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Unidirectional and frequency-selective propagation of spin waves in thin-film double-layer YIG microwaves and spin-wave diodes based on them

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The modes of unidirectional propagation of spin waves (SW) in a tangentially magnetized and transversely confined microwave formed from two layers of yttrium-iron garnet (YIG) with different magnitudes of saturation magnetizations inside each layer are demonstrated. The micromagnetic modeling method based on the numerical solution of the Landau–Lifshitz–Gilbert equation was used to study the modes of propagation of the SW when dissipation in the structure is taken into account. On the basis of the construction of transmission spectra and dispersion characteristics of SW, a two-frequency unidirectional mode of SW propagation is investigated; the accompanying effect is a significant manifestation of the properties of nonreciprocity of surface SW. For inverse bulk SW, hybridization of high-frequency and low-frequency modes is found, manifesting itself in the dispersion characteristics mellowing. The unidirectional nonreciprocal mode of multimode propagation of SW in bilayer microwaves of finite width can be used to realize spintronics and magnonics devices, e. g., spin diodes and functional multiband interconnect elements in integrated topologies of magnon networks.

Keywords: magnonics, multilayer magnetic films, spin waves, dispersive characteristics, micromagnetic modeling, microwave, nonreciprocity.

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1. Introduction

The use of spin waves (SW) allows encoding information signals by changing the amplitude or phase of the wave, which makes it possible to build up logical elements that perform signal processing functions [1–8]. Interest in multilayer structures based on antiferromagnetic, ferromagnetic and ferrimagnetic systems is caused by the ability to control the dispersion, dissipation, and interaction of SWs with the spin and electronic subsystems of the structures [9,10]. For example, for ferromagnetic/heavy metal structures, studies are currently being conducted on the possibility of controlling the SW spectrum due to the asymmetric exchange interaction of Dzyaloshinskii–Moriya [11]. Magnonic multilayer structures are a promising basis for the development of modules for functional elements of magnonics and spintronics, which are used in the processing of information signals [12], including for performing logical operations in the microwave and THz ranges [13–15]. Magnonic structures based on transversely limited magnetic microwaveguides of finite size [16] belong to the class of electrodynamic open waveguide systems and can be considered, for example, as single-layer microwaveguides of rectangular cross-section, filled with a gyrotropic medium, with boundary conditions of „magnetic wall“ type, for which the dispersion law was obtained in a number of studies [17,18]. Obtaining the dispersion relationships for SWs in transversely limited thin-film microwaveguides in an analytical form is difficult, and to study the spectra of eigenwaves in such structures, methods of numerical micromagnetic modeling [19] implemented on the basis of finite element methods or finite difference methods in time domain are widely used. For example, in [20] the propagation of SWs in a two-layer structure based on YIG layers with different saturation magnetizations was numerically studied, however, the mechanism of nonreciprocal nature of the SW propagation in the case of transverse and longitudinal magnetization of a double-layer microwaveguide was not identified. At the same time, for the design of non-reciprocal magnon logic devices [21] it turns out to be important to take into account the transformation of the dispersion characteristics of the SW when changing both the geometric dimensions and the orientation of the magnetization field direction. In the [22] and [23], the analytical theory of propagation of exchange-dipole spin waves in boundless two-layer dipole-coupled magnetic films is presented and experimentally investigated. At the same time, research aimed at creating a magnon transistor [24] could be continued if there is a method that makes it possible to implement modes of unidirectional propagation of SW in magnon structures. Therefore, the task of designing and developing devices based on spin-wave diodes is very important.

In this study, the micromagnetic modeling method is used to study the transformation of the SW spectrum in a two-layer microwaveguide depending on its geometric dimensions. At the same time, the case of the effect is considered of the microwaveguide parameters and the direction of the magnetization field on the frequency range where the non-reciprocal mode of propagation of magnetostatic surface waves is realized. Based on the calculation results, the concept of spin-wave diode is proposed, which makes it possible to implement unidirectional signal propagation modes.

