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Control of the direction of propagation of spin waves in an ensemble of laterally and vertically connected ferrite microstrips

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The possibility of controlling the direction of propagation of spin waves in an ensemble of laterally and vertically connected microstrips of iron-yttrium garnet (YIG) is shown by numerical modeling. Using the finite element method, the magnitude of the coupling length of spin waves in lateral and vertical geometries was calculated. The numerical value of the spin wave coupling coefficients was found by the finite element method as a result of solving a system of Maxwell equations with a magnetic permeability tensor obtained from the linearization of the Landau-Lifshitz equation. By integrating the equation of coupled waves, the possibility of changing the direction of propagation of the spin-wave signal in the structure under consideration is shown. The signal transmission spectra obtained in micromagnetic modeling indicate a change in the nature of the localization of the spin wave power in the output sections of the microwave with a change in the frequency at the input of the structure. The system of laterally and vertically connected microwave diodes is an element of interconnections for three-dimensional topologies of magnon networks, while demonstrating the functionality of spatial-frequency signal demultiplexing. Keywords: spin waves, magnonics, lateral structures, magnonic crystal, ensembles of related structures.

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1. Introduction

Magnons, which are quanta of spin-wave excitations, can be carriers of a signal, in the case when the spin-wave propagation mode (SW) in ferro- or ferromagnetic films and structures is implemented. The main advantages of using SW include a wide range of SW, whose frequencies can range from a few GHz to hundreds of GHz [1–3] and wavelengths from tens of nanometers to millimeters. The combination of magnon elements makes it possible to create magnon networks (MN) consisting of connected spin-wave elements. The simplest element can be a band of a ferromagnet, bounded in two directions, which is a waveguide of spin waves or, from electrodynamic point of view — a waveguide with a gyrotropic medium. The gyrotropy properties are given by the direction of the external magnetic field, along which the direction of magnetization is arranged in the ferromagnet with sufficient magnetic field values for saturation. The materials for spin wave conductors are currently considered to be YIG films that can be used for information processing and at the same time provide technological integration with the existing semiconductor architecture [3–7]. Recently, it has been shown that a three-dimensional (3D) magnon crystal in the form of a meander [8,9] can provide vertical spin-wave transport by using vertical sections of the magnon waveguide. It was also experimentally demonstrated that the creation of multilayer topologies of three-dimensional structures with the violation of translation symmetry allows to consider the created elements as interconnection nodes for vertically integrated topologies of MN. It is also worth noting, that the use of dielectric YIG films gives more advantages than metallic films because of significantly lower losses on the propagation of spin waves in YIG.

In the present work the dipole fields of scattering of magnon strips for performing vertical and lateral transfer of spin waves and signal transmission between magnonic strips in two mutually orthogonal directions are considered. Each strip is made of thin YIG films. Numerical simulations based on the finite element method (FEM) and micromagnetic (MM) simulation with time and frequency resolution were used to study the dynamics of spin wave propagation in the YIG coupled waveguides system. At the same time, a study was made of the spin wave propagation modes in the arrays of the microwaveguides in question when varying the angle of magnetization.

2. The studied structures and numerical modelling

To study the propagation of spin waves, we considered the structure shown in Fig. 1, which is represented by microwaveguides located in the nodes of a rectangular matrix formed from a YIG film with saturation magnetization $4pM_0 = 1750\,\mathrm{Oe}$. Each microwaveguide has a thickness of $d = 10\,\mu$m, a width of $c = 300\,\mu$m, and a length of $l = 6000\,\mu$m. The lateral clearance between

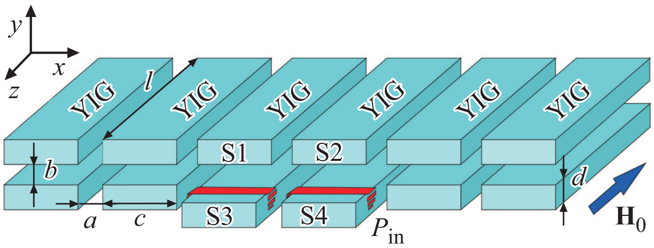

Figure 1. The image of the studied structure consisting of the YIG microstrips array. The red strips depict an area for exciting a spin-wave signal at numerical simulation.

