International Symposium SPIN WAVES 2024

Saratov, Russia

August 26-29, 2024

Spin Waves 2024
International Symposium

Saratov State University

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The Spin Waves Symposium has traditionally been held for more than 50 years every two-three years in St. Petersburg at Ioffe Institute of the Russian Academy of Sciences. The first organiser of the symposium was Prof. Alexander. G. Gurevich – author of well-known books on the topic of Spin waves.

In 2007, after some break, the Symposium was revived and held again in St. Petersburg. During the 2007-2018 period, Spin Waves Symposia became a forum for active international networking, with organising and program committees including leading researchers from all over the world. Many prominent scientists were attending the meeting and presented their recent results.

In 2024 we start the next chapter in the Symposium history and expand its geography. Spin Waves - 2024 will be held in Saratov - the city where the research on spin waves and their applications is being conducted for several decades.

Organizers

- Kotelnikov Institute of Radio-Engineering and Electronics, RAS
- Saratov State University
- Scientific Council of the Russian Academy of Sciences on Condensed Matter Physics (Section 'Magnetism')

Organizing Committee

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- L.E. Svistov, P.L. Kapitza Institute for Physical Problems, RAS
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- M.A. Morozova, Saratov State University
- S.V. Grigoriev, Petersburg Nucler Physics Instutute, NRC «Kurchatov Institute»
- A.B. Ustinov, St. Petersburg Electrotechnical University «LETI»
- A.A. Mukhin, Prokhorov General Physics Institute, RAS
- A. R. Safin: Kotelnikov Institute of Radio-Engineering and Electronics, RAS
- A.A. Fraerman, Institute for Physics of Microstructures, RAS
- Y.V. Khivintsev: Kotelnikov Institute of Radioengineering and Electronics of RAS, Saratov Branch

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	August 26	August 27		August 28		August 29	
09:30-09:45	Arrival/Registration	**THz spin dynamics** *chair - Ansar Safin*	**I-27-01** Elena Mishina *Efficient THz spintronic emitters with intrinsic amplitude and polarization control*	**Magnonics - I** *chair - Alexander Sadovnikov*	**I-28-01** Alexander Khitun (on-line) *Magnonic combinatorial memory*		
09:45-10:00							
10.00-10.15			**O-27-02** Leonid Shelukhin *Interface-enhanced picosecond THz pulses generation in spintronic emitters Co/Pt*		**O-28-02** Алексей Устинов *Магнонная резервуарная вычислительная система с токовым управлением*	**Low-dimensional and frustrated magnetism- I** *chair - Alexander Mukhin*	**I-29-01** Mike Zhitomirsky (on-line) *Longitudinal magnons: new collective quantum excitations in large-S magnets.*
10:15-10:30			**O-27-03** Evgeny Karashtin *Terahertz radiation by planar spintronic emitter grating*		**O-28-03** Andrei Telegin *DMI modulation in HM/FM heterostructures with a nonmagnetic space layer*		
10.30-10:45			**O-27-04** Natalia Sherstyuk *Control of the order parameters in ferroelectrics using intense THz pulses*		**O-28-04** Maksim Bakhmetiev *Spin-waves probe of percolation threshold in exchange-biased system*		**O-29-02** Mikhail Prosnikov *Spin dynamics and phonon zeeman effect in $CoTiO_3$ revealed by Raman scattering in high magnetic field*
10:45-11:00			**O-27-05** Alexander Mukhin *Electro active Terahertz magnetic excitations in orthoferrites at low temperatures*		**O-28-05** Evgeny Skorokhodov *Investigation of the gyrotropic mode in magnetic vortex system by magnetic resonance force microscopy*		**O-29-03** Vasily Glazkov *Microwave study of the quasy-2D decorated square kagomé lattice magnets $ACu_7(TeO_4)(SO_4)_5Cl$ (A=Na, K, Cs, Rb)*
11.00-11.15			**I-27-06** Evgeny Mashkovich *Nonlinear Terahertz-driven dynamics of order parameters*		**O-28-06** Мария Амельченко *Микромагнитное моделирование ферромагнитного метаматериала в программе MAXLLG*		**O-29-04** Sergey Ovchinnikov *Effect of spin fluctuations on the electronic structure of frustrated 2D strongly correlated systems*
11.15-11.30				Group Photo			**O-29-05** Vera Klekovkina *Analysis of Terahertz absorption spectra and inelastic neutron scattering of frustrated magnet $Tb_2Ti_2O_7$*
11:30-12:00		Coffee-break		Coffee-break		Coffee-break	
12.00-12.15		**Magnetophotonics at ultrafast and ultrasmall scales** *chair - Roman Pisarev*	**I-27-07** Vladimir Belotelov *All-dielectric nanophotonics for optomagnetism*	**Magnonics - II** *chair - Yuri Filimonov*	**I-28-07** Anatolii Rinkevich *Electrodynamics of exchange-coupled metallic nanostructures in magnetic field*	**Low-dimensional and frustrated magnetism - II** *chair - Pavel Maximov*	**I-29-06** Arseny Syromyatnikov *Antiferromagnets with random vacancies and substitutional spins on the triangular lattice*
12:15-12:30							
12.30-12.45			**O-27-08** Pavel Usachev *Time-resolved spin dynamics in EuO probed by photo-induced Faraday effect*		**O-28-08** Andrey Azovtsev *Terahertz antiferromagnetic magnons excited by picosecond strain pulses in NiO*		**O-29-07** Alexander Smirnov *Crossover between pseudospin paramagnet and spin liquid in a chain antiferromagnet Cs_2CoCl_4*
12.45-13.00			**O-27-09** Anatolii Fedianin *Laser-induced THz dynamics of spin correlations in cubic antiferromagnets*		**O-28-09** Petr Gerevenkov *Laser-induced magnetoacoustic wavepackets formation controlled by relative polarizations of SAW and MSW components*		**O-29-08** Elizaveta Dvoretskaya *Nonlinearity of the magnetic susceptibility of a Co{2+} mono-ion magnet in the paramagnetic region above the magnetic ordering temperature*
13:00-13:15			**O-27-10** Iaroslav Filatov *Sagittally propagating magnetoelastic waves excited by localized laser pulse*		**O-28-10** Valentin Sakharov *Bragg resonances of anisotropic spin wave modes and wide band gap formation in subwavelength periodic magnonic structures*		**O-29-09** Леонид Свистов *Магнитные свойства $LiCu_3O_3$ – квазидвумерного антиферромагнетика на квадратной решётке со случайно распределенными магнитными и немагнитными ионами*
13:15-13:30			**O-27-11** Vladimir Skidanov *Exchange coupling between two ferromagnetic metallic nanolayers revealed by transverse Kerr effect*		**O-28-11** Анастасия Бир *Невзаимный параметрический резонанс в 1D и 2D бикомпонентных магнонных кристаллах*		**O-29-10** Тимофей Солдатов *Низкочастотная спиновая динамика квазидвумерного ферро-антиферромагнетика $BaCdVO(PO_4)_2$*

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	August 26	August 27	August 28	August 29
13.30-14:30		Lunch	Lunch	Lunch
14:30-15:00	**Opening**			
15.00-15.15		**Antiferromagnets and exotic magnetic structures** *chair - Leonid Svistov* **I-27-12** Pavel Maksimov *Kitaev materials: the search for spin liquid*	**Artificial and composite magnetic structures** *chair - Sergey Ovchinnikov* **I-28-12** Irina Bobkova *Composite magnetic excitations in superconductor/magnet heterostructures*	**Spintronics** *chair - Sergey Nikitov* **I-29-11** Konstantin Zvezdin *Spintronics – MRAM and beyond*
15:15-15:30	**Topological magnetic structures** *chair - Alexander Moskvin* **I-26-01** Valery Uzdin *"Concrete" theory of topological magnetic solitons*			
15.30-15:45		**O-27-13** Yurii Bunkov *Magnon BEC from 1 mK to room temperature*	**O-28-13** Igor Burmistrov *Localization of magnons at superconducting vortex in chiral magnet - superconductor heterostructure*	**O-29-12** Dmitrii Romanenko *Coherent resonance in a narrowband noise-controlled chaotic spin-wave self-oscillator*
15:45-16:00	**I-26-02** Maksim Sapozhnikov *Dzyaloshinsky-Moriya interaction and topological magnetic states in Co/Pt films*	**O-27-14** Andrey Andrianov *Fermi surface, nesting, and magnetic phase transition: case of the hcp heavy rare-earth metals*		**O-29-13** Mikhail Bazrov *Detection of canted phase in ferrimagnetic structure through spin-orbit torque investigation*
16.00-16.15		**O-27-15** Александр Москвин *Особенности спиновых взаимодействий и спиновых структур в ян-теллеровских магнетиках*	Coffee-break	**O-29-14** Юрий Хивинцев *Спиновая накачка в структуре магнонный кристалл-Pt*
16.15-16.30	**O-26-03** Irina Kalentyeva *Various topological magnetic states in thin ferromagnetic Co/Pd films*	**O-27-16** Alexander Ovsyannikov *Exchange interactions and phase transitions in rare-earth ortoferrites $RFeO_3$ (R=Ho,Tb,Dy)*	**O-28-14** Alexey Drovosekov *Special features of magnetic resonance in metal-insulator nanogranular composites*	**O-29-15** Roman Morgunov (on-line) *Spin-orbit torque probed by brillouin light scattering in NiFe/Ta/IrMn and NiFe/Cu/IrMn structures*
16:30-16:45	**I-26-04** Mikhail Otrokov (on-line) *Intrinsic Magnetic Topological Insulators of the $MnBi_2Te_4$ Family*	**O-27-17** Евгений Васинович *Слабые ферримагнетики типа $YFe_{1-x}Cr_xO_3$: отрицательная намагниченность и спиновая переориентация*	**O-28-15** Lyubov Azarova *The study of spin-wave dynamics in amorphous ferromagnets by the method of small-angle neutron scattering*	**Closing**
16:45-17:00		**O-27-18** Igor Zobkalo *On the antisymmetric and symmetric interactions in multiferroic manganites*	**O-28-16** Alexander Nosov *Thin films of yttrium orthoferrites for antiferromagnetic spintronics*	Coffee-break
17.00-17.15	**Posters-I and coffee (17.00-19.00)**	**Posters-II and coffee (17.00-19.00)**	**O-28-17** Ansar Safin *Electrically tunable sub-Terahertz resonance in antiferromagnet-based heterostructure*	
	Welcome party		**Symposium dinner**	

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Poster session programm
(26/08 and 27/08, 17:30-19:30)

No.	Name	Poster Title
P-01	G. M. Amakhanov	Исследование с помощью обратного спинового эффекта холла спиновой накачки поверхностными магнитостатическими волнами, бегущими в направлениях «легкая» и «трудная» оси намагничивания, в микроструктурах ЖИГ/Pt
P-02	V. V. Balayeva	Spin waves in nanoscale lateral coupled ferrite structure
P-03	T. V. Bogdanova	Controlling the propagation of surface magnetoelastic waves in antiferromagnetic heterostructures
P-04	A. V. Bogomolova	Magnetic field-controlled double negative media based on antiferromagnetic semiconductors for the Terahertz frequency range
P-05	P. T. Bolokhova	Field-induced incommensurate-commensurate transitionsin frustrated magnets
P-06	G. M. Dudko	Микромагнитное моделирование распространения ПМСВ в пленках ЖИГ с кубической анизотропией
P-07	A. A. Fedorova	Spin wave propagation along zigzag-modulated domain wall in iron garnet film
P-08	I. O. Filchenkov	MEMS-controlled zigzag microwave filter
P-09	Yu. A. Filimonov	Влияние вторичных спиновых волн на спиновую накачку параметрическими спиновыми волнами
P-10	D.A. Gabrielyan	Spin pumping on acoustic mode from an antiferromagnet α-Fe2O3 tunable by magnetic field
P-11	F. E. Garanin	Study of spin wave propagation in a YIG film with magnetite nanoparticles
P-12	F. E. Garanin	Study of spin wave propagation in a system of laterally coupled microwave guides
P-13	S. A. Hetmanov	Система шифрования на основе спиновых волн при их распространении в латеральной структуре двух кольцевых резонаторов
P-14	V. M. Gordeeva	Магнон-фотонное взаимодействие в гетероструктурах сверхпроводник/ферромагнетик
P-15	A. M. Kalashnikova	Laser-induced spin-reorientation transitions in iron oxides Fe3O4 and Fe3BO6
P-16	D. V. Kalyabin	Influence of external pressure on the THz mode in the antiferromagnet α−Fe2O3
P-17	S. N. Kashin	Spin dynamics of the ferromagnet–helical transition in Holmium films
P-18	A. A. Kholin	Epitaxial films of YIG with symmetric diamagnetic boundary conditions
P-19	P. S. Komkov	Когерентный резонанс в широкополосных микроволновых спин-волновых генераторах хаоса под воздействием шума
P-20	E.E. Kozlova	Terahertz spin pumping on antiferromagnetic mode from Cobalt oxide
P-21	V. Ya. Krivnov	Magnetic properties of ferro-antiferromagnetic spin triangle chain
P-22	M. A. Kuznetsova	Dzyaloshiskii-Moriya interaction in Pt/Co/CoO thin films
P-23	M. E. Letushev	Change of magnetic dominance type in the ferrimagnetic system Pt/CoGd/W
P-24	N. D. Lobanov	Bragg resonances in coupled magnon crystals with different periods
P-25	N. D. Lobanov	Influence of spin hall effect in the layered structure of magnon crystal/normal metal/magnon crystal
P-26	A. A. Martyshkin	Propagation of spin waves in a ferrite film with a periodic semiconductor array of stripes on top of the surface
P-27	R. V. Masliy	Controlled modes of propagation of a spin-wave signal in lateral Gigamodes with an orthogonal element
P-28	A. A. Matveev	Control of the gain bandwidth for the microwave signals in a spin transfer nanoscillator using an external magnetic field
P-29	O. V. Matveev	Spin waves demultiplexing using spin current
P-30	A. A. Meshcheryakov	Исследование явления гибридизации мод в гетероструктуре антиферромагнетик/ферромагнетик
P-31	A. Yu. Mitrofanova	Dynamics of coupled antiferromagnetic oscillators
P-32	M. A. Morozova	Брэговские резонансы в мультиферроидной структуре YIG/HZO
P-33	Yu. V. Nikulin	Влияние локальной тепловой неоднородности на спиновую накачку в структуре ЖИГ/Pt
P-34	V. V. Pavlov	Ultrafast magneto-optical phenomena in magnetic semiconductors EuX (X = Te, Se, O)
P-35	R. V. Pisarev	Magnetic excitations and spin-phonon coupling in the CoF2 antiferromagnet
P-36	V. D. Poimanov	Подавление обменных спиновых волн в пленке с частичным магнитным покрытием
P-37	A. V. Prikhodchenko	Structure implications on magnet characteristics of Pt/Co/MgO and WTe2/Pt/Co/MgO films
P-38	K. A. Pshenichniy	Измерение спинволновой динамики в геликоидальных магнетиках методом малоуглового рассеяния нейтронов
P-39	A. S. Ptashenko	Investigation of spin wave dispersion in multilayer ferromagnetic structures with periodic metallic screen
P-40	A. B. Rinkevich	Magnetic susceptibility of frustrated Yb2Ti2O7 nanocomposite
P-41	A. B. Rinkevich	Microwave properties of 3d ferromagnetic nanocomposites Fe/epoxy with particle clustering
P-42	A. V. Sadovnikov	Non reciprocal propagetion of spin waves in a metal-coated YIG adjacent stripes
P-43	A. F. Shishelov	Domain structure of epitaxial superlattices Pd/Co/CoO

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Poster session programm
(26/08 and 27/08, 17:30-19:30)

P-44	M. E. Seleznev	Обратный спиновый эффект холла в структуре ЖИГ – платина на основе пленки ЖИГ с пониженной намагниченностью насыщения
P-45	A. V. Telegin	Picosecond carrier dynamics in CdCr2Se4 ferromagnetic spinel
P-46	O. S. Temnaya	Control of magnon-polariton coupled modes in toroidal cavity
P-47	O. V. Usmanov	CEF parameters and magnetic properties correlations in rare-earth orthoferrites RFeO3 (R = Ho, Tb, Tm)
P-48	A. B. Ustivon	Моделирование комплексного коэффициента прохождения активного кольцевого резонатора на магнонном кристалле
P-49	A. B. Ustivon	Модель магнонного микрорезервуара на основе нанометровых пленок ЖИГ
P-50	A. B. Ustivon	Спин-волновая линия задержки на основе керамической пластины ЖИГ для резервуарных компьютеров
P-51	D. A. Volkov	Influence of polarization type on ferromagnetic resonance
P-52	S. L. Vysotskiy	Обратный спиновый эффект холла в структуре ЖИГ(111)-платина в малых полях подмагничивания

International Symposium Spin Waves 2024
Oral Session Program

Topological magnetic structures

I-26-01 **V.M. Uzdin**, I.S. Lobanov, “CONCRETE” TEORY OF TOPOLOGICAL MAGNETIC SOLITONS

I-26-02 **M.V. Sapozhnikov**, DZYALOSHINSKY-MORIYA INTERACTION AND TOPOLOGICAL MAGNETIC STATES IN Co/Pt FILMS

O-26-03 **I.L. Kalentyeva**, M.V. Dorokhin, A.V. Zdoroveyshchev, R.N. Kryukov, D.A. Tatarskiy, M.P. Temiryazeva, A.G. Temiryazev, A.V. Sadovnikov, VARIOUS TOPOLOGICAL MAGNETIC STATES IN THIN FERROMAGNETIC Co/Pd FILMS

I-26-04 **M. Otrokov**, INTRINSIC MAGNETIC TOPOLOGICAL INSULATORS OF THE MnBi2Te4 FAMILY

THz spin dynamics

I-27-01 **E.D. Mishina**, A.M. Buryakov, M.V. Sapozhnikov, V.L. Preobrazhensky, EFFICIENT THZ SPINTRONIC EMITTERS WITH INTRINSIC AMPLITUDE AND POLARIZATION CONTROL

O-27-02 **L.A. Shelukhin**, A.V. Kuzikova, A.V. Telegin, V.D. Bessonov, A.M. Kalashnikova, INTERFACE-ENHANCED PICOSECOND THz PULSES GENERATION IN SPINTRONIC EMITTERS Co/Pt

O-27-03 **E.A. Karashtin**, N.S. Gusev, M.V. Sapozhnikov, P.Yu. Avdeev, E.D. Lebedeva, A.M. Buryakov, TERAHERTZ RADIATION BY PLANAR SPINTRONIC EMITTER GRATING

O-27-04 E.D. Mishina, K.A. Brekhov, **N.E. Sherstyuk**, CONTROL OF THE ORDER PARAMETER IN FERROELECTRICS USING INTENSE THZ PULSES

O-27-05 **A.A. Mukhin**, A.M. Kuzmenko, V.Y. Ivanov, A.Yu. Tikhanovskii, G.A. Komandin, ELECTRO ACTIVE TERAHERTZ MAGNETIC EXCITATIONS IN ORTHOFERRITES AT LOW TEMPERATURES

I-27-06 **E. Mashkovich**, NONLINEAR TERAHERTZ-DRIVEN DYNAMICS OF ORDER PARAMETERS

Magnetophotonics at ultrafast and ultrasmall scales

I-27-07 **V.I. Belotelov**, ALL-DIELECTRIC NANOPHOTONICS FOR OPTOMAGNETISM

O-27-08 **P.A. Usachev**, L.A. Shelukhin, V.N. Kats, D.V. Averyanov, I.S. Sokolov, O.E. Parfenov, A.N. Taldenkov, A.M. Tokmachev, V.G. Storchak, V.V. Pavlov, TIME-RESOLVED SPIN DYNAMICS IN EuO PROBED BY PHOTO-INDUCED FARADAY EFFECT

O-27-09 **A.E. Fedianin**, A.M. Kalashnikova, J.H. Mentink, LASER-INDUCED THZ DYNAMICS OF SPIN CORRELATIONS IN CUBIC ANTIFERROMAGNETS

O-27-10 **Ia.A. Filatov**, P.I. Gerevenkov, N.E. Khokhlov, A.M. Kalashnikova, SAGITTALLY PROPAGATING MAGNETOELASTIC WAVES EXCITED BY LOCALIZED LASER PULSE

O-27-11 **V.A. Skidanov**, EXCHANGE COUPLING BETWEEN TWO FERROMAGNETIC METALLIC NANOLAYERS REVEALED BY TRANSVERSE KERR EFFECT

Antiferromagnets and exotic magnetic structures

I-27-12 **P.A. Maksimov**, KITAEV MATERIALS: THE SEARCH FOR SPIN LIQUID

O-27-13 **Yu.M. Bunkov**, MAGNON BEC FROM 1 mK TO ROOM TEMPERATURE

O-27-14 **A.V. Andrianov,** FERMI SURFACE, NESTING, AND MAGNETIC PHASE TRANSITION: CASE OF THE HCP HEAVY RARE-EARTH METALS

O-27-15 **А.С. Москвин,** ОСОБЕННОСТИ СПИНОВЫХ ВЗАИМОДЕЙСТВИЙ И СПИНОВЫХ СТРУКТУР В ЯН-ТЕЛЛЕРОВСКИХ МАГНЕТИКАХ

O-27-16 **A.K. Ovsianikov**, O.V. Usmanov, I.A. Zobkalo, EXCANGE INTERACTIONS AND PHASE TRANSITIONS IN RARE-EARTH ORTOFERRITES $RFeO_3$ (R=Ho,Tb,Dy)

O-27-17 **Е.В. Васинович**, А.С. Москвин, СЛАБЫЕ ФЕРРИМАГНЕТИКИ ТИПА $YFe_{1-x}Cr_xO_3$: ОТРИЦАТЕЛЬНАЯ НАМАГНИЧЕННОСТЬ И СПИНОВАЯ ПЕРЕОРИЕНТАЦИЯ

O-27-18 **I.A. Zobkalo,** ON THE ANTISYMMETRIC AND SIMMETRIC INTERACTIONS IN MULTIFERROIC MANGANITES

Magnonics - I

I-28-01 **A. Khitun**, MAGNONIC COMBINATORIAL MEMORY

O-28-02 Р.В. Гапончик, М.П. Костылев, **А.Б. Устинов**, МАГНОННАЯ РЕЗЕРВУАРНАЯ ВЫЧИСЛИТЕЛЬНАЯ СИСТЕМА С ТОКОВЫМ УПРАВЛЕНИЕМ

O-28-03 **A.V. Telegin**, V.A. Bessonova, Y.K. Kim, A.S. Samaradak, DMI MODULATION IN HM/FM HETEROSTRUCTURES WITH A NONMAGNETIC SPACE LAYER

O-28-04 **M.V. Bakhmetiev,** R.B. Morgunov, SPIN-WAVES PROBE OF PERCOLATION THRESHOLDIN EXCHANGE-BIASED SYSTEM

O-28-05 **E.V. Skorokhodov**, V.L. Mironov, D.A. Tatarsky, A.A. Fraerman, INVESTIGATION OF THE GYROTROPIC MODE IN MAGNETIC VORTEX SYSTEM BY MAGNETIC RESONANCE FORCE MICROSCOPY

O-28-06 **М.Д. Амельченко**, Ф.Ю. Огрин, С.В. Гришин, МИКРОМАГНИТНОЕ МОДЕЛИРОВАНИЕ ФЕРРОМАГНИТНОГО МЕТАМАТЕРИАЛА В ПРОГРАММЕ MAXLLG

Magnonics - II

I-28-07 **A.B. Rinkevich**, D.V. Perov, M.A. Milyaev, V.V. Ustinov, ELECTRODYNAMICS OF EXCHANGE-COUPLED METALLIC NANOSTRUCTURES IN MAGNETIC FIELD

O-28-08 **A.V. Azovtsev**, N.A. Pertsev, TERAHERTZ ANTIFERROMAGNETIC MAGNONS EXCITED BY PICOSECOND STRAIN PULSES IN NiO

O-28-09 **P.I. Gerevenkov**, Ia.A. Mogunov, Ia.A. Filatov, N.S. Gusev, M.V. Sapozhnikov, N.E. Khokhlov, A.M. Kalashnikova, LASER-INDUCED MAGNETOACOUSTIC WAVE PACKETS FORMATION CONTROLLED BY RELATIVE POLARIZATIONS OF SAW AND MSW COMPONENTS

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Topological magnetic structures

"CONCRETE" TEORY OF TOPOLOGICAL MAGNETIC SOLITONS

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Magnetic topological structures such as skyrmions, hopfions, torons and other "topological solitons" are of great interest both for fundamental science and for storing, processing and displaying information in new spintronics technologies. An important factor for any practical applications is the stability of such systems with respect to thermal fluctuations and random external perturbations. This draws additional attention to the nature of so named *topological protection* of magnetic systems from fluctuations. Such protection may be associated with the existence of topological indices, which are integer numbers that are preserved during continuous magnetization transformations. If these numbers are different for two magnetic states, then continuous transformations of magnetization cannot lead to a transition from one state to another.

For magnetic moments localized on a discrete lattice, topological considerations, strictly speaking, are not applicable. Here we can only talk about the size and shape of the energy barriers separating topologically different (in the continuous limit) states. The relationship between stability in continuous and discrete models will be discussed based on transition state theory for magnetic degrees of freedom. This approach involves constructing the energy surface of a magnetic system as a functional of all variables that uniquely determine the magnetic configuration. Local minima on this surface define the ground and metastable states, and the minimum energy paths between them indicate the most likely scenario for the magnetic transition. In the harmonic approximation for the shape of the energy surface in the vicinity of minima and saddle points, the lifetime of magnetic states can be calculated [1].

A scaling theory has been developed that makes it possible to reduce the lattice constant while maintaining the size and shape of the topological soliton [2,3]. It is shown how the activation energy and the pre-exponential factor in the Arrhenius law change as the lattice constant tends to zero. The calculations carried out shed light on the nature of stability and topological protection mechanisms of magnetic skyrmions.

When calculating the dynamics of magnetic topological systems, a comparison is made of the simulation results based on the Landau-Lifshitz-Gilbert equation and the generalized Thiel equation, which considers a given set of low-energy excitations of the equilibrium magnetic structure. The importance of preserving the Hamilton structure of the equations of motion when moving to a reduced description is shown [4].

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DZYALOSHINSKY-MORIYA INTERACTION AND TOPOLOGICAL MAGNETIC STATES IN Co/Pt FILMS

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The presented talk reports the results of work at the IPM RAS on the study of the properties of magnetic states, including topological ones, observed in Co/Pt films, and the possibility of controlling the properties of magnetic states using deformations and ion irradiation. Multilayer and bilayer CoPt films were obtained by magnetron sputtering. The ultra-thin thickness of the layers (0.5-1 nm) leads to the fact that effects associated with the boundaries of the layers begin to play a significant role. This leads to the appearance of perpendicular magnetic anisotropy and surface Dzyaloshinsky-Moriya interaction (DMI) in such structures.

We investigated two ways to change the material parameters of the samples, which led to the possibility of controlling their magnetic properties. The first method is irradiation with He+ ions, with an energy of 30 kEV and fluences of 10^{14}-10^{16} cm^{-2}. Such irradiation will disrupt the homogeneity of the layer boundaries, which leads to a decrease in perpendicular magnetic anisotropy, which was known previously. At the same time, we discovered that DMI depends on the radiation fluence non-uniformly and at average doses can increase several times.

Using FIB, irradiation with helium ions can be performed locally, and thus we lithographed 2D lattices of locally irradiated areas with a diameter of 100-400 nm. These regions with locally changed material parameters serve as pinning centers for magnetic skyrmions and make it possible to create lattices of magnetic skyrmions with a high topological charge density. This allowed us to study the topological Hall effect in such systems. To directly measure the topological Hall effect, we have developed a technique for simultaneously measuring the value of the total Hall effect and the magneto-optical Kerr effect (Fig. 1). The magnetic skyrmions themselves were studied by Lorentz transmission electron microscopy (LTEM). It was discovered that the structure of skyrmions depends on the diameter of the region in which they are pinned

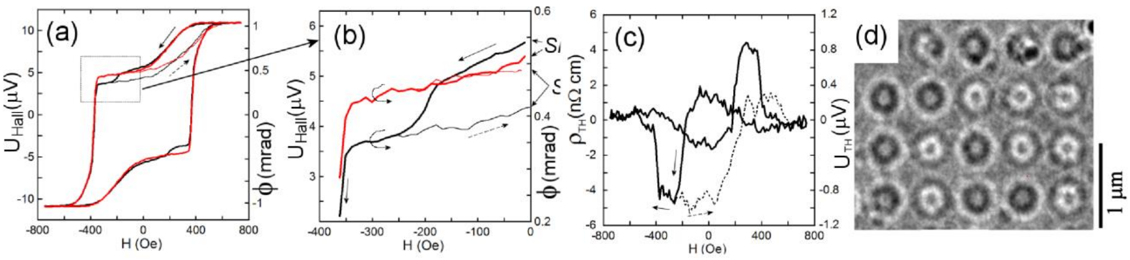

Fig. 1. (a) (a) MOKE hysteresis loops (red line) and Hall effect (black line) for the nanostuctured Co/Pt film, plotted on the same scale. Minor loops are drawn with thinner lines. (b) Detail view of a step on the Hall curve which occurs at the moment of formation of the skyrmion lattice. (c) Hysteresis curve of the topological Hall effect. The dotted line is the minor hysteresis loop. (d) LTEM image of a lattice of skyrmions in nanostructured Co/Pt film.

The second method we investigated for controlling the magnetic states of Co/Pt films is elastic deformation. Strain can be applied to the samples either by bending the substrate on which the magnetic film is deposited (uniaxial strain) or by applying an electric field to the Co/Pt/ferroelectric structure. In the latter case, the symmetry of the

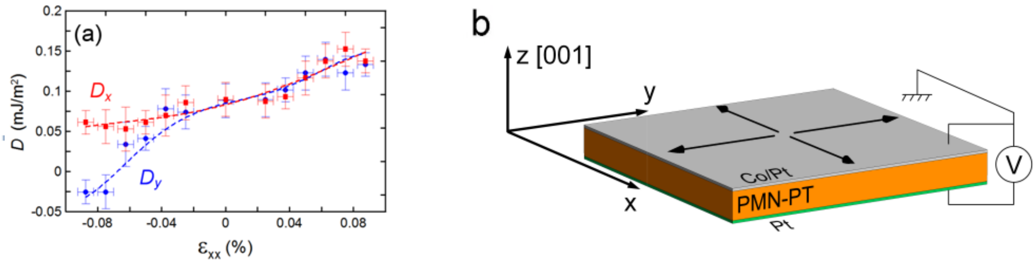

Fig. 2. (a) iDMI constants (Dx; y) measured along the x and y directions as a function of the applied strain (the case uniaxial strane). (b) Scheme of measuring a sample on a ferroelectric substrate (uniform deformations)

deformation depends on the symmetry of the ferroelectric substrate surface (Fig. 2).

In the course of this study, we discovered that deformations of 0.01% (ultimate strength of the samples), depending on the specific situation, can lead to an increase in DMI by a factor of 2, a decrease in DMI and a change in its sign, as well as the appearance of anisotropic DMI. In the latter case, the DMI constants along different axes have different signs. Such a significant change in DMI leads to a change in the magnetic structure of the images. We theoretically predicted and then experimentally discovered zigzag domain structures that are realized in a system with anisotropic DMI (Fig. 3). During the studies, the DMI value was measured using BLS methods, and the magnetic states of the samples were studied using magnetic force microscopy. Due to the possibility of using an electric field to control the magnetic properties of Co/PT/ferroelectric structures, they can be considered as promising systems for practical applications.

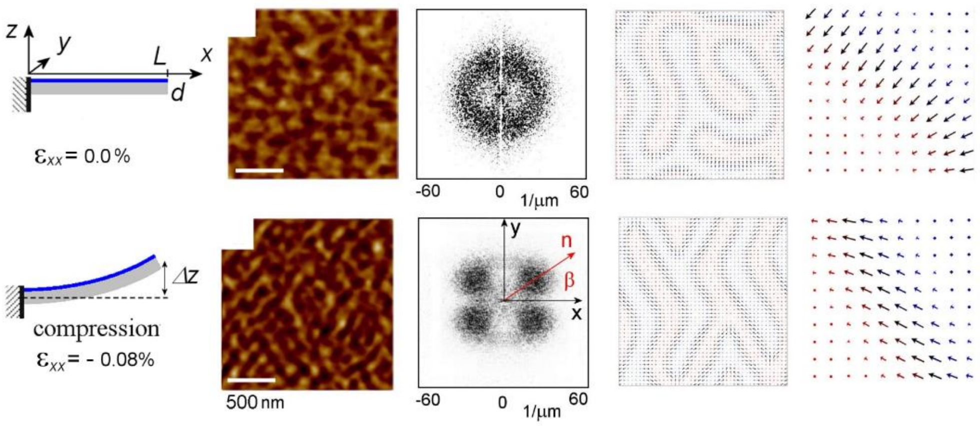

Fig. 3. First column: Measurement geometry for uniaxial strain. The gray part of the sample is the substrate and the blue part is the multilayer magnetic film. One end of the sample is fixed, while the other can be bent, causing deformation of the magnetic film. The corresponding strains ε_{xx} are indicated. Second column: MFM images of domains obtained under the corresponding strains. Third column: corresponding spatial Fourier spectra of domain structures. The deformation is applied along the x axis. Fourth column: domain structures obtained by micromagnetic modeling methods. Fifth column: enlarged image of domain walls

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VARIOUS TOPOLOGICAL MAGNETIC STATES IN THIN FERROMAGNETIC Co/Pd FILMS

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Thin multilayer ferromagnetic/heavy metal films are considered promising media for magnetic recording, and Co/Pd films are a good example of such materials. This work will present studies of the magnetic properties and micromagnetic structure of multilayer Co/Pd films with different bilayer thicknesses ($[Co(0.3\times t\ nm)/Pd(0.5\times t\ nm)]_{10}$), but with the same Co and Pd ratio. The choice of layer thicknesses and tooling values (t = 0.9-1.3) was based on our earlier results on multilayer Co/Pt films [1,2].

The samples under study were successively deposited on Si, GaAs and Si_3N_4 substrates by electron beam evaporation at 300°C with a tenfold repetition. Transmission electron microscopy (TEM) and X-ray diffraction (XRD) studies suggest that the films studied are highly mixed alloys. Using magnetic force microscopy (MSM) and Lorentz transmission electron microscopy (L-TEM), the presence of various micromagnetic features in the films was shown (fig.1). Along with the well-known 360º-domain walls and skyrmions, some new features were discovered that were interpreted as skyrmioniums and a combination of skyrmioniums with domain walls.

It was found that the type and density of micromagnetic features strongly depend on the value of the tooling coefficient t. The effect is associated with the peculiarities of interfacial magnetic interactions in samples with highly mixed interfaces.

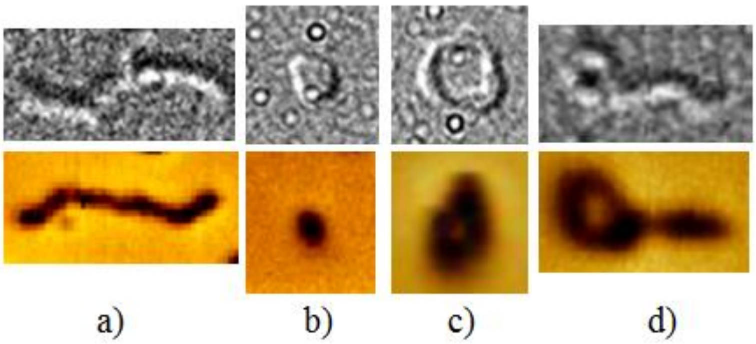

Fig. 1. Magnetic topological states found in the studied samples: 360° domain walls (a), skyrmions (b), skyrmioniums (c) and a combination of domain wall and skyrmionium (d).

This work was supported by RNF (#21-79-20186).

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INTRINSIC MAGNETIC TOPOLOGICAL INSULATORS OF THE MnBi2Te4 FAMILY

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Recently, MnBi2Te4 has been theoretically predicted and then experimentally confirmed to be the first intrinsic antiferromagnetic TI (AFMTI) [1-3]. This opens a new field that focuses on intrinsically magnetic stoichiometric compounds: several MnBi2Te4-derived MTIs were synthesized right away [4], such as (MnBi2Te4)·n(Bi2Te3), MnBi2−xSbxTe4, (MnSb2Te4)·n(Sb2Te3), Mn2(Bi,Sb)2Te5, and MnBi2Se4. As a result, MnBi2Te4 and related compounds have been predicted to be a platform for realizing highorder topological insulator and superconductor states, Weyl semimetal phase, skyrmions, quantized magnetoeletric coupling, and Majorana fermions. Moreover, MnBi2Te4-based systems are predicted and/or observed to show 12 different types of Hall effect [5,6], some of them are fundamentally new, such as the layer Hall effect [6]. A number of technological applications have also been envisioned, in particular, chiral interconnect devices based on the high-Chern-number topological heterostructures [7].

Concerning current challenges of this field, we will discuss the issue of the Dirac point gap in the MnBi2Te4 topological surface state that caused a lot of controversy. While the early experimental measurements reported on large gaps, in agreement with ab initio calculations, a number of further studies claimed to observe a gapless dispersion of the MnBi2Te4 Dirac cone. A number of possible theoretical explanations of this unexpected behavior have been put forward, which we will discuss in the context of the available experimental data [8,9].

I acknowledge the support by MCIN/AEI/10.13039/501100011033/ (Grant PID2022-138210NB-I00) and "ERDF A way of making Europe", by Ayuda CEX2023-001286-S financiada por MICIU/AEI/10.13039/501100011033, as well as MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1) promoted by the Government of Aragon.

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THz spin dynamics

EFFICIENT THZ SPINTRONIC EMITTERS WITH INTRINSIC AMPLITUDE AND POLARIZATION CONTROL

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Of the main THz emitters—nonlinear crystals, both organic and inorganic, semiconductor antennas, and spintronic emitters—spintronics provides the most wide spectrum and intrinsic parameter control. Here, we present spintronic emitters based on in-plane anisotropy magnetic nanostructures that uniquely regulate the amplitude and polarization of THz waves using only magnetic field strength.

Two types of magnetic nanostructures were fabricated by magnetron sputtering in magnetic field: Co/Pt bilayers and spin valves based on Co/Pt and FeCoTb containing multilayers. To measure the parameters of THz generation we utilized the conventional method of THz time-domain spectroscopy [1].

Co/Pt emitters operate based on the inverse spin-Hall effect (ISHE), where a THz wave is created by a charge current flowing in a platinum layer, which in turn is created by a spin current generated in the layer. The direction of polarization of the emitted THz waves from ISHE depends on the direction of the injected spin current and the spin polarization of the electrons, which is opposite to the magnetization. The orientation and strength of the magnetizing field determine both the magnetization and polarization of the THz wave, with the polarization perpendicular to the magnetization.

In the Co/Pt bilayer, magnetic field should be directed along the hard axis. Then by the magnetic field ramp within the anisotropy field, magnetization rotates by 180^o without changing its value. It gives rise to the THz wave polarization rotation by 180^o as well while its amplitude remains constant. Thus, the proposed structure is a pure polarization rotator.

In the spin valves, magnetic field should be directed along the easy axis of magnetization. The for two types of valves mechanisms are different. In Co/Pt/Co/IrMn structure, antiferromagnetic IrMn layer provides pinning of magnetization direction in the neighboring Co layer. For unmagnetized structure, magnetization in two Co layers is are antiparallel. Then charge currents are parallel and enhances the generated THz field. When magnetic field higher than coercive field H_C, is applied to the structure, magnetizations in two Co layers become parallel. Then the charge currents from two sources, directed antiparallel, cancel each other, resulting in almost zero THz field. Modulating magnetic field provides modulation of THz wave amplitude with very high efficiency. For FeCoTb/Cu/FeCoTb structure, FeCoTb layers provide two independent sources of THz waves, while copper control the value of magnetization. Modulation of magnetization around coercive field of softer FeCoTb component gives rise of amplitude modulation around 30%.

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INTERFACE-ENHANCED PICOSECOND THz PULSES GENERATION IN SPINTRONIC EMITTERS Co/Pt

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Generation of electromagnetic radiation in the terahertz (THz) frequency range is a fundamental problem, and sources of such radiation are in demand in a number of applications [1]. Spintronic emitters are promising sources of broadband pulses with frequencies from fractions of THz up to 20 THz [2]. However, the radiation intensity of such sources is still inferior to alternatives, in particular, generators based on nonlinear optical effects in lithium niobate and organic crystals [3]. Therefore, it is necessary to optimize the structures for spintronic emitters.

The aim of this work is to determine the effect of the ferromagnet/heavy metal (FM/HM) interface on the efficiency of converting optical femtosecond laser pulses to THz pulses. For this purpose, a series of heterostructures and Co-Pt alloys with different interfaces was selected (in brackets, layer thicknesses in nm):

1) Si/Ta(2)/Pt(3)/Co(1.2)/Ta(2), a structure with a sharp FM/HM interface;

2) Si/Ta(2)/$Co_{75}Pt_{25}$(4.6)/Ta(2) — FM-HM alloy;

3) Si/Ta(2)/Pt(3)/$Co_{25}Pt_{75}$(0.4)/$Co_{50}Pt_{50}$(0.4)/$Co_{75}Pt_{25}$(0.4)/Co(1.2)/Ta(2) — structure with gradient FM/HM interface.

Time-resolved THz spectroscopy was used as the main technique. A femtosecond laser pulse with a central wavelength of 800 nm and fluence up to 15 mJ/cm^2 induced ultrafast demagnetization up to 30 % in ferromagnetic layers. As a result, a spin-polarized current pulse is injected into the platinum layer, which is converted into a transverse electric current pulse due to the inverse spin Hall effect (ISHE). This is the source of a picosecond pulse of THz radiation. It was detected by electro-optical sampling.

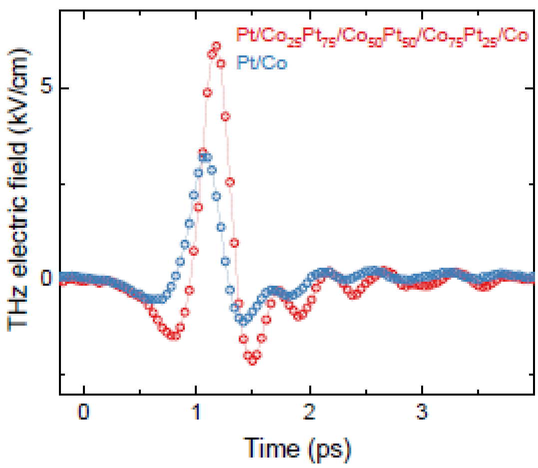

Fig. 1. Time profile of THz emission obtained by laser-induced excitation of Co/Pt structure with sharp interface (blue symbols) and multilayer structure with gradient interface between Co and Pt (red symbols).

THz radiation generation with a maximum frequency of 3 THz was observed in all the studied structures. In structure #3 with a gradient Co-Pt interface, the energy conversion is the highest. The peak electric field obtained at the fluence 2.5 mJ/cm2 in such a structure reached 6 kV/cm (see Fig. 1), being 2 times higher than in structure #1 with a sharp interface, and also exceeds the typical values for samples of this composition [4].

A similar trend in the Dzyaloshinsky-Moriya interface interaction (iDMI) was previously observed for these samples [5]. Thus, the interface design has a significant impact on the spin-orbit effects responsible for both iDMI and ISHE and the associated THz emission.

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TERAHERTZ RADIATION BY PLANAR SPINTRONIC EMITTER GRATING

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In the last decade, promising sources of THz radiation based on a multilayer magnetic nanostructure, which consists of a thin ferromagnetic layer (FM) having a boundary with a thin layer of normal (usually heavy) metal (NM), have been actively studied. It is known that such a structure can act as a broadband THz emitter, comparable in efficiency to semiconductor analogues [1, 2]. When such a system is irradiated with a femtosecond optical pulse of high intensity, a short pulse of "pure" spin current flows from the FM to the NM. This spin current induces an electric current due to the inverse spin Hall effect in the NM. Such time-dependent electric current emits a short and broadband electromagnetic wave pulse corresponding to the terahertz frequency range. Recently, a structure with two iron layers separated by a 4 nm thick platinum layer was studied [2]. Buth Fe layers inject spin current into Pt. The electric current generated in platinum is either compensated for the ferromagnetic state of the system or summed for the antiferromagnetic state. Thus, it is possible to control the emission of the THz signal by an external magnetic field applied to the system. The limitation for such a system is the presence of other boundary layers near the iron layers. In particular, the antiferromagnet IrMn also emits THz signal due to the same mechanism, but roughly ten times less effective than Pt [4]. Therefore, the ratio of signal intensity in the "on" and "off" states of the device is approximately 15.

In this work, the spintronic emitter gratings are studied which are periodic systems of stripes made of thin films of a ferromagnet / heavy metal (in particular, Co(2nm)/Pt(2nm) or W(2nm)/Co(2nm)/Pt(2nm) manufactured by magnetron sputtering). The stripe width varies from 2 μm to 500 μm, and the period is 4-1000 μm. We show that the amplitude of THz signal radiated by such gratings depends on whether they are magnitized along or perpendicular to stripes (it is greater for the perpendicular direction of magnetization with respect to the stripe orientation than for the parallel one). As the period of the structure decreases, the ratio of the amplitudes of THz radiation increases. This is explained by the fact that the electric current resulting from the inverse spin Hall effect flows either along or across the stripes, respectively. With a structure period of 1000 μm (and stripe width 500 μm), there is practically no difference in the signals. The observable difference appears for the period of 300 μm and stripe width of 150 μm (Fig.1 (a)). The structure with a period of 100 μm (stripe width 50 μm) provides a two-fold difference (Fig.1 (b)), and with a period of 50 μm (stripe width 25 μm) — three times. This is explained by the fact that the period of the structure becomes smaller than the characteristic wavelength of the radiation (300 μm for a frequency of 1 THz), which makes it possible to effectively control the emission of the THz signal by applying an external magnetic field. In this case, there are no fundamental restrictions on the ratio of signals in the "on" and "off" states of the device: as the width of the stripes decreases the effect increases. Besides, the efficiency of such spintronic emitter may be increased by decreasing the distance between the stripes in the grating. In order to demonstrate this we study gratings with stripe width equal to 6 μm and 2 μm. Studying the polarization dependence of the emitted THz signal provides information regarding remagnetization of the stripes.

We also demonstrate that the emission spectrum of a THz signal from periodic structures depends on the angle between the normal to the structure and the THz wave detector. In particular, installing a non-transmitting screen near the normal direction leads to a shift of the spectral maximum to lower frequencies (about 0.5 THz). On the other hand, selecting a region near the normal direction using a diaphragm leads to a shift of the maximum in the emission spectrum to higher frequencies (about 1.5 THz). This is due to the fact that the periodic structure is an antenna array. Most noticeable effect is obtainde for large periods (300-1000 µm).

Thus, the periodic system of stripes based on multilayer spintronic terahertz emitters with a period of the order of 10-1000 µm makes it possible to effectively control the amplitude of THz radiation by applying a magnetic field, as well as the radiation spectrum by installing a diaphragm.

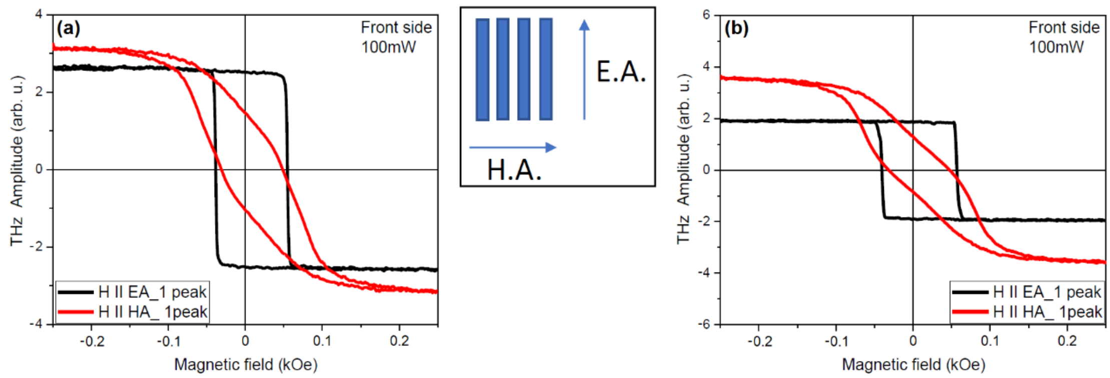

Fig. 1. The peak-to-peak terahertz amplitude dependence on the magnetic field applied either parallel (black line, E.A.) or perpendicular (red line, H.A.) to stripes made of a Co(2nm)/Pt(2nm) structure on a quartz substrate for (a) grating period 300 µm, stripe width 150 µm and (b) grating period 100 µm, stripe width 50 µm. The schematic of the stripes is shown in the inset in the middle.

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CONTROL OF THE ORDER PARAMETER IN FERROELECTRICS USING INTENSE THZ PULSES

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The development of modern laser and terahertz technologies has made it possible to identify a number of promising practical applications of THz radiation and the effects it causes in ferroic materials. The main advantage of using THz radiation for ferroics is the ability to directly influence the state of the order parameter without using electrodes, which allows manipulating this state in a shorter time than "traditional" electronic device technologies allow. This effect allows us to move to all-optical switching and further to all-optical computing with minimal energy losses on the element. For ultrashort time ranges, recording changes caused by the electric/magnetic field of a laser (THz) pulse is a rather complex task, which often cannot be solved by conventional electrophysical methods. In this regard, optical methods such as linear and nonlinear (SHG) spectroscopy and microscopy come to the fore.

Here we report the results of experimental studies of polarization modulation induced by strong picosecond THz pulse in well-known ferroelectric materials: $SrTiO_3$, Si-doped PbGeO and TGS single crystals, $BaSrTiO_3$ and BiTiO thin films. Studies of ultrafast polarization modulation were carried out using the method of nonlinear optical spectroscopy, where the SHG intensity served as a measure of THz-induced polarization due to the general proportionality of the SH field to the ferroelectric polarization vector. The dependencies of the SHG intensity on the THz field and polarization hysteresis loops as well as the models for ultrafast THz-induced polarization modulation, are discussed. Theoretical modeling was carried out based on the Landau-Khalatnikov equation and the Duffing equation. The direct influence of the field on the soft regime under conditions of oscillatory and relaxation dynamics was considered.