2. The structure under study and micromagnetic modeling

Films and composite structures [25] based on yttrium-iron garnet (YIG) are often used as materials in dielectric magnonics [17] due to the record-low dissipation parameters during SW propagation [26]. Typical paths of SWs in YIG have lengths of a few centimeters for micron-thick YIG films. The microwaveguide under study (Figure 1) is formed by a two-layer YIG film with layer thicknesses of $d_1 = 6.9\,\mu$m, $d_2 = 8.9\,\mu$m and saturation magnetizations of $M_{s1} = 72$ kA/m, $M_{s2} = 138$ kA/m of each layer, respectively. Geometric dimensions of the waveguide under consideration are as follows: total thickness — $L_z = d_1 + d_2$, width — $L_y = 100\,\mu$m, length — $L_x = 1.6$ cm (Figure 1). The microwaveguide was placed in a homogeneous static magnetic field of $B_0 = \mu_0 H_0 = 67$ mT oriented, depending on the type of excited SWs, either along y axis for surface SWs or along x axis for bulk SWs. SWs were excited by a dynamic magnetic field linearly polarized along z axis localized in a spatial region (antenna) with a size of $w_{in} \times L_y \times L_z$ located in the $x = L_x/2$ section (Figure 1). The time dependence of the dynamic field was specified by a function of the following form: $h_z(t) = h_0 \operatorname{sinc}(2\pi f_0(t - t_0))$ (h_0 being amplitude of the dynamic field, f_0 being cutoff frequency, t_0 being time

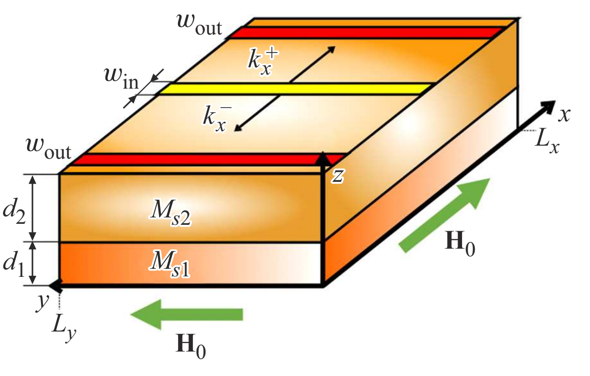

Figure 1. Scheme of the transversely limited two-layer magnon microwaveguide under study. The orientation of the external magnetic field $\mathbf{H}_0$ for various types of SWs is shown with arrows.

shift of the pulse). The transmission spectrum $|S_{12}(f)|$ of SWs was plotted using time realizations $m_z(t, x, y, z)$ obtained in the plane of the output antennas w_{out} located at a distance of $7 \cdot 10^3\,\mu$m from the input antenna. The MuMax3 micromagnetic modeling software [27] was used for the calculations. The $L_x \times L_y \times L_z$ computational area was divided into $8192 \times 32 \times 16$ cells with spatial dimensions of $1.9 \times 3.125 \times 0.98\,\mu\text{m}^3$, other parameters were as follows: total modeling time $t_s = 900$ ns, $h_0 = 0.1$ mA/m, $t_0 = t_s/2$, $f_0 = 5$ GHz, $w_{in} = 5\,\mu$m. Micromagnetic modeling is based on the numerical solving of the Landau–Lifshitz–Gilbert equation for magnetization motion:

$$\frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t} = -\frac{\gamma}{1+\alpha^2}\mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{eff}(\mathbf{r},t) - \frac{\alpha\gamma}{M_s(1+\alpha^2)}\mathbf{M}(\mathbf{r},t) \times (\mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{eff}(\mathbf{r},t)),$$

