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RESEARCH ARTICLE

Nonreciprocal propagation of spin waves in a bilayer magnonic waveguide based on yttrium-iron garnet films

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Abstract
Objectives. Nonreciprocal spin wave effects can manifest themselves in metalized films of ferrite garnets. By studying the dynamics of spin waves in micro- and nano-scale magnetic films, the possibility of using multilayer dielectric films of yttrium iron garnet (YIG) to ensure the manifestation of the nonreciprocity effect is demonstrated. This approach offers advantages compared to the use of a layered YIG/metal structure due to significantly lower spin-wave losses in the two-layer YIG film consisting of layers with different values of magnetization. Such films can be used in logical elements to create controllable Mach–Zehnder interferometers based on magnonic principles. The purpose of this work is to reconcile the concept of nonreciprocal spin-wave propagation of a signal with the simultaneous manifestation of the effects arising from the propagation of spin waves in microwave guides formed by finite-width YIG films.
Methods. We used an experimental microwave spectroscopy method based on a vector network analyzer along with a finite difference method to perform a numerical simulation of the dispersion characteristics of spin waves in two-layer magnonic microwave guides. An analytical model was also used to obtain a dispersion equation based on the magnetostatic approximation.
Results. Based on measurements of the amplitude and phase responses, the possible coexistence of two frequency ranges for the propagation of a spin-wave signal in a two-layer magnon microwave guide based on a YIG film formed by two layers with different values of saturation magnetization was demonstrated. Regimes of nonreciprocal propagation of a spin-wave signal were revealed. A numerical model was using to study the formation mechanisms of spin wave modes in the spectrum of a two-layer structure formed due to the finite dimensions of the microwave guide. An analytical model was used to evaluate the transformation of the mode spectrum. The experimental data are in good agreement with the results of the proposed numerical and analytical models.
Conclusions. The possibility of frequency-selective propagation of spin waves in a magnon microwaveguide consisting of two layers with different saturation magnetization values is demonstrated. Multimode propagation of spin waves can occur inside a two-layer structure in two frequency ranges. At the same time, this process is accompanied by a strong nonreciprocity of spin-wave signal propagation, which manifests itself in a change in the amplitude and phase responses when the direction of the external magnetic field is reversed. The proposed two-layer spin-wave waveguide concept can be used in the manufacture of magnon interconnects and magnon interferometers with the support of multiband regimes of operation.

Keywords: spin waves, nonreciprocity, microstructures, waveguide, magnonics

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НАУЧНАЯ СТАТЬЯ

Эффекты невзаимности при распространении спиновых волн в двухслойном магнонном микроволноводе на основе пленок железо-иттриевого граната

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Резюме
Цели. Эффекты невзаимности спиновых волн могут проявляться в металлизированных пленках феррит-гранатов. В настоящее время актуальной задачей является исследование динамики спиновых волн в микро- и наноразмерных магнитных пленках. Использование многослойных диэлектрических пленок железо-иттриевого граната (ЖИГ) обеспечивает проявление эффекта невзаимности и в то же время дает большее преимущество по сравнению со слоистой структурой ЖИГ/металл ввиду значительно меньших спин-волновых потерь в двуслойной пленке ЖИГ, состоящей из слоев с различными значениями намагниченности. Такие пленки могут найти применение в задачах магнонной логики для создания управляемых интерферометров типа Маха – Цендера на основе принципов магноники. Цель настоящей работы – объединение концепции невзаимного спин-волнового распространения сигнала и одновременного проявления эффектов, возникающих при распространении спиновых волн в микроволноводах, образованных пленками ЖИГ конечной ширины.
Методы. В работе используются экспериментальный метод микроволновой спектроскопии на основе векторного анализатора цепей и метод конечных разностей для численного моделирования дисперсионных характеристик спиновых волн в двуслойных магнонных микроволноводах. Также использована аналитическая модель, в рамках которой получено дисперсионное уравнение на основе магнитостатического приближения.