The results of the impact of a powerful THz pulse on ferroelectrics, obtained by the THz pump – SHG probe, show that such an impact only leads to a dynamic switching of polarization, i.e. after the end of exposure to the THz pulse, the system returns to its initial state. However, theoretical calculations show that such a switch is possible when certain experimental conditions are achieved, which are currently not realized. The factors influencing the dynamic nonlinear optical response include, first of all, the magnitude of the THz pulse power.

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ELECTRO ACTIVE TERAHERTZ MAGNETIC EXCITATIONS IN ORTHOFERRITES AT LOW TEMPERATURES

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Rare earth (R) orthoferrites $RFeO_3$ are centrosymmetric orthorhombic (Pbnm) weak ferromagnets possessing rich magnetic properties, in particular, various spin-reorientation transitions, determined by anisotropic R-Fe interactions. Rare earth ions occupy non-centrosymmetric positions (C_s) allowing local magnetoelectric coupling, unlike Fe^{3+} ones, which at high temperatures determine a centrosymmetric magnetic structure forbidding magnetoelectric effects. However, at low temperatures, $T < 3$-4 K, when rare earth ions (Tb, Dy, …) are ordered into non-centrosymmetric structures, magnetoelectric phenomena associated with the manifestation of electric polarization [1-3] and electroactive magnetic excitations [4], become allowed.

Here we report on comprehensive terahertz studies of magnetic excitations in $TbFeO_3$ orthoferrite which exhibits at 6 - 8 K, the iron spin reorientation from the *a* axis to the *c* axis, i.e. from $\Gamma_4(G_xF_z)$ to $\Gamma_2(G_zF_x)$ structure, and with a further temperature decrease, an antiferromagnetic ordering of Tb^{3+} Ising moments occurs into $\Gamma_8(a_xg_y)$ configuration at ~3.5 K, which is accompanied by the reorientation of Fe^{3+} spins back to the Γ_4 high temperature structure. Polarized transmission spectra of single crystalline $TbFeO_3$ plates of a- and c-cuts were measured using a coherent quasimonochromatic spectrometer with frequency tunable generators based on the backward wave oscillator at frequencies 3-33 cm^{-1} as well as an original pulsed time-domain terahertz spectrometer (TDS) at frequencies 7-80 cm^{-1} at temperatures 1.8 – 300 K. Dramatic evolution of the two antiferromagnetic resonance (AFMR) modes of the Fe –subsystem, quasiferromagnetic, M_1 and quasiantiferromagnetic M_2, was observed during the spontaneous reorientation transitions. Among them, the most remarkable is the manifestation of the electroactivity of the AFMR modes below ordering of the terbium subsystem. Using various polarization geometries we revealed that in the low temperature $\Gamma_4(G_xF_z)$ structure the M_1 mode is excited by e_x, e_y *ac* electric field components in addition to h_x, h_y magnetic ones, while the M_2 mode is excited not only h_z magnetic component but also e_z electrical one. Moreover, at frequencies below $M_{1,2}$ modes we observed at ~10 cm^{-1} for e||c an additional electroactive absorption line identified as an excitation in the antiferromagnetic Tb subsystem.

The observed phenomena were analyzed taking into account allowed local magnetetoelectric interactions in the Tb^{3+} ions possessing quasidoublet ground state in a crystal field. It was shown that electrodynamic response of interacting Fe and Tb moments are determined not only magnetic but also magnetoelectric and dielectric susceptibilities.

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Magnetophotonics at ultrafast and ultrasmall scales

ALL-DIELECTRIC NANOPHOTONICS FOR OPTOMAGNETISM

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All-dielectric nanostructures are very promising for effective spin control in magnetic materials using femtosecond laser pulses. Such structures with specially adjusted parameters make it possible to obtain various optical resonances in a magnet (optical waveguide modes, Mie modes, Fabry-Perot resonance) and, thereby, distribute the optical spin angular momentum (the effective magnetic field of the inverse magneto-optical Faraday and Cotton-Mouton effects) in a magnetic material in the right way, which eventually leads to excitation of various spin modes with high amplitude [1-4].

In particular, in magnetophotonic crystals and nanostructured magnetic films, it is possible to excite standing spin waves limited in one or all three dimensions. When optical resonances are excited in magnetic nanospheres or nanocylinders, it becomes possible to reconstruct the local and inhomogeneous effective field of the reverse Faraday effect within a wide range to excite high-order standing modes.

On the other hand, due to the deposition of a non-magnetic nanolattice to a magnetic film, laser pulses excite ultrashort traveling spin waves with a length of about 100-300 nm, which is significantly less than the wavelength of light in a magnet. In this case, nanolattices play a dual role – they allow not only to excite short spin waves, but also to observe them, which is impossible for homogeneous magnetic films. Along with this, the use of nanolattices gives birth to a novel optomagnetic effects, for example, the inverse transverse Kerr effect, which significantly expands the range of functionality for controlling spins by light.

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TIME-RESOLVED SPIN DYNAMICS IN EuO PROBED BY PHOTO-INDUCED FARADAY EFFECT

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The manipulation of magnetic materials with light has become a highly promising concept in developing innovative magneto-optical devices [1]. Compared to traditional methods using magnetic fields, light offers faster and more efficient control over electron spins due to shorter timescales involved in optical processes [2]. This study probes the time-dependent behavior of spins in the ferromagnetic semiconductor EuO following excitation by light.

Near the Curie temperature (T_C = 70 K) photo-excitation in EuO significantly enhances the exchange interaction between excited d-electrons and surrounding lattice spins compared to the ground state. This leads to a transient reinforcement of the ferromagnetic order with a slight raise in the Curie temperature. The impact of the change in exchange interaction is readily measurable using the photo-induced Faraday effect. Time-resolved measurements provide insights into the creation and subsequent decay of the photo-induced magnetization.

To this end, we have developed a pump-probe technique based on time-resolved Faraday effect on a broad timescale up to hundreds microseconds. The novel approach offers direct observation of spin dynamics in EuO, providing a deeper understanding of the light-induced manipulation of magnetism in this material (Fig. 1).

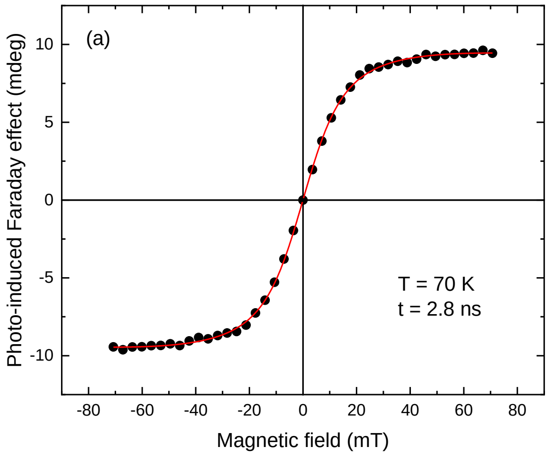

Fig. 1. (a) The photo-induced Faraday effect as a function of magnetic field, measured at a temperature of 70 K and a time delay t = 2.8 ns. (b) The evolution of the photo-induced Faraday effect at 70 mT over time after excitation at t = 0.

This work was supported by the Russian Science Foundation (projects 24-12-00348, 24-19-00038, 20-79-10028, 22-13-00004).

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LASER-INDUCED THZ DYNAMICS OF SPIN CORRELATIONS IN CUBIC ANTIFERROMAGNETS

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Two-magnon mode is the magnetic excitation with one of the highest frequencies among magnetic modes. Being observed in antiferromagnets, two-magnon mode is usually defined as a coupled magnon pair with opposite wavevectors. Zero momentum of this pair allows light to interact with entire Brillouin zone (BZ) including its edge, where the exchange interaction plays the key role.

Spontaneous Raman scattering (RS) on two-magnon modes was extensively studied since 1960th, both experimentally and theoretically [1-3]. Recent impulsive stimulated Raman scattering (ISRS) experiments demonstrated the excitation of such modes by femtosecond laser pulses and linked their generation to laser-induced changes in the exchange interaction [4-7]. However, when comparing the spectra obtained in two types of experiments, one can detect differences that, in particular, raises a question of whether the contribution from two-magnon modes in a certain part of the Brillouin zone is the same in the case of RS and ISRS [4,8].

In this work, our goal is to study theoretically the possibility of excitation and detection of ultrafast magnetic dynamics by femtosecond linearly polarized laser pulses and compare it to the case of the RS. For this purpose, we need to introduce the single framework and define the Raman tensor across the Brillouin zone that describes the interaction of a certain two-magnon mode with light. The use of classical ferromagnetic and antiferromagnetic vectors, in this case, does not allow us to introduce the Raman tensor, since they do not describe the ground state, which is a complex superposition of wave functions [9], and two-magnon modes [6,10].

In this work, we carry out the analysis of RS and ISRS in cubic antiferromagnets within the single framework, in which spin correlations are the microscopic parameter describing spin dynamics [10]. Based on introduced approach, we obtain the Raman tensor and its dependence on the wavevector. We derived the selection rules for the ISRS and compare its spectrum with the spontaneous Raman scattering and experimental data.

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SAGITTALLY PROPAGATING MAGNETOELASTIC WAVES EXCITED BY LOCALIZED LASER PULSE

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In magnonics, spin waves (SW) are used to encode, transfer and process information in computational devices, which in principle can outperform traditional electronics [1]. The significant experimental progress is achieved using magnetostatic SW of GHz frequency range, which propagate laterally in films of ferro- and ferrimagnetic materials [2]. The excitation of coherent sagittally propagating antiferromagnetic SW of THz frequency is demonstrated recently as well [3]. However, an increase of working SW frequency, scaling-down of future magnonic devices to nanometer range, and extension of a planar designing approach to the third dimension with simultaneous maintaining of SW propagation distances at high values, are still required. Thus, one of the critical issues is to develop excitation mechanisms, for which SW will possess high group velocity, low damping and possibility to propagate coherently in magnonic structures and heterostructures in either of three dimensions. In this work we demonstrate experimentally the laser excitation of coherent magnetoelastic waves, propagating sagittally in the ferrite garnet. We used the thin gold capping film on the iron garnet surface to increase the localization of femtosecond laser pulse and spectrally broaden in-depth excitation profile.

Laser-induced magnetization dynamics is measured using optical pump-probe technique, in which pump pulses of 515 nm central wavelength were used. Chosen pump wavelength allows for strong absorption profile inside the studied sample of bismuth-doped yttrium iron garnet without capping film. To increase manifold the localization profile of the pump pulse excitation near the surface we cover the sample by Au film with thickness of 100 nm. For the detection we used femtosecond probe pulses with wavelengths of 900 and 450 nm, which being directed onto the sample from the side opposite to the excited surface realize the geometries of the magneto-optical double Faraday effect and the polar Kerr effect, respectively. The use of the two distinct detection geometries provided the separation of the contributions to the measured magnetization dynamics, which are: uniform across the sample thickness precession of magnetization with frequency of ferromagnetic resonance (FMR) and non-uniform mode. In the Kerr geometry upon pumping the Au film at the garnet surface, we observed the time delay of 230 ps between excitation and the magnetization dynamics observation corresponding to a nonuniform mode. Also, tuning the applied in-plain external magnetic field in the range 300-700 mT we observed linear increase of the FMR mode frequency and the superlinear increase of the nonuniform mode frequency. The theoretical analysis including dispersion of exchange spin waves and longitudinal acoustic (LA) phonons allowed us to establish that the nonuniform mode is, in fact, magnetoelastic wave.

Thus, we demonstrate that the increase of in-depth localization of excitation profile in ferrite garnet results in the excitation of magnetoelastic wavepacket, propagating sagittally between samples surfaces. We confirm this by measuring the wavepacket group velocity, which corresponds to the sound velocity in the sample. Also, provided theoretical analysis confirms our interpretation of the experimental results. The experimentally measured dependence of the frequency of the non-uniform mode on the external magnetic field magnitude corresponds to the theoretically calculated one of magnetoelastic wave, which we determine as the cross point of the exchange SW and LA phonons dispersions. Thus, we demonstrate experimentally the possibility to excite magnetoelastic waves by strongly in-depth localized laser pulses. The amplitude of magnetoelastic waves demonstrated in our experiments is a one order higher than that of the uniform precession. Therefore, the provided results not only ensure the propagation of coherent SW in the third dimension, but also show that coupling of magnetic and phonon sub-systems allows for an efficient resonant excitation of collective dynamics, which can propagate coherently in the magnonic heterostructures.

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EXCHANGE COUPLING BETWEEN TWO FERROMAGNETIC METALLIC NANOLAYERS REVEALED BY TRANSVERSE KERR EFFECT

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Exchange coupling between ferromagnetic films is used for hysteresis loop bias of one of two nanolayers in spintronic valve. Magnetization directions are collinear in both layers and coercive fields differ by more than an order of magnitude this case [1].

Exchange bias can be described only by phenomenological way as a rule. The mechanism of exchange coupling can be cleared in more details by investigation of its dependencies upon magnetic parameters of each of two nanolayers such as coercive fields, anisotropy fields and easy axes directions.

The present investigation was made on bilayer permalloy/iron (Py/Fe) structure with equal thickness values (40 nm) evaporated on silicon substrate. Both ferromagnetic films are uniaxial in plane with anisotropy field values along hard axes 4 Oe and 12 Oe, critical field values along easy axes 2 Oe and 10 Oe accordingly for Py (82Ni-18Fe) and Fe.

Hysteresis loop of bilayer was observed by means of transverse Kerr effect from Py film for collinear easy axes and mutually perpendicular easy axes of magnetic layers in Py/Fe bilayer. Kerr effect in Fe is more than that one in Py almost by an order of magnitude with opposite sign due to difference between 3*d*-band fillings. Therefore layers magnetizations coupling caused by mutual spin diffusion through Py/Fe interface can be investigated by magnetooptical signal registration.

Hysteresis loops caused by magnetization reversal observed for Fe, Py and Py/Fe structures along collinear easy axes are shown in Fig. 1. Lines represent the directions of easy axes whereas arrow shows directions of external field. Magnetooptical signal from Py/Fe bilayer (right graphs) is equal to signal from Fe film (left graphs) in spite of Py layer screening influence. This fact should be interpreted in terms of mutual spin diffusion between Py and Fe. As a result bilayer Py/Fe suffers reversal as whole object for collinear easy axes in Py and Fe.

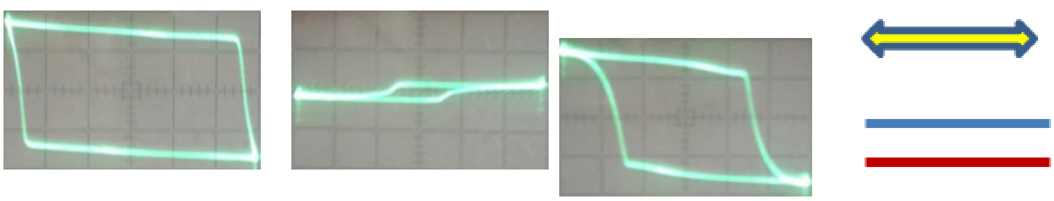

Fig.1. Magnetization reversal along collinear easy axes in Py and Fe films: Fe(40 nm) (left), Py(40 nm) (centre) and Py/Fe bilayer (right).
Magnetic field scale factor 4 Oe/cm.

All possible mutual orientations of easy axes of Py and Fe layers and external field exhibit coupling features due to exchange between diffused and domestic electrons in both layers (for ex. Fig. 2). Magnetization reversals of Py/Fe structure along hard axis of Fe and perpendicular easy axes in Py (Fig. 2, right) look like independent in every magnetic layer but critical field in Py layer is enhanced by a factor 1.6 in comparison with alone Py film.

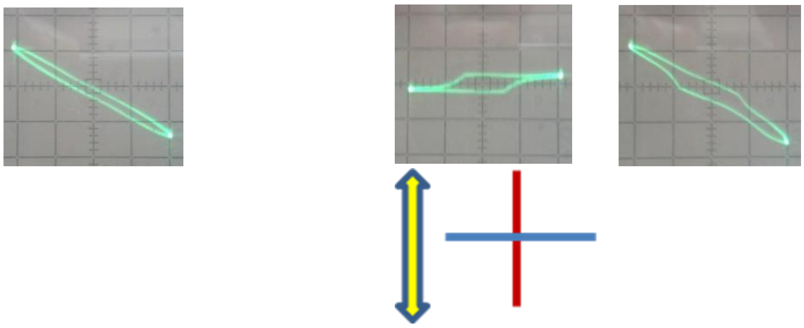

Fig.2. Magnetization reversal along hard axis in Fe (left), easy axis in Py (centre) and Py/Fe bilayer (right).

Dynamic behaviour of magnetization distribution near the boundary of one of two layers seems to be of interest for spin waves propagation modelling.

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Antiferromagnets and exotic magnetic structures

KITAEV MATERIALS: THE SEARCH FOR SPIN LIQUID

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Frustration is a universal concept which describes a situation where several competing interactions are present, and the compromise of such interactions may result in a completely exotic ground state. In frustrated magnets such competition can yield a loss of long-range magnetic order due to strong quantum fluctuations - a so-called quantum spin liquid state. Fractional excitations of spin liquids drew interest as a path towards topoligical quantum computation, which is stable towards small errors, plaguing standard quantum computing platforms. A notable example is an anisotropic exchange model proposed by Alexei Kitaev, which has a spin liquid ground state and is exactly solvable.[1] Examples of materials with Kitaev interaction and how it is manifested in experiments will be discussed.

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MAGNON BEC FROM 1 mK TO ROOM TEMPERATURE

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This year marks 40 years since the discovery of magnon Bose-Einstein condensation in antiferromagnetic superfluid 3He-B [1]. Under the conditions of BEC, a macroscopic number of quasiparticles occupied a single quantum state. Its formation is determined by the well-known BEC formation relation, which includes the density, temperature and mass of quasiparticles. In experiments with superfluid 3He-B, the nuclear magnetic induction signal, as usual, decayed with time T2*, determined by the inhomogeneity of the external magnetic field. However, the induction signal was restored with some time delay, which means the spontaneous formation of a coherent state of magnons. In this case, there is no spin-spin relaxation process and the signal lifetime is determined by spinlattice relaxation (the lifetime of the magnons themselves). This behavior of the signal was explained by the redistribution of the magnon density due to “spin” superfluidity - the spatial countercurrent of superfluid currents of 3He-B quantum states with opposite magnetic moments [2]. In general, this process belongs to one of the mechanisms providing magnon BEC [3]. Further studies showed that the deflected magnetization breaks up into two domains. In one region it is stationary, and in the second it precessing spatially coherently and exhibits the quantum properties of a Bose condensate (mBEC). In a magnetic field gradient, the mBEC "swims" towards an area of lower magnetic field. Thus, from the behavior of the BEC signal and its frequency, it is possible to determine the number of magnons that arose after various quantum manipulations.

Magnon BEC was also discovered in Yttrium Iron Garnet (YIG) films magnetized perpendicular to the film plane. In [4], it was shown theoretically that this quantum state can be formed even at room temperature. In a number of studies, the formation of magnon BEC in YIG was demonstrated experimentally [5-8]. An overview of these works will be presented in the lecture.

Last year, we were able to directly observe a magnon BEC optically using the Faraday rotation effect [9]. In these experiments, the amplitude and phase of magnetization precession in the YIG film were measured outside the region of magnons excitation. According to the semiclassical Landau-Lifshitz-Hilbert (LLG) theory, the deflected magnetization should propagate from the excitation region in the form of spin waves. This is precisely the distribution we observed in our setup at a low amplitude of magnon excitation. The situation changed dramatically with increasing magnon density. The magnetization deflection increased sharply outside the excitation region, and it became spatially homogeneous [10]. At a low pump power of 0.05 mW, precessing magnetization is observed mainly in the pump region. As the power increases to 6 mW, the precession deflection angle increases sharply even outside the pumping region. The dependence of the precession phase also strongly depends on the magnon concentration. Thus, at low power, excitation of spin waves beyond the pump region is observed. The length of the spin waves is determined by the shift of the magnetic field from the resonant one, in good agreement with the LLG theory. However, at high pump powers, the spin waves disappear and regions of uniform precession are formed on both sides of the

exciting band. Figure 1 shows the change in the spatial distribution of the precession phase with increasing pump power and, accordingly, the magnon density.
We compared the experimental results with the LLG theory. To do this, we simulated the spatial distribution of precession at different magnon pump energies. The model showed good agreement with experimental results at low pump values. However, it was not possible to obtain a state of spatially uniform precession outside the excitation region at any pump value [10]. In other words, the results of our experiments are not described within the framework of the semiclassical LLG theory.

The transition from spin waves to the magnon Bose condensate occurs at magnetization deviation angles of about 4°, as shown in [11], which is consistent with the critical value of the magnon density predicted in [4].

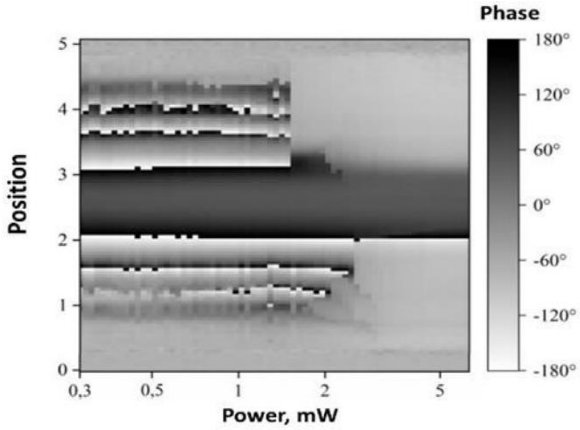

Fig. 1. Spatial distribution of the precession phase with increasing pump power. A transition from spin waves to coherent precession outside the excitation region is visible, corresponding to Bose condensation of magnons.

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FERMI SURFACE, NESTING, AND MAGNETIC PHASE TRANSITION: CASE OF THE HCP HEAVY RARE-EARTH METALS

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The occurrence of the long-periodic (helical, sine, cycloid etc.) magnetic structures in metals if often associated with the “nesting” phenomenon, when the magnetic wavevector ***q*** is directly governed by the geometry of the Fermi surface. Namely, ***q*** appears to be exactly equal to the extreme diameter of the certain fragment of the Fermi surface.

In some cases the shape of this fragment, in turn, may be modified under the slight variation in the lattice parameters – up to its complete elimination (that would be the Lifshitz transition by definition.) As a consequence, the long-periodic magnetic order is suppressed in favor of the simple ferromagnetic structure, constituting therefore a specific magnetic phase transition.

This scenario leads immediately to the characteristic dependencies of the magnetic properties on the lattice parameters.

There are strong reasons to suggest that this scenario takes place in the elemental heavy rare-earth metals with *hcp* structure (Gd, Tb, Dy *etc.* and their solutions with each other and non-magnetic yttrium.) The expected characteristic dependencies have been observed experimentally as well as supported by ab initio calculations.

In particular, the helical order in Tb have been completely suppressed by the uniaxial elastic tension as low as 0.5 kbar. The obtained magnetic phase diagram demonstrates the good agreement with the expectations.

Various aspects of this magnetic phase transition are discussed.

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ОСОБЕННОСТИ СПИНОВЫХ ВЗАИМОДЕЙСТВИЙ И СПИНОВЫХ СТРУКТУР В ЯН-ТЕЛЛЕРОВСКИХ МАГНЕТИКАХ

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К ян-теллеровским (ЯТ) магнетикам мы относим соединения на основе янтеллеровских 3*d*- и 4*d*-ионов с конфигурациями типа $t_{2g}^{n_1}e_g^{n_2}$ в высокосимметричном октаэдрическом, кубическом или тетраэдрическом окружении и с основным орбитальным *E*-дублетом [1-3]. Это соединения на основе тетра-комплексов с конфигурацией d^1 (Ti^{3+}, V^{4+}, Cr^{5+}), низкоспиновой (LS) конфигурацией d^3 (V^{2+}, Cr^{3+}, Mn^{4+}), высокоспиновой (HS) конфигурацией d^6 (Fe^{2+}, Co^{3+}), окта-комплексы с HS-конфигурацией d^4 (Cr^{2+}, Mn^{3+}, Fe^{4+}, Ru^{4+}), LSконфигурацией d^7 (Co^{2+}, Ni^{3+}, Pd^{3+}), а также окта-комплексы с конфигурацией d^9 (Cu^{2+}, Ni^{1+}, Pd^{1+}, Ag^{2+}) [3].

Все ЯТ-конфигурации d-ионов включают один e_g-электрон или одну e_gдырку сверх устойчивых, полностью или наполовину заполненных, оболочек. В этом смысле они похожи на конфигурации многочисленного семейства ионов с одним *ns*-электроном сверх заполненных оболочек, например 6*s*-электроном в Hg^+, Tl^{2+}, Pb^{3+}, Bi^{4+}. Эти ионные конфигурации являются неустойчивыми относительно реакции диспропорционирования, или даже несуществующими (missing oxidation states). Так, в $BaBiO_3$ вместо номинальной валентности 4+ висмут предпочитает устойчивые валентные состояния Bi^{3+} и Bi^{5+} с полностью заполненными оболочками. Однако, в отличии от ионов с *ns*-электронами для ЯТионов мы имеем дело с орбитальным вырождением для e_g-электронов/дырок, а значит, возможностью конкуренцией между эффектом Яна-Теллера, приводящим к орбитальному упорядочению [1], и эффектом анти-ЯТ-диспропорционирования, приводящим к формированию системы электронных и дырочных центров *S*-типа с орбитально невырожденным основным состоянием [2,3], эквивалентной системе эффективных композитных спин-синглетных или спин-триплетных бозонов в немагнитной, или магнитной решетке.

В класс ЯТ-магнетиков попадает большое число перспективных материалов с конкуренцией орбитальных, спиновых и зарядовых степеней свободы, находящихся в центре внимания современной физики конденсированного состояния, таких как манганиты $RMnO_3$, ферраты $(Ca,Sr)FeO_3$, рутенаты RuO_2, $(Ca,Sr)RuO_3$, $(Ca,Sr)_2RuO_4$, широкий ряд ферропниктидов (FePn) и феррохалькогенидов (FeCh), 3D-никелаты $RNiO_3$, 3D-купрат $KCuF_3$, 2D-купраты (La_2CuO_4, ...) и никелаты $RNiO_2$, соединения на основе серебра (AgO, AgF_2), рутено-купраты $RuSr_2GdCu_2O_8$… [3]. Эти материалы обладают богатым спектром уникальных свойств от различных типов орбитального [1], спинового, зарядового, а также спин-зарядового упорядочения, необычного металлического поведения (“strange, bad metal”), до переходов металл-изолятор и “экзотической” спинтриплетной сверхпроводимости [3]. Ряд ЯТ-магнетиков либо являются мультиферроиками ($RMnO_3$, CuO), либо рассматриваются как перспективные мультиферроики ($RNiO_3$). В общем случае для описания ЯТ-магнетиков необходимо учитывать электронно-колебательные взаимодействия с активными в эффекте Яна-Теллера локальными решеточными E_g-модами [1], или полносимметричными «дыхательными» (breathing) A_{1g}-модами, активными в реакции диспропорционирования.

В данной работе мы рассматриваем особенности спиновых взаимодействий

$$H_{spin} = \sum_{i>j} J_{ij}(\mathbf{S}_i \cdot \mathbf{S}_j) + \sum_{i>j} j_{ij}(\mathbf{S}_i \cdot \mathbf{S}_j)^2 + \sum_{i>j} \mathbf{d}_{ij}[\mathbf{S}_i \times \mathbf{S}_j] + V_{an}$$

− изотропного билинейного и биквадратичного обмена, антисимметричного обмена Дзялошинского-Мория, одно- и двухионной анизотропии, и спинмагнитных структур в различных ЯТ-магнетиках, включая традиционные системы с кооперативным ЯТ-упорядочением типа $KCuF_3$ и $LaMnO_3$ [1], а также многочисленные ЯТ-магнетики с переносом заряда и анти-ЯТ-диспропорционированием, для описания которых можно использовать модель зарядовых триплетов и S=1 псевдоспиновый формализм Райса-Снеддона [4]. Анти-ЯТ-диспропорционирование приводит к формированию систем, которые эквивалентны системам эффективных композитных спин-синглетных или спинтриплетных бозонов, «движущихся» в немагнитной («однозонные» ЯТ-магнетики – AgO, $RNiO_3$), или магнитной («двухзонные» ЯТ-магнетики – $SrFeO_3$, Sr_2RuO_4, FePn/FeCh,…) решетке. Для таких систем характерно не только многообразие магнитных коллинеарных и неколлинеарных, в частности и геликоидальных, структур, но и появление необычных немагнитных фаз (AgO, $RNiO_2$), а также возможных спин-триплетных сверхпроводящих фаз (Sr_2RuO_4, RuO_2, FePn, FeCh).

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EXCANGE INTERACTIONS AND PHASE TRANSITIONS IN RARE-EARTH ORTOFERRITES RFeO3 (R=Ho,Tb,Dy)

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Rare-earth orthoferrites $RFeO_3$ (R is a rare-earth element) represent an important family of magnetic compounds. The studies on these compounds habe been started several decades ago [1]. The crystal structure of $RFeO_3$ is described by space group Pbnm. Thes magnetic structures in this family were obtained by neutron powder diffraction. These studies show that these compounds have high Neel temperatures T_N ~ 600 - 700 K, below which the Fe moments order antiferromagnetically with a weak ferromagnetic component along the *c*-axis and propagation vector $\boldsymbol{k}$ = (0 0 0).

In addition to Heisenberg exchange interactions of type Fe-Fe, Fe-R, R-R, an important role in determining the magnetic properties plays the Dzyaloshinsky-Moria interaction (DMI) [2], leading to the weak ferromagnetism. With temperature decrease, increasing exchange interaction between Fe^{3+} and R^{3+} ions leads to a rebalance of energies of the magnetic interactions, which causes spin reorientation transitions. Different combinations of DMI and rare-earth ions with different ionic radii and filling of outer shells lead to a variety of magnetic effects.

Thus, it is of significant interest to calculate the values of exchange interactions within the iron subsystem J_{ij}^{Fe-Fe}. The calculation of the values of exchange interactions can be performed based on experiments on inelastic neutron scattering. Our experiments were performed on spectrometer PUMA (MLZ) and IN20 (ILL) for samples $TbFeO_3$, $DyFeO_3$ and $HoFeO_3$. Examples of measured maps are shown in Figure 1. Dispersion curves, crystal field levels, and the energy gap are clearly visible in these maps.

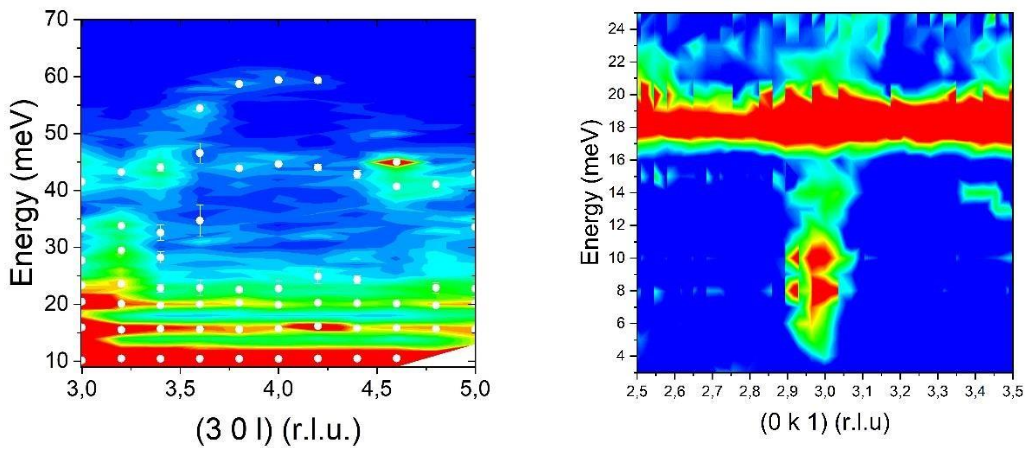

Fig. 1. Energy maps, obtained at IN20. The colors show the intensity, the white dots –positions of the inelastic peaks. Left) Map for $HoFeO_3$ measured at temperature T=65K. Right) Map for $DyFeO_3$ measured at temperature T=10K.

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СЛАБЫЕ ФЕРРИМАГНЕТИКИ ТИПА $YFe_{1-x}Cr_xO_3$: ОТРИЦАТЕЛЬНАЯ НАМАГНИЧЕННОСТЬ И СПИНОВАЯ ПЕРЕОРИЕНТАЦИЯ

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Термин «слабый ферримагнетизм» был предложен в 1977 г. [1] для описания специфического магнитного упорядочения в замещенных слабых ферромагнетиках с конкурирующими знаками вектора Дзялошинского в парах Fe-Fe, Cr-Cr и Fe-Cr. Магнитные свойства слабых ферримагнетиков типа $RFe_{1-x}Cr_xO_3$, $Fe_{1-x}Cr_xBO_3$, $Mn_{1-x}Ni_xCO_3$ активно исследовались в 80-е годы прошлого века как экспериментально, так и теоретически [2]. Рост интереса к этим материалам в последнее десятилетие связан с их уникальными свойствами, в частности, наблюдением точек температурной и концентрационной компенсации магнитного момента, спиновой переориентации, эффекта перестраиваемого обменного смещения (exchange bias) [3] и перспективами их практического применения в магнитной памяти, магнитокалорике, термомагнитных переключателях и других многофункциональных устройствах.

Нами рассмотрены основные механизмы формирования магнитной анизотропии и спин-переориентационных эффектов. В рамках теоретического подхода мы представляем гамильтониан слабого ферримагнетика $YFe_{1-x}Cr_xO_3$ в виде суммы вкладов изотропного обменного взаимодействия, антисимметричного обмена Дзялошинского-Мория (DM) и одноионной анизотропии 2-го и 4-го порядков: $H = H_{ex} + H_{DM} + H_{SIA}$. Модельные расчеты температурных и концентрационных зависимостей намагниченности и энергии конфигураций $\Gamma_4(G_x)$, $\Gamma_2(G_z)$ и $\Gamma_1(G_y)$ для слабоферримагнитных замещенных составов проведены в рамках обобщенной теории молекулярного поля [4].

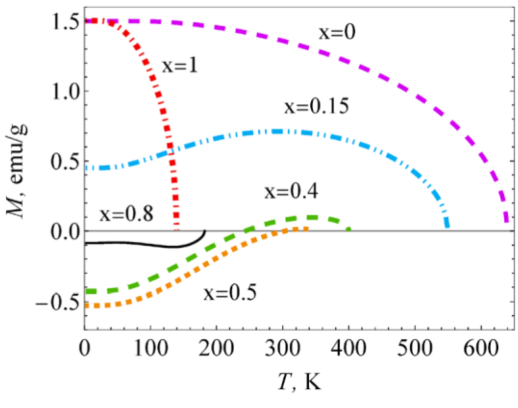

Рис. 1. Температурная зависимость намагниченности $YFe_{1-x}Cr_xO_3$ при различных концентрациях хрома.

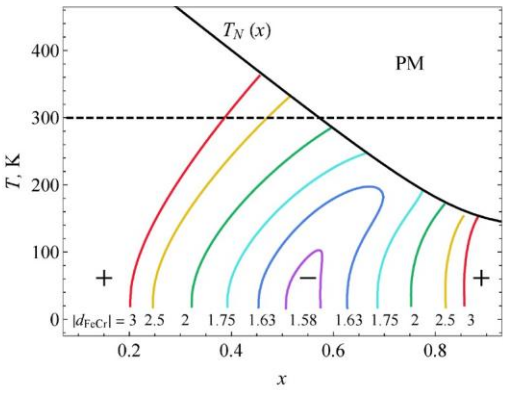

Рис. 2. Фазовая *T*–*x* диаграмма областей компенсации намагниченности при различных значениях d_{FeCr}. Знак "+" указывает на область "положительной" намагниченности.

На рис. 1 представлены результаты расчета температурных зависимостей намагниченности слабого ферримагнетика $YFe_{1-x}Cr_xO_3$ при некоторых значениях концентрации от $x = 0$ до $x = 1$ в предположении о сохранении магнитной конфигурации Γ_4.

Анализ модели показал, что когда вектор Дзялошинского d_{FeCr} для пары ионов Fe-Cr противоположно направлен векторам d_{FeFe} и d_{CrCr} (для пар Fe-Fe и CrCr, соответственно) намагниченность резко падает с отклонением от родительских составов, но при $|d_{FeCr}| > |d^{(cr)}|$, где $d^{(cr)} = -1.55$ К, на T–x фазовой диаграмме появляется и растет с ростом $|d_{FeCr}|$ область отрицательной намагниченности с двумя точками компенсации. На рис. 2 представлена фазовая T–x диаграмма слабого ферримагнетика, где кривая $T_N(x)$ ограничивает область магнитного упорядочения, а тонкие линии обозначают линии точек компенсации, то есть смены знака намагниченности при различных величинах параметра d_{FeCr}.

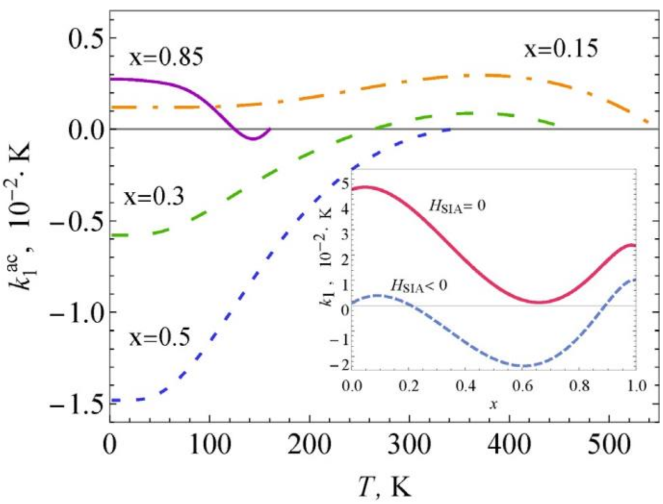

Рис. 3. Пример температурной зависимости первой константы анизотропии k_1 для асплоскости при различных x; на вставке показана зависимость $k_1(x,T)$

В отличие от $YFeO_3$ и $YCrO_3$, которые являются слабыми ферромагнетиками с основной магнитной структурой типа Γ_4 ниже температуры Нееля, слабые ферримагнетики ортоферриты-ортохромиты $YFe_{1-x}Cr_xO_3$ обнаруживают полную или частичную спинпереориентацию типа $\Gamma_4 - \Gamma_2$ в широком диапазоне замещения [1]. Такое неожиданное поведение, обычно типичное для ортоферритов с магнитными редкоземельными ионами (Er, Tm, Dy, ...), объясняется, главным образом, сильным уменьшением вклада DM-взаимодействия в магнитную анизотропию. Расчеты показывают (см. рис. 3), что первая константа анизотропии k_1 (фактически, разность энергий в фазах Γ_4 и Γ_2) испытывает минимум вблизи концентрации $x = 0.65$, т.е. здесь фаза Γ_4 менее выгодна, в сравнении с родительскими составами. При учете одноионной анизотропии первая константа может становиться отрицательной, что объясняет переход в фазу Γ_2.

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ON THE ANTISYMMETRIC AND SIMMETRIC INTERACTIONS IN MULTIFERROIC MANGANITES

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Magnetic interactions in orthorhombic rare-earth manganese oxides $RMnO_3$ and RMn_2O_5 are of great interest due to the diverse magneto-electric properties of these families. The electric polarization in both $RMnO_3$ and RMn_2O_5 is due to the ordering of the magnetic manganese ions and is of the same order of magnitude, suggesting that the mechanisms responsible for this phenomenon are similar. However, there are some essential differences in the configuration of magnetic interactions. That is, if in $RMnO_3$ Mn^{3+} ions, located in an octahedral surroundings of oxygen, form a single manganese magnetic system, then in RMn_2O_5 there are two manganese systems formed by Mn^{3+} ions located near the base of the oxygen pyramid, while Mn^{4+} ions surrounded by oxygen octahedra. The difference in the proposed microscopic mechanisms of multiferroicity in $RMnO_3$ and RMn_2O_5 can be regarded as the consequence of this difference.

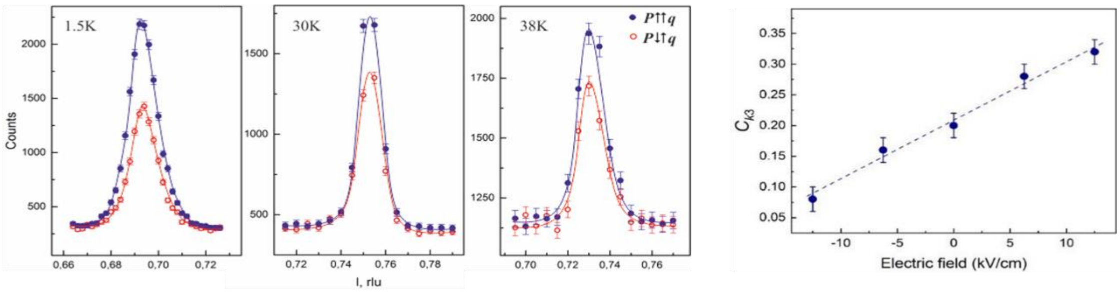
As a magnetic mechanism that ensures the occurrence of ferroelectric polarization in orthorhombic manganites $RMnO_3$, atomic displacements due to minimization of the Dzyaloshinsky-Moriya (DM) interaction energy i.e. antisymmetric striction — are considered [1]. To explain the magnetoelectric interactions in RMn_2O_5, the symmetric exchange striction model [2] is often used, which is associated with an almost collinear magnetic order. In both cases, these theoretical approaches consider the manganese magnetic structure only.

In order to clarify experimentally the applicability of one or the other model for the description of the mechanisms of multiferroicity in these compounds, single crystals of RMn_2O_5 (R = Eu, Tb, Nd) [3 - 6], $RMnO_3$ (R = Dy, Ho) [7, 8] were studied using polarized neutron diffraction.

The results obtained for all measured RMn_2O_5 crystals (R = Eu, Tb, Nd) [3 - 6] indicate the presence of a chiral contribution to magnetic scattering in these systems. Thus, measurements of the intensity of scattered neutrons for two directions of polarization of neutrons incident on the crystal, made on $TbMn_2O_5$, show the presence of chiral scattering in three magnetically ordered phases [4] (Fig. 1a). Chiral scattering was also observed for the compounds $EuMn_2O_5$ [3], $NdMn_2O_5$ [5], and $Nd_{0.8}Tb_{0.2}Mn_2O_5$ [6]. All these observations are a clear indication of the presence of an antisymmetric interaction in the system. Moreover, this type of scattering was absent at those temperatures where there is no ferroelectric polarization. The connection between the antisymmetric DM interaction and electricity is also evidenced by the fact that in the course of research it was possible to change the population of chiral domains by applying an external electric field (Fig. 1b) [4 – 6].

In the $DyMnO_3$, electrical polarization occurs at the temperature of the transition to the cycloidal chiral structure and increases smoothly as the temperature decreases. However, when Dy^{3+} was ordered into a structure with a propagation vector different from that one of the Mn^{3+} magnetic system, a decrease in electric polarization was observed [9]. At the same time, no such effect was observed for compounds with partial replacement of Dy by Ho [10]. Our studies allow one to confirm the assumption that the increase in polarization in $DyMnO_3$ is due to the influence of rare earth magnetic systems. The ordering of this latter at such high temperatures is induced by magnetic order on manganese with a corresponding propagation vector. This situation contributes to the (symmetric) exchange-striction mechanism of generation of electric polarization. However, due to the spontaneous ordering of a rare earth system with a different wave vector, this mechanism is switched off. Measurements on the dopped manganite $Dy_{0.8}Ho_{0.2}MnO_3$ show that in this compound spontaneous ordering of the rare-earth subsystem occurs with the same wave vector as that of the manganese subsystem. And the coherent spatial propagation of two magnetic systems leads to increased polarization.

Our series of studies of $RMnO_3$ and RMn_2O_5 allow us to draw reasonable conclusions that these compounds involve both magnetic mechanisms of ferroelectric polarization generation: both symmetric and antisymmetric striction.



a) b)

Fig. 1. a) Intensity of the magnetic satellite (0 0 1)$^+$ in $TbMn_2O_5$, measured at temperatures corresponding to different magnetic phases [4]. The difference in intensity for P↑↑q and P↑↓q corresponds to the difference in the population of chiral domains. b) Electric field dependence of chiral domain population in $NdMn_2O_5$ [5].

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Magnonics

MAGNONIC COMBINATORIAL MEMORY

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In this work, we consider a type of magnetic memory where information is encoded into the mutual arrangement of magnets. The device is an active ring circuit comprising magnetic and electric parts connected in series. The electric part includes a broad-band amplifier, phase shifters, and attenuators. The magnetic part is a mesh of magnonic waveguides with magnets placed on the waveguide junctions. There are amplitude and phase conditions for auto-oscillations to occur in the active ring circuit. The frequency(s) of the auto-oscillation and spin wave propagation path(s) in the magnetic part depends on the mutual arrangement of magnets in the mesh. The propagation path is detected with a set of power sensors. The correlation between circuit parameters and spin wave path is the basis of memory operation. The combination of input/output switches connecting electric and magnetic parts, and electric phase shifters constitute the memory address. The output of the power sensors is the memory state. We present experimental data on the proof-of-the-concept experiments on the prototype with three magnets placed on top of a single-crystal yttrium iron garnet $Y_3Fe_2(FeO_4)_3$ (YIG) film. There are three selected places for the magnets to be placed. There is a variety of spin wave propagation paths for each configuration of magnets. The results demonstrate a robust operation with an On/Off ratio for path detection exceeding 35 dB at room temperature. The number of possible magnet arrangements scales factorially with the size of the magnetic part. The number of possible paths per one configuration scales factorial as well. It makes it possible to drastically increase the data storage density compared to conventional memory devices. Magnonic combinatorial memory with an array of 100×100 magnets can store all information generated by humankind. Physical limits and constraints are also discussed.

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МАГНОННАЯ РЕЗЕРВУАРНАЯ ВЫЧИСЛИТЕЛЬНАЯ СИСТЕМА С ТОКОВЫМ УПРАВЛЕНИЕМ

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В последние годы одним из путей развития вычислительных устройств стало аппаратное воплощение искусственных нейронных сетей. В работе [1] была впервые предложена реализация резервуарных вычислений с использованием спиновых волн. Экспериментальная реализация резервуарных вычислений на принципах магноники была впервые выполнена на технологии перестраиваемых СВЧ-автогенераторов с временной задержкой в цепи обратной связи [2]. Задержку обеспечивала ферромагнитная пленка. Ввод информационного сигнала в активное кольцо, являющееся физическим резервуаром, осуществлялся благодаря использованию электронно-управляемого аттенюатора в цепи обратной связи, что обеспечивало зависящее от времени изменение коэффициента усиления кольца. Одной из актуальных задач для дальнейшего усовершенствования резервуарных вычислительных систем является разработка новых механизмов ввода данных в активное кольцо.

В настоящей работе исследовался физический резервуар в виде активного спин-волнового кольца, в которое ввод данных осуществляется металлической полоской с током, которая, будучи расположенной на поверхности ферромагнитной пленки регулирует коэффициент передачи спиновых волн.

Блок-схема исследуемого физического резервуара показана на рис. 1(а). Для возбуждения и приема спиновых волн используются микрополосковые антенны, расположенные на поверхности пленки (рис. 1(б)).

В качестве носителя входных данных для активного кольца служит ток, протекающий через миниатюрную металлическую полоску. Величина тока зависит от времени. При подаче положительного напряжения на полосок происходит локальное уменьшение внутреннего магнитного поля пленки ЖИГ, а при подаче отрицательного напряжения происходит локальное увеличение магнитного поля. Такая локальная неоднородность поля вызывает рассеяние спиновых волн [3, 4], что приводит к изменению суммарных потерь на распространение спиновых волн в пленке ЖИГ.

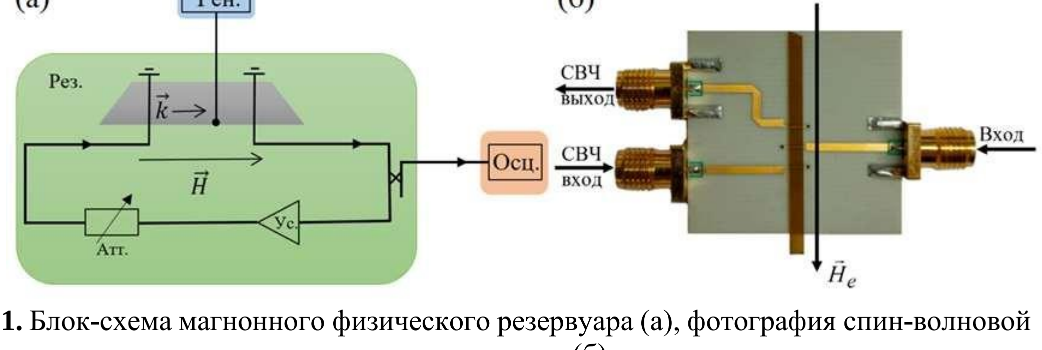

Рис. 1. Блок-схема магнонного физического резервуара (а), фотография спин-волновой линии задержки (б)

Экспериментальное исследование проводилось с помощью подачи случайной последовательности импульсов с генератора импульсов на управляющую металлическую полоску. На рисунке 2(а) изображен типичный вид входного (сверху) и выходного (снизу) сигналов резервуара для длительности импульсов равной 1 мкс. По измеренным осциллограммам выходного сигнала резервуара проводился расчет его производительности с использованием теста кратковременной памяти (ТКП) и теста проверки четности (ТПЧ). Черный график на рисунке 2(б) показывает результаты расчетов емкостей ТКП и ТПЧ при различных длительностях случайных импульсов. Видно, что с ростом длительности входных импульсов происходит сначала увеличение емкости теста ТКП, а затем его уменьшение. Емкость теста ТКП максимальна при длительности импульсов равной 0.2 мкс. Это можно объяснить тем, что при малых длительностях импульсов (короче, чем период оборота сигнала по кольцу) система не может начать движение в сторону равновесия. При больших длительностях входных импульсов система приходит в равновесие и забывает свои предыдущие состояния. Из красного графика на рисунке 2(б) видно, что тест ТПЧ растет с увеличением длительности входных импульсов. Это объясняется тем, что с ростом длительности входных импульсов растет и нелинейность переходного процесса активного кольца за счет нелинейного затухания СВ в пленке ЖИГ. Максимальная емкость ТПЧ для исследованного экспериментального макета достигалась при длительности импульсов 5 мкс.