the microwaveguides is $a = 10\,\mu$m, while the vertical clearance along x axis is $b = 30\,\mu$m. The sources used to excite the SW in numerical simulation are located on two microwaveguides on the bottom layer with a size of $300 \times 30 \times 10\,\mu$m.

In the first step, the value of the spin-wave length in the lateral and vertical geometries was calculated using the finite element method [10] (FEM). The system is put into external constant magnetic field $H_0 = 1200$ Oe, directed along the z axis. The YIG microstrips, whose dielectric permeability is a scalar quantity and constant, and whose magnetic permeability can be expressed by a tensor, the components of which depend on frequency [10], are selected as ferromagnetic material. If you know the type of the $\hat{\mu}$ tensor, you need to solve the Maxwell equations for the structure in Fig. 1, *c* with corresponding boundary conditions. If an external magnetic field is directed along the axis z, a surface magnetostatic wave (SNW) will propagate in the YIG film. Solving in a linear approximation the equation of the motion of the magnetization vector (Landau–Lifshitz equation excluding dissipation) under the action of the periodic magnetic field [11], which is a small addition to the constant magnetization field, It is possible to obtain a tensor of ferromagnetic permeability of the ferromagnet [12].

Since the simulation is carried out in the frequency region, it is assumed that all components of the electromagnetic field depend on the harmonic frequency. In this case the

