Microwave Magnetics

Brillouin Light Scattering Spectroscopy of Magneto-acoustic Resonances in Thin Film YIG/GGG Square Resonator

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Abstract — We study experimentally with the spatial resolution the local excitation of the magnetoacoustic resonance in the laterally confined magnetic structure. We have prepared a polished layered yttrium iron garnet – gadolinium gallium garnet square film resonator, which demonstrates high-efficient magnetoacoustic coupling. This structure was placed in constant magnetic field and excited by microwave current. We demonstrate by the means of Brillouin light scattering technique the spatial localization of high Q-factor (Q ~ 10^5-10^6) magneto-acoustic resonance. We separate the distribution of magnetic and acoustic modes. We found that acoustic resonance was confined in the center of the excited magnetic resonant mode. By the exciting the resonant modes in YIG layer one can control the area of acoustic resonance excitation in the GGG substrate.

Index Terms—Microwave magnetics, magnetostatic waves, magnetoacoustic effects, Brillouin scattering.

I. INTRODUCTION

Magneto-elastic coupling of spin waves and acoustic waves enables the control of magnetization characteristics in magnetic materials [Ganguly 1976, Feng 1982, Wiegert 1987, Wiegert 2001]. The recent detailed theoretical and experimental study of multiferroic layered structures demonstrated, that magnetoelastic interaction of an acoustic wave with a ferromagnetic thin film allows to excite elastically driven ferromagnetic resonance (FMR) [Weiler 2011] and strain-mediated spin wave (SW) propagation [Cherepov 2014, Chowdhury 2015].

Brillouin light scattering (BLS) spectroscopy is widely used as a powerful experimental tool enabling direct visualization of spin-wave propagation with the spatial resolution and extremely high sensitivity of measurements. In work [Demokritov 2001] BLS method was applied for visualization of linear and nonlinear dynamics of spin-wave excitation (magnons). This was the beginning of detailed studies of spatio-temporal characteristics of magnetization waves in various magnetic media. BLS technique was used to visualize three-magnon decay processes of magnetostatic wave (MSW) [Mathieu 2003, Kurebayashi 2011, Beginin 2013], to study the dynamics of magnetic nano-oscillators [Madami 2011, Demidov 2014, Demidov 2015] and to study the propagation of spin waves in the film waveguides [Demidov 2015, Sheshukova 2014, Beginin 2014], including the effects of the spin-wave scattering by inhomogeneities of the YIG film [Duerr 2014, Gieniusz 2013] and spin wave propagation in irregular and gradient magnonic structures [Davies 2015, Sadovnikov 2015]. The experimental study of Bose-Einstein condensation of magnons at room temperature was also performed by the means of BLS [Demokritov 2006]. In these works only the magnetic excitations was investigated with BLS in detail. It is known that other types of waves (electromagnetic, acoustics waves) can be excited in layered magnetic structures [Zilberman 1989]. BLS can be also used to investigate hybrid waves [Rojdestvenski 1993] among which the "fast" magneto-elastic waves (MEW) can be excited in the bilayer fabricated from yttrium iron garnet (YIG) and gadolinium gallium garnet (GGG) layers [Eshbach 1963, Auld 1968]. GGG substrate is used as an acoustic waveguide for shear acoustic waves [Zilberman 1989]. In this case the magnetic and elastic components of the fast MEW are localized on the layers of the YIG/GGG structure. This opens the possibility to use BLS technique for the separation of coupled resonances, which have not been previously performed.

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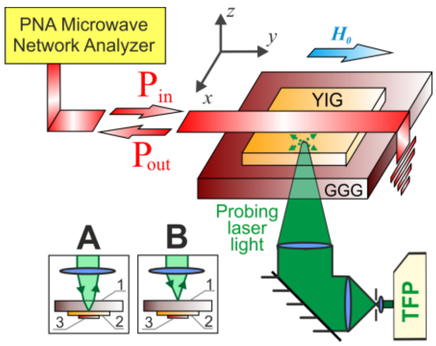

Fig. 1. (Color online) Schematic of the microwave and BLS experiment. PNA microwave network analyzer was used to measure return loss (S_{11}) parameter. TFP is abbreviation for Tandem Fabry-Perot interferometer. On the insets: backscattering configuration of BLS measurements of magnetic resonance (A) and acoustic resonance (B) in layered YIG/GGG structure. 1 – GGG substrate; 2 - YIG film; 3 - microstrip transducer.

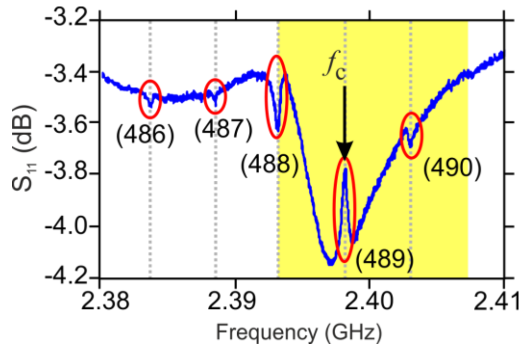

Fig.2. (Color online) Frequency dependence of return loss (S_{11}) parameter. Input power is $P_0 = -15$ dBm. Bias magnetic field is $H_0 = 320$ Oe. The magneto-acoustic resonance at the frequency f_c=2398 MHz is allocated inside the frequency region of first MSW resonance mode of a YIG resonator (depicted with the yellow region). The narrow acoustic resonances are circled in the figure. Number of acoustic half-wavelength in the YIG/GGG structure is depicted within the brackets.