where γ is gyromagnetic ratio, α is dimensionless attenuation parameter, M_s is saturation magnetization, $\mathbf{M}$ is magnetization per unit volume of the magnetic material, $\mathbf{H}_{eff}$ is effective magnetic field. In this case, the boundary conditions at $x = 0$ and $x = L_x$ were specified in the form of periodic boundary conditions. When numerically integrating the LLG equation, only the following types of interactions are taken into account: Zeeman, exchange and magnetostatic (dipole-dipole) types of interaction. In this case, the effective magnetic field $\mathbf{H}_{eff}$ has the following form: $\mathbf{H}_{eff} = \mathbf{H}_0 + \mathbf{H}_{ms} + \mathbf{H}_{ex}$, where $\mathbf{H}_0$ is external magnetic field, $\mathbf{H}_{ms}$ is magnetostatic field, $\mathbf{H}_{ex}$ is exchange field [7]. The exchange interaction can be neglected in the under-consideration case of thick ferrite films (of the order of $10\,\mu$m) and small values of the spin wave propagation constants ($< 10^4\,\text{cm}^{-1}$). In this case, the interlayer interaction has only a dipole-dipole nature.

Micromagnetic modeling consisted of two stages. At the first stage of modeling, the static problem of the distribution of internal static magnetic fields and magnetization in microwaveguides was solved for a given orientation of the external magnetic field H_0; at the second stage, the problem of excitation of dynamic magnetization $m(x, y, z, t)$ with a given dynamic field $h_z(t)$ was solved. In the course of solving the dynamic problem, successive time realizations of z-component of $m_z(t, x, y, z)$ were obtained for the $y = L_y/2$ section with a fixed time step of $\Delta t = 1/2f_0$. Then, using the two-dimensional Fourier transform for realizations of $m_z(t, x, y, z)$, the dependences of amplitudes of the SW spectrum $D(f, k_x, z)$ on frequency f and propagation constants k_x at fixed values of z coordinate were calculated. The resulting dependences of the $D_s(f, k_x)$ amplitudes were obtained by summing the amplitudes of the $D(f, k_x, z)$spectra over the entire thickness of the microwaveguide. The resulted $D_s(f, k_x)$ dependences represent the dispersion characteristics of SWs in a two-layer microwaveguide. The SW propagation occurs only along the x axis; therefore, in the following only the corresponding propagation constant $k = k_x$ will be considered.

