Spin-wave excitations in YIG films grown on corrugated substrates

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Abstract. Yttrium-iron garnet (YIG) film was deposited by ion-beam sputtering on gadolinium gallium garnet (GGG) substrate with the periodical array of grooves ion-etched in its surface. Spin-wave excitations in the fabricated structure were studied by the ferromagnetic resonance (FMR) method and by the spin-wave spectroscopy. Results were compared with ones for the YIG film deposited on GGG substrate without the periodical relief.

1. Introduction
Magnetic films deposited on substrates with etched 1D or 2D pattern are being widely investigated due to their possible applications for high-density recording media, magnetic field sensors, MEMS technology [1, 2, 3]. Recently, it was also suggested to use corrugated (or in other words profiled) films of yttrium-iron garnet (YIG) as one of the possible realization of the vertically integrated 3D magnonic structures to increase density of magnonic and spintronic elements [4]. In particular, it was theoretically shown [4] that spin waves (SW) can propagate in the meander-like YIG films, and such structure works as a magnonic crystal forming forbidden (Bragg) zones for the SW.

Experiments on the SW excitations in the corrugated magnetic films were previously limited only by the structures based on ferromagnetic metals and by the ferromagnetic resonance technique [5, 6] as the method to study them. Meanwhile, YIG has much lower SW damping in comparison with ferromagnetic metals and is more suitable for magnonic purposes, so that development of the technology for fabrication of the corrugated YIG films and experimental study of the SW excitations in them remain to be important challenges.

Recently, the possibility was demonstrated to use ion beam sputtering for growing YIG films on gadolinium gallium garnet (GGG) substrates with a quite good quality allowing SW propagation for distances more than 200 μm [7]. In this work, we applied this technology to fabricate the corrugated YIG film and experimentally studied the SW excitations in it using the FMR technique and the SW spectroscopy.
2. Sample fabrication and measurement technique

In order to form corrugated shape of the YIG film, the periodic array of grooves was preliminarily etched in the part of GGG substrate by photolithography and ion etching. The YIG film with the thickness $d=0.15\,\mu m$ was deposited by the ion-beam sputtering using procedure described in [7, 8]. After fabrication, geometrical parameters of the sample were measured by scanning electron microscopy (SEM) and stylus profilometry: the structure period was $P\approx20\,\mu m$, grooves' depth $s\approx1.5\,\mu m$, width $w_1\approx8\,\mu m$; unetched stripes between neighboring grooves had the width $w_2\approx10\,\mu m$ (figure 1). For SEM imaging, a $20 \times 20 \times 1\,\mu m$ piece of platinum was deposited on the sample surface to get rid of the surface charge.

The ferromagnetic resonance (FMR) spectrum was measured by the cavity FMR technique at the frequency of 9.85 GHz for the in-plane bias magnetic field $H$ applied at different angles $\theta$ with respect to the etched grooves direction (see figure 1a).

In order to perform the SW spectroscopy, the microstrip antennas (MA) with the length $l=250\,\mu m$, the width $w_s=4\,\mu m$, and with distances $L$ between exciting and detecting transducers varied from $L=10$ to $160\,\mu m$ were fabricated directly on the YIG surface (figure 1b). The MA had the pads with the pitch 150 $\mu m$ to provide the electrical contact with the microwave probes. To fabricate MA, we used the lift-off process involving DC magnetron sputtering and photolithography. In addition to MA fabricated on the corrugated YIG, several antennas were also placed on a part of the sample without the periodical corrugation for comparison of results for corrugated and non-corrugated YIG film. SW propagation measurements were carried out using a vector network analyzer (VNA) along with a microwave probe station similar to [7]. Orientation of the applied magnetic field $H$ with respect to the wave vector of SW excited by antennas corresponded to the magnetostatic surface wave (MSSW) [9]. In the experiment, we measured magnitude ($S_{21}^{Mag}$) and phase ($S_{21}^{Ph}$) of the transmission coefficient. Dispersion characteristics were calculated from the measured phase characteristic by analogue with [7].

3. Results and discussion

3.1. FMR spectrum

FMR measurement results are summarized in figure 2. The FMR spectrum of the reference sample (part of the sample where YIG film was deposited on the flat GGG substrate) contained two responses (see curve 1 in figure 2a). Intensive absorption peak we refer to the uniform FMR, while the second one having small intensity – to spin wave resonance (SWR) caused by the standing spin wave across the thickness of YIG film. Both of responses had a very weak dependence on $\theta$ (see open symbols in [7]).
that is typical for polycrystalline films. Uniform FMR response had the linewidth $\Delta H \approx 6 \text{ Oe}$. In the FMR spectrum of the corrugated YIG film, two main features were observed similar to ones reported earlier for the arrays of separate stripes [10] and two-component magnonic crystals [11]. The first one was the shift of the resonant field for the most intensive absorption peak $H_0$, that we relate to the quasi-uniform FMR, when the angle $\theta$ changed from 0 to 90°. This shift originates from the shape anisotropy induced by the periodical array of grooves. Here we note, that the intensive peak was split into two responses with the linewidth $\Delta H_1 \approx 13 \text{ Oe}$ and $\Delta H_2 \approx 9 \text{ Oe}$. This also means that 1D array of grooves in the substrate increases the value of $\Delta H$. The second particularity was that the FMR spectrum contained the series of additional responses resulted from the standing SW across the width of YIG stripe elements in the grooves or between them. In the angle range $\theta=0-20^\circ$, these peaks had the resonant fields $H_{\text{res}}$ lower than the uniform FMR and were caused by the standing MSSW, while for the range $\theta=40-90^\circ$ additional responses were located at the fields higher than $H_0$ and originated from standing magnetostatic backward volume waves (MSBVW). Besides, we observed the response caused by SWR showing the same dependence on $\theta$ as the quasi-uniform FMR peak.

