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Propagation of nonreciprocal spin waves in a multilayer magnonic crystal

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The possibility of frequency-selective propagation of spin waves in a magnonic microwave guide with a magnonic crystal consisting of two layers with different values of the saturation magnetization in the layers is demonstrated. It is shown that multimode propagation of spin waves can occur inside a two-layer structure in two frequency ranges, while the presence of a magnonic crystal on the surface of the structure leads to the manifestation of a band gap in one of the frequency ranges. At the same time, the process of propagation of a spin-wave signal is accompanied by a strong nonreciprocity, which manifests itself in a change in the amplitude-frequency characteristics when the direction of the external magnetic field is reversed, while the frequency range of the band gap differs depending on the direction of the field. The proposed concept of a two-layer spin-wave waveguide can underlie the manufacture of multichannel filters or magnonic logic devices.

Keywords: magnonics, nonlinearity, nonlinear systems, multilayer systems, spin waves.

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1. Introduction

For a long time, multilayer films based on ferromagnetic materials that support different modes of spin-wave propagation have been of research interest due to the continuous development of both technologies for creating magnetic layers on non-magnetic substrates and the development of ideas for applying spin waves to information signal processing tasks [1]. Such structures are made in the form of single magnetic films, double magnetic films and multilayer magnetic films, consisting of ferromagnetic (FM), antiferromagnetic (AFM) and non-magnetic (NM) films of various thicknesses and arrangement of layers, among which FM/NM multilayer structures caused a large interest in the last decade [2]. The use of multilayer dielectric films of yttrium iron garnet (YIG) ensures the nonreciprocity effect and at the same time gives a greater advantage over the well-known layered YIG/metal structures due to significantly lower spin-wave losses in a two-layer YIG film consisting of layers with different values of magnetization. In turn, the study of controlling the dispersion characteristics of spin waves is an interesting task in view of the use of microwaves, for making magnon networks of signal processing devices for building integrated circuits [3–5]. One of the most promising candidates for efficient spin-wave coupling between functional units of the magnon network are spatially inhomogeneous magnetic structures [6]. By periodically varying the parameters of magnetic materials, magnon crystals (MCs) can be fabricated, which are widely used for spin wave computation [4]. The MC can exhibit a complex zone structure with strong dispersion and anisotropy [7]. The spatial and frequency filtering features of MCs have obvious advantages in magnon applications [8,9].

Thus, the use of multilayer spatially structured ferrite garnet films can serve as the basis for next generation low power computing based on magnonics principles [10–12].

This paper studies the peculiarities of signal propagation in a magnon waveguide formed by an YIG-film consisting of layers of different magnetization with a periodic structure on the surface. Dispersion characteristics for such systems are constructed and mechanisms for controlling the mode spectrum by changing the direction of the external magnetic field are discussed. The proposed concept of a two-layer spin-wave waveguide with MK can be the basis of the manufacture of controlled magnon interconnections with support for multiband operation modes.

2. Structure under study

Fig. 1 shows a schematic representation of the studied bilayer magnon structure in two configurations, with and without a periodic series of grooves. Thus on the surface of the configuration in Fig. 1, *b*, there is a magnon crystal. A pure YIG layer of $t_1 = 7\,\mu$m thickness with saturation magnetization $4\pi M_1 = 904$ G is located on a gallium gadolinium garnet (GGG) substrate, and on it — a LPG layer of $t_2 = 9\,\mu$m thickness with saturation magnetization $4\pi M_2 = 1738$ G. The structures under study are placed in a uniform external magnetic field $H_0 = 670$ Oe oriented along the axis x, to effectively excite surface magnetostatic waves (SMSW) [13]. The groove width was $w_{\mathrm{d}} = 200\,\mu$m, so the period of the structure was $400\,\mu$m.

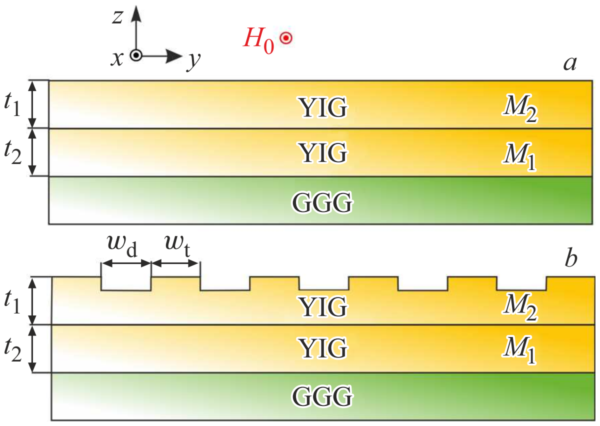

Figure 1. Schematic of the considered structure in two configurations: bilayer waveguide (a), bilayer waveguide with MC on the surface (b).