Результаты. На основе измерений амплитудно-частотных и фазо-частотных характеристик показана возможность сосуществования двух частотных диапазонов для распространения спин-волнового сигнала в двуслойном магнонном микроволноводе на основе пленки ЖИГ, образованной двумя слоями с различными значениями намагниченности насыщения. Выявлены режимы невзаимного распространения спин-волнового сигнала. С помощью численной модели исследованы механизмы формирования в спектре двуслойной структуры ширинных мод спиновых волн, образующихся вследствие конечных размеров микроволновода. Оценка трансформации спектра мод также проведена при использовании аналитической модели. Экспериментальные данные хорошо согласуются с результатами предложенных численной и аналитической моделей.

Выводы. Продемонстрирована возможность частотно-селективного распространения спиновых волн в магнонном микроволноводе, состоящем из двух слоев с различным значением величины намагниченности насыщения. Показано, что многомодовое распространение спиновых волн может осуществляться внутри двухслойной структуры в двух диапазонах частот. В то же время этот процесс сопровождается сильной невзаимностью распространений спин-волнового сигнала, что проявляется в изменении амплитудно- и фазо-частотных характеристик при изменении направления внешнего магнитного поля на противоположное. Предложенная концепция двухслойного спин-волнового волновода может лежать в основе изготовления магнонных межсоединений и магнонных интерферометров с поддержкой многополосных режимов работы.

Ключевые слова: спиновые волны, невзаимность, микроструктуры, волновод, магноника

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INTRODUCTION

Magnetic thin film systems (MTFS) are used for signal processing [1], magnetic recording and information storage [2, 3], and new applications of metamaterials [4]. The variety of MTFS includes systems of single magnetic films, double magnetic films, and multilayer magnetic films consisting of ferromagnetic (FM), antiferromagnetic, as well as nonmagnetic (NM) films of various thicknesses and arrangements of layers, of which FM/NM multilayers have recently attracted the greatest interest [5]. The study of relaxation processes in magnetic spin systems is one of the most interesting and topical problems. In particular, this is due to recent active research revealing prospects for the practical use of multilayer magnetic film structures.

When creating information processing systems at microwave frequencies, in which information is encoded through the amplitude and phase of magnetostatic spin waves (SW) [6–8] propagating in ferrite films, it is important to study the dispersion of various types of magnetostatic SW, which determines the characteristics of such devices. The concept of magnon logic is being developed for use in a large number of magnon elements, such as majority gates, half-adders, NOR, XOR logic elements [9]. The possibility of creating such elements is due to the linear modes of SW interference in magnonic microwave guides. In particular, the forming block of magnon networks is based on the Mach–Zehnder interferometer, demonstrating the possibility of both constructive and destructive interference of different SW modes in the output section of the interferometer [10]. The use of multilayer dielectric films of yttrium iron garnet (YIG) ensures the manifestation of the nonreciprocity effect as well as offering an advantage over the well-known YIG/metal layered structures due to significantly lower spin-wave losses in a two-layer YIG film consisting of layers having different magnetization values. Ferromagnetic thin YIG films have a significantly lower dynamic damping of SW compared to metallic magnetic films, which has been shown even for the case of YIG of nanometer thickness [20]. Such films can be used in problems of magnon logic to create controllable Mach–Zehnder type interferometers based on magnonic principles.

SW dynamics in nanoscale FM films have been the subject of research in recent decades [11]. One of the promising areas of study is the application of SW for signal processing devices, since the wavelength of SW is shorter than that of electromagnetic waves in the gigahertz frequency range [8]. Thus, the miniaturization of magnonic devices becomes an urgent problem [12]. The concept of dielectric magnonics represents an alternative to semiconductor signal processing devices [14, 17–19]. In magnonic media, information is carried by SW (or magnons) instead of electrons. Thus, the use of structured YIG provides the basis for the next generation of low power computing [14, 21, 22]. A magnonic microwave guide is a universal element of interconnection between magnonic functional blocks within a magnon network [23, 24]. The lateral limitations of a magnonic waveguide [25, 26] comprise an internal feature that determines the characteristics of SW propagation along the junction. The simultaneous use of lateral restrictions and multilayer structure for SW propagation has application in frequency- and space-selective modes of waveguide operation.