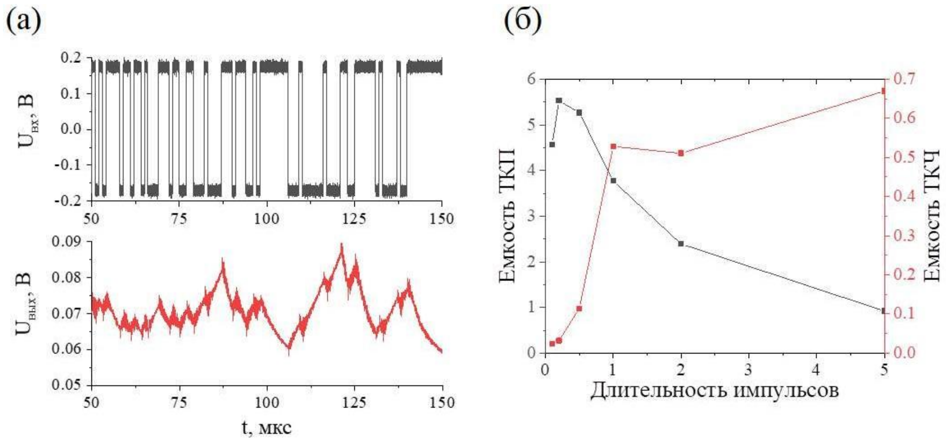

Рис. 2. Фрагмент осциллограммы входной случайной последовательности импульсов и выходного сигнала резервуара для длительности импульсов 1 мкс (а) и зависимость емкостей ТКП и ТКЧ от длительности импульсов входной случайной последовательности (б)

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DMI MODULATION IN HM/FM HETEROSTRUCTURES WITH A NONMAGNETIC SPACE LAYER

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In the 1990s, the nanoscience revolution triggered swift progress in ultra-thin film technologies which resulted in a rapidly growing interest in chiral magnetic structures such as skyrmions. Being topologically protected they are regarded as the promising candidates for the role of stable information carriers in a new generation of energy efficient information processing technologies. In this regard, a bilayer composed of a heavy metal (HM) and a ferromagnetic metal (FM) film with pronounced anisotropic Dzyaloshinskii-Moriya interaction (DMI) seems to be especially interesting. Considered to be short ranged, recently long-range oscillatory DMI behavior with spacer thickness has been reported in ferromagnetic layers separated by a nonmagnetic space layer [1].

In this paper we investigate the role of a Ru spacer as a DMI mediator between Co and Pt in Ta (3 nm)/Pt (5)/Ru (t_{Ru})/Co(1.2)/Ru (1)/Ta (2) (where t_{Ru} = 0-2.2 nm) nanostructures obtained by magnetron sputtering on SiO_2 substrates. The DMI was measured using Brillouin light scattering (BLS) spectroscopy in the Damon-Eshbach (DE) mode [2]. The prominent feature of the obtained BLS spectra is that the frequency shift is different depending on the direction of the saturating field (Fig.1). Without the Ru spacer, the DMI value was -0.341 ±0.02 mJ/m^2, consistent with the DMI value of the Pt/Co/Ru trilayer

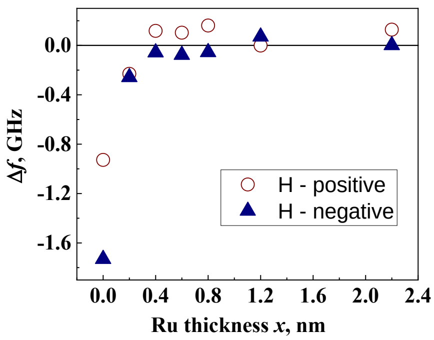

Fig. 1. The frequency difference from BLS spectra for Pt/Ru_x/Co nanostructures.

Finally, a theoretical model based on the redistribution of the density of states due to the Rashba related in-plane symmetry breaking [1] was extended for the cases considered. It is not supposed to exactly correspond to the physical system under study but to highlight its most important features.

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SPIN-WAVES PROBE OF PERCOLATION THRESHOLDIN EXCHANGE-BIASED SYSTEM

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A sharp change in the properties of materials as the concentration of a substance added to them increases can be described in percolation theory as the percolation threshold, considered as a special type of phase transition [1]. There are numerous theoretical models explaining the formation of a jump in electronic conductivity and the emergence of an infinite fractal in conductor-insulator composites [2]. To analyze the concentration dependence of electrical conductivity, an approach based on a combination of mean field theory and percolation theory is used. In [3], this approach was applied to explain electrical conductivity in exchange-biased NiFe/Cu/IrMn structures. Sharp changes of the exchange bias field, the uniaxial anisotropy field, and others magnetic parameters with increase of Cu effective thickness were discussed. In this work, we report the influence of the percolation threshold associated with increase in Cu layer thickness in the range copper 0.5 nm < t_{Cu} < 1.3 nm on spin-waves in a ferromagnetic NiFe layer.
In Fig. 1 shows the dependence of the mean shift of resonant scattering frequencies $\Delta\omega_{S-A}$ on the effective thickness of the copper spacer. This dependence was obtained from the Brillouin light scattering spectra for a series of NiFe/Cu/IrMn samples with inversion of the external magnetic field H = +3 kOe and H = -3 kOe. The percolation threshold changes the sign of the $\Delta\omega_{S-A}(t_{Cu})$ dependence in the region of thicknesses 0.5 nm < t_{Cu} < 1.3 nm at which an infinite fractal appears [3].

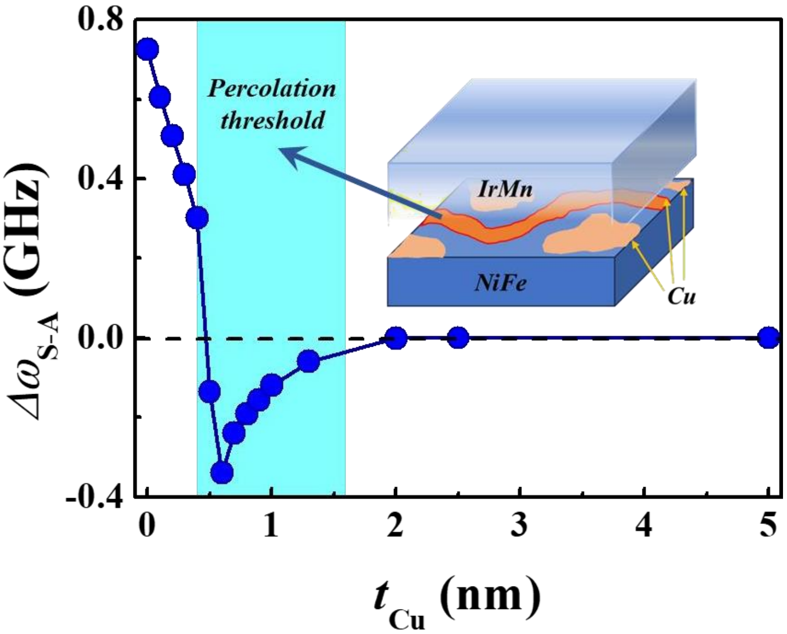

Fig. 1. Dependence of the mean shift of resonant scattering frequencies $\Delta\omega_{S-A}$ on the copper spacer thickness. The inset shows a visualization of the percolation threshold.

It has been established that the shift in the resonant scattering frequencies of the spin-waves of the Stokes and anti-Stokes lines upon inversion of the external magnetic field occurs due to the percolation threshold. The formation of an infinite fractal directly affects the propagation of thermal spin-waves in the NiFe layer and occurs due to the formation of “magnetic bridges” between the NiFe and IrMn layers in the transverse direction as the copper layer increases. The percolation threshold depends on the three-dimensional system of copper islands.

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INVESTIGATION OF THE GYROTROPIC MODE IN MAGNETIC VORTEX SYSTEM BY MAGNETIC RESONANCE FORCE MICROSCOPY

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One of the important tasks of microwave diagnostics is to study gyrotropic oscillations of the vortex distribution of magnetization in submicron-sized ferromagnetic disks, which is associated with the prospect of creating compact microwave generators in which gyrotropic oscillations of magnetic vortices are used to modulate current through tunnel contacts due to the effect of giant (tunnel) magnetoresistance (so-called vortex spin-transfer nanoscillators) [1]. Magnetic resonance force microscopy(MR FM) is one of the most convenient tools for studying the dynamic properties of a system of magnetic vortices[2]. This method is based on the magnetostatic interaction of the magnetic probe of a scanning probe microscope with the magnetization of a ferromagnetic particle precessing under the action of microwave pumping. MRFM is a highly sensitive method that allows the study of FMR spectra of individual particles in a zero magnetic field and does not require the manufacture of large arrays of patterned structures. This report presents the results of a study of the gyrotropic mode both in single magnetic vortices and in systems of interacting vortices (fig.1).

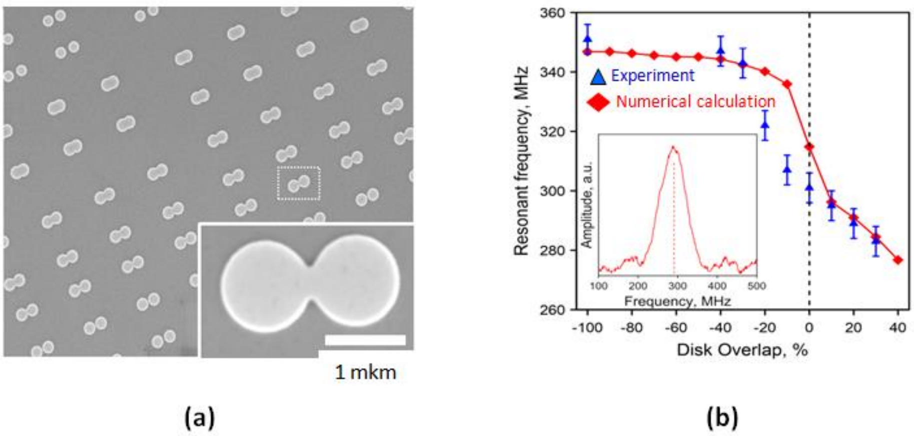

Fig. 1. (a) SEM image of an array of ferromagnetic disks with varying degrees of overlap. (b) The dependence of the resonant frequency of the system of two interacting magnetic vortices on the distance between the centers of the disks. The insert shows the experimental MRFM spectrum for disks with an overlap of 20%.

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МИКРОМАГНИТНОЕ МОДЕЛИРОВАНИЕ ФЕРРОМАГНИТНОГО МЕТАМАТЕРИАЛА В ПРОГРАММЕ MAXLLG

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Ферромагнитные метаматериалы (ФМ ММ) представляют собой управляемые магнитным полем искусственно созданные среды, работающие в микроволновом диапазоне частот. Классическим примером ФМ ММ со свойствами «левой» среды является поперечно намагниченная ФМ матрица, содержащая периодическую структуру из тонких проводящих проволок бесконечной длины, с периодом T (где $T \ll \lambda$, λ - длина волны в среде) и радиусом r_1 (см. Рис.1). Каждая из проволок отделена от ФМ матрицы посредством немагнитного изолятора радиусом r_2. Эффективные материальные параметры ФМ ММ являются одновременно отрицательными величинами в интервале частот, находящемся между двумя характерными частотами: плазменной частотой f_p, расположенной выше частоты ФМ резонанса при поперечном намагничивании $f_\perp$, и частотой антирезонанса f_{ar}. В работе [1] была разработана электродинамическая модель для такого ФМ ММ и показана возможность существования в нем обратной электромагнитной волны (ОЭМВ) в микроволновом диапазоне.

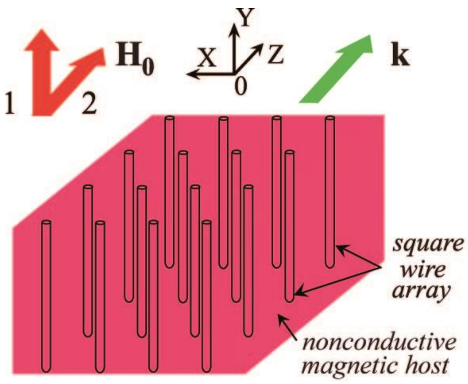

Рис.1. Схематическое изображение безграничного ФМ ММ в случае поперечного (1) и продольного (2) намагничивания.

В данной работе с использованием программного пакета MaxLLG мы подтверждаем правильность аналитической электродинамической модели, разработанной в [1] для поперечно намагниченного безграничного по всем направлениям ФМ ММ и демонстрируем возможность сохранения у него дважды отрицательных свойств при ограничении ФМ ММ в одном из направлений (вдоль проволок). В этом случае слой нормально намагниченного ФМ ММ должен граничить с обеих сторон с проводящими (металлическими) плоскостями. Помимо этого, мы демонстрируем возможность существования ОЭМВ на частотах от $f_\perp$ до f_{ar} при продольном намагничивании, начиная с некоторой толщины металлизированного с обеих сторон слоя ФМ ММ.

В основе работы программного пакета MaxLLG лежит расчет уравнений Максвелла методом конечных разностей во временной области (FDTD) в сочетании с уравнением движения вектора намагниченности Ландау-Лифшица-Гильберта [2].

На Рис.2 приведены результаты расчета дисперсионных характеристик ЭМВ, существующих в рассматриваемом ФМ ММ при двух видах намагничивания как в отсутствие, так и при наличии ограничения в одном из направлений. Красными сплошными линиями показаны кривые, полученные на основе аналитических расчетов [3]. Видно, что ОЭМВ существует как в безграничном, так и в ограниченном по толщине нормально намагниченном ФМ ММ. В случае продольного намагничивания, ОЭМВ появляется только при определенной толщине ФМ ММ.

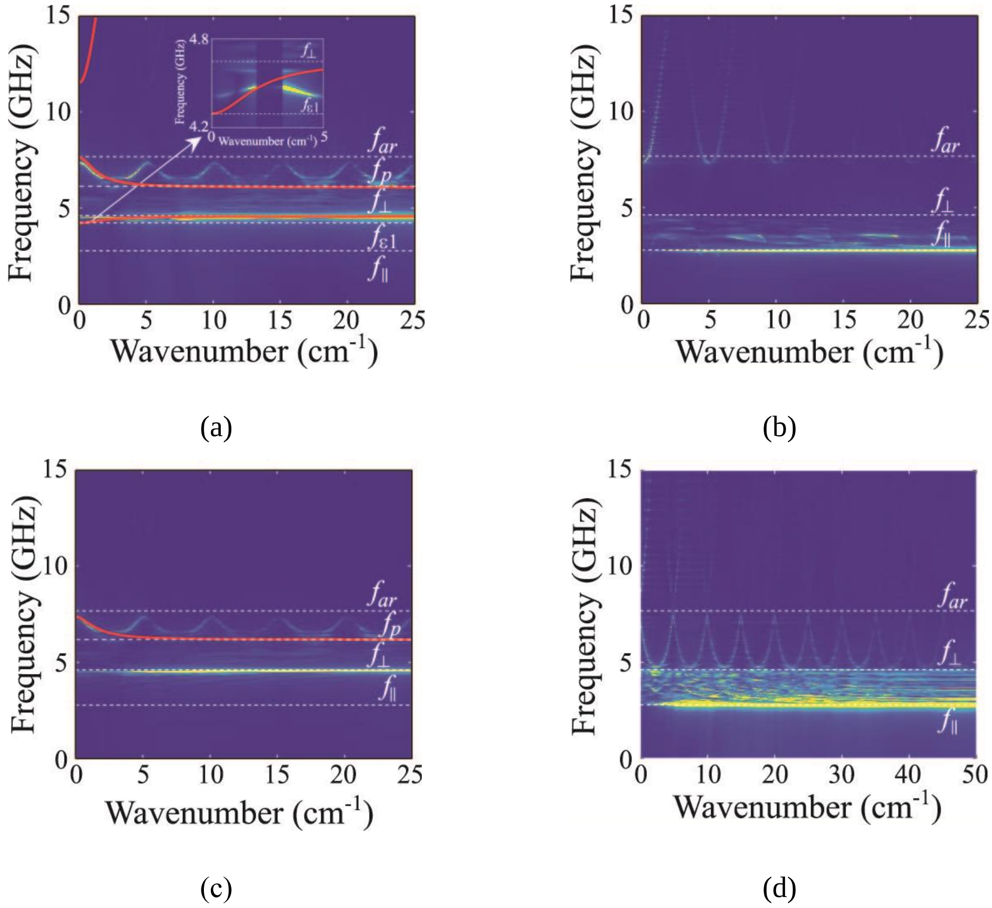

Рис. 2. Дисперсионные характеристики ЭМВ, существующих в безграничном поперечно (a) и продольно (b) намагниченном ФМ ММ, а также в нормально (c) и продольно (d) намагниченном металлизированном слое ФМ ММ толщиной 1.1 см (c) и 5 мм (d). На (a-d) расчеты выполнены для H_0=795.8 А/м, M_0=0.014 Тл, ε_r=16, r_1=100 мкм, r_2=300 мкм, T=2 мм и $\sigma = 10^8$См/м.

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ELECTRODYNAMICS OF EXCHANGE-COUPLED METALLIC NANOSTRUCTURES IN MAGNETIC FIELD

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Electrodynamics of metallic multilayers presents itself as an interesting and practically valuable object of investigation. One of directions, which attracts most attention, is investigation of the microwave properties of exchange-coupled nanostructures and superlattices. At the early stage, the microwave analog of the giant magnetoresistance has been discovered [1]. The approximate equality of DC magnetoresistance for these nanostructures and the relative variation of the microwave transmission coefficient was established [2]. This effect was called as microwave giant magnetoresistive effect (μGMR). The magnitude of the effect can reach of dozens of percent and the saturation fields can vary from dozens of Oe to dozens of kOe. The study was performed of this effect in "current-perpendicular-to-plane" geometry [3]. The effect μGMR was studied in the reflected wave, and it was established that the magnitude of the effect in this case is essentially lower and does not exceed 2-3%.

This paper is devoted to review of the results of recent years in the field of electrodynamics of metallic multilayers. Investigation of the (CoFe/Cu) superlattices, which have very high magnetoresistance, let us to obtain a record μGMR magnitude [4]. Further investigations showed that the spin-wave resonances can be observed in these superlattices [5]. A special group of the samples was prepared, composed of (CoFe/Cu) superlattices grown on the dielectric substrates of different thickness. The sample obtains strong nonreciprocity for the reflected wave if the substrate thickness equals to ¼ or ¾ of the wavelength. It is possible to increase of μGMR magnitude in reflected wave by 10 times [6]. The effect μGMR is discussed in the trilayer nanostructures and in the spin valves, containing an antiferromagnetic layer [7, 8]. In these nanostructures, the magnetic fields were μGMR is realized, equal to 100-200 Oe, and the magnitude of variations exceeds 20%. These nanostructures are prospective for applications in high frequency sensors and electronic devices.

The results were obtained within the state assignment of Ministry of Science and Education of Russia (themes "Spin" No 122021000036-3 and "Function" No 122021000035–6).

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TERAHERTZ ANTIFERROMAGNETIC MAGNONS EXCITED BY PICOSECOND STRAIN PULSES IN NiO

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Antiferromagnets can host ultrafast spin dynamics in the terahertz (THz) frequency range [1], but an energy-efficient generation of THz magnons necessary for high-speed information processing devices is challenging. Fortunately, some antiferromagnetic compounds possess substantial magnetoelastic coupling between spins and strains, which opens the way for their excitation by mechanical stimuli. Here, we report a theoretical study of the spin dynamics excited in single-crystalline NiO by picosecond acoustic pulses, which can be created by optomechanical transducers driven by femtosecond laser pulses.

To describe the interrelated spin and strain dynamics in the antiferromagnetic nickel oxide having a strong magnetoelastic coupling, we carry out micromagnetoelastic simulations based on the numerical solution of the Landau-Lifshitz-Gilbert equations for sublattice magnetizations and the elastodynamic equation for mechanical displacements. Our advanced modeling is distinguished from the preceding simulations by the correct description of the two-way magnetoelastic coupling between the Néel vector and lattice strains. The numerical calculations are performed with the aid of an in-house software previously used to quantify the strain-induced magnetization dynamics in ferromagnetic films [2-4]. The upgraded version of this software makes it possible to describe magnetoelastic phenomena occurring in antiferromagnetic and ferrimagnetic crystals via the introduction of two spin sublattices.

The exchange energy of NiO is calculated with the account of intersublattice interactions quantified by an effective antiferromagnetic exchange and intrasublattice interactions governed by the ferromagnetic exchange between the nearest neighbors. The total energy density also allows for the easy-plane anisotropy, a weak easy-axis anisotropy, the latter defining the energetically most favorable spin directions in the (111) crystallographic planes, dipolar interactions between spins, and the magnetoelastic coupling with two coefficients extracted from the experimental data on the NiO spontaneous strains [5]. The effective exchange parameters and anisotropy constants involved in our two-sublattice model of NiO are found by reproducing the measured frequencies of two antiferromagnetic resonance (AFMR) modes (240 GHz and 1.1 THz) [6-8] and the spin-wave dispersion [6].

The simulations show that the propagating bipolar pulse of the longitudinal strain generates correlated counterclockwise and clockwise precessions of the sublattice magnetizations, which have a complex spatial distribution in the region behind the pulse front. The spatiotemporal analysis of the simulation data reveals that the spin dynamics excited by the pulses with durations τ smaller than about 7 ps comprises a monochromatic spin wave with the frequency $\nu \approx 450$ GHz. Moreover, a second monochromatic wave having the frequency $\nu \approx 2$ THz emerges at $\tau \leq 3$ ps. Importantly, the acoustic pulses with durations $\tau \leq 3$ ps appear to be capable of creating THz-frequency antiferromagnetic magnons in the absence of external magnetic fields.

To clarify the origin of the revealed monochromatic spin waves, we compare the dispersion $\nu_{AF}(k)$ of antiferromagnetic magnons with the dispersion relation $\nu_L(k) = c_L k/(2\pi)$ of the longitudinal elastic waves traveling with the velocity $c_L = 6.9\times10^5$ cm s^{-1} in NiO. For two-sublattice antiferromagnets, the dispersion relation can be written as

$$\nu_{AF}(k) = \sqrt{\nu_0^2 + [c_{AF}k/(2\pi)]^2}\ , \qquad (1)$$

where ν_0 denotes the frequency of the lower or higher AFMR mode, and c_{AF} is the velocity of the antiferromagnetic spin wave, which in NiO is about 5.9×105 cm s-1 according to our micromagnetic simulations. Figure 1 shows that the dependences νAF(k) and $\nu_L(k)$ cross at the wave numbers $k_{low} \approx 40\times10^5$ rad cm^{-1} and $k_{high} \approx 190\times10^5$ rad cm^{-1} yielding the crossing-point frequencies νlow ≈ 450 GHz and $\nu_{high} \approx 2$ THz. Since the parameters of the crossing points are close to the frequencies and wave numbers of the monochromatic spin waves generated by the 1- and 3-ps-long acoustic pulses, we arrive at the conclusion that the excitation of such waves is due to the phenomenon of magnetoacoustic resonance.

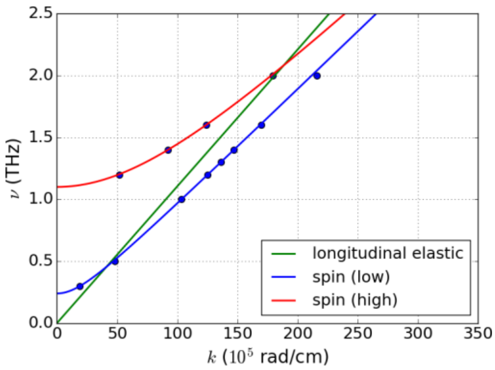

Fig. 1. Dispersion relations of spin and elastic waves in NiO. Points denote the results of micromagnetic simulations obtained for spin waves excited at the NiO surface by a fictitious local magnetic field oscillating with a frequency ν. The curves represent two branches of the spin-wave dispersion relation resulting from the fitting of Eq. (1) to the simulation data, while the straight line shows the dispersion of the longitudinal elastic waves in NiO.

Thus, we predict that the spectrum of the strain pulse should contain significant components at the crossing-point frequencies to be capable of generating spin waves with considerable magnitudes. Our findings shed light on the magnetoacoustic phenomena in antiferromagnets and indicate that the single-crystalline NiO is a promising material for the development of ultrafast magnonic devices with a low power consumption.

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LASER-INDUCED MAGNETOACOUSTIC WAVEPACKETS FORMATION CONTROLLED BY RELATIVE POLARIZATIONS OF SAW AND MSW COMPONENTS

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In the last few years, nonlinear spin-wave processes have attracted great interest from the point of view of constructing magnonic elements. On the one hand, nonlinear processes make it possible to implement a magnonic half-adder and amplifier [1] - the basic elements of digital magnonics [2]. On the other hand, nonlinear processes are necessary to obtain a nonlinear activation function, a basic element of neuromorphic devices [3]. As was shown recently, the interaction of an acoustic and magnetic waves can act as a source of nonlinearity for magnonics [4]. An important role in this case is played by both the magnetoelastic constants, which depend on the selected material, and the overlap integral, which depends on the relative polarizations of the magnetostatic (MSW) and surface acoustic (SAW) waves [5].

In this work, we experimentally demonstrate formation of short packets of laser-induced magnetoacoustic waves. The all-optical pump-probe measurements were carried out on a simple structure of a 20 nm thick polycrystalline ferromagnetic NiFe (Py) film on a single-crystalline Si-(110) substrate. Py is a promising magnonic material, and its magnetic parameters and thickness are close to metal films, in which laser-induced excitation of propagating wave packets with a propagation length sufficient for magnon devices was previously demonstrated [6,7]. The SAW were excited by the pump pulse due to the thermal expansion of the Py film, as indicated by the absence of excitation in the clean substrate. When waves are excited, three wave packets, identified as Rayleigh, Love and Sezawa-type, propagate with distinct polarizations and phase velocities. When these packets propagate in a film/substrate structure with a magnetization orientation in the Py layer corresponding to backward volume or surface magnetostatic waves, a change in the phase velocities of the magnetoacoustic packets is observed, depending on the magnetization orientation.

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BRAGG RESONANCES OF ANISOTROPIC SPIN WAVE MODES AND WIDE BAND GAP FORMATION IN SUBWAVELENGTH PERIODIC MAGNONIC STRUCTURES

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The main feature of spin wave spectrum in magnonic crystals (MCs) that used in various applications [1,2] is forbidden gap formation at the frequencies f_B of the Bragg resonances taking place when wavelength λ of spin waves and period Λ of MC meet the condition $\lambda(f_B) = 2\Lambda/n$. In subwavelength case when $\lambda \gg \Lambda$, MCs become an effective medium for the spin waves. However, magnetostatic surface waves (MSSW) propagating in such subwavelength periodic structures (SPS) demonstrate several interesting particularities [3] in the amplitude-frequency characteristics of transmission coefficient $S_{21}(f)$. In the present work, we show possibility of interaction between MSSW and anisotropic spin wave modes (ASW) [4-6] in SPS. Such ASWs appear in films of yttrium-iron garnet (YIG) due to cubic magnetocrystalline anisotropy and are grouped close to the f_0 border for the films with the thickness ≥ 4 μm. ASW dispersions have lower incline compared to MSSW and, therefore, the structure period that is subwavelength for MSSW can meet the Bragg condition for ASW as it was shown for dynamic MC created by surface acoustic waves [7].

For the simulation in OOMMF [8], we used the parameters of SPS considered in [3] and based on the YIG film with the thickness ≈7.7 μm and (111) cubic anisotropy with anisotropy field - 40 Oe. Grooves etched in the YIG surface with the period 8 μm have depth of 1.05 μm and width of 3.2 μm. External field of 200 Oe was applied along the grooves (along *y* axis) while propagation of spin waves was perpendicular to them (*x* axis), which corresponds to the MSSW configuration. Periodic boundary conditions were applied along the grooves. Total sample dimensions were $x \times y \times z = 2080\ \mu m \times 75\ nm \times 7.725\ \mu m$ with the cell size $\Delta x \times \Delta y \times \Delta z = 320\ nm \times 75\ nm \times 75\ nm$. To obtain $S_{21}(f)$ and dispersion curves, we used the standard procedure [9] of sinc-pulse excitation and further Fourier transform of magnetization dynamics in the structure. To reduce the influence of spin wave reflection from the sample edges (x=0 and x=2080 μm), we introduced regions of high damping at the edges changing according to the geometrical progression.

Obtained results are presented in Fig. 1. One can see the appearance of ASW close to the f_0 frequency. For flat YIG film, ASW causes formation of oscillations in $S_{21}(f)$ with the amplitude up to ≈2 dB due to the interference (curve 2 in Fig. 1a). In the studied SPS, a group of oscillations with the larger amplitudes (up to ≈6 dB) forms as the result of interaction between ASW and MSSW in the same region around f_0 (curve 3 in Fig. 1a,b). In the experiment, however, $S_{21}(f)$ curve shows much larger oscillations in this region (curve 4 in Fig. 1b). It worth to note that found Bragg resonances in SPS may form additional regions of Van Hove singularities in the MSSW spectrum. Thus, SPS covered with a Pt layer can demonstrate an increase of the spin current detected in Pt at corresponding frequencies.

Another interesting phenomenon is the formation of a deep and wide dip in the $S_{21}(f)$ curve (marked with the asterisk in Fig. 1b, 1d). The origin of the dip is not related to either the Bragg resonance or any eigenmode in the system. We believe that the dip results from the interaction of MSSW propagating in the part of the YIG film without protrusions and MSSW propagating in the system of periodical resonators that are form by the protrusion between grooves on the film surface.

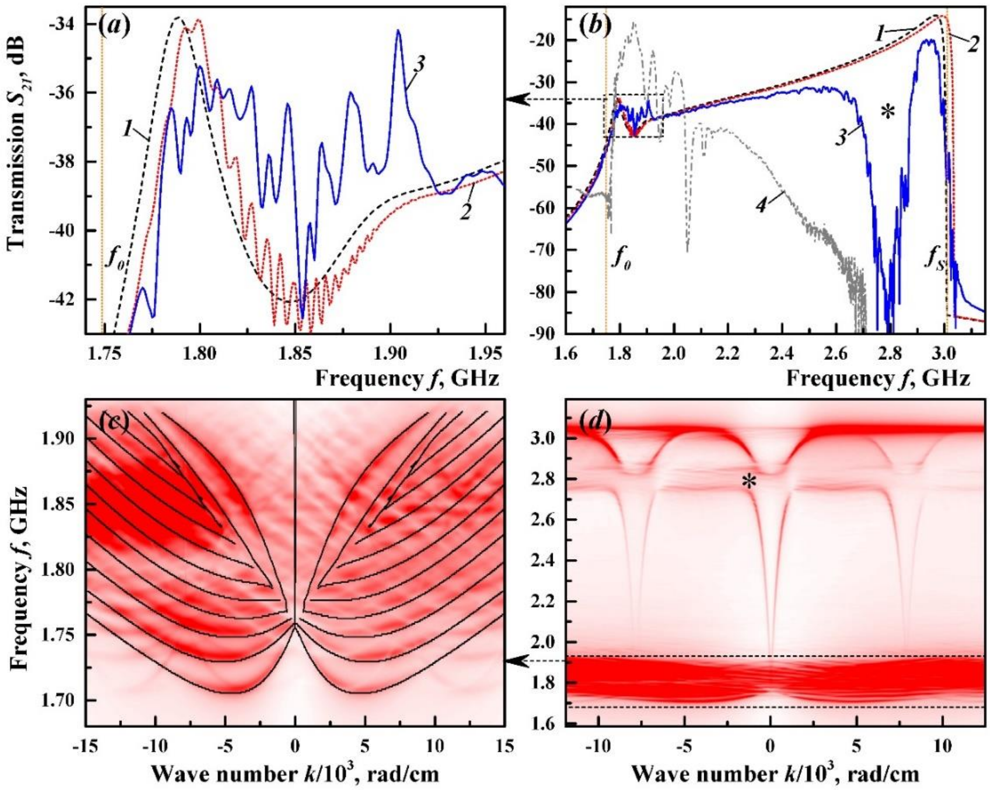

Fig. 1. Simulated transmission (a, b) and dispersion (c, d) spectra in the considered structure. (a) and (c) show the areas outlined in (b) and (d), respectively. $S_{21}(f)$ curves correspond to: 1, 2 – flat YIG film without and with anisotropy, respectively; 2 – SPS; 4 – experimental curve.

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НЕВЗАИМНЫЙ ПАРАМЕТРИЧЕСКИЙ РЕЗОНАНС В 1D И 2D БИКОМПОНЕНТНЫХ МАГНОННЫХ КРИСТАЛЛАХ

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Метаматериалы представляют собой искусственно созданные среды, свойства которых отличаются от природных сред. Концепция создания метаматериалов базируется на использовании периодических структур из субволновых элементов, период которых T является намного меньше длины волны λ, т.е. $T \ll \lambda$. В последнее время к метаматериалам начали относить и искусственные среды, у которых период структуры сравним с длиной волны, т.е. $T \sim \lambda$. В таких метаматериалах волна с волновым числом, удовлетворяющим условию Брэгга, отражается от периодической структуры и не проходит через среду. В результате на частотах брегговских резонансов образуются так называемые полосы непропускания, или запрещенные зоны. Метаматериалы, где условие Брэгга выполняется для спиновых волн, получили название магнонные кристаллы (МК) [1]. В таких кристаллах часто в роли магнитной матрицы выступает диэлектрический ферромагнетик – пленка железо-иттриевого граната (ЖИГ), на поверхности которой создается либо одномерная (1D) [2], либо двумерная (2D) [3] периодическая структура. 1D и 2D МК в виде комбинации двух магнитных материалов в свою очередь получили название бикомпонентных магнонных кристаллов (БКМК)

В настоящей работе приводятся результаты экспериментального исследования нелинейных характеристик 1D и 2D бикомпанентных магнонных кристаллов, работающих в условиях трехволнового параметрического распада поверхностной МСВ (ПМСВ).

1D бикомпонентный магнонный кристалл был создан на основе пленки ЖИГ толщиной d_1=10 мкм и с намагниченностью насыщения 1750 Гс, на поверхность которого наносилась периодическая структура из супертонких полосок пермаллоя [$Ni_{80}Fe_{20}$] толщиной d_2=50 нм, шириной a=40 мкм и периодом T=120 мкм. 2D БКМК был выполнен на основе пленки ЖИГ длиной l=15 мм и шириной w=4 мм, на поверхности которой располагалась 2D решетка из пермаллоевых дисков диаметром D=50 мкм и периодом T=100 мкм. При исследовании передаточных характеристик 1D и 2D БКМК было установлено, что в линейном режиме в 2D БКМК помимо запрещенных зон (ЗЗ), обусловленных отражением бегущей поверхностной магнитостатической волны (ПМСВ) от периодической структуры, образуются дополнительные полосы непропускания. Появление последних связано с возбуждением спин-волновых резонансов в пермаллоевых дисках бегущей ПМСВ в ЖИГ-матрице. В нелинейном режиме, реализуемом на частотах, где трехволновый параметрический распад бегущей ПМСВ в ЖИГ-матрице запрещен, на частотах дополнительных спин-волновых резонансов наблюдалось параметрическое возбуждение коротковолновых СВ, которое было невзаимным. На рис.1 приведены карты распределения квадрата амплитуды переменной намагниченности, полученные на установке бриллюэновской спектроскопии для 1D БКМК, как на частотах ПМСВ f_1 и f_2, так и на вдвое меньших частотах $f_1/2$ и $f_2/2$, соответствующих частотам параметрически возбуждаемых СВ. Из представленных на рисунке 1а,б результатов следует, что когда частота сигнала f_1 находится в спектре ПМСВ, но вне полосы непропускания (см. рис. 1а), то увеличение амплитуды переменной намагниченности на половинной частоте сигнала $f_1/2$ с ростом мощности сигнала на частоте f_1 не наблюдается (см. рис. 1б). Если частота сигнала f_2 находится в спектре ПМСВ, но теперь в полосе непропускания (см. рис.1в), то в этом случае появляется отклик на половинной частоте $f_2/2$ (см. рис. 1г) с ростом мощности сигнала на частоте f_2, что свидетельствует о наличии на данных частотах трехволнового параметрического резонанса.

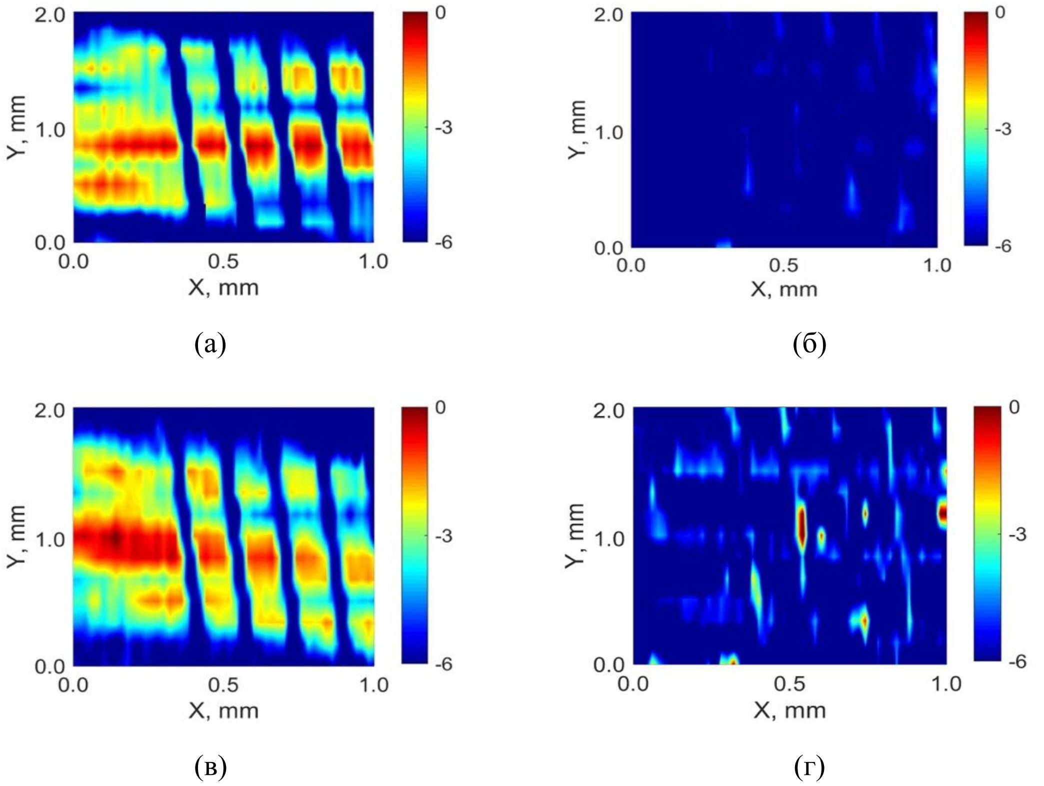

Рис. 1. Пространственные распределения намагниченности ПМСВ (левая панель) и параметрически возбуждаемых СВ (правая панель) 1D БКМК с решеткой из пермаллоевых полосок, измеренные с помощью установки бриллюэновской спектроскопии.

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Artificial and composite magnetic materials

COMPOSITE MAGNETIC EXCITATIONS IN SUPERCONDUCTOR/MAGNET HETEROSTRUCTURES

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The ability to control the dispersion law of spin waves is one of the most important requirements for the engineering of magnonic devices. Thin-film hybrid structures consisting of a ferromagnetic or antiferromagnetic insulator and a superconductor have broad prospects in this field. In this talk two main mechanisms to modify the spin wave dispersion laws via superconductivity are discussed.

The first one is based on the stray magnetic field emitted by the magnetization dynamics. It is reflected, focused, and enhanced inside the ferromagnet by the supercurrent induced in the superconductor, such that the group velocity of spin waves is strongly enhanced [1]. The second mechanism originates from the presence of a surface exchange interaction between the magnetic insulator and the superconductor. Due to this interaction an effective exchange field is induced in the latter, which repeats the profile of the magnetization of the magnet, including the magnon. This leads to the appearance of spin polarization of the quasiparticles in the superconductor and the generation of triplet Cooper pairs in it. In its turn, this quasiparticle and pair polarization strongly renormalizes the spin wave dispersion [2,3].

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LOCALIZATION OF MAGNONS AT SUPERCONDUCTING VORTEX IN CHIRAL MAGNET - SUPERCONDUCTOR HETEROSTRUCTURE

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Superconductor-chiral ferromagnet heterostructures have recently attracted much attention due to an experimental demonstration of stable skyrmion-vortex coexistence [1]. Typically, in the case of thin superconducting film (thickness much less London's penetration length, $d_S << \lambda_L$) it hosts the so-called Pearl's superconducting vortices [2]. Such a vortex produces an inhomogeneous magnetic field with typical Pearl's length $\lambda=(\lambda_L)2/d$. This magnetic field results in nonuniform magnetization profile in otherwise homogeneously magnetized thin film. If we use the standard parametrization for magnetization in the thin chiral ferromagnetic film as $M=M_s(e_r\cos\theta(r)+e_z\sin\theta(r))$, then the corresponding solution for θ is given as $\theta(r)=\gamma[K_1(r/l)-l/r]$, where $K_1(z)$ stands for modified Bessel function of the second kind [3]. The ratio of exchange energy to anisotropic energy determines the length scale l as $l2=A/K$. Parameter $\gamma=(l/\lambda)\ (M_s\varphi_0/8\pi A)$ <<1, where φ_0 the flux quantum, controls the strength of the vortex magnetic field.

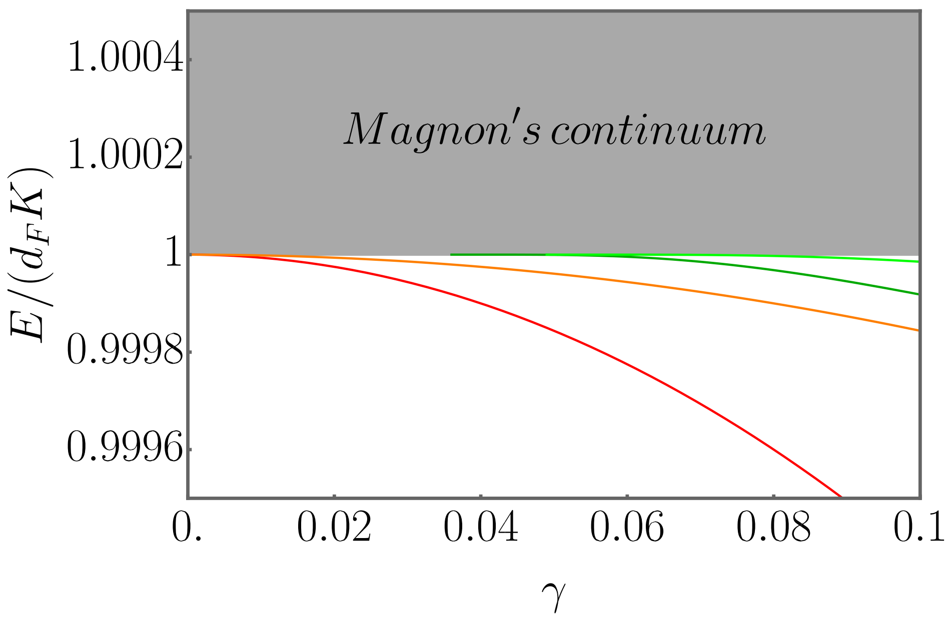

Fig. 1. Sketch of energy spectrum of magnons localized on inhomogeneous magnetization created by Pearl's vortex.

Scattering of magnons on such an inhomogeneous magnetization profile is described by the Bogoliubov-de Gennes type equation [4]. Interestingly, in the case of γ<<1 the problem (in the first approximation) is reduces to Schrodinger equation for spectrum of two-dimensional hydrogen atom with length l/γ playing a role of the Bohr radius. The corresponding energies of localized states counted from the edge of magnon continuum are given as E_n=-d_FKγ2/(16n2), where n=1,2,… However, since the true potential in effective Schrodinger equation is different from Coulomb potential 1/r, there are only finite number of localized states, N=(γλ/l)1/2 >>1. The energies of these last states re given as E_n=-2.12 d_FKγ2 (1-n/N)6/N2. The sketch of the energies of localized states is shown in Fig. 1. In addition, we found the scattering cross-section of magnons on the inhomogeneous magnetization created by Pearl's vortex.

Also we discuss how the presence of skyrmion affects the state localized on the Pearl's vortex.

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SPECIAL FEATURES OF MAGNETIC RESONANCE IN METAL-INSULATOR NANOGRANULAR COMPOSITES

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Films of metal-insulator nanogranular composites M_xD_{100-x} with different compositions and percentage of metallic and dielectric phases (M = Fe, Co, Ni, CoFeB; D = Al_2O_3, SiO_2, ZrO_2, $LiNbO_3$; $x \approx 10-80$ at.%) were studied by magnetic resonance. The experiments were carried out in a wide range of frequencies ($f = 7-37$ GHz) and temperatures ($T = 4.2-360$ K) at different orientations of the magnetic field with respect to the film plane.

It was found that at concentrations of the metallic ferromagnetic (FM) phase below the percolation threshold, the experimental spectra, besides the usual signal of the FM resonance (FMR), contain an additional absorption peak characterized by a double effective g-factor $g \approx 4$. Furthermore, the observed peak demonstrates a number of other unusual properties:

- It is better manifested in the longitudinal geometry of the resonance excitation.
- With an increase of the FM phase content, the peak demonstrates an additional frequency shift depending on the orientation of the external field with respect to the film plane.
- The temperature dependence of the peak intensity has a non-monotonic character with a maximum in temperature. This maximum shifts to higher temperatures with an increase of the FM phase content.

The appearance of such a peak in the resonance spectra can be explained within the framework of the "giant spin" model by excitation of "forbidden" ("double-quantum") transitions inside the FM nanogranules with a change in the spin projection $\Delta m = \pm 2$ [1,2]. Within the framework of this approach, it is possible to explain the better manifestation of the peak with $g \approx 4$ in the longitudinal geometry of the resonance excitation [2], as well as the anomalous temperature dependence of its intensity [1,2]. The unusual frequencyfield and orientational dependences observed for the peak with $g \approx 4$ are well described taking into account the presence of effective dipolar fields inside the film: the "demagnetization field" and the "Lorentz fields" [3].

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THIN FILMS OF YTTRIUM ORTHOFERRITES FOR ANTIFERROMAGNETIC SPINTRONICS

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During several last years antiferromagnetic (AFM) spintronics [1] became an important field of research, exploiting the Néel vector for control of spin- and orbital-dependent transport properties in the wide frequency range of up to the units of terahertz. "Weakly ferromagnetic" orthoferrites of general formula $RFeO_3$, where R is a rare-earth element, are potential candidates for AFM spintronic applications since, depending on the type of rare-earth element, the frequencies of their ferromagnetic (FM) and AFM resonances cover the range from ~0.1 till 1 THz. Yttrium orthoferrite $RFeO_3$ probably is the most studied model "weakly ferromagnetic" material [2]. The record values of domain wall motion of about ~ 20 km/s were discovered in it and the processes of relativistic domain wall dynamics were extensively studied. Most studies have been carried out for bulk $YFeO_3$ samples, both single crystals and polycrystalline ones. However, modern technologies require thin films and nanostructures. In these nanosized objects variations of structural and magnetic properties with thickness are non-trivial and require experimental confirmation. In this work, the structural and magnetic characteristics of ultrathin single-crystal films of $Y^{57}FeO_3$ orthoferrite were studied at the ESRF synchrotron and the Kurchatov Center [3-5].

Ultrathin $Y^{57}FeO_3$ films were obtained by magnetron sputtering on the *r*-Al_2O_3 substrate at the M.N. Mikheev Institute of Metal Physics. A set of films covering the thickness range of 2.5÷40 nm were prepared and investigated. X-ray diffraction measurements were carried out at the Kurchatov Institute confirmed the presence of a *Pnma* structure characteristic of $YFeO_3$ orthoferrite. The films turned out to be highly textured with *c*-axis (the largest lattice parameter of 0.76032 nm) perpendicular to the film plane for most samples (but not all). Additional reflections corresponding to inclusions of the $Y_3Fe_5O_{12}$ phase and reflections characterizing the hexagonal modification of $YFeO_3$ were also identified for the thinnest films.

Mössbauer spectra were measured by reflectometry using a synchrotron Mössbauer source at ESRF (station ID18) in the temperature ranges from 3.5 K to 273 K and from 273 K to 700 K. In addition to the sextet characterizing $YFeO_3$, the reflection spectra revealed an additional sextet corresponding to a lower magnetic field ultrafine field. Changes in the spectra with temperature and under the influence of an external field made it possible clarify that at least three sextets in different proportions characterize the spectra depending on the thickness of the $YFeO_3$ film. The Mössbauer parameters for the two additional sextets correspond to the ferrimagnet $Y_3Fe_5O_{12}$, which has two positions for the Fe atoms (ortho- and tetrahedral) in the unit cell with an occupancy of 2:3.

Analysis of the temperature dependences of Mössbauer reflection spectra showed a decrease in the Néel temperature T_N with decreasing film thickness. For film thicknesses of ~ 28 nm, ~ 6.5 nm and ~ 4 nm, the values of T_N were found to be TN=593 ± 2 K, 580 ± 2 K and 567 ± 2 K, respectively. The T_N value for bulk single crystal was found to be

650 K. The value of the critical parameter $\beta \cong (0.28 \div 0.3) \pm 0.02$, was determined, which turned out to be slightly less than the one for the for bulk orthoferrite ($\beta \cong 0.34$). The transformation of the spectra, in particular the appearance of a quadrupole doublet in the center of the magnetic sextet, starting already at 66 K for the thinnest film, and an increase in its area with a further increase in temperature, indicates a consistent transition from the AFM to the superparamagnetic state for individual clusters or regions containing impurity phases in films.

A consistent change in the orientation of the AFM axes in $Y^{57}FeO_3$ with temperature was also discovered, so that the angle defining the direction of the hyperfine field B_{hf} relative to the surface plane changes on average from ~ 63° to ~ 45°, that is, with increasing temperature, the antiferromagnetic axis turns toward the surface.

The effect of depth selectivity in reflection spectra was revealed when comparing spectra measured at different grazing angles. In the spectrum measured at the larger grazing angle of 2.97 mrad, the proportion of doublets in the central part of the spectrum increases noticeably. Processing of the spectra showed that the paramagnetic structure is present mostly in the region of the interface with the substrate in a layer with a thickness of the order of ~1 nm at the depth of ~3 nm.

Thus we show that for thin films of $Y^{57}FeO_3$ on the *r*-Al_2O_3 substrates with the thicknesses in the range of 2.5÷40 nm complex variation of structural and magnetic properties is observed. The most interesting transformations are observed for the thinnest films. The details of such variations must be taken into account while modeling and interpreting the results for the nanostructures of AFM spintronics and prototype devices.

