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Influence of the Electrical Conductivity of a Metal Screen on the Propagation of Spin Waves in YIG Bilayer Films

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This study investigates the influence of the electrical conductivity of a metal screen on the propagation characteristics of spin waves in a bilayer film consisting of yttrium iron garnet (YIG). Using numerical modeling with the finite element method, dispersion characteristics were obtained for various values of the metal screen's electrical conductivity. It was found that decreasing the electrical conductivity of the metal screen reduces the interaction of the waves with it. As frequency and wave number increase, the propagation characteristics of spin waves become more similar to those in a regular bilayer film without a metal screen. These results can be utilized in developing new magnonic devices with improved characteristics and the ability to control spin wave propagation processes, opening new prospects for the advancement of magnonics and spintronics.

Keywords: magnonics, spin waves, multilayer waveguides, yttrium iron garnet, nonreciprocity.

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1. Introduction

Multilayer films based on ferromagnetic materials have attracted considerable attention of the scientific community in recent decades because of the constant development of technologies for creating magnetic structures on nonmagnetic substrates [1]. Magnetic thin-film systems, including single, double and multilayer structures constitute a mixture of ferromagnetic (FM), antiferromagnetic (AFM) and nonmagnetic (NM) layers of various thicknesses and locations, attracting particular interest in multilayer structures of FM/NM in the last decade [2].

The modern search for new spin-wave signal utilization methods for processing of information stimulates ideas about the application of non-reciprocity properties of spin waves (SW) propagating in multilayer structures [1]. Iron-lithium garnet (lignite) is widely used as the main material for magnonics because of its well developed manufacturing technology and low propagation losses. YIG-based thin films can serve as a basis for creating laminar structures such as YIG/metal, demonstrating the manifestation of the non-reciprocity effect in case of reversal of the direction of the SW propagation or any change of the orientation of the external bias field. Double-layer films consisting of the YIG layers with various magnetization have a number of advantages compared with the YIG/metal structures because of the increase of the propagation losses [3]. Despite the known attenuation of SW in case of metallization of the surface of ferromagnetic films [4,5], the effect of the electrical conductivity of the metal on this attenuation has not been previously studied.

The study of waveguide structures based on double-layer YIG films is of considerable interest, especially from the point of view of their use as components of magnon networks. Special attention is paid to the study of propagation modes in magnon microwaves created from multilayer ferrite films, since these structures allow the control of interference modes and can be important elements for the creation of Mach–Zehnder [6]. Non-linear modes of signal propagation in microwave waveguides based on thin YIG films are also possible and are studied using various methods [7–14]. Additionally, multilayer films can be applied for creation of devices with switchable characteristics and spin-transfer devices, which opens up new opportunities for creating energy-efficient and high-speed devices for storing and processing information [15–20].

The features of signal propagation in a multilayer structure which is a multilayer film of an iron-lithium garnet with a metal screen on the surface was studied in this paper. The magnetic film in question consists of two layers of a ferromagnet with different magnetization. Various mechanisms for controlling the spin wave spectrum during changes in the electrical conductivity of a metal screen have been studied. The transformation of the SW spectra was analyzed using mathematical modeling based on the finite element method, which manifests itself in the effect of shifting the high-frequency and low-frequency bands of the spin spectrum when the structure parameter changes. Thus, the use of the features of the SW spectra in double-layer YIG films and methods for controlling the properties of SW in case of the metallization of structures has the potential for designing magnon networks and creating promising magnetoelectronic devices.

2. The studied structure

We consider a mathematical model that allows evaluating the electrodynamic characteristics of gyrotropic structures periodic in one of the spatial directions for studying the effect of metallization on the propagation of spin waves in the structure under consideration. The structure under consideration is a multilayer film of $[Y_3Fe_5O_{12}]$ with a metal screen on the surface. The magnetic film material consists of two ferromagnetic layers with different magnetization. The metal screen is located at a distance of $\Delta d = 1\,\mu$m from the surface of the magnetic film. The geometry of the simulation corresponds to the excitation of magnetostatic surface waves (MSSW) tangential to the magnetized film.

Maxwell's equations for the structure shown in Figure 1 with appropriate boundary conditions are solved to describe the electrodynamic characteristics. The Periodic Boundary Condition (PBC) are defined at the right and left boundaries of the computational domain, which makes it possible to calculate the dispersion characteristics of spin waves for the first reduced Brillouin band. They are written as follows

$$\mathbf{E}(x+L, y) = \mathbf{E}(x, y)\exp(-j\beta_y L),$$

where β_y is the component of the wave vector along the axis y (longitudinal wave number).

