of phonons with electromagnons [6].

Symmetry analysis shows a key role of the inhomogeneous magnetoelectric interaction in observed phenomena both in an appearance of spontaneous polarization in cycloidal structure and electroactive spin excitations. The observed electromagnons can be interpreted as spin oscillations with non-zero wave vectors **k** corresponding to a wave vector of the modulated magnetic structure ($\mathbf{k}_0$|| b-axis), which interact with homogeneous ac electric field. The tuning of electromagnon contribution to the refraction index by moderate magnetic fields in a wide frequency rang allows the design of a new optoelectronic devices.

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ON FRUSTRATED MAGNETOELECTRIC WITH INCOMMENSURATE MAGNETIC ORDER IN MAGNETIC FIELD

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We discuss a model nonfrustrated magnetoelectric in which strong enough magnetoelectric coupling produces incommensurate magnetic order leading to ferroelectricity. Properties of the magnetoelectric in magnetic field directed perpendicular to wave vector describing the spin helix are considered in detail. Analysis of classical energy shows that in contrast to naive expectation the onset of ferroelectricity takes place at a field H_{c1} that is lower than the saturation field H_{c2}. One has $H_{c1} = H_{c2}$ at strong enough magnetoelectric coupling. We show that at $H = 0$ the ferroelectricity appears at $T = T_{FE} < T_N$. Qualitative discussion of phase diagram in $H - T$ plane is presented within mean field approach.

MAGNETIC AND MAGNETOELECTRIC (ME) DYNAMICS IN RMn_2O_5 (R = Gd, Eu, and Er)

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The dynamics of multiferroic crystals RMn_2O_5 (R = Gd, Eu,and Er), showing magnetic and ferroelectric phase transitions with close transition temperatures (30-40 K) was studied in the frequency and temperature ranges 20-300 GHz (1-10 cm^{1}) and

5-50 K, respectively. The magnetic resonance spectra and mixed magnetoelectric excitations were observed in $GdMn_2O_5$. The most intensive mixed magnetoelectric excitations were observed when the antiferromagnetic resonance and low-lying lattice mode frequencies were closed. The effect of magnetic field on magnetic resonance spectra and mixed magnetoelectric excitations was studied.

In $ErMn_2O_5$ and $EuMn_2O_5$ only low-intensity non-depending from magnetic field absorption signals were observed over the full operating frequency range at temperatures near 36-40 K. These signals seem to be caused by the soft lattice modes near the phase transitions to incommensurate magnetic and ferroelectric states.

Magnetic and dielectric susceptibilities has been studied for the crystals also. Combined analysis of susceptibility, magnetic and magnetoelectric dynamics was performed.

MICROWAVE CHARACTERISTICS OF FREQUENCY-AGILE FERRITE-FERROELECTRIC COMPOSITE MATERIAL

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A combination of ferrite and ferroelectric materials in a layered structure provides the possibility of simultaneous "magnetic" and "electric" tuning of its microwave characteristics [1]. In other words, a new frequency-agile composite material can be created. The purpose of this work is theoretical and experimental investigations of tuning characteristics of such materials at microwave frequencies. In particular, a planar hybrid spin-electromagnetic wave resonator was composed of two rectangular layers; the first layer was 500-μm-thick, 1-mm-wide and 1.15-mm-long ceramic barium strontium titanate (BST) slab. The second layer was 7-μm-thick, 1-mm-wide and 1-mm-long single-crystal yttrium iron garnet (YIG) film. In accordance with theory, the in-plane dimensions for the YIG and BST layers were chosen to be equal in order to maximize the electromagnetic coupling between their main modes (ferromagnetic mode in YIG and dielectric mode in BST) and reduce spurious influence of their higher order modes. The electric field tunability of the hybrid wave resonator was studied in a wide range of bias magnetic fields *H*. The maximum tuning frequency range of 260 MHz was realized through variation of the voltage applied to the BST layer for *H*=1400 Oe (see figure). A theory for the hybrid wave excitations, based on a coupled-mode approach, provides a good description of the experimental data.

The work was supported in part by Grants from the Russian Foundation for Basic Research (Grant 05-02-17714), Russian Federal Agency for Education (Projects RNP/2.1.1.1382 and NSh-8860.2006.2), Government of St.Petersburg, ARO (Grants W911NF-04-1-0299, W911NF-05-1-0179, and W911NF-04-1-0247), and ONR (Grant N00014-05-1-0664).

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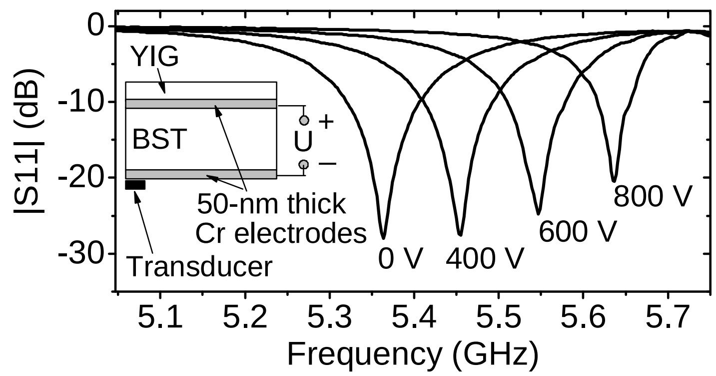

SPIN WAVES IN PARTIALLY RANDOMIZED SUPERLATTICES AND INHOMOGENEOUS FERROMAGNETS

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The first part of this talk is dedicated to the theory of the spectrum and damping of spin waves in partially randomized superlattices (SLs). The SL with one-dimensional (1D) and tree-dimensional (3D) inhomogeneities (IHs) is considered, which models random displacements of interfaces from their initial periodic arrangement and random deformations of the interfaces, respectively. We derive the correlation function (CF) of the SL and show that effects of IHs on the wave spectrum strongly depend on the asymptotic behaviour of this CF. The CF for 1D IHs exponentially tends to zero for $r_z \to \infty$, while for 3D IHs it tends to nonzero asymptote. This leads to a sharp decrease in the wave damping and an increase in the effective gap at the boundary of the SL Brillouin zone in the 3D case as compared to the 1D case. Effects of a mixture of IHs of both 1D and 3D dimensionalities are studied. Cross correlations between IHs of different dimensionalities are considered. We derived the CF of the mixture of cross-correlated 1D and 3D IHs and show that it tends to zero in accordance with a power law (r^{-1}). It is shown that positive cross correlations partly suppress effects of 1D and 3D IHs on the wave spectrum: the gap at boundary of the Brillouin zone increases and wave damping decreases. The situation also is considered, when the gap in the spectrum at the first Brillouin zone boundary of the SL is closed under the action of the 1D IHs. The phenomenon of the partial opening of this gap, that is, of partial restoration of the wave spectrum of the SL is found when the 3D IHs cross correlated with the 1D IHs add to the SL. It is shown that all these unusual effects are due to the slowly decay of the CF.

In the second part of the talk the theory of effects of the 1D and 3D IHs of the magnetic anisotropy and exchange on the frequencies and widths of the FMR and SWR lines with taking into consideration the multiple processes of spin waves is considered. The calculation of the effects of the magnetic anisotropy IHs is carried out by the method of the averaged Green's function in the coherent potential approximation (CPA). The resonance frequencies and linewidths are obtained for the first time for the whole region of values of the correlation wave number of IHs k_c ($r_c = k_c^{-1}$ is the correlation radius, $2r_c = D$ is the value of grains in poly- or nanocrystals). For the FMR at $k_c = 0$ the linewidth is maximum and corresponds to the well-known limiting case of independent grains. When $k_c > 0$ the effect of exchange narrowing of the FMR line switches on as a consequence of the exchange coupling between the grains. In the limiting case of the strongly bounded grains (large k_c) the calculated dependence of the linewidth on k_c corresponds to the law obtained from the scaling arguments. Large narrowing of the FMR and SWR linewidths with the decrease of the correlation radius of IHs is the substantiation of the main advantage of the nanocrystalline and amorphous materials over usual polycrystals when they are used at high frequency devices. We calculate also effects of IHs of the exchange constant. The standard CPA can not be used in this case because the exchange is a nonlocal parameter of the Hamiltonian. We develop the Green's function formalism and derive the analog of the Dyson and CPA equations for the long-wave IHs of the nonlocal parameters. Contrary to the standard formalism, the analog of the Dyson equation contains not the Green's functions but the derivatives of these functions. We apply this obtained CPA equation to the study of effects of the 1D IHs of the exchange on the spectrum of spin waves in a ferromagnet.