The authors are grateful to the ESRF administration and personally to A.I. Chumakov for performing measurements at ID18 (the HC4300 proposal).

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THE STUDY OF SPIN-WAVE DYNAMICS IN AMORPHOUS FERROMAGNETS BY THE METHOD OF SMALL-ANGLE NEUTRON SCATTERING

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Amorphous magnetic materials are of considerable interest from both fundamental and applied points of view. The low coercive field of amorphous magnets is an important property for their application as a core materials in electrical transformers. The presence of structural as well as magnetic disorder plays an important role in amorphous systems. The search for a correct description of the formation and growth of spin clusters in amorphous systems is a complex task. The properties of such spin clusters under the influence of an external magnetic field depend on their morphology. Therefore, from the magnetism point of view, interesting aspects are: (1) correlation between structural and magnetic properties; (2) understanding the behaviour of spin clusters and (3) investigation of magnetic excitations in such systems. Despite some success in describing the static properties of magnetically soft amorphous magnets [1, 2], their dynamic characteristics and, in particular, the characteristics of the magnon dispersion have not been studied in detail. Thus the problem of direct measurement of the spin wave spectrum by neutron scattering methods turns out to be relevant.

The dispersion of spin waves in an amorphous ferromagnet can be described through the model of a ferromagnet with random anisotropy: $\epsilon(q) = Aq^2 + g\mu_B H + \delta\omega(q)$, where $\delta\omega(q)$ is a linear in $|q|$ additive [1, 3, 4]. In this paper, we investigate the temperature dependence of the energy characteristics in the spin wave spectrum of the amorphous ferromagnetic alloy $Fe_{48}Ni_{34}P_{18}$ and show that it is possible to obtain information not only about the spin-wave stiffness, but also about the characteristic random anisotropy constant that determines the appearance of the additive $\delta\omega(q)$. We use the method of small-angle scattering of polarized neutrons to prove the significance of the additional term $\delta\omega(q)$ in the dispersion. The measurements were carried out at different values of the external magnetic field H and the neutron wavelength λ. The neutron scattering map is a circle of a certain radius centered at the point $q = 0$ (Fig.1). The spin-wave stiffness A is extracted directly from the λ-dependence of the radius of this circle. The spin-wave stiffness A of an amorphous alloy decreases slightly from 140 to 110 meV Å^2 with an increase in temperature in the range of 50 to 300 K. The field dependence of the radius demonstrates the presence of an additive δω(q) in the form of an energy gap, which is practically independent of field and temperature. Therefore, the experiments have revealed an internal "effective energy gap" associated with random anisotropy in the spin wave spectrum of the $Fe_{48}Ni_{34}P_{18}$ alloy over a wide range of temperatures and magnetic fields. The "gap" value of 0.015 meV was measured with an accuracy of 0.002 meV, which is a record achievement in terms of its accuracy. The presence of a linear additive in the spectrum of spin waves is experimentally demonstrated, confirming the validity of the "random anisotropy theory" for amorphous ferromagnets.

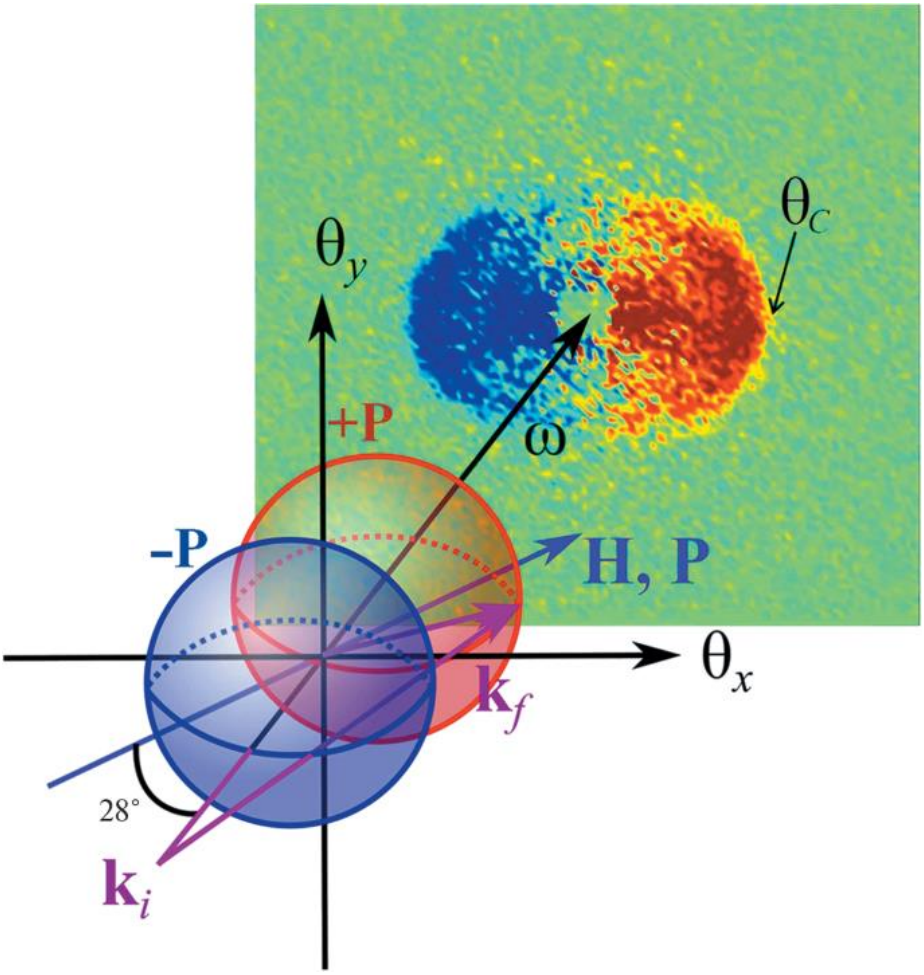

Fig. 1. Kinematic scheme of small-angle neutron scattering by spin waves in a ferromagnet.

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ELECTRICALLY TUNABLE SUB-TERAHERTZ RESONANCE IN ANTIFERROMAGNET-BASED HETEROSTRUCTURE

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Antiferromagnetic (AFM) materials have natural resonance frequencies in the sub-THz or THz ranges. Thus, it is tempting to use antiferromagnets (AFM) as active layers in THz-frequency oscillators [1] and detectors [2]. It has been shown theoretically [2] that both uniaxial and biaxial AFMs can be used for the resonance quadratic rectification of a linearly polarized AC spin current of THz frequency and could have a sensitivity in the range of 100–1000 V/W.

Let us consider the antiferromagnet-normal-metal heterostructure (see the inset in Fig.1) with the antiferromagnetic easy plane (EP) oriented in the angle θp to the surface plane, and hard axis nh is perpendicular to the EP. An additional bias DC current in the normal metal layer (here Pt) is used for tuning the AFM high-frequency mode (near 0.17 THz for jdc=0) and for a partial regeneration of the system losses. Based on our previous theoretical analysis [2,3,6] applied to the hematite crystal, we analyzed the so-called "σ-model" equation describing the dynamics of Neel vector l(t); we have found the analytical expressions for both low and high frequencies of hematite as functions of current density for an arbitrary angle of inclination of the easy plane relative to the sample plane.

Our theoretical analysis showed that decreasing the angle between the sample plane and the easy antiferromagnetic plane leads to an increase in the value of threshold current density. Thus, our analysis shows that minimizing the critical tuning current would be desirable for the easy plane to be oriented perpendicular to the sample plane, which can be achieved by choosing a unique substrate.

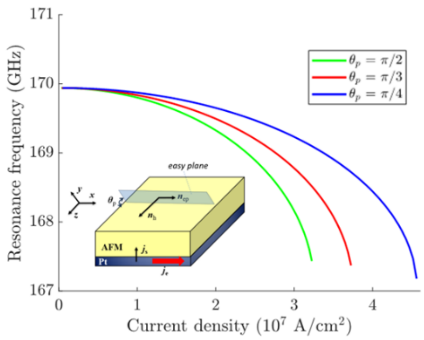

Fig. 1. Dependence of the AFMR oscillation frequency on the input bias electrical current density flowing in the Pt layer for different orientations of easy plane relative to the sample plane (θp=π/2, π/3, π/4). The inset is an image of the proposed AFM-Pt heterostructure.

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Low-dimensional and frustrated magnetism

LONGITUDINAL MAGNONS: NEW COLLECTIVE QUANTUM EXCITATIONS IN LARGE-*S* MAGNETS

M. Zhitomirskii

Coherently propagating spin waves or magnons are the lowest energy excitations in ordered magnetic solids. They obey bosonic statistics and have integer spin-quantum numbers $\Delta S^z = \pm 1$. For an easy-axis antiferromagnet, these are seen in the form of two ascending and descending AFMR branches. The standard picture of magnons needs to be updated for magnetic materials with a substantial single-ion anisotropy comparable to the magnetic exchange. Specifically, the infrared absorption experiments on Van der Waals spin-2 antiferromagnets $FePS_3$ and $FePSe_3$ [1,2] have demonstrated presence of unusual magnetic excitations that exhibit four times larger splitting in magnetic field in comparison to the normal AFMR modes. We identify these new excitations with longitudinal magnons, which correspond to full reversal of single iron spins ($S = 2$) and have a total angular momentum $\Delta S^z = \pm 4$. We develop a theoretical description of the longitudinal magnons and demonstrated that they acquire a small finite dispersion thus providing an example of new type of coherently propagating modes in ordered magnetic systems. We also argue that condensation of longitudinal magnons in a magnetic field in strongly anisotropic materials can produced various exotic multipolar states.

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SPIN DYNAMICS AND PHONON-ZEEMAN EFFECT-IN $CoTiO_3$ REVEALED BY RAMAN SCATTERING IN HIGH MAGNETIC FIELD

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A trigonal honeycomb antiferromagnet $CoTiO_3$ recently excited the condensed matter community due to observation of the Dirac magnons [1], which are direct counterpart of the widely known massless Dirac electrons in graphene [2].

In this talk, we present the results of the comprehensive Raman scattering study of the magnetic and lattice dynamics of $CoTiO_3$ single crystals using the polarized and azimuthally-resolved technique in a wide temperature range 4–300 K and in DC magnetic field up to 30 T.

Acoustic and optical magnon branches were observed in the antiferromagnetic (AFM) phase. The AFMR resonance modes directly provide the spin gap value of about 1 meV, and were used, together with all other excitations, for further reexamination of the exchange structure of $CoTiO_3$. Extremely dampened but clearly observed modes at temperatures above T_N hint at strong short-ordering effects.

The spin-phonon effect was observed close and below T_N, in accordance with predictions of the DFT calculations, which show that only the particular phonons should be affected due to dynamical angular modulation of the exchange Co-O-Co paths [3]. Moreover, magnetic fields up to 30 T allowed us to observe competition between the spin-phonon and magnetoelastic interactions [4]. Surprisingly, a large splitting of the doubly degenerate chiral phonon modes was observed indicating presence of the phonon Zeeman effect, see Fig 1. Additionally, strong coupling with low energy electronic excitations of the orbitally degenerate Co^{2+} magnetic $3d^7$ ions also plays an important role in this splitting.

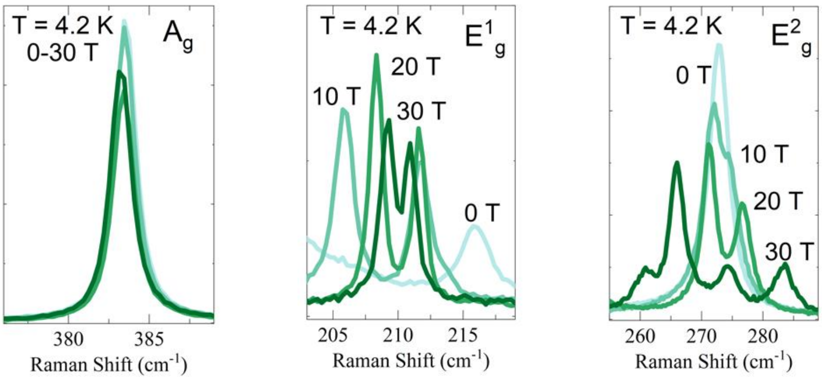

Fig 1. Pronounced phonon Zeeman effect on chiral E^1_g and E^2_g phonons of $CoTiO_3$. Note absence of the splitting and only small magnetoelastic shift of the A_g mode.

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MICROWAVE STUDY OF THE QUASY-2D DECORATED SQUARE KAGOMÉ LATTICE MAGNETS $ACu_7(TeO_4)(SO_4)_5Cl$ (A=Na, K, Cs, Rb)

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2D kagomé lattice constructed from corner-sharing triangles is one of the archetypal models of the frustrated magnetism. Traditional kagomé lattice consists of hexagonal voids surrounded by triangles. Square kagomé lattice (SKL) [1] is a development of this model, it consists of alternating square and octagonal voids, as shown at Fig. 1. Theoretical considerations and numeric simulations predicts variety of possible scenarios for the physics of SKL magnets depending on the ratios of exchange interactions ranging from the spin-liquid behavior for ideal 2D equilateral SKL to complicated forms of order for coupled SKL layers with non-equivalent in-layer couplings [2].

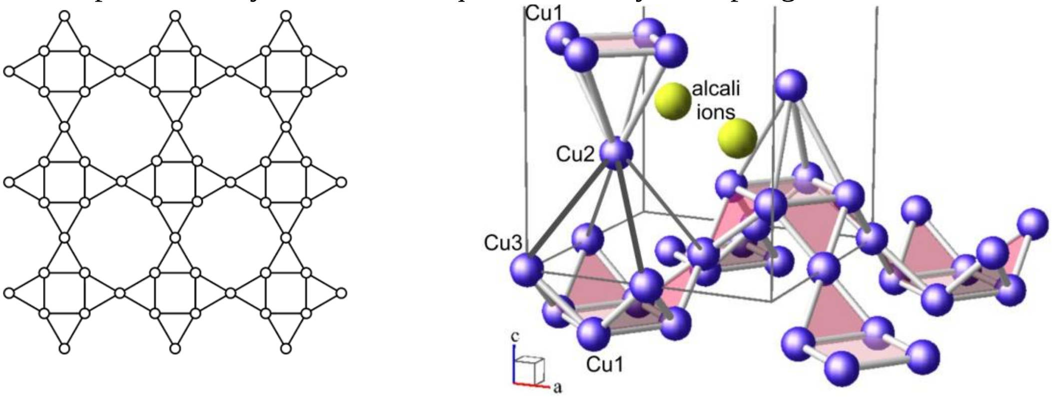

Fig. 1. (left) Fragment of a 2D equilateral square kagomé lattice. (right) Fragment of the nabokoite crystallographic structure (only copper and alkali ions' positions are shown) demonstrating 2D SKL layers formed by copper ions in Cu1 and Cu3 positions and 'decorating' copper ions in inter-layer Cu2 position.

Recently synthesized nabokoite family compounds $ACu_7(TeO_4)(SO_4)_5Cl$ (A=Na, K, Cs, Rb) [3] provides possible realization of a SKL antiferromagnet. Additional complication of nabokoite crystalline structure (see Fig.1) is that the SKL layers (Cu1 and Cu3 positions in nabokoite structure) are 'decorated' by the seventh copper ion taking inter-layer Cu2 position. Magnetization and specific heat study [3,4] demonstrate that Curie-Weiss temperatures for all nabokoite family members is around 100-200 K indicating presence of strong antiferromagnetic couplings within SKL layers. Low temperature magnetic ordering was observed for K and Na compounds only at the temperatures around 3-4 K. This supports theoretical predictions [2] on the spin-liquid behavior of the SKL antiferromagnet. Freezing of this spin liquid into the ordered state for K- and Na-nabokoites at $T \ll \Theta$ rises questions both on the type of the formed magnetic order and on the nature of magnetic ordering in these compounds.

In the present talk we report results of the study of microwave properties of nabokoite family compounds. These include magnetic resonance in the ordered and paramagnetic phases of nabokoites and study of the high-frequency (~10 GHz) dielectric properties of these compounds.

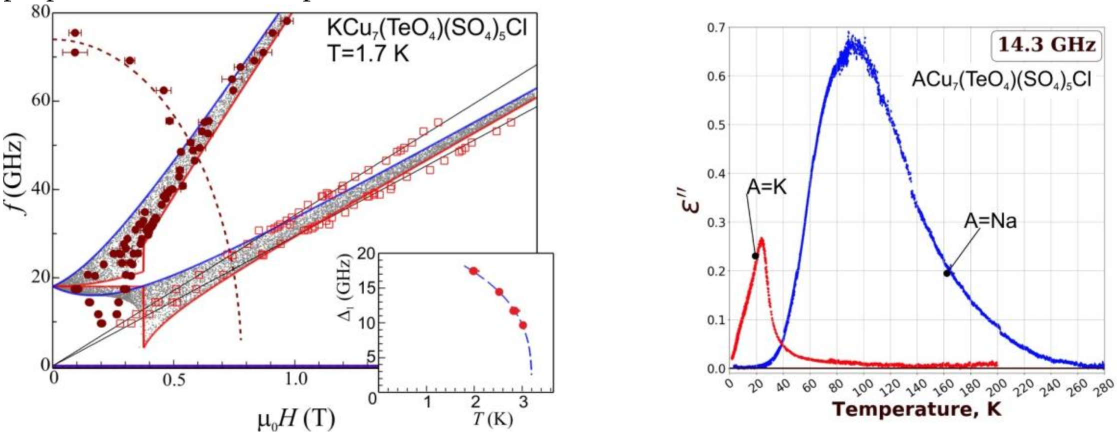

Fig. 2. (left) AFMR frequency-field dependence for powder sample of K-nabokoite at T=1.7 K. Circles – AFMR absorption, squares – boundaries of EPR response from paramagnetic defects. Solid lines and gray shading – simulation in the model of spiral magnetic ordering. Dashed curve – guide to the eye for the high-frequency resonance mode. Inset: temperature dependence of the spin-wave spectrum gap. (right) Temperature dependence of high-frequency dielectric losses in Na and K- nabokoites.

Paramagnetic resonance absorption observed in nabokoites turns out to be very small, it corresponds to concentration of paramagnetic centers amounting to less than 3% per copper ion of nabokoite. The observed paramagnetic response is most likely dueto some defects, while the decorated SKL lattice of copper ions remains EPR-silent. On cooling below the Neel temperatures (for K- and Na-nabokoites) additional antiferromagnetic resonance (AFMR) absorption appears. AFMR frequency-field dependence features asymptotic f(H) slope well different from that expected for g≈2.0 2.3 Cu^{2+} ions (see Fig.2). This can be semi-quantitatively explained assuming that the magnetic order in K- and Na-nabokoites is non-collinear one [4]. High-frequency (~10 GHz) dielectric properties measurements [5] reveal possible driving force for the magnetic ordering in Na and K-compounds: both of these compounds demonstrate dielectric anomalies (at ε ’ and ε ’ ’) at 26 K (K) and 96 K (Na) (see Fig. 2). Lattice distortions accompanying these dielectric anomalies can lift frustration of the inter-layer couplings via displacement of alkali ions and Cu2 ions (see Fig. 1) which can be the cause of the formation of magnetically ordered state.

The work was supported by Russia Science Foundation grants 22-12-00259 (V.Glazkov, Ya.Rebrov; magnetic resonance and dielectric measurements) and 23-23- 00205 (P.Berdonosov, A.Murtazoev; samples preparation).

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EFFECT OF SPIN FLUCTUATIONS ON THE ELECTRONIC STRUCTURE OF FRUSTRATED 2D STRONGLY CORRELATED SYSTEMS

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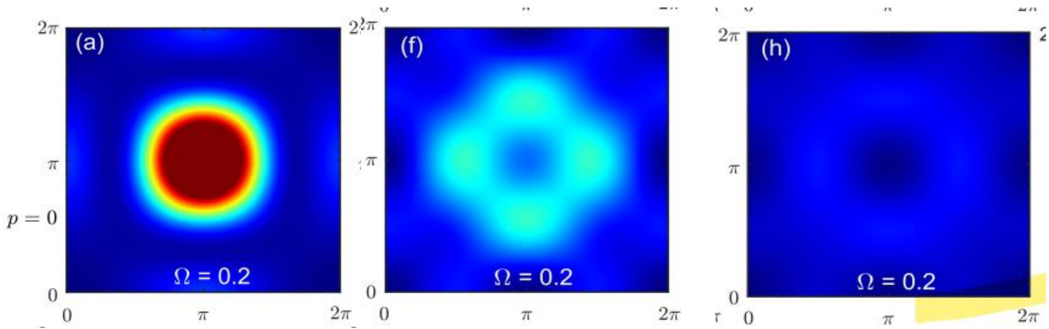
Spin fluctuations are known to determine specific properties of low dimensional strongly correlated electronic systems. Effect of frustrations is less studied. Recently we have developed a cluster perturbation approach to treat both electronic structure (single particle properties) and spin fluctuations (two particle properties) within the cluster perturbation theory (CPT) approach. We applied spin-CPT and charge-CPT to the p-d two-band Hubbard model and calculated one- and two-particle correlation functions, namely, electronic spectral function and spin and charge susceptibilities [1]. The doping dependence of the spin susceptibility was studied within spin-CPT and CPT-RPA, that is, the CPT generalization of the random phase approximation (RPA). In the underdoped region, both our methods resulted in the signatures of the upper branch of the spin excitation dispersion with the lowest excitation energy at the (π, π) wave vector and no presence of low-energy incommensurate excitations. In the high doping region, both methods produced a low energy response at four incommensurate wave vectors in qualitative agreement with the results of the inelastic neutron scattering experiments on overdoped cuprates. Spin susceptibility map for Ω=0.2 and 3 doping levels from spin-CPT with 3x3 unit cell is shown in the Fig.1.



Hole doping p=0 p=1/9 p=2/9

Fig.1. Doping dependence of the imaginary part of dynamical magnetic susceptibility

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ANALYSIS OF TERAHERTS ABSORPTION SPECTRA AND INELASTIC NEUTRON SCATTERING OF FRUSTRATED MAGNET $Tb_2Ti_2O_7$

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The spectral and magnetic properties of a geometrically frustrated crystal $Tb_2Ti_2O_7$ with a pyrochlore structure have been actively studied for more than 20 years. There are competing antiferromagnetic exchange and ferromagnetic dipole interactions between Tb^{3+} ions in $Tb_2Ti_2O_7$ (Curie-Weiss temperature is −13 K). According to theoretical studies, long-range antiferromagnetic order in $Tb_2Ti_2O_7$ should be observed below a temperature of ~1.8 K [1]. However, magnetic ordering is not experimentally observed down to temperatures of 0.015 K. Nevertheless, in a number of experiments a phase transition of unknown nature was observed at temperatures below 1 K. The explanation of the spin-liquid state of $Tb_2Ti_2O_7$ is still discussed in the literature. The magnetic properties of a crystal are determined by both interactions between ions and the magnetic properties of the ions. Therefore, it is important to study the energy spectrum of Tb^{3+} ions in this crystal.

In a trigonal crystal field of D_{3d} symmetry at the position of the Tb^{3+} ion in a perfect $Tb_2Ti_2O_7$ crystal, the ground and first excited states of the Tb^{3+} ion are non-Kramers doublets. The energies of the first and second excited energy levels are 12 cm^{-1} and 84 cm^{-1} [2], respectively. In the low-energy part of the inelastic neutron scattering spectra, an intense line is observed near energy of ~ 1 cm^{-1} [3]. In the terahertz absorption spectra, a broad line is observed in the frequency range corresponding to energies of 10-22 cm^{-1} [4]. The presence of these lines indicates splitting of the ground and first excited doublets of the Tb^{3+} ions. One possible explanation for these splittings is interaction with a low-symmetry crystal field, which can be induced by defects in the crystal lattice. Observations of magnetoelastic effects of extremely large magnitude in $Tb_2Ti_2O_7$ indicate strong electron-strain interactions.

In this work, within the framework of the one-particle approximation, we calculated low-temperature terahertz absorption and inelastic neutron scattering spectra corresponding to magnetic dipole transitions between sublevels of the ground doublet and between sublevels of the ground and first excited doublets, split by the random strains [5] induced by point defects in a nonstoichiometric crystal. Our calculations qualitatively reproduce the features of the spectra measured in [3, 4].

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ANTIFERROMAGNETS WITH RANDOM VACANCIES AND SUBSTITUTIONAL SPINS ON THE TRIANGULAR LATTICE

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We discuss theoretically static and dynamical properties of XY and Heisenberg antiferromagnets on the triangular lattice with random vacancies and substitutional spins. It is shown that the distortion of 120^o magnetic order produced by a single defect is described by electrostatic equations for a field of an electrically neutral complex of six charges located around the impurity [1,2]. The first finite term in the multipole expansion of this field is the octupole moment which decays as $1/r^3$ with the distance r. The linearity of equations allows to describe analytically the distortion of the long-range magnetic order at a small concentration c of defects. We obtain analytically renormalization of the elastic neutron scattering cross section and the magnon spectrum ε_k in the leading order in c. We find that the scattering on impurities renormalizes weakly the bare spectrum ε_k at k>>c . However, the renormalization is substantial of the long-wavelength magnon spectrum at k<< c and there is a parametrically large region in which magnons with not too small momenta are overdamped and localized. This strong modification of the long-wavelength spectrum leads to the stabilization of the slightly distorted magnetic long-range order at $T<T_N\sim S^2J/\ln(1/c)$ and to the considerable change in the density of states and in the specific heat. The overdamped modes arise also in quasi-2D spin systems on a stacked triangular lattice [2].

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CROSSOVER BETWEEN PSEUDOSPIN PARAMAGNET AND SPIN LIQUID IN A CHAIN ANTIFERROMAGNET Cs_2CoCl_4

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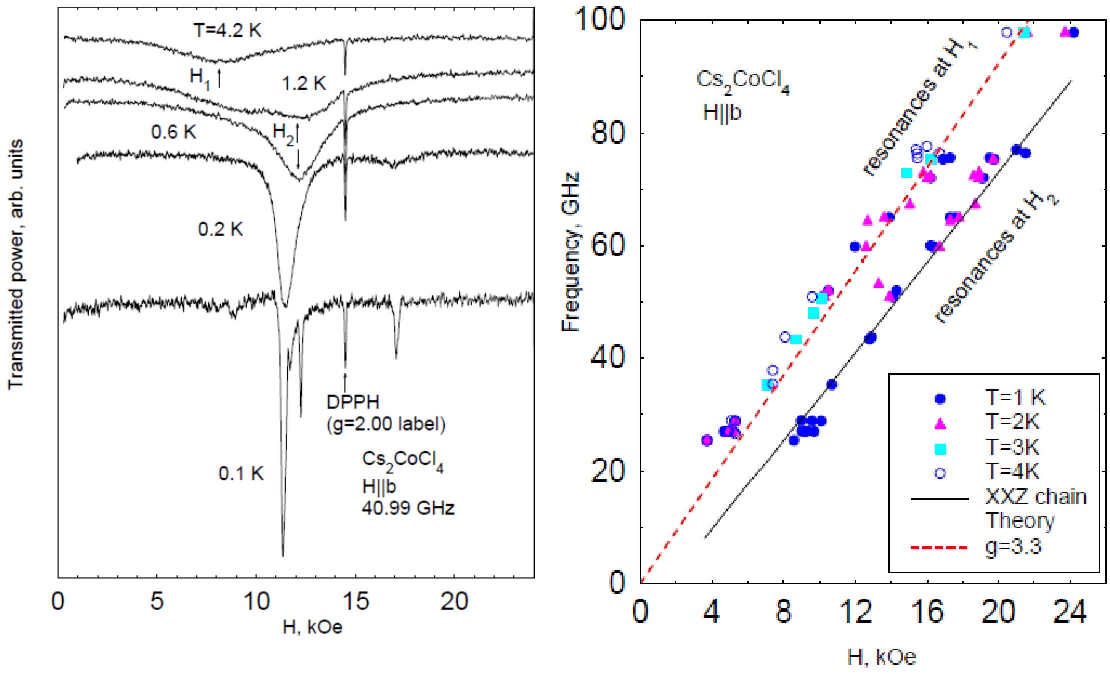
Crystal structure of Cs_2CoCl_4 contains Co^{2+} ions (S=3/2) arranged within layers with a triangular lattice. The exchange interaction along the bases exceeds that along sides of isosceles triangles. The frustration of lateral exchanges on a triangle results in the effective exchange network which may be viewed as a system of spin chains along the bases of triangles. The chains are only weakly coupled, both inside and between the layers [1], as in the well-known isomorphic compound Cs2CuCl4 [2], which demonstrates magnetic responses of a 1D antiferromagnet. A strong single-ion anisotropy with a characteristic energy of 7 K separates the upper spin doublet of Co^{2+} from the lower one, which enables one to use the pseudospin S=1/2 representation at low temperatures. A strong anisotropy of exchange and renormalization of g-factor naturally arise in this representation [3]. Finally, the system can be considered as an ensemble of weakly interacting strongly anisotropic chains of spins S=1/2 (the so-called XXZ chains). Due to the non-commuting action of the transverse magnetic field and anisotropy, these chains have a number of remarkable properties because of quantum entanglement of states, see, for example, [1, 4]. In particular, in zero field, the ground state is a quantum-critical spin liquid, and in moderate fields the chains have a long- range antiferromagnetic order with strongly reduced ordered spin component. And finally, in the field before saturation, a spin-liquid phase appears again. Thus, Cs_2CoCl_4 represents a convenient model object for studying the quantum phases of XXZ chains and phase transitions between them.

We studied the dynamics of uniform spin oscillations of Cs_2CoCl_4 at temperatures from 0.1 to 7 K by electron spin resonance (ESR) in the range of 25-120 GHz in the magnetic field ***H*** oriented along the crystallographic axis b. This orientation corresponds to non-commuting action of magnetic field and anisotropy. Above the Néel temperature T_N=0.22 K [3] but below the characteristic exchange temperature we expect the magnetic properties will correspond to an uncorrelated ensemble of XXZ chains. At the same time, there should be strong spin correlations within a chain due to the intrachain exchange of pseudospins J=3 K. Our results show that at a temperature of 4-5 K, ESR with a g-factor of 3.3 is observed at all frequencies of the range. This value of the g- factor corresponds to the resonance of single pseudospins, as follows from the theoretical assessment in [3]. We denote the values of resonant fields of this type as H_1. As the temperature decreases, a second resonant mode appears in the field $H_2 > H_1$, and this H_2-resonance dominates below 1 K down to 0.3 K. Here, most of the spectral weight of the ESR is at the H_2-resonance and the spectrum is shifted down from the paramagnetic position recorded at T=4 K. The temperature evolution of 46 GHz ESR is illustrated in Fig.1, and the frequency-field diagram of the observed resonances is shown in Fig.2.

The resonance frequencies in H_2-fields observed in the temperature range 0.3-1 K correspond well to the theoretical dependence of the most intense (lower) maximum of the spectral density of the excitation continuum of S=1/2 XXZ chain obtained numerically by the DMRG method [4] (solid line in Fig. 2). This theoretical dependenceis calculated with the use of exchange and anisotropy parameters determined experimentally in [3] and the value of the g-factor 3.3 obtained in our experiment at a T=4 K. Thus, the theoretical dependence in Fig.2 does not contain any fitting parameters. The transition of the resonance field from H_1 to H_2 occurs by the continuous spectral density flow from H_1 to

H_2, in the form of a temperature crossover, without critical behavior, while antiferromagnetic correlations appear within the chains.

Hence, we can conclude that ground states of the XXZ chains are realized within the spin system of Cs_2CoCl_4 in this temperature range, while mutual correlations of neighboring chains are destroyed by temperature.



Below T_N=0.25 K and down to the lowest temperature of the experiment 0.1 K, we observe another drastic change in the spectrum at the transition to the antiferromagnetic long-range order, which is due to inter-chain interaction. This spectrum change with the formation of new lines occurs via phase transition at the Néel point. We will report about the ESR spectrum of this phase later.

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NONLINEARITY OF THE MAGNETIC SUSCEPTIBILITY OF A Co^{2+} MONO-ION MAGNET IN THE PARAMAGNETIC REGION ABOVE THE MAGNETIC ORDERING TEMPERATURE

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Interest in single-molecule (SMM) and single-ion (SIM) magnets, capable of storing magnetization within a single molecule or ion, is growing due to their potential use in quantum computing. The study of linear susceptibility to an alternating field is a standard approach for determining magnetism SIM. However, SIM can exhibit unusual magnetic properties at low temperatures, similar to those observed in spin glasses [1,2].

The study of mono-ionic complexes based on Co^{2+} ions makes it possible to detect the peculiarities of their magnetic properties at low temperatures. The work identified the second and third harmonics of magnetic susceptibility at temperatures in the range from 2 to 4 K, which is slightly higher than the Neel temperature. The maximum values of the second and third harmonics were recorded at a frequency of about 1 Hz and in a field of 1 kOe (Fig.1) and 3.2 kOe.

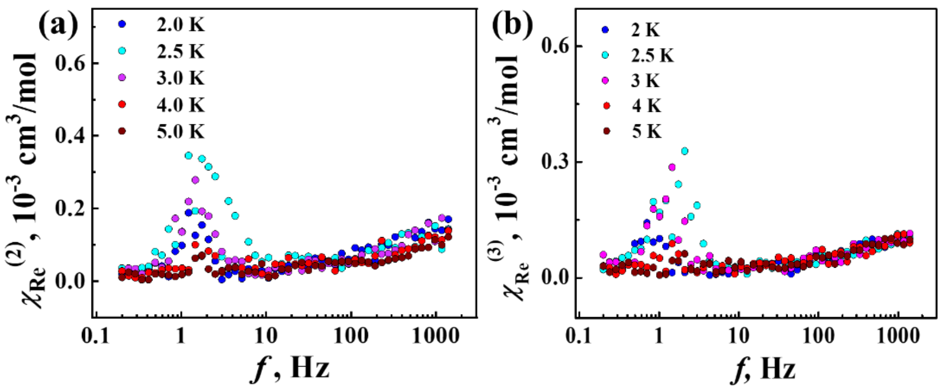

Fig.1. Frequency dependences of the real $\chi_{Re}^{(2)}$ (a) and $\chi_{Re}^{(3)}$ (b) parts of the magnetic susceptibility of the sample in a constant field of 1000 Oe for harmonics n = 2, 3 at atemperature in the range of 2 – 5 K.

An analysis of the dependences of these characteristics on the field and temperature showed that nonlinear effects are associated with the formation of a spin glass state at low temperatures. In this state there is no long-range spin order, but there are clusters of spins in the spin glass state. The spin-glass state in combination with the Co^{2+} ion with high magnetic anisotropy is unusual in that the exchange interaction is significantly lower than the energy of single-ion anisotropy.

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МАГНИТНЫЕ СВОЙСТВА $LiCu_3O_3$ – КВАЗИДВУМЕРНОГО АНТИФЕРРОМАГНЕТИКА НА КВАДРАТНОЙ РЕШЁТКЕ СО СЛУЧАЙНО РАСПРЕДЕЛЕННЫМИ МАГНИТНЫМИ И НЕМАГНИТНЫМИ ИОНАМИ

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$LiCu_3O_3$ является новым квазидвумерным магнетиком (S=1/2) с замещением магнитных ионов немагнитными. Кристаллическая структура $LiCu_3O_3$ содержит «тройки» магнитных плоскостей ионов Cu^{2+}(S=1/2) находящихся в узлах квадратной решетки. Ионы Li^+ занимают те же кристаллографические позиции, что и позиции Cu^{2+} с разными степенями замещения для внутренней и внешних плоскостей – 20% и 40% [1]. Такие тройки квадратных плоскостей (B-A-B) разделены плоскостями немагнитных ионов Cu^+, что определяет квазидвумерность $LiCu_3O_3$ Степень замещения во внутренних плоскостях (A) меньше порога протекания в квадратной решётке, поэтому магнитные ионы в таких плоскостях образуют бесконечный кластер, в то время как во внешних плоскостях (B) степень замещения критически близка к порогу протекания. Такие необычные образцы стабильны при нормальных условиях и имеют воспроизводимые свойства.

В монокристаллах $LiCu_3O_3$ были проведены ЯМР исследования на ядрах ^7Li, измерения намагниченности и электронного спинового резонанса, в результате которых были обнаружены частичное магнитное упорядочение при температуре T_{c1} = 123 K и изменение магнитного состояния при $T_{c2}\approx 30$ K. Высокотемпературный переход мы связываем с возникновением магнитного порядка в плоскостях с меньшим разбавлением, а низкотемпературный переход – упорядочению в плоскостях с сильным разбавлением. Широкие спектры ЯМР ниже T_{c1} отражают установление непрерывного распределения направлений или величин магнитных моментов, характерное для спиральных, спин-модулированных структур или структур с замороженным беспорядком.

При измерениях намагниченности был обнаружен спин-флоп переход, который указывает на наличие слабой одноосной анизотропии магнитной структуры. Относительно малое значение магнитной восприимчивости отражает жёсткость спиновой системы ($\mu_0 H_{sat}\approx 200$ T).

Работа С.К. Готовко, Л.Е. Свистова была поддержана грантом РНФ 22-12-00259 (обработка данных ЯМР и вычисления, ЭСР измерения).
Работа А.А. Буша, В.И. Козлова была поддержана Министерством высшего образования РФ FSFZ-2023-0005 (рост кристаллов $LiCu_3O_3$).

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НИЗКОЧАСТОТНАЯ СПИНОВАЯ ДИНАМИКА КВАЗИДВУМЕРНОГО ФЕРРО-АНТИФЕРРОМАГНЕТИКА $BaCdVO(PO_4)_2$

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В кристаллах $BaCdVO(PO_4)_2$ со слоистой магнитной структурой на квадратной решетке реализуется особый тип фрустрации ферро- и антиферромагнитных обменных связей на сторонах и диагоналях квадратов. Теоретический анализ показывает, что в этих условиях в полях, близких к насыщению, может реализо- ваться фаза спинового нематика, в которой средний магнитный момент на узле решетки равен нулю, однако существуют корреляции, нарушающие инвариант- ность по отношению к поворотам в спиновом пространстве и не нарушающие инвариантность относительно обращения времени [1-3].

Температура Нееля $BaCdVO(PO_4)_2$ равна 1.05 К, а спины в слабом поле упорядочены коллинеарно [4]. Предшествующие эксперименты показывают, что при низких температурах антиферромагнитное упорядочение спинов исчезает в поле H_{c1} = 4 Т, однако насыщение магнитного момента происходит в поле H_{sat} = 6.5 Т. Причем в поле H_{c1} момент достигает 98 % от полного насыщения. В диапазоне полей от H_{c1} до H_{sat} предполагается формирование спин-нематического состояния [4].

В нашей работе мы изучили спектры магнитного резонанса в $BaCdVO(PO_4)_2$ в диапазоне частот 0.5 - 100 ГГц при температурах от 0.45 К до 2 К, включая об- ласть полей от H_{c1} до H_{sat}. Спектр антиферромагнитного резонанса содержит две резонансные моды с щелями Δ_1 = 12.8 ГГц и Δ_2 = 17.3 ГГц и полностью соответствует спектру коллинеарного антиферромагнетика с двухосной анизотропией. Примечательным в нашем исследовании [5] является обнаружение в специальном эксперименте на низкой частоте 2 ГГц и с продольной поляризацией микроволнового поля спин-флип моды, которая демонстрирует полное смягчение в поле H_{c1} = 4 Т, а не в поле насыщения H_{sat} = 6.5 Т. Этот результат показывает, что магнитное упорядочение, в том числе и нематического типа, в интервале полей между H_{c1} и H_{sat} отсутствует, а неполное насыщение связано, по-видимому, с не- большим количеством дефектов. Недавние эксперименты по ЯМР [6] подтвер- ждают отсутствие нематической фазы в сильных полях, полагая, что слабая оста- точная полевая зависимость намагниченности выше поля H_{c1} = 4 Т скорее всего связана с наличием слабого взаимодействия Дзялошинского-Мория.

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Spintronics

SPINTRONICS – MRAM AND BEYOND

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Interest in spintronic heterostructures based on magnetic tunnel junctions (MTJs) is primarily driven by their effective use for recording and storing information. In recent years, Magnetic RAM has begun to be actively introduced into various areas of industry, primarily in the automotive, becoming an indispensable technical solution for the new generation of automotive chips. However, the applied opportunities offered by spintronics is not limited to information storage. The microwave dynamics of magnetization in such structures is of particular interest. It has been shown the possibility to generate an alternating (microwave) signal constant spin-polarized current in MTJs excited by spin-polarized direct current [1]. Based on this effect, a new generation of alternating signal generators for telecommunication devices is being developed. Of no less interest is the opposite effect – the spin-transfer diode [2]. When an alternating spin-polarized current with a frequency close to the resonant one is passed through the MTJ, a constant voltage component appears. It can be obviously used for a microwave signal detection. In the first works, the efficiency of rectifying an alternating signal did not exceed 1.4 mV/mW. In 2014, a sensitivity of a spin-transfer diode at room temperature of 12000 mV/mW was experimentally demonstrated [3] through the use of a constant bias current. Subsequently, it was demonstrated a possiblity toenhance the microwave sensitivity up to 210,000 mV/mW [4-5].

The development of spin-transfer diodes from the first experiments to prototype microwave devices are covered in the talk. An opportunities and methods for increasing the microwave sensitivity are shown and the physical mechanisms behind this are explained. The possibilities of resonant frequency engineering and the transition to broadband rectification are discussed. The influence of magnetic distribution on the features of rectification is considered. Finally, possible practical applications of the mentioned effects are discussed.

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COHERENT RESONANCE IN A NARROWBAND NOISE-CONTROLLED CHAOTIC SPIN-WAVE SELF-OSCILLATOR

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The phenomenon of coherent resonance was discovered in model systems excited by noise and manifested itself in the existence of an optimal level for the noise signal, at which the noise-induced oscillations of the dynamic system became more coherent [1]. In the power spectrum, the fluctuation peak had optimal characteristics, i.e. was most pronounced against the background of a noise pedestal at a certain optimal noise level. Research carried out on radiophysical self-oscillators [2] and their models [3] addressed the situation when the self-oscillating system was in a pre-generation mode, and oscillations in the system were excited by noise. Studies of coherent resonance under the influence of noise on a self-oscillating system, in which natural oscillations would already be generated in the absence of noise, have not been carried out. In such systems, another phenomenon was studied - synchronization of self-oscillations in the presence of noise.

In this paper, we propose to study the phenomenon of coherent resonance in solid-state chaotic distributed self-oscillators of the microwave range, capable of forming chaotic sequences of dissipative envelope solitons in the absence of external noise influence. The scientific novelty of this kind of research is due to the fact that until now coherent resonance has been studied mainly on model systems, which include noise-excited systems and self-oscillators with Andronov-Hopf bifurcation. In distributed dynamic systems that exhibit chaotic dynamics in an autonomous mode, the phenomenon of coherent resonance has not been observed.

The experimental setup of a non-autonomous self-oscillating system consists of a broadband solid-state microwave GaAs power amplifier, a cavity resonator, a variable attenuator and a broadband nonlinear delay line on magneto static surface waves (MSSW) tunable by a magnetic field connected in series in a ring. An external signal was input into the ring through a directional coupler connected to the feedback circuit in front of the microwave power amplifier.

In the experimental study, an external noise signal was applied from a vector signal generator to the input of a solid-state power amplifier at a frequency of 2.06 GHz. The excitation spectrum of the MSW was higher in frequency range of 2.35-2.4 GHz. As a consequence, the external microwave noise signal affected only the gain of the solid-state power amplifier, without directly affecting the signal generated in the ring system. In this case, a sequence of chaotic relaxation pulses was generated in the ring system in the absence of an external noise signal (see [4])

Time realizations of the signal generated in the ring, taken from the detector head after the directional coupler and time realizations of the external microwave noise signal with a spectrum width Δf = 1.5 MHz, supplied to the input of the power amplifier is shown at Fig.1.

As can be seen from Fig. 1, generation in a ring system begins at time intervals where the amplitude of the noise signal drops to zero or is quite small. The amplitude of the generated signal increases exponentially with a weak external influence and sharply decreases to zero with a large amplitude of the noise signal. The repetition period of the generated sequence depends on the bandwidth of the external noise signal and its amplitude. As the power of the external signal increases to 0 dBm, the oscillogram shows a noticeable increase in the average period between generated pulses. A further increase in the amplitude of the external influence almost completely suppresses the signal generation in the ring. At P_{ext}=11 dBm, signal generation in the ring system terminated. Increasing the spectral width of the external noise signal leads to a decrease in the power level required to suppress generation in the ring system. So, at Δf=5 MHz, generation in the ring system stops when the external signal power P_{ext}=15 dBm. And at Δf=0.5 MHz, no suppression of signal generation was observed. The latter is associated with a long average period of external influence.

The dependence of the autocorrelation time of the generated signal on the intensity of the noise showed at Fig.1. An increase in the autocorrelation time can be observed for certain values of the noise signal band. The appearance of a maximum on the autocorrelation dependence appears for values of noise bands greater than or equal to the spectrum width of the generated chaotic signal.

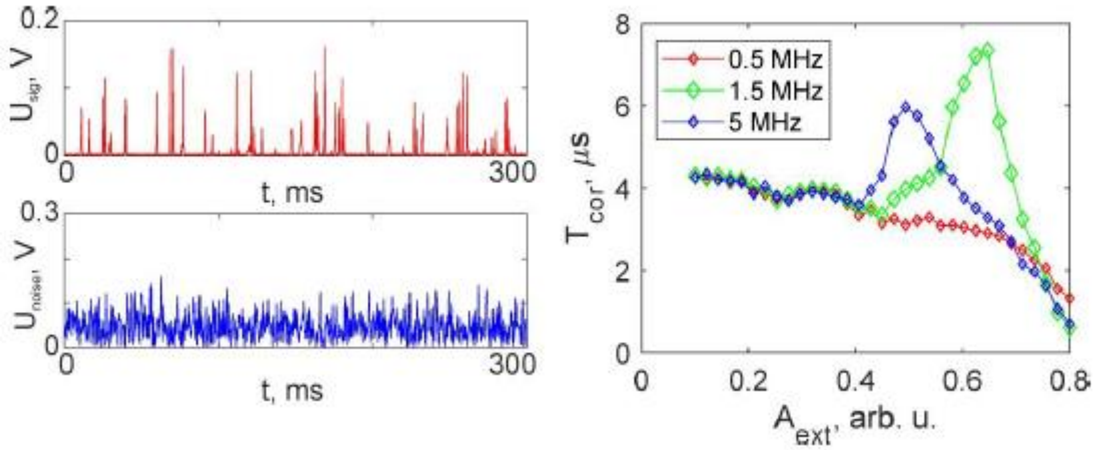

Fig. 1. Oscillogramm of generated signal and external noise (left column) and dependence of correlation time on amplitude of external noise (right column).

This work was supported by RSCF (#23-22-00274).

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DETECTION OF CANTED PHASE IN FERRIMAGNETIC STRUCTURE THROUGH SPIN-ORBIT TORQUE INVESTIGATION

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The use of ferrimagnetics for spintronics applications can presumably provide fast and energy-efficient switching of magnetic states combined with high stability of these states [1]. It has been shown experimentally that the spin-orbit torque (SOT) can induce effective magnetic fields larger than in ferromagnetic-based metallic structures [2] [3]. It has also been found that current-induced switching of magnetisation orientation can occur in the sub-nanosecond range [4], and the domain wall motion speed can reach several kilometers per second [5]. This set of properties is usually characteristic of states near magnetic or angular momentum compensation, which is due to the presence of two antiparallel ordered magnetic sublattices in the ferrimagnet, which respond differently to changes in temperature or composition. The near magnetic compensation state can be remarkable not only for the high efficiency of SOT, but also for the possibility of breaking the antiferromagnetic ordering between the sublattices of the ferrimagnet. The presence of such a phase, the so-called spin-flop or non-collinear ordering, is found in both theoretical [6] and experimental [7] temperature-field (T-H) diagrams. This effect is usually observed in strong magnetic fields and recorded using the Anomalous Hall Effect (AEH) and is not considered to be practically significant.

In this work, the violation of antiferromagnetic ordering was detected by the change in the direction of the effective field induced by the spin-orbital torque without changing the type of dominance in the ferrimagnetic structure. The effect is observed both at external heating of the sample and as a result of Joule heating with increasing passing current (Fig 1a). In the investigated W(4)/Co70Tb30(y)/Ru (2 nm) structure, the oblique region was observed near room temperature and at external fields of the order of 0.1 Tesla. This allowed us to study the dependence of the induced SOT field at the successive transition between three phases: the region of Tb predominance, the region of non-collinear ordering and the region of Co predominance (Fig 1b).

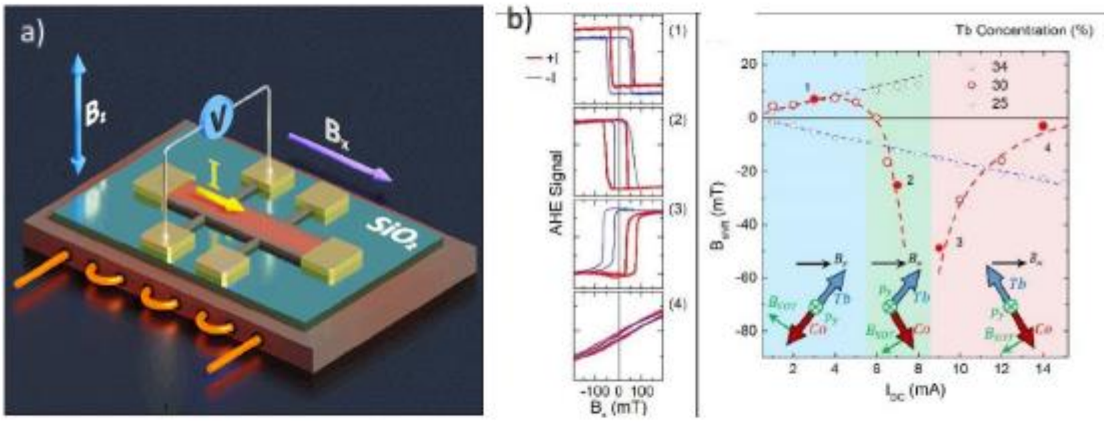

Fig. 1. a) The experimental scheme shows the mutual orientation of the propagated current and two external orthogonal fields, as well as the possibility of heating the stage. b) Dependence of the loops shift on the magnitude of the transmitted DC current for those samples with different atomic contents obtained in the presence of the DC field in plane B_x =+ 0. 1 T region of Tb dominance is marked in blue, the region of Co dominance in red, and the region with non-collinear alignment of spins in the Co and Tb sublattices in green. The diagrams indicate the orientation of the effective field acting on the Co sublattice in the result of SOT. Examples of hysteresis loops for cases marked in red are shown in the (1)-(4) insets.

