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Control of spin wave properties in a planar zigzag-shaped YIG-microwaveguide with a diamond-shaped resonator

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The possibility of using the resonance effect to control the signal arising in the process of spin wave (SW) propagation in an iron-yttrium-garnet (YIG) magnetic film with periodic geometry changes in the form of zigzag fractures with the addition of an YIG resonator in the central fracture section has been investigated. Using numerical modelling techniques, it has been shown that the zigzag structure can produce SW non-transmittance zones. It is also shown that it is possible to control the number and depth of the non-transmittance zones on the amplitude-frequency characteristics by varying the distance between the boundary of the YIG microwave waveguide and the resonator. It is demonstrated that the introduction of a diamond-shaped microresonator into the system makes it possible to suppress two frequency zones of non-transmittance at simultaneous formation of one zone with high goodness-of-fit. The reason for the formation of non-transmittance zones in the spectrum of the zigzag magnon structure is similar to the mechanism of formation of forbidden zones in the spectra of SW magnon crystals. The proposed structure can be used as a controlled microwave signal filter.

Keywords: magnonics, planar systems, inhomogeneity, periodic systems.

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1. Introduction

The rapid advancement of information technologies raises the requirements imposed on data processing, storage, and transmission systems. This necessitates the improvement of hardware components of IT systems. One promising approach is the use of magnonic and phonon excitations in ferrite-dielectric structures. Magnonics is a new research direction in the field of microwave physics that offers the possibility of data processing with the use of magnons or spin waves (SWs) without the release of Joule heat [1–3].

One method of controlling spin-wave transport is transformation of the effective magnetic field within a microstructure. This approach may be implemented by changing the local properties of magnonic waveguides or by varying the orientation and magnitude of the bias field. The study of mechanisms supporting spin-wave transport in multilevel topologies of magnonic networks (MNs) based on complex magnonic structures turns out to be an important step on the way to increasing the number of functional elements in MNs. Periodic magnonic crystals are the examples of such structures [4,5].

The key property of periodically structured magnetic films is the capacity to produce forbidden and allowed bands in the SW frequency spectrum or establish preferred wave propagation directions. The properties of forbidden bands (regarded as a means for controlling the characteristics of magnonic crystals) may have a complex dependence on external parameters. For example, forbidden bands and their properties may be controlled by external magnetic fields, spin-polarized current, or metallization of the structure [6,7].

In the present work, the feasibility of using the resonance effect to control the signal arising in the process of SW propagation in a magnetic film made of yttrium iron garnet (YIG) with periodic geometry changes in the form of zigzag fractures was investigated. An YIG resonator supporting ferromagnetic resonance (FMR) [8] was also used to control SW properties in periodic structures. FMR is one of the variations of electronic magnetic resonance. The essence of this phenomenon is that a ferromagnet absorbs the electromagnetic field energy selectively (at frequencies matching natural frequencies of an YIG resonator). FMR is observed when an YIG crystal is introduced into an external constant magnetic field. An YIG resonator has an important advantage in providing an opportunity to tune the frequency within a wide range and at a sufficiently high rate. Frequency tuning is effected by varying the magnitude of the external magnetic field. One may rearrange forbidden frequency bands in SW propagation and alter their Q factor by adjusting the distance between an YIG resonator and a waveguide.

Zigzag periodic structures were examined via micromagnetic modeling, and their natural mode spectrum was plotted. The regimes of control over the frequency ranges of forbidden bands in the SW spectrum corresponding to various types of structure geometry were revealed. The interest in such structures arises from their potential applications as functional microwave electronic devices (filters, noise suppressors, power limiters, etc. [9–11]).