The nonreciprocity of SW has been known since the work of Damon and Eshbach [8], in which it was predicted that the magnetization precession amplitude of surface modes should be asymmetric with respect to the propagation direction. This now well-known behaviour has been experimentally measured in micro- and nano-sized magnetic films using, for example, the Mandelstam–Brillouin spectroscopy method [27, 28]. The nonreciprocal behaviour of SW has also been studied for FM films with different magnetic anisotropy on the surface [28–32], for films with interband magnon transitions [33], as well as for exchange-coupled films [34]. In addition, it has been theoretically and experimentally shown that the Dzyaloshinskii–Moriya interfacial interaction [37–39] induced in ultrathin FM layers coated with heavy metal films has a remarkable effect on SW spectra, causing nonreciprocity in the dispersion characteristics. However, the use of YIG dielectric films provides a greater advantage over metal films due to significantly lower spin-wave losses in YIG.

On the other hand, SW nonreciprocity, which can manifest itself in the phase, amplitude, or frequency dependence of the direction of SW propagation, is a potentially powerful tool for applications in communication and logic devices used in data processing [39–41]. Nonreciprocal wave propagation phenomena have been the focus of research on photonic and electronic structures. It was found that such structures provide operating modes in insulators, circulators, and gyrators [42, 43]. In the same way, nonreciprocal effects that manifest themselves during SW propagation determine the functional modes of operation of magnonic devices [39, 44, 45]. In order to create interferometers of the Mach–Zehnder type, it will be decisive to study the modes of SW propagation in a magnon microwaveguide of finite width made of a multilayer ferrite film.

In this paper, we study the spin-wave dynamics in a two-layer magnon waveguide using a numerical model, as well as micromagnetic simulation and an experimental study based on microwave spectroscopy. By analyzing the magnetic properties of each layer and their equilibrium configurations, optimal conditions are predicted for increasing the frequency nonreciprocity coefficient of counter SWs in the Damon–Eshbach configuration, which are then confirmed by simulation. Such counter SWs can be measured using microwave spectroscopy for a prototype two-layer YIG-based microwave guide. The proposed concept of a two-layer spin-wave waveguide can inform the manufacture of magnon interconnectors and magnon interferometers with the support of multiband regimes of operation.

1. STRUCTURE AND EXPERIMENTAL RESULTS

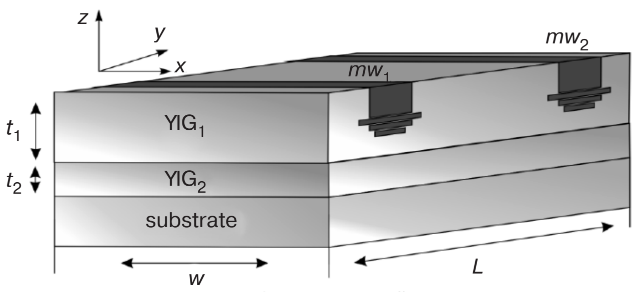

Fig. 1. Schematic representation of a two-layer magnon microwave waveguide with microwave antennas on top of one of the layers

Figure 1 shows the scheme of the investigated two-layer spin-waveguide structure. Single-crystal ferromagnetic two-layer ferrite YIG [$Y_3Fe_5O_{12}$] films (NII MV, Zelenograd, Russia) 0.5 × 7 mm^2 in size, epitaxially grown on gallium gadolinium garnet (GGG) [$Gd_3Ga_5O_{12}$(GGG)] substrates (NII MV), whose plane coincided with the (111) crystallographic plane, were used for the study. When creating a film on a GGG substrate, we first grew a pure YIG layer 7 μm thick with a saturation magnetization of $4\pi M_1$ = 1738 G (we will call this layer YIG$_1$), and a 9 μm thick YIG layer doped with gallium and lanthanum was grown on it with a saturation magnetization $4\pi M_2$ = 904 G (we will call this layer YIG$_2$). The structure is placed in a uniform external magnetic field H_0 = 670 Oe, oriented along the positive or negative direction of the x axis. The width of both samples was w = 500 μm, and the length was L = 7 mm. Input and output microwave transducers (Mikran, Russia) with a width of 30 μm were attached to the structure and marked in Fig. 1 as "mw_1" and "mw_2."