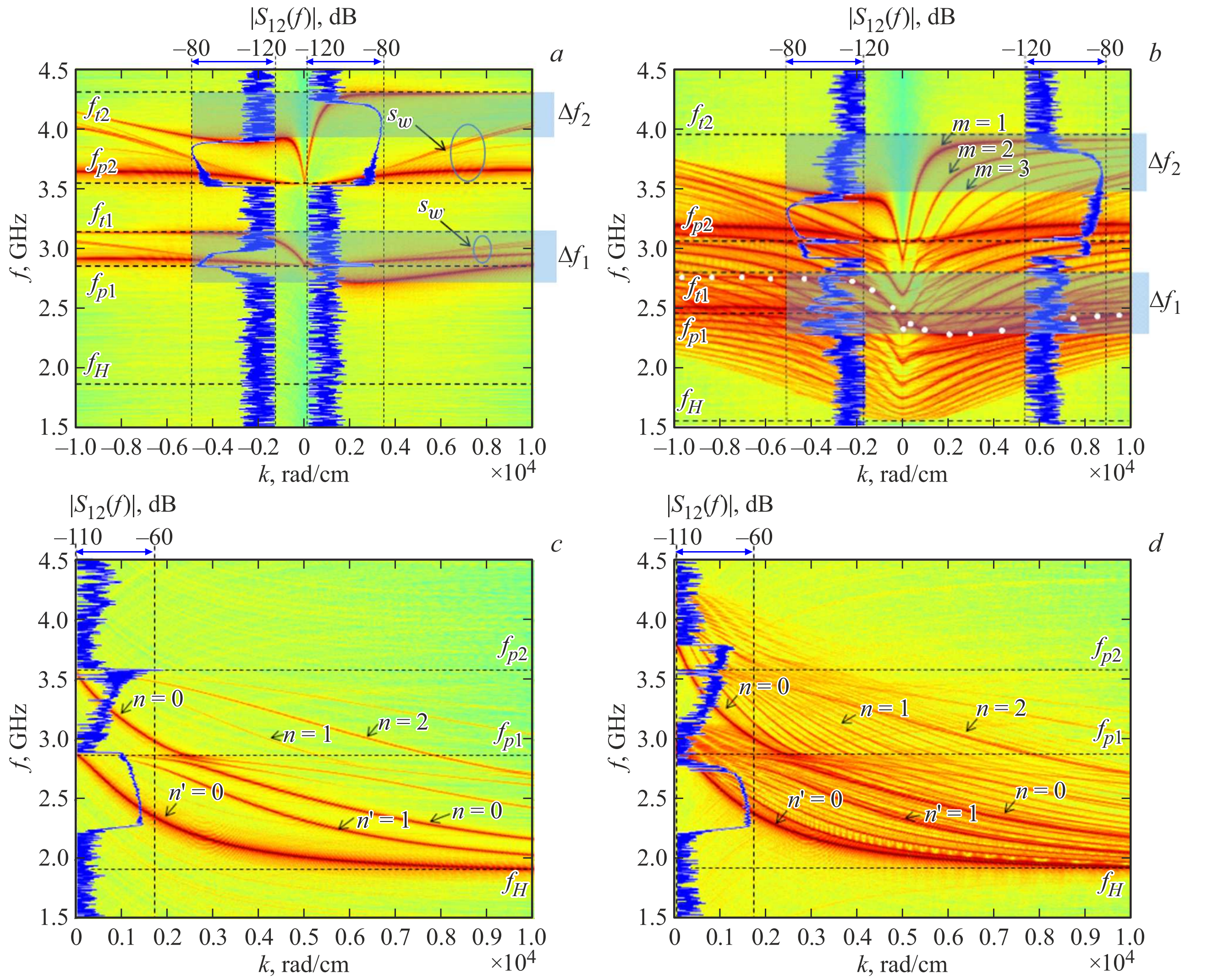

Figure 2. Dispersion characteristics of MSSW (a, b) and BBMSW (c, d) in a two-layer structure: $a), c)$ $L_y = \infty$, $b), d)$ — $L_y = 100\,\mu$m.

The results of calculating the dispersion characteristics $D_s(f, k)$ of SWs and the frequency dependences of the spectral power density $|S_{12}(f)|$ of SWs in the plane of the output antennas for different geometries of microwaveguides and orientation of the external magnetic field are presented in Figure 2 in the form of a color-coded map and blue curves, respectively. Figure 2 also shows frequency boundaries of the existence of magnetostatic SWs. With $k \to 0$ frequencies $f_{p1,2}\sqrt{f_H(f_H + f_{M1,2})}$ correspond to the beginning of SW dispersion branches, with $k \to \infty$ frequencies $f_{t1,2} = f_H + 1/2 f_{M1,2}$ correspond to the short-wave limit, where $f_H = \gamma\mu_0 H_{0i}$, $f_{M1,2} = \gamma\mu_0 M_{s1,2}$, $\gamma = 28\,\mathrm{GHz/T}$ is gyromagnetic ratio, H_{0i} is internal static magnetic field at a given orientation of the external field.

Figure 2, a shows the dispersion characteristics and transmission spectrum of SW in an infinite $(L_y = \infty)$ flat double-layer microwaveguide magnetized along y axis, the internal magnetic field is equal to the external field: $H_{0i} = H_0$. In this case, to consider the boundless structure in the (x, z) plane for $y = 0$, $y = L_y$ sections, periodic boundary conditions were established during micromagnetic modeling. Figure 2, a shows that SWs exist in two frequency ranges: low-frequency range in the region of $[f_{p1}, f_{t1}]$ and high-frequency range in the region of $[f_{p2}, f_{t2}]$. Also, it can be seen that in each frequency range there are SW branches with non-reciprocal $(k^+(f) \neq k^-(f))$ and reciprocal propagation patterns $(k^+(f) = k^-(f))$. As analysis of the distributions of the magnetization component $m_z(z)$ shows, branches with $k^+(f) = k^-(f)$ belong to the highest thickness modes of dipole-exchange SWs in magnetic films with free spins at the interfaces of ferrimagnetic layers [28]. In Figure 2, a the set of these dispersion branches is indicated as S_w. From the point of view of the practical use of SWs in functional elements of magnonics, non-reciprocal SWs are of the greatest interest, therefore S_w modes are not considered. The lowest modes in these ranges are SWs with an exponential distribution of $m_z(z)$ over thicknesses of the ferrimagnetic layers. In the case of single-layer boundless microwaveguides, the lowest SW modes in the magnetostatic approximation correspond to magnetostatic surface waves (MSSW) [29]. A distinctive property of MSSW is the localization of maxima of the $m_z(z)$ distribution at one of the interfaces of ferrimagnetic layers depending on the direction of propagation and the strong dependence of the dispersion characteristics on the symmetry of the boundary conditions [30].