This work was supported by the Russian Ministry of Science and Higher Education (State Task No. FZNS-2023-0012).

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СПИНОВАЯ НАКАЧКА В СТРУКТУРЕ МАГНОННЫЙ КРИСТАЛЛ-Pt

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С помощью обратного спинового эффекта Холла исследована спиновая накачка обратными объемными магнитостатическими волнами (ООМСВ) в структуре на основе магнонного кристалла (МК) из пленки железоиттриевого граната (ЖИГ) и микрополоски Pt. Одномерный МК изготавливался из пленки ЖИГ толщиной 7.4 μm вытравливанием решетки из канавок шириной *w*=10 μm, глубиной δ=0.2 μm, длиной 6 mm и периодом Λ=170 μm. Микрополоска платины имела толщину 4 nm, ширину 25 μm, длину 6 mm и ориентировалась вдоль канавок. На рис. (а) кривой 2 показан вид АЧХ МК, где видны полосы непропускания, отвечающие частотам брэгговских резонансов (БР), которые согласуются с результатами микромагнитного моделирования спектра ООМСВ в МК, см. рис.(b) и АЧХ структуры, см. кривую 1 на рис. (а). Обнаружен резонансный рост сигнала ЭДС на БР, см. кривую 3 на рис.(а). что отражает рост эффективности спиновой накачки. Резонансное усиление спиновой накачки объясняется ростом эффективности электрон-магнонного рассеяния за счет формирования в спектре ООМСВ на частотах БР участков дисперсии с высокой плотностью состояний – сингулярностей ван Хова [1].

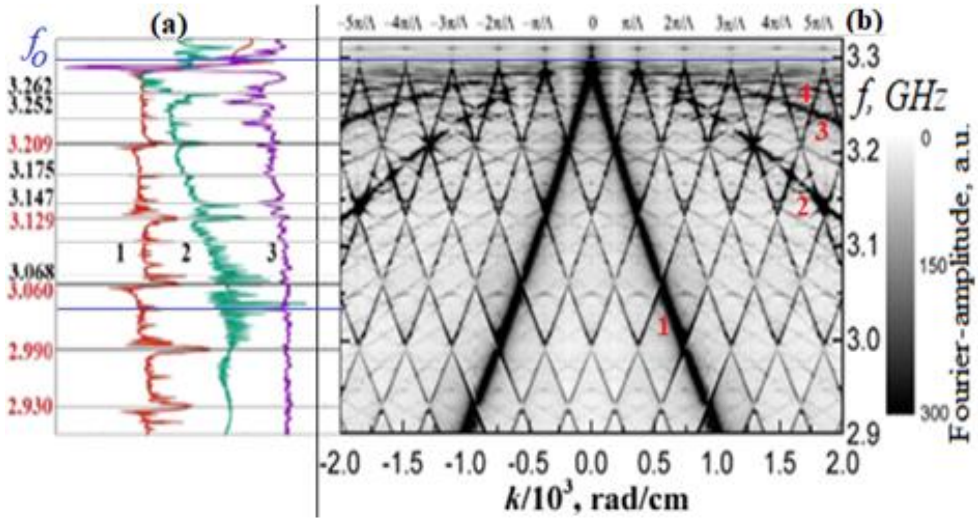

Рис. 1. (а) микромагнитное моделирование спектра ООМСВ в МК, где 1-4 номера наиболее интенсивных мод ООМСВ, дисперсионные кривые которых отвечают исходной пленке ЖИГ. (b) Цифрами 1 и 2 обозначены соответственно, рассчитанная и экспериментальная зависимости $S_{12}(f)$. Кривая 3 экспериментальная зависимость $V_{ISHE}(f)$. Горизонтальные линии с указанием частоты (GHz) на кривых 1-3 показывают соответствие рассчитанных и экспериментальных особенностей частотам БР в спектре на рис.(а). H=590 Э.

Работа поддержана грантом РНФ 22-19-00500.

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EXPLORING THE INTERACTION OF SINGLE-MOLECULE MAGNETS WITH FERROMAGNETIC MICROPARTICLES: IMPLICATIONS FOR MOLECULAR ELECTRONICS

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The magnetic properties of ordinary magnets are determined by the collective behavior of millions of atoms with unpaired electron spins. However, single-molecule magnets (SMMs) are different in that they contain just one spin center surrounded by an organic cage. Due to their small dimensionality and homogeneity, SMMs represent potentially promising candidates for use in magnetic data and quantum computing. However, their use is limited by two factors: residual magnetization at low temperatures and the difficulty of interaction with solid materials.

In our work, we focused on studying the interaction of SMMs with ferromagnetic microparticles, which is key to integrating these molecules into hybrid metal-organic structures and creating, for example, molecular spin valves.

We have developed a new method for functionalizing micropowders of molecular magnets and obtained the following results:

1. The introduction of Er3+ complexes into ferromagnetic media leads to a change in their magnetic relaxation. We discovered two ways that microparticles influence the relaxation of Er^{3+} ions: firstly, chemical binding of the compound to the metal surface, and secondly, magnetic-dipole interaction caused by the remanent magnetization of the matrix.

2. An internal magnetic field makes it possible to avoid direct and quantum tunnel relaxation, while Raman and Orbach relaxations turn out to be sensitive to chemical bonds between complexes and ferromagnetic particles. Magnetic relaxation can be controlled using an external magnetic field, which provides a residual memory effect and the desired relaxation rate.

3. We discovered the appearance of relaxation maxima in the frequency dependence of magnetic susceptibility when mixing demagnetized ferromagnetic microparticles with an erbium-based molecular magnet complex. However, at a temperature of 2 K, neither ferromagnetic metal microparticles nor molecular complexes exhibited magnetic relaxation in the accessible frequency range (0.1-1400 Hz) for the SQUID magnetometer. X-ray photoelectron spectroscopy (XPS) of the composite material showed oxidation of the 10-coordinated complex to the 8-coordinated complex upon contact with the surface of demagnetized metal microspheres.

These results highlight the promise of SMM in various technological applications and open new avenues for the development of molecular electronics.

This work was supported by by the program of the Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry RAS 124013100858-3.

Poster session

ИССЛЕДОВАНИЕ С ПОМОЩЬЮ ОБРАТНОГО СПИНОВОГО ЭФФЕКТА ХОЛЛА СПИНОВОЙ НАКАЧКИ ПОВЕРХНОСТНЫМИ МАГНИТОСТАТИЧЕСКИМИ ВОЛНАМИ, БЕГУЩИМИ В НАПРАВЛЕНИЯХ «ЛЕГКАЯ» И «ТРУДНАЯ» ОСИ НАМАГНИЧИВАНИЯ, В МИКРОСТРУКТУРАХ ЖИГ/Pt

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Исследование с помощью обратного спинового эффекта Холла (ОСЭХ) спиновой накачки бегущими спиновыми волнами (СВ) в структурах типа железоиттриевый гранат (ЖИГ) - платина (Pt) представляет интерес для разработки энергоэффективной элементной базы на принципах магнонной спинтроники [1]. Отметим, что влияние кристаллографической анизотропии на спектр дипольных ПМСВ в пленках ЖИГ различных кристаллографических ориентаций хорошо исследовано [2], однако эффекты спиновой накачки в основном рассматривались в структурах ЖИГ/Pt с кристаллографической ориентацией (111). Целью данной работы является исследование спиновой накачки бегущими поверхностными магнитостатическими волнами (ПМСВ) в структуре на основе пленки ЖИГ с кристаллографической ориентацией (100).

Для проведения экспериментов использовалась пленка ЖИГ(100) толщиной 16.1 мкм, намагниченностью насыщения $4\pi M_0$=1750 Гс и ΔH=0.5 Э, из которой вырезались два образца так что в одном случае стороны пленки совпадали с направлением [100], а в другом [110]. При этом в образцах поверхностные магнитостатические волны (ПМСВ) могли распространяться вдоль «трудной» [100] или «легкой» [110] осей намагничивания. С использованием методов магнетронного распыления, фотолитографии и ионного травления на поверхности пленок ЖИГ изготавливались медные микроантенны (МА) для возбуждения и приема ПМСВ, контакты для измерения ЭДС в Pt элементе длиной 620 мкм и шириной 200 мкм. Измерения проводились по методике согласно [3]

На рис.1 приведены результаты измерения ЭДС при распространении ПМСВ в структурах ЖИГ(100)/Pt для случая намагничивания в «легком» (а) и «трудном» (б) направлениях. Кривые 1 и 3 отвечают случая распространения ПМСВ вдоль границы ЖИГ/Pt и 2 и 4 – вдоль границы ЖИГ/ГГГ. Кривые 1 и 2 получены при одной полярности магнитного поля, а кривые 3 и 4 при смене направления магнитного поля на обратное. Можно видеть, что знак ЭДС зависит только от направления поля подмагничивания H и не меняется с изменением направления распространения ПМСВ, что отвечает механизму ОСЭХ (рис.1 а, б).

В свою очередь, поле кубической анизотропии приводит к смещению положений частот спектра ПМСВ и, соответственно, зависимостей $U_{ОСЭХ}$ (f). Характер зависимостей $U_{ОСЭХ}$ (f) существенно не меняется при намагничивании структуры в «трудном» (кристаллографическое направление типа [100]) или «легком» (кристаллографическое направление типа [110]) направлениях, и отвечает характеру плотности состояний в спектре ПМСВ [4]. При этом максимальные значения ЭДС для структуры, намагниченной в «легком» направлении (рис.1 а), оказываются на частоте длинноволновой в два раза больше, чем для «трудного» направления (рис.1 б), что можно связать с наличием в спектре (см. рис.2) дисперсионных кривых с малой групповой скоростью и высокой плотностью состояний [5].

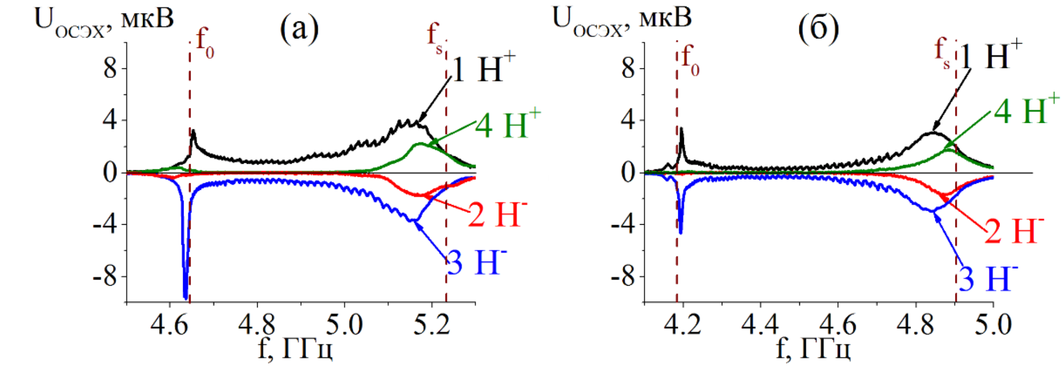

Рис. 1. Частотные зависимости ЭДС U, измеренные при P_{in}=10 дБм и H=939 Э, в структурах, отвечающие случаям «легкая» (а) и «трудная» (б) осей намагничивания для 4х случаев распространения ПМСВ; пунктирными линиями отмечены нижняя (f_0) и верхняя (f_s) частотные границы спектра ПМСВ.

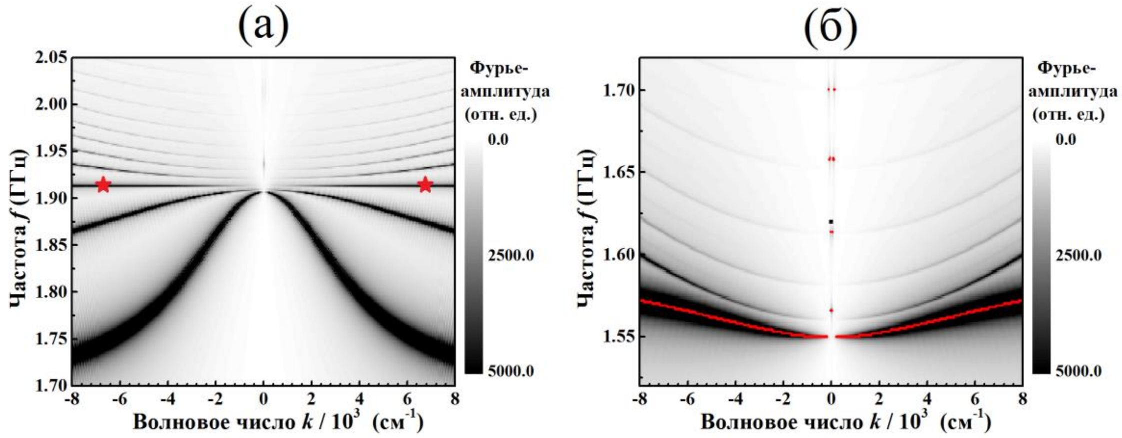

Рис. 2. Спектр дипольно-обменных волн ПМСВ в пленке ЖИГ(100) намагниченной «легком» (а) и «трудном» (б) направлениях. Звездочкой выделен участок дисперсии с высокой плотностью состояний СВ.

Работа поддержана грантом РНФ № 22-19-00500.

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SPIN WAVES IN NANOSCALE LATERAL COUPLED FERRITE STRUCTURE

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Spin waves are promising information carriers due to their weak attenuation and short wavelength, which makes it possible to create much smaller nanoscale devices for data processing. [1]

The structures under study are laterally bound ferromagnetic films made of yttrium iron garnet (YIG) $Y_3Fe_5O_{12}$. The thickness of the films is 100 nanometers, and the width and length are on the order of micrometers. The diagram of the structure is shown in Fig. 1. The external magnetic field $\overline{H}_0$ was directed in two ways: along the x–axis - surface magnetostatic waves (SMSW), along the y-axis - backward volume magnetostatic waves (BVMSW). The alternating magnetic field $\overline{h}$ is directed perpendicular to the plane of the structure.

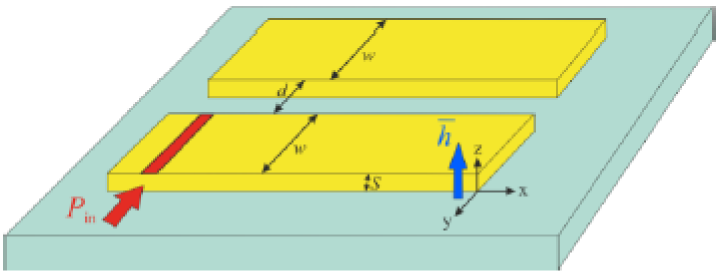

Fig. 1. Diagram of the structure based on laterally bound ferromagnetic films.

The main feature of the coupled structure is the propagation of two normal modes, symmetric and antisymmetric, at the same frequency [2]. This leads to periodic pumping of the signal between the layers along the structure length. The coupling length depends on the magnitude of the magnetic field, the orientation of the static magnetization of the waveguides, and the geometry of the structure. The equation for the coupling length can be obtained, for example, by energetically considering of bound MSW [3]:

$$\Lambda = 2\pi / (k_1 - k_2).$$

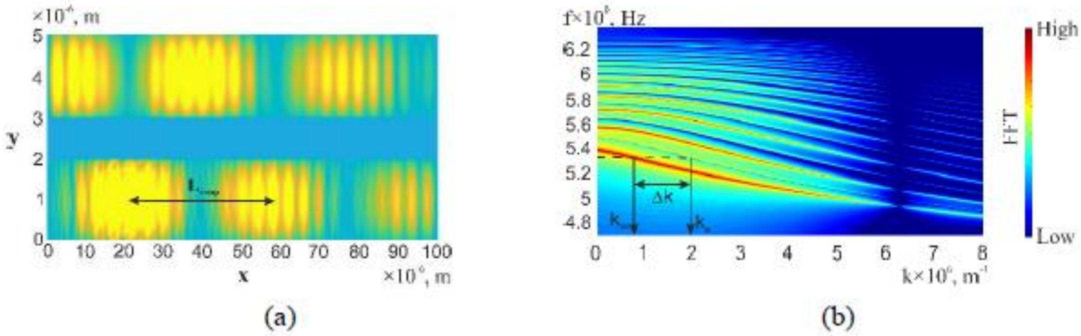

Fig. 2. (a) Distribution of *z*-th component of the dynamic magnetization deviation from the stationary state $\Delta m_z(x, y, t)$, (b) Dispersion characteristic of the BVMSW for bonded films.

In this paper, the propagation of spin waves and power pumping in laterally coupled structures of nanometer thickness are investigated. Using the MuMax3 software and data processing in Matlab, the dispersion characteristics of the MSW in the structure, the distribution of the magnitude of the dynamic magnetization deviation from the stationary state, as well as the dependence of the energy and frequency values of spin waves on the parameters of the coupled system were obtained.

At the Figure 3, the dependences of the MSW cutoff frequency for the first mode on the gap between the films d are obtained. As the gap increases, the coupling weakens, and the cutoff frequency decreases, rushing to the theoretical value for infinite single films. SMSV are indicated in red, and BVMSV in blue.

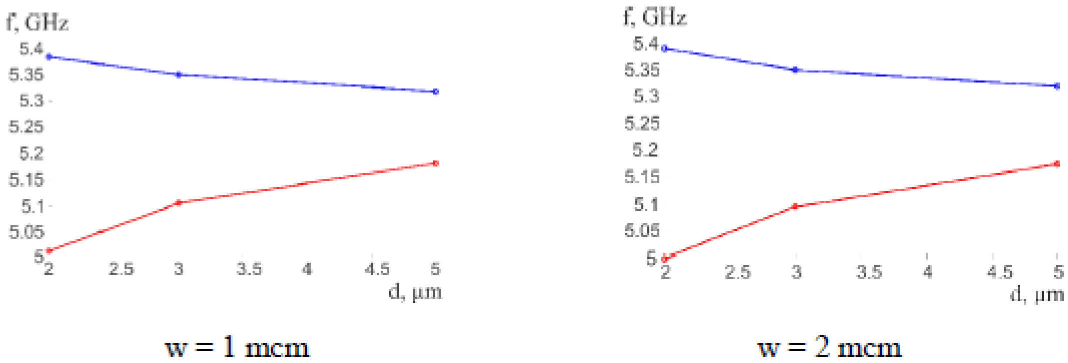

Fig. 3. Dependence of the cutoff frequency of the first mode on the gap d.

The Figure 4 shows the dependence of the coupling length on the gap d. As the films width increases, the values of the pumping length increase at any d. And for any width w of films, an increase in the gap leads to a nonlinear increase in the coupling length.

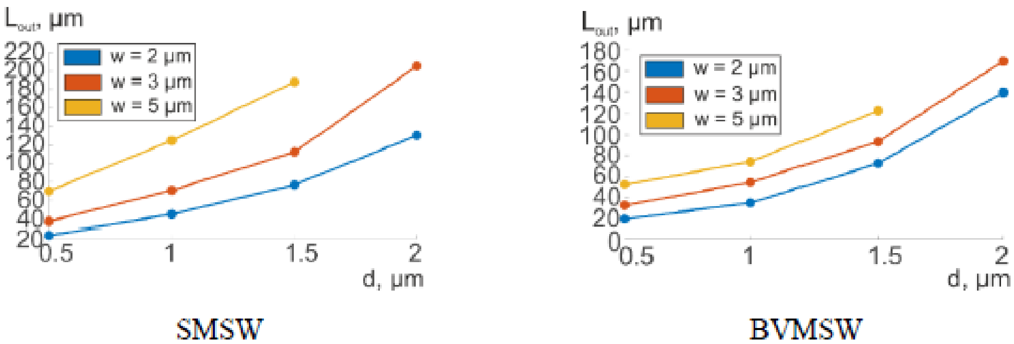

Fig. 4. Dependence of the coupling length on the distance between the films d at different widths w.

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CONTROLLING THE PROPAGATION OF SURFACE MAGNETOELASTIC WAVES IN ANTIFERROMAGNETIC HETEROSTRUCTURES

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The modern electronics field covers a wide range of devices aimed at producing, transmitting, and detecting signals. The electronic industry has developed devices with operating frequencies limited to the GHz range. However, there is potential to expand this range by utilizing new technologies and materials, drawing on advancements in spintronics and magnonics [1, 2]. Through the use of antiferromagnetic (AFM) materials, it becomes possible to process signals at terahertz frequencies, making them attractive for practical applications as well [2].

The study of phase transitions (PTs), especially those occurring in magnetically ordered materials, remains the subject of intense research. One particularly noteworthy type of PT is the "order-to-order" transition, such as the spin-reorientation (SRP) [3], which can be triggered by factors like alterations in external elastic stresses.

For the creation of controlled devices, it provides the possibility of controlling the properties of magnetoelastic waves of the AFM structure using deformations. However, in previous studies, less attention has been paid to the effect of deformations on the frequencies of quasiferro- and antiferromagnetic modes in the field of SRP.

Let us consider the propagation of shear surface elastic Love waves [4] in a heterostructure containing a thin magnetic AFM layer on an elastic substrate (Fig. 1). Love waves are shear elastic waves. For them to exist, it is necessary that the velocity of the transverse acoustic waves in the layer be less than in the substrate ($S_{t1} < S_{t2}$, *where* $S_{t1} = C_{441}/\rho_1$ *and* $S_{t2} = C_{442}/\rho_2$). To solve the problem of finding the ground state, let us represent the vectors m and **l** in spherical coordinates. Let θ_L be the angle between the vector **l** and the z-axis, φ_H be the angle between H and the x-axis, φ_L be the angle between the projection **l** on the plane [$\mathbf{e}_x\mathbf{e}_y$], ξ be the angle between m and the projection m on the plane [$\mathbf{l}\mathbf{e}_z$], and also introduce the coefficient $\eta=|m|^2/(2M_0)$, where M_0 is the magnetization of the saturation. The paper also emphasizes that the influence of voltage and magnetic field can be significant when approaching the SRP point, but in order to reach them, uniaxial pressure must be applied. Therefore, it is necessary to consider SRP not only in a magnetic field, but also with the application of pressure.

The magnetization dynamics of sublattices for AFM materials with weak ferromagnetism is described using standard Landau–Lifshitz equations. However, due to the small magnitude of the magnetization vector $|m| \ll |l|$ and $l^2=1-m^2\approx 1$, where $\mathbf{M_1}$ and $\mathbf{M_2}$ are the magnetization of the two sublattices, the system of equations of the vectors $\mathbf{M_1}$ and $\mathbf{M_2}$ can be reduced to the equation of motion of only the antiferromagnetic vector **l**, which can be obtained from free energy:

$$W_{AFM} = \frac{1}{2}\epsilon m^2 - \beta_1^2(l \cdot n)^2 + m \cdot [d \times l] - 2H_0(m \cdot e_H)$$
$$-\frac{1}{6}\beta'\left((l \cdot e_x)^2 - \left(l \cdot e_y\right)^2\right)\left(4\left((l \cdot e_x)^2 - \left(l \cdot e_y\right)^2\right)^2 - 3\right) - \frac{3}{2}\lambda\sigma\left(l \cdot e_p\right)^2, \quad (1)$$

where ϵ - uniform exchange constant, **l** - antiferromagnetic vector, **m** - ferromagnetic vector, H_0 - external magnetic field, β_1 and β' uniaxial and hexagonal anisotropy constants, λ - magnetostrictive constant and σ - external pressure applied along the $\mathbf{e_p}$ and d axis - Dzyaloshinsky-Moriya vector, e_x and e_y are the unit vectors along the x-axis and the y-axis and n is the orthogonal vector.

Having a solution to the equation, we can write the expressions for the AFM resonance frequencies. The solution of the equation for the dynamic vector s gives expressions for the frequencies of the lower and upper modes of the AFM.

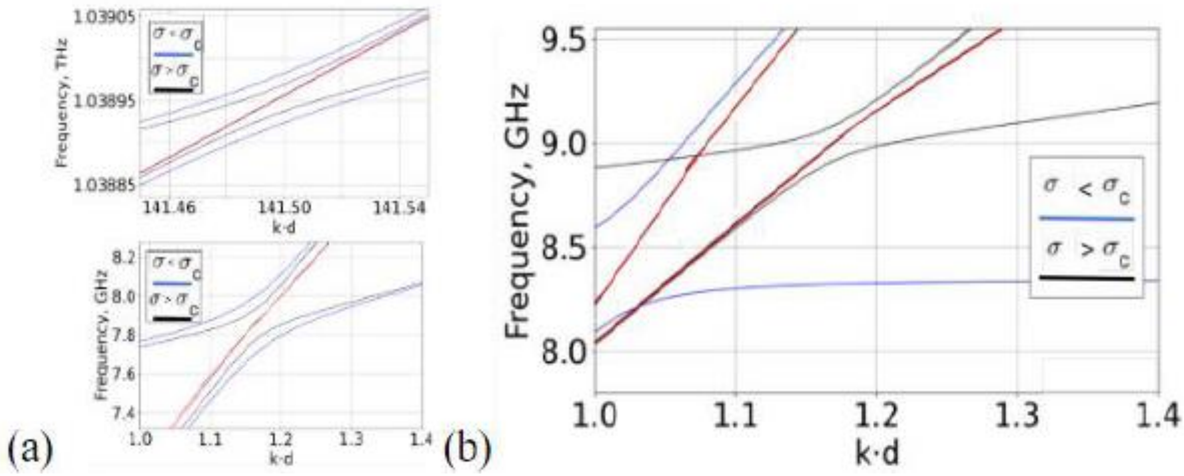

Fig.1 a) Angular dependence of the frequency of the lower ferromagnetic mode; b) Dependence of the frequency of the upper ferromagnetic mode on relative strains.

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MAGNETIC FIELD-CONTROLLED DOUBLE NEGATIVE MEDIA BASED ON ANTIFERROMAGNETIC SEMICONDUCTORS FOR THE TERAHERTZ FREQUENCY RANGE

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Magnetic semiconductors are of considerable interest for modern electronics and spintronics, since they allow to manipulate of a variable magnetization using a magnetized solid-state plasma [1]. V.G. Veselago predicted the existence of so-called "left-handed" or double negative media that have a negative refractive index due to both negative permittivity and permeability [2]. Such media support the propagation of the backward electromagnetic wave (BEMW), the phase and group velocity vectors of which have opposite directions. In addition, he suggested that it is necessary to look for double negative media among anisotropic gyrotropic media, because their permittivity and permeability are simultaneously negative in a certain frequency range [3, 4]. The Veselago theory made it possible to give impetus to create double negative media based on metamaterials [5, 6].

It is well known that magnetic semiconductors placed in an external magnetic biased field H_0 are bigyrotropic media, possessing the permittivity and permeability that are described by Hermitian tensors of the second rank [3, 4]. For the magnetized electron plasma, the permittivity changes sign at both the cyclotron and plasma frequencies of electrons. One of these characteristic frequencies (the cyclotron frequency) is located in microwave frequency range and the other (the plasma frequency) can be located in the terahertz frequency range. The crystal lattice of an antiferromagnetic (AFM) consists of two magnetic sublattices, the magnetization vectors of which are directed oppositely to each other. As a result, the strength of an internal magnetic field H_i of the AFM is much greater than the strength of the magnetic biased field H_0 ($H_i >> H_0$). As a result, all four characteristic resonant frequencies of the AFM are placed in the terahertz frequency range, in which the permeability changes its sign [7]. Thus, by combining the electrical properties of the electron plasma with the magnetic properties of the AFM, it is possible to create double negative media for terahertz frequency range.

In this work, a theoretical study of the BEMWs existing in the bigyrotropic left-handed media controlled by a magnetic biased field is presented. The bigyrotropic media are both transversely (a, c) and longitudinally (b, d)magnetized AFM semiconductors (SCs) with electrical and magnetic loss. It is shown that the BEMWs are observed in the terahertz frequency ranges, in which the effective material parameters of the AFM SCs are double negative. We also demonstrate the control of the BEMW dispersion characteristics not only by changing the magnetic biased field direction and strength, but also by variation a material magnetization and thickness, an electron concentration in a solid-state plasma, as well as the electrical and magnetic loss.

The calculations of the electrodynamic characteristics of slow BEMWs in an AFM SC performed in this work are of interest for the development of functional devices of terahertz spintronics.

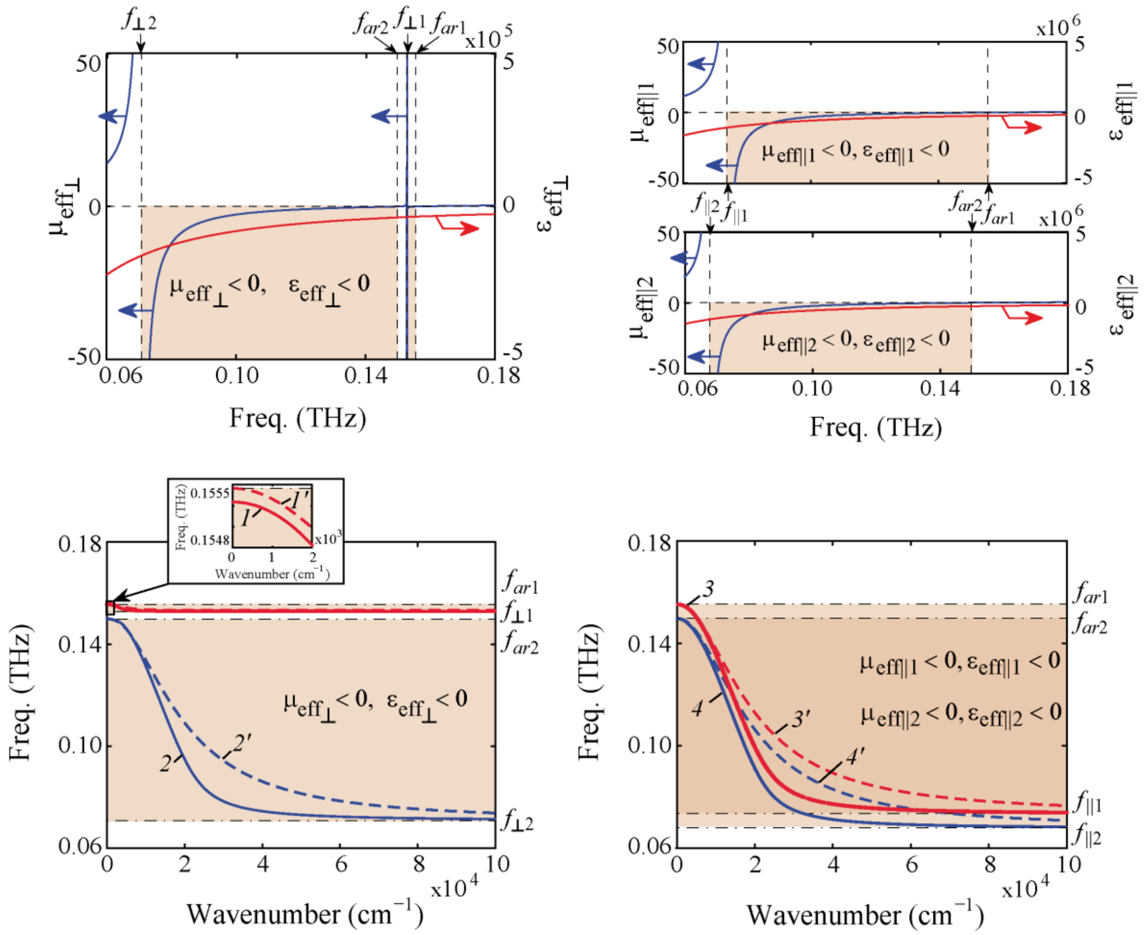

Fig.1. (a),(b) The frequency dependences of the effective permeabilities $\mu_{eff\perp}, \mu_{eff||1}$, $\mu_{eff||2}$ (blue lines) and permittivities $\varepsilon_{eff\perp}$, $\varepsilon_{eff||1}$, $\varepsilon_{eff||2}$ (red lines) calculated for the transversely (a) and the longitudinally (b) magnetized AFM SC.(c),(d) The dispersion characteristics of the backward EMWs existing in transversely (c) and longitudinally (d) magnetized AFM SC in the absence of loss ($\nu_e = 0$ and $\alpha = 0$- dotted lines *1', 2', 3', 4'*) and in the presence of loss ($\alpha = 4 \cdot 10^{-2}$ and $\nu_e = 10^{12}$ rad/s- solid lines *1, 2, 3, 4*). The fill marks the frequency regions, in which the effective material parameters are double negative.Calculations were performed for the europium telluride for $N = 10^{19}$ cm^{-3}, H_0=10^3 Oe, H_E=36000 Oe, H_A=8000 Oe, M_s=11600 G and ε_r=6.9.

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FIELD-INDUCED INCOMMENSURATE-COMMENSURATE TRANSITIONS IN FRUSTRATED MAGNETS

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We perform an analysis of the ground-state energy in Heisenberg helimagnets with an easy-plane anisotropy. It is shown that a small magnetic field in the easy plane can gradually change the vector of the magnetic structure and produce a first-order transition between phases with incommensurate and commensurate magnetic orderings. Predictions of our theory are in agreement, in particular, with experimental data observed in $RbFe(MoO_4)_2$ [1,2].

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МИКРОМАГНИТНОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ ПМСВ В ПЛЕНКАХ ЖИГ С КУБИЧЕСКОЙ АНИЗОТРОПИЕЙ.

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Кубическая кристаллическая анизотропия в пленках ЖИГ приводит к появлению в спектре поверхностной магнитостатической волны (ПМСВ) анизотропных прямых (и/или) обратных объемных спиновых волн (АПОСВ и АООСВ), которые занимают некоторую полосу частот вблизи длинноволновой границы спектра ПМСВ f_0. Такие АОСВ могут давать вклад в рассеяние ПМСВ на акустических поверхностных волнах [2] а также в процессы электрон-магнонного рассеяния в экспериментах по спиновой накачке в структурах ЖИГ-платина [3]. Цель данной работы – микромагнитное моделирование влияния кубической анизотропии на дисперсионные характеристики дипольно-обменных ПМСВ в пленках ЖИГ на подложках гадолиний галлиевого граната кристаллографической ориентации (111) и (100). Рассматриваются спектры в 2D (пленка не ограничена в направлении, перпендикулярном направлению распространения волны) и 3D геометрии (пленка ограниченных размеров) для пленки ЖИГ толщиной 4 мкм при поле H_0 = 200 Э.

Для моделирования в OOMMF [4] использовались стандартные параметры пленок ЖИГ с кубической анизотропией. Вдоль оси *y* прикладывалось внешнее поле, а распространение спиновых волн полагалось перпендикулярным ему (ось *x*), что соответствует конфигурации ПМСВ. В 2D геометрии вдоль оси *y* применялись периодические граничные условия. Для получения дисперсионных кривых использовалась стандартная процедура [5] возбуждения sinh-импульсом и дальнейшего Фурье-преобразования динамики намагничивания в структуре. Для уменьшения влияния отражения спиновых волн от краев образца на краях были введены области сильного затухания, изменяющиеся по закону геометрической прогрессии. Для кубической анизотропии типа (111) и (001) исследовалась трансформация спектра АСВ в зависимости от толщины ФП при различных величинах поля подмагничивания и направлениях распространения ПМСВ относительно трудных кристаллографических осей.

Для выбранной толщины пленки ЖИГ спектр ПМСВ существенно определяется как неоднородным обменом, так и магнитной анизотропией, см. рис.1. В случае пленок ЖИГ/ГГГ(111) можно видеть эффекты гибридизации и расталкивания дисперсионных кривых, рис.1а. Микромагнитное моделирование для 3D структур показывает, что наиболее значимые изменения в спектре волн ограниченной пленки ЖИГ, по сравнению с неограниченной в направлении приложенного магнитного поля, связаны с доминированием эффектов размерного квантования, задаваемых размерами пленки ЖИГ и возбуждающей антенны, рис.1г.

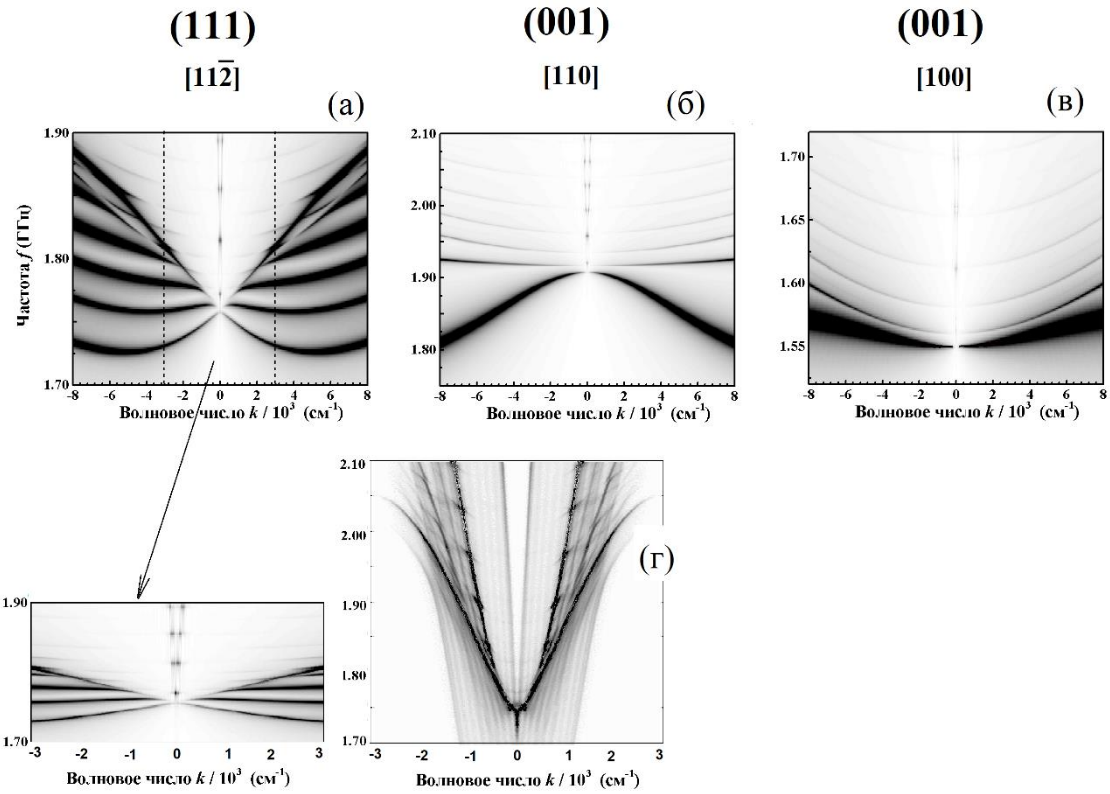

Рис.1

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SPIN WAVE PROPAGATION ALONG ZIGZAG-MODULATED DOMAIN WALL IN IRON GARNET FILM

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For spin-wave electronics and magnonics, a perspective application of domain walls (DW) as natural waveguides of spin waves [1]. At the same time, it should be kept in mind that domain structure (DS) can be different from simple strip structures and can be irregular (modulated) in terms of the length of domains and film thickness, which will significantly change the conditions of spin-wave propagation. In magnetic films with uniaxial perpendicular anisotropy in the case of zero external magnetic fields, the balanced DS is usually labyrinthine or stripe-like. It is known that in some cases the DS becomes more complex with the appearance of periodic modulations along the DW [2-3].

Using the methods of micromagnetic modeling [4], we have identified the features of the spatial propagation of the spin-wave beam profile along the structure shown in Fig. 1. The studied object is a 10 mkm thickness iron garnet film $(Y,Bi)_3(Fe,Ga)_5O_{12}$ on GGG substrate. The period of the domain structure is 4 μm and the period of modulations of the domain wall is comparable to it.

Fig.1. The modulated domain structure of iron garnet film.

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MEMS-CONTROLLED ZIGZAG MICROWAVE FILTER

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The study of methods of spin-wave signal transmission in irregular magnetic structures is of great interest [1-2]. A magnon waveguide based on an yttrium- iron garnet (YIG) magnetic film can act as a connecting element between functional units of a magnon network. The study of spin wave dynamics in periodic magnon structures is of particular interest [3].

The peculiarity of the proposed control method is the use of micromechanical systems to change the distance between the ferromagnetic waveguide and the resonator. This approach offers the possibility of precise and instantaneous control of the forbidden zones, which opens new perspectives for the development of high-performance spin-wave devices. This study details the mechanism and results of forbidden zone control using a ferromagnetic resonator.

This paper presents the results of the study of YIG structure on gallium-gadolinium garnet (GGG) substrate. Figure 1a shows a schematic representation of a zigzag-shaped YIG microwave with the following parameters: waveguide width a = 200 μm, length of the regular part b = 400 μm, length of the inclined part of the waveguide c = 800 μm, the total length of the structure is 5650 μm. The diagonals of the YIG resonator are 300 μm and 500 μm. The microresonator changed its position along the f axis. When propagating along a zigzag waveguide, the spin wave is repeatedly reflected on the fractures of the structure, resulting in the formation of 2 forbidden zones on the spectrum (Fig. 1b, blue line).

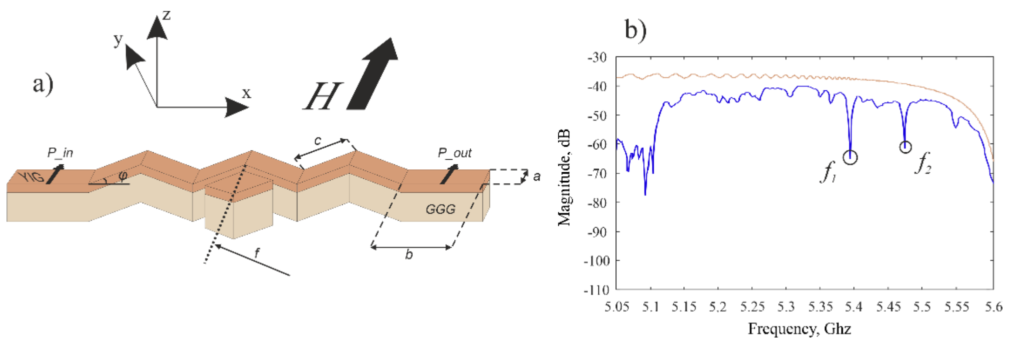

Fig.1. a) Schematic representation of a periodic zigzag structure; b) Amplitude-frequency characteristics.

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ВЛИЯНИЕ ВТОРИЧНЫХ СПИНОВЫХ ВОЛН НА СПИНОВУЮ НАКАЧКУ ПАРАМЕТРИЧЕСКИМИ СПИНОВЫМИ ВОЛНАМИ В СТРУКТУРАХ YIG/Pt

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С помощью обратного спинового эффекта Холла исследована спиновая накачка в структурах YIG/Pt бегущими поверхностными магнитостатическими волнами (ПМСВ) в условиях параметрической неустойчивости. Эксперименты выполнялись со структурами на основе пленок YIG с кристаллографической ориентацией (111) и (100). Исследовался вклад в спиновую накачку со стороны вторичных спиновых волн (ВСВ) [1], образующихся в результате беспороговых процессов слияния параметрических спиновых волн (ПСВ) с законами сохранения:

$$f_1 + f_2 = f_3, \qquad \vec{k}_1 + \vec{k}_2 = \vec{k}_3, \tag{1}$$

где частоты $f_{1,2}$ и волновые вектора $\vec{k}_{1,2}$ отвечают ПСВ, а f_3 и $\vec{k}_3$ характеризуют ВСВ. При этом анализировалась зависимость величины ЭДС U, генерируемой на контактах к платине за счет обратного спинового эффекта Холла, от уровня падающей мощности P (U=U(P)). Показано, что в тех случаях, когда частота ВСВ f_3 отвечает частоте сингулярности [2,3] в плотности состояний в спектре спиновых волн (СВ) зависимость U=U(P) демонстрирует линейных характер, несмотря на ограничение мощности ПМСВ за счет параметрической неустойчивости. Такой эффект в условиях параметрической неустойчивости первого порядка получил название «нелинейное усиление спинового тока» [4,5] и объяснялся передачей углового момента из решетки магнонам [4] и малым затуханием СВ на «дне» спектра [5].

В экспериментах по спиновой накачке ПМСВ, линейный характер зависимости U=U(P) наблюдается в некоторой полосе частот Δf вблизи длинноволновой границы спектра ПМСВ f_0 при условии, что частоты ПСВ $f_{1,2}$ отвечают частоте «дна» f_H в спектре СВ ($f_{1,2} \approx f_H$), а частота ВСВ f_3 попадает в полосу частот Δf.

Проведено микромагнитное моделирование спектра анизотропных дипольно-обменных СВ сопоставление расчетов с экспериментальными зависимостями интервала частот для пленок ЖИГ(111) и (100). Показано, что кубическая магнитная анизотропия существенно может влиять на интервал полей в котором зависимость U=U(P) демонстрирует линейный характер.

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SPIN PUMPING ON ACOUSTIC MODE FROM AN ANTIFERROMAGNET α-Fe_2O_3 TUNABLE BY MAGNETIC FIELD

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Lately, materials with magnetic properties have been drawing significant interest as they lack some limitations inherent to conventional electronics. Among these, antiferromagnets are particularly promising due to their native frequencies ranging from hundreds of gigahertz to several terahertz. The interest in these materials for fundamental and applied research is linked to their unusual structure, notably due to the slight canting of the magnetic sublattices. This effect enables the experimental study of ferromagnetic resonance (FMR) spectra and spin pumping in the tens of gigahertz range at room temperature. However, a major drawback in the application of magnetic materials is the relatively low quality factor of the quasi-ferromagnetic and antiferromagnetic modes compared to standard radiotechnical solutions. A potential solution could be to explore the acoustic mode that arises in the same magnetic material under specific excitation conditions [1].

This study examines the phenomenon of spin pumping on acoustic mode from canted antiferromagnet with frequency tuning via an external static magnetic field. Measurements were conducted on a monocrystalline disk of α-Fe2O3, with a thickness of 500 microns, grown by the flux method, which was coated with a thin layer of platinum, approximately 10 nm thick.

Figure 1 shows the dependence of the resonance frequency on the constant external magnetic field, confirming the possibility of tuning resonances in the acoustic mode by a magnetic field. The inset of Figure 1 demonstrates the ISHE voltage responses from the acoustic mode on the α-Fe2O3/Pt sample at various magnetic fields.

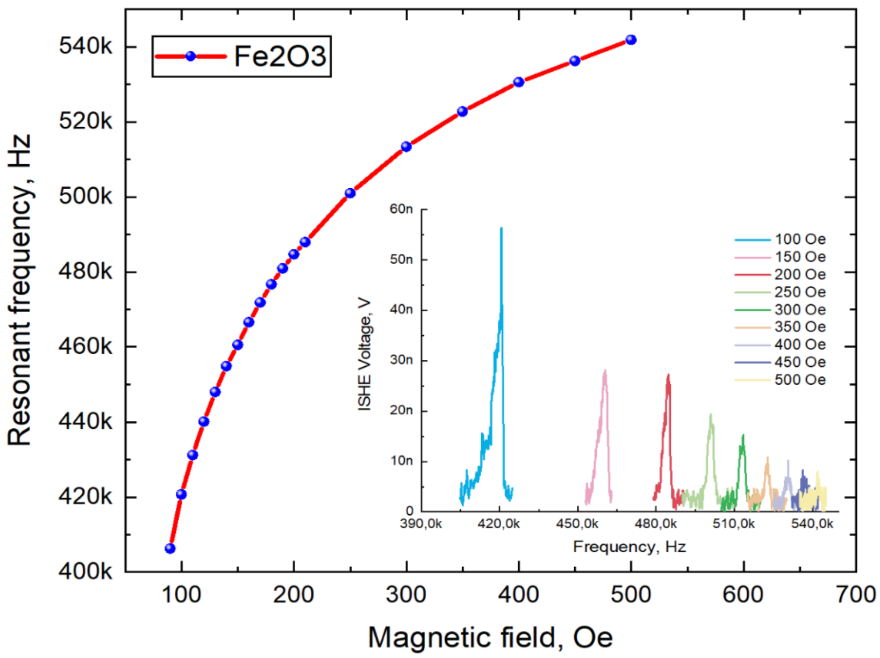

Fig.1 Dependence of the resonance frequency on the constant external magnetic field. The inset shows the ISHE Voltage response at various magnetic fields.

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STUDY OF SPIN WAVE PROPAGATION IN A YIG FILM WITH MAGNETITE NANOPARTICLES

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Recently, a new direction of spintronics has been actively developing using ferrite garnets - magnonics [1], in which the transport properties of spin-polarized electrons are not used, and information transfer occurs by transmitting a signal using spin waves (SW) [2]. With this approach, it is possible to implement a whole series of functional signal processing blocks on the principles of magnonics [3-5].

Also, much attention is currently being paid to the possibility of using magnetic media in biomedicine. Magnetic nanoparticles are actively used in biomedicine due to their unique properties, such as high sorption capacity and the possibility of remote control. In addition to diagnostic purposes, magnetite nanoparticles contrast well in MRI; they are also used for targeted delivery of drugs.

Yttrium iron garnet (YIG) films are used as a magnetic material used to form magnetic waveguide structures, demonstrating record low values of SW attenuation, including at nanometer YIG thicknesses [6-7]. In this work, we will consider a YIG film with magnetite nanoparticles deposited on it.

The microwave guide under study is a two-layer structure, where the first layer contains a YIG film with a length of L_2 = 4 mm, a width of L_1 = 300 μm, and a thickness of b_1 = 10 μm on a gallium-gadolinium garnet (GGG) substrate with a thickness of b_2 = 10 μm, and on the second layer in the region of a = 1 mm, with a periodicity of d = 10 μm, magnetite nanoparticles with a thickness of b_3 = 10 μm are located (see Fig. 1 (a, b)). It is also important to note that magnetite nanoparticles have the shape of a half cylinder with parameters w_1 = 10 μm and w_2 = 5 μm, where w_2 is void.

Micromagnetic modeling was performed for this structure. In micromagnetic modeling, conditions were created for the excitation of a surface magnetostatic wave (SMW), in which an external magnetic field H_0 was applied along the Y axis in the positive and negative directions to observe changes in the propagation of SW in the structure. The external magnetic field parameter H_0 was 1200 Oe.

The considered system of waveguide structures has 2 ports. The P_{in} port acted as an input antenna on which the microwave signal was excited and had a width of 30 μm. The P_{out} port acted as receivers for propagating spin waves and also had a width of 30 μm.