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SPIN WAVES IN SILICON DIOXIDE FILMS WITH COBALT NANOPARTICLES ON GALLIUM ARSENIDE

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We have studied spin waves in the Damon - Eshbach (DE) geometry in films consisting of ferromagnetic metal nanoparticles embedded in an insulating matrix. In the framework of the developed theoretical model, it is found that the main factors, which influence surface spin waves, are the conductivity, the magnetic inhomogeneity through the film thickness and the spin noncollinearity of nanoparticles. These factors cause different changes of dispersion curves. It is revealed that dispersion curves of surface spin waves in films with the spin noncollinearity of nanoparticles have two branches. The upper branch is the DE surface spin-wave mode. The lower branch is degenerated in nanocomposites with the ferromagnetic spin ordering and is non-degenerated in nanocomposites with the spin noncollinearity of nanoparticles. In the DE geometry volume spin waves are degenerated. It is found that in the nanocomposite film with a nonzero value of the conductivity the degeneration of volume waves is removed and volume spin wave modes have the backward character. On the basis of the study we draw a conclusion that dispersion curves of spin waves propagating in nanocomposite structures can be used as an effective tool for the characterization of nanocomposites.

The developed theoretical model has been verified by Brillouin light scattering measurements of dispersion characteristics of surface spin waves in the DE geometry on granular films containing cobalt nanoparticles in amorphous silicon dioxide matrix on a GaAs substrate, SiO_2(Co)/GaAs. These heterostructures are characterized by promising electron transport properties leading to the injection GMR [1-3]. Using information provided by dispersion curves of surface spin waves propagating along opposite surfaces of nanocomposite films (Fig. 1), we have found that near GaAs substrates nanocomposite films are close to the ferromagnetic state and at free surfaces nanocomposites are superparamagnetic. Moreover, surface spin waves show the existence of a conduction layer near the interface.

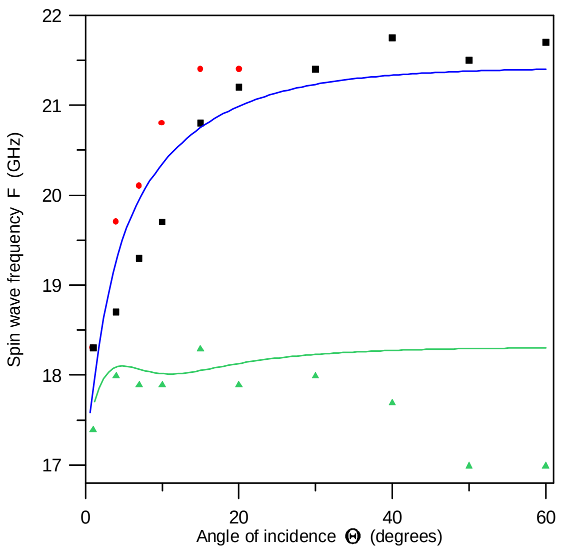

Fig. 1. Spin wave frequency vs angle of incidence for the SiO_2(Co)/GaAs sample with Co concentration x = 83 at.% at H = 3.0 kOe.

This work was supported by the Russian Foundation for Basic Research (grant N 06 - 02 - 17030)

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MAGNETOELASTIC GROUND STATE AND WAVES IN FERROMAGNET – NONMAGNETIC DIELECTRIC MULTILAYER STRUCTURE

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The periodic magnetoelastic (ME) ground state that spontaneously arises due to the ME and thermoelastic interactions between layers of a multilayer structure (MS) consisting of alternating ferromagnetic and nonmagnetic dielectric layers is studied. We assume that the method of MS preparation is corresponded to the absence of elastic stresses resulted from the interaction between the MS layers at the preparation temperature T_0 and to the homogeneous orientation of magnetization vectors in the plane of magnetic layers. We also assume that each ferromagnetic layer has passed to the state with spontaneous magnetostriction strains corresponding to the initial orientation of the magnetization vector before the joining of the layers between each other. Properties of the ME ground state, such as the equilibrium static elastic strains of the MS layers, the orientation of the static part of the magnetization vector of these layers depending on the value and orientation of the magnetic field and the temperature, are calculated. It is shown that the ME ground state gives rise to three new terms in the MS energy, which describe different types of the effective magnetic anisotropy. Two of them result from the ME interaction between the MS layers. The third term results from the thermomagnetic interaction between the MS layers. It is shown that all three terms of the effective magnetic anisotropy may have the same order of magnitude. Effects of these terms of the magnetic anisotropy on the MS magnetization curves are studied.

Effects of initial periodic inhomogeneities of the magnetic and elastic parameters as well as effects of static periodic elastic stresses resulted from the spontaneous ME ground state, on the spectrum of ME waves and on the ferromagnetic resonance frequency of the MS are investigated. The ME waves are considered for the case when the magnetic field is applied perpendicular to the layers along the MS axis and exceeds the magnetic saturation field, that is, when the static part of the magnetization vector is also directed along the MS axis. The equation of the dispersion law of ME waves is obtained analytically and investigated by numerical methods. It is shown that in the vicinities of crossings of the elastic wave dispersion curve with the localized frequencies of all spin-wave modes the ME resonances are observed. In the case when some ME resonance coincides with the gap (forbidden zone) at the Brillouin zone boundary the ME coupling results in the broadening of the localized spin-wave level into the new permitted zone placed inside the gap. For the long waves in the vicinity of the ME resonance corresponding to the zero spin-wave mode the dispersion law equation takes the simple form analogous to the equation of the dispersion law of the coupled magnetostatic and elastic waves in a homogeneous ferromagnet. The ferromagnetic resonance frequency is modified in the general case by all three terms of the effective magnetic anisotropy as well as by the isotropic ME term which leads to the gap in the spin wave spectrum at zero internal field (the instability point of the magnetization vector orientation). In contrast to the ME gap of the homogeneous ferromagnet the latter ME gap in the MS is proportional to the relation between the thickness of the ferromagnetic layer and the MS period.

This work was supported by the Russian Foundation for Basic Research, Grant No. 07-02-00419 and Grant of the Russian Federation President, SS-6612.2006.3.

COLLECTIVE SPIN EXCITATIONS IN LATERAL MAGNETIC SUPERLATTICES: LONG-WAVELENGTH LIMIT

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It is well known that periodic systems (superlattices) acquire novel physical properties whenever band gaps in the spectrum of their collective excitations appear to be at D=mλ/2, where D is the lattice period, λ the wavelength of excitations, and m are integers. However, the properties of periodic systems can also be interesting in the long-wavelength limit (λ>>D). In that case the excitation "sees" a homogeneous but anisotropic medium [1]. This situation is analogous to light propagation in natural crystals, whose optical properties like birefringence are described in crystal optics. We find an analog of birefringence in magnetic superlattices. Our samples are lateral structures in thin Fe-V layers with one-dimensional modulation of the magnetic permeability. Measuring the frequencies of spin precession excited directly by a beam of femtosecond laser, we mark *crossing* in the excitation spectra from the single-frequency ("ordinary wave") to the two-frequency ("extraordinary wave") regime with a reorientation of an external static magnetic field **H** with respect to the direction of lattice periodicity (Fig.1) [2]. It is interesting that the crossover occurs in the structures having small enough periodicities (< 1 μm). The explain the observed phenomenon, we have analytically calculated the eigenfrequencies in the long-wavelength limit of a model system of alternating stripes with two different magnetizations. This analysis reveals a key role of long-wavelength dipolar fields generated by the spin motions and obeyed to the usual electromagnetic boundary conditions at internal interfaces in the heterostructures. The observed collective effects in lateral magnetic superlattices open the door for their usage in novel devices of microwave photonics, in which the band pass is driven by orientation of external magnetic field.
This work was supported by RFBR (# 07-02-01305)

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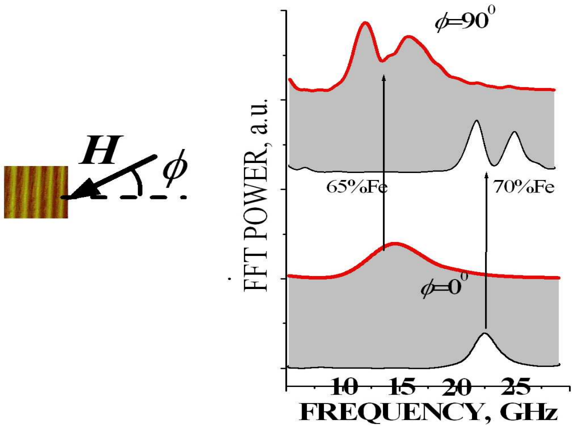

Fig.1 Crossover in the excitation spectra with reorientation of external field **H**

MAGNETIC PROPERTIES AND EXCITATIONS OF A TWO-SUBLATTICE MAGNETIC SYSTEM WITH AN INCOMMENSURATE PHASE

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CuB_2O_4 metaborate is characterized by a specific sequence of phase transitions with a decrease in temperature: first, at ≈ 20 K, the transition from a paramagnetic phase to the antiferromagnetic phase in a tetragonal plane occurs, and then, at ≈ 10 K, the transition to a helical phase with a magnetic structure wave vector monotonically growing from zero value along the tetragonal **c** axis takes place [1, 2]. Spins of copper ions occupy two nonequivalent positions 2b and 4b. Spins in the 2d position form a three-dimensional lattice, where the exchange interaction with four nearest neighbors is responsible for the existence of the commensurate phase in the temperature region 10÷20 K. Spins in the 4d position form zig-zag chains located in cavities of the three-dimensional lattice, which are parallel to the **c** axis and antiferromagnetically ordered along this axis in the commensurate phase. In this phase the exchange interactions between spins of different subsystems are frustrated.