3. Numerical modelling method

Numerical simulation was carried out by solving the system of Maxwell equations using the finite element method in the COMSOL Multiphysics software product. The dispersion characteristics were calculated assuming that the components of the electromagnetic field depend on frequency according to the harmonic law [14]. The equation for the electric field strength vector had the following form:

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

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

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

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

$$\mu_a(f) = \frac{f_M f}{f_B^2 - f^2}.$$

It should be noted that this method allows the calculations to take into account the inhomogeneous distribution of the internal magnetic field of electromagnetic spin simulations.

The finite element method for calculating the eigenwave spectrum in magnetic microwave waveguides is suitable for the analysis of eigenwaves and power transfer processes in the frequency area near the origin of the spin wave spectrum, i. e. at $k \approx k0\sqrt{\varepsilon}$ and is most efficient for film magnetic waveguides with layer thicknesses of the order of units and tens of microns [15].

4. Results of numerical modelling

Fig. 2 shows the dispersion characteristics of the spin wave modes propagating in the magnon waveguide, which have been obtained using the finite element method. Here are the cases where the saturation magnetizations coincide in the layers, so Fig. 2, a shows the case where both layers $M = 904$ G, and Fig. 2, b for $M = 1738$ G, i.e. the waveguides in these cases have homogeneous magnetization. This shows two distinct frequency bands characteristic of each magnetization value, namely the low frequency band (LF) in Fig. 2, a and the high frequency band (HF) in Fig. 2, b, the

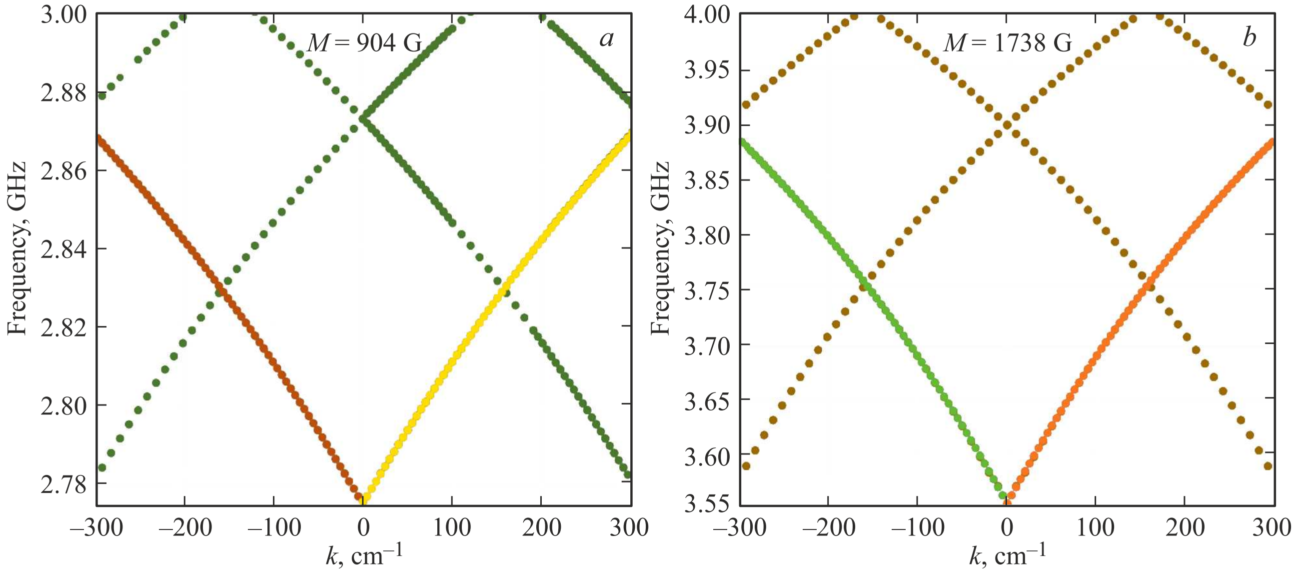

Figure 2. Spin wave dispersion characteristics for a waveguide with homogeneous saturation magnetization $M = 904$ G (a) and a waveguide with homogeneous saturation magnetization $M = 1738$ G (b).

