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Spin wave propagation in a YIG/FeRh composite structure as a system of coupled microwaveguides

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In this paper present that it is possible to control the characteristics of spin waves (SW) in a system of lateral magnetic waveguides made of iron yttrium garnet (YIG) by changing the characteristics of the antiferromagnetic iron-rhodium (FeRh) layer located above these waveguides. In particular it is shown that by changing the geometric parameters and magnetization of the FeRh layer one can control the amplitude and phase of SW propagating in lateral microwaveguides. The modes under which dips appear on the transmittance amplitude-frequency response (AFR) due to redistribution of the SW power are revealed, and their location can be controlled by changing the properties of the FeRh layer. The results obtained can be used to create microwave demultiplexers and taps based on the proposed structure.

Keywords: spin waves, antiferromagnetic, magnonics, lateral structures

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1. Introduction

Recently, a new direction in the study of spin-wave processes in irregular micro- and nanoscale magnetic structures has been rapidly developing — magnonics [1]. The main advantages of magnonic devices are the possible small size, low Joule losses and, as a result, low power consumption. The study of the properties of structures based on the magnonic principles opens up new possibilities for creating miniature devices for transmitting, storing and processing information signals in the microwave range [2,3].

In the manufacture of magnonic structures, films of ferromagnetic materials are used, primarily films of yttrium iron garnet (YIG), which demonstrate record-breaking low values of SW attenuation. Among other YIG-based structures, systems of lateral magnetic waveguides used as filter elements in magnon networks are being actively studied. In such structures, spin waves turn out to be coupled due to dipole fields formed at the boundaries of microwave guides; in this case, both linear and nonlinear modes of SW propagation can be implemented in the system. In this case, due to the width limitation in each individual microwave guide, the SW spectrum is a set of width modes due to discrete values of transverse wave numbers determined by the waveguide width. Thus, the mode of intermode spin-wave coupling in planar topology can be implemented in the system. The study of nonlinear modes of coupled SWs propagation in such microwave guides is important in view of the possibility of using such structures in information signal processing devices, such as half-adders [4]. Also, such a structure is a model system for the nonlinear physics of dissipative systems as a whole [5].

Of particular interest are studies of methods to control the characteristics of SW in such structures. One of the methods of such control is the creation of a composite structure, in which, by using the properties of the added component (region, layer), it is possible to change the mode of operation. By using ferroelectric or piezoelectric layers, it turns out to be possible to implement the control mode for the SW coupling characteristics in the lateral YIG microstrips [6,7].

Recently, antiferromagnetic materials have been considered as one of the potential elements for magnonic devices [8]. Thus, in particular, alloys based on FeRh [9,10] are being actively studied, which have high magnetization in the ferromagnetic phase at low temperatures, and also have significant magnetoelectric, pyroelectric, and piezoelectric effects that occur near the metamagnetic phase transition of the 1st genus.

In the present article, we study the regimes for controlling the coupling of spin waves based on a composite structure implemented on the basis of lateral YIG microstrips with a FeRh layer located above them. In this case, due to the laser radiation focused on the FeRh layer, the mechanism of switching of the spin-wave signal is implemented in the system, which is observed as a redistribution of the SW power between the lateral stripes.

2. Studied structures and numerical modelling

Figure 1 shows a schematic representation of the structure under study, which consists of two microstrips (S_1 and S_2) oriented along the x axis and connected through the side

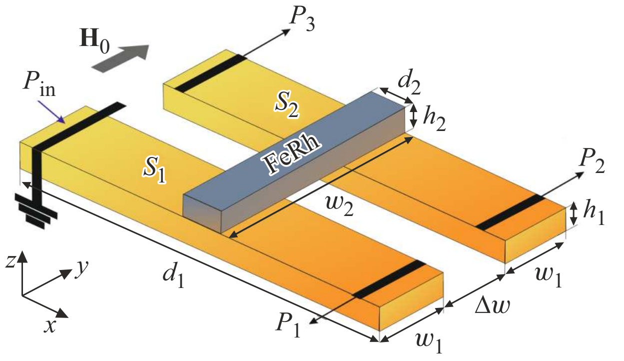

Figure 1. Parameters of the studied structure.