At 10 K spins in the 4d position are ordered in the tetragonal plane, which can be possible only upon dominance of the exchange interaction between chains. Compatibility of this interaction with interactions inside the chains is analogous to an ANNY model and causes the appearance of incommensurability in ordering of a magnetic system of copper metaborate. Growth of magnetization of spins in the 4d position with a decrease in temperature against nearly saturation magnetization of spins in the 2d position results in the above-mentioned monotonic growth of a wave vector. In this study, the behavior of the system has been simulated and an spin-wave spectrum has been calculated.

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LOCALIZED NONLINEAR OSCILLATIONS IN A FERROMAGNET IN A MAGNETIC FIELD

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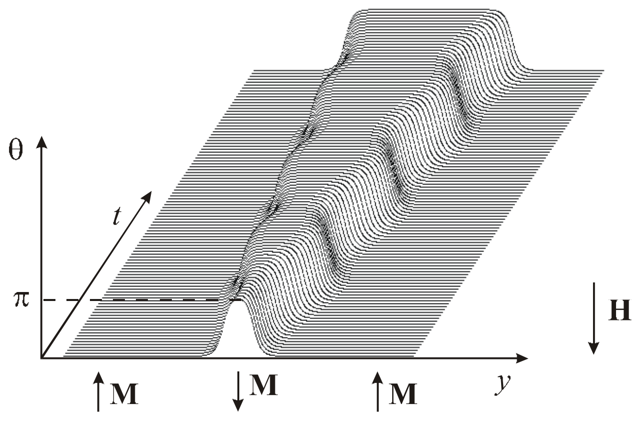
In the case of an easy-axis ferromagnet the Landau-Lifshits equation allows for both two-soliton and multi-soliton solutions in addition to the single-soliton one. The influence of an external magnetic field and that of dissipation on the two- and multi-soliton solutions are yet to be more thoroughly investigated. The paper attempts at investigating the influence of an external magnetic field and of attenuation on the dynamics of the nucleus of magnetization reversal, which is a two-soliton formation in the form of the two interacting domain walls, this dynamics being investigated in ferromagnets. We shall consider one-dimensional, localized in space, non-linear oscillation of magnetization in the biaxial ferromagnet in the magnetic field which is parallel to the easy magnetization axis.

The investigation of the influence of an external magnetic field and damping on the dynamics of localized single-dimensional magnetic inhomogeneities is thus reduced to examining a system of ordinary non-linear differential equations which describe the evolution of the parameters of two-soliton solutions of the Landau-Lifshits equations. The numerical analysis of the dynamic system thus obtained enabled the authors to establish that in ferromagnets the dynamics of the nucleus of magnetization reversal strongly depends on the initial amplitude, external magnetic field, damping, quality factor and in-plane anisotropy.

At the initial amplitudes lager then critical value there takes place a decomposition of the breather into two interacting 180-degree domain walls of the same polarity with the formation of domain of the reversed magnetization. In the fields which are smaller than the Walker fields, there takes place a forward movement of the walls thus formed. As damping increases, the time increases of the decomposition of the magnetization reversal nucleus in the form of a breather into a domain of reversed magnetization limited by the two domain walls with the opposite topological charges. The growth of the external magnetic field results in a shorter time of the breather split into a soliton-antisoliton pair and thus in a shorter formation time of the reverse-magnetization domain. The latter is in good qualitative agreement with the result of the experimental examination into the dependence of time the formation of the reversed magnetization domain on the value of the impulse magnetic field [1]. The same movement nature is observed in weak ferromagnets, too.



In ferromagnets in the fields that are greater than the Walker field, in the process of decomposition, the interacting domain walls perform an oscillatory movement alongside with the forward one (see fig.). As this happens, the wall structure changes from time to time from the Bloch one into the Neel one, and vice versa. At the moment of the maximum approach the structure of the walls becomes a Neelean one.

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COUPLED WAVES SPECTRUM OF A FERROMAGNETIC AT THE ACCOUNT OF PERMANENT-MAGNET INTERACTION

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In papers [1, 2] the existence of pure antiferromagnetic oscillations (oscillations only a components of antiferromagnetism vector) has theoretically been predicted. These oscillations were termed as electromagnons or antimagnons. In [1, 2] also was shown that electromagnons (antimagnons) are excited only by an alternative electric field. They can exist only in multisublattices magnetics in which magnetic atoms do not coincide with centre of symmetry. In this paper the spectrum of the coupled oscillations is theoretically obtained and the reflectivity (*R*) of electromagnetic waves (EMW) from a surface of two-sublattice dielectric ferromagnet (FM) [2] with magnetoelectric effect is investigated. The case of FM with crystalline structure $D_{2h}^1 = Pmmm$ is considered. The energy of FM includes the magnetic, the electric and the magnetoelectric terms [3]. In the ground state vectors of polarization **P** and antiferromagnetism **L** are equal to zero and a vector of ferromagnetism $\mathbf{M} \parallel \mathbf{z}$. For a finding of the dispersion equation propagated inside FM, the coupled system of equations of Landau-Lifshits, motion of polarization vector and Maxwell were used. Waves are propagated along the $\mathbf{x}$ axis ($\mathbf{k} \parallel \mathbf{x} \parallel \mathbf{n}$), **n** is the normal to surface of FM. On surface of FM normally drops the EMW $e_z = h_0 \exp(-i\omega t + ikx)$. The linearized system of coupled equations describes the interaction of components $h_y, m_x, m_y, l_x, l_y, e_z, p_z$. We shall note that in the given geometry the oscillations of m_x, m_y are excited by the field component h_y in a microwave region and the oscillations of l_x, l_y are excited by the field component e_z through oscillations of polarization p_z in an infrared region. In case of absence of a spatial dispersion for waves of magnetization and polarization the dispersion equation are a polynomial of the eighth degree on a frequency and the second degree on a wave number. For a finding of *R* the system of boundary conditions on the surface of FM was used. The given system together with linearized system of the coupled equations and the dispersion equations allows us to calculate *R*. The analysis of the dispersion equation show that in a spectrum of the coupled oscillations exists three branch with activation and two gaps in the microwave region (oscillations m_x, m_y) and in the infrared one (oscillations p_z). In areas of activation branches the increasing of *R* is observed. In the gap regions the plateau of *R* is observed. Oт this plateau *R* is close to unity.

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TIME RESOLVED OBSERVATION OF DOMAIN WALL DEPINNING AND PROPAGATION IN SPIN VALVE NANOWIRES

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In view of introducing new magnetic storage devices (MRAMs) and magnetic logic systems, ultrashort magnetisation reversal dynamics is now a subject of extensive research.

By using time-resolved XMCD-PEEM microscopy at synchrotron radiation sources, we are able to study the field-induced dynamics of a domain wall injected in a nanowire, with resolution of the order of 100 nm and temporal resolution of 100 ps.

The measurements are carried out in pump-probe mode, by exploiting the time-resolution of synchrotron radiation. Short magnetic pulses produced by copper microcoils (or current pulses flowing through the sample) are synchronised with the photon bunches [1].

Images are taken for different delays between pump and probe to follow domain wall propagation in the nanowire. Since these measurements are carried out in stroboscopic mode, only reproducible domain wall behaviour can be measured. In this work we have studied Co/Cu/NiFe nanowires (500 nm wide) made by electron beam lithography and lift-off (or ion beam etching) techniques.

In order to assure reproducible domain wall nucleation and propagation, nanowires are curved or zigzag shaped. Applying magnetic field pulses with an adapted geometry enables us to create a domain wall in the curved section of the wire. XMCD-PEEM images have then been used to examine the reproducibility of domain wall depinning and propagation. The chemical selectivity of XMCD -PEEM allows us to separate the Cobalt and Permalloy layer contribution and to study the mutual influence on the magnetisation dynamics.

Before we proceeded to the synchrotron measurements, we evaluated the domain wall movement under magnetic field with respect to the changes in GMR of the spin valve structure.

Our future objective is to observe spin-polarised current induced domain wall depinning and propagation.

