Insertion loss and dispersion of spin waves in magnonic crystals of finite length

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Abstract

The specific features of the dispersion characteristics of the magnonic crystals having the finite length are discussed. It is demonstrated that the spin-wave spectrum of a spatially finite magnonic crystal (MC) is characterized by the presence of the allowed bands of frequencies where the spin waves may propagate, and the stop-bands (Bragg resonances) where propagation of the spin waves is hindered. It is found that inside the stop-bands the dispersion properties of the finite-length MC differ from that characteristic for an infinite-length MC. It was shown that such a difference depends on the length of the magnonic crystal.

1. Introduction

Magnonic crystals (MCs) are new class of metamaterials with periodically modulated magnetic properties where spin waves can propagate [1]. Reviving interest in such structures is stimulated by fundamental and applied researches [2]. In particular, the periodic magnetic waveguides were used for development of the resonators, filters, delay lines, signal-to-noise-enhances, and directional couplers [3-5]. Microwave properties of such metamaterials can be tuned in a wide frequency range with magnetic field. Most attention was attracted to study of the linear properties of MCs and their dispersion characteristics. However, investigations of the MC properties are commonly performed assuming that a MC has an infinite number of periods. In this case the eigen-frequency spectrum has allowed bands and stop-bands. Spin waves can only propagate in the allowed bands, but can only propagate inside the stop-gaps, which are caused by the Bragg resonances. In the case of MCs which have a finite number of periods, instead of the complete band gaps the stop bands characterized with comparatively high spin-wave decay appear. Spin waves can propagate inside such stop-bands in spite of the fact that the propagation losses are relatively high. The aim of this work is to study the dispersion characteristics and spin-wave propagation in the finite-length MCs.

2. Theoretical research

The theoretical research utilized a one-dimensional magnonic crystal, which was an yttrium iron garnet film strip of 12 μm-thick and 2 mm-wide. Grooves with 2 μm-depth, 50 μm-width, and a period of T = 400 μm have been positioned on the waveguide surface perpendicular to its longer axis. The bias magnetic field was directed along the grooves in a plane of the MC. The geometry of the structure that was used for the calculation is shown in Fig 1(a). The numerical calculation of the insertion loss and dispersion characteristics has been performed in terms of transmission matrices [6]. The numerical modeling results demonstrating an influence of the MC length on transfer and dispersion characteristic are presented in Fig 1(b) and Fig 1(c), respectively.

The dispersion curve section that corresponds to one of the MC stop-band is shown in the insert of Fig 1(c). There are three curves that plotted for the different numbers of the periods in the Fig 1. The curve

1 corresponds to the number of periods n=1, in a case when insertion loss is relatively low. The curves 2 and 3 are plotted for n=15 and n=1000, respectively.

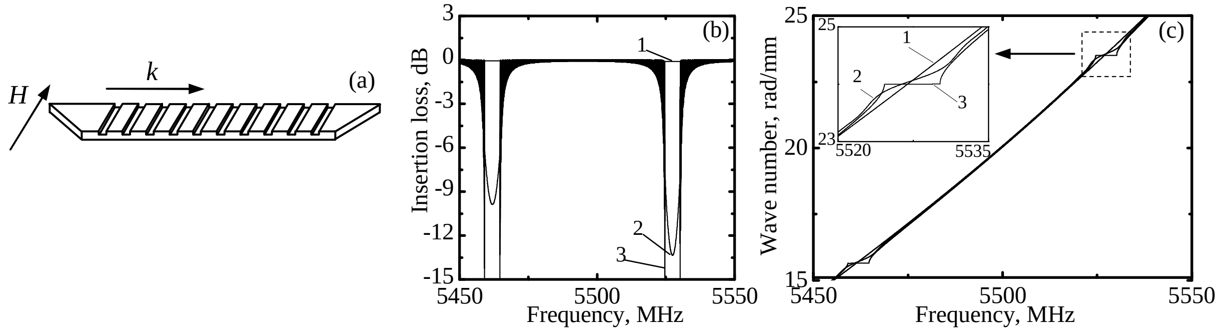

Fig. 1: (a) Geometry of investigation structure. (b) Fragments of the amplitude-frequency characteristics of the magnonic crystal calculated for structure consist of 1 period (curve number 1), 15 periods (curve number 2) and 1000 periods (curve number 3). (c) Dispersion characteristics of the magnonic crystal.

