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Nonreciprocity of spin waves in magnonic crystals created by surface acoustic waves in structures with yttrium iron garnet

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ABSTRACT

Experimental results of investigations of nonreciprocity for surface magnetostatic spin waves (SMSW) in the magnonic crystal created by surface acoustic waves (SAW) in yttrium iron garnet films on a gallium gadolinium garnet substrate as without metallization and with aluminum films with different electrical conductivities (thicknesses) are presented. In structures without metallization, the frequency of magnonic gaps is dependent on mutual directions of propagation of the SAW and SMSW, showing nonreciprocal properties for SMSW in SAW – magnonic crystals even with the symmetrical dispersion characteristic. In metalized SAW – magnonic crystals the shift of the magnonic band gaps frequencies at the inversion of the biasing magnetic field was observed. The frequencies of magnonic band gaps as functions of SAW frequency are presented. Measured dependencies, showing the decrease of magnonic gaps frequency and the expansion of the magnonic band gap width with the decreasing of the metal film conductivity are given. Such nonreciprocal properties of the SAW – magnonic crystals are promising for signal processing in the GHz range.

1. Introduction

Magnonic crystals represent a magnetic media with artificially created spatially periodic variations of some of their parameters sensitive for the spin waves [1,2]. A magnonic crystal exhibits magnonic band gaps in which the propagation of magnetic (spin or magnetostatic) waves is forbidden. Magnonic band gaps are due to the artificial periodicity of the magnetic properties that acts as a Bragg reflection grating for spin waves with the proper wavelength. Different configurations of magnonic crystals possessing unique properties are invented and are under wide investigations during the last fifteen years (see, for example [3–14]). In [9] it was shown that the periodic variations of magnetic properties may be created in magnetics by a surface acoustic wave (SAW) due to magnetostriction. The depth ($\sim$25 dB) of the corresponding magnonic band gaps at reasonable SAW intensity is comparable with that in "usual" static magnonic crystals (see, for example, [6]).

A certain attention is paid at the present time to investigations of magnonic crystals with nonreciprocal properties for spin waves [13–16] promising for signal processing applications. Nonreciprocity of waves usually means the change of parameters of the wave at the reverse of the direction of its propagation. Nonreciprocity in magnonic crystals may appear as the change of magnonic band gaps at the reverse of the direction of spin wave propagation. These properties of magnonic crystals are usually achieved due to an asymmetry of the forward and backward branches of spin wave dispersion curves in metalized magnetic structures [17]. The use of metal layers in such magnonic crystals, however, is needed to be cleared more. The influence of metal films with finite conductivity on spin wave nonreciprocity in magnonic crystals based on magnetic-metal structures was studied theoretically in [16]. As far as we know only one work [18] on experimental investigations of the metal thickness dependence of spin wave propagation in magnonic crystals was published at the present time. No publications are recognized at the present time on discussion of nonreciprocity in SAW – magnonic crystals.

In the present work we describe results on studying of manifestations of7 nonreciprocal properties of surface magnetostatic spin waves (SMSW) in the dynamic magnonic crystals arising at propagation of surface acoustic waves (SAW) in structures containing yttrium iron garnet (YIG) layers, including metalized YIG layers. The influence of metalizing films conductivity on the properties of SAW – magnonic crystals (frequency positions and the breadth of the magnonic band gaps) are experimentally investigated.

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2. Method and experimental setup

As in static magnonic crystals spin waves in dynamic crystals cannot propagate at the frequencies within the magnonic band gap and are effectively reflected at those frequencies. In the case of SAW – dynamic magnonic crystals the frequency of the reflected SMSW, f_r, are shifted (up or down) by the frequency of SAW, F, with respect to the frequency of the incident SMSW, f_i, in accordance with laws of inelastic scattering of SMSW on SAW [19–21]: $f_r = f_i \pm F$, $/\boldsymbol{k_r}/+/\boldsymbol{k_i}/= /\boldsymbol{q}/$, where $\boldsymbol{k_r}$ and $\boldsymbol{k_i}$ – wave vectors of reflected and incident SMSW, respectively, and $\boldsymbol{q}$ – wave vector of SAW, sign + in the equation corresponds to the case of counter-propagation of SAW and spin wave. The frequencies at which these reflected waves reach their maximum levels equal to the frequencies of magnonic gaps. It is convenient to study magnonic crystals using these reflected waves. The reasons for this are the following. The reflected waves and the incident wave have different frequencies spaced at the frequency of the SAW [19,20]. They do not interfere with each other when using a selective receiver that permits to measure reflected signals at relatively low levels of the input waves in comparison with the direct magnonic band gap measurements demanding much more powerful SAW [9]. In the present work we had been using this “reflected wave method”.

Configuration of our experimental arrangement is schematically depicted in Fig. 1. We used the reflected waves approach described here above and so called “bridge method” for SAW excitation in YIG–GGG samples [9], when SAW excited in the piezoelectric plate transfer to YIG–GGG structure through an acoustic contact especially created between the adjacent surfaces of the plate and the structure. YIG films of ~5-μm-thick grown on 500-μm-thick GGG substrate of (111) crystallographic plane were used in our experiments. The YIG–GGG samples were cut out in the shape of $18 \times 5\ \mathrm{mm}^2$ rectangular. Aluminum films through a mask were deposited on the YIG surface as shown in Fig. 1 by the thermal evaporation method in vacuum (without substrate heating). The length of Al films was 6 mm, the width was 5 mm. It should be noted, that the experimental results, as our experiments showed, were practically independent of the length of the film of Al, provided that it was longer than 3 mm.

