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To cite this article: V.V. Vitko *et al* 2017 *J. Phys.: Conf. Ser.* **929** 012027

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Investigation of spin waves in magnonic crystal based on periodically metallized YIG film

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Abstract. A theoretical model of ferrite film magnonic crystals made with periodic metallization of the film surface was developed taking into account finite metal conductivity. Results show that finite metal conductivity affects to the insertion losses. The theoretical calculations have a good agreement with the experimental results.

In recent years, magnonic crystals made with periodical variation of magnetic waveguide properties has received significant attention in both physics and engineering. Distinguished features of the spin-wave devices are low insertion losses and magnetic field tunability in a wide frequency range. Performance characteristics of such devices are determined by the dispersion of spin waves (SWs) [1], [2]. One of the important features of the magnonic crystal (MC) is the presence of band gaps in the SW spectrum, i.e. frequency bands in which the propagation of the SW is forbidden [3]. The periodical variation of waveguide properties in this case can be implemented in a form of ferrite thickness and width modulation, external field modulation, periodical metallization etc. [4]. The MCs with periodical metallization of ferrite surfaces are perspective for observation of a variety of different linear and nonlinear SW phenomena [5]. The present work is devoted to the investigation of the SWs dispersion and transmission characteristics of the MCs based on periodically metallized YIG film taking into account conductivity and thickness of the metal electrodes.

The first step of the investigation is deriving of a dispersion relation of the surface SWs taking into account conductivity and thickness of metal electrodes. Investigated structure shown in Fig. 1 consists of the metal layer and ferrite film on the dielectric substrate stacked along the z -axis. The ferrite layer has a thickness of a_f , a magnetic permeability of μ_f , and a saturation magnetization of $4\pi M_s$. The dielectric substrate has a thickness of a_d and a relative dielectric permittivity ϵ_d . The metal layer has a thickness of a_m and a complex relative dielectric permittivity $\epsilon_m = 1 - i\sigma/(\epsilon_0\omega)$, where ω is an angular frequency and σ is a metal conductivity.

The investigated structure is infinite in the xz plane and magnetized to the saturation along z -axis. We assume that SWs propagate along the x -axis that is perpendicular to the external magnetic field H_0 in order to execute conditions for the surface SW propagation.



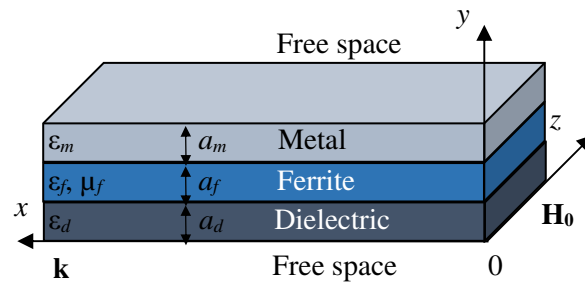


Figure 1. The dielectric-ferrite-metal structure

It is well known that Maxwell's equations can be divided on two systems of differential equations describing two fundamental sets of *TE*- and *TM*-modes with following field structures $\mathbf{E}(0,0,E_z)$, $\mathbf{H}(H_x,H_y,0)$ and $\mathbf{E}(E_x,E_y,0)$, $\mathbf{H}(0,0,H_z)$, respectively. The Helmholtz equations are derived from the Maxwell's equations for each layer: a free space above and below structure, a ferrite, a dielectric and a metal with the complex dielectric permittivity ϵ_m . The application of electrodynamic boundary conditions for the two tangential component of the electric and magnetic fields gives six homogeneous equations, which is equal to the number of undetermined constants. These homogeneous equations have solutions only if the determinant of the system is vanished. Therefore, the transcendental dispersion relation described spectra of the SW in the dielectric-ferrite-metal structures taking into account metal conductivity was obtained.

Numerical modelling was carried out for typical parameters for an epitaxial yttrium iron garnet (YIG) film on a gadolinium gallium garnet (GGG) substrate. The conductivity of metal electrodes was varied in a range from 50 kS/m to 700 kS/m. Following parameters were chosen for numerical calculation: $a_f = 9.8 \mu\text{m}$, $\epsilon_f = 14$, $4\pi M_s = 143398 \text{ A/m}$, $a_d = 500 \mu\text{m}$, $\epsilon_d = 14$, $a_m = 2 \mu\text{m}$, $H_0 = 82919 \text{ A/m}$. The result of the numerical solution of the obtained dispersion relation for real frequencies provided complex wavenumbers. Imaginary part describes Joule's losses in metal electrodes and real part defines a phase shift. Dispersion characteristics and group velocity of the surface SWs in the metallized ferrite for various metal conductivity are shown in Fig. 2(a, b).