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MAGNETIC RESONANCE IN FERRITE NANOPARTICLES DISPERSED IN GLASS

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Great attention is currently paid to magnetic particles dispersed in glassy matrices, i.e., so called magnetic glass ceramics. Potassium-aluminum-boron glasses activated by Fe and Mn were shown in our previous papers to have magnetic properties characteristic of magnetically ordered substances at the low activator concentrations (several mass %) and to keep transparency in the visible and near infrared spectral ranges, demonstrating high magneto-optical Faraday rotation. In depth knowledge of the phase state of paramagnetic additions: diluted ions – clusters – nanoparticles, at all stages of the glass synthesis and subsequence thermal treatment will allow creating purposely novel materials for magneto-optical devices. Here we present electron magnetic resonance (EMR) investigation of glass systems Al_2O_3-K_2O-B_2O_3 with additions of Fe_2O_3 (1.5 or 3.0 mass %) and MnO (1.5, 2.0, and 2.5 mass %) in dependence on technology conditions and Fe and Mn concentration.

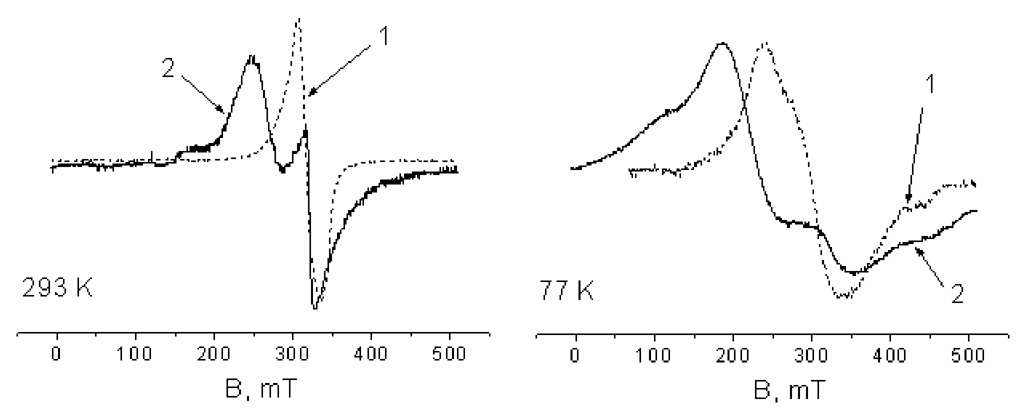

Fig.1. EMR spectra of samples with 1.5 % Fe_2O_3 and 1.5% MnO (1) and 3.0 % Fe_2O_3 and 2.5% MnO (2) for two temperatures. Both samples were subjected to thermal treatment at 560°C. Vertical scale in the right picture is enlarged in four times relatively to the left one.

For as-synthesized samples well-resolved electron paramagnetic resonance (EPR) spectra are observed from Fe and Mn ions diluted in the glass matrix, viz., the characteristic single line of Fe^{3+} with $g = 4.3$ as well as the hyperfine sextet of Mn^{2+} at $g = 2.0$. These spectra are superposed with a broad underlying resonance line corresponding to g~2. This line gradually disappears with temperature of measurements is lowered. Such behaviour is characteristic of superparamagnetic resonance (SPR). Heat treatment brings changes in the EMR spectra. For all samples line with g = 4.3 of Fe^{3+} as well as the hyperfine sextet of Mn^{2+} at $g = 2.0$ disappear while the SPR spectra increase and turn into well developed structure characteristic for ferromagnetic resonance. This behaviour shows that diluted paramagnetic ions are gradually joining and forming nanoparticles and that the average size of the latter is growing. Fig.1 demonstrates EMR spectra for two samples prepared at the same conditions but differs with each other in doping ions concentration. In less doped glass (curve 1) intense line with g=2.002÷2.006 and ΔB= 10÷20 mT is observed. In more heavily doped glasses (curve 2) doublet line appears, the first component of the doublet coincides with the line described above, the second one with g = 2.24÷2.26 is broader (ΔB = 52÷80 mT). The temperature lowering effects in broadening and the intensity decrease for both lines. Besides, it makes evidence the existence of the second component in the sample 1 spectrum (curve 1, from the right). Note also the peculiar shoulder in the low field part of the sample 2 spectrum (curves 2). EMR spectra characteristics and their temperature behaviour are discussed taking into account particles heterogeneities and their anisotropy temperature dependence.

SPIN TORQUE INFLUENCE ON THE NOISE SPECTRUM OF MAGNETIC TUNNEL JUNCTIONS

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The observation of steady magnetization excitations induced by spin transfer torque has been reported by several groups in magnetic nanostructures traversed by a spin-polarized current of sufficient density. Here we show that below the critical current density, spin torque impacts also magnetization thermal fluctuations: in particular, we observed that the noise spectrum of TMR read-heads strongly depends on the direction and amplitude of the applied DC-current.

The electrical noise of 300 nm diameter TMR read-heads has been measured in a range of 1 to 10 GHz as a function of magnetic field, DC current bias and temperature. Measurements were performed both in the parallel and anti-parallel magnetic states. We observed several peaks in the noise spectra that shift with the applied DC field and DC current bias. These peaks are attributed to thermally activated ferromagnetic resonance excitations (FMR) in the free layer, with peak frequency following the Kittel law [1].

The most interesting feature of the noise spectra is a pronounced asymmetry with respect to the sign of the current. For positive current the normalized noise peak grows, while for negative currents the normalized peak amplitude is reduced. Finally for opposite magnetic field values, the effects of positive and negative currents are exchanged. In other words, symmetric points in the H-I phase diagram exhibit the same behaviour. This observation indicates that spin transfer torque reduces or enhances the thermal fluctuations as a function of the DC-current direction, depending on whether it tends to favor or disfavor the equilibrium magnetic configuration.

The influence of the spin-torque term on magnetic fluctuations is modelled using the macrospin approximation in the framework of linear response theory. Magnetization dynamics is assumed to follow the Landau-Lifschitz-Gilbert equation modified with the spin transfer terms [2]. We observe a good agreement between the model predictions and the experimental data.

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CALCULATION OF THE SPIN-TORQUE IN NON-COPLANAR DOUBLE SPIN VALVE STRUCTURES FM1/P/FL/FM2

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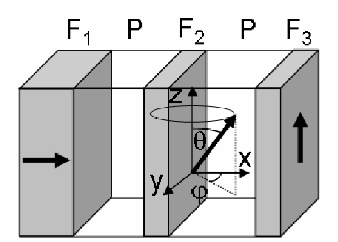

Geometry of the structure

Recently the possibility of changing the magnetisation state in a magnetic thin film element by the transfer of spin angular momentum has been widely discussed by theoreticians and experimentalists [1, 2]. This spin transfer effect can induce either a reversal of the magnetisation and is thus of interest for magnetic memory devices, or it can induce large angle steady state oscillations, which are of interest for novel type of RF oscillators. In most studies so far, the corresponding structures were spin valve or tunnel junctions that contain two magnetic layers: a pinned reference layer or polarizer and a free layer. For the optimisation of the functionalities of such structures more complex systems have been suggested, making use of a double spin valve or tunnel junction structure [3], containing three magnetic layers: FM layer 1 – free layer – FM layer 2. At SPINTEC the double spin valve structures are being investigated in the context of RF oscillators, using an out of plane magnetised polarizer for FM1 and an in-plane magnetised analyser to monitor the magnetisation motion of the planar free layer, see Fig. 1.

We therefore have extended the current models on CPP GMR and spin torque to non-collinear double spin valve structure FM1/P/FL/P/FM2, where FM1 and FM2 are the pinned ferromagnetic layers, FL is the free one domain ferromagnetic layer with magnetisation $\vec{M} = M_0(\sin\theta\cos\varphi;\ \sin\theta\sin\varphi;\ \cos\theta)$ depending on arbitrary angles θ and φ. Different to the spin torque deduced by J. Slonczewski [1], the spin torque in any layer *i* is written as $\vec{T}_i = \frac{J_{sd}}{\hbar}\left[\vec{M}_i \times \vec{m}_i\right]$, that contains implicitly the magnetisation and spin accumulation vectors. In case of two layers when two magnetizations always find themselves in the same plane the spin torque term in the free layer may be written as a superposition $\vec{T} = a\left[\vec{M} \times \vec{M}_1\right] + b\left[\vec{M} \times \left[\vec{M} \times \vec{M}_1\right]\right]$, where terms proportional to a due to the exchange interaction between M_1 and M_2, and terms proportional to b are real "spin torque". In this work it is shown that in contrary to the previous case, in the case of three layers the presentation of torque as a superposition of terms containing the vector products and double vector products coming separately from the polariser and analyser is not valid any more, which proves that contributions to the torque from FM1 and FM2 are non-additive due to the non-local origin of the phenomenon.