In the high-frequency region of $[f_{p2}, f_{t2}]$, a wave with a propagation constant $k(f) > 0$ corresponds to a SW with a maximum amplitude at the interface between the layer with greater magnetization M_{s2} and the external non-magnetic medium. The dispersions of such a mode weakly depend on the boundary conditions of the layer interface and are close to the dispersion characteristics of the Damon–Eshbach wave [30] in a single-layer flat waveguide with the same magnetization M_{s2}. The SW mode with $k(f) < 0$ is localized at the interface between two magnetic media. The effect of asymmetric boundary conditions at the interface between layers results in the existence of a mode of unidirectional SW propagation for wave numbers $|k| < 0.3 \times 10^4$ rad/cm in the frequency range from 4 GHz to f_{t2} indicated in Figure 2, *a*) as Δf_2.

In the range of propagation constants $k(f) > 0$ corresponding to the low-frequency region of $[f_{p1}, f_{t1}]$, SWs are localized at the interface of layers with different magnetizations. SWs with $k(f) < 0$ are localized at the interface of the layer with lower magnetization M_{s1} and the external non-magnetic environment. The manifestation of asymmetric boundary conditions is also observed in the dispersion characteristics of SWs in the low-frequency region. Near the beginning of the SW spectrum $(0 < |k| < 0.2 \times 10^4$ rad/cm), in the range indicated as Δf_1, a unidirectional transfer of SW energy in the „$-x$“ direction is observed (SW group velocity is $v_g < 0$) except for a small area near $|k| \approx 0$. Unidirectional and non-reciprocal modes of SW propagation in a flat two-layer microwaveguide can be used to implement spin diodes and valves [27,31]. At the same time, it follows from the analysis of the obtained frequency dependences of the power spectral density $|S_{12}(f)|$ that the mode of unidirectional SW branching is implemented in the system under consideration, and is manifested in the different attenuation of SW propagating in directions opposite to each other in the case when the direction of the external magnetic fields is orthogonal to the direction of SW phase velocity.

Figure 2, *b* shows the dispersion characteristics and transmission spectrum $|S_{12}(f)|$ of SW in a transversely limited ($L_y = 100\,\mu$m) two-layer microwaveguide magnetized along y axis. In this case, natural boundary conditions were established in the (x, z) plane for sections $y = 0$, $y = L_y$. In transversely limited microwaveguides, quantization of propagation constants along y axis in the frequency ranges of $[f_{p1}, f_{t1}]$ and $[f_{p2}, f_{t2}]$ results in the appearance of width modes of surface SWs characterized by indices m $(m = 1, 2 \ldots)$ and the trigonometric distribution of magnetization across the width of the microwaveguides [17]. At frequencies of $f < f_{p1}$ and $f < f_{p2}$, the dispersion characteristics are represented by branches of width modes belonging to both bulk and surface SW types. In the high-frequency region of $[f_{p2}, f_{t2}]$ in the frequency range of Δf_2, a mode of unidirectional propagation of width modes of surface SWs effectively excited by the antenna is observed. In other frequency ranges, the propagation of SWs is non-reciprocal for surface-type waves and reciprocal for bulk-type waves. As follows from the analysis of the power spectral density $|S_{12}(f)|$, the efficiency of SW excitation in these frequency ranges is significantly lower. Thus, in the case of transversely limited two-layer microwaveguides, the modes of non-reciprocal and unidirectional propagation can be effectively implemented only in one high-frequency range.