The shape of the dispersion curves on Fig 1. is described as follows. There is no effective reflection of spin waves off the periodic structure outside the stop bands. Moreover, in this case the dispersion characteristic looks like ferrite film dispersion characteristic. That section of dispersion corresponds to an allowed band. However, if spin-wave frequency is close by stop bands, then Bragg condition $K_1(a-s)+K_2s\approx\pi$ approximately satisfies. The wave undergoes the Bragg reflection, transmits energy to a reflection wave and decays during propagation. This leads to a strong spectrum transformation [7].

In the case of in infinite MC the incident wave has to be fully reflected at the Bragg resonance frequencies. This appears as the band-gaps. However, for finite MC as shown in Fig 1, instead of the band gaps the stop bands with high decay appear. If the length of MC is increasing then the decay in the stop bands is rising by the law $e^{-k''d}$ where k'' is the damping constant and d is the structure length.

The MC dispersion characteristic is transformed by the re-reflection as follows. Dispersion curve, as is shown in the spectrum given in Fig 1(c). When the number of periods increases, slope of the curve bend increases also. For example, when n = 1 the slope corresponds the slope of an YIG film dispersion curve and equals 8 mm/(rad·s); when n = 1000 the slope equals 1000 mm/(rad·s). In the last case the dispersion characteristic looks like an infinite MC dispersion characteristic [8].

3. Experimental research

For an experimental investigation the initial waveguides were cut from a larger single-crystal YIG film grown on 500 thick gadolinium gallium garnet (GGG) substrate. The waveguides were tested with the “magnetic well” set-up which provided the local non-destructive monitoring of the magnetic-film magnetic properties. The high-quality YIG-film waveguide which demonstrated the narrowest ferromagnetic resonance line-width of 0.6 Oe at 4.5 GHz and homogeneous magnetic characteristics was chosen for the further fabrication of the magnonic crystal. The orthophosphoric acid was used to etch the grooves in the film surface. The parameters of the received structure were identical to the above mentioned in the theoretical study. The standard delay line construction was utilized for excitation and reception of spin waves [9].

The experiments have been performed to measure the insertion loss and phase-frequency characteristic of the different length MCs. It is well known that dependence between phase-frequency and dispersion characteristic can be written as

$$\varphi(f)=n\cdot T\cdot k(f), \tag{1}$$

where φ is the accumulated phase. The excitation and reception losses have been taken into account for calculation of the insertion loss. A comparison between theoretical and experimental characteristics for the MC, that had 18 periods, is represented in Fig 2. As is seen from Fig. 2(a), the frequency positions and relative depth of all the stop bands are in accordance with the theoretical predictions.

The Fig 2(b) shows both a good qualitative and quantitative coincidence between theoretical and experimental phase-frequency characteristic. Also, from the insert in Fig 2(b) one can see that the theoretical dispersion curve twist in the stop band coincidences with the experimentally obtained one.

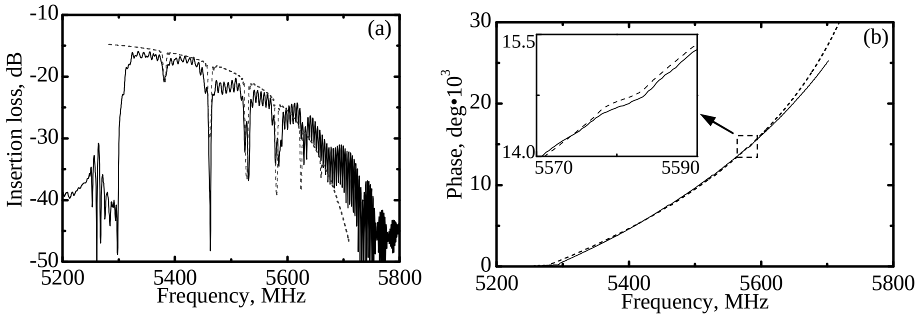

Fig. 2: (a) Insertion loss of the magnonic crystal. (b) Dispersion characteristics of the magnonic crystal. Solid line – experimental data, dashed line – theory.

4. Conclusion

It is shown that the finite length of the MCs leads to disappearance of the complete band gaps in the transfer characteristic and discontinuities in the dispersion curve. The shape of the characteristics is defined by the length of periodic structure. These conclusions should be taken into account in studies of linear and nonlinear wave processes in the finite-length periodic magnetic structures.

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