Using the vector network analyzer (model E8362C PNA, Keysight Technologies, USA), an experimental study of the characteristics of the SW was carried out. Figures 2a and 2b show the frequency dependence of the modulus of the gain $|S_{21}|$ in the positive direction of the external magnetic field (red curve), as well as in the negative direction (blue curve), which was measured when the output transducer is located at the end of the structure. Two well-defined frequency bands can be observed: the low frequency (LF) band (2.92–3.01 GHz) in Fig. 2a and the high frequency (HF) band (3.61–4.0 GHz) in Fig. 2b. When the direction of

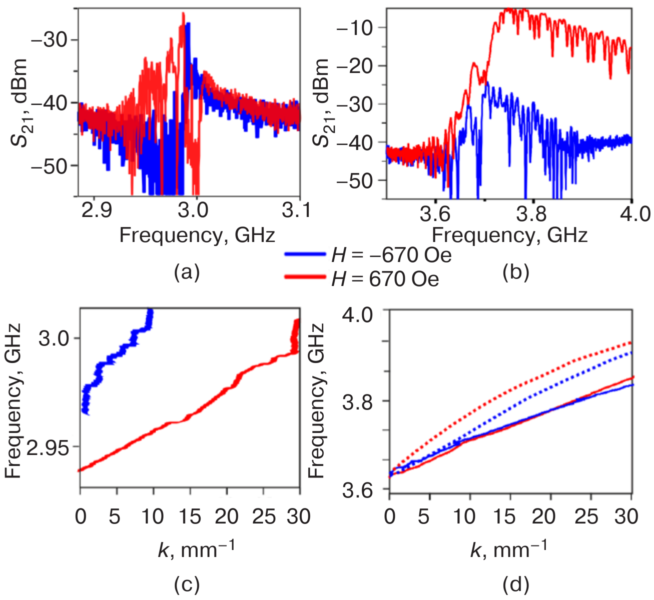

Fig. 2. Transmission coefficient modulus and dispersion characteristics of SW at the output of the structure

the external magnetic field changes, the bandwidth can be seen to change in the LF and HF regions. The SW amplitude decreases in the case of a negative direction of the external magnetic field due to the fact that the microstrip converter was located on one side of the sample, namely, on the YIG_1 side.

Figures 2d and 2c show the measured dispersion characteristics of SWs propagating along a two-layer structure for the positive (solid red curve) and negative (solid blue curve) directions of the external magnetic field in different frequency ranges: low-frequency and high-frequency, respectively. The dotted lines show the results of micromagnetic modeling of the dispersion characteristic in the HF range. A change in the direction of the external magnetic field alters the characteristics of SW propagation in a two-layer structure as a result of different values of magnetization saturation in the layers of the structure under study. All measurements were carried out at a magnetic field value of 670 Oe.

2. NUMERICAL SIMULATION

An analytical model of the dispersion equation was developed based on the magnetostatic approximation for a YIG waveguide of finite width and a dispersion of a two-layer film FM1/FM2, described in [25]. Equation (3) from [19] was used with the replacement of $k_x^2 + k_y^2 - k$ and $k_z = \frac{n\pi}{\omega}$, $n = 1, 2, 3, \ldots$, where n is the mode index of the transversal SW. Figure 3a shows the results of solving the SW dispersion equations in a two-layer structure for w = 500 μm. With the help of numerical simulation using the finite element method, a direct solution of the system of Maxwell equations for the first three SW modes for a two-layer system was obtained. This result corresponds to the dispersion characteristic for Fig. 3a, where each mode is indicated by color: red curve corresponds to n = 1; blue curve corresponds to n = 2; green curve corresponds to n = 3. Good agreement was found between the solution of the eigenmode problem and the analytical approach. Although the modes appear to be the same for the lower branch of the dispersion characteristic, the SW propagates in the YIG layer with a lower saturation of magnetization.