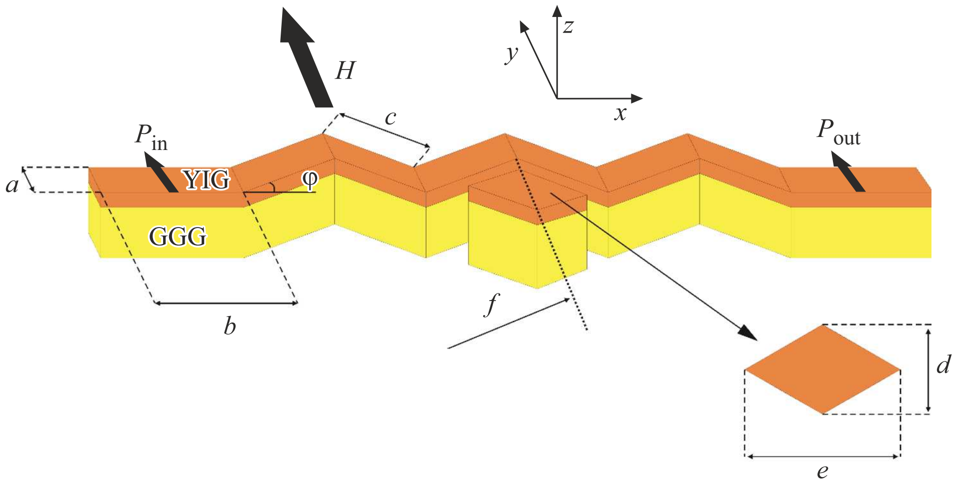

Figure 1. Diagram of the structure under study.

2. Structure under study

In the present study, we investigate the effects arising in the process of SW propagation in magnonic crystalline microwaveguides with a zigzag profile. The results of examination of an YIG structure on a gadolinium gallium garnet (GGG) substrate are presented. Figure 1 shows the schematic diagram of a zigzag-shaped YIG microwaveguide with the following parameters: waveguide width $a = 200\,\mu$m, regular part length $b = 400\,\mu$m, and inclined part length $c = 400\,\mu$m; the total length of the structure was $2900\,\mu$m. The YIG resonator diagonals were $d = 300\,\mu$m and $e = 500\,\mu$m. The microresonator position varied along axis f. The angle of inclination of the zigzag part relative to the input section was $\varphi = 30°$. The microwaveguide had rectangular bases at the opposite ends, where input microstrip antenna P_{in} for SW excitation and output microstrip antenna P_{out} for signal readout were located. The YIG saturation magnetization is $M_s = 139$ G, and the magnitude of the external magnetic field directed along the y axis was $H_0 = 1200$ Oe. A linear waveguide with width a and a similar length was used as a reference structure.

Numerical study

The mumax3 [12] program was used for numerical modeling. This software package is designed to solve temporal and spatial problems related to SW propagation in structures. With this aim in view, the structure is mapped to a grid and the Landau–Lifshitz–Gilbert equation is solved at each node:

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma[\mathbf{H}_{\text{eff}} \times \mathbf{M}] + \frac{\alpha}{M_s}\left[\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}\right],$$

where $\mathbf{M}$ is the magnetization vector, $\alpha = 10^{-5}$ is the YIG film damping parameter, $\mathbf{H}_{\text{eff}} = \mathbf{H}_0 + \mathbf{H}_{\text{demag}} + \mathbf{H}_{\text{ex}} + \mathbf{H}_{\text{a}}$ is the effective magnetic field strength, $\mathbf{H}_0$ is the external magnetic field strength, $\mathbf{H}_{\text{demag}}$ is the demagnetization field strength, $\mathbf{H}_{\text{ex}}$ is the exchange field strength, $\mathbf{H}_{\text{a}}$ is the anisotropy field strength, M_s is the saturation magnetization of the material, and $\gamma = 2.8$ MHz/Oe is the gyromagnetic ratio. The exchange constant parameter for the YIG film is $A_{\text{ex}} = 3.612$ pJ/m.

Mumax3 uses the finite difference method to solve numerically the micromagnetism equations. This method allows for highly accurate approximation of differential equations characterizing magnetic processes, which is especially useful in modeling of such complex structures as periodic waveguides.

To study SW propagation in a periodic zigzag structure, a microstrip antenna with a width of $30\,\mu$m was positioned in the input section of the examined structure. A microwave signal was fed to this antenna. The structure was magnetized tangentially along the y axis to excite a magnetostatic surface wave (MSSW). An antenna in the output section of waveguide was used for signal reception in the numerical experiment.

Amplitude-frequency characteristics (AFCs) of SWs were obtained via numerical modeling by feeding a signal to the input section of the structure and recording the magnetization amplitudes in the output section. The results of micromagnetic modelling were processed in Matlab. AFCs for various system parameters were plotted using the two-dimensional Fourier transform.