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TIME RESOLVED MAGNETO-OPTICAL IMAGING OF MAGNETIC DOMAINS WRITTEN IN COPT FILMS WITH FEMTOSECOND LASER PULSES

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Performing time resolved magneto-optical imaging with a high spatial resolution on the ultrafast time scale is of great interest for studying magnetic nano-devices operating with a potential high bandwidth in the TeraHertz regime. Concerning the temporal resolution, magneto-optics performed with femtosecond laser pulses appears to be a powerful method for investigating the physical processes involved in the laser induced ultrafast demagnetization [1] as well as the magnetization precession and damping [2]. In this work we study magnetic domains, induced optically in ferromagnetic CoPt films, using a Magneto-Optical Pump Probe Imaging (MOPPI) technique with a temporal and spatial resolution of 150 fs and 300 nm respectively [3]. The experimental set-up consists in time resolved Kerr magneto-optical pump probe measurements, where the magnetization dynamics is induced (wavelength λ=800 nm) and probed (λ=400 nm) with femtosecond optical pulses delivered by an amplified Titanium-Sapphire laser operating at 5 kHz. Figure 1a) shows the magneto-optical image of a 300 nm magnetic domain which is first switched in a CoPt/Glass film with a density of pump energy of 4 $mJ.cm^{-2}$ without applied static magnetic filed H_0. The image is then recorded for a pump probe delay t = 300 fs with a density of laser excitation of 1 $mJcm^{-2}$. The differential $\Delta M/|M|$ contrast is due to a partial demagnetization (~25%) of the film. In figure 1b) the logo of our institute IPCMS is written by switching the magnetization to the reverse state on a $CoPt_3/Al_2O_3$ film with a pump fluence of 8 $mJcm^{-2}$ and for H_0 = -50 Oe after saturation with H_0 = +4 kOe. We have also studied the all optical switching on a $CoPt_3$ thin film using circularly polarized light similarly to the optical switching of ferromagnetic GdFeCo films [4].

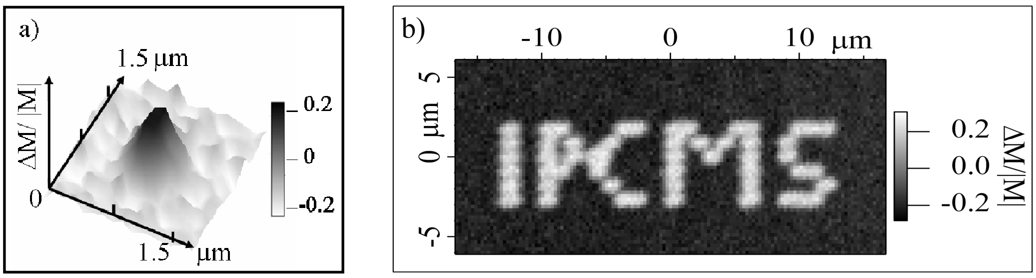

Fig. 1. a) MOPPI of a magnetic dot switched on a CoPt/glass film with a pump fluence of 4 $mJcm^{-2}$ (H_0=0). b) The logo IPCMS is written on a $CoPt_3/Al_2O_3$ film with a pump fluence of 8 $mJcm^{-2}$ (H_0= -50 Oe). For both images, the reading is performed at a fixed pump-probe delay (300 fs) and for a pump fluence of 1 $mJ.cm^{-2}$.

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TOWARDS COMPACT EXPERIMENTAL DEVICES FOR INVESTIGATING THE ULTRA-FAST MAGNETIZATION DYNAMICS

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The study of the ultrafast spin dynamics using femtosecond laser sources brings unique information on the fundamental mechanisms involved in the time dependent magnetization over a broad temporal range (100 fs – 1 ns). With the perspective of implementing femtomagnetism in convenient laboratory environments it is also worth investigating new experimental configurations which are compact and provide both high spatial and temporal resolutions: typically a few hundreds of nanometers [1] and a few tens of femtosecons [2]. We focus here on such approach.

We have developed a pump probe magneto-optical Kerr and Faraday setup based on a compact low power diode pumped fiber laser source similar to those used for amplifying optical signals in optical fiber telecommunications. We demonstrate that it can conveniently be used to investigate the ferromagnetic resonance in the temporal domain of thin films and submicron magnetic structures deposited on a high temperature conductive substrate.

The experimental configuration is shown in figure 1. Both pump and probe beams are tightly focused and the Faraday rotation and ellipticity are detected after a polarization bridge with a high (50 kHz – elasto-optic modulator) or low (217 Hz – mechanical chopping) modulation frequency.

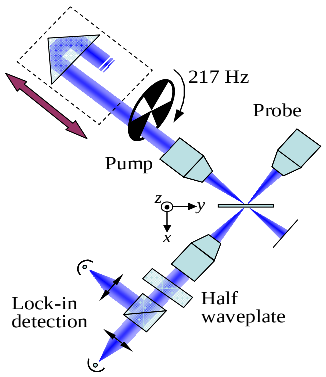

Figure 1. Sketch of the experimental setup in the Faraday configuration with a polarization cube analysis

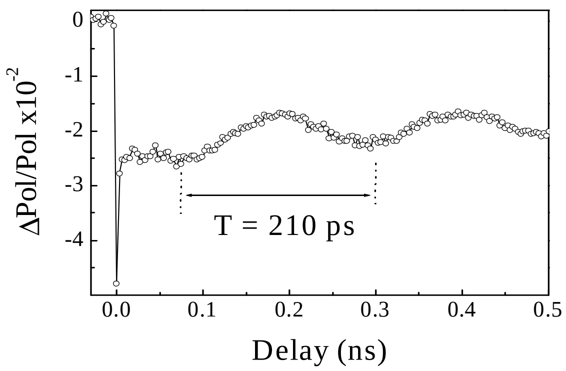

Figure 2. Precession of the magnetization observed on the polar component of the 7.5 nm Ni/glass thin film.

Figure 2 shows the dynamics of the polar signal ΔPol/Pol obtained on a 7.5 nm thick film of Ni grown by sputtering on a glass substrate. An external static field H_0 = 3kOe is applied for the complementary directions $\phi = 5°$ and 175° where ϕ is the angle between H_0 and the normal to the sample plane. In addition to the ultrafast demagnetization, a precession with 210 ps period clearly shows up. The respective advantages provided by such compact (~1m^2) femtosecond setup will be emphasized.

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SPIN WAVE FILTERS ON THE BASE OF SPUTTERED GARNET FILMS FOR MICROWAVE APPLICATIONS

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We report a fabrication of yttrium-iron-garnet (YIG) films sputtered on gadolinium-gallium-garnet (GGG) substrates, a study of the sputtered films and a construction of spin wave filters. YIG films have been sputtered on (111) GGG substrates by pulsed laser deposition. From FMR spectra we have obtained the FMR linewidth ΔH and the difference between the magnetization $4\pi M$ and the uniaxial anisotropy field H_A with the axis perpendicular to the film surface. It is found that the sputtered YIG films are characterized by narrow FMR linewidths and by high values of the in-plane anisotropy field. High values of the in-plane anisotropy field are due to a lattice mismatch between sputtered YIG films and GGG substrates.

Spin wave filters are realized as one-channel and two-channel filters. The applied magnetic field H is parallel to the YIG film structure and is orthogonal to propagating surface spin waves. The one-channel spin wave filter is constructed on the base of the sputtered sample. Its amplitude-frequency characteristic presented in Fig. 1 shows that narrow frequency bandwidth can be achieved in filters on sputtered YIG films.

Difference in $4\pi M$ - H_A between sputtered YIG films and YIG films produced by the liquid phase epitaxy gives us opportunity to construct a two-channel filter. Amplitude-frequency characteristic of the two-channel filter on the base of sputtered and epitaxial YIG films is presented in Fig. 2. The epitaxial film with $4\pi M$ - H_A = 1750 Oe is placed on the sputtered film, so the GGG substrate of the sputtered film forms a gap. This leads to a decrease in interaction between spin waves propagated in the epitaxial film and to some growth of signal losses.

This work was supported by the Russian Foundation for Basic Research (grant N 06 - 02 - 17030).

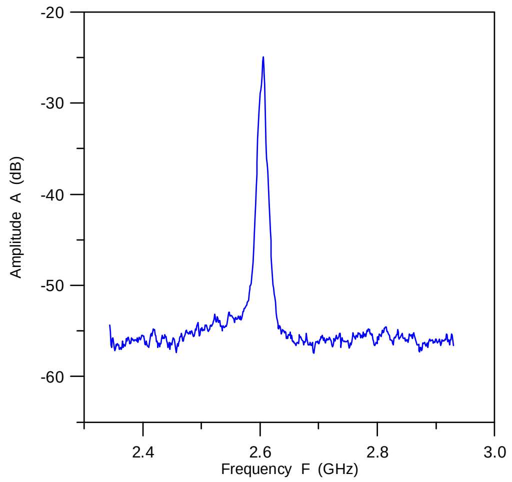

FIG. 1: Amplitude-frequency characteristic of the one-channel spin wave filter on the base of sputtered YIG film.