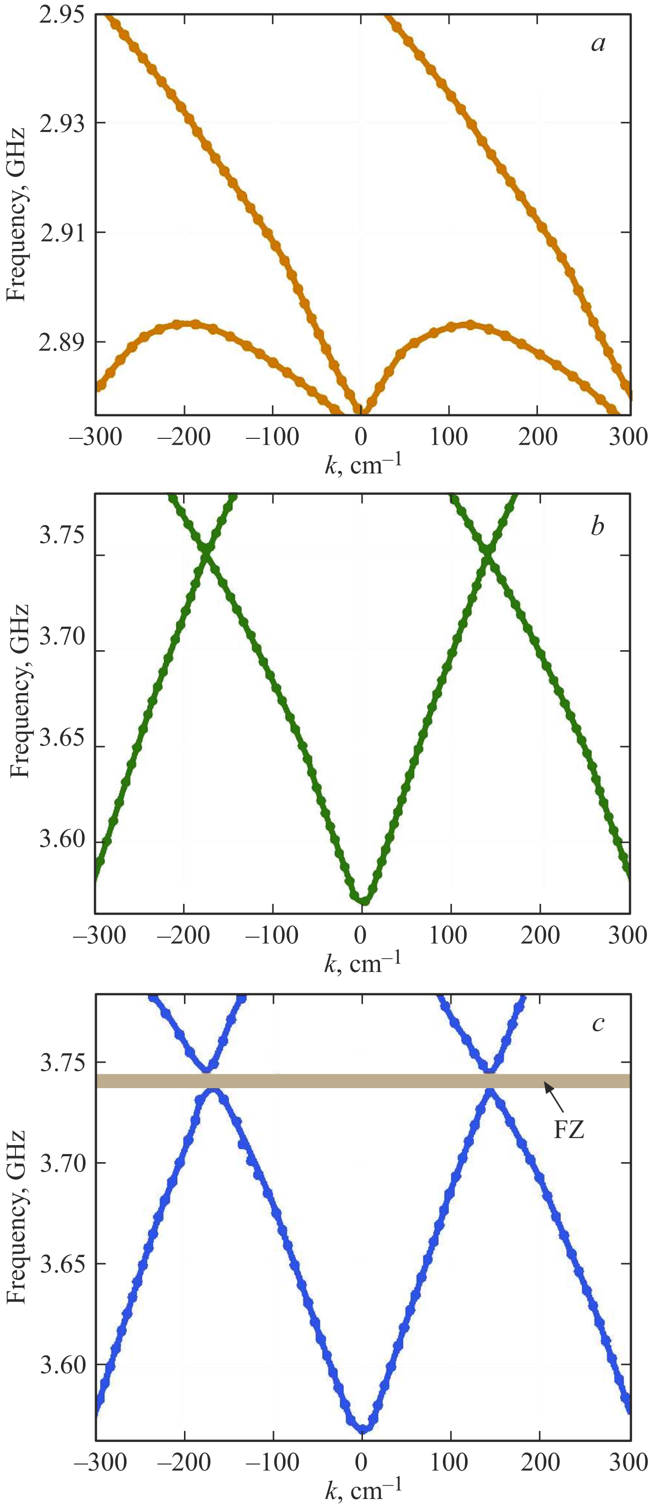

Figure 3. Dispersion characteristics of spin waves in a bilayer waveguide with different magnetizations in the layers: (a) LF area, (b) HF area; (c) dispersion characteristic for the HF area in the structure with MK.

frequency domain being determined by the magnetization value. In this case, the dispersion characteristics are symmetrical when the direction of the external magnetic field is reversed, i.e. in the area of negative wave numbers. That is, there is no effect of nonreciprocal wave propagation. In turn, in a bilayer system where the layer magnetization will be 904 and 1738 G two frequency bands should be observed at which the waves can propagate.

The results of a bilayer structure with different magnetizations in the layers are presented below (Fig. 3, a, b). In this case, both HF and LF frequency bands are observed simultaneously in the structure. It can be seen that with a change in the field polarization, the dispersion characteristics change strongly, especially in the low-frequency range, which shows the strongly nonreciprocal behavior of the SW in the two-layer structure.

Fig. 3, c shows the dispersion characteristic of SW in the case of a periodically varying geometric parameter on the surface, i.e. a magnon crystal. It can be seen that a forbidden zone (FZ, marked in Fig. 3, c, which corresponds to the wave number $k \sim k_B = 2\pi/L$, where L — period of the structure, which is 400 μm, is formed in the dispersion characteristic in the HF range of the studied structure. Thus, in the case in question $k_B = 157\,\mathrm{cm}^{-1}$. It is worth noting, that in the NP area, the dispersion characteristics are not distorted at all, indicating that it is the MC that introduces changes to the SW pass spectrum. Thus, by changing the structure period, we can achieve forbidden zones at different wave numbers and, due to nonreciprocal behavior of the spin waves, the frequency at which the forbidden zone appears to be different, which opens the possibility of creating multichannel filters and applications in communications or logic devices [16].

5. Conclusion

A study was made of the modes of the spin-wave signal propagation in a two-layer magnon waveguide. Numerical modelling and study of the propagation dynamics of SW in a bilayer system with MC bounded in transverse direction from iron yttrium garnet were carried out by the finite element method. The forbidden zones in such a system have been identified, and it is shown, how the geometrical parameters of the waveguides influence the dynamics of spin waves and the forbidden zones in wave propagation in different directions. It is shown that two-layer structures support two frequency bands for the spin waves propagation. The results confirm the possibility of spin wave propagation in the low and high frequency bands, with the possibility of filtering the signal at forbidden zone frequencies. These results open up new ways of manufacturing magnon devices that exploit the effects of non-reciprocal signal propagation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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