

Theoretical analysis of microwave magnonic crystals of finite length

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Abstract. Propagation of spin waves in a one-dimensional magnonic crystal to a finite distance have been studied theoretically. It was shown that, in contrast to the ideal spatially unlimited magnonic crystals with zero loss, there are no band gaps in the real magnonic crystals. The effective spectrum of spin waves at frequencies close to the Bragg resonances strongly depends on the magnonic crystal length.

1. Introduction

Propagation of waves in physical systems and media with periodically varying parameters has been studied during many years (see, e.g., [1-3] and references therein). The interest in studies of this kind is due to the possibility of creating waveguide media with advanced dispersion properties, which could be further used for development of new devices.

In recent years, an increased interest in studies of magnetic spatially periodic structures has been observed [4,5]. After the studies [6,7] were published, these objects are frequently named "magnonic crystals" (MCs) or "magnetic superlattices". Originally, these structures were studied in the late 1970s and early 1980s [8-15]. The reason for the present-day interest in magnonic crystals is that, on the one hand, media of this kind are a convenient experimental model for studies of linear and nonlinear wave effects and methods of signal generation and conversion and, on the other hand, these crystals can be used to develop a new generation of microwave devices [15-22].

Studies of spin-wave phenomena in spatially periodic structures are based on the dispersion laws. A theory of the spectrum is commonly developed in terms of the model of an infinite periodic structure with zero loss. As a result, the eigenwave spectrum $\omega(k)$ has band gaps at certain frequencies. The propagation of spin waves (SWs) at these frequencies is prohibited and the dispersion characteristic has discontinuities. However, magnonic crystals of finite length with nonzero loss are used in practice. Therefore, there are, instead of band gaps, bands in which SWs propagate, even though their decay is strong. The frequency dependence of the insertion loss (amplitude-frequency characteristic) shows alternation of pass bands with small and large losses. The latter bands are hereinafter called "stop bands". The dispersion characteristic has no discontinuities observed in the case of an infinite structure, but there are strong deviations in the dispersion law near the stop band boundaries. These specific features of the dispersion can affect, e.g., the manner in which SW envelope Bragg solitons are formed [22-25].

It should be emphasized that, despite the variety of the existing approaches to description of properties of magnonic crystals, the dispersion characteristics (spectra) of SWs in magnonic crystals



have been theoretically studied in detail only for the case of infinite periodic magnetic structures [26,27].

The goal of our study is theoretical investigation of insertion loss and dispersion law of magnonic crystals of finite length.

2. Theoretical investigation

The structure under study is shown schematically in figure 1. The structure is a single-crystal iron-yttrium garnet (YIG) film waveguide having grooves on the film surface. It is important to note that the position of the stop bands in the frequency spectrum depends on the configuration of the periodic structure, materials from which it is fabricated, and magnitude and direction of the external magnetic bias field. The parameters of the studied structures were chosen so that several stop bands due to the Bragg reflection of SWs were situated in that part of the dispersion characteristic which is determined by the dipole-dipole mechanism.

For numerical simulation of SW spectra in magnonic crystals we used the method of wave transfer matrices [28, 29]. This approach makes it possible to take into account the finite dimensions and the decay of waves and to study their influence on SW spectrum. Let us briefly consider the main relations used in the present study.

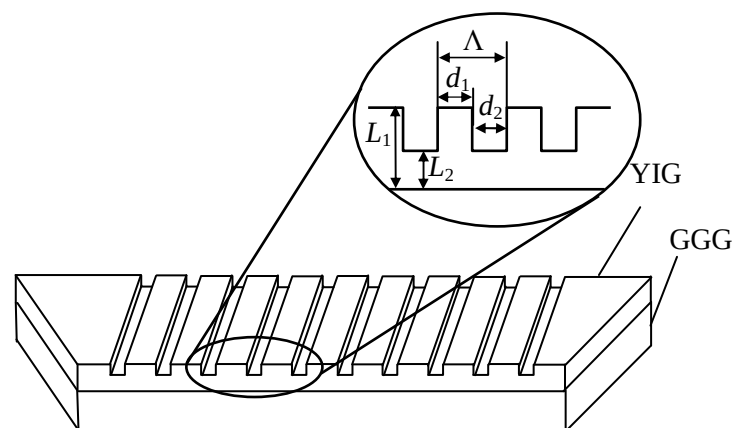


Figure 1. Schematic representation the magnonic crystal.