SAW was excited by an interdigital transducer (IDT) with 23 MHz center frequency fabricated by photolithography on the surface of the Y-Z $\mathrm{LiNbO_3}$ base plate. SAW passed to the GGG–YIG sample through a special acoustic contact between the base plate and YIG–GGG sample as shown in Fig. 1. Insertion losses at SAW excitation in GGG–YIG structures in 50-Ω circuit with matching were estimated in our experiments as ~10 dB. The power of SAW at frequency 20 MHz was equaled to 0.1 mW. SMSW were excited and detected by means of an aluminum strip-antenna of 20-μm-width and 0.5-μm-thick deposited onto the surface of the dielectric plate (alumina) and placed on the surface of YIG film as shown in Fig. 1. The microwave power supplied to the antenna for the excitation of SMSW was equal to 1 μW. Natural microscopic irregularities of the adjacent surfaces of the YIG–GGG structure and the antenna on the dielectric plate did not allow the SAW to leak into the dielectric plate, in contrast with the surfaces of the $\mathrm{LiNbO_3}$ base plate and YIG–GGG structure where a special liquid lubricant created acoustic contact. The dielectric plate with the antenna positioned on the surface of the YIG–GGG brings, as experiments showed, to addition attenuation of the SAW less than 1 dB. The apertures of IDT and the antenna were 5 mm. The edges of YIG–GGG structures were subjected to a special treatment (tapered by a diamond needle file) to minimize SAW and SMSW reflections from the structure's edges. External magnetic field $H_O = 640$ Oe was applied parallel to the antenna.

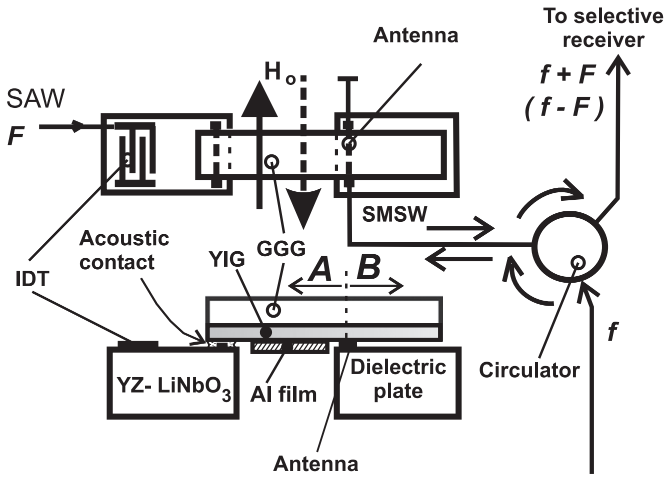

Fig. 1. Top and side views of the configuration of experimental samples and connections to measurement circuits.

3. Experimental results and discussion

First of all, the structures without metallization and then the structures with relatively thick aluminum films of 3 μm (greater than the depth of the skin layer) were investigated.

Microwave signals of frequency f in the range from 3.5 GHz to 3.9 GHz were applied to the antenna through a circulator. The antenna could excite SMSW in both directions and could also be used to detect the SMSW coming to it from both directions. The efficiency of excitation of the relatively long SMSW used in our experiments was practically equal in both directions due to rather thin YIG films (without metallization) [22]. Output signals from the antenna were measured by a selective receiver tuned to frequencies $f+F$ or $f-F$, where F is the frequency of SAW. When the receiver was tuned to $f-F$, the signal corresponding to the reflected SMSW arising in area **B** (see Fig. 1) where SAW and SMSW of frequency f propagate in the same direction is measured. When the receiver is tuned to $f+F$ the reflected SMSW arising in area **A** is measured. In this case, the reflected signal occurs at counter-propagation of the SAW and SMSW (see Fig. 1). When measuring samples with metal films the distance between the metal film and the antenna along the wave propagation must be no longer than 0.5 mm. Our experiments showed, in this case, this distance practically did not influence the measurement results (the change of the levels of measured signals did not exceed 1 dB).

Relative levels, A, of reflected SMSW measured as a function of frequency f of incident SMSW at $F = 20$ MHz and $H_O = 640$ Oe are presented in Fig. 2 for different experimental situations: a) pure YIG–GGG structure without metallization; b) metalized YIG–GGG with Al film of 3-μm – thick, for mutually opposite directions of magnetic field. The maximum of the curve 1 in Fig. 2a (SAW and SMSW propagates in the same direction – area **B** in Fig. 1) is achieved at $f_1 = 3.6403$ GHz and that of the curve 2 in Fig. 2a (counter-propagation – area **A** in Fig. 1) is achieved at $f_2 = 3.6205$ GHz, in agreement with the theory of inelastic scattering of SMSW by SAW [19,20] (corresponding explanatory chart of scattering is given in Fig. 3a). This means that the magnonic band gap frequencies depend on the direction of SMSW propagation relative to the direction of SAW propagation. Thus, SAW – dynamic magnonic crystals have nonreciprocity properties for SMSW even with the symmetrical dispersion characteristic (without any metal covering) and the reference direction here is set by the direction of SAW propagation rather than by the direction of the biasing magnetic field.