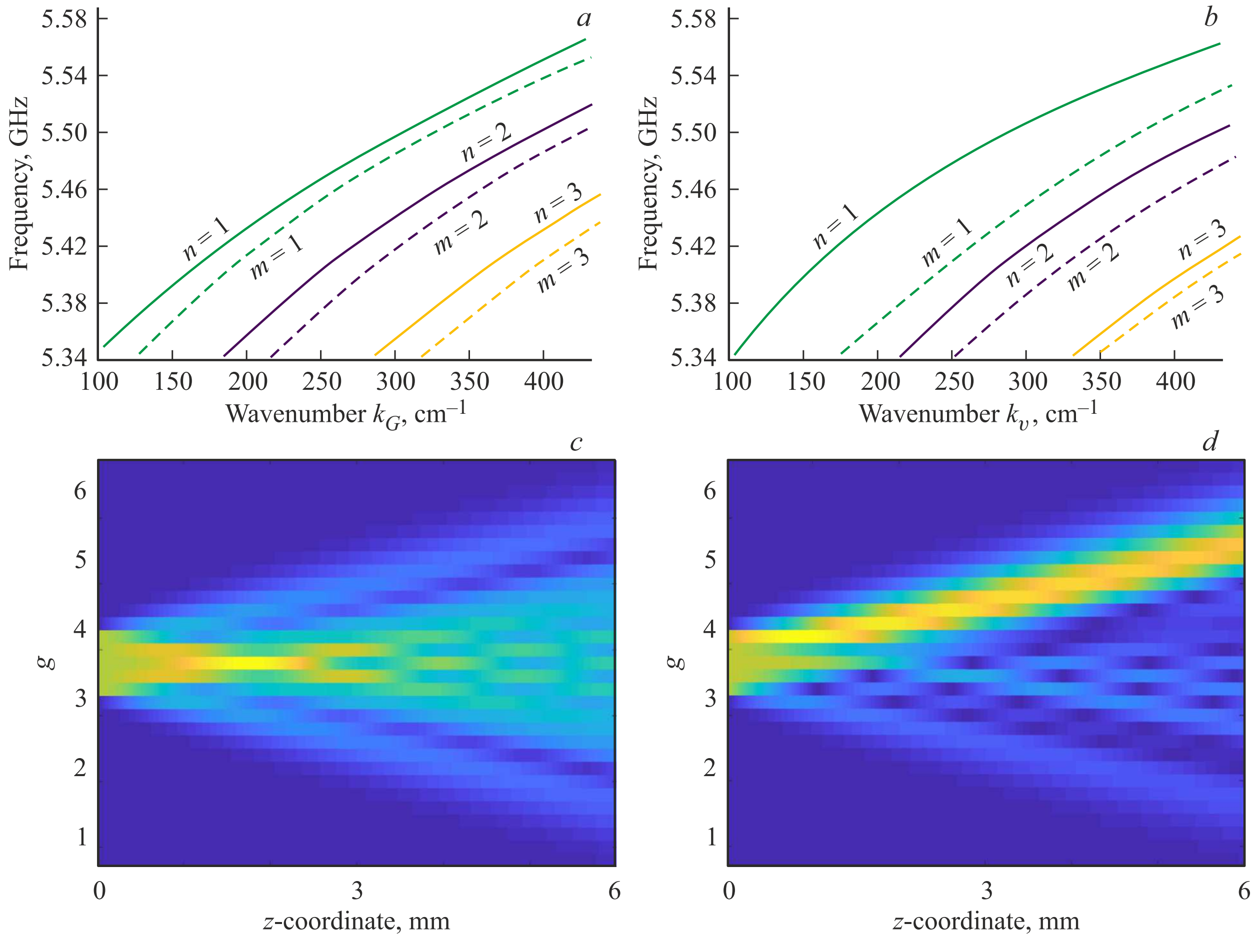

Figure 2. The dispersion characteristics for the spin waves for the lateral coupling case (*a*) and vertical coupling (*b*). The dotted line shows asymmetric forms, while symmetric forms are shown with a solid line. The order of the symmetric form is indicated by the symbol *n*, for the asymmetric — by *m*; *c* — distribution of intensity of the spin beam in theY-section of the structure; *d* — distribution of the dorsal bundle intensity in the Y-section of the structure at phase shift between the sources in a collimated beam mode.

