Magnonic crystals based on ferrite and multiferroic periodic structures

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Abstract. A comparison of spectrum characteristics of ferrite and multiferroic magnonic crystals has been made for the first time. It is shown that ferrite-ferroelectric magnonic crystal band gaps shift in the low frequencies against ferrite magnonic crystal. Theoretical and experimental results are in good agreement.

1. Introduction

Recent years an increased interest for investigation of spin waves propagating in spatially periodic magnetic film waveguide (the so-called magnonic crystals) takes place [1,2]. A feature of the spin wave spectrum of such structures is the presence of band gaps that appear due to Bragg reflection. Such structures can be made of ferrite films [3,4] or of ferrite-ferroelectric structures [5,6]. In the latter case, their dispersion characteristics can be controlled by both magnetic and electric field. It is assumed that such structures can become the basis of the functional microwave (MW) devices of the new generation. At the same time, a survey of the literature shows that the ferrite-ferroelectric periodical structures were studied not enough.

The aim of the present work is an investigation of the performance characteristics of the multiferroic magnonic crystals and their comparison with ferrite-film magnonic crystals.

2. Theoretical investigation

Investigated ferrite-ferroelectric structure is shown in figure 1. It consists of an yttrium iron garnet (YIG) film. A ferroelectric slab can be placed on the top of a periodic magnetic structure. Ferroelectric slab is assumed to be in a paraelectric phase with a high dielectric constant. This assumption is correct for barium strontium titanate (BST) ceramic of the composition $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ at the room temperature. Spin waves (SWs) can propagate in the single ferrite magnonic crystal. Hybrid spin-electromagnetic waves (SEWs) propagate in the layered periodic ferrite-ferroelectric structure.

Consider the development of the electrodynamic model of the structure. The multiferroic structure is assumed to be magnetized by uniform magnetic field $H$ along the $z$ axis, and the waves runs in the direction perpendicular to the direction of the $x$ axis (Fig. 1). This field orientation corresponds to propagation of quasi-surface SWs or SEWs [5] with the maximum of the field distribution occurring...
on the upper interface. We do not take into account existence of the dielectric substrate because it has a low dielectric constant about 10.

Figure 1. Schematic representation of the magnonic crystal based on ferrite-ferroelectric structure.

Figure 2. The theoretical (top) and experimental (bottom) transmission characteristics of magnonic crystal (solid line) and multiferroic magnonic crystal (dotted line). Left graphs correspond $H=1001$ Oe, right graphs correspond to $H=1450$ Oe.

The theoretical model is developed in two stages. In the first stage we derive the dispersion equation and calculate the dispersion characteristics of the SWs in free ferromagnetic film [8] and the SEWs in the homogeneous ferrite-ferroelectric waveguiding structure [7]. As a second step we calculate the dispersion relation of the SEWs in periodic ferrite-ferroelectric structure. We used the following formula obtained by the method of coupled waves [9]:
\[
\cos(K\Lambda) = \cos(k_{l_1}) \cos(k_{l_2}) \frac{k_1^2 + k_2^2}{2k_1k_2} \sin(k_{l_1}) \sin(k_{l_2}),
\]

where \(K\) is a Bloch wave vector, \(\Lambda\) is a period of the structure, \(k_1\) and \(k_2\) are wave numbers of SEWs propagating in thin and thick sections of the structure with \(d_1\) and \(d_2\), respectively, \(l_1\) and \(l_2\) are the distances passed by the wave in the thin and thick sections of the structure (see Figure 1). Finally, the amplitude-frequency characteristics (AFC) of the multiferroic periodic structure are calculated by the following formula:

\[
H = 20\log(e^{-\alpha x}),
\]

where \(\alpha = \left| \frac{dk(\omega)}{dH} \right| \Delta H + \varepsilon_d \left| \frac{dk(\omega)}{d\varepsilon_d} \right| \tan \delta\) is a spatial damping decrement of the SWs and SEWs, correspondingly [10], \(\Delta H\) is the half-width of the curve of the ferromagnetic resonance, \(\tan \delta\) is a tangent of dielectric losses of the ferroelectric layer.