3. Numerical simulation method

The finite element method based on solving the system of Maxwell equations was used for numerical simulation and calculation of electromagnetic wave spectra. The spins in the system are considered as free in this approach, the exchange interaction is not taken into account. It is assumed that the components of the electromagnetic field depend on the frequency according to the harmonic law $e^{j\omega t}$, which allows solving the second-order equation for the electric field strength vector $\mathbf{E}$:

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

where $k = \omega/c$ is the wave number in vacuum, $\omega = 2\pi f$ is the circular frequency, f is the frequency of the electromagnetic wave, $\varepsilon = 14$ is the effective dielectric permittivity for the YIG layer.

The magnetic permeability tensor of each layer was specified according to the electromagnetic description of the gyrotropic medium [5]:

$$\hat{\mu}_{1,2} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mu_{1,2}(\omega) & -i\mu_{a1,2}(\omega) \\ 0 & i\mu_{a1,2}(\omega) & \mu_{1,2}\omega \end{bmatrix}$$

$$\mu_{1,2}(\omega) = \frac{\omega_H(\omega_H + \omega_{M1,2}) - \omega^2}{\omega_H^2 - \omega^2},$$

$$\mu_{a1,2}(\omega) = \frac{\omega_{M1,2}\omega}{\omega_H^2 - \omega^2},$$

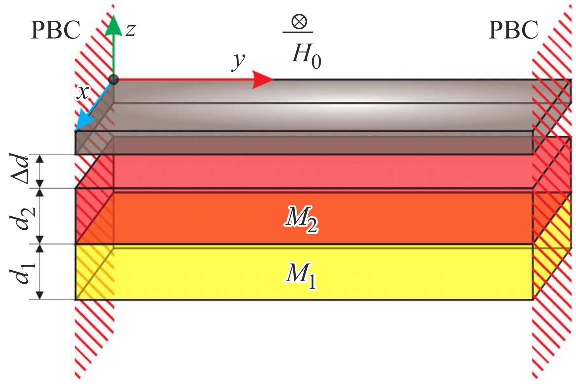

Figure 1. Diagram of the structure under study.

where $\omega_{M1,2} = \gamma 4\pi M_{1,2}$, $\omega_H = \gamma H_0$, $\gamma = 2\pi\cdot 2.8$ MHz/Oe — gyromagnetic ratio in the YIG film, $M_{1,2}$ — saturation magnetization of each layer. One period of the structure was considered to simulate the propagation of natural waves in a periodic structure.

First, dispersion characteristics were obtained for spin waves propagating in the positive and negative directions of the axis y by solving an analytical equation from previous studies for a two-layer structure without a metallized screen Figure 2 [21].

The dispersion characteristics were calculated for a structure shown on Figure 1, in which one layer consists of pure YIG with a thickness of $d_1 = 6.9\,\mu$m and saturation magnetization of $4\pi M_1 = 1738$ Oe (YIG 1), and the second layer — of YIG with a thickness of $d_2 = 8.9\,\mu$m and saturation magnetization $4\pi M_2 = 904$ Oe (YIG 2). In addition to the effect of deflection of one of the dispersion branches because of the impact of the metal near the waveguide structure, a gradual decrease of its impact is observed when the electrical conductivity of the metal screen changes in the HF region of the SW propagation spectrum. A similar dynamics is observed in the LF region up to a certain level, a reversal of the sign of the group velocity at lower k is observed in case of the electrical conductivity below $9e4$ S/m. The dependence of the location of the metal screen on forward and reverse spin waves was studied in more detail earlier Figure 3 [22].

For the structure shown in Figure 1 with layers of thickness $d_1 = 8.9\,\mu$m and $d_2 = 6.9\,\mu$m, saturation magnetization $4\pi M_1 = 904$ Oe (YIG 1) and $4\pi M_2 = 1738$ Oe (YIG 2). A deviation and return of the branch of the inverse MSSW dispersion characteristic is observed in the HF region with a decrease of the electrical conductivity of the metal screen, while another area of branch inflection occurs in the area marked with an arrow in Figure 3, with the value of the electrical conductivity of the screen equal to $9e4$ S/m. The nature of the propagation of reverse spin waves also changes in the LF region, in addition to the impact of the screen on the branch of the dispersion characteristic of the corresponding direct MSSW with a