3. Results

Figure 2 presents the numerically calculated AFCs. Two non-transmittance bands at frequencies $f_1 \approx 5.37$ GHz and $f_2 \approx 5.46$ GHz with a sufficiently high Q factor stand out against the continuous background of the reference rectangular waveguide (Figure 2, a, blue curve) in the AFC of the studied structure (Figure 2, a, orange curve) at a distance of $200\,\mu$m between the waveguide and

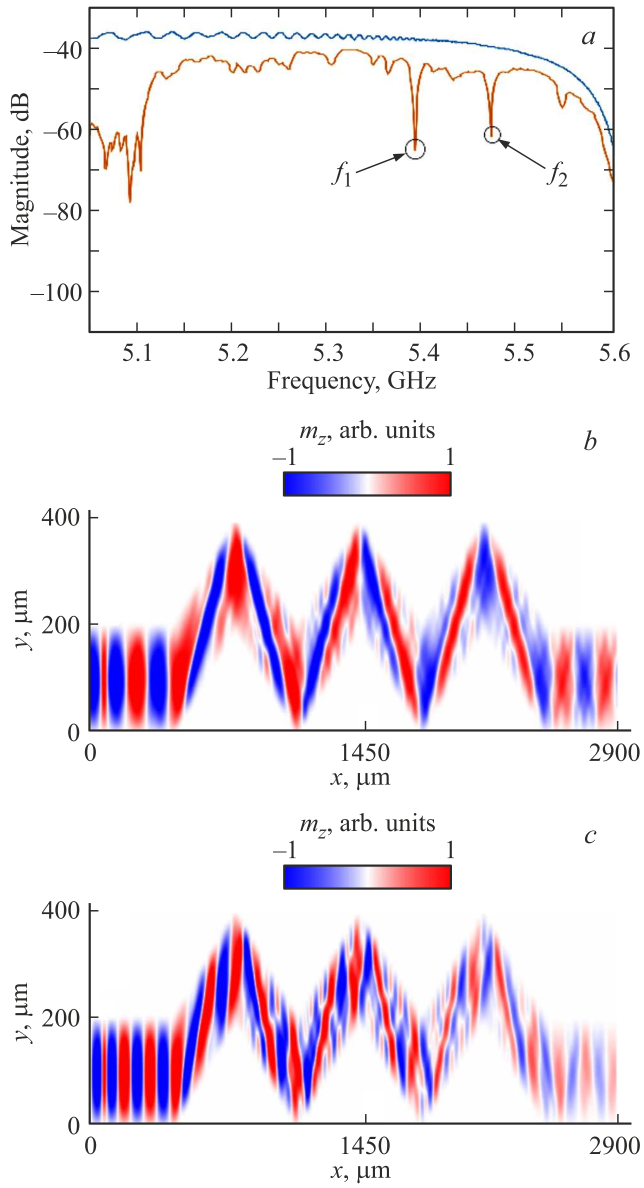

Figure 2. *a*) AFCs for the reference structure (blue curve) and the structure in Figure 1 at a distance of 200 μm between the waveguide boundaries and the resonator (orange curve); *b*) SW spatial distribution at a frequency of 5.2 GHz; *c*) SW spatial distribution at frequency $f_1 \approx 5.37$ GHz of the non-transmittance band.

the microresonator. This effect is induced by repeated SW reflection off each fracture of the structure. Spatial distribution maps of dynamic magnetization component m_z, which may be regarded as the SW phase in the waveguide at frequencies $f = 5.2$ GHz (Figure 2, *b*) and f_1 (Figure 2, *c*), were also plotted. It can be seen that only a fraction of the SW power reaches the output waveguide section at non-transmittance band frequency f_1. At the same time, an SW with wavelength $\lambda_1 = 180\,\mu$m is excited in the input section of the microwaveguide at frequency f_1, while the wavelength at this frequency in the curved section is $\lambda_{c1} = 240\,\mu$m. With the curved section length being $c = \frac{b}{\cos(\varphi)} \approx 465.1\,\mu$m, one may state that relation $\lambda_{c1}/c \approx 1/2$ is satisfied, which corresponds to the condition that the „inclined“ section length is two times greater than the SW length. Taking into account the $\lambda = 2D/n$ Bragg resonance condition for a magnonic crystal, where n is a natural number and D is the magnonic crystal period, one may note that the mechanisms of formation of non-transmittance bands in the proposed structure and traditional magnonic crystalline structures are similar. Thus, it may be pointed out that the cause of formation of non-transmittance bands in the zigzag magnonic structure spectrum is similar to the mechanism shaping forbidden bands in the SW spectra of magnonic crystals formed, e.g., by a periodic system of grooves or apertures on the surface of an YIG microwaveguide positioned at distance D from each other [13–15]. One may then introduce parameter $D_{\text{eff}} = 2c$ (effective period of the considered structure) and obtain the following relation for the wavelength in the curved section: $\lambda_{c1} = D_{\text{eff}}/4$. The emergence of a non-transmittance band with central frequency f_2 in the signal transmission spectrum may be associated with shortening of the wavelength, which establishes the conditions for the formation of a reflected wave and destructive interference of incident and reflected waves at fractures of the structure. The dispersion relation for MSSWs in a film [1] or a microwaveguide allows one to obtain the following estimate: with the frequency changing by 100 MHz (i. e., for input signal frequency f_2), the relation for the wavelength in the curved section takes the form of $\lambda_{c1} = D_{\text{eff}}/8$. A qualitative similarity to structures based on meander-shaped waveguides, where the first Bragg resonance is lacking in the SW spectrum due to the fulfillment of the „gliding plane“ symmetry condition [16–18], may be noted.