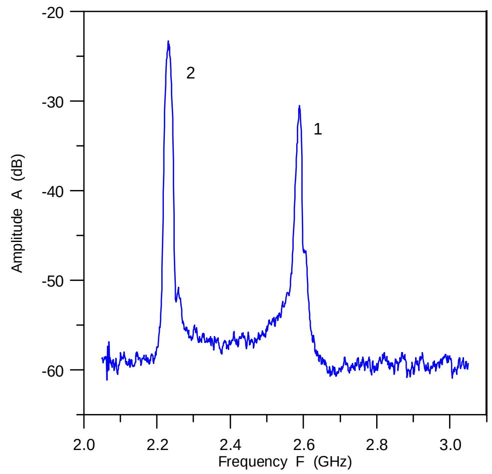

FIG. 2: Amplitude-frequency characteristic of the two-channel spin wave filter on the base of sputtered YIG film (1) and the epitaxial YIG film (2).

GENERATION OF THE BROADBAND CHAOTIC SIGNAL IN THE SELF-OSCILLATION SYSTEM WITH NONLINEAR TRANSMISSION LINE ON MAGNETOSTATIC WAVES

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Currently the use of the chaotic signals as a new data carrier in communications, radar and others applications is one of the important line of telecommunication systems development [1]. During the last years the investigations determined to study chaotic generation in the ring self-oscillation system have been carried out. In these systems the transmission line on the magnetostatic waves is used as a nonlinear element [2, 3]. The nonlinear characteristics of this line are determined by parametric excitation of exchange spin waves in the ferromagnetic films. The stochastic self-modulation of the oscillating signal is a result of this parametric excitation.

In the paper the experimental results of the broadband chaotic generation in the MW range in the ring self-oscillation system based on the solid state power amplifier and broadband nonlinear transmission line at the magnetostatic surface wave (MSSW) and backward volume magnetostatic waves (BVMSW) excitation are presented. The chaotization of the ring self-oscillation system eigenmodes, excited in the bandwidth of the transmission line on magnetostatic waves, is cause of the parametric excitation of the exchange spin waves by magnetostatic waves and of the nonlinearity of solid state power amplifier. It's shown, that the generation of the broadband chaotic signal with the nearly continuous spectrum is determined by the features of the dynamic characteristic of the nonlinear transmission line on MSSW. This feature is connected with the presence of the falling region on the dynamic characteristic of this transmission line in the long-wave part of the MW range. In the case of the BVMSW excitation on the dynamic characteristic of the nonlinear passive element, the region of the power limit is also observed. However the dynamic characteristic in this case has not the falling region. The experimental investigation of the external harmonic signal influence of various power levels on the generation regimes of the ring self-oscillation system is presented in this paper.

The important applied result of this work is the possibility of the broadband chaotic signal generation tuning by the external bias field. The integrated power of this signal in the ring is the nearly equal to the power saturation of the amplifier.

This work was supported by the Russian Foundation for Basic Research (grant no. 06-02-16451), the President grant (grant no. МК-1320.2007.9) and the program of the Federal Agency on Education of Russia Federation and CRDF (grant no. Y4-P-06-02)

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NONLINEAR MAGNETOSTATIC WAVES IN COUPLED FERROMAGNETIC STRUCTURES

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Magnetostatic waves (MSW), what propagate in ferromagnetic films and which intensive study began actually last twenty years, take up the special place in physics of nonlinear wave processes, since they have a number of fundamental preferences before other types of waves in solid substances [1]. It is connected to variety of the nonlinear phenomena accompanying magnetostatic waves propagation and convenience of their experimental study. The study of nonlinear properties of these waves is of interest also in connection with an opportunity of use them in different nonlinear microwave devices. To the present time the extensive theoretical and experimental material on study of nonlinear phenomena on MSW in single wave guide structures, which characteristics are determined by a ferromagnetic film basically, is accumulated. Only linear characteristics of MSW in coupled ferromagnetic structures are well studied at a present time. Not a lot of works, directed, basically, on study of dispersion features of nonlinear MSW in structures consisting of layers of a various nature [2] or on study of relative influence of waves, propagating on different frequencies in a single film [3], are devoted to investigation of nonlinear waves in similar structures [4]. However, it is necessary to emphasize that use of coupling significantly expands functionalities of electrodynamics systems. Thus, problems devoted to study of coupled waves in various nonlinear systems and substances, including in coupled ferromagnetic structures, are represent significant scientific interest.

At the present report the features of nonlinear wave processes and effects of self-influence at excitation of various types of MSW in coupled ferromagnetic structures and possibility of governing nonlinear processes in ferromagnetic films at coupling variation are considered. With use of various approaches in the assumption, that coupling has electrodynamic character and nonlinearity of each of the films depends only on variable magnetization of this film, nonlinear models for the description of MSW distribution in the coupled structure in the form of two coupled nonlinear Schrödinger equations are constructed [5]. Coupling in this case results not only in change of values of group velocity, dispersion and nonlinearity coefficients in the equations, but also to occurrence of cross members, i.e. to occurrence of nonlinear coupling.

It is shown, that use of electrodynamic coupling in layered ferromagnetic structure enables effectively to operate various characteristics of nonlinear processes at excitation magnetostatic waves: parameters of the processes connected with solitary waves formation; parameters describing development of self-modulation; character of development of complex dynamics of envelope behaviour, connected with transition to chaotic behaviour.

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THE STUDY OF THE ORIGIN AND EVOLUTION OF THE MAGNETIC INHOMOGENITIES OF SOLITON AND BREATHER TYPE IN MAGNETICS WITH ANISOTROPY LOCAL INHOMOGENITIES

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It is known that in real magnetics the appearance of magnetic parameters local changes happens due to structural and chemical non-homogeneities and local influence (mechanical, thermal or solar). As it is usually difficult to make a precise (microscopic) calculation, one is to model the functions, which describe the parameters of a non-homogeneous material [1]. The case is especially interesting, when the size of a magnetic non-homogeneity and the size, describing a non-homogeneity of parameters of a stuff, are of the same order. It results in considerable complication of Landau-Lifshitz equation for the magnetization. Although the task of excitation and distribution of the magnetization waves, under certain conditions, is reduced to the studies of the modified sine-Gordon equation with floating factor [2]. The investigation of big perturbations influence on the solution of modified sine-Gordon equation in general case can be investigated only with the help of numerical methods [3]. In dynamic, when in the area of such non-homogeneities (or defects) a temporally or spatial non-homogeneous perturbation acts, under certain conditions, a strongly non-linear waves of magnetic character can be aroused. Such waves are weakly investigated.

In the research a non-linear dynamic of domain walls (DW) (sine-Gordon equation kinks) for the case of 1D and 2D non-homogeneity of the material parameters (for example, magnetic anisotropy constant) was investigated with the help of numerical methods. For the 1D case we have studied the origin and evolution of the structure of three types of magnetic non-homogeneous appearing in anisotropy non-homogenity region – fading breazer, fading breazer passing in soliton, soliton. The value areas for the parameters governing the possibility of their existence and the frequency of internal shape mode oscillation of domain wall are found. For the 2D case we have investigated the dynamic of solitary bending waves, which appear on the DW crossing of defect region, and the origin and evolution of the magnetic non-homogeneities of soliton and breazer type, localized in this region.

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COLLECTIVE MODES AND LOCAL MAGNON STATES FOR MAGNETIC DOT ARRAYS WITH PERPENDICULAR ANISOTROPY

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Magnetic structures consisting of submicron size magnetic dots arrayed in two-dimensional lattice have attracted recently a great attention because of possible application of them in high-density magnetic storage devices. The direct exchange interaction between dots is absent and a sole source of interaction is the long-range magnetic dipole interaction. They often manifest magnetic properties absent in bulk magnets or continuous thin films. For small enough dots (the diameter < 200 nm) the magnetization inside of a dot is almost uniform, producing the total magnetic moment m. For larger dot sizes, so called vortex state, with the only total magnetic moment m caused by out-of plane vortex core appears.

The ground state of an array of magnetic particles (magnetic dots), which are ordered in a square 2D lattice and whose magnetic moment is perpendicular to the lattice plane, is chessboard antiferromagnetic (AFM). Being subject to an external magnetic field perpendicular to the system plane, the AFM state is stable at low fields $H < H_1 = 2.3 \cdot H_*$, the ferromagnetic (FM) (saturated) state is stable at strong fields $H > H_0 = 9.03 \cdot H_*$, where $H_* = m^2 / a^3$ is characteristic field of magnetic dipole interaction, is a lattice spacing, with complicated structures at $H_1 < H < H_0$.