In the course of solving the problem of transmitting a spin-wave signal to reduce reflections of SW from the boundaries of the computational domain at the boundaries of the structure shown in Fig. 1 (a, b), the shaded area introduced absorbing layers with an exponentially increasing attenuation coefficient α [8-9].

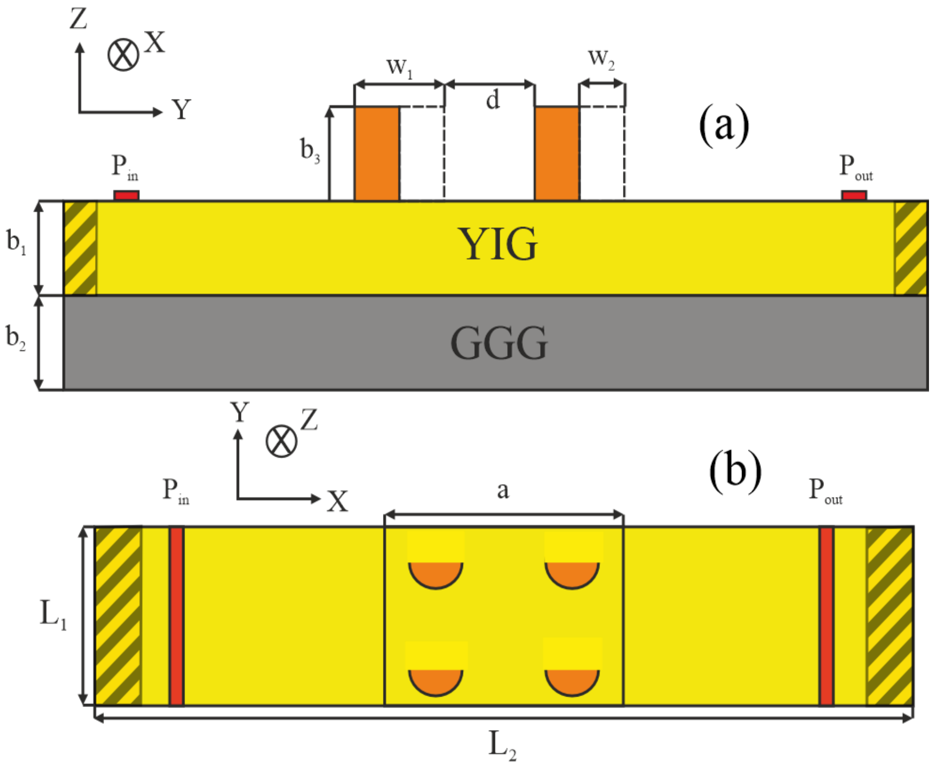

Fig.1. Schematic representation of a YIG film with magnetite nanoparticles in the z – y section (a), in the y – x section (b).

Thus, using numerical modeling, the structure with magnetite nanoparticles was studied. This structure can be used as a microwave signal filter controlled by the magnetic field orientation.

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STUDY OF SPIN WAVE PROPAGATION IN A SYSTEM OF LATERALLY COUPLED MICROWAVE GUIDES

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Currently, the development of ideas of magnonics [1-2], aimed at studying the processes of transfer of a magnetic moment or electron spin instead of charge transfer, opens up new possibilities for the use of spin waves (SW) for constructing the element base of devices for processing, transmitting and storing information. As such devices, it is possible to create irregular structures, for example, waveguides with varying widths. Yttrium iron garnet (YIG) films are used as a magnetic material used to form magnetic waveguide structures, demonstrating record low values of SW attenuation, including at nanometer YIG thicknesses [3-4]. In this work, we will consider a system of two waveguides located in parallel with a gap *d* of varying width.

The structure under study is a system of laterally coupled waveguide microwaveguides - two trapezoidal microwaveguides with varying widths (see Fig. 1). These microwave guides are YIG films with a thickness of 10 μm. The structure has the following parameters: the length of the microwave guides L = 7000 μm, the width of the larger part of the microwave guide w_1 = 200 μm, the width of the smaller part w_2 = 50 μm, the gap width d varied from 20 μm to 80 μm.

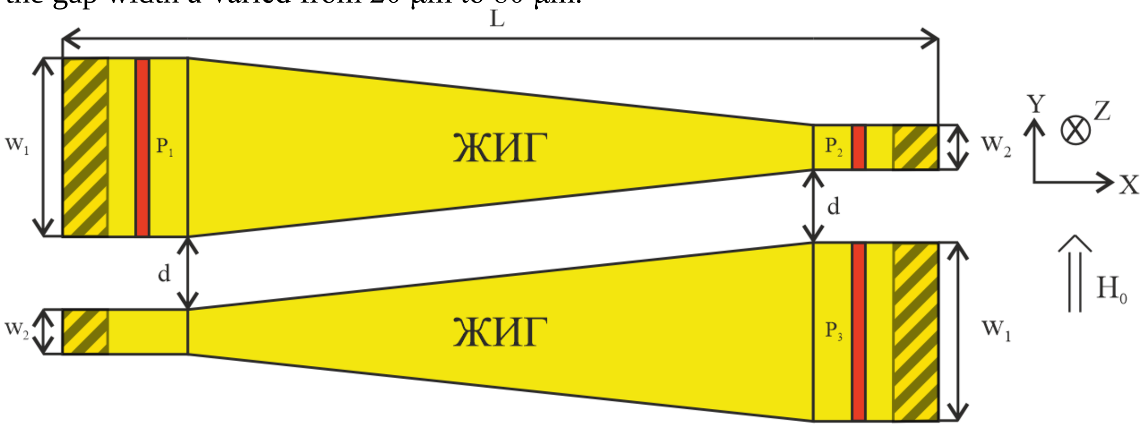

Fig.1. Schematic representation of a system of laterally coupled waveguide microwaveguides.

Micromagnetic modeling was performed for this structure. In micromagnetic simulation, conditions were created for the excitation of a surface magnetostatic wave (MSW), in which an external magnetic field H_0 was applied along the Y axis. The value of the external magnetic field parameter H_0 was 1200 Oe.

The considered system of waveguide structures has 3 ports. Port P_1 acted as an input microstrip on which a microwave signal was excited. Ports P_2 and P_3 acted as receivers of propagating spin waves.

In the course of solving the problem of spin-wave signal transmission, absorbing layers with an exponentially increasing attenuation coefficient α were introduced at the boundaries of the structure, shown in Fig. 1 by the shaded area, to reduce reflections of SW from the boundaries of the computational domain [5-6]. As a source of excitation of the spin-wave signal, a microstrip antenna P_1 with a width of 30 μm was located immediately after the attenuation region, and the detecting regions P_2 and P_3 were located at the output of the structure, as shown in Fig. 1.

The study was carried out in the MuMax^3 software package [7], in which the simulated structure was divided by a grid, at the nodes of which the Landau-Lifshitz equation with Hilbert damping was numerically solved [8-9].

$$\frac{\partial \vec{M}}{\partial t} = \gamma\left[\overrightarrow{H_{eff}} \times \vec{M}\right] + \frac{\alpha}{M_{s(x,y)}}\left[\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right] \quad (1)$$

where $\vec{M}$ is the magnetization vector, $\alpha = 10^{-5}$ is the YIG film attenuation parameter, $\overrightarrow{H_{eff}} = \overrightarrow{H_0} + \overrightarrow{H_{demag}} + \overrightarrow{H_{ex}} + \overrightarrow{H_a}$ is the effective magnetic field, $\overrightarrow{H_0}$ – external magnetic field, $\overrightarrow{H_{demag}}$ – demagnetization field, $\overrightarrow{H_{ex}}$ – exchange field, $\overrightarrow{H_a}$ – anisotropy field, $\gamma = 2.8$ MHz/Oe – gyromagnetic ratio.

Thus, a system of laterally coupled waveguides was studied using numerical simulation. As the gap d between the microwave guides increases, the efficiency of SW transfer decreases. This structure can be used as a directional branch of a microwave signal to create devices for processing information signals on the principles of magnonics.

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СИСТЕМА ШИФРОВАНИЯ НА ОСНОВЕ СПИНОВЫХ ВОЛН ПРИ ИХ РАСПРОСТРАНЕНИИ В ЛАТЕРАЛЬНОЙ СТРУКТУРЕ ДВУХ КОЛЬЦЕВЫХ РЕЗОНАТОРОВ

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Данная работа посвящена использованию латеральных структур на основе двух резонаторов, как технического средства защиты информации, генерирующего закрытый ключ шифрования. Основой для такой методики послужат способности к направленному ответвлению и формированию кольцевой моды магнитостатической волны. Управляя частотой подаваемого сигнала и геометрическими параметрами системы можно корректировать, как амплитуду спиновой волны (СВ), так и направление распространения сигнала [1].

Используемая в данной работе структура представляет собой две полоски шириной в 500 мкм, расположенных параллельно друг другу, между которыми размещены два кольцевых резонатора. Все элементы выполнены на основе пленки железо - иттриевого граната (ЖИГ, YIG) на подложке из галлий – гадоллиниевого граната. Толщина слоя ЖИГ составляет 10 мкм, а зазор между микроволноводами составляет 50 мкм, при этом величина зазора выбрана из условия реализации режима многомодовой связи магнитостатических волн. Расстояние между двумя резонаторами - d может варьироваться для обеспечения наибольшего числа шаблонов кодировки информации. По тому же принципу выбираются длинны плеч резонаторов – R1 и R2 вдоль направления осей x и y, соответственно. По всему пространству структуры формируется однородное статическое магнитное поле $\boldsymbol{H}$, направленное вдоль оси x для эффективного возбуждения поверхностных магнитостатических волн. На концах каждой полоски устанавливаются антенны P1 – P4. Антенны – выходы P2, P3, P4 расположены, соответствуя своему порядку, на правом конце первого волновода и, соответственно, на концах второго. Они предназначены для снятия выходного сигнала приходящей волны. Антенна P1 используется для возбуждения спиновой волны в структуре и расположена на левом конце первого волновода [2].

Для реализации широкоформатного кодирования необходимо прибегнуть к созданию нескольких конфигураций системы. Под ними будут подразумеваться разные расстояния d, R1 и R2. Каждое их значение соответствует определённому ключу шифрования и заносится в него двоичным кодом. Далее будут рассмотренные все возможные варианты составления ключа. За отведённое время измерений (стандартно выделяется 300 нс) будут сняты от 10 до 30 состояний конфигурации из них выделяются состояния-шаблоны, заранее определённые по их показаниям намагниченности на выходах P2, P3, P4.

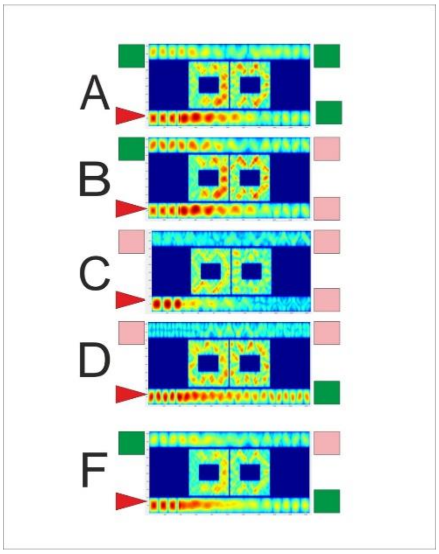

Рис. 1. Примеры состояния-шаблона. Красная стрелка указывает на расположение антенны P1, зелёные и розовые квадраты – выходы P2, P3, P4.

На Рис. 1 зелёные квадраты отображают состояния выходов, принятые за логическую единицу, розовые – логический ноль. Условия принятия логического нуля или единицы на выходе определяются индивидуально для каждой конфигурации, в зависимости от её общей намагниченности за время работы системы. Так можно увидеть, что условия выбора 1 или 0 в состояние-шаблоне B отличаются от условий выбора в состояние-шаблоне A, так как они относятся к разным диапазонам частот. При кодировании сигнала будут использованы амплитудные показатели на выходах P2, P3, P4, которые соответствуют 0 либо 1, как было уже обозначено выше. Каждое состояние-шаблон принимается, как элементарный массив данных, включающий в себя показания на выходах P2, P3, P4 в двоичном коде. Данные массивы можно продемонстрировать на Рис. 1, состояния-шаблоны A,B,C,D,F соответствуют массивам: [1,1,1], [1,0,0], [0,0,0], [0,0,1], [1,0,1].

Таким образом, за время наблюдений, данные состояния-шаблоны чередуют друг друга в каждой из конфигураций, что формирует условную эволюцию состояний системы. Она зависит не только от смены конфигураций, но и от частоты. На Рис. 2 показан пример эволюции системы в одной конфигурации.

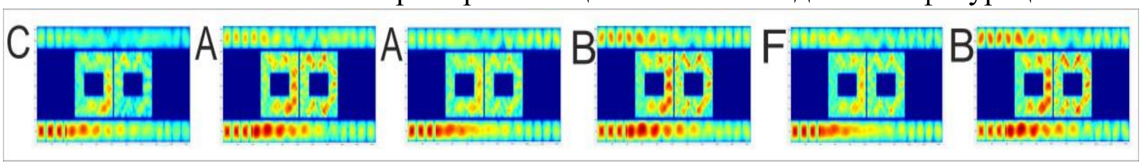

Рис 2. Эволюция состояний системы на частоте 5.21e9 Гц.

Таким образом, для каждой конфигурации подбирается набор уникальных массивов данных, который не будет соответствовать другой конфигурации или другой частоте за тот же промежуток времени. Весь шифр собирается из 10-30 таких элементарных массивов, в совокупности, представляющие собой массив шифрования или дешифрования информации размерами от 90 бит.

Полный ключ шифрования является меньшим по объёму массивом данных, состоящим из параметров возбуждаемой спиновой волны, расстояния d, R1, R2;

величины магнитного поля H, и т.п., представленных в двоичном коде. Для его использования, необходимо конвертировать внесённую информацию и внести в настройки структуры. На выходе моделирования образуется массив данных по z-компоненте намагниченности, который будет шифровать или дешифровать нашу информацию. Для усложнения кодировки можно использовать ансамбль разных конфигураций, составляя сложный и уникальный массив шифрования.

Таким образом, система кольцевых резонаторов представляет собой сложный комплекс шифрования информации, доступный только при наличии данной системы. Изменения любого из параметров структуры приводит к непредсказуемой смене каждого элементарного массива всего массива шифрования. Гибкость кодировки информации достигается сменой ключа шифрования и добавлением ансамбля конфигураций и их частот, а также временем наблюдения системы. В заключении, необходимо отметить приемлемую скорость создания ключа шифрования, а также его надежную размерность

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МАГНОН-ФОТОННОЕ ВЗАИМОДЕЙСТВИЕ В ГЕТЕРОСТРУКТУРАХ СВЕРХПРОВОДНИК/ФЕРРОМАГНЕТИК

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Режим ультрасильной связи в системах с гибридизацией, когда энергия взаимодействия подсистем друг с другом сопоставима с энергиями самих этих подсистем, сопровождается различными интересными квантовыми эффектами. В числе прочего этот режим может наблюдаться в сверхпроводящих наноструктурах с ферромагнетиками, где в качестве взаимодействующих подсистем выступают магноны в ферромагнетике и фотонная мода Свихарта в электромагнитном резонаторе, при гибридизации образующие магнон-поляритонные моды. В частности, было экспериментально [1] и теоретически [2] продемонстрировано, что режим ультрасильной магнон-фотонной связи реализуется в гетероструктурах S/F/I/S с ферромагнитным металлом.

Данный доклад посвящен теоретическому описанию магнон-фотонного взаимодействия в симметричных гетероструктурах с двумя ферромагнитными металлами S/F/I/F/S. Демонстрируется, что взаимодействие ферромагнетиков через поля мейснеровских токов в сверхпроводнике приводит к дополнительному расщеплению магнон-поляритонных мод по сравнению со случаем структуры с одним ферромагнетиком. Величина данного расщепления соответствует режиму ультрасильной связи, что делает исследуемые системы перспективным объектом для приложений магноники.

Работа была поддержана РНФ (№22-42-04408).

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LASER-INDUCED SPIN-REORIENTATION TRANSITIONS IN IRON OXIDES Fe_3O_4 and Fe_3BO_6

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Search for effective and fast methods for controlling the magnetic state of matter is in the focus of studies in spintronics, magnonics and femtomagnetism. From this point of view, spin-reorientation (SR) transitions are promising. SR transitions are a change of orientation of the easy axis of magnetization under an external stimulus. It was shown experimentally that the SR transition can be induced by femtosecond laser pulses and occur over times of the order of several picoseconds in a group of iron oxides – rare earth orthoferrites. In this materials a change of a magnetic anisotropy is possible due to the contribution from rare earth ions to magnetic anisotropy energy [1, 2]. Here we demonstrate that an ultrafast SR transition can be induced by laser pulses in iron oxide without rare earth ions – a ferrimagnet magnetite Fe_3O_4 and a weak ferromagnet iron borate Fe_3BO_6.

We performed femtosecond time-resolved studies of magneto-optical Kerr effect in Fe_3O_4 [3] and Fe_3BO_6 single crystal at various laser pulse fluences and sample temperatures. Based on the characteristic thresholds and saturation of the amplitude precession of magnetization as a function of the pump fluence, we could conclude that a laser pulse induces the SR transitions in these materials.

The possibility to induce an ultrafast SR transition in magnetite is associated with the presence of a Verwey transition that is close in temperature and occurs at times of the order of 1 ps [4]. Depending on laser fluence and temperature, the photo-induced SR transition occurs either in a whole excited material or in separate domains, signifying its first-order character beyond the thermal equilibrium. In addition, we found that laser-driven SR transition is the underlying mechanism of laser-induced magnetization precession in magnetite in a wide temperature range even above the ST transition temperature, which is again associated with its 1st order.

The underlying mechanism of the SR transition in the iron borate differs from magnetite, since Fe_3BO_6 does not have a structural-electronic transition at close temperatures. Excitation of magnetization precession appeared to be possible only for temperatures below the temperature of SR transition. In addition, the magnetization does not start to precess immediately after excitation, but there is a delay of 5 - 15 ps depending on temperature. A similar behavior of magnetization during an ultrafast SR transition was found in the rare-earth orthoferrite $ErFeO_3$ in [2]. The delay time was associated with the time required to change the magnetic moment of Er^{3+} ion. The observation of similar dynamics in iron borate also indicates the existence of a “bottleneck” process which is responsible for the finite time of change in magnetic anisotropy during the SR transition and can be assigned to a finite time of response of the Fe-O coordination complexes to laser excitation.

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INFLUENCE OF EXTERNAL PRESSURE ON THE THz MODE IN THE ANTIFERROMAGNET α−Fe2O3

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Modern electronics has a wide variety of devices for generating, transfer and detecting signals. In electronics, there is a tendency to increase the speed of information transfer and to expand the range of operating frequencies. However modern electronic industry is able to develop only devices that operating frequencies are limited to GHz. It is possible to expand the range of operating frequencies by applying new technologies and materials using achievements in spintronics and magnonics [1, 2]. These fields explore elementary excitation, such as the interaction of elastic and magnetic waves in ferro- and antiferromagnetic materials. The use of antiferromagnetic (AFM) materials allows to process signals at terahertz frequencies, which makes them attractive also for practical applications [2, 3].

Another aspect that is widely studied in magnetically ordered systems is the possibility for the control of magnetization with an electric field through stress. But the question of the influence of mechanical deformations on the frequency of the antiferromagnetic modes does not exist, so the development of a theory is an important task.

We consider a model of small deformations of a thin plate in an external magnetic field. When the plate is bent inside it, stretching occurs in some places, and compression occurs in others. To study the frequency characteristics, we used Brillouin light scattering spectroscopy (BLS).

We consider the antiferromagnetic resonance in a bulk single crystal of hematite. The description of the dynamics AFM based on a system of two Landau–Lifshitz equations for magnetization sublattices was proposed. However, it is possible to reduce to one vector equation for the antiferromagnet vector $\boldsymbol{l}$. The model for the N'eel vector $\boldsymbol{l}$ equations can be obtained directly from the total energy using the magnetic symmetry of the antiferromagnet obtain an equation for dynamic component $\boldsymbol{s}$ with condition ($\boldsymbol{l}=\boldsymbol{l_0}+\boldsymbol{s}$):

$$\frac{d\ s^2}{dt^2} - \gamma(l_0 \cdot H)\cdot\left[l_0 \times \frac{d\ s}{dt}\right] - \gamma^2[s \times H_D](l_0 \cdot H) + 2\gamma^2 M_0 H_E \beta_1 s(l_0 \cdot n)^2 + \gamma^2 s(l_0 \cdot H)^2 - \\ -16M_0^2 \varepsilon p_z \gamma^2 \frac{\delta_{12}-\delta_{11}}{C_{11}-C_{12}}((l_0 \cdot l_z)-(l_0 \cdot l_y))s + 16\gamma^2 \varepsilon M_0^2 \beta'\left(s(l \cdot e_x)^5 + s(l \cdot e_y)^5\right) = 0, \tag{1}$$

where $\boldsymbol{M_0}$ is saturation magnetization, γ is the gyromagnetic ratio, $\boldsymbol{H_D}$ is the Dzyaloshinsky-Moriya field, $\boldsymbol{H}$ is external magnetic field, $\boldsymbol{h}=\boldsymbol{H}/2M0$ is the vector along the magnetic field, ε is exchange constant, $H_E= \varepsilon/2M_0$ is the exchange field, $\beta_1=H_{EA}/2M_0$ is the second order anisotropy constant and $\beta'=H_A/2M_0$ is the sixth order anisotropy constant, δ_{12} and δ_{11} are magnetoelastic constants, C_{12} and C_{11} are elastic constants, $\boldsymbol{e_x}$ and $\mathbf{e_y}$ are the unit vectors along the x-axis and the y-axis and $\boldsymbol{n}$ is the orthogonal vector. Having a solution to the equation, we can write the expressions for the AFM resonance frequencies. The solution of the equation for the dynamic vector s gives expressions for the frequencies of the lower and upper modes of the AFM.

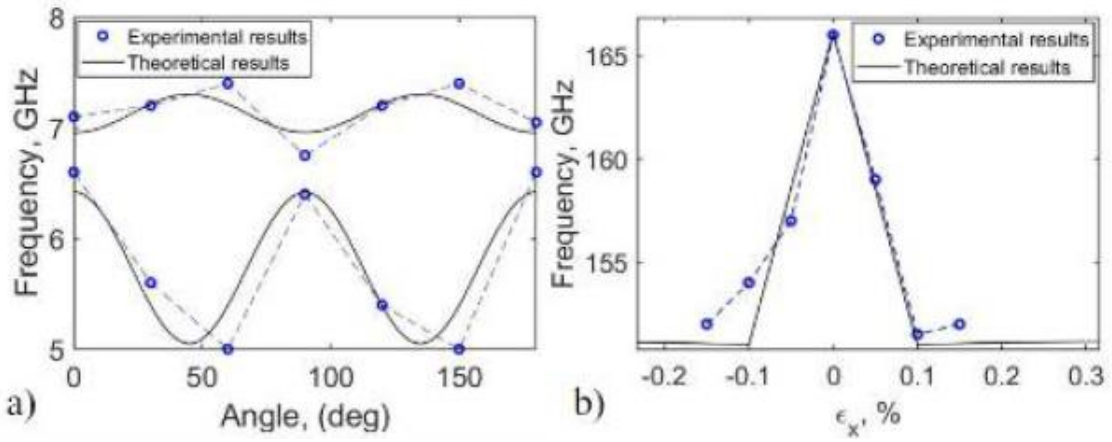

Fig.1. a) Angular dependence of the frequency of the lower ferromagnetic mode; b) Dependence of the frequency of the upper ferromagnetic mode on relative strains.

In addition, we calculated the theoretical dependence of the frequency of the quasi-ferromagnetic mode on the angle in the sample plane at zero strain (Fig. 1(a)). The quasi-ferromagnetic mode has at least two rotation angles of 180 degrees. Also the dependence of the frequency of the antiferromagnetic mode on relative strains is shown in Fig. 1(b). The range of relative deformations is from -0.2 % to 0.2 %. It can be seen that with increasing strain (0.1 %), the frequency shift of the AFM mode reaches about 10 GHz. Note that the resulting dependence is symmetrical about zero level of deformation.

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SPIN DYNAMICS OF THE FERROMAGNET–HELICAL TRANSITION IN HOLMIUM FILMS

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Due to the fact that Holm implements various magnetic phase transitions (fan, spiral, spin-slip) with changes in temperature and/or magnetic field [1], it becomes possible to study thermodynamic parameters near extreme points under different conditions. The complex magnetic structure of metallic holmium is the result of competition between exchange interactions and crystal field interactions [2]. The turn-on period of the spin helix in holmium is quite long, for example, each period is 12 lattice settings of 5.6 Å along the c axis in the Ho section. Multiple noncollinear spin structures and transitions between them, initiated by field and temperature, attract attention due to the unusual coexistence of complex spin phases in Ho.

Low-level frequency susceptibility measurements (~100-1500 Hz) and magnetic viscosity measurements at lower frequencies (~0.01 Hz) were carried out, and magnetic relaxation dynamics were studied in 400 nm thick Ho films undergoing ferromagnetic (FM) and helical transitions. phase states (Helix). During the FM-Helix transition, sharp changes in the actual and minimum values of magnetic susceptibility are observed, occurring at temperatures of 15-30 K, both in the absence of external fields and in fields of 4 kOe and -6.5 kOe, which is consistent with the magnetic field obtained in this work. phase diagram (Fig. 1).

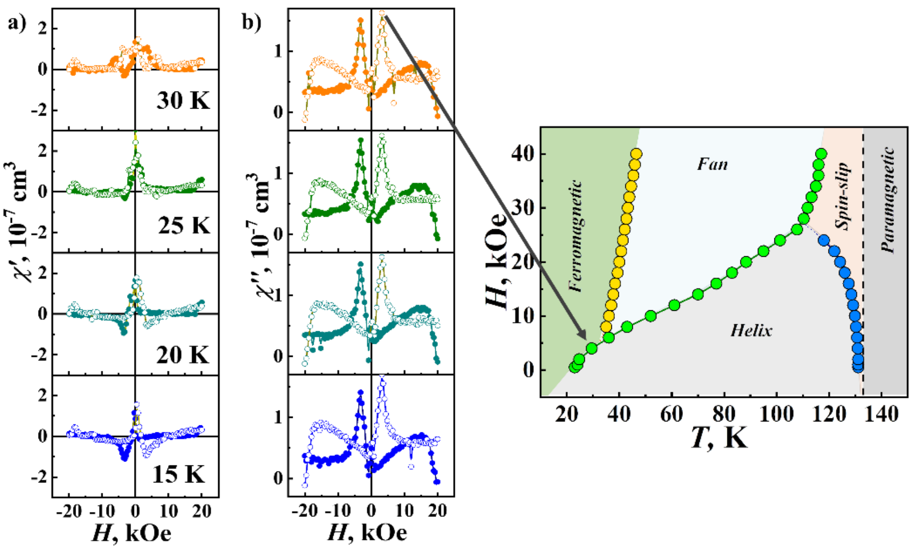

Fig. 1. DC field effects on AC magnetic susceptibility at 15 K – 30 K: real part (a) and imaginary part (b). The inset on the right shows the magnetic phase diagram obtained by SQUID magnetometry. The arrow shows the corresponding position of the peak of the imaginary part of the magnetic susceptibility on the phase diagram.

Hysteresis effects were revealed in the components of magnetic susceptibility during cyclic changes in the external field, which indicates a relatively fast process with a duration of about 10 ms that accompanies the FM-Helix transition. It was found that the process of slow magnetic relaxation is also sensitive to this transition. In addition, the field dependence of magnetic viscosity noticeably decreases during the FM-Helix transition. The proposed methodologies for studying relaxation processes in materials with a multiphase spin structure are considered universally applicable and allow a better understanding of transitions between spin states in materials exhibiting a non-collinear spin structure.

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EPITAXIAL FILMS OF YIG WITH SYMMETRIC DIAMAGNETIC BOUNDARY CONDITIONS

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This work presents the results of the synthesis and investigation of YIG epitaxial films with symmetric and asymmetric diamagnetic boundary conditions. The symmetry of the boundary conditions is created by introducing one or two additional layers of diamagnetic garnet YSGG into the GGG/YIG structure. The spin dynamics in the heterostructure with symmetric GGG/YSGG/YIG/YSGG and asymmetric GGG/YSGG/YIG boundary conditions is compared. The role of the diamagnetic spacer in the GGG/YSGG/YIG structure for nanofilms was studied [1].

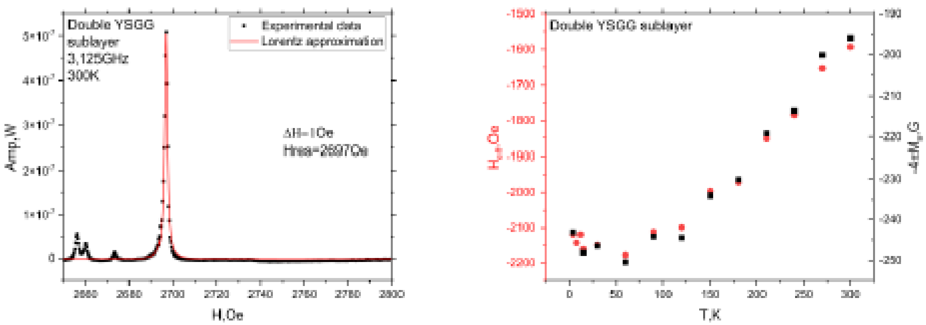
The synthesis of heterostructures was carried out by the method of liquid phase epitaxy. The synthesis of diamagnetic YSGG layers with a thickness of 5.5 (spacer) microns and 2.5 microns was carried out on the «Rost - 1» growth system. The synthesis of the YIG base layer with a thickness of 12.3 microns of the composition $Y_3Fe_{4.9}In_{0.1}O_{12}$ was carried out on an LPEF growth system.

The spin dynamics were studied using the out of plane FMR method in the frequency range of 1.5 GHz to 9.5 Hz and the temperature range of 300K to 4.2K. The FMR absorption spectra were registered with a vector network analyzer attached to a broadband stripline. The sample was disposed face-down over a stripline and the transmission signals (S21) were recorded. During the measurements, a frequency of microwave signals with the input power of −20 dBm was constant, while the out of-plane magnetic field H was swept across the resonance area. Each recorded spectrum was fitted by the Lorentz function which allowed us to define the resonance frequency and the FMR linewidth

$$\frac{\omega}{\gamma} = H + H_{eff}, \quad (1)$$

where H_{eff} is calculated as

$$H_{eff} = \frac{2K_u}{M_s} - 4\pi M_s, \quad (2)$$



(a) (b)

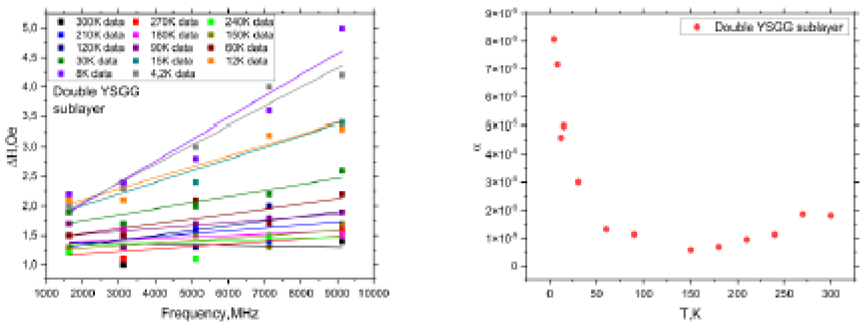
Fig.1. FMR spectrum with Lorentz approximation (a) and temperature dependences of the effective anisotropy field and saturation magnetization (b) in GGG/YSGG/YIG/YSGG.

Figure 1(a) shows the FMR spectrum with a Lorentz approximation at a temperature of 300 K of a sample with two YSGG layers, which differs slightly from the spectrum for one YSGG layer sample. H_{res} in the symmetrical structure has increased slightly while the line width has decreased. The ΔH_{sim} is 1Oe, and the ΔH_{asim} is 1.2Oe.

Figure 1(b) shows the temperature dependence of the effective field of anisotropy and saturation magnetization of a symmetrical structure, which is slightly different for an asymmetric structure. The temperature dependence of the resonant field is determined mainly by the demagnetizing field of YIG. The contribution of the uniaxial anisotropy field is insignificant. Gilbert damping coefficient is calculated as [2]

$$\Delta H = \frac{4\pi\alpha f}{\gamma} + \Delta H_0, \qquad (3)$$

where ΔH_0 is the inhomogeneous broadening which is attributed to magnetic nonuniformity and surface defects.



(a) (b)

Fig.2. Frequency and temperature dependences of the line width (a) and temperature dependences of the Gilbert damping coefficient (b) in GGG/YSGG/YIG/YSGG.

Figure 2(a) shows the frequency dependences of the FMR line widths in GGG/YSGG/YIG/YSGG for different temperatures, which make it possible to determine the Gilbert damping coefficient (1). Figure 2 (b) shows the temperature dependence of the Gilbert damping coefficient for a symmetric structure. At a temperature of 300 K, the Gilbert damping coefficient is 1,8*10-5. The minimum value of the Gilbert coefficient is 5,7*10-6 at a temperature of 150K. Alpha growth at temperatures below 50 K is associated with impurity relaxation mechanisms.

Epitaxial ferrite garnet heterostructures with small Gilbert damping coefficient and symmetric diamagnetic boundary conditions were synthesized, which can be used to create devices in magnonics.

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КОГЕРЕНТНЫЙ РЕЗОНАНС В ШИРОКОПОЛОСНЫХ МИКРОВОЛНОВЫХ СПИН-ВОЛНОВЫХ ГЕНЕРАТОРАХ ХАОСА ПОД ВОЗДЕЙСТВИЕМ ШУМА

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В возбудимых шумом системах наблюдается фундаментальное нелинейное явление, которое называется когерентным резонансом [1]. Оно заключается в том, что у шумового воздействия имеется оптимальный уровень, при котором колебания, индуцируемые шумом, становятся наиболее близкими к регулярным. Когерентный резонанс наблюдается в модели нейрона Ходжина-Хаксли [2], осцилляторе ФитцХью-Нагумо [3], химической реакции Белоусова-Жаботинского [4]. Рассматривая хаотические динамические системы, данный эффект наблюдался теоретически только в бистабильной цепи Чуа [5], а также в двух связанных идентичных хаотических осцилляторах Лоренца [6]. В работе [6] явление когерентного резонанса наблюдалось в режиме "on-off" перемежаемости, при котором происходило переключение состояния под воздействием шума. В данной работе демонстрируется экспериментальное наблюдение эффекта когерентного резонанса в многомодовых микроволновых спин-волновых генераторах хаоса под воздействием сверхвысокочастотного (СВЧ) шумового сигнала с ограниченным спектром.

Исследуемая система состоит из последовательно соединенных в кольцо спин-волновой линии передачи в конфигурации «линия задержки», поддерживающей как трех-, так и четырехволновые нелинейные спин-волновые взаимодействия, транзисторного усилителя мощности, работающего в режиме линейного усиления для генерируемого в кольце хаотического СВЧ сигнала, полосно-пропускающего фильтра и переменного аттенюатора. Хаотический СВЧ сигнал генерируется в полосе 2-4 ГГц при напряженности внешнего постоянного магнитного поля 358 Э. Центральная частота шумового воздействия - 2.1 ГГц, а его ширина полосы частот меняется в интервале 1-80 МГц. Спектр мощности хаотического СВЧ сигнала характеризуется центральной частотой f_{ch}=3 ГГц и шириной полосы частот Δf_{ch}=1.4 МГц по уровню 58 дБ относительно максимального значения спектральной мощности.

При подаче внешнего шумового СВЧ сигнала, не превышающего уровень интегральной мощности P_n=-12 дБмВт, он не оказывает заметного влияния на огибающую хаотического СВЧ сигнала, которая имеет такой же вид, как и в автономном режиме генерации (см. рис. 1a). При дальнейшем увеличении мощности шумового СВЧ сигнала (см. рис. 1b) огибающая хаотического СВЧ сигнала начинает подавляться на тех временных интервалах, где мгновенные значения амплитуды шумового сигнала соответствуют нелинейному режиму работу усилителя. Как следует из рис. 1c, при дальнейшем увеличении мощности шумового СВЧ сигнала длительность интервалов, на которых хаотическая динамика системы полностью подавлена, увеличивается. Наличие таких временных интервалов свойственно перемежаемости типа "on-off", при которой происходит переключение между двумя устойчивыми состояниями. На рис. 1d представлены зависимости времени автокорреляции хаотического СВЧ сигнала от мощности шумового СВЧ сигнала, полученные при различных полосах шума. Видно, что на каждой зависимости имеется максимум времени автокорреляции, который наблюдается при определенной мощности шума, т.е. исследуемая система демонстрирует явление когерентного резонанса. При этом с ростом полосы шумового СВЧ сигнала максимальное значение время автокорреляции уменьшается.

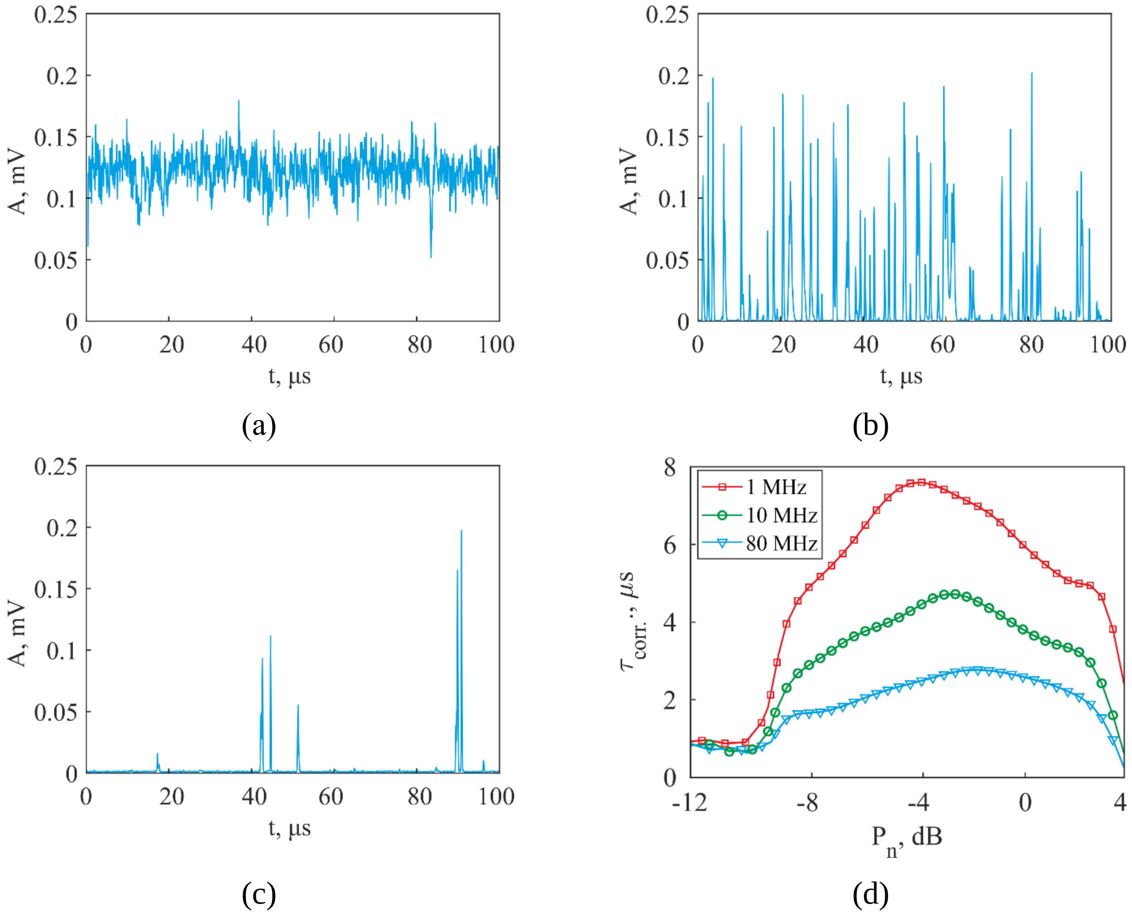

Рис 1. - Временные ряды (a-c) хаотического СВЧ сигнала, генерируемого в схеме кольцевого автогенератора на основе спин-волновой линии передачи под действием внешнего шумового СВЧ сигнала различного уровня мощности $P_{n:}$ -12 дБмВт (a), -4 дБмВт (b) и +4 дБмВт (c). Результаты (a-c) получены для Δf_n=80 МГц. На (d) приведено семейство кривых, демонстрирующих зависимость времени автокорреляции хаотического СВЧ сигнала τ_{corr} от мощности шумового СВЧ сигнала при изменении полосы частот шума Δf_n.

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TERAHERTZ SPIN PUMPING ON ANTIFERROMAGNETIC MODE FROM COBALT OXIDE

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Spin pumping in magnetic materials is one of the most powerful methods for detecting pure spin currents. Researchers in modern spintronics are focused on multisublattice magnetic materials such as antiferromagnets (AFM), because due to exchange enhancement, they exhibit a number of unique properties [1]: subterahertz and teraherz (THz) resonance frequencies, high speed of spin waves and domain walls, amplification of spin current due to excitation of evanescent modes, etc.

In this work, terahertz spin pumping on the antiferromagnetic mode from cobalt oxide in high magnetic fields was theoretically and experimentally investigated. Fig. 1 shows the dependence of the rectified output voltage caused by the inverse spin Hall effect on the frequency. The red curve on Fig. 1 illustrates the optically measured spectrum of cobalt oxide [2]. As one can see, our results are qualitatively the same as [2].

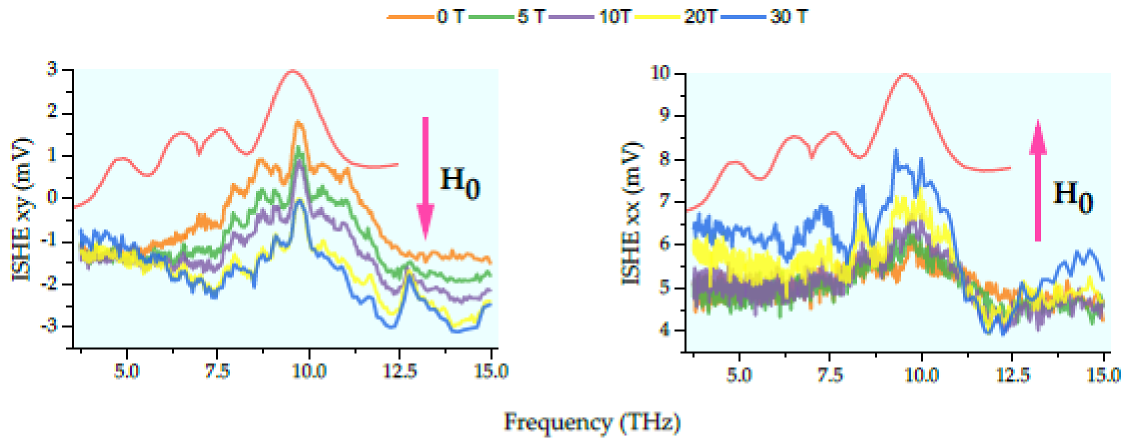

Fig.1 Antiferromagnetic mode output voltage dependence on frequency.

This work was carried out within the framework of the state assignment of the Kotel'nikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences.

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MAGNETIC PROPERTIES OF FERRO-ANTIFERROMAGNETIC SPIN TRIANGLE CHAIN

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Low-dimensional quantum magnets on geometrically frustrated lattice have been extensively studied [1]. An important class of these systems includes lattices consisting of triangles. The simplest and typical example of such systems is spin-1/2 delta-chain. The delta-chain with competing ferro (F) and antiferromagnetic (AF) interactions attract interest recently [2,3]. We study another example of frustrated spin-1/2 model with ferromagnetic and antiferromagnetic interactions which is an extension of the delta-chain. This model represents a linear chain of triangles connected by the ferromagnetic interactions J as shown in Fig.1. The properties of the model depend on the frustration parameter $\alpha = J_2/J_1$, which is a ratio between AF and F interactions in triangle. The ground state is ferromagnetic for $\alpha < 0.5$ at any value of J. At $\alpha_c = 0.5$ the quantum phase transition occurs. The properties of the model at $\alpha = \alpha_c$ are highly non-trivial. The ground state manifold at αc includes isolated magnons and specifically overlapping localized multi-magnon complexes. The ground state is macroscopically degenerate in zero magnetic field and the residual entropy is non-zero. The spectrum of excitations has a specific multi-scale structure which consists of rank-ordered subsets. Each subset is responsible for the appearance of the peak in the temperature dependence of the specific heat.

For $\alpha>\alpha_c$ the ground state phase diagram consists of the singlet and the ferrimagnetic phases. The ground state spin S_{tot} in the ferrimagnetic phase is $S_{tot} = S_{max}/2$ and there is the gap to the state with $S = (S_{tot}+1)$, which leads to an existence of the magnetization plateau. The singlet phase is gapless and the magnetization plateau exists in definite region of the singlet phase. The considered model at large value of α demonstrates a topological equivalence of the phase states in opposite limits $J\to 0$ and $J\to\infty$, and there is a smooth crossover between these limits.

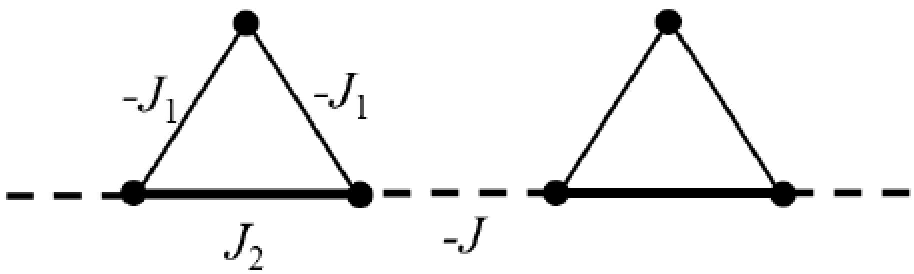

Fig.1. Triangle chain model (all $J>0$).

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DZYALOSHISKII-MORIYA INTERACTION IN Pt/Co/CoO THIN FILMS

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Thin magnetic films Pt/Co/CoO have significant potential for future applications in spintronics and magnetoelectronics [1-2]. The emergence of effects such as perpendicular magnetic anisotropy, Dzyaloshinskii-Moriya interaction (DMI), exchange bias, and others in this magnetic system allows for the control of topological magnetic structures. The presence of "heavy metal/ferromagnet" and "ferromagnet/antiferromagnet" interfaces is a crucial factor for inducing these effects, enabling the realization of spin-orbit and exchange interactions at the interfaces.

Samples with different oxidation times (ranging from one to three minutes and no oxidation) were prepared in the study. The initial Pt layer of 10 nm thickness was deposited using magnetron sputtering on a silicon substrate, followed by a 1 nm Co layer using molecular beam epitaxy. Oxidation was carried out with oxygen at a pressure of 1 bar, and then the layer was covered with a 50 nm Pd layer. Optimal cleaning and annealing parameters for Pt were also determined to prevent atmospheric effects.

Dependencies of the magnetic parameters of the films on oxidation time, such as the effective magnetic anisotropy magnitude and saturation magnetization, were measured using a vibrating sample magnetometer. Mandelstam-Brillouin light scattering based on the difference in stokes and anti-stokes field frequencies was used to determine the effective DMI constant:

$$D_{eff} = 2\, M_s \Delta f \,/(\pi\gamma\, k_i),, \quad (1)$$

where M_s is saturation magnetization, Δf is difference of stokes and anti-stokes frequency component, γ = 176 GHz/T is the gyromagnetic ratio, k_i is the momentum along the i-direction.

The obtained spectra (Fig. 1) were analyzed to plot the dependence of frequency difference Δf on oxidation time considering different external fields.

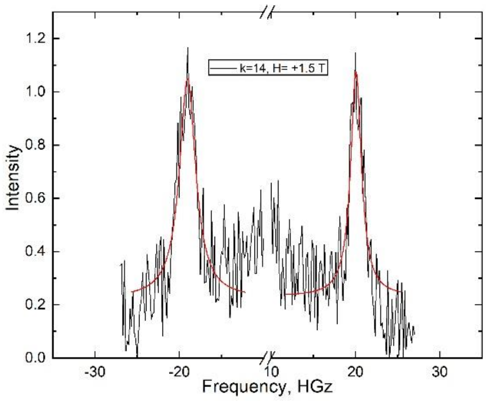

Fig.1. Example of BLS spectra (sample of 1 min oxidation).

As a result, the trend of the DMI sign changing with increasing oxidation time of the ferromagnetic layer was shown in the dependence (Fig. 2).

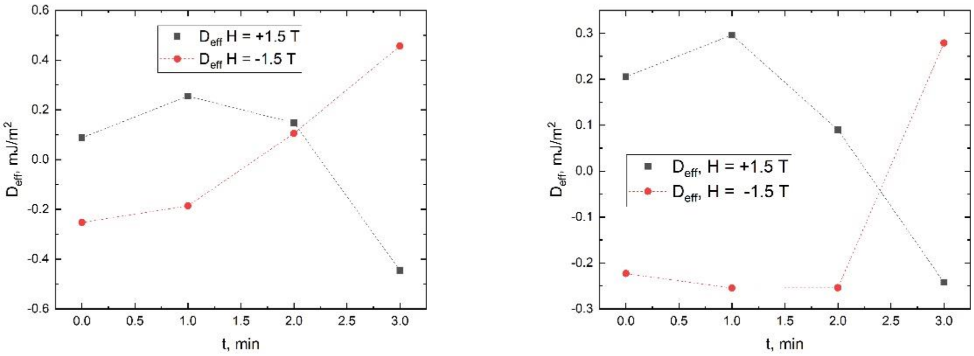

Fig.2. Dependences D_{eff} to oxidation time for k=7, k=14

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CHANGE OF MAGNETIC DOMINANCE TYPE IN THE FERRIMAGNETIC SYSTEM Pt/CoGd/W

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Ferrimagnetic films of the composition Pt(40)/[Co46Gd54](40)/W(x)/Pt(y) grown by magnetron sputtering in ultra-high vacuum on the surface of oxidized silicon substrates were studied. The ferrimagnetic alloy CoGd has unique properties that are characteristic of both ferromagnets and antiferromagnets. Due to the deposition technology, it is possible to control the concentration of elements, which makes it possible to obtain samples with different types of dominance such as Co-rich and Gd-rich, as well as samples in a state of compensation.