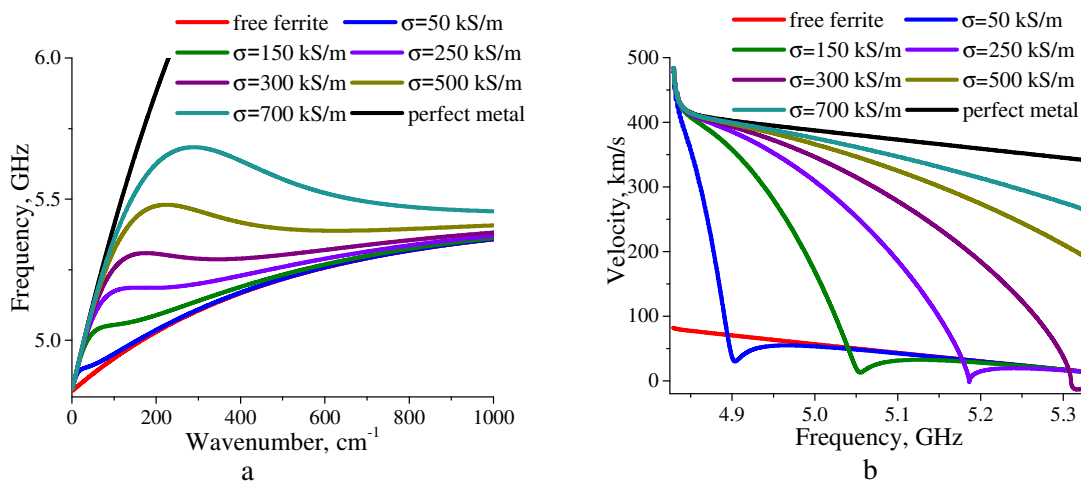


Figure 2. Dispersion characteristics of SWs (a) and dependences of group velocity on frequency (b) at different metal conductivity

One can see from Fig. 2 (a) that the increase from zero to infinity of the metal conductivity leads to change the behaviour of the dispersion characteristic from dispersion in free ferrite to perfectly metallized one. The same behaviour was also observed for the group velocity (see Fig.2 (b)). Note that the wavenumber increase provides electromagnetic field localization inside the ferrite film that leads to reduce of metal screen influence [6].

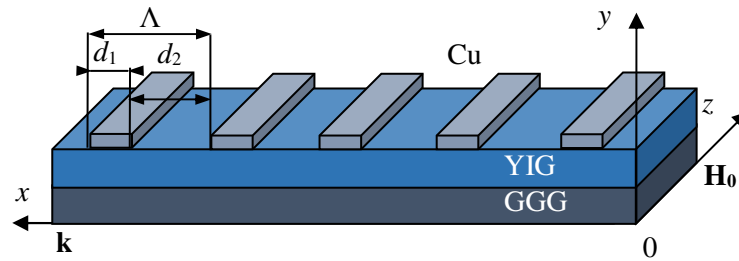


Figure 3. The MC metal-ferrite structure

The second step is the investigation of the transmission characteristics of the MC with periodical metallization that is shown in Fig. 3. The investigated structure is consisted of a metal grating on the surface of the ferrite film. The width of the metal strips is d_1 , the distance between metal strips is d_2 , and the period of the structure is $\Lambda = d_1 + d_2$.

The developed dispersion relation was used for a numerical calculation of transmission characteristics of the MC. According the transfer-matrix method [7] the wave propagation through the one period Λ of the investigated MC was described by the multiplication of T-matrixes, that had the

$$\text{following form: } T_{\Lambda} = T_1 T_2 T_3 T_4, \text{ where } T_1 = \begin{bmatrix} e^{-K_m(\omega)d_1} & 0 \\ 0 & e^{K_f(\omega)d_1} \end{bmatrix}, \quad T_2 = \begin{bmatrix} 1/(1-\Gamma) & \Gamma/(1-\Gamma) \\ \Gamma/(1-\Gamma) & 1/(1-\Gamma) \end{bmatrix},$$

$$T_3 = \begin{bmatrix} e^{-K_f(\omega)d_2} & 0 \\ 0 & e^{K_f(\omega)d_2} \end{bmatrix}, \quad T_4 = \begin{bmatrix} 1/(1+\Gamma) & -\Gamma/(1+\Gamma) \\ -\Gamma/(1+\Gamma) & 1/(1+\Gamma) \end{bmatrix}. \quad \text{Here } K_m(\omega) = ik_m(\omega) - \alpha_m(\omega),$$

$K_f(\omega) = ik_f(\omega) - \alpha_f(\omega)$, $k_f(\omega)$ and $k_m(\omega)$ are the wavenumbers of SW in the free ferrite film and the metallized one, $\alpha_f(\omega)$ and $\alpha_m(\omega)$ are the dumping decrements in corresponding sections, Γ is a reflection coefficient between these sections. Therefore, the propagation of the SW in the MC with N periods was described by the following multiplication $T_{\Sigma} = \prod_{w=1}^N T_{\Lambda} = (T_{\Lambda})^N$. The transmission

characteristics was obtained as $S_{21} = 20 \log_{10} (1/T_{\Sigma_{11}})$. This method is suitable for the calculation of transmission characteristics of the finite-length periodic structure taking into account insertion losses.