The long-range character of interaction of magnetic dots leads to unique properties of collective excitations in this system, which are absent in both continuous thin films and for dipole coupled spins in the 3D lattice. Especially for FM state non-analytic dependence of collective mode frequencies on quasi-momentum $\vec{k}$ appears, $\omega - \omega_0 \propto |\vec{k}|$ при $\vec{k} \to 0$. For AFM state, the spectrum consists from two energy bands, which are connected at the border of the Brillouin zone of dot the lattice at zero magnetic field, but these two bands are well separated by energy gap at high enough fields $H < H_1, H_1 - H \sim H_1$. In this case, the $\omega(\vec{k})$ dependence is analytic for lower band, but the singularity of type $\omega - \omega_0 \propto |\vec{k}|$ at $\vec{k} \to 0$ is present for higher band. These peculiarities leads to non-standard Van Hove singularity in the density of state $N(\omega)$, $N(\omega) \sim |\omega - \omega_0|$.

Real magnetic dot arrays are big, but finite systems, and the border effects plays an important role in their static and dynamic properties. In particular, their spectrum includes some modes, localized near the border. These modes are am analogy of surface states (Tamm states) known for usual crystals. Their amplitude can be present as $\psi \sim \exp[ikl_{\parallel} - pl_{\perp}]$, $l_{\parallel}$ и $l_{\perp}$ number the lattice cites along the border and perpendicular to it, respectively. The quantity k having a sense of quasimomentum along the border line, the condition $p = p(k) > 0$ determine the region of the existence of such modes. For FM state, the local mode is located above the continuum spectrum. For AFM, this mode is well defined for the border of (1,1) type. It is located below the continuum, it softens at the grooving of the field value and leads to the state instability.

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MAGNATOELECTRIC INTERACTIONS AND SPIN WAVES SPECTRUM IN YTTRIUM IRON GARNET

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Results of investigation of magnetoelectric effects in yttrium iron garnet (YIG) are reported. In the unit cell of crystal structure of YIG (space group O_h^{10}) the magnetic Fe ions occupy 16 positions of the *a* type and 24 positions of the *d* type [1]. Thus a complete description of the magnetic dynamics YIG is liable to use 80 dynamic variables. The aim of our investigations was reduce variables number to minimal retaining variables which connect with magnetoelectric interaction.

Such magnetoelectric variables must change their sign by action of the operator of spatial inversion $\bar{1}$, as vector of electrical polarization $\boldsymbol{P}$

$$\bar{1}\boldsymbol{P} = -\boldsymbol{P}. \quad (1)$$

It means that these variables must be connected with Fe ions which were transformed one into another by $\bar{1}$. It is a property of Fe ions in *d* positions. They were distributed between two sublattices with magnetization $\boldsymbol{M}_{d1}$ and $\boldsymbol{M}_{d2}$ according to principle:

$$\bar{1}\boldsymbol{M}_{d1}=\boldsymbol{M}_{d2},\ \bar{1}\boldsymbol{M}_{d2}=\boldsymbol{M}_{d1}. \quad (2)$$

Corresponding to this distribution the antiferromagnetic vector

$$\boldsymbol{L}=(\boldsymbol{M}_{d1}-\boldsymbol{M}_{d2}) \quad (3)$$

changes its sign by acting of $\bar{1}$

$$\bar{1}\boldsymbol{L}=-\boldsymbol{L}, \quad (4)$$

as vector $\boldsymbol{P}$ (1). The vector $\boldsymbol{L}$ was be used for solution of two problems. At the first the components of vectors $\boldsymbol{L}$, $\boldsymbol{M}=(\boldsymbol{M}_{d1}+\boldsymbol{M}_{d2})$ and $\boldsymbol{P}$ are constituents for composition of invariants with respect to all operations of symmetry of the space group O_h^{10}. The magnetoelectric interaction V_{ME} in YIG is determined by these invariants. At the second the interaction of the vector $\boldsymbol{L}$ with spin of Fe ions in the *a* position must determinate that searched magnetoelectric variables, which were mentioned above.

Unlike *d* position the *a* position is not transformed by operation $\bar{1}$. Therefore the Fe ions in *a* position may be united into common sublattice with magnetization $\boldsymbol{M}_a$. The vectors $\boldsymbol{M}_a$, $\boldsymbol{M}_{d1}$ and $\boldsymbol{M}_{d2}$ form the three-sublattice model, which is sufficient for description of magnetoelectric effects on YIG. Spin waves spectrum in this model contains six branches. Two acoustic and two optical branches are known from two-sublattice model YIG [2]. Two additional branches are caused by vector $\boldsymbol{L}$ vibrations. There are electromagnon branches (they are named by antimagnons in [3]), because they can be exited by electric field due to magnetoelectric interaction V_{ME}. It was received the spectrum of coupled magnetoelectric waves (EMW) and electromagnons, which was used for description of EMW polarization plane rotation (Faraday effect). Another electroactive excitation in YIG (for example optical phonons) may interact with EMW also, but these interactions don't influence of Faraday rotation.

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MODES INTERACTION IN MICROSTRIP'S FMR SPECTRA

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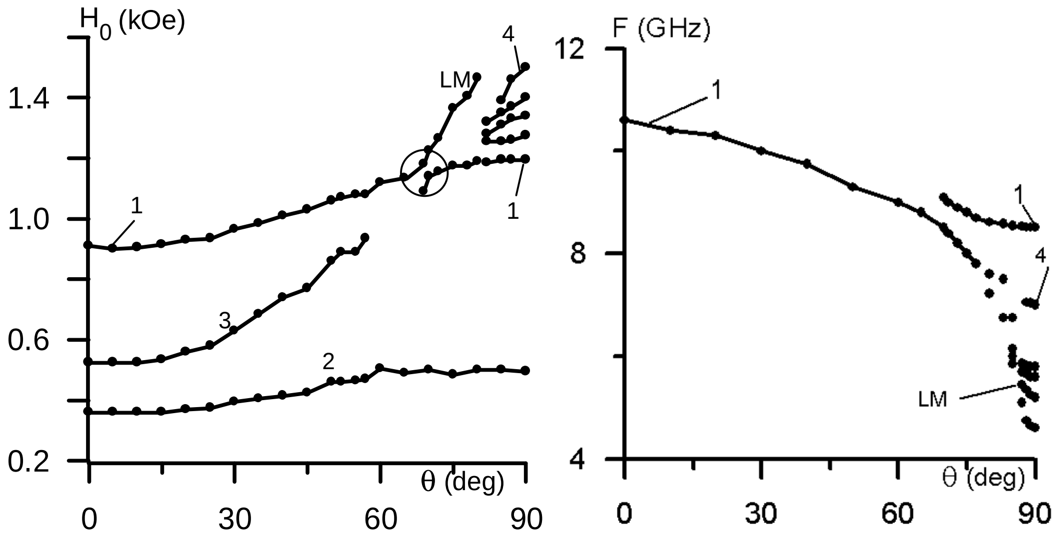
In long narrow magnetic microstripe of rectangular cross-section one can observe in addition to well-known dipole and exchange spin-wave excitations 1) discretisation of spin-wave spectra caused by lateral confinement effect at θ=0° [1] and 2) localised near the stripe's edges modes (LM) at θ =90° [2] where θ is the angle between direction of tangential bias magnetic field and the longitudinal axis of the stripe. In this work the possibility of resonant interaction of microstripe's spin-wave modes will be shown using ferromagnetic resonance technique.

We have investigated the microstrip array FMR spectra at 9,85 GHz depending on the angle θ. The array was fabricated from 60 nm-thick $Fe_{10}Ni_{60}Cr_{25}$ film magnetron sputtered on Si (111) substrate. Using e-beam lithography the stripes with a width of w=3 μm, a length of 90 μm, and a distance between the stripes 1.5 μm were performed at 4×3 mm^2 area. The experimental dependence of microstripe array FMR peaks position on the angle θ is shown in the figure (a). Marks 1,2,3,4 correspond to quasiuniform mode, SWR, Damon-Eschbah mode and BVMSW mode, respectively; LM corresponds to localised mode. Comparising with the calculated angular dependence of SW spectrum on the direction of external magnetic field H_0=1 kOe - see figure (b) - demonstrate the possibility of modes interaction.



a b

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PARAMETRIC MAGNATOELECTRIC EFFECTS INTO ALTERNATING MAGNETIC FIELD

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Magnitoelectric effects are magnetization of sample by electric field and its electrical polarization by magnetic field [1]. Both effects are caused by magnitoelectric interaction Φ_{ME}, which combine the components of antiferromagnetism $\boldsymbol{L}$, magnetization $\boldsymbol{M}$, and electrical polarization $\boldsymbol{P}$ vectors [2]:

$$\Phi = -\lambda^{\alpha\beta\gamma} L^{\gamma} M^{\beta} P^{\alpha} \tag{1}$$

The products of components $\boldsymbol{L}$, $\boldsymbol{M}$ and $\boldsymbol{P}$ (1) must be invariant with respect to all operations of group symmetry of crystal; therefore the magnetic interaction may exist in substance with special crystalline symmetry and magnetic ordering [2]. This interaction determines specific coupling of electricity and magnetism, which is not described by classical Faraday-Maxwell electrodynamics.