It is known about the temperature dependences of the magnetization of the sublattices of such an artificial ferrimagnet. When, with increasing temperature, a change in the contributions of the sublattices is observed, which as a result affects the behavior of the ferrimagnet. However, in this system, the effect of an irreversible change in the type of dominance was discovered, which is probably associated with the redistribution of ions inside the ferrimagnet.

This study shows the temperature dependence of this effect. Local areas with the opposite type of dominance were also obtained, created by local heating of the ferrimagnetic film using plasma etching.

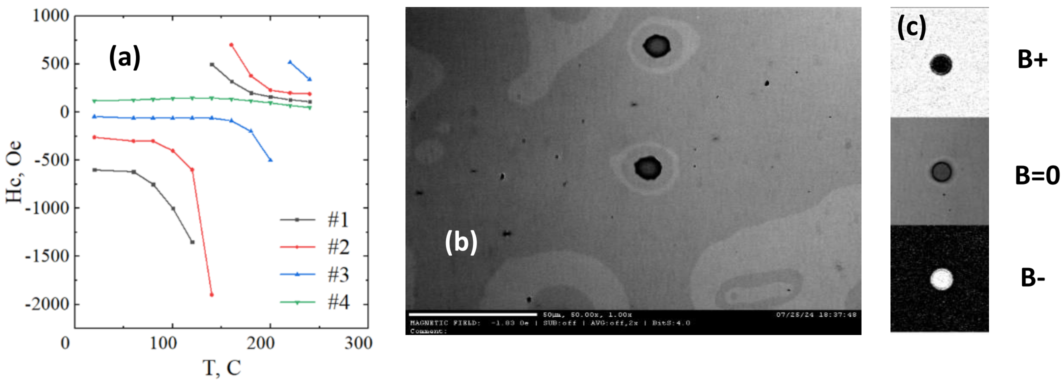

Fig. 1. – (a) temperature dependence of the coercive force, the sign of the coercive force characterizes the type of dominance (minus it is Co-rich); (b) Kerr images with local areas with inverted dominance type; (c) also Kerr images of the local inverse region taken with subtraction.

This work was supported by the Russian Ministry of Science and Higher Education for the state task, Project No. FZNS-2023-0012.

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BRAGG RESONANCES IN COUPLED MAGNON CRYSTALS WITH DIFFERENT PERIODS

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The propagation of spin waves in magnon crystals (MCs), ferromagnetic films with periodically changing parameters, has been actively studied in the problems of modern magnonics [1]. In the present paper, we investigate a structure consisting of two coupled MCs separated by a dielectric interspace. The layered structure is placed in an external magnetic field directed tangentially to the plane of the structure, so that magnetostatic surface waves (MSSW) will propagate in the structure. The purpose of this work is to investigate the formation of band gaps in the propagation of magnetostatic waves in the structure of coupled MCs with different geometrical and magnetic parameters.

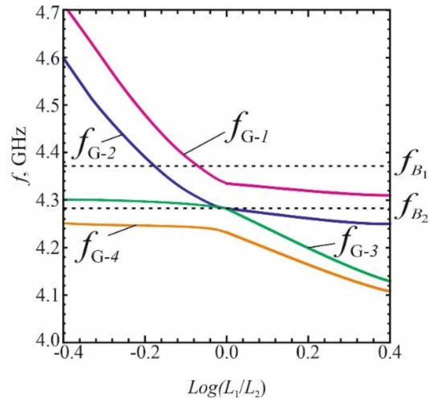

Fig. 1. Dependence of the central frequencies of the band gaps.

The feature of the considered coupled structure, in comparison with a single MC, is the propagation at the same frequency of two normal waves-symmetric and antisymmetric MSSW [2], the difference between the phase velocities of which is determined by the electrodynamic coupling parameter. In contrast to the structure consisting of two MCs with the same periods [3], we show that the formation of several band gaps in the first Bragg resonance region takes place.

Fig. 1 shows the dependence of the central frequencies of band gaps G − 1, G − 2, G − 3, G − 4 on the ratio of periods L_1/L_2 at $L_2=200\ \mu m$, L_1 is varying. Fig. 1 shows that an increase in $Log(L_1/L_2)$ from -∞ to 0 leads to a downward shift of the frequencies of the G-1 and G-2, while the positions of the G-3 and G-4 practically do not change. Fig. 1 also shows that as $Log(L_1/L_2)$ increases from 0 to +∞, the opposite case occurs: G-3 and G-4 shift down in frequency, while the position of the G-1 and G-2 remains almost unchanged.

Thus, it is shown that the use of such coupled layered structures extends the functionality of magnon crystal-based devices, which can be used in microwave electronics as tunable microwave filters, phase shifters, and delay lines.

This work was supported by the Russian Science Foundation (project № 23-79-30027).

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INFLUENCE OF SPIN HALL EFFECT IN THE LAYERED STRUCTURE OF MAGNON CRYSTAL/NORMAL METAL/MAGNON CRYSTAL

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At this stage of electronics development, the transition from classical electronics to quantum electronics is an actual task. One of the most popular branches of quantum electronics is magnonics [1], which studies the propagation of spin waves in magnetic materials. Spintronics has also been gaining popularity recently [2]; unlike conventional electronics and magnonics, in spintronics the transfer of information takes place using a spin current [3].

In this paper, we consider a layered structure consisting of magnon crystals (MC-1 and MC-2) separated by a layer of normal metal (e.g., platinum) (Fig. 1a). The magnon crystals are ferromagnetic films with periods and thicknesses. The structure is placed in an external magnetic field oriented tangentially to the plane of the structure, with a spin wave propagating in MC-1 and MC-2 along the y-axis.

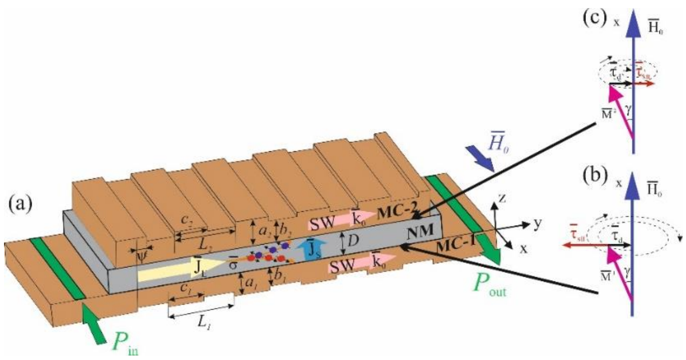

Fig. 1. (a) Scheme of the investigated structure MC-1/NM/MC-2. Scheme of the magnetization vector precession in (a) MC-1, (c) MC-2.

When a voltage is applied to the normal metal layer, an electric current of density $\boldsymbol{J_c}$ flows in it. Due to the spin Hall effect, electrons with opposite directions of spins move in two directions: with one direction of spins to the boundary of NM|MC-1 (Fig. 1b), and with the other direction of spins to the boundary of NM|MC-2 (Fig. 1c), as a result a spin current with a density $\boldsymbol{J}_s$ in the direction of the z-axis flows. As a consequence, due to the transfer of spin torque at the layer boundaries, there is an increasing spin wave in one MC (if the spins in the NM are oppositely directed with respect to the magnetic moments in the MC) (Fig. 1b) and a decreasing spin wave in the other MC (spins in the NM are co-directed with the magnetic moments in the MC) (Fig. 1c).

This features make it possible to control the power of the signal delivered to one or another port of the coupled structure using the spin current in the active layer. The purpose of this work is to investigate the effect of spin current in the normal metal on band gap formation and on power redistribution between MCs output ports.

This work was supported by the Russian Science Foundation (project № 23-29-00759).

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PROPAGATION OF SPIN WAVES IN A FERRITE FILM WITH A PERIODIC SEMICONDUCTOR ARRAY OF STRIPES ON TOP OF THE SURFACE

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The interest of recent years in semiconductor/ferromagnetic structures is due to the development of new methods for creating structured ferromagnetic films on semiconductor substrates [1]. Of particular interest are bilayer heterostructures consisting of iron-ittrivium garnet films grown on gallium arsenide substrate [2]. Optically injected free charge carriers in the GaAs semiconductor layer allow controlling the dispersion characteristics of spin waves propagating in the YIG film [3].

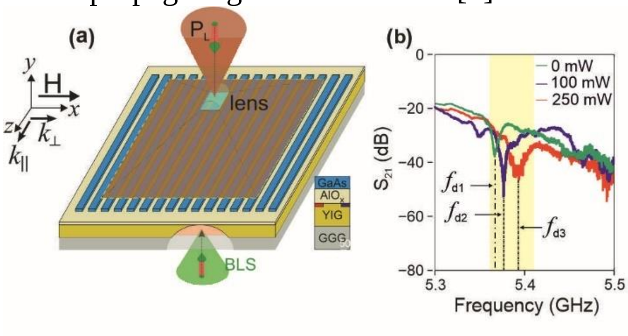

Fig.1. (a) Schematic representation of the investigated structure. (b) Amplitude-frequency characteristic of SP at different laser irradiation power P_L.

A schematic representation of the investigated structure is shown in Fig. 1a. GaAs strips are deposited parallel to each other on the YIG layer through an AlOx buffer layer. The AlOx buffer layer used during the fabrication of the structure is necessary for the compatibility of different crystal structures of LIG and GaAs [2]. Fig.1b shows the amplitude-frequency characteristics of the CB propagating in the YIG film under varying laser power directed at the GaAs strip array. Experimental and numerical calculations show that by changing the direction of the magnetic field, the efficiency of nonreciprocal propagation of CB in the coupled structure with a metallic layer above it can be increased. Thus, the effect of effective nonreciprocal propagation of CB in a coupled system with an overlying metallic layer arises. In such a system, a simple method to control the nonreciprocal propagation of spin waves using geometry and equilibrium configuration can be realised.

This work was supported by the Ministry of Education and Science of Russia (Project #FSRR-2023-0008).

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CONTROLLED MODES OF PROPAGATION OF A SPIN-WAVE SIGNAL IN LATERAL GIGAMODES WITH AN ORTHOGONAL ELEMENT

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In this article, we investigate the effect of the laser-controlled magnitude of the dipole coupling to realize the transfer of a spin-wave signal in the lateral and vertical directions in a system of orthogonal micro-waveguides. The paper shows the possibility of creating a signal divider and a logic gate with a controlled delay of the output signal.

The transfer of the magnetic moment or spin of an electron instead of charge transfer opens up new possibilities for using spin-wave quanta - magnons - to develop methods and approaches for processing, transmitting and storing signals encoded as the amplitude and phase of spin waves (SW) in the microwave and terahertz range. At the same time, the lengths of the excited SW range from hundreds of microns to tens of nanometers and can change under the influence of various factors: the magnitude and direction of the magnetization field, by varying the type and magnitude of the anisotropy of the magnetic material, by irradiating the surface of magnetic films with focused laser radiation.

In this paper, the modes of propagation of spin waves in arrays of micro-waveguides formed by two layers of gigs were investigated. The mechanisms leading to the formation of various "patterns" formed by a spin-wave signal during its propagation in a system of longitudinally irregular thin-film magnetic microwaves located in each layer of the structure are investigated..

Micromagnetic modeling [1] was carried out for a system of laterally and vertically coupled ferrite microwaves (Fig. 1) [2-3] from an iron-yttrium garnet film located on a substrate of gallium gadolinium garnet (GGG). The microwave guides are made in the form of elongated strips, L = 6 mm long, b = 300 microns wide and c = 10 microns thick, forming a structure that consists of two waveguides located with gaps in the horizontal plane and one waveguide located perpendicular above them. The saturation magnetization of the JIG was 139 Gs, and the magnitude of the external magnetic field directed along the y axis was 1200 Oe. The numerical study was carried out at a frequency of 5.2 GHz. This magnetization configuration provided effective excitation of surface spin waves. Coupled ferrite structures expand the functional capabilities of microwave devices due to an additional control parameter - the connection between microwave waves propagating in individual ferromagnetic films.

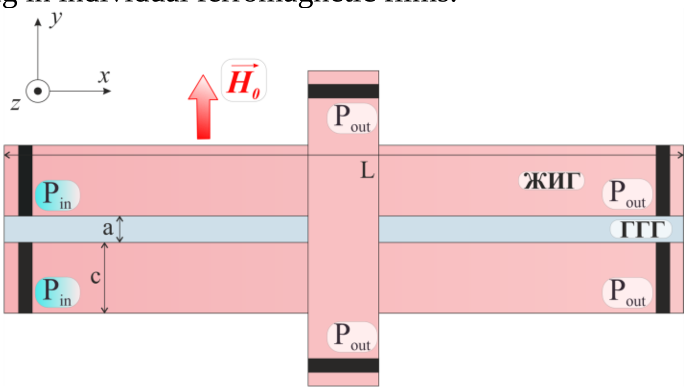

Fig. 1. Schematic representation of the lattice of micro-waveguides. The following designations are introduced in the figure: a – horizontal gap; c – width; L – length of microwave diodes; Pin and Pout – microstrip antennas for excitation and reception of microwave, respectively.

In the course of the work, a study was carried out on the dual control of the characteristics of CB in the lattice of gigamodes when implementing simultaneously lateral and vertical communication types.

The study of the features of the processes of formation of spin wave beams for the structure of coupled magnetic waveguides has been carried out.

The propagation features and mechanisms of changing the spatial distribution of the spin-wave beam profile are revealed with the combined manifestation of the effects of anisotropic signal propagation, dipole coupling and nonlinear dependence of medium parameters on power.

This work was supported by RNF (#20-79-10191).

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CONTROL OF THE GAIN BANDWIDTH FOR THE MICROWAVE SIGNALS IN A SPIN TRANSFER NANOSCILLATOR USING AN EXTERNAL MAGNETIC FIELD

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Magnetic tunnel junctions (MTJs) are the promising candidates for the building blocks of the spintronic devices [1]. Based on the excitation of microwave generation when a spin-polarized current is passed through the MTJ, it is proposed to design amplifiers, magnetic field sensors and neuromorphic circuits [1-3]. The Investigation of the methods for controlling the amplification properties in such spintronic amplifiers is of scientific and practical interest [2]. This work introduces a theory describing the effect of an external magnetic field on the gain bandwidth $\Delta\Omega$ for microwave signals.

The description of the dynamics of magnetization in the studied structure (see Fig.1) is possible using the method of Hamiltonian formalism [3]. The analysis of the equation for complex amplitude c characterizing the amplitude of the magnetization precession leads to the following expression for the gain bandwidth

$$\Delta\Omega = \sqrt{1 + \left(\frac{N}{G_+ - G_-}\right)^2}\,\frac{F_j}{\sqrt{p_0}},$$

where $N = N(H_0, \theta_0)$ – coefficient of the nonisochronicity, G_+, G_- – the coefficients of positive and negative losses respectively, F_j - the normalized amplitude of oscillations of the input microwave current density, p_0 – self-oscillation power. Since nonisochronicity coefficient depends on the polar angle Θ_0 of the external magnetic field it is possible to control the gain bandwidth when adjusting the external magnetic field orientation. In this work, an expression for N is obtained taking into account the perpendicular magnetic anisotropy.

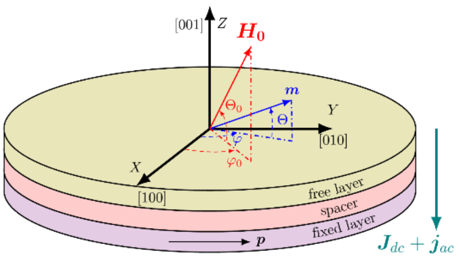

Fig.1. The scheme of the investigated MTJ structure.

The work was carried out within the framework of the state assignment of the Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences (FFWZ-2022-0015).

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SPIN WAVES DEMULTIPLEXING USING SPIN CURRENT

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Nowadays, spin waves propagating in ferromagnetic films attract much attention of researchers due to the possibility of their use in magnonic devices [1-3]. Magnonic devices such as directional couplers, microwave filters, Fabry-Perot resonators, circulators for signal coupling and multiplexing, logic gates, half-adders, and majority gates have been proposed. In this work, a layered structure of the ferromagnetic film/normal metal/magnonic crystal is proposed to realize the demultiplexing function [4,5].

At this report the theoretical model describing the propagation of spin waves in the structure of ferromagnetic film/normal metal/magnonic crystal is constructed. The dispersion relation and wave equations for direct and reflected spin waves in the studied structure are obtained. In such a structure, there is the formation of four forbidden gaps – bands of non-transmission of spin waves. It is shown that the structure allows the function of demultiplexing spin-wave signals - depending on the frequency, the signal exits through different ports of the structure (through the ferromagnetic film/normal metal/magnonic crystal or through the magnonic crystal). It has been established that spin current in such a structure makes it possible to effectively control the frequency branch of channels. The effect of spin current on the signal branch at the band gap frequencies significantly prevails over the effect of spin current at frequencies outside the band gap. It is shown that with a current of positive polarity at the band gap frequencies, the proportion of power output through the ferromagnetic film increases, i.e., the operating attenuation decreases. With a current of negative polarity at the band gap frequencies, the proportion of power output through the ferromagnetic film decreases, i.e. the operating attenuation increases. At the same time, the proportion of power coming out through the magnonic crystal, i.e. transient attenuation and decoupling, changes slightly with a change in the magnitude and polarity of the spin current. Thus, spin current allows you to control exclusively the working attenuation of this coupler, practically without affecting the transient attenuation and decoupling.

The described effect makes it possible to consider the ferromagnetic film/normal metal/magnonic crystal structure as a basic element for frequency demultiplexing of microwave signals with magnetic and electric control.

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ИССЛЕДОВАНИЕ ЯВЛЕНИЯ ГИБРИДИЗАЦИИ МОД В ГЕТЕРОСТРУКТУРЕ АНТИФЕРРОМАГНЕТИК/ФЕРРОМАГНЕТИК

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В данной работе исследуется взаимодействие между собой спиновых возбуждений в ферромагнитном (ФМ) и антиферромагнитном (АФМ) слоях гетероструктуры. Гетероструктура представляет собой расположенный на подложке из ниобата лития $LiNbO_3$ слой оксида никеля NiO толщиной 101 нм, на который нанесён слой пермаллоя NiFe толщиной 10,5 нм. Оба материала были нанесены методом реактивного магнетронного распыления. Взаимодействие спиновых возбуждений в этих слоях, а именно низкочастотной моды колебаний в слое оксида никеля и ферромагнитной моды колебаний в слое пермаллоя приводит к гибридизации мод, что было экспериментально исследовано методом Мандельштам-Бриллюэновской спектроскопии. Гибридизация мод возникает из-за взаимного влияния магнитных подрешёток АФМ и магнитной решётки ФМ, связанных обменным взаимодействием на границе между слоями [1]. Аналитическое описание явления гибридизации мод основано на методе Гамильтонова формализма [2], в котором Гамильтониан плотности магнитной энергии, выражается в виде:

$$\mathcal{H} = -\gamma\mathbf{H}(\mathbf{M_1}+\mathbf{M_2}+\mathbf{M_{FM}}) + 2\pi\gamma(\mathbf{M_{FM}}\mathbf{z})^2 + \frac{\gamma K_h}{M_s^2}[(\mathbf{M_1}\mathbf{z})^2 + (\mathbf{M_2}\mathbf{z})^2] - \frac{\gamma K_e}{M_s^2}[(\mathbf{M_1}\mathbf{y})^2 + (\mathbf{M_2}\mathbf{y})^2] + \gamma\Lambda\mathbf{M_1}\mathbf{M_2} + \gamma\Lambda_c(\mathbf{M_1}+\mathbf{M_2})\mathbf{M_{FM}}, \quad (1)$$

где γ — гиромагнитное отношение, **H** — внешнее магнитное поле, M_s — намагниченность насыщения АФМ, $K_{h,e}$ — константы кристаллографической анизотропии АФМ трудной и лёгкой оси, соответственно, Λ — константа обменного взаимодействия между подрешётками АФМ, Λ_c — константа обменного взаимодействия между АФМ и ФМ слоями.

Работа выполнена в рамках государственного задания Министерства науки и высшего образования Российской Федерации (тема No FFWZ-2022-0015) и при финансовой поддержке Российского научного фонда (грант 20-79-10191).

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DYNAMICS OF COUPLED ANTIFERROMAGNETIC OSCILLATORS

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An antiferromagnetic (AFM) oscillator is a two-layer heterostructure of a nonmagnetic metal (NM) and an antiferromagnet. A constant electric current flows through a NM layer, that leads to the rotation of magnetizations in the AFM, which, in turn, results in the flowing of an alternating electric current through the NM layer. This alternating current is the output terahertz signal of the antiferromagnetic oscillator. Understanding the dynamics of AFM oscillators is important for the implementation of communication and computing devices operating in the THz frequency range. Due to the low power of a single AFM oscillator, it is also necessary to study the dynamics of coupled antiferromagnets, and in particular, their synchronization. To describe the dynamics of 10 coupled through a common NM layer AFM oscillators, we use the pendulum model [1, 2]

$$\ddot{\varphi}_k + \alpha\omega_{\mathrm{ex}}\dot{\varphi}_k + \frac{\omega_{\mathrm{e}}\omega_{\mathrm{ex}}}{2} sin2\varphi_k = \sigma j_{\mathrm{DC}_k}\omega_{\mathrm{ex}} - \kappa\omega_{\mathrm{ex}}\sum \dot{\varphi}_{k'}, \quad (1)$$

where $\omega_{\mathrm{ex}} = 2\pi \cdot 27.5\mathrm{rad}\cdot\mathrm{THz}$ is a frequency of the exchange field, $\omega_{\mathrm{e}} = 2\pi \cdot 1.75\mathrm{rad}\cdot\mathrm{GHz}$ is the anisotropy field frequency, the damping $\alpha = 9.57 \cdot 10^{-3}$, $\sigma = 2\pi \cdot 4.32\,\mathrm{rad}\cdot\mathrm{Hz}\cdot\mathrm{cm}^2/\mathrm{A}$ is a spin-transfer coefficient, j_{DC_k} is the electric current, flowing through the k-th AFM oscillator, $\kappa = 5.78 \cdot 10^{-4}$ is a coupling coefficient. Fig. 1 demonstrates the modeling results of the system (1) for different j_{DC_k}. Here there is no synchronization for $\kappa = 0$ and for non-zero coupling coefficient with $j_{\mathrm{DC}_k} \in [5{,}5.2] \cdot 10^8\,\mathrm{A/cm^2}$. However, for $j_{\mathrm{DC}_k} \in [5{,}5.05] \cdot 10^8\,\mathrm{A/cm^2}$ there is a synchronization. One can also find an order parameter [2]

$$r(t) = \frac{1}{N}\left|\sum exp\,[i\varphi_k(t)]\right|, \quad (2)$$

that quantifies the phase synchronization of the system. The closer the order parameter to 1, the better the synchronization. For aforementioned cases, the time average of (2) are 0.2, 0.3 and 0.99.

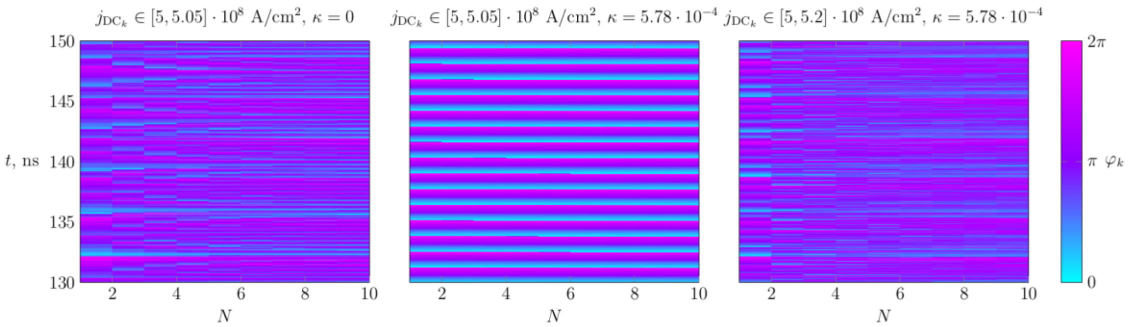

Fig.1. Phase dynamics of 10 coupled through a common NM layer AFMs.

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БРЭГОВСКИЕ РЕЗОНАНСЫ В МУЛЬТИФЕРРОИДНОЙ СТРУКТУРЕ YIG/HZO

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Одна из альтернативных концепций по преодолению ограничений, накладываемых стандартной КМОП электроникой, лежит в области магноники, основной принцип который заключается в использовании спиновых волн или магнонов вместо электронов в качестве носителей информации [1]. Однако, наиболее перспективным является использование мультиферроидных материалов, свойствами спиновых волн в которых можно управлять не только с помощью магнитного, но и электрического поля [2]. Одним из наиболее широко распространенных материалов, в котором возможно распространение спиновых волн, является ферромагнитная пленка железо-иттриевого граната (YIG) [1], и одним из перспективных сегнетоэлектрических материалов в настоящее время является оксидный сегнетоэлектрик на основе оксида гафния [3].

В работе выявлены гистерезис и перестройка частоты запрещенных зон (полос непропускания в спектре спиновых волн) в многослойной структуре YIG/TiN/HZO/TiN (железо-иттриевый гранат гранат/нитрид титана/оксид гафния-циркония/нитрид титана, 100 нм/20 нм/10 нм/20 нм) с периодической модуляцией толщины. Данная структура создана с использованием жидкофазной эпитаксии пленки YIG и атомно-слоевого осаждения пленок TiN и HZO, что позволяет эффективно комбинировать слои и позволяет сохранить ферромагнитные и сегнетоэлектрические свойства каждого слоя. Полученная структура демонстрирует взаимодействие магнитной и сегнетоэлектрической подсистем. Разработанная технология создания канавок на поверхности делает такую конструкцию брэгговской отражающей решеткой.

В работе показано, что слой HZO в составе многослойной структуры демонстрирует свойство гистерезиса, двухуровневое состояние и эффект пробуждения. В слое YIG было обнаружено распространение спиновых волн. В полосе возбуждения спиновых волн наблюдается брэгговская запрещенная зона. Положение запрещенной зоны зависит от напряжения (поляризация HZO); при изменении напряжения происходит перестройка частоты; направление сдвига запрещенной зоны в электрическом поле изменялось при коэрцитивном напряжении. Зависимость частоты зоны от напряжения имела тип “бабочка”.

Практическая значимость результата заключается в том, что гистерезисная зависимость положения запрещенной зоны спиновых волн от поляризации сегнетоэлектрика позволяет использовать такую структуру в качестве ячейки памяти.

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ВЛИЯНИЕ ЛОКАЛЬНОЙ ТЕПЛОВОЙ НЕОДНОРОДНОСТИ НА СПИНОВУЮ НАКАЧКУ В СТРУКТУРЕ ЖИГ/Pt

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С помощью обратного спинового эффекта Холла исследовано влияние локальной тепловой неоднородности на спиновую накачку бегущими поверхностными магнитостатическими волнами (ПМСВ) в микроструктурах ЖИГ/Pt. Для проведения экспериментов использовалась эпитаксиальная пленка железо-иттриевого граната (ЖИГ) толщиной 42 мкм, намагниченностью насыщения $4\pi M_0$=1750 Гс и ΔH=0.6 Э. На поверхности пленки ЖИГ методами магнетронного распыления, фотолитографии и ионного травления изготавливались медные микроантенны (МА) для возбуждения и приема ПМСВ, а также Pt микрополоски длиной 190 и 230 мкм, шириной 2.8 мкм, расположенные на расстоянии 2 мкм друг от друга между антеннами. Расстояние между Pt микрополосками и антеннами составляло 13 мкм. Изготовленная структура помещалась между полюсами электромагнита таким образом, что внешнее магнитное поле H=939 Э было направлено касательно к поверхности параллельно МА (геометрия возбуждения ПМСВ) и перпендикулярно Pt микрополоскам. К МА с помощью СВЧ-зондов подключался векторный анализатор цепей, который также выступал в качестве источника СВЧ сигнала. Измерения ЭДС проводились с помощью селективного вольтметра, который подключался к одной из Pt микрополосок (детектирующей), в режиме импульсной модуляции меандром с частотой 11.33 КГц. Для создания эффекта локального нагрева, через другую Pt микрополоску (инжектирующую) пропускался постоянный ток I=0÷900 мкА.

В эксперименте, частотная зависимость ЭДС U(f), обусловленная спиновой накачкой бегущими ПМСВ из ЖИГ в Pt, характеризовалась двумя пиками вблизи длинноволновой (f_0) и коротковолновой (f_s) границ спектра ПМСВ. Такая зависимость соответствовала распределению плотности состояний в спектре ПМСВ η(f) [1], характеризующемуся сингулярностями вблизи границ f_0 и f_s [2]. При протекании тока I=900 мкА через инжектирующую Pt микрополоску наблюдался сдвиг зависимости U(f) вниз по частоте на величину ≈15 МГц и уменьшение амплитуды длинноволнового пика ЭДС в ≈2.5 раза. Такое поведение ЭДС может быть связано с неоднородным локальным нагревом пленки ЖИГ, возникающим при протекании постоянного тока через инжектирующую Pt микрополоску. Локальный нагрев приводит к снижению намагниченности и смещению вниз по частоте спектра ПМСВ, распространяющейся в пленке ЖИГ непосредственно вблизи детектирующей Pt микрополоски, относительно спектра ПМСВ в области пленки ЖИГ под возбуждающей МА. Это приводит к тому, что плотность состояний магнонов, на которых могут рассеиваться электроны платины, снижается, что в свою очередь приводит к ослаблению процессов электрон-магнонного рассеяния и уменьшению амплитуды длинноволнового пика ЭДС.

В том случае, когда I=0, намагниченность в областях пленки ЖИГ вблизи детектирующей Pt микрополоски и под МА одинаковая, и спектр ПМСВ по мере ее распространения в пленке ЖИГ не меняется. Таким образом, плотность состояний магнонов в спектре ПМСВ и эффективность процессов электрон-магнонного рассеяния не уменьшаются.

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ULTRAFAST MAGNETO-OPTICAL PHENOMENA IN MAGNETIC SEMICONDUCTORS EuX (X = Te, Se, O)

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Ultrafast phenomena related to the control and manipulation of electronic and spin states are in the focus of modern research in the field of physics of magnetism, magnonics and spintronics. This activity is motivated by new experiments on ultrafast magnetic phenomena, revealing new fundamentally important mechanisms of electronic, spin and orbital dynamics occurring on femto- and picosecond time scales. On the other hand, the new results open up potential opportunities for the creation of high-speed magnetoelectronic and magneto-optical devices. In this report**,** the hierarchy of time for various physical processes will be considered – from the fastest nonlinear coherent processes to the slower ones associated with the dynamics of magnetization.

Europium chalcogenides EuX (X = Te, Se, O) possess unique physical properties determined by the electronic structure (see Fig. 1). Spectroscopy of the centrosymmetric magnetic semiconductors EuTe and EuSe reveals spin-induced optical second harmonic generation in the band gap vicinity at 2.1–2.4 eV [1]. The second harmonic arises due to a nonlinear optical susceptibility caused by the magnetic dipole contribution combined with induced magnetization. Application of external magnetic field up to 6 T results in crossover from the inverse Faraday effect taking place on the femtosecond time scale to the optical orientation phenomenon with an evolution in the picosecond time domain in EuTe near the absorption band gap [1]. The pump-probe technique demonstrates the femtosecond optical orientation as a triggering mechanism of magnetization precession in EuO-based ferromagnets (see Fig. 1) [2].

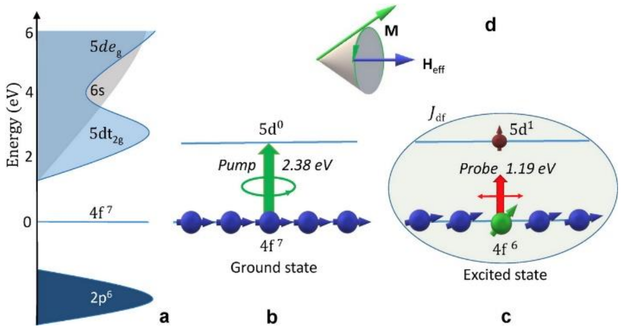

Fig.1. (a) E-k energy band diagram; (b) optical excitation of $4f^75d^0 \rightarrow 4f^65d^1$ electronic transition; (c) two-color pump-probe technique for magnetization precession measurements; (d) optically induced magnetization precession in EuO [2].

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MAGNETIC EXCITATIONS AND MAGNON-PHONON INTERACTION IN THE ANTIFERROMAGNETIC CoF_2

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Antiferromagnetic CoF_2 with a tetragonal crystal structure (space group $P4_2/mnm$, $Z = 2$) attracts a lot of attention during several decades due to its ground state $3d^7$ ($S = 3/2$) that is split by the strong spin-orbit interaction, see, e.g. recent publication [1,2] and Refs. therein. In this talk, we report results on magnetic and phonon excitations and interaction between them. Results were obtained using a high-resolution infrared Fourier spectrometer on oriented single crystals of CoF_2. The study was performed in the spectral range 30–650 cm^{-1} and in the temperature range from 5 to 650 K below and above the Neel temperature $T_N = 39$ K.

Low temperature data at $T = 5$ K are shown in Fig. 1 for the two main polarizations, $E||a$ and $E||c$, of the transmitted (T) and reflected (R) light. The both spectra are highly polarized and this allows the reliable distinguishing between magnonic and phononic excitations. One (M) and two (2M) magnon excitations are observed in transmitted light for $E||c$. Besides these collective magnetic modes, another mode M_{ex} is observed at the wave number 209 cm^{-1} which can be attributed to single ion transition between the ground and the first spin-orbital state of the multiplet.

Below T_N we observed significant phonon-magnon coupling between magnons and phonons, predominantly when quadratic coupling contribution attains substantial magnitude, in particular for the A_{1g} mode and to a lesser degree for the B_{2g} mode.

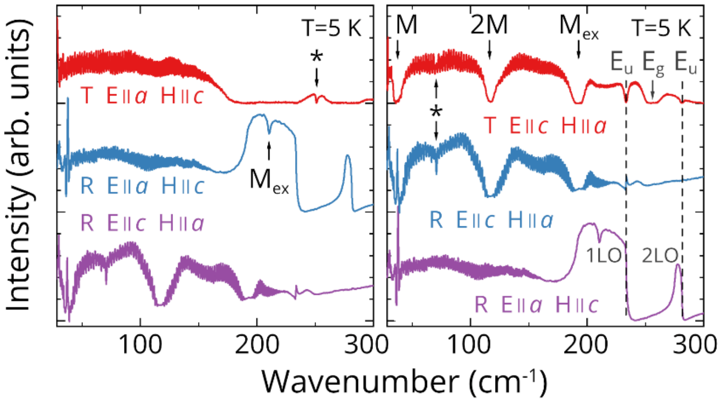

Fig. 1. Transmission (T) and reflection (R) spectra of CoF_2 at $T = 5$ K for the light polarizations $E||a$ and $E||c$. M, 2M and M_{ex} mark magnetic excitations.

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ПОДАВЛЕНИЕ ОБМЕННЫХ СПИНОВЫХ ВОЛН В ПЛЕНКЕ С ЧАСТИЧНЫМ МАГНИТНЫМ ПОКРЫТИЕМ

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В настоящее время использование устройств терагерцевого диапазона в магнонике представляется недалекой перспективой [1]. Магноны с высокими энергиями, принадлежащие обменному диапазону длин волн (ОСВ), могут быть получены, например, при антиферромагнитных колебаниях. В этой связи актуализируются исследования в области управления сигналами, передаваемыми с помощью обменных спиновых волн.

Ранее в [1] были описаны основные магнонные логические модули, в которых управляющий элемент в виде магнитной полоски ориентирован перпендикулярно волноводу. Киральная связь между СВ, распространяющимися в обменно- или дипольносвязанных пленках или антеннах может быть использована для управления амплитудами и сдвигом фазы СВ в киральных магнонных резонаторах [2].

При описании волновых процессов при распространении СВ существенна их киральность, определяющая направление прецессии намагниченности. Как следует из уравнения динамики изолированного магнитного момента, оно однозначно определяется внешним магнитным полем. Обменное взаимодействие может изменить знак эффективного поля, и прецессия станет антиларморовской с мнимым волновым числом, а соответствующая СВ - эванесцентной.

Рассматривается структура, состоящая из пленки с магнитным покрытием с управляемой равновесной намагниченностью, разделенные тонкой немагнитной прослойкой. Характер межслойного обменного взаимодействия может быть как ферромагнитным, так и антиферромагнитным в зависимости от толщины прослойки. Экспериментальные исследования с такими структурами показывают существенную разницу в амплитудах волн, проходящих через область с магнитным покрытием [3]. Следовательно – подобная структура может быть использована в качестве магнонного вентиля [1].

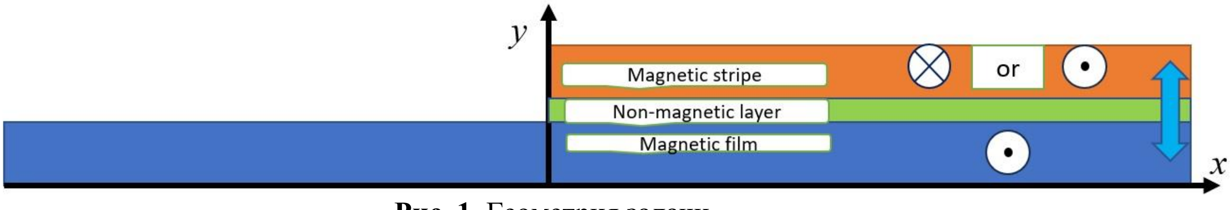

Рис. 1. Геометрия задачи.

Наблюдаемое различие в амплитудах можно объяснить антиларморовским характером прецессии намагниченности в пленке. Следует отметить, что эти результаты остаются справедливыми и в случае более длинных обменнодипольных волн.

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STRUCTURE IMPLICATIONS ON MAGNET CHARACTERISTICS OF Pt/Co/MgO and WTe2/Pt/Co/MgO FILMS

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In our work, we investigated the influence of the structure of Pt/Co/MgO and WTe_2/Pt/Co/MgO thin films on the magnetic properties. The objects of the study were two series of samples in which the platinum thickness was varied: SiO_2/Pt(2-10 nm)/Co(0.9 nm)/MgO(2 nm)/SiO2(4 nm) and SiO_2/WTe2(7 nm)/Pt(0-10 nm)/Co(0.9 nm)/MgO(2 nm)/SiO_2(4 nm) obtained by magnetron sputtering on SiO_2 substrate. The magnetic parameters were investigated based on magnetic hysteresis loops using a vibromagnetometer (7410 VSM, LakeShore) in the directions of the external magnetic field in and out of the plane of the film. The thickness values of the film layers were recorded using a quartz thickness meter during sputtering and further refined after structure formation by X-ray reflectometry using a Colibri X-ray diffractometer. As a result, the roughness of the interfaces and the material density were determined.

Comprehensive studies of the structure and basic magnetic properties of the films have been carried out. The dependences of the investigated parameters on the thickness of the platinum sublayer were plotted. It was found that the density of the platinum film can vary up to 25% of the bulk density, which may be the result of structural relaxation of the layer. All films of Pt/Co/MgO and WTe_2/Pt/Co/MgO composition show perpendicular magnetic anisotropy, the magnitude of which strongly depends on the thickness of the platinum sublayer. Films grown on the telluride layer exhibit half the coercivity compared to films without tungsten telluride. In both cases, the coercivity increases by an order of magnitude with increasing platinum thickness up to 10 nm.

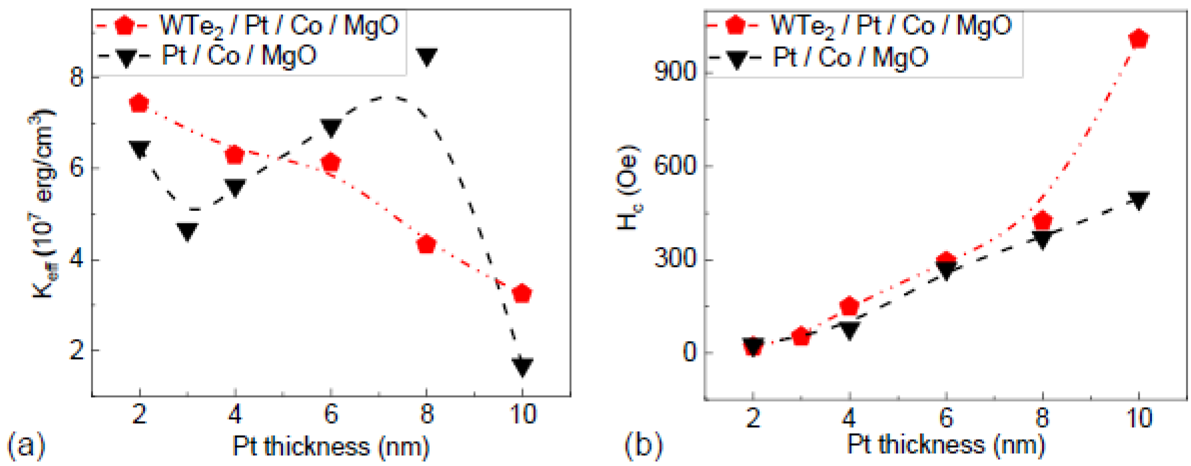

Fig. 1. Dependence of effective anisotropy (a) and coercivity (b) on Pt layer thickness for Pt/Co/MgO and WTe_2/Pt/Co/MgO systems

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ИЗМЕРЕНИЕ СПИНВОЛНОВОЙ ДИНАМИКИ В ГЕЛИКОИДАЛЬНЫХ МАГНЕТИКАХ МЕТОДОМ МАЛОУГЛОВОГО РАССЕЯНИЯ НЕЙТРОНОВ

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Соединения $Fe_{1-x}Co_xSi$ и $Mn_{1-x}Fe_xSi$ являются твердыми растворами с кристаллической структурой B20. Эти соединения магнитно упорядочивается ниже T_C в спиновую спиральную структуру с малым вектором распространения k [1,2]. По аналогии с магнитной структурой MnSi и FeGe спиновая спираль индуцируется антисимметричным обменным взаимодействием Дзялошинского-Мория (ДМ), обусловленным отсутствием центра симметрии в расположении магнитных атомов железа и кобальта (модель Бака-Йенсена) [3]. Согласно этой модели спиральный порядок стабилизируется за счёт обычного обменного взаимодействия и взаимодействия Дзялошинского-Мория при этом волновой вектор определяется как $k = SD/A$, где A — жёсткость спиновых волн, D — коэффициент взаимодействия Дзялошинского-Мория. С приложением магнитного пол формируется однодоменная коническая структура, которая остается стабильной вплоть до критического поля H_{c2}, когда происходит переход из конического состояния в ферромагнитное, при этом $g\mu_B H_{c2} = Ak^2$ [4].

Методом малоуглового рассеяния поляризованных нейтронов нами были экспериментально измерены такие параметры магнитной системы как волновой вектор спирали k, критическое поле Hc_2 , и жесткость спиновых волн в широком температурном диапазоне в соединениях $Mn_{1-x}Fe_xSi$ с x =0.0, 0.03, 0.06, 0.09 [5,6], $Fe_{1-x}Co_xSi$ с x = 0.25, 0.30, 0.50 [7], и соединении Cu_2OSeO_3 [8]. Эксперименты показали, что модель Бака-Йенсена на количественном уровне хорошо описывает характерные параметры системы во всем температурном диапазоне от 0 до критической температуры T_C.

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INVESTIGATION OF SPIN WAVE DISPERSION IN MULTILAYER FERROMAGNETIC STRUCTURES WITH PERIODIC METALLIC SCREEN

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This study investigates the influence of the configuration of multilayer ferromagnetic films on the behavior of spin waves. The focus of the research is on creating magnonic crystals (MC) with the ability to effectively control and manipulate the flow of spin waves (SW) over a wide frequency range[1, 2].

The investigated structure consists of a bilayer ferromagnetic film with a periodic copper overlay. The films have different thicknesses d_2=9μm, d_1=7μm with different saturation magnetizations M_1=904Gs, M_2=1738Gs, enabling the study of various modes of spin wave propagation. The waveguide was placed in a uniform external magnetic field H_0=670Oe oriented perpendicular to the propagation of SW in the waveguide plane for effective excitation of surface magnetostatic waves (SMSW)[3]. For numerical modeling and calculations, the highly efficient tool of full-wave modeling, the High-Frequency Structure Simulator (HFSS), is used. HFSS solves Maxwell's equations based on the Polder permeability tensor and applies the finite element method (FEM) to solve three-dimensional and two-dimensional electrodynamics problems[4].

Based on the results of numerical modeling, it can be concluded that there is a signal in the two-frequency ranges. With the addition of a periodic copper overlay to the system, forbidden signal propagation zones are formed in the high-frequency region, corresponding to Bragg forbidden bands.

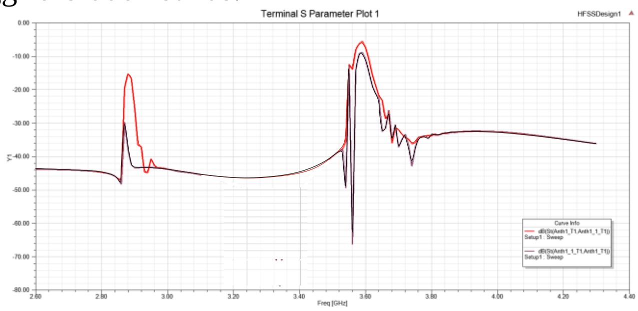

Fig.1. Dispersion characteristics of spin waves.

The obtained results confirm the potential of multilayer ferromagnetic films for creating devices with controllable SW characteristics. This opens up prospects for the development of new technologies in the field of spintronics.

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MAGNETIC SUSCEPTIBILITY OF FRUSTRATED $Yb_2Ti_2O_7$ NANOCOMPOSITE

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In recent years, the magnetic properties of rare earth titanates with the pyrochlore structure have been studied very intensively. Their chemical composition is expressed by the formula $R_2Ti_2O_7$, where R is a trivalent rare earth metal ion. A method of neutron scattering allowed one to find that the ground magnetic state of $Yb_2Ti_2O_7$ is a "splayed ferromagnet". In this case, the magnetic moments of the Yb^{3+} ions, located at the vertices of the tetrahedral, are directed outside this tetrahedron, in contrast to the rule "two spins in – two spins out" typical for "spin ice" [1].

The work is devoted to the investigation of the magnetic properties of the nanocomposite with $Yb_2Ti_2O_7$ titanate particles. Opal matrices were chosen as a base for the preparation of the nanocomposites. These are structures of amorphous silicon dioxide-based submicron spheres from 200 to 350 nm in diameter [2].

The magnetization curves and temperature dependences of the susceptibility were measured. Figure 1b shows the temperature dependence of the inverse susceptibility for the bulk sample pressed from ytterbium titanate powder.

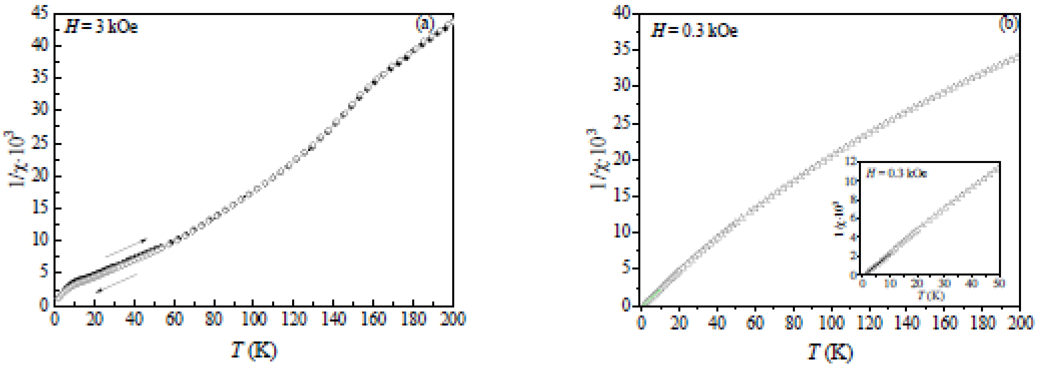

Fig. 1. Temperature dependences of the inverse magnetic susceptibility: (a) for the nanocomposite sample, measured in the field of 3 kOe; (b) for the bulk sample, measured in the field of 0.3 kOe

One can see that the Curie-Weiss law for the bulk titanate is approximately fulfilled in the temperature range from 2 to 12 K. The Curie-Weiss temperature value $\theta_{CW} \approx 0.7$ K is comparable to the one known from the literature [3]. In contrast to the bulk titanate, for nanocomposite samples, there are very pronounced deviations from the Curie-Weiss law even upon measurement in the fields of 3 kOe (Figure 1a). The dependences measured during cooling and heating almost coincide, so there is no temperature hysteresis in the susceptibility.

The AC susceptibility of the nanocomposite was explored in the frequency range from 10 Hz to 10 kHz. The frequency dependence of the real part of the complex magnetic susceptibility is found to satisfy a two-oscillator model described in the framework of Cole-Cole formalism [4]. One-oscillator model well describes experimentally obtained frequency dependences of the AC susceptibility only in the frequency range from 800 Hz to 10 kHz, whereas two-oscillator model well describes these dependences in a whole frequency range from 10 Hz to 10 kHz (Figure 2a).

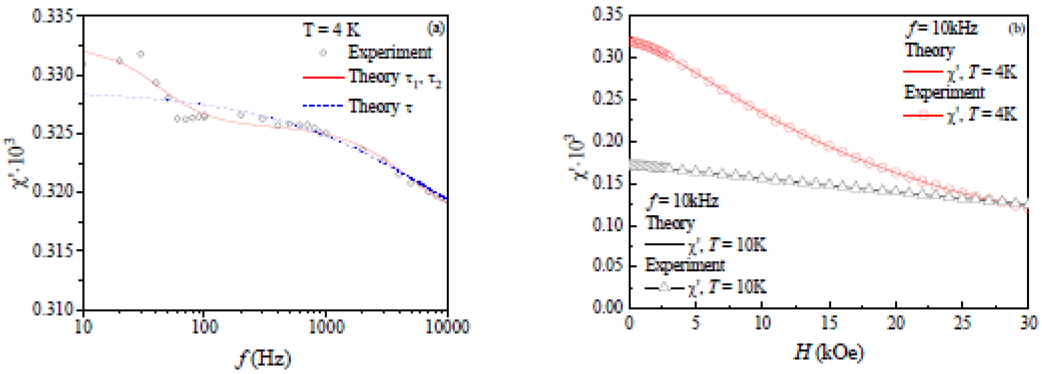

Fig. 2. Results of fitting of the frequency dependency – (a) and the field dependences – (b) of the real part of the AC susceptibility for the nanocomposite with the ytterbium particles

The spin relaxation times corresponding to these oscillators are determined. At the temperature of 4 K, these values are equal: $\square_1 = 3.44*10^{-5}$ s and $\square_2 = 3.85*10^{-3}$ s. The fact that at T = 4 and 10 K two relaxation times are required to describe the frequency dependence of the AC susceptibility indicates that these relaxation processes are not related to the spin ice state. In the fields up to 30 kOe, the magnetic field dependence of the real part of the complex magnetic susceptibility of the nanocomposite was measured (Figure 2b). The field dependence of the AC susceptibility is found to be described by the modified Cole-Cole formula [5]. The characteristic field H_r upon which the real part of the susceptibility decreases by a factor of 2 compared to the value at $H = 0$ is calculated. At the temperature T=4 K, the value of the field H_r turned out to be 17 kOe, and at the temperature T=10 K – H_r =64 kOe. Therefore, the characteristic field of this dependence increases while increasing the temperature.