The structure had a period $\Lambda = 400 \mu\text{m}$, groove length $d_2 = 50 \mu\text{m}$, and groove depth $\Delta L = L_1 - L_2 = 2 \mu\text{m}$. The initial film thickness L_1 was $12 \mu\text{m}$. The saturation magnetization of the ferrite was 1750Gs . We assumed in the calculation that the grooves are oriented perpendicular to the SW propagation direction. The external magnetic bias field with strength of 1205Oe was assumed to be directed within the film plane along the grooves. This configuration corresponds to propagation of surface SWs in a the magnonic crystal. The calculation was done for the ideal case in which the ferromagnetic resonance linewidth and, consequently, the SW damping were taken to be zero.

Figure 2 shows the results of a numerical simulation of the influence of a magnonic crystal on its insertion loss and dispersion characteristics. The insets of figure 2 show scaled-up parts of the insertion loss and dispersion characteristics, which correspond to the rejection bands of the magnonic crystal. Curves 1 in figure 2 corresponds to the case of a structure with a single period. It can be seen in the figure that the damping introduced in the SW propagation at all frequencies is nearly zero and the dispersion characteristic is similar to that of a homogeneous YIG film. Curves 2 and 3 are plotted for the structures comprising 15 and 1000 periods, respectively.

The run of these dependences can be explained as follows. Outside the rejection bands, when the phase accumulation on a period of the structure is not a multiple of π , there is no effective reflection of SWs from the periodic structure. The resulting phase accumulation is proportional to the distance travelled by the wave. A transmission band is observed in the MC spectrum, and the dispersion characteristic of the MC is similar to that of a homogeneous film.

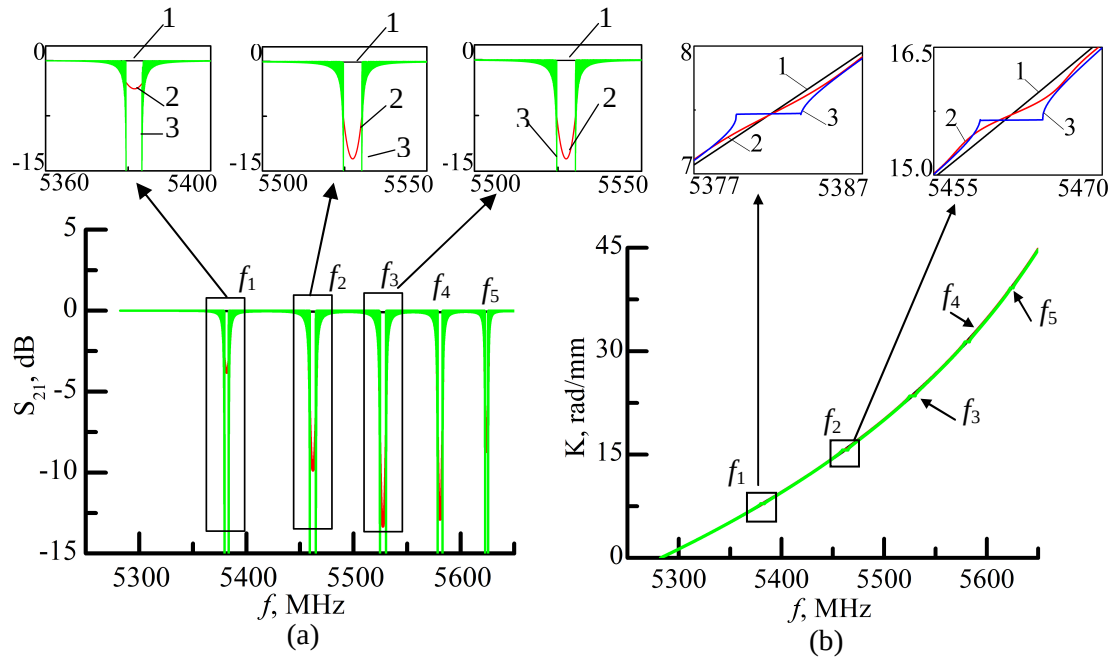


Figure 2. The insertion loss (a) and the dispersion characteristic (b) of magnonic crystal.