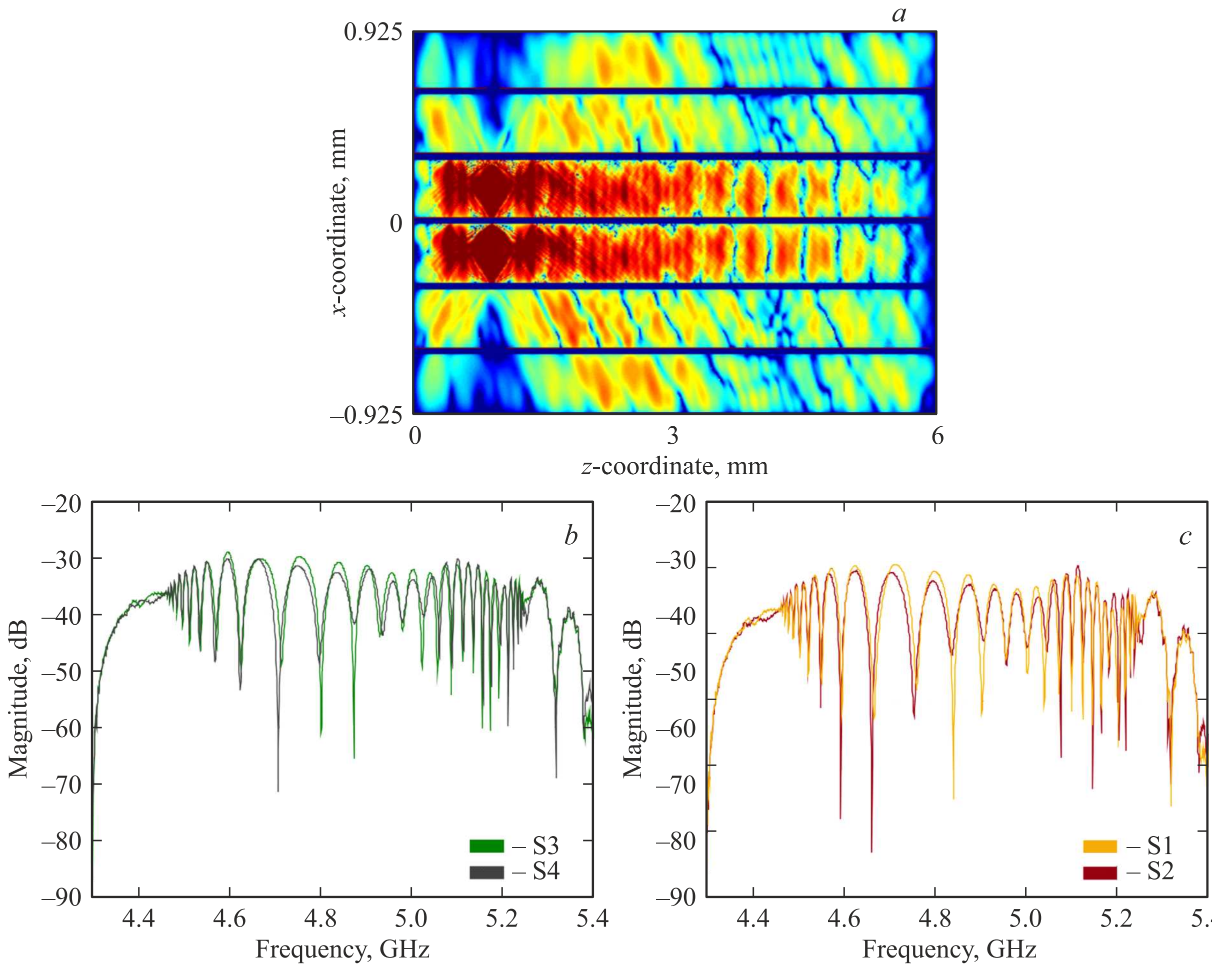

Figure 3. The results of micromagnetic simulation: *a* — spatial spin wave intensity distribution $I(x, z)$ in case of wave excitation in microstrips S1 and S2; it b — spectral power density, detected in output sections of microwaveguides S3 and S4; *c* — power spectral density observed in output sections of microwaveguides S1 and S2.

Maxwell equations for the electric field **E** stress vector follow the second-order equation

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

where $k = \omega/c$ — electromagnetic wavelength constant in vacuum,$\omega = 2\pi f$ — circular frequency, f —linear frequency. Solving the eigenproblem on the basis of equation (1) it is possible to obtain dispersion characteristics for waves propagating in an ensemble of laterally and vertically connected ferrite microstrips. The dispersion characteristics for the lateral coupling case (Fig. 2, *a*) and the vertical coupling (Fig. 2, *b*).are plotted in Fig. 2. The range of eigen forms of each system is a set of symmetric and antisymmetric forms for each of the width forms of the individual microwaveguide operator [13]. The order of the width form of the symmetric type is indicated by the symbol *n*, for the asymmetric — by the symbol *m*. Calculation was made for the first three width forms. The numerical value of the coefficients C_v and C_L was calculated by calculating the difference between the wave numbers of the symmetric k_s and the antisymmetric k_{as} forms [13]:

$$C_{V,L} = |k_s - k_{as}|. \quad (2)$$

Using the calculated values of the C_V and C_L coefficients, a numerical integration of the related wave equation system [14–16] was carried out to describe the spin-wave propagation of the signal in the ensemble of connected ferrite microstrips

$$\frac{dA_{qg}}{dz} = i\beta A_{qg} + iC_v(A_{q+1,g} + A_{q-1,g}) + iC_L(A_{q,g+1} + A_{q,g-1}), \quad (3)$$