wall, and located across the top layer of FeRh. A lateral gap between the side walls of the microwave guides S_1 and S_2 $\Delta w = 40$ μm. Each microstrip is a waveguide $d_1 = 7000\,\mu$m long, $w_1 = 200\,\mu$m wide and $h_1 = 10\,\mu$m thick. Yttrium iron garnet (YIG) $Y_3Fe_5O_{12}$ [11] with saturation magnetization $M_0 = 139$ G and ferromagnetic resonance line width $\Delta H = 0.54$ Oe was used as a material for microwave guides in numerical simulations. The FeRh layer is located in the center of the structure above S_1 and S_2 and has the following dimensions: the length of d_2 varies from 50 to 150 μm, width $w_2 = 440\,\mu$m, height $h_2 = 10\,\mu$m. The magnetization of the FeRh material in the ferromagnetic state $M_{fr} = 215$ G, the magnitude of the magnetization can be controlled by heating, near room temperature.

The structure was placed in an external static magnetic field $H_0 = 1200$ Oe in the direction of the y axis for efficient excitation of surface magnetostatic waves (SMSW). In this configuration, a microwave signal was applied to the input antenna P_{in}, located on S_1. In this geometry along the microstrips, it turned out to be possible to excite and control SMSW [12,13]. The signal was received by the output antennas P_1, P_2 and P_3 on S_1 and S_2, respectively.

Using a vibrating magnetometer (VSM) BM-2 [14], hysteresis loops were experimentally measured, based on which the magnetization values of the FeRh alloy were determined. Measurements are carried out according to the following scheme. The sample under study was placed in a uniform magnetic field and set into oscillatory motion with a constant frequency and amplitude. During the experiment, the magnetic field of the oscillating sample created an alternating voltage in the nearby measuring coils, which was proportional to the magnetic moment of the sample. The signal from the measuring coils recorded the dependence of the magnetic moment on the magnetizing field. Thus, it is possible to obtain a magnetization curve of the FeRh layer, from which it can be seen that at a field of 1200 Oe the magnetization of the FeRh layer was $M_{fr} = 215$ G at a temperature of $T = 300$ K.

By solving the system of Maxwell equations by the finite element method in the COMSOL Multiphysics software product, we calculated the spatial dependences of the magnitude of the internal magnetic field $H_{int}(x)$ inside the S_1 microstrip (also for S_2) at different degrees of heating of the FeRh layer, that is, the degree of influence of the magnetization of the M_{fr} layer was studied (Fig. 2). In this case, the simulation was carried out in the frequency region and it was assumed that all components of the electromagnetic field depend on the frequency according to the law $e^{i\omega t}$. In this case the Maxwell's equations for the electric field strength vector $\mathbf{E}$ follow the second-order equation:

$$\nabla \times (\hat{\mu}^{-1} \nabla \times \mathbf{E}) - k^2 \varepsilon \mathbf{E} = 0,$$

where $k = \omega/c$ is wave number in vacuum, $\omega = 2\pi/f$ is circular frequency, f is electromagnetic wave frequency, ε is effective value of permittivity. In this case, the magnetic permeability tensor for tangential magnetization has the form

$$\hat{\mu} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \mu(f) & i\mu_a(f) \\ 0 & i\mu_a(f) & \mu(f) \end{vmatrix},$$

$$\mu(f) = \frac{-f_H(f_n + f_M) - f^2}{f_H^2 - f^2},$$

$$\mu_a(f) = \frac{f_M f}{f_H^2 - f^2},$$

where $f_M = \gamma 4\pi M_0$, $f_M = \gamma H_{int}(x)$, γ is the gyromagnetic ratio.