As it follows from (1), the interaction Φ_{ME} determines the effective electric field:

$$E_{eff}^{\alpha} = -\frac{\partial \Phi_{ME}}{\partial P^{\alpha}} = -\lambda^{\alpha\beta\gamma} L^{\gamma} M^{\beta}\,. \tag{2}$$

Which forms electrical polarization

$$P^{\alpha} = \kappa E_{eff}^{\alpha} = -\kappa\lambda^{\alpha\beta\gamma} L^{\gamma} M^{\beta}\,, \tag{3}$$

κ – electrical susceptibility. The M^{β} is induced by static magnetic field, then P^{α} (3) describes the static magnitoelectric effect. The signal of dynamic magnitoelectric effect is described by $M^{\beta}(t)$ induced by oscillating magnetic field

$$H(t) = H_m \sin \omega t\,. \tag{4}$$

This signal may be amplified by the resonance effect, if $\omega = \omega_0$ is an eigenfrequency of $M(t)$ vibrations. For antiferromagnetic the values ω_0 are frequencies of antiferromagnetic resonance (AFMR). At present the dynamic magnitoelectric effects were investigated for ordinary AFMR in field $H(t) \perp H_0$ with frequency $\omega = \omega_0$ [2]. There exists parametric AFMR in field $H(t) \parallel H_0$ with double frequency $\omega = 2\omega_0$ [3]-[4]. The properties of polarization P^{α} (3) caused by parametric AFMR (parametric magnetoelectric (PME) effect) is a subject of this report discussion.

The most favorable conditions for observation PME signals are received. These conditions unite the conditions of magnitoelectric effect existence and parametric AFMR excitation. It is found that this different conditions coexist in foresublattice antiferromagnetic Cr_2TeO_6 with crystalline stricture of thirutile.

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FERROMAGNETIC RESONANCE CHARACTERIZATION of the Fe/MgO (001), Fe/GaAs(100), Fe/Si(111) FILMS

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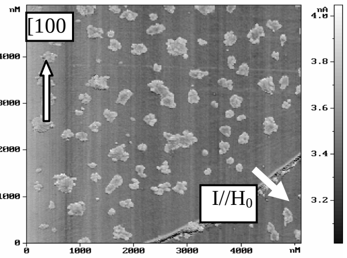
Different aspects of the structure-magnetism and morphology-magnetism correlation Fe films are the objects of considerable interest. The magnetooptic Kerr effect (MOKE), atomic force microscopy (AFM), scanning tunnelling microscopy (STM) and SQUID magnetometry techniques were used for characterization of magnetic parameters, hysteresis lopes and morphology of the nanoislands Fe/MgO films. However, the correlation between ferromagnetic resonance (FMR) properties and morphology of the Fe films haven't been discussed to our knowledge. The purpose of this work is to report about our investigation of the magnetic parameters of the Fe/MgO(100), Fe/GaAs(100) and Fe/Si(111) films receiving by MBE and magnetron sputtering by means of FMR and its correlation with data measured by AFM, MOKE and magnetic force microscopy (MFM) techniques.

As an example the AFM image of the Fe/MgO(100) film with thickness $t \approx 40$ Å is shown on Fig.1. Both separate islands and rounded mounds with lateral dimensions from $\approx 50nm$ to $\approx 500nm$ are seen. Fig.2 illustrates the resonance magnetic field $H_r(\theta)$ and FMR linewidth $\Delta\mathrm{H}(\theta)$ as a function of angle θ between magnetic field and [100] axis of Fe film (see. Fig.1) measured at frequency 9.85 GHz in tangentially magnetized film. Note, that FMR linewidth for film magnetized in "hard" directions ($\theta \approx 0, 90^0$) are 2-3 times smaller than for film magnetized in "easy" ($\theta \approx 45, 135^0$) directions. An increase of $\Delta\mathrm{H}$ in "easy" directions could be attributed to more pronounced role of demagnetization filed in that case. The thickness dependencies of the magnetization ($4\pi M_0$), FMR linewidth ($\Delta\mathrm{H}$), anisotropy field (H_A) and constant ($K1$) are shown on Fig.3 by curves 1-4, respectively. Magnetoresistance measured for current direction parallel to magnetic filed and perpendicular to MgO facets is shown on Fig.4

Fig.1



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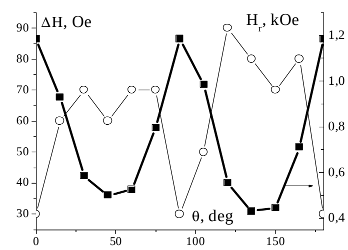


Fig.3

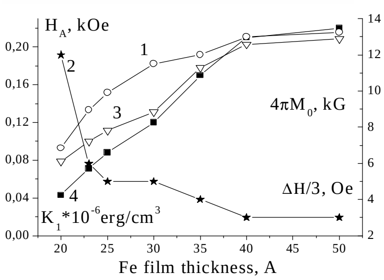
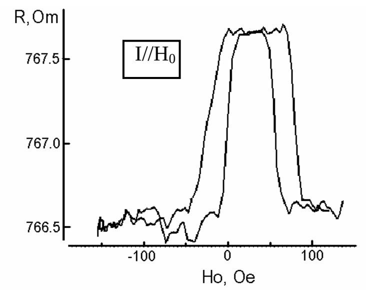


Fig.4



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OUT-OF-PLANE EXCHANGE ANISOTROPY IN (AF/F) NiO/PERMALLOY BI-LAYERS

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The magnetic properties of (antiferro/ferro) NiO/permalloy bi-layers are compared to those of single permalloy films through magnetometric VSM (vibrating sample magnetometry) measurements, ferromagnetic resonance (RF using the strip-line technique) and Brillouin Light Scattering (BLS in backscattering geometry). The samples consist in polycrystalline sputtered films of fixed permalloy thickness (10.4 nm) and, concerning the bi-layers, of variable NiO thickness (from 6 to 47 nm), cooled in presence of an in-plane magnetic field previously to their experimental study. The VSM measurements as well as the RF and BLS spectra obtained under an in-plane applied magnetic field are fully consistent with the conventional model of a magnetic density of energy depending of **H** and of the usual magnetic parameters which can be satisfactorily fitted : M (magnetization), A (stiffness exchange), $H_\perp$ (perpendicular anisotropy field), supplemented, in the case of bi-layers, by an in-plane anisotropy field H_a and a bias exchange field H_e. However, in the case of an out-of-plane applied magnetic field, this model does not account for the experimental results. We introduce a new term in the expression of the density of energy which allows to recover agreement with the observed behaviour whatever is the direction of **H** : this term can be identified as an additional perpendicular anisotropy field $\delta H_{\perp\alpha}$, the amplitude of which is proportional to $\cos[\alpha]$, where α stands for the angle between **H** and the direction normal to the bi-layer ; the value of $\delta H_{\perp 0}$ reaches a few kOe and is then significantly higher than the in-plane terms H_a and H_e ; indeed $\delta H_{\perp\alpha}$ is absent for the single layer. The origin of this out-of-plane exchange anisotropy will be discussed in the communication.

DYNAMIC RESPONSE OF THE MAGNETISATION TO A SUB-PICOSECOND HEAT PULSE

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The dynamic behaviour of ferromagnetic materials at elevated temperatures is currently attracting many researchers from both fundamental (pump-probe experiments) and applied (heat-assisted magnetic recording) points of view. One of the main issues of the high-temperature dynamics is the rate of magnetisation relaxation and switching. In the present work, using the Langevin dynamics simulations with an atomistic spin model, we demonstrate the occurrence of several important effects of the macrospin dynamics at elevated temperatures.

It is found that the ferro- to paramagnetic phase transition can occur on a time scale of less than one picosecond, in agreement with published experimental data. However, the recovery of the magnetisation can take place on very different time scales, depending on the magnetic state after heating. It is on the time scale of picoseconds if the system retains some “memory”' of the initial state, but can take up to two orders of magnitude longer if the magnetic state is completely disordered after heating. The existence of a slow recovery of the magnetisation after full demagnetisation is experimentally confirmed.

We also demonstrate an excellent quantitative agreement between atomistic modelling based on Landau-Lifshitz-Gilbert equation and the macro-spin model based on Landau-Lifshitz-Bloch equation [1]. Consequently, the LLB equation could serve as a basis for micromagnetics at elevated temperatures. Importantly, this equation can be used even for temperatures above T_C and, thus, provides a suitable basis for pump-probe experiment modelling. We demonstrate the capabilities of a micromagnetic LLB equation investigating the temperature dependent magnetisation dynamics of FePt nano-particles [3].

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