where: A_{qg} — amplitude of a spin wave in a waveguide, propagating in the z direction, lower suffix numbers — number of a waveguide along horizontal (q) and vertical (g) directions, respectively; β — wave number of a spin wave at the f frequency in a single insulated waveguide; C_V– and C_L– — vertical and horizontal coupling coefficients, respectively. Spin waves dynamics in the studied system are defined with values of β, C_{V-}, C_{L-}, which, in their turn, depend on the orientation of a static magnetic field relative to longitudinal direction z. In this case, the calculation of the coupling coefficients can be carried out taking into account the heterogeneous distribution of the internal magnetic field value. On the basis of the numerical integration of system of equations (3) the study of the features of the processes of the formation of spin-wave beams in the linear case for systems of connected magnetic waveguides was carried out. The calculation showed that the change of the signal frequency leads to the possibility of formation of a directional beam, as can be seen from Fig. 2 *c, d* of value distribution charts $|A_{qg}|$. The results are well consistent with the isofrequency characteristics for the coupled waveguide system studied in [14–16] works under variation of the magnetization field. In Fig. 2, *c, d* you can see that the signal is distributed from the source area in beam diffraction mode, resulting in a power redistribution between all sections located on the output regions of microwaveguides. When the phase shift between the input microwaveguides is changed to a value of $\pi/2$, there is a formation of a spin waves beam spreading at an angle to the z.axis. The observed effect can be explained by constructing isofrequency characteristics for the coupled waveguide system, as this was done in work [14]. On the isofrequency characteristics, a point corresponding to the selection of a certain pair of values (k_z, k_x) can be noted, at which the formation of a superdirective beam of spin waves [17] is observed.The phase shift at the source of the wave excitation determines the transverse wave number k_x. In the next step, micromagnetic modeling (MM) was performed in the MuMax3 [18] program based on the numerical solution of the Landau–Lifshitz–Hilbert equation [19,20]. The MM method allows numerical solving of the problem of excitation and propagation of SW in an ensemble of laterally and vertically connected ferrite microstrips. Determining the excitation area and parameters of the input signal, it is possible to observe the stationary mode of establishing the wave process in the structure. By constructing the spatial distribution of spin wave intensity $I(x, z)$ in the case of wave excitation in microstrips S1 and S2, it has been shown how the SW intensity is distributed between microwaveguides in the lateral direction (Fig. 3, *a*). In this case, the MM method also produces a power spectral density observed in the output sections of microwaveguides S3 and S4 (Fig. 3, *b*) and in the output sections of micro waveguides S1 and S2 (Fig. 3, *c*). From the comparison of the latter, it follows that the power of the spin-wave signal is redistributed between the YIG microstrips in the frequency range from 4.4 GHz to 5.4 GHz. The obtained spectral characteristics are in the form of alternating signal transmission strips with losses on SW propagation at a distance of 6 mm (−30 dB) and frequency bands, where there is a significant attenuation of the signal to the level of −70 dB, which is due to the redistribution of SW power between the YIG microstrips. The characteristic wave propagation mode is well described by the method of solving the related wave equations using the coupling coefficients obtained by taking into account the heterogeneous internal field profile in the YIG microstrips.

3. Conclusion

Thus, the constructed mathematical model, describing the features of spin wave propagation in an array with the size of 2×6 YIG microstrips, allows us to assert that when exciting two central microwaveguides in the array the mode of the diffraction of spin-wave signal is replaced by the mode of formation of a spin-wave beam. The formed beam is propagated at an angle to the longitudinal axis of the system. The values of spin-wave coupling coefficients for the cases of plane (lateral) and vertical coupling for the array of microdimensional structures are obtained on the basis of the finite element method. The modes of spatial-frequency signal selection were demonstrated by micromagnetic simulation. It should be noted that this class of ensembles of magnonic structures can be used to extend the functionality of information processing devices on the principles of magnonics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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