Let us consider the dispersion characteristics of SW in an infinite ($L_y = \infty$) flat two-layer microwaveguide magnetized along x axis (Figure 2, *c*). With this field orientation, backward bulk spin waves (BBSW) propagate with trigonometric distributions of magnetization across the thickness of the magnetic layers. Just like in the case of MSSW, the internal magnetic field is equal to the external field — $H_{0i} = H_0$. SWs exist in two overlapping frequency ranges: $[f_{p1}, f_H]$ and $[f_{p2}, f_H]$. It can be seen in Figure 2, *c*) that the lowest thickness mode $(n = 0)$ for a film with higher magnetization can exist in a region with lower magnetization, because the lower limit of the existence of BBSW is the same. If a transversely limited two-layer structure is considered(Figure 2, *d*), then additional splitting of the branches of the dispersion characteristics occurs due to the additional quantization of the SW propagation constants along the y axis and width modes appear. All branches with different magnetization distributions across the thickness are split into additional branches with different magnetization distributions across the waveguide width. It is worth noting that the propagation of BBSW is reciprocal in nature and the dispersion characteristics are given only for the case of $k > 0$.

Let us analyze how the frequency range will change depending on the difference in the magnetizations of the

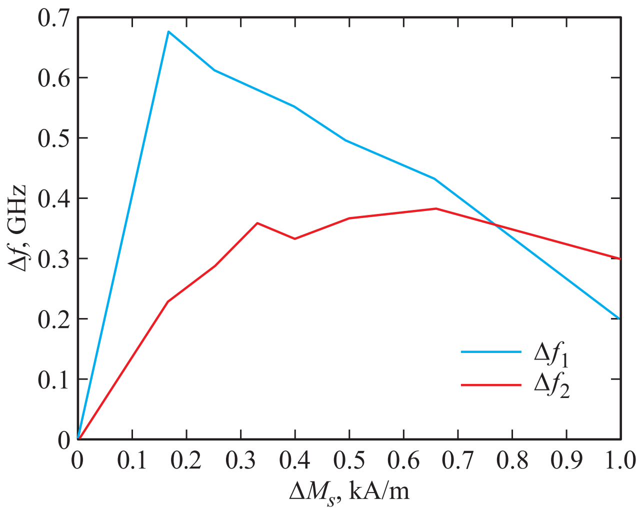

Figure 3. Dependence of frequency ranges of unidirectional SW propagation on the difference between the magnetizations of the layers.