**Figure 2.** FMR spectrum for the reference sample (curve 1) and for the corrugated YIG film at $\theta=0$ (curve 2) and $\theta=90^\circ$ (curve 3) (a) and angular dependence of FMR-responses (b). Insets in (a) show zoomed parts of the spectrum. Open symbols in (b) correspond to the reference sample: open squares – to uniform FMR, open diamonds – to SWR response.

### 3.2. Frequency dependencies of transmission coefficient

In the case of the YIG film on the plane GGG substrate, the MSSW transmission band was clearly observed by VNA (curve 1 in figure 3 and 4). Frequency dependencies of MSSW transmission coefficient magnitude had the maximum values typical for YIG/GGG structures fabricated by ion-beam sputtering. This is demonstrated in figure 3 showing transmission bands measured for the sample using MA with the following parameters $L=160 \mu\text{m}$, $l=250 \mu\text{m}$, $w_s=4 \mu\text{m}$ (curve 1); and measured earlier [7] on another sample with the thickness of $\approx 0.25 \mu\text{m}$ by the coplanar waveguide antennas (CA) having $l=400 \mu\text{m}$, $w_s=7 \mu\text{m}$, $L=100 \mu\text{m}$ (curve 2) or $L=200 \mu\text{m}$ (curve 3). Maximum values of $S^{\text{Mag}}_{21}$ detected by MA were just in the middle between the maximums of $S^{\text{Mag}}_{21}$ measured by CA that is in the accordance with the values of $L$ used in both cases. This means that propagation losses were about the same for both samples. However, the sample with MA showed significantly wider MSSW propagation range than the sample with CA because of the filtering properties of antennas [12].
Figure 3. Dependence of transmission coefficient magnitude on frequency for the MSSW propagating in YIG film deposited on flat GGG substrate at $H=120$ Oe. Measurements were performed with the microstripe antennas with $L=160$ μm (curve 1) and coplanar waveguide antennas with $L=100$ μm (curve 2) and $L=200$ μm (curve 3).

For the YIG film on the plane GGG substrate, we obtained MSSW dispersion $k=k(f)$ with the MSSW wavenumber $k$ up to $\approx 10^4$ rad/cm (curve 4 in figure 4c). Measured dispersion coincided with the Damon-Eshbach theory [9] for $d=150$ nm, $4\pi M_S\approx 1.75$ kG.

However, for the corrugated YIG film, and the same distance between antennas as for the flat film ($L=160$ μm or 8 periods of the structure), the output signal was close to the cross-talk level (curve 3 in figure 4a). For smaller distances $L$, frequency dependence of $S_{21}^{\text{corr}}$ possessed resonant peaks. As an example, curve 2 in figure 4a for $L=20$ μm had 3 distinct resonances marked as r1, r2, r3. They were accompanied by the resonant behavior of the transmission coefficient phase $S_{21}^{\text{ph}}$ (figure 4b). Positions of these resonances almost corresponded to $k=n\pi/w_2$ (where $n=1,2,3,\ldots$) i.e. to the MSSW resonances across the width $w_2$. Slight shift of the resonance positions might be caused by anisotropy induced by the form of striped structure. Strong decrease of the resonance intensity with the frequency reflects the decrease of the MSSW excitation efficiency (compare with the behavior of the curve 1). As the distance between exciting and detecting antennas decreased, the level of cross-talk signal grew. Therefore, $S_{21}^{\text{corr}}(f)$ dependence for the case of $L=20$ μm was around 20 dB higher than such dependence for $L=160$ μm (compare curves 2 and 3 in figure 4a).

Figure 4. Dependence of transmission coefficient magnitude (a) and phase (b) on the frequency for MSSW propagating in the flat YIG film (curve 1, $L=160$ μm) and corrugated YIG film (curve 2 for $L=20$ μm, curve 3 – for $L=160$ μm) at $H=120$ Oe, and dispersion characteristic (c) obtained from the phase of transmission coefficient for the flat YIG film (curve 4). Curve 5 shows the dispersion according to Damon-Eshbach theory [9].
Note, that observed resonant frequencies could be associated with even Bragg resonances, $kP=2\pi n$ [11]. However, we could not see any odd resonance typical for the magnonic crystals. We believe that in our case the non-horizontal parts of the structure had low microwave susceptibility and high losses (magnetically dead in the microwave range). As a result, MSSW possessed strong dumping at frequencies that were far from resonance condition $kw^2=\pi n$. The reason of poor magnetic properties of the YIG film on walls of grooves etched in GGG can lie in the possible substrate surface amorphization caused by the ion bombardment [13, 14].

4. Conclusions

In summary, we experimentally explored SW excitations in YIG film deposited on GGG substrate with the array of etched grooves, which depth was 10 times larger than YIG film thickness. For this structure, we found formation of the standing SW modes across the width of the horizontal parts of the structure but did not find any evidence of the SW propagation through the non-horizontal parts of the corrugated YIG film. The last could be due to the sample imperfections (specifically related with the geometrical imperfections of the etched groves) and due to a very high aspect ratio $d/s$ that forms “magnetic walls” on the non-horizontal parts of the corrugated YIG film [15].

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