In this letter, we study in detail the excitation of magnetic and acoustic resonance in the square YIG/GGG resonator using spatially resolved BLS spectroscopy. This method allowed direct measurement of magnetic and acoustic excitations with the exceptional sensitivity. By the means of BLS technique, we have measured the spatial intensity distribution of coupled magnetic and acoustic oscillation at the frequencies of magneto-acoustic resonances in the YIG/GGG structure at room temperature. We demonstrate the spatial separation of magnetic and acoustic resonances in high Q-factor magnetoacoustic resonator. We show that for the fundamental mode of YIG square resonator the area of acoustic excitation has much smaller size. Narrowing of acoustic resonance area was caused by non uniformity of excitation of acoustic waves by standing spin wave in YIG layer. Our experimental study provides clear evidence of acoustic wave excitation by resonant modes of square magnetic thin film resonator. As a result, exciting the resonant modes in YIG layer, one can control the area of acoustic resonance excitation.

II. EXPERIMENTAL RESULTS

YIG film with saturation magnetization of $M_0 = 1740/(4\pi)$ G and thickness of $d = 13$ μm was epitaxially grown on GGG substrate. The optical polishing technique was used to create the highly parallel transparent plates of the YIG/GGG structure. Fabricated sample with the wedge angle less than 2 arcseconds was used for excitation of magneto-acoustic resonances. The square thin film resonator with the dimensions of 1x1 mm was fabricated by the means of laser scribing technique [Sheshukova 2014, Beginin 2014]. Integral thickness of the layered structure YIG/GGG was $D = 371$ μm. For excitation of MSW resonances, we used a microstrip transducer with the width of 0.5 mm, placed in the center of the film resonator. YIG film was in-plane magnetized along the transducer, as shown in Fig. 1.

Magneto-acoustic resonances were experimentally detected using E8362C PNA Microwave Network Analyzer.

Frequency dependences of return loss S_{11} parameter of the hybrid resonator at the power values from –30 dBm to 0 dBm was measured in frequency range from 1.5 GHz to 3 GHz.

Absorption peaks at the frequencies of excitation of resonant MSW modes in the spectrum of the reflected microwave signal were observed. The frequency of these peaks can be smoothly tuned by the variation of the applied magnetic field value H_0. Magneto-acoustic peaks were excited and observed only in MSW resonance frequency band.

The narrow peaks along the spectra of MSW resonant modes were separated with the frequency step of $\Delta f = 4.9$ MHz, as shown on Fig. 2 with dashed gray vertical lines. This narrowband peak was caused by the resonance excitation of transverse (shear) elastic waves in the YIG/GGG structure. The frequency of these peaks do not depend on the bias magnetic field value H_0, and the intervals Δf are good matched with calculated frequency separation of shear acoustic resonances for the YIG/GGG structure $\Delta f_{st} = v_{st}/(2D) = 4.8$ MHz, where $v_{st} = 3.57*10^5$ cm/s is the speed of the transverse acoustic waves in GGG (for comparison, the transverse acoustic wave velocity in YIG has the value of $v_{st} = 3.85*10^5$ cm/s).

BLS measurements were performed to provide the spatial map of dynamic magnetization and acoustic resonance at the frequencies of peaks shown in Fig. 2. We used backscattering BLS configuration for visualization of the spatial map of magneto-acoustic resonance at room temperature. The intensity of the inelastic scattered light at the focal point of the laser beam was proportional to the square of the amplitude of magnetic or acoustic wave. The continuous-wave single-frequency laser operating at a wavelength of 532 nm was used for experiment. The light scattered from the magnetic and acoustic oscillations was analyzed by a six-pass tandem Fabry–Perot (TFP) interferometer.

Direct spatial imaging of phonon and magnon scattering intensity was performed by two-dimensional mapping of the probing laser spot over the sample surface.

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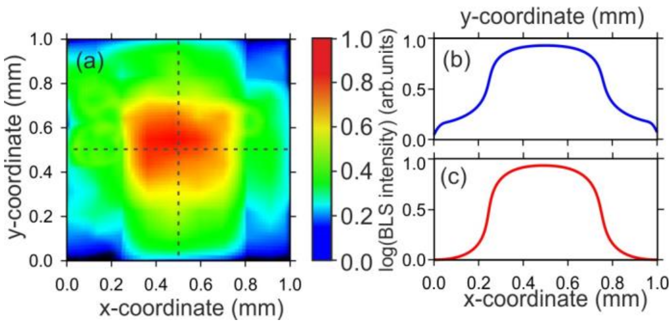

Fig. 3. (Color online) Logarithmically scaled magnetic resonance intensity map (a) recorded for the excitation frequency of f_c=2398 MHz and the x- and y-section of the spatial distribution (b,c). Measurements were performed using BLS by focusing on a surface of YIG film.