To estimate the nonreciprocity phenomenon, we use the nonreciprocity coefficient in the form $\kappa_{HF} = f_+ - f_-$, where f_+ is the frequency of SW propagation in the positive direction of the y axis, while f_- is the frequency of SW propagation in the negative direction of the y axis with the same wavenumber k. The nonreciprocity coefficient for the lower branch of the dispersion characteristic is determined in the same way: $\kappa_{HF} = f_+ - f_-$. Both coefficients are shown in Fig. 3b and Fig. 3c for w = 500 μm. Thus, as the wavenumber increases, the nonreciprocity coefficient decreases for the upper branch of the dispersion characteristic but increases for the lower one. This opens up opportunities for creating waveguide structures offering the function of signal demultiplexing, filtering and parallel data processing across two separate frequency ranges.

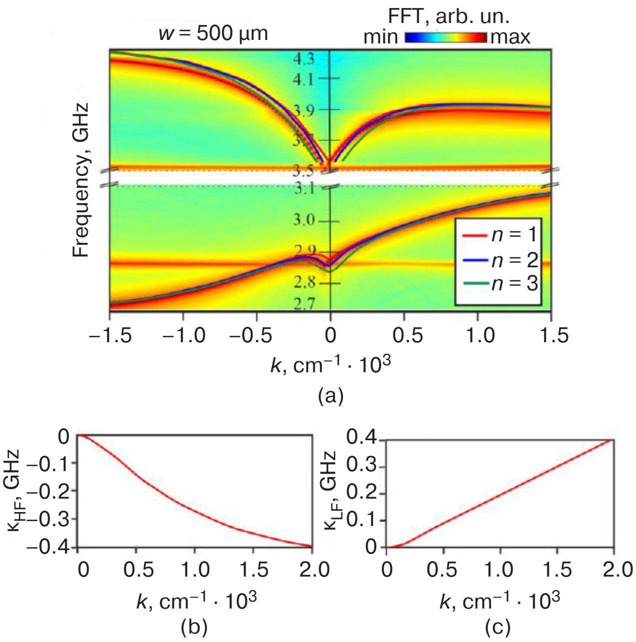

Fig. 3. (a) Dispersion characteristics measured using the analytical model and as a result of micromagnetic modeling; (b) nonreciprocity coefficient κ_{HF} for the HF region; (c) nonreciprocity coefficient κ_{LF} for the LF region

The distribution of the internal magnetic field was estimated by means of a micromagnetic simulation performed using the *MuMax3* program code [47].

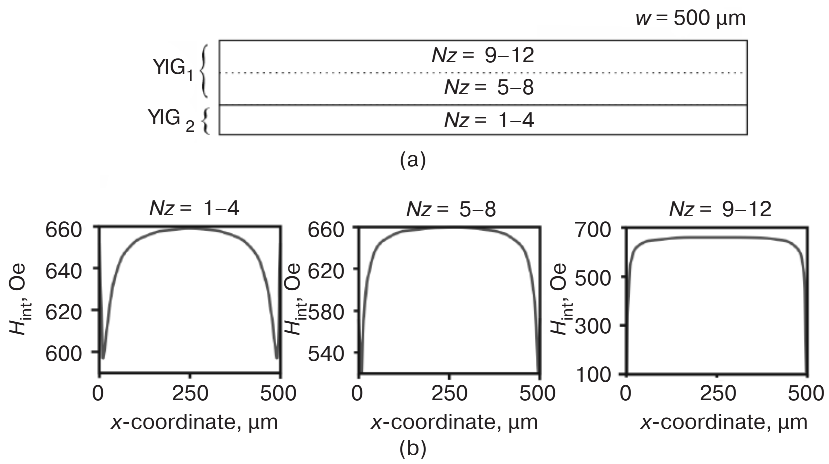

Fig. 4. (a) Schematic representation of simulation along the *z*-axis in *MuMax3*; (b) profiles of internal magnetic fields in layers for $w = 500$ μm