The change in the magnetization of the FeRh layer can occur, for example, due to the action of laser radiation of different intensity. The abscissa axis in Fig. 2 shows the value of the x coordinate in the range $0 < x < d_1$. It follows from the analysis of the $H_{int}(x)$ profiles that, with an increase in the magnetization M_{fr} at the location of the FeRh layer with S_1 and S_2, a strong decrease in the internal magnetic field is observed, the resulting dip increases in size with an increase in M_{fr}. A change in the magnitude of the internal field is accompanied by a change in the spectrum SMSW, as well as in the coupling coefficient of

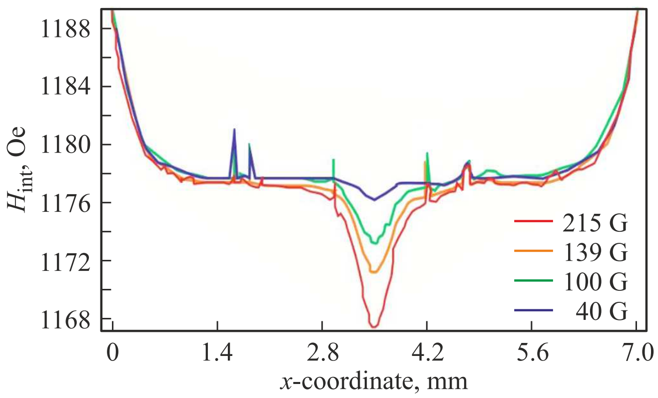

Figure 2. Graph of the distribution of the YIG internal magnetic field along the x axis for different values of the magnetization of the FeRh layer M_{fr}.