In general, considering the run of the magnetization curves, the temperature dependences of the DC susceptibility, and the frequency dependence of the AC susceptibility, we can conclude that the studied magnetic properties of nanocomposite ytterbium titanate do not provide arguments in favor of the existence of quantum spin ice in this composite at low temperatures. Taking into account the results of [6], they are rather consistent with the idea of a nanocomposite in which magnetic ordering close to ferromagnetic is realized.

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MICROWAVE PROPERTIES OF 3D FERROMAGNETIC NANOCOMPOSITES Fe/EPOXY WITH PARTICLE CLUSTERING

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Synthesis of nanocomposites consisting of metal nanoparticles immersed in a polymer matrix has become a significant active field due to their physical properties attractive for applications. The interest in creating composites containing ferromagnetic metal particles in a dielectric matrix is mainly due to their use as radio-absorbing materials to reduce the reflection of microwave radiation, as well as, in connection with the prospects for the development of 6G communications, to shield mobile device blocks from spurious signals.

To create such composites with specified properties, as well as to correctly interpret the results of experimental studies, it is necessary to use an adequate theoretical model that determines the dynamic ferromagnetic parameters of these materials in the microwave range. The authors have proposed to determine the tensor of the complex magnetic permeability $\overleftrightarrow{\boldsymbol{\mu}}^m$ of three-dimensional nanocomposite media containing ferromagnetic particles of various shapes and spatial orientation using the following relations [1,2]

$$\overleftrightarrow{\boldsymbol{\mu}}^m = (1-\theta_V)\overleftrightarrow{\mathbf{I}} + \theta_V \overleftrightarrow{\boldsymbol{\mu}}(\overleftrightarrow{\mathbf{L}}), \tag{1}$$

$$\overleftrightarrow{\mathbf{L}} = (1-\theta_V)\overleftrightarrow{\mathbf{N}}, \tag{2}$$

where θ_V is the volume fraction of the ferromagnetic substance in a nanocomposite, $\overleftrightarrow{\mathbf{I}}$ is the unit tensor, $\overleftrightarrow{\boldsymbol{\mu}}$ is the Polder tensor for a ferromagnetic particle in the form of an arbitrary ellipsoid, $\overleftrightarrow{\mathbf{N}}$ is the demagnetizing tensor for a solitary particle of a given shape and spatial orientation, $\overleftrightarrow{\mathbf{L}}$ is the effective demagnetizing tensor for the particle that takes into account the presence of other particles in the medium.

The formulas (1), (2) correspond to a hypothetical composite medium in which all particles have the same ellipsoidal shape and are equally oriented relative to the direction of the magnetization field. If some composite medium contains particles of different shapes and/or spatial orientation, then each of them has its own tensor $\overleftrightarrow{\mathbf{N}}$, and therefore the corresponding tensor $\overleftrightarrow{\mathbf{L}}$.

Using the theory, the field dependences of the transmission and reflection coefficients, as well as the dissipation of microwaves in a wide range of microwave frequencies and ferromagnetic phase concentrations for particles of various shapes are obtained. In particular, the absorption of microwaves by a composite containing spherical iron nanoparticles has been considered, with special attention paid to absorption in weak magnetic fields [3]. The field dependences of the transmission, reflection and dissipation coefficients have been experimentally investigated in [4], where a satisfactory, but not complete correspondence between theory and experiment has been established. A possible reason for the discrepancies between the theory and the experimental results may be the presence of clusters of nanoparticles in the composite. This work shows that this assumption is correct. A further development of the theory described above is to take into account the influence of particle aggregates (clusters) on the microwave characteristics of composite media.

Based on electron microscopy data, it is found that the composite materials under consideration consist of individual spherical iron particles, aggregates of particles in the form of ellipsoids of several microns in size, as well as chains of spherical particles. Taking into account the shape and spatial orientation of aggregates and chains, as well as their demagnetizing factors, the permanent magnetic fields acting on all ferromagnetic components of the composite are determined. It turns out that the magnetic field inside the clusters differs from the average magnetic field in the sample depending on the demagnetization tensors of the clusters and their average magnetization.

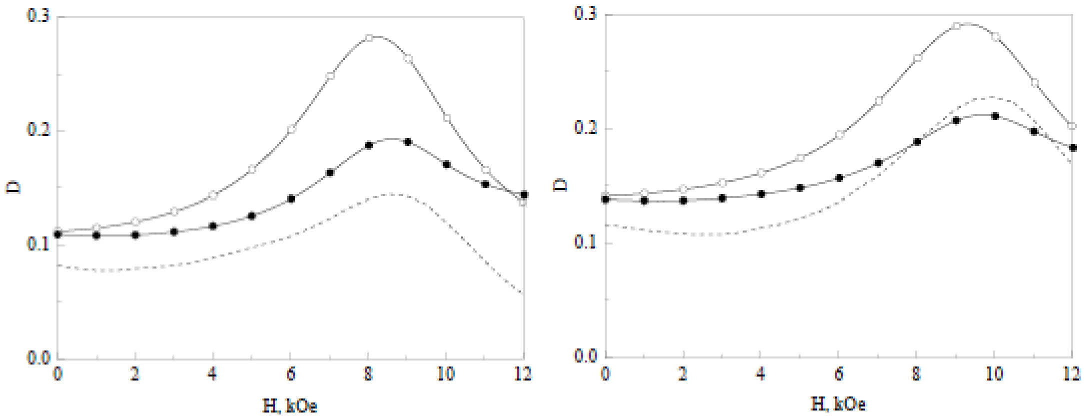

Fig.1. Dissipation characteristics for the 3D ferromagnetic nanocomposites Fe/epoxy. The frequencies are 26 GHz (left) and 29 GHz (right); θ_v = 0.02.

Fig. 1 shows the results of experimental measurements of the field dependences of the dissipation coefficients for composites with a volume fraction of the ferromagnetic phase equal to 0.02, in comparison with the results of theoretical calculations. Here the dotted lines are for the experimental data; the solid lines with filled circles correspond the theory that takes into account clusters and non-spherical particles; the solid lines with open circles are for the theory that assumes that all particles are spherical.

In the calculations assumed that 10% of ferromagnetic particles form chains, which were considered as the ellipsoids with the axis ratio of 1:1:7, and 40% are the isolated spherical particles. In addition, the remaining 50% of the particles form clusters in the form of ellipsoids with an axis ratio of 3:3:1. Next, the magnetic permeability tensor was averaged over all possible spatial orientations of non-spherical particles

It is obvious that taking into account the clustering of the particles makes it possible to obtain a much better agreement of the theoretical results with the experimental data.

The results were obtained within the state assignment of Ministry of Science and Education of Russia (themes “Magnet” No 122021000034–9, “Spin” No 22021000036-3 and “Function” No 122021000035–6).

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NON RECIPROCAL PROPAGATION OF SPIN WAVES IN A METAL-COATED YIG ADJACENT STRIPES

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Studies of spin pulse transfer in planar and multilayer magnetic structures allow us to say that spin waves (SWs) can be used as information carriers in low-energy computing devices [1,2]. In addition, the non-reciprocal properties of SWs have been exploited in spintronic devices such as diodes, insulators, gyrators and circulators [3]. Improving the non-reciprocal amplitude ratio of differently directed CWs can benefit CW devices such as diodes and insulators.

A schematic representation of the investigated system is shown in Fig. 1 (a) Two yttrium-iron-garnet (YIG) lateral waveguides S1 and S2 (length 8 mm, width µm and thickness 10 µm) are arranged laterally parallel to each other with a gap on a gadolinium-gallium-garnet (GGG) substrate. The metal layer is placed over the lateral structure with an air gap. For the microwave measurements, 30 µm wide microstrip antennas, marked in red, were used in the input and output sections of the waveguides. The distance between the input and output transducers was 5 mm. An external magnetic field of H = 1200 E was applied along the x-axis. The results of the microwave measurements are shown in Figure 1(b).

Experimental and computational calculations show that by changing the direction of the magnetic field, one can improve the efficiency of non-reciprocal SW propagation in the proportional distribution of YIG waves with a metallic layer over the coupling structure. Thus, a coupled system with an overlying metal layer has the effect of effective non-reciprocal SW propagation. In such a system, it is possible to implement a simple method to control the non-reciprocal propagation of spin waves using geometry and an equilibrium configuration.

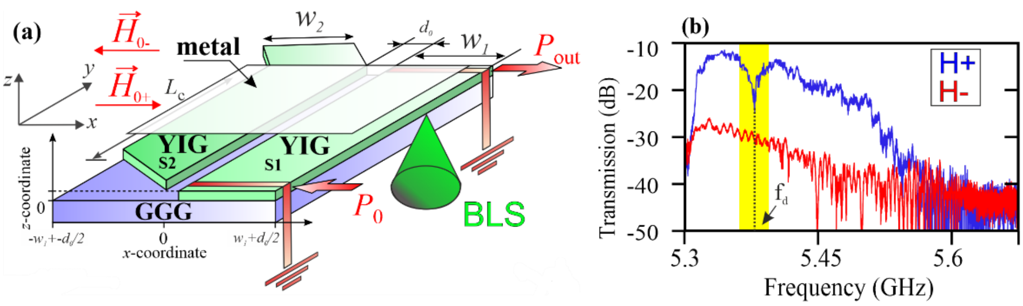

Fig.1. Schematic image of the investigated structure (a); Transmission of SW through the first stripe S1 measured with VNA

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DOMAIN STRUCTURE OF EPITAXIAL SUPERLATTICES Pd/Co/CoO

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Magnetic superlattices Si(111)/Cu/[Pd/Co/CoO]$_n$/Pd grown by molecular beam epitaxy in an ultrahigh vacuum with number of layer, *n* from 1 to 11 were studied. With the growth of metallic layers on top of the oxide at $n \geq 2$, the epitaxial orientation of the layers is preserved, although the crystallographic order is somewhat disturbed due to the oxide layers.

An increase in the number of repetitions leads to a change in the shape of the domain structure from wide domains with smooth domain walls to a labyrinthine structure, which is associated with the appearance of magnetostatic energy of interlayer exchange, which contributes to the closure of the magnetic flux.

It is shown that in systems characterized by a labyrinth domain structure with a small number of layers, it is possible to modify the domain structure by the action of a magnetic probe in combination with a magnetic field. For Si(111)/Cu/[Pd/Co/CoO]$_7$/Pd, in the absence of an additional applied field, it is possible to form bubble domains smaller than 300 nm using a magnetic probe.

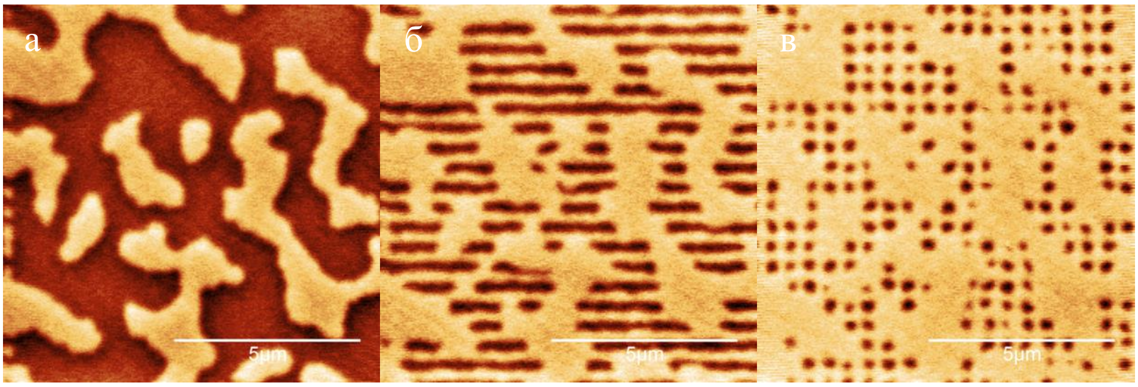

Fig. 1 – MFM-image of the domain structure of the film Si(111)/Cu/[Pd/Co/CoO]$_7$/Pd obtained with the power of MFM: (a) in the residual state, (b) after passing in semi-contact mode with a step along the vertical axis of 500 nm with a magnetic probe, (c) after passing in semi-contact mode with a step along the horizontal axis of 500 nm without additional external field.

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ОБРАТНЫЙ СПИНОВЫЙ ЭФФЕКТ ХОЛЛА В СТРУКТУРЕ ЖИГ – ПЛАТИНА НА ОСНОВЕ ПЛЕНКИ ЖИГ С ПОНИЖЕННОЙ НАМАГНИЧЕННОСТЬЮ НАСЫЩЕНИЯ

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Обратный спиновый эффект Холла (ОСЭХ) [1] в структурах пленка железоиттриевого граната (ЖИГ) – платина активно исследуется в связи с перспективами построения энергоэффективной элементной базы магнонной спинтроники [2]. При проведении экспериментов обычно используются эпитаксиально выращенные на подложке из гадолиний-галлиевого граната кристаллографической ориентации (111) пленки ЖИГ с намагниченностью насыщения $4\pi M_1$=1750 Гс.

В данной работе представлены результаты исследования ОСЭХ в структуре на основе волновода из пленки легированного ЖИГ с намагниченностью насыщения $4\pi M_2$=550 Гс толщиной 26 мкм с плоскостными размерами 5×10 мм, на поверхности которого с помощью технологий вакуумного напыления и фотолитографии формировалась полоска из платины шириной 25 мкм, толщиной 4 нм, длиной 4 мм (R=8 кОм), ориентированная вдоль длинной стороны волновода. Внешнее постоянное магнитное поле H прикладывалось касательно к поверхности структуры перпендикулярно длинной стороне волновода, что соответствовало геометрии поверхностных магнитостатических волн (ПМСВ) [3], которые возбуждались и принимались микрополосковыми антеннами шириной 40 мкм. Расстояние между антеннами равнялось 7 мм. Регистрировались частотные зависимости коэффициента передачи макета $S_{12}(f)$ и генерируемой на полоске платины ЭДС U.

Следует отметить, что в экспериментах с пленками ЖИГ величина поля H обычно выбирается достаточно большой для того, чтобы область частот наблюдения ПМСВ не попадала в область трехмагнонных (3М) процессов [3], поскольку при этом мощность ПМСВ ограничивается, что приводит к снижению регистрируемой ЭДС. На рисунке 1а приведены рассчитанные зависимости от величины поля H верхних граничных $f_{s1,2} = f_H + \frac{f_{m1,2}}{2}$ (линии 1, 3) и нижних граничных $f_0 = \gamma\sqrt{H(H + 4\pi M_{1,2})}$ (линии 2, 4) частот ПМСВ [3] для ЖИГ с намагниченностями насыщения $4\pi M_{1,2}$ =1750 Гс и 550 Гс, соответственно, $f_{m1,2} = \gamma 4\pi M_{1,2}$, $f_H = \gamma H, \gamma = 2.8\frac{\text{МГц}}{\text{Э}}$. Видно, что в диапазоне, например, 300 – 500 Э, для пленки с $4\pi M_1$ вся полоса наблюдения ПМСВ в области частот 2 – 4 ГГц находится в области 3М распадов (выше, чем частота $f = 2\gamma H$ (кривая 5 на рисунке)). Чувствительность $S=U/P_{мсв}$ в этом случае не превышает 10^{-4} В/Вт [4]. (Величина $P_{мсв}$ определялась по разнице уровней отраженных от входной антенны ПМСВ мощностей для величины поля H_1, отвечающей условиям эксперимента, и $H \gg H_1$). В то же время, для пленки с $4\pi M_2$ ПМСВ в этом интервале полей не подвержена 3М распадам (см. рис. 1а), при этом чувствительность S составила $S \sim 10^{-3}$ В/Вт, что по порядку величины сопоставимо с результатами для пленок чистого ЖИГ. Таким образом, с помощью повышения входной мощности можно обеспечить достижение высоких уровней генерируемой ЭДС.

На рисунке 1б приведены частотные зависимости коэффициента передачи макета с исследованной структурой S_{12}(f) (черная линия) и ЭДС (красная линия) при H=440 Э. Отметим, что вид зависимости U(f) не содержит типичного для структур, использующих нелегированные пленки ЖИГ, ярко выраженного максимума ЭДС вблизи длинноволновой (низкочастотной) границы f_0 области наблюдения ПМСВ. Одной из причин такой зависимости U(f) может являться неоднородность магнитных параметров пленки по толщине, приводящее к росту гибридизации дипольной ПМСВ с обменными модами структуры [5,6]. При этом из-за высокой эффективности рассеяния электронов на обменных спиновых волнах величина ЭДС на частотах $f > f_0$ растет.

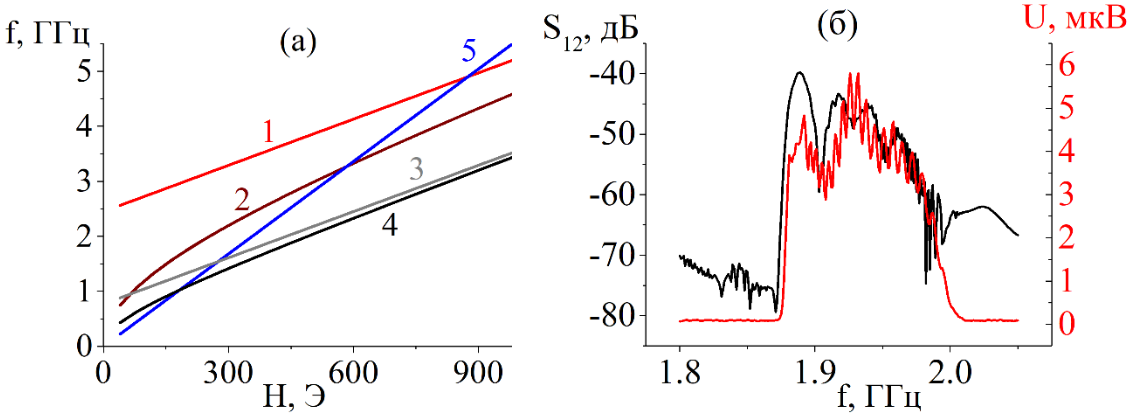

Рис. 1. а) зависимости от величины поля H верхних граничных (линии 1, 3) и нижних граничных (линии 2, 4) частот ПМСВ для ЖИГ с намагниченностями насыщения $4\pi M_{1,2}$ =1750 Гс и 550 Гс, соответственно, где линия 5 соответствует зависимости $f_H = 2\gamma H$; б) частотные зависимости коэффициента передачи макета с исследованной структурой S_{12} (черная линия) и ЭДС (красная линия) при H=440 Э.

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PICOSECOND CARRIER DYNAMICS IN $CdCr_2Se_4$ FERROMAGNETIC SPINEL

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The development of spintronics requires materials with ultrafast magnetooptical (MO) phenomena and spin transport at terahertz (THz) frequencies. Yet being underestimated magnetic semiconductors can be one of the promising materials [1]. Here we present the ultrafast MO response for $Hg_{1-x}Cd_xCr_2Se_4$ ($0 \le x \le 1$) thin films and crystals in the IR/THz spectral range. The dynamic of the MO effects was studied by an optical and THz pump-probe method.

It was shown that the femtosecond laser pulses are able to trigger oscillations of the Faraday rotation in the ferromagnetic $CdCr_2Se_4$ films below the Curie point. Tuning the photon energy of the pump pulses we revealed two different mechanisms, pump polarization dependent and the polarity of the applied magnetic field dependent one, which induce precession in this material. The impurity transitions play a decisive role and leads to a distinct anomaly in the magnetoabsorption of spinel. It was shown that the estimated signal risen front and the decay time in that case are about 1 ps and 3-6 ps, respectively, depending on the temperature of spinel.

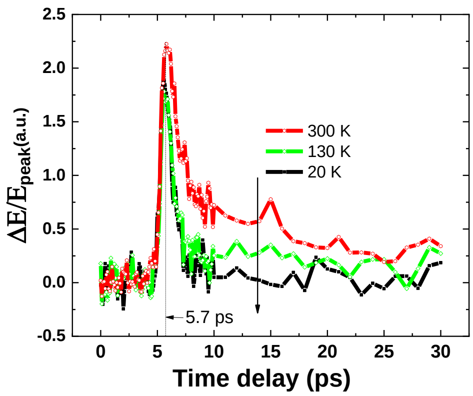

Fig.1. The temporal profile of the THz response in spinel at different temperatures.

The ultrafast dynamic in spinel crystals and films is saved in case of a THz pump-probe scheme (Fig.1). The effects of magnetic linear birefringence and dichroism were observed in spinel crystals in the frequency range 0.5-2.5 THz at temperatures below the magnetic ordering by a THz pump-probe method. The maximal rotation of the light polarization plane associated with a high-frequency response to the DC anisotropic magnetoresistance in spinel reached about 4.3 rad/cm at H=1 kOe.

Therefore, one can conclude that the chromium spinels can be considered for studying various ultrafast and THz phenomena.

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CONTROL OF MAGNON-POLARITON COUPLED MODES IN TOROIDAL CAVITY

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The exploration of magnon-polaritons in toroidal waveguides is of paramount importance due to their potential applications in various fields such as photonics, spintronics, and quantum information processing [1, 2]. These unique hybrid quasiparticles arise from the coupling between magnons, the collective excitations of spins in magnetic materials, and photons, the quanta of electromagnetic radiation. Toroidal waveguides offer a promising platform for studying these phenomena due to their ability to confine both light and spin waves within a compact and controllable structure. Precision in controlling damping assumes critical importance at the juncture of "exceptional points," which denote special degeneracy points in the system where normal modes coalesce, amplifying sensitivity. Harnessing these exceptional points also enables fine-tuning of spin-photon coupling strength.

In this work, we study magnon-polariton interaction in a toroidal waveguide loaded with two spheres of yttrium-iron garnet (YIG), the transmission coefficient of which is shown in Fig.1. It is evident that near the intersection point of the two frequencies, their repulsion (frequency hybridization) occurs, which is enhanced by the presence of two YIG spheres. Introducing additional losses, induced by an external electric circuit, enables the merging of the system's normal frequencies, leading to appearance of the exceptional point. We demonstrate that the presence of two YIG spheres results in both an increase in the system's quality factor and an enhancement in its sensitivity to external electromagnetic radiation, potentially enabling the utilization of such systems as high-sensitivity magnetic field sensors with loss compensation.

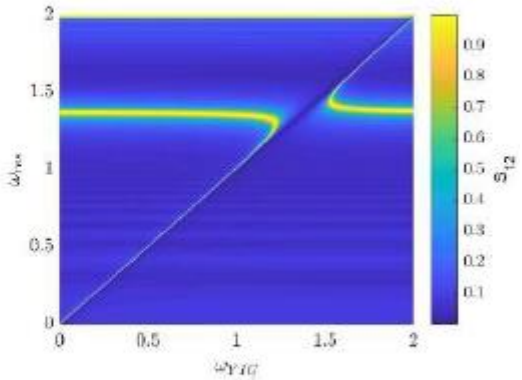

Fig 1. Transmission power spectrum $|S12(\omega_{res},\omega_{YIG})|$. Both frequencies ω_{res}, ω_{YIG} are normalized to the resonance frequency ωnorm.

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CEF PARAMETERS AND MAGNETIC PROPERTIES CORRELATIONS IN RARE-EARTH ORTHOFERRITES RFEO3 (R = HO, TB, TM)

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Based on the $RFeO_3$ compounds (R = Ho, Tb, Tm) XRD data the sets of crystalline electric field (CEF) parameters were obtained within the framework of the point charge model in the temperature range 4 – 300 K for the corresponding rare earth ions R^{3+} [1-3]. Optimal algorithms for calculating CEF parameters in the PyCrystalField software environment are considered [4, 5]. With the obtained sets of parameters the energy levels splitting of the ground state multiplet of the considered R^{3+} ion was calculated, as well the temperature dependences of the splitting spectra and the isothermal magnetization curves $M(H)$ modelling. Bulk magnetization evaluated from CEF was compared to experimental data [6, 7].

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МОДЕЛИРОВАНИЕ КОМПЛЕКСНОГО КОЭФФИЦИЕНТА ПЕРЕДАЧИ АКТИВНОГО КОЛЬЦЕВОГО РЕЗОНАТОРА НА МАГНОННОМ КРИСТАЛЛЕ

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Активные кольцевые резонаторы (АКР), основанные на ферромагнитных пленках, представляют большой интерес для СВЧ электроники. На основе АКР возможно создание таких приборов как фильтры [1], генераторы нелинейных колебаний [2] и резонаторы [3] с достаточно большой добротностью (порядка 50000). К преимуществам таких приборов относится легкость получения разнообразных рабочих характеристик путем выбора величины внешнего магнитного поля и топологии ферромагнитной пленки Магнонный кристалл является одним из возможных структур для конструирования АКР.

В настоящей работе была разработана модель активного кольцевого резонатора на магнонном кристалле (МК). Полученные теоретические данные хорошо согласуются с экспериментально измеренными характеристиками. На основе разработанной модели было проведено моделирование фазо-частотной характеристики (ФЧХ) АКР и исследованы особенности ФЧХ вблизи резонансных частот.

Магнонный кристалл с петлей обратной связи представляет собой активный кольцевой резонатор, схема которого показана на рисунке 1. Петля обратной связи состоит из СВЧ усилителя 2, который компенсирует потери, возникающие в МК, переменного аттенюатора 3, необходимого для регулирования усиления, и магнонного кристалла 1. Для ввода и вывода сигнала используются направленные ответвители 4 и 5 соответственно.

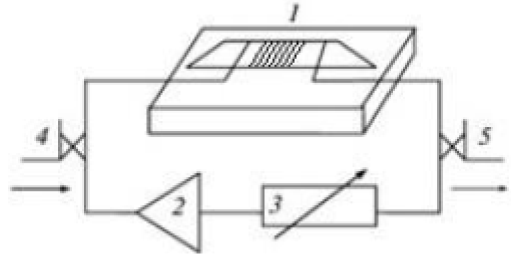

Рис. 1. Схема активного кольцевого резонатора.

При проведении моделирования предполагалось, что пленка железо-иттриевого граната имеет толщину L_1 = 5.2 мкм и намагниченность насыщения M_0 = 1950 Гс. Канавки на поверхности ферромагнитной пленки имеют глубину h = 0.5 мкм и протяженность d_2 = 50 мкм. Общее число канавок N = 20, а период Λ = 150 мкм. Для возбуждения в МК поверхностных спиновых волн (ПСВ), пленка ЖИГ подмагничивается однородным магнитным полем напряженностью Н = 1417 Э. Полуширина ферромагнитного резонанса ΔН составила 0.6 Э. Входная и выходная антенна находились на расстоянии d = 6 мм.

Для вывода уравнения, описывающего коэффициент передачи АКР, было принято, что в кольце циркулирует бесконечное число затухающих волн. Резонанс в кольце возникает на частотах, удовлетворяющих условию синфазного сложения циркулирующих волн. На основе данных рассуждений была получена следующая формула [4]:

$$H_p = \frac{1}{2}\frac{e^{g-\alpha(\omega)d}}{\cosh\left(g-\alpha(\omega)d\right)-\cos\left(k(\omega)d\right)}, \quad (1)$$

где g – безразмерный коэффициент усиления кольца, α(ω) – декремент затухания спиновых волн, k(ω) – дисперсионный закон спиновых волн в МК, который рассчитывается с помощью метода волновых матриц передачи [5]. Полученный результат показан на рисунке 2 (а). Моделирование ФЧХ АКР проводилось с помощью следующего выражения [4]:

$$\varphi = \operatorname{arctg}\left(\frac{\sin\left(k(\omega)\cdot d\right)}{\cos\left(k(\omega)\cdot d\right)-\exp\left(-\left(g-\alpha(\omega)\right)\cdot \mathrm{d}\right)}\right) \pm R\pi, \quad (2)$$

На рисунке 2 (б) и 2 (в) показаны результаты расчета ФЧХ АКР (пунктирная линия). Видно, что кривая осциллирует вокруг ФЧХ магнонного кристалла (сплошная линия), внося, тем самым, некоторый фазовый сдвиг в циркулирующие в кольце спиновые волны. Подобные АКР можно использовать для изучения нелинейных спин-волновых процессов и для разработки магнонных резервуарных компьютеров [6].

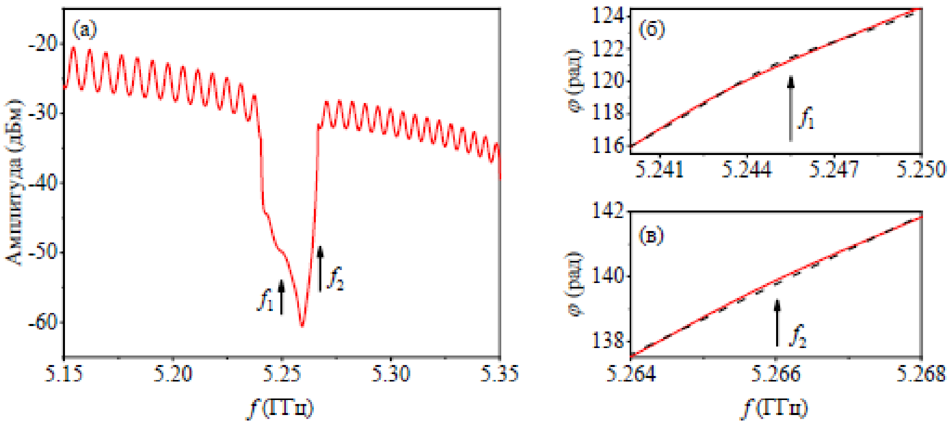

Рис. 2. Теоретическая АЧХ АКР (а) и ФЧХ (б и в). Красным показана ФЧХ МК, пунктирным ФЧХ АКР.

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МОДЕЛЬ МАГНОННОГО МИКРОРЕЗЕРВУАРА НА ОСНОВЕ НАНОМЕТРОВЫХ ПЛЕНОК ЖИГ

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Магнонный активный кольцевой осциллятор (МАКО), содержащий в цепи обратной связи спин-волновую линию задержки (СВЛЗ), представляет собой перспективную платформу для резервуарных вычислений [1-5]. В таких системах для создания СВЛЗ используются эпитаксиальные пленки железо-иттриевого граната (ЖИГ) толщиной порядка единиц микрометров. В этом случае для достижения времени задержки порядка сотен наносекунд расстояние между спин-волновыми антеннами составляет единицы миллиметров. Такие размеры СВЛЗ ограничивают возможность микроминиатюризации резервуарных вычислительных систем. Недавно было показано, что современные пленки ЖИГ нанометровой толщины, выращенные с использованием жидкофазной эпитаксии на подложках гадолиний-галлиевого граната (ГГГ), демонстрируют превосходную стехиометрию и кристаллическую структуру [4,6]. В этих пленках поверхностные магнитостатические спиновые волны (ПМСВ) характеризуются чрезвычайно низкими групповыми скоростями порядка 100 м/с, что позволяет значительно уменьшить размеры СВЛЗ и резервуаров на их основе. Практическим способом возбуждения и приема ПМСВ в таких пленках является использование антенн в виде коротких участков копланарных линий (КПЛ) передачи [7, 8]. В работе [9] было показано, что СВЛЗ на нанометровых пленах ЖИГ могут быть использованы для создания микроминиатюрных СВЧ генераторов, которые при толщине пленки ЖИГ 100 нм и расстоянии между КПЛ-антеннами 56 мкм обеспечивает уровень фазового шума -115 дБн/Гц при отстройке 10 кГц от частоты генерации 5 ГГц. Предложенная конструкция МАКО может быть использована для реализации микроминиатюрной резервуарной вычислительной системы, в которой ввод информационного сигнала осуществляется с помощью управляемого аттенюатора, обеспечивавшего изменение коэффициента усиления в цепи обратной связи. В такой схеме мощность сигнала на выходе определяется балансом между усилением и нелинейным затуханием спиновых волн. Изменение коэффициента усиления в цепи обратной связи выводит МАКО из стационарного состояния. Теоретическая модель описывающая переходные процессы в МАКО была предложена в работе [10]. Такая модель может быть использована не только для описания наблюдаемых в эксперименте результатов, но и предсказания характеристик резервуарной вычислительной системы [11]. В рамках данной работы такая модель будет использована для расчета рабочих характеристик микроминиатюрной резервуарной вычислительной системы на нанометровых пленках ЖИГ.

Для моделирования переходных процессов в микроминиатюрном МАКО была разработана трехэтапная процедура численного расчёта. На первом шаге с помощью теоретической модели, описанной в работе [7] проводилось моделирование комплексного коэффициента передачи микроскопической СВЛЗ, показанной на рис.1.а. Моделирование было выполнено при различных параметрах СВЛЗ для определения влияния геометрии КПЛ-антенн и характеристик пленок

ЖИГ на производительность резервуара. Вторым шагом является моделирование передаточной характеристики МАКО. Кольцо включает в себя СВЛЗ, а также компактные микроэлектронные элементы, такие как СВЧ усилитель, аттенюатор (модулятор), управляемый внешним генератором сигнала произвольной формы (ГСПФ) и направленные ответвители (см. рис. 1.а). На заключительном шаге на основе теоретической модели, представленной в работе [10], производится расчет временной характеристики сигнала на выходе МАКО, пример которой показан на рис 1.б красной линией. Расчет выполнен для входного сигнала, показанного на этом рисунке черной линией. Для оценки производительности предложенной конструкции использованы тесты контроля четности и кратковременной памяти. Из полученных результатов следует, что микрорезервуар на нанометровых пленках ЖИГ не уступает по своим характеристикам традиционным резервуарным вычислительным системам на микроных пленках ЖИГ. Таким образом, использование КПЛ антенн для возбуждения и приема спиновых волн в нанометровых пленках ЖИГ, а также микросхем усилителей обеспечивает возможность создания магнонных резервуарных вычислительных систем на чипе.

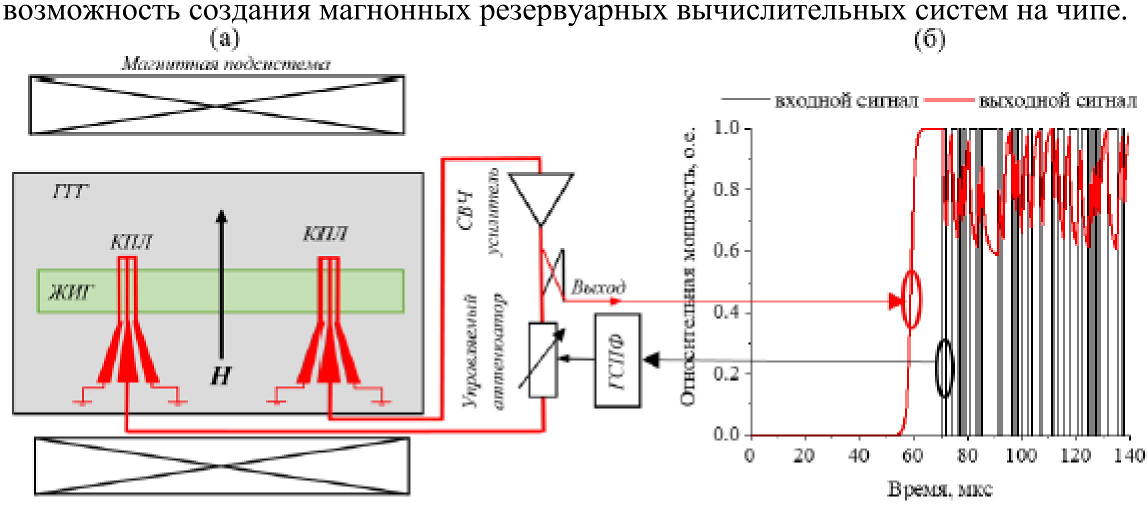

Рис. 1. Схема микроминиатюрного МАКО на нанометровой пленке ЖИГ (а); входной (красная линия) и выходной сигналы микрорезервуара (б)

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СПИН-ВОЛНОВАЯ ЛИНИЯ ЗАДЕРЖКИ НА ОСНОВЕ КЕРАМИЧЕСКОЙ ПЛАСТИНЫ ЖИГ ДЛЯ РЕЗЕРВУАРНЫХ КОМПЬЮТЕРОВ

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В настоящее время промышленно выпускаемые устройства спин-волновой электроники чаще всего основаны на эпитаксиальных пленках железо-иттриевого граната. Пленки обеспечивают малые потери на распространение сверхвысокочастотных (СВЧ) спиновых волн, большие времена задержки, а также возможность электронного управления устройствами. Вместе с тем, производство эпитаксиальных пленок ЖИГ является достаточно сложным и дорогостоящим процессом. В качестве альтернативы таким пленкам предлагались пленки из других материалов, либо пленки ЖИГ, выращенные другими методами. Подобные материалы демонстрируют более высокие потери, однако в кольцевых системах с компенсацией потерь усилителями величина затухания спиновых волн отходит на второй план.

В настоящей работе экспериментально исследована спин-волновая линия задержки (СВЛЗ) на основе керамической ферромагнитной пластины, а также возможности ее применения в качестве нелинейного элемента в активных кольцевых структурах, в частности, магнонном резервуарном компьютере.

За основу экспериментального макета СВЛЗ была взята традиционная схема, состоящая из возбуждающей и приемной антенн, а также волновода спиновых волн (см. рис. 1). В работе использовалась керамическая пластина ЖИГ толщиной 500 мкм. Длина пластины составляла 30 мм, а ширина - 3 мм. Намагниченность насыщения пластины была примерно 1300 Гс. Полуширина линии ферромагнитного резонанса около 6 Э. Пластина намагничивалась постоянным магнитным полем напряженностью 754 Э. Поле было направлено в соответствии с конфигурацией Демона-Эшбаха.

Столь высокое значение полуширины линии ферромагнитного резонанса приводит к росту потерь при распространении спиновых волн. Для уменьшения потерь мы металлизировали одну из поверхностей пластины ЖИГ, вдоль которой распространялись спиновые волны. В результате групповая скорость CD становилась больше, а затухание меньше. Для этого ферромагнитная пластина устанавливалась на металлизированную с одной стороны поликоровую подложку толщиной 500 мкм. Для возбуждения и приема поверхностных спиновых волн в металлизации были вытравлены две щелевые линии передач - входная и выходная антенны. Ширина щелей составляет 50 мкм, а длина - 8 мм. Расстояние между антеннами - 10 мм. Для подвода СВЧ сигнала к щелевым линиям на обратной стороне поликоровой пластины были сформированы подводящие микрополосковые линии и переходы микрополосок-щелевая линия [1].

Используя векторный анализатор цепей были экспериментально исследованы волноведущие свойства пластины, а также передаточная характеристика СВЛЗ. Использование толстой пластины, металлизации и щелевых антенн позволило добиться широкого диапазона частот, в котором существуют спиновые волны. Экспериментальная дисперсионная характеристика спиновых волн ограничена частотами от 3.46 до 6.37 ГГц. Величина групповой скорости меняется в диапазоне от 5400 до 12000 км/с (см. рис 2 (*в*)). Относительно высокая групповая скорость обусловливает достаточно низкий уровень потерь. Так, максимум коэффициента передачи СВЛЗ на частоте 3.56 ГГц составляет -8.8 дБ (см. рис 2(*г*)). Время задержки имеет низкое значение - порядка 10 нс на той же частоте. Экспериментальное исследование показало, что в пластине нелинейные процессы обуславливаются в основном нелинейным затуханием, возникающим при уровне входной мощности свыше 17 дБм (см. рис 2(*б*)).

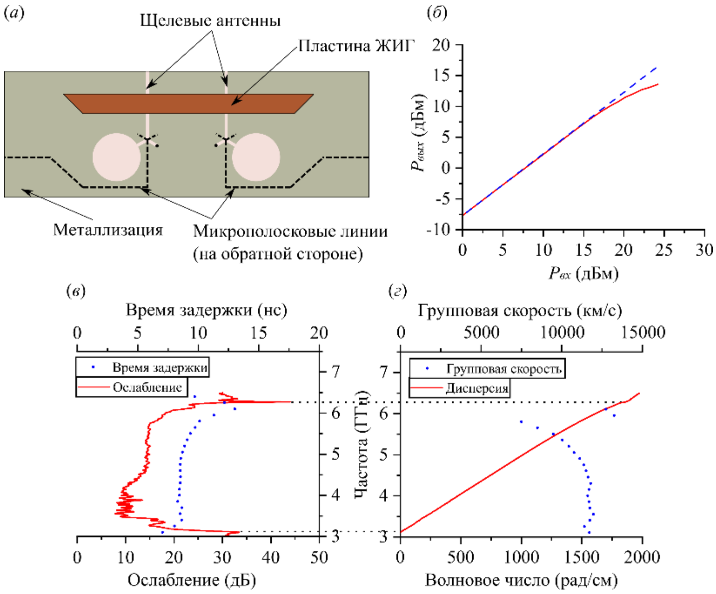

Рис.1. Макет СВЛЗ (*а*); зависимость выходной мощности от входной (*б*); АЧХ и зависимость времени задержки от частоты (*в*); дисперсия спиновых волн и зависимость групповой скорости от частоты.

Описанная конструкция линии задержки была использована в качестве нелинейного элемента в магнонном резервуарном компьютере (МРК) на основе спин-волнового кольцевого генератора. Конструкция МРК подробно описана в работах [2-6]. Экспериментальные исследования показали, что использование металлизированных керамических пластин ЖИГ позволило улучшить одну из ключевых характеристик резервуара - память. Так, например, емкость теста кратковременной памяти [7] составил 3.5, что примерно в полтора раза больше чем в предыдущих экспериментальных работах.

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INFLUENCE OF POLARIZATION TYPE ON FERROMAGNETIC RESONANCE

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In recent years, there has been a significant surge in the development of new devices based on magnetic phenomena, highlighting their growing relevance in technological innovation. These devices, exploiting the principles of magnetism, are proving to be crucial for advancements in radio engineering, sensor technology, and energy-efficient electronics [1,2].

This work examines the impact of linear and circular polarization of microwave fields on ferromagnetic resonance (FMR). Based on the experiments conducted, it was revealed that ferromagnetic absorption predominantly depends on the component of the alternating magnetic field directed perpendicular to the constant magnetic field. As can be seen in Fig. 1, there is a reduction in the level of FMR absorption with circular polarization compared to linear polarization. These findings can be utilized in the development of specialized devices, such as microwave polarizers. Moreover, based on the inverse spin Hall effect, detectors for linearly polarized waves can be developed. This opens up new prospects in the development of microwave radiation control technologies and broadens the capabilities for precise detection of polarization states.

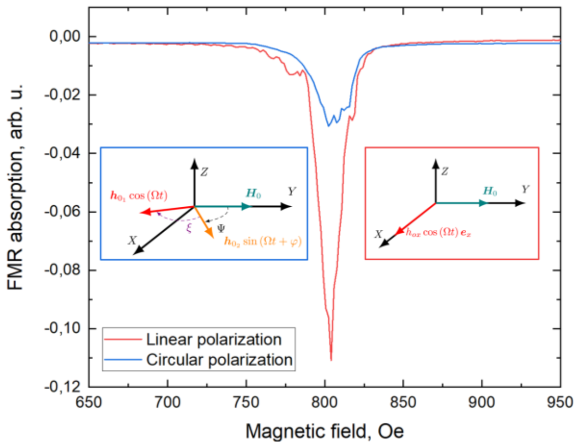

Fig. 1.. FMR absorption spectra for linearly (red) and circularly (blue) polarized excitation. Inset rectangles show the excitation field vectors in the coordinate system (red rectangle for linear and blue rectangle for circular polarization).

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ОБРАТНЫЙ СПИНОВЫЙ ЭФФЕКТ ХОЛЛА В СТРУКТУРЕ ЖИГ(111)-ПЛАТИНА В МАЛЫХ ПОЛЯХ ПОДМАГНИЧИВАНИЯ

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Исследование обратного спинового эффекта Холла (ОСЭХ) в структурах «пленка железоиттриевого граната (ЖИГ) – платина» проводится, как правило, с использованием пленок ЖИГ кристаллографической ориентации (111) при достаточных для насыщения пленки ЖИГ величинах поля подмагничивания H. В этом случае изменение угла α между направлением поля H (приложенного касательно к поверхности структуры) и, например, проекцией оси легкого намагничивания в плоскости пленки ЖИГ $\langle 1\bar{1}0\rangle$ практически не влияет на спектры возбуждаемых поверхностных или обратных объемных магнитостатических волн, в отличие от малых величин H, когда в пленке ЖИГ формируется доменная структура [1]. Возможность наблюдения ОСЭХ в малых полях подмагничивания была показана в [2], однако зависимость результатов измерений от величины угла α не рассматривалась.

В данной работе проведено сравнение результатов генерации ЭДС по механизму ОСЭХ в двух структурах на основе волноводов из пленки ЖИГ(111) толщиной 15,4 мкм с намагниченностью насыщения 4πM=1750 Гс с плоскостными размерами 5×10 мм, длинные стороны которых были ориентированы в направлениях α=90° (структура 1) и α=0 (структура 2). На поверхности волноводов с помощью технологий магнетронного напыления и фотолитографии формировалась полоски из платины шириной 25 мкм, толщиной 4 нм, длиной 4 мм (R≈12 кОм), ориентированные вдоль длинной стороны волновода. Внешнее постоянное магнитное поле H направлялось перпендикулярно длинной стороне волновода, что для насыщенной пленки ЖИГ соответствовало геометрии поверхностных магнитостатических волн (ПМСВ) [3], которые возбуждались и принимались проволочными антеннами диаметров 40 мкм. Расстояние между антеннами равнялось 7 мм. Регистрировались частотные зависимости коэффициента передачи макета, из которых определялись длинноволновые (низкочастотные) границы f_0 полос наблюдения спин-волновых возбуждений (СВВ), а также генерируемой на полоске платины ЭДС в интервале уменьшения величины H от 110 Э до 0.

На рисунке 1а кривыми 1 и 1’ представлены зависимости f_0(H) для величин H, отвечающих насыщенному состоянию пленки ЖИГ. (Здесь и далее кривые без штриха и со штрихом отвечают структуре 1 и структуре 2, соответственно.) Частотные зависимости максимальной регистрируемой в полосе частот ЭДС U* представлены на рис. 1б кривыми 1^U и $1'^U$.

При H≈60 Э для каждой из структур наблюдаемая полоса частот ПМСВ разделяется на две, зависимости f_0(H) для которых представлены кривыми (2 и 3) и (2’и 3’), соответственно. Из их сравнения видно, что при уменьшении величины H области частот наблюдения противофазных (2 и 2’) и синфазных (3 и 3’) колебаний намагниченности в доменах [4], а также уровни генерируемой ЭДС (сравн. кривые (2^U и $2'^U$) и (3 и $3'^U$) для двух структур заметно различаются. Так, например, в структуре 2 полоса частот существования противофазных колебаний перестает наблюдаться при уменьшении H до 49 Э (кривая 2' на рис. 1а), тогда как в структуре 1 она наблюдается до H≈32 Э (кривая 2 на рис. 1а).

При уменьшении H с 32 Э до 26 Э никаких спин-волновых возбуждений не наблюдалось. В интервале H=26 – 3 Э в обеих структурах регистрируется СВВ, обусловленное волнами смещения доменных границ [5]. Отметим, что частотные зависимости $f_0(H)$ для обеих структур практически совпадают (сравн. кривые 4 и 4' на рис. 1а). Однако генерация ЭДС в структуре 1 происходит значительно эффективнее (сравн. кривые 4^U и $4'^U$ на рис. 1б).

Таким образом, показано, что результаты детектирования спин-волновых возбуждений в структуре «ненасыщенная пленка ЖИГ(111) – платина» зависят от направления намагничивания (в плоскости структуры) относительно кристаллографических осей пленки ЖИГ(111). В исследованных структурах наибольших величин ЭДС достигала при намагничивании структуры вдоль проекции на плоскость пленки ЖИГ оси легкого намагничивания.

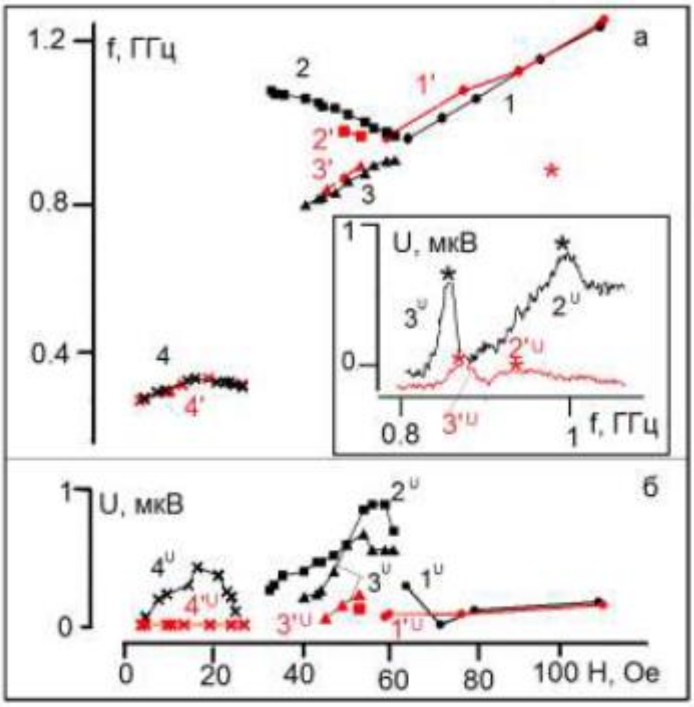

Рис. 1. Зависимости от величины поля H а) длинноволновой (низкочастотной)границы ПМСВ f_0; б) генерируемой ЭДС для структур 1 и 2 (цифры без штриха и со штрихом, соответственно). На вставке к рис. 1а показаны фрагменты частотных зависимостей U*(f) при H =54 Э

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