For this, a model corresponding to the experimental sample of the structure under study is considered. The cell size in the system was $4.00 \times 4.00 \times 1.25$ μm^3, while the damping constant $\alpha = 10^{-4}$. The material and the configuration were chosen according to the parameters used in the experiment. The resolution of the computational domain along the *Nz* axis was numbered by 12 layers, which is shown in the diagram in Fig. 4a. The coordinate system is based on the global coordinate system shown in Fig. 1. Figure 4b shows the results of numerical simulation of the profiles of internal magnetic fields in corresponding layers *Nz*, $w = 500$ μm. As the structure's width changes, the internal magnetic fields can be seen to critically decrease by *Nz* = 1–4. Even in the upper layers, internal magnetic fields are impacted by demagnetizing fields and structure boundaries, which in turn strongly affects the propagation spectra of SW in this type of the structure.

The inhomogeneous distribution of the internal magnetic field leads to a more pronounced nonreciprocal behavior of the spin-wave signal. In the two-layer system proposed in [48], frequency nonreciprocity can be turned on and off by simply switching from antiparallel to parallel magnetization without any rotation of the applied magnetic field. Such switching can be conveniently controlled by applying, for example, spin-transfer or spin-orbit torques via a local current. In addition, both parallel and antiparallel states are well known from giant magnetoresistance and tunneling magnetoresistance applications and can be tuned to ensure stability under remanent magnetization. For a real two-layer waveguide, such switching becomes possible by replacing YIG material, for example, by CoFeB [48, 49] and NiFe [50]. This would make it possible to realize an additional degree of freedom for dual-band communication. On the other hand, such replacement can lead to higher losses of SW propagation in metal films. Thus, two-layer YIG waveguides demonstrate the ability to imitate the widely studied dynamic properties of FM-heavy metal layers at the same time as representing a simple approach for controlling the value of nonreciprocity through geometry and equilibrium configuration.

CONCLUSIONS

Thus, the propagation modes of a spin-wave signal in a coupled two-layer ferromagnetic system have been studied. Microwave spectroscopy was used to study the transmission characteristics of SW in a two-layer YIG waveguide. Using the magnetostatic approach along with numerical simulation of the eigenvalue problem, it was demonstrated that the dipole interaction between FM layers, which is created by dynamic magnetizations, is a significant source of nonreciprocity in SW frequencies. The distribution profiles of the internal field and the nonreciprocity coefficient for a two-layer structure are calculated. A transformation of dispersion curves propagating in two opposite directions is revealed. It is shown that two-layer structures support two frequency bands of SW propagation. The formation mechanisms of SW width modes in the spectrum of a two-layer structure, which are formed due to the finite dimensions of the microwaveguide, are studied in a magnonic microwaveguide. In this case, modes corresponding to waves with different group velocity signs are observed in the wave spectrum.

The confirmation of the obtained results by micromagnetic simulation demonstrates the possibility of SW propagation in the low-frequency and high-frequency ranges of two layers in experimentally observed localization of SW modes. As well as opening up new ways to fabricate nonreciprocal magnonic devices, these results encourage a deeper study of this type of system with the aim of optimizing their design to meet the desired application requirements. In this case, the proposed concept of a two-layer spin-wave waveguide can underlie the manufacture of magnon interconnectors and magnon interferometers with the support of multiband regimes of operation.

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Authors' contributions

S.A. Odintsov—condicting, prosessing, and analyzing the numerical and experimental studies, writing the text of the article.

E.H. Lock—creating the experimantal model.

E.N. Beginin—development of numerical research methodology.

A.V. Sadovnikov—development of the research concept, conducting the experimental studies, and editing the article.

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