Upper graphs in the figure 2 demonstrate theoretical results. The calculation was carried out for the ferrite layer having parameters corresponding to single-crystal YIG film: \(4\pi M_s = 1760\, \text{G}, d_1 = 5.7\, \mu\text{m}, d_2 = 4.8\, \mu\text{m}, \varepsilon_f = 14\), \(\Delta H = 0.5\, \text{Oe}\). Parameters of the ferroelectric layer correspond to the ceramic solid-state solution of \(\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3\): \(\varepsilon_d = 1200\), \(L_d = 1000\, \mu\text{m}, \tan \delta = 10^{-2}\). Period of the structure \(\Lambda\) was equal 400 \(\mu\text{m}\). The width of the groove \(l_2\) was 50 \(\mu\text{m}\). It is seen that the attachment of the ferroelectric slab to the surface of the YIG film magnonic crystal leads to the frequency shift of the band gaps. The increase of magnetic field leads to increase of the shift value. This is due to the existing of the region of a strong dispersion of the SEWs which corresponds to the maximum hybridization between the spin waves in the ferrite film and the electromagnetic waves in the ferroelectric slab.

3. Experiment

To verify the theoretical results, we carried out an experiment with a magnonic crystal formed from a YIG film by chemical etching. The fabricated sample of the magnonic crystal had a width of 2 mm and a length of 60 mm. The YIG film with thickness \(d_1 = 5.8\, \mu\text{m}\) and saturation magnetization of 1750 G was grown by liquid-phase epitaxy on a gadolinium-gallium garnet (GGG) substrate. The ferromagnetic resonance line-width \(\Delta H\) was 0.5 Oe. To avoid possible unwanted reflected spin waves, the edges of the MC were cut at an angle less than 45°. The experimental periodic structure had a geometry similar to that in the calculations, namely a period \(\Lambda\) of 400 \(\mu\text{m}\), a groove length of 50 \(\mu\text{m}\), and a groove depth of 1.1 \(\mu\text{m}\).

A delay line structure was used for the measurements. Spin waves were excited and received using short-circuited input and output microstrip antennas having a length of 2 mm and a width of 50 \(\mu\text{m}\). The experimental device was placed between poles of an electric magnet in a uniform magnetic field. The distance between the antennas was 8 mm. Thus, 20 periods of the structure under study were situated along the SW propagation path. Delay line design allows the slab of BST overlay on the entire region of the magnonic crystal. A Rodhe & Schwarz ZVA-40 vector network analyzer was used to measure the amplitude-frequency characteristics of the sample under study.

The experimental results are shown in the bottom graphs in the fig. 2. As is seen from the figure, the presence of the periodicity leads to the formation of band gaps both in magnonic crystal and in multiferroic structure. It can be readily seen that the theory sufficiently well describes the characteristic features of the stop bands, namely, their frequency position. Our numerical simulations
did not take into account the SW excitation and reception losses. Therefore, the theoretical curve shows a loss which is smaller than that observed in the experiment. The results are in good agreement with previous theoretical calculation [11, 12].

We used dispersion equation of spin-electromagnetic waves propagating in infinite in plane ferrite-ferroelectric structure. At the same time the experimental structure had a width of 2 mm. Discrepancies between the frequency shift of the stop bands in the experimental and numerical data could be explained by this assumption.

4. Conclusions

In conclusion, amplitude-frequency characteristics of ferrite and multiferroic magnonic crystals has been studied. It is shown that ferrite-ferroelectric magnonic crystal band gaps shifts in the low frequencies against ferrite magnonic crystal. The value of the frequency shift depends on magnetic field. Thus, magnonic crystals based on the planar multiferroic structure consisting of ferrite and ferroelectric layers can find a variety of applications.

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