Transmission characteristics of the investigated MCs were calculated using the described model. In order to check the adequacy of the developed theory, we carried out an experimental research for MCs that were fabricated using an epitaxial YIG film of $a_f = 9.8 \mu\text{m}$ thickness on $a_d = 500 \mu\text{m}$ thick GGG substrate. The ferromagnetic resonance linewidth of the YIG film was $\Delta H = 0.4 \text{ Oe}$ at 5 GHz. A copper grating was formed on the YIG film surface by a thermal evaporation followed by a wet photolithography. It constituted by 8 copper stripes with a period of $\Lambda = 600 \mu\text{m}$ and 16 copper stripes with a period of $\Lambda = 300 \mu\text{m}$. Every strip has the width of $d_1 = 25 \mu\text{m}$, the thickness of $a_m = 2 \mu\text{m}$, and resistivity of $0.1 \mu\Omega \cdot \text{cm}$. Two 50- μm -wide and 3-mm-long microstrip antennas with a separation of 7.75 mm are used for excitation and detection of SWs. Values of magnetic field H_0 and a saturation magnetization $4\pi M_s$ were the same as in the previous section.

The comparison of theoretical and typical experimental results of the transmission characteristic are shown in Fig.4 (a, b) for 8 and 16 stripes, respectively. Numerical calculations for perfect metal electrode and metal with conductivity of $\sigma=98$ kS/m are shown by blue and red lines, respectively.

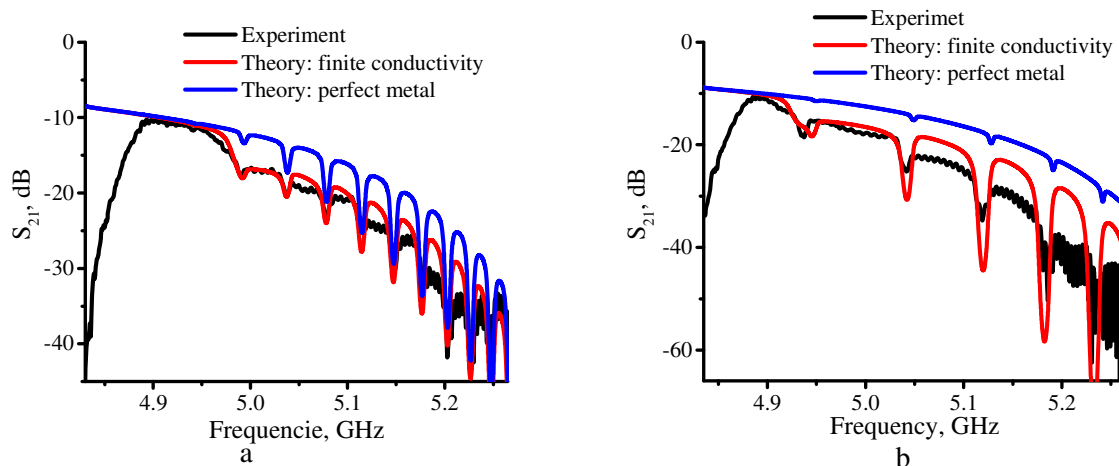


Figure 4. The comparison of experimental and theoretical results of transmission characteristics for MC with 8 periods of 600 μm (a) and with 16 periods of 300 μm (b)

One can see from Fig. 4 (a, b) well pronounced band gaps on transmission characteristics. The YIG film had unpinning surface spins that lead to standing SW resonances and appearance of additional dips in experimental transmission characteristics. Note that increasing of number of periods provides to increase insertion losses. Besides the reduction of the MCs period from 600 to 300 μm leads to the increase of the frequency range between band gaps (from 46 MHz to 106 MHz). It should be noted numerical results obtain for the metal conductivity have a good agreement with experimental ones.

In conclusion, the developed theoretical model provides possibility to investigate a wide range of problems connected with the propagation of SWs in metallized ferrite films and MCs. The dispersion characteristics of SWs in ferrite film with metallization were calculated taking into account the metal conductivity. Transmission characteristics for two types of MCs were experimentally investigated and numerically simulated. It was shown that theoretical calculations have a good agreement with experimental results.

This work was supposed in part by the project Goszadanie, the Russian Foundation of Basic Research (project № 16-32-00715 mol_a), and the Academy of Finland.

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