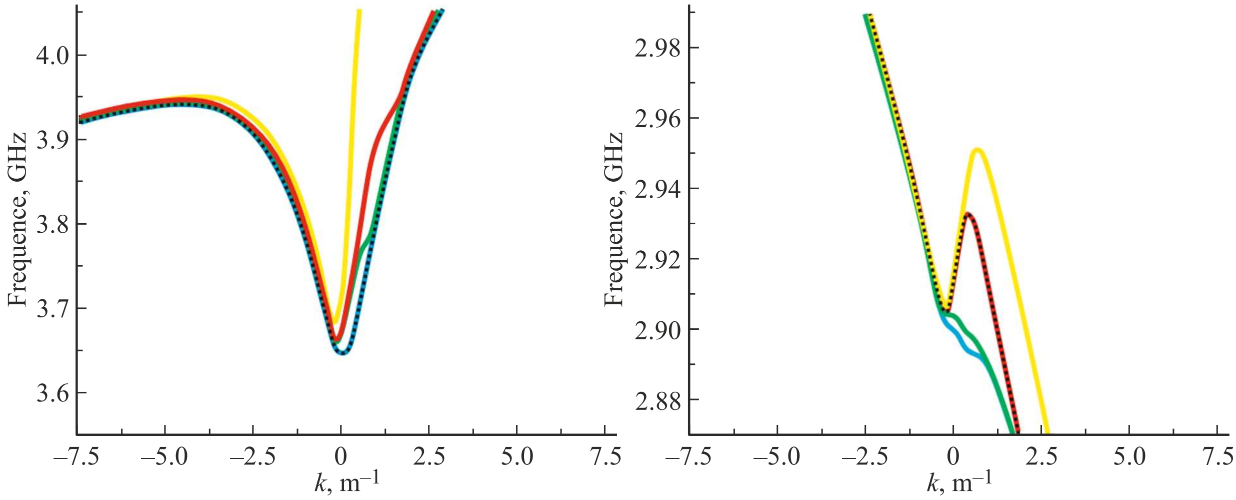

Figure 2. The dispersion characteristics for a structure with a metal shield near the layer with the lowest magnetization at various parameters of the electrical conductivity of the metal shield: 59980000 S/m (yellow line), 90000 S/m (red line), 37500 S/m (green line), 3750 S/m (blue line) and the dispersion characteristics obtained as a result of solving the analytical equation (black dotted curve).

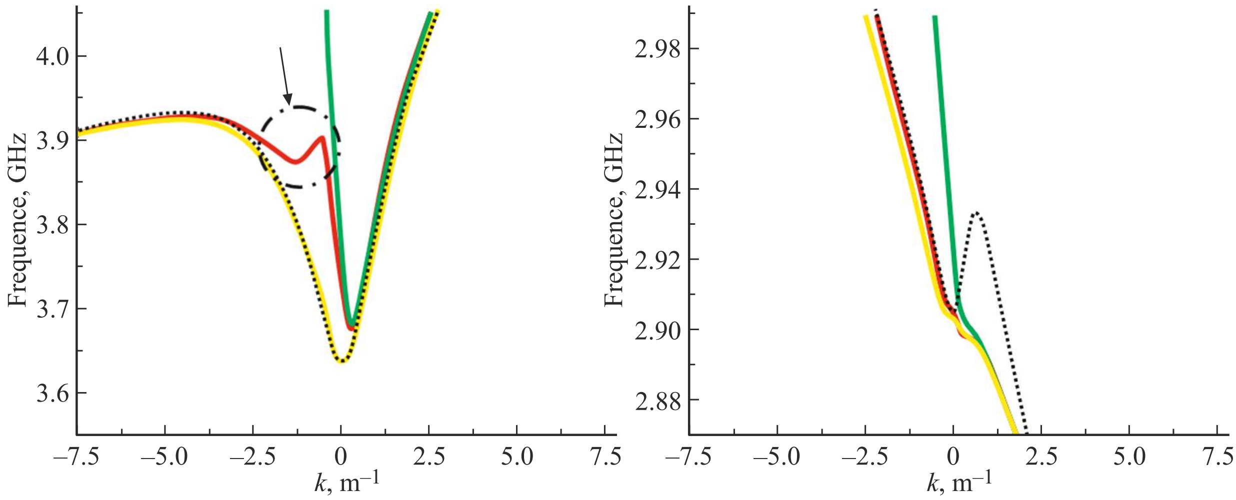

Figure 3. Dispersion characteristics for a structure with a metal shield near the layer with the highest magnetization at various parameters of the electrical conductivity of the metal shield: 59980000 S/m (yellow line), 90000 S/m (red line), 3750 S/m (green line) and the dispersion characteristics obtained as a result of solving the analytical equation (black dotted curve).

decrease of the impact of the screen on the propagation character with a decrease of the electrical conductivity of the metal screen.

These results indicate a significant impact of the electrical conductivity of the metal screen on the nature of the propagation of spin waves in multilayer structures, which may be useful in the design of magnonic devices and circuits for information processing.