In the case when an SW propagates with a carrier frequency close to the stop band, a certain role is played, together with the dispersion of the medium, by the periodicity-caused dispersion. When the Bragg reflection condition is approximately satisfied, the wave begins to experience reflection and thereby decays, with its energy transferred to back-reflected waves. This is equivalent to the SW wave number becoming complex. This fact must be manifested in the frequency transmission coefficient of an infinite magnonic crystal as band gaps in which propagation of waves is impossible. However, it can be seen in figure 2(a) that, in the case of an MC with finite length, the transmission characteristic has, instead of band gaps, bands with comparatively large, but finite insertion loss, i.e., stop bands. With increasing length of a periodic magnetic structure, the loss within the band gap also grows as $\exp(-k''d)$, where k'' is the damping decrement within the stop band, and d is the length of the periodic structure. The dependences of the loss introduced within the stop band on the structure length are shown on the logarithmic scale for the first four rejection bands in figure 3(a).

The waves re-reflected by the periodic structure make a substantial contribution to the formation of phase-frequency and, consequently, dispersion characteristics of a magnonic crystal. In the dispersion characteristic, the stop bands appear as "bending" bands (Figure 2(b)). With increasing number of periods, these bands change their slope ratio $\Delta f/\Delta K$ (see figure 3(b)). For example, at $n = 1$, the slope ratio of the dispersion characteristic within the rejection band corresponds to that for the regular YIG film and $\Delta f/\Delta K \rightarrow 8 \text{ mm}/(\text{rad s})$. At $n = 1000$, the plot of $\Delta f/\Delta K$ is nearly vertical and has a value on the order of $1000 \text{ mm}/(\text{rad s})$, and the dispersion characteristic is almost similar to the dispersion characteristics corresponding to infinite periodic structures reported, e.g., in [6, 7, 24].

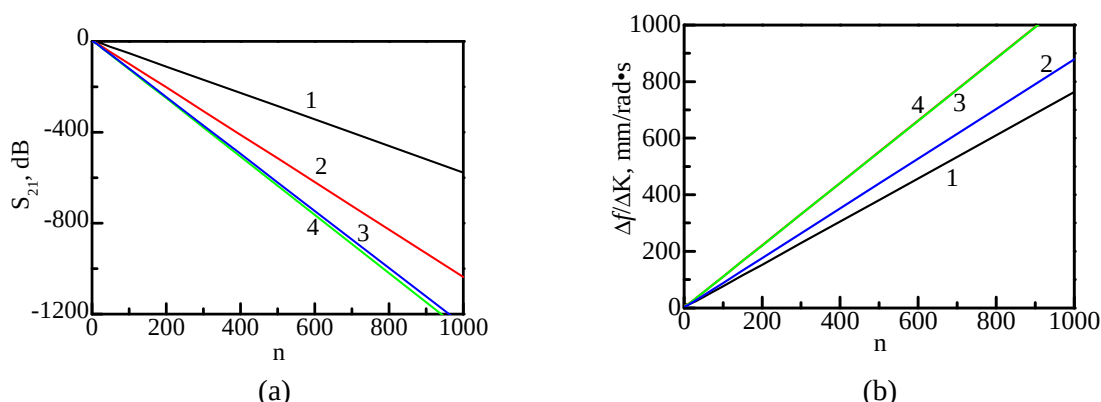


Figure 3. (a) The insertion loss at frequencies of stop bands MC. (b) The slope of dispersion characteristic of the magnonic crystal at frequencies of stop bands MC. Digits is the number of Brillouins band gap.

3. Conclusions

The method of wave transfer matrices was used for numerical analysis of the wave spectrum in a spatially periodic magnetic structure. An influence of the length in the formation of the dispersion and transmission characteristics of a one-dimensional magnonic crystal was studied. It was shown that an increase in the length of the periodic magnetic structure results in a rise in the insertion loss and in the slope of the dispersion characteristic at the Bragg resonance frequencies. A decrease in the length of the structure make smaller the contribution of waves re-reflected by the periodic structure to the formation of the magnonic crystal characteristics. The data obtained can be used for studies of linear and nonlinear spin wave processes in periodic magnetic structures.

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