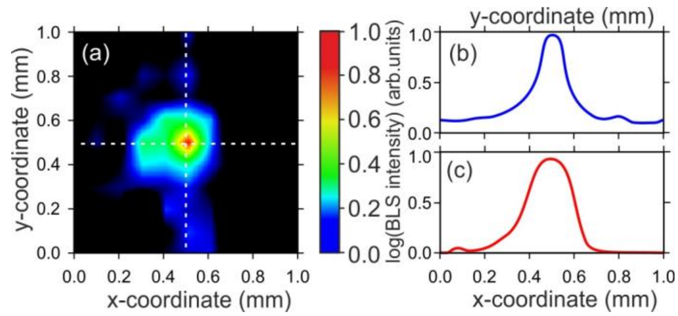

Fig. 4. (Color online) Logarithmically scaled acoustic resonance intensity map (a) recorded for the excitation frequency of f_c=2398 MHz and the x- and y-section of the spatial distribution (b,c). Measurements were performed using BLS by focusing on top surface of GGG substrate.

The scattered light flux was proportional to the intensity distribution of the magnetic and acoustic oscillations in a YIG or GGG layer.

Two methods were used to separate magnetic and acoustic resonance: polarization of scattered light and focusing the incident light beam. It is known, that the light scattered from magnons is generally polarized 90 degrees away from the incident light [Borovik-Romanov 1982, Cottam 1986]. In contrast there is no polarization change for scattering from phonons. For visualization of the dynamic magnetization and, as a consequence, the magnetic resonance, laser beam was focused on the surface of the YIG film from the transparent GGG substrate and a polarized 90-degrees filter was applied to eliminate the influence of phonon scattering induced by acoustic oscillation at GGG substrate. In contrast, for visualization of acoustic oscillations the polarized 90-degrees filter was removed and laser beam was focused on GGG substrate surface. The diameter of the focal spot was 20 μm. The spatial map was measured in x-y plane of YIG film. Figure 3 presents the results of visualization of magnetic resonance at the center frequency of magneto-acoustic resonance f_c = 2398 MHz (indicated by an arrow in Fig. 2). The excitation was performed with input microwave power of $P_{in} = -15$ dBm. Magnetic resonance map shown in Fig.3 agree well with those obtained experimentally in saturated YIG magnetic square [Demidov 2007] and theoretically in Permalloy dot [Bailleul 2006]. The spatial map of acoustic resonance is shown in Fig.4 a. The number of acoustic mode was equal to $n = f_n/\Delta f = 489$. Both in Fig.3 and Fig.4 the panels "b" and "c" show the central section of spatial map along y- and x-direction respectively (along the dashed lines, depicted in Fig.3a and Fig.4a).

Comparison of maps and transverse sections on Fig. 3 and Fig. 4 clearly shows that the area of acoustic resonances has smaller size, than area of magnetic resonances. Moreover the magnetostatic and elastic resonances have asymmetrical profiles. The spatial map was also measured at frequency of f = 2364 MHz, which is tuned from magneto-acoustic resonance. As expected, the acoustic resonances at the GGG substrate surface were completely disappeared.

Number of acoustic half-waves over the thickness of the YIG film at the frequency of magneto-acoustic resonance f_n can be estimated from relation $2d/\lambda_{st} = 17$, where $\lambda_{st} = 2D/n = 1.5$ μm is the length of a transverse sound wave. In this case, the overlap integral of the thickness distribution of the acoustic and magnetic resonances has small value. Moreover, the low magnetostriction in YIG film causes even more weak radiation of sound wave in GGG substrate. The losses due to acoustic waves scattering can be reduced by precision polishing of GGG-substrate. However, magneto-acoustic resonance is excited only at the maximum intensity of magnetic oscillations in the YIG film. That was confirmed by a relative narrowing of the area of acoustic resonance in the GGG substrate. The asymmetry of the dynamic magnetization pattern (Fig. 3) and acoustic intensity distribution (Fig. 4) of magneto-acoustic resonance could be explained by the screening of YIG film by the microstrip transducer. Our experimental study provides clear evidence of acoustic wave excitation by resonant modes of square magnetic thin film resonator. As a result, the control of the area of acoustic resonance excitation can be performed by excitation the resonant eigenmodes in the square YIG layer.

III. CONCLUSION

In conclusion, we have shown by the means of Brillouin light scattering technique the spatial localization of magneto-acoustic resonance with high Q-factor. We separate the spatial distribution of magnetic and acoustic modes and show that the efficient coupling between the magnetic and acoustic resonance can be achieved. We demonstrate the phenomena of area narrowing of the magneto-acoustic excitation. That is allows to decrease negative influence of inhomogeneity of a thickness of YIG-GGG structure. This is extremely important for implementation of high-Q magneto-acoustic resonators in higher frequencies range.

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