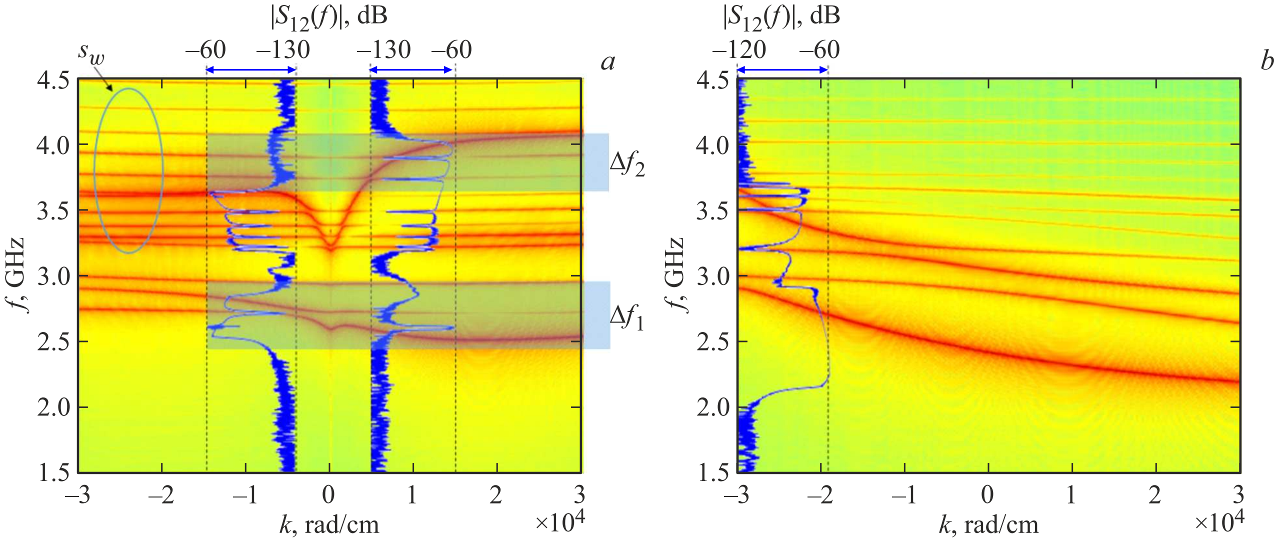

Figure 4. Dispersion characteristics of MSSW (a) and BBMSW (b) in a two-layer structure at $L_y = \infty$ and signal transmission spectra plotted with blue curves.

layers. Figure 3 shows the dependences of the frequency ranges of unidirectional SW propagation on the difference in the magnetizations of the layers $\Delta M_s = M_{s2} - M_{s1}$. The frequency boundaries of the regions were determined by the condition of equality of the SW group velocity on the dispersion characteristics on the corresponding branches. It can be seen that Δf_1 and Δf_2 depend non-monotonically on the difference in magnetizations ΔM_s. This fact can be used to optimize spin-wave non-reciprocal devices for specific requirements.

Let us consider how the SW dispersion characteristics change when thickness of the layers of the two-layer structure under study is reduced to $d_1 = 0.69\,\mu$m and $d_2 = 0.89\,\mu$m, respectively. To simplify the analysis, let us consider only the case of infinite two-layer waveguides.

It can be seen from Figure 4 that the spectrum is a set of SW branches with different distributions of magnetization over the thickness. There is an infinite number of modes with a trigonometric distribution over the thickness (horizontal lines in Figure 4, a), higher modes cross the main mode and hybridization effects occur, i. e. pushing the main mode away from the higher ones. It is important to note that in submicron films the mode of unidirectional propagation is retained, but effects associated with the hybridization of lower SW modes with higher thickness modes are superimposed. The effects of SW hybridization are also clearly visible on the frequency dependences of the power spectral density $|S_{12}(f)|$, where they also correspond to „dips" near the hybridization frequencies.

3. Conclusion

Dispersion characteristics, frequency transmission coefficients, and modes of unidirectional propagation of spin waves in two-layer magnetic structures based on YIG films are studied at different orientations of the external magnetic field, geometric and material parameters of the magnetic layers.

It is shown that in transversely magnetized flat two-layer structures there are two frequency ranges with unidirectional propagation of single-mode spin waves, depending on the difference in the saturation magnetizations of the magnetic layers. In double-layer transversely magnetized microwaveguides, similar regimes of unidirectional propagation of multimode spin waves also exist. The proposed structure is the simplest embodiment of a spin-wave diode, which makes it possible to obtain modes of unidirectional propagation of SW when the field is oriented across the short axis of the microwaveguide, and at the same time, when the direction of the magnetic field is reoriented, the mode of bidirectional propagation of backward bulk spin waves will be realized, and the effect of mode hybridization will be observed, existing separately in the high-frequency and low-frequency ranges of SW propagation in such a structure. The unidirectional mode of SW propagation in transversely limited microwave guides based on two-layer films can be used to implement spin diodes. The operating principle is based on the non-reciprocal mode of SW propagation, and in contrast to metallized structures, where the non-reciprocal mode of propagation is also implemented, systems of double-layer microwaveguides have a lower level of dissipation due to the absence of ohmic losses in the metal.

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Conflict of interest

The authors declare that they have no conflict of interest.

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