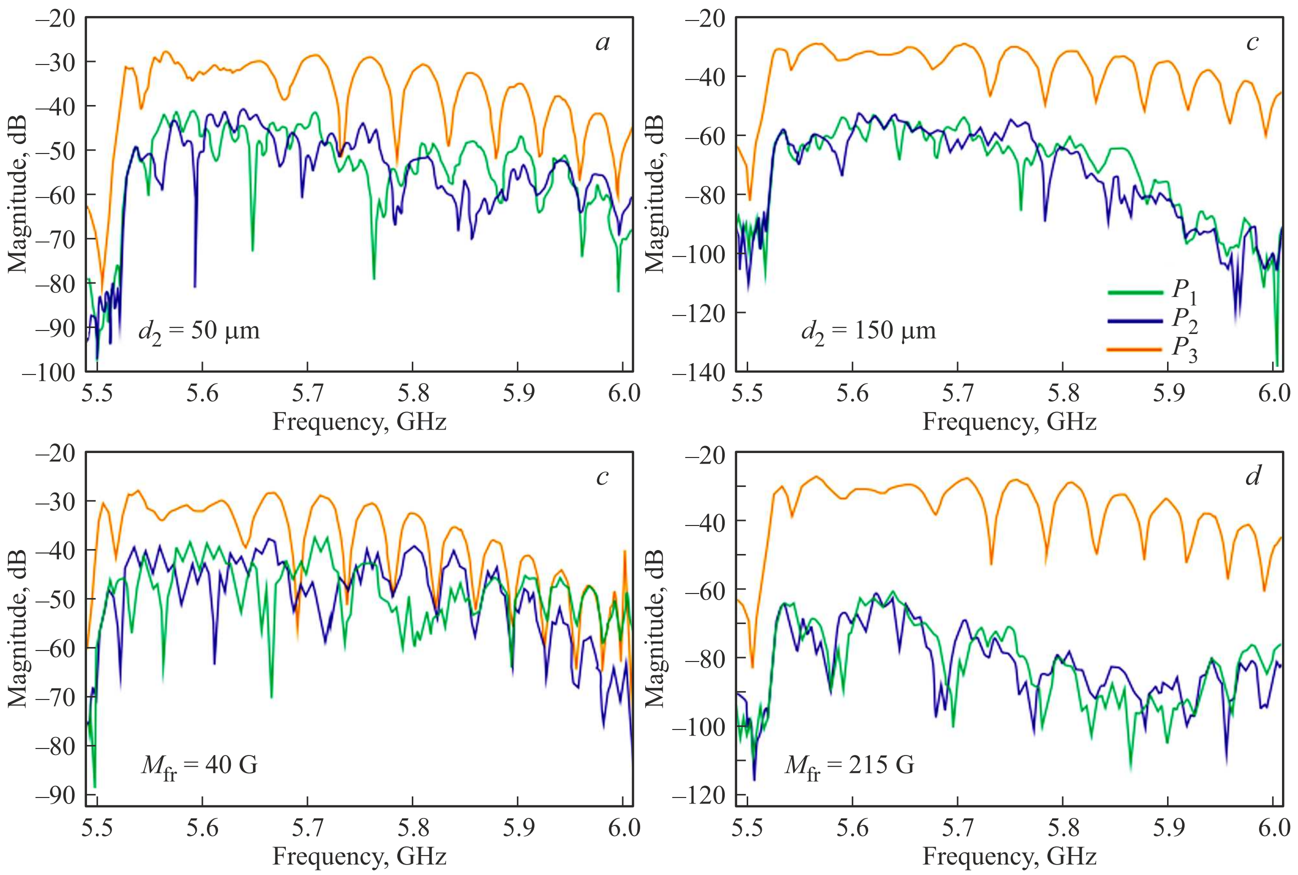

Figure 3. Frequency response obtained by micromagnetic modeling, taken from the P_1, P_2 and P_3 ports. When changing the length d_2 (a). When changing magnetization of the layer M_{fr} (b).

SWs propagating along the lateral microwave guides. It should be also noted that the increase in the magnitude of the internal field near the edges of the computational domain in the interval $0 < x < 1$ mm and $6 < x < 7$ mm is caused by the features of the numerical model and does not affect the data obtained further when solving the problem of spin wave propagation. Since in these areas regions with an increased value of the damping constant were created to reduce the reflection of the spin wave from the boundaries of the structure.

Numerical micromagnetic modeling (MM) was carried out in MuMax3 software [15] based on the numerical solution of the Landau–Lifshitz–Gilbert equation [16,17]. The MM method enables to solve numerically the problem of SW excitation and propagation in a system of lateral microwave guides with a FeRh load. Determining the excitation area and parameters of the input signal in the system, it is possible to observe the stationary mode of establishing the wave process. To determine the control modes of the structure under study, the transfer characteristics were calculated in the regions corresponding to each of the output antennas (P_1, P_2, P_3). Figure 3, a, b shows the frequency dependences of the spectral power density of the spin-wave signal in the composite structure under study for two control methods due to the FeRh layer, namely, by changing the length d_2 and magnetization M_{fr}, respectively. The calculations were performed by the MM method with P_{in} excited by a pulsed signal and performing a Fourier transform. In Fig. 4, blue, green, and orange indicate the frequency dependences of the signal for the regions of the output antennas P_1, P_2, and P_3 of the structures S_1 and S_2 respectively. It can be seen in Fig. 3, a that at a constant value of magnetization $M_{fr} = 139$ G (equal to the YIG magnetization) and selection of length $d_2 = 150\,\mu$m the amplitude value on P_1 and P_2 decreased by 20 dB, but on P_3 it did not change. In Fig. 3, b we can observe that with an increase in M_{fr} a similar situation occurs, also on the ports P_1 and P_2 the amplitude decreases, but is much larger at $M_{fr} = 215$ G. At high values of magnetization, the signal is redirected to P_3. It is important to note that the dip frequencies can be controlled by selecting the parameters of the FeRh layer, which can be used for spatial-frequency selection of the signal applied to the P_{in} input of the structure.

3. Conclusion

Thus, in the present article, we have carried out a numerical study of SW propagation in a YIG/FeRh composite structure in the form of a system of coupled microwave guides. It is shown that by changing the characteristics of the FeRh antiferromagnetic located above the lateral microwave guides, it is possible to modulate the SW propagation, in particular, to redirect the spin-wave signal to one output. The properties of the $Fe_{48}Rh_{52}$ alloy allow for several control paths. The effects of controlling the modes of space-frequency signal separation in the YIG/FeRh composite system enable to create couplers and power dividers of a spin-wave signal in planar topologies of magnon networks for selective processing of information signals.

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Conflict of interest

The authors declare that they have no conflict of interest.

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