To reveal the influence of the diamond-shaped microresonator on non-transmittance bands, the frequency dependence of the spin-wave signal spectral power density was then plotted (see Figure 3) for different distances between the boundary of the „curved“ section of the zigzag microwaveguide and the resonator. The AFCs in Figure 3 demonstrate that non-transmittance bands f_1

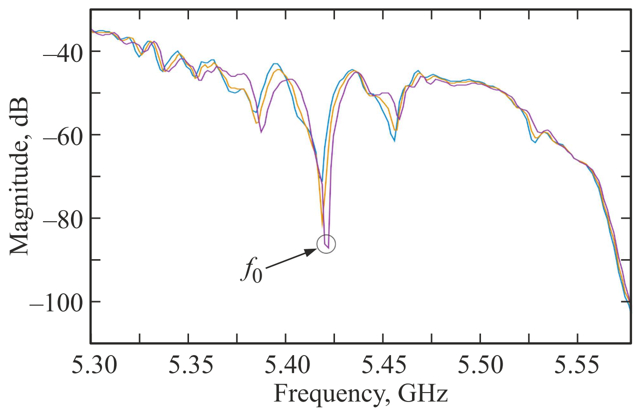

Figure 3. AFCs of the structure at a distance of 40 μm (blue curve); 30 μm (yellow curve); and 20 μm (magenta curve) between the waveguide and the resonator.

and f_2 disappear gradually as the resonator gets closer to the microwaveguide; at the same time, central non-transmittance band f_0 forms and grows deeper. This is attributable to the fact that a fraction of the SW power is absorbed at frequencies near the non-transmittance band due to the dipole-dipole interaction of a traveling wave with the YIG resonator field in the process of propagation along the waveguide structure examined above. The mechanism of interaction between an SW and the resonator is close to the one detailed in [8]. As the distance between the waveguide and the resonator decreases, the coupling efficiency in the resonator–waveguide system increases, and the AFC undergoes a more profound change. It may be noted that, when implemented experimentally, this control method provides an opportunity to use the methods of precision micromechanical displacement [19].

Thus, the proposed planar structure based on an YIG microwaveguide and a diamond-shaped resonator may serve as a controlled microwave filter for logic-based signal processing applications.

4. Conclusion

Numerical calculations revealed that an YIG waveguide with a periodic section in the form of zigzag fractures may alter the frequency composition of an SW passing through it, forming non-transmittance bands in the signal transmission spectrum. In addition, a resonator added to the structure provides an opportunity to control these non-transmittance bands. The composition of non-transmittance bands is controlled by adjusting the distance between the waveguide and the resonator. The mechanism of formation of non-transmittance bands is similar to the process of formation of forbidden bands in SW spectra of magnonic crystals. Forbidden bands of magnonic crystals provide the key advantage in managing the transmission of SWs. They serve as an efficient mechanism for controlling the transfer of magnetic moment in the crystal structure. These control procedures open up opportunities for the development of new devices and technologies utilizing the magnetic properties of materials. This structure may be used as a spatial frequency filter of microwave signals to design devices for magnonics-based data signal processing.

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Conflict of interest

The authors declare that they have no conflict of interest.

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