4. Conclusion

The impact of the electrical conductivity of a metal screen on the nature of the propagation of spin waves in a double-layer film based on an iron-lithium garnet was considered in this paper. The dispersion characteristics for various values of the electrical conductivity of the metal screen were obtained by numerical simulation using the finite element method. We found based on the obtained results that a decrease of the electrical conductivity of the metal screen results in a decrease of the interaction of waves with it. Moreover, the nature of the propagation of spin waves with an increase in the frequency and wavenumber of the spin wave becomes more similar to the case of wave propagation in an ordinary double-layer film without a metal screen. These results are important for further studies in the field of magnonic electronics and spintronics. They can be used for designing magnonic devices with improved characteristics and the ability to control the processes of propagation of spin waves. They can also be useful in creating new methods of transmitting and processing information based on spin waves.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S.A. Nikitov, A.R. Safin, D.V. Kalyabin, A.V. Sadovnikov, E.N. Beginin, M.V. Logunov, M.A. Morozova, S.A. Odintsov, S.A. Osokin, A.Yu. Sharaevskaya, Yu.P. Sharaevsky, A.I. Kirilyuk. UFN **190** 1009 (2020). (in Russian).

[2] I.V. Vetrova, M. Zelent, J. Solys, V.A. Gubanov, A.V. Sadovnikov, T. Scepka, J. Derer, R. Stoklas, V. Cambel, M. Mruczkiewicz. Appl. Phys. Lett. **118**, 212409 (2021).

[3] A.G. Veselov, S.L. Vysotsky, G.T. Kazakov, A.G. Sukharev, Yu.A. Filimonov. Radiotekhnika i elektronika **39**, 2067 (1994). (in Russian).

[4] N.M. Kozhevnikov. Dis. kand. fiz.-mat. nauk. Vliyanie parametricheskikh spinovykh voln na dispersiyu i zatukhanie magnitostaticheskikh voln v plenkakh zhelezoittrievogo granata (2011).

[5] A.G. Gurevich, G.A. Melkov. Magnetization Oscillations and Waves. CRC Press, London (1996).

[6] A.A. Grachev, A.A. Martyshkin, S.E. Sheshukova, A.V. Sadovnikov, S.A. Nikitov. Elektronika i mikroelektronika SVCh, **1**, 387 (2019). (in Russian).

[7] P.E. Zilberman, S.A. Nikitov, A.G. Timiryazev. Pisma v ZhTF, **42**, *3*, 82 (1985). (in Russian).

[8] A.D. Boardman, S.A. Nikitov, N. Waby. Phys. Rev. B **48**, 13602 (1993).

[9] M. Chen, M. Tsankov, J. Nash, C. Patton. Phys. Rev. Lett. **70**, 1707 (1993).

[10] R.W. Damon, J.R. Eshbach. J. Phys. Chem. Solids **19**, 308 (1961).

[11] T.W. O'Keeffe, R.W. Patterson. J. Appl. Phys. **49**, 4886 (1978).

[12] S.N. Bajpai. J. Appl. Phys. **58**, 910 (1985).

[13] M.A. Morozova, S.V. Grishin, A.V. Sadovnikov, D.V. Romanenko, Yu.P. Sharaevskii, S.A. Nikitov. Appl. Phys. Lett. **107**, 242402 (2015).

[14] A.V. Chumak, P. Kabos, M. Wu, C. Abert, C. Adelmann, A. Adeyeye, J. Akerman, F.G. Aliev, A. Anane, A. Awad. IEEE Transact. Magn. **58**, *6*, 0800172 (2002).
DOI: 10.1109/TMAG.2022.3149664

[15] Yu.A. Yusipova. Izv. vuzov. Elektronika **24**, (in Russian). *2*, 160 (2019).

[16] P.V. Kuptsov. FTT **65**, *6*, 943 (2023). (in Russian).

[17] H. Suhl. J. Phys. Chem. Solids **1**, 209 (1957).

[18] V.E. Demidov, M. Evelt, V. Bessonov, S.O. Demokritov, J.L. Prieto, M. Munoz, J. Ben Youssef, V.V. Naletov, G. de Loubens, O. Klein, M. Collet, P. Bortolotti, V. Cros, A. Anane. Sci. Rep. **6**, 32781 (2016).

[19] U.-H. Hansen, V.E. Demidov, S.O. Demokritov. Appl. Phys. Lett. **94**, 252502 (2009).

[20] A.V. Sadovnikov, E.N. Beginin, M.A. Morozova, Yu.P. Sharaevskii, S.V. Grishin, S.E. Sheshukova, S.A. Nikitov. Appl. Phys. Lett. **109**, 042407 (2016).

[21] S.A. Odintsov, S.E. Sheshukova, S.A. Nikitov, E.H. Lock, E.N. Beginin, A.V. Sadovnikov. J. Magn. Magn. Mater. **546**, 168736 (2022).

[22] A.S. Ptashenko, S.A. Odintsovo, E.G. Locke, A.V. Sadovnikov. FTT **66**, 1 (2024). (in Russian).

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