Far-Infrared Ferromagnetic Resonance of Magnetic Garnet for High Frequency Electromagnetic Sensor

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For the sensor probe of high frequency magnetic field in GHz region, $(BiLu)_3Fe_5O_{12}$ films were prepared by liquid phase epitaxy technique and ferromagnetic resonances were investigated in high frequency region. Magneto-optical (MO) effect of magnetic garnet was utilized for the imaging sensor of the magnetic field distribution. However, for the application to the characterization of high frequency magnetic field in the GHz frequency region, usual MO measurements are difficult to detect the magnetic filed as the decreasing of the permeability of magnetic garnet. Magnetic resonance is an effective way to induce magnetic moment and enhance the magnetooptical effect in high frequency region of GHz order. In order to understand the possibility of magnetic field sensor of high frequency in detail, far-infrared magnetic resonances were measured at the high frequencies up to 315 GHz in pulsed high magnetic field. Taking account into sensitivity of MO signals and magnetic resonance intensities, magnetooptical method using a garnet film is effective at the frequencies below 100 GHz.

***Index Terms*—Ferromagnetic resonance, garnet film, high frequency, magneto-optical effect.**

I. Introduction

THE magneto-optical imaging (MOI) of the magnetic flux using Bi substituted magnetic garnet film are used for the characterization of the high T_c superconductors since the investigations was started in the end of 1980' [1]–[3]. The Faraday rotation of the magnetic garnet film makes possible visualization of magnetic flux. When the garnet film is placed on the superconductor in the magnetic field below the temperature of T_c, the area of the garnet film on the superconductor is not magnetized due to the Meissner effect of the superconductor. With increasing applied magnetic field, the magnetic flux penetrates in the superconductor. The partially penetrated magnetic flux partially magnetizes the garnet film and partially induces the Faraday effects. Thus, the observed image through the polarized optical microscope reflects the distribution of the magnetic flux penetrated in the superconductor. For the MOI technique, garnet films with in-plane magnetic anisotropy are widely used because magnetic domain aligned in the film plane do not disturb the spatial resolution due to magnetic domain wall width. We have already succeeded the preparation of good quality magnetic film with in-plane anisotropy using $(BiLu)_3(FeGa)_5O_{12}$ system [4].

Recently, the MOI technique has attracted much attention for the probe sensor of the high frequency magnetic field. The frequency of the microwave in wireless communication or other electronic devices is recently becoming higher and higher for the rapid and huge amount of data communication. The probe sensor using MO effect has great advantages because of the low invasiveness of the electromagnetic field and high speed response to the change of the magnetic field [5]. The problem is that the permeability of ferrite garnet decreases in the high frequency region due to so-called Snoek's limit [6]. The decreasing of the permeability also decreases the MO effect. However, it was found that the ferromagnetic resonance (FMR) is effective phenomena to enhance the MO effect [7]. Induced magnetic moment also induces Faraday effect of the magnetic garnet. Thus, in order to detect the magnetic field components of the higher frequency electromagnetic field, optical measurement system was improved to measure in a tunable DC magnetic field (see [7]).

In this paper, we focused on ferromagnetic resonance of the magnetic garnet film at the frequencies up to far-infrared region (~several hundreds GHz). For high sensitive observation of magnetic field by MO effects, large induced magnetic moments are necessary to enhance MO effects. The large and sharp resonance spectrum is a sign of the strength of induced magnetic moment.

II. Experimental

For the magnetic garnet film preparation, liquid phase epitaxy (LPE) technique is used as it is easy to control the film composition and is suitable for the preparation of films with optically smooth surface. The mixed raw powder materials were put into a Platinum crucible and then heated up above melting point. $PbO - Bi_2O_3 - B_2O_3$ was used as the flux. For the garnet film, the $Bi_{3-x}Lu_xFe_5O_{12}$ (BLIG) films were prepared in this experiment. The BLIG film is such a film which show large and sharp FMR resonance.

The films were grown on $Gd_3Ga_5O_{12}$ (GGG) (111) and (110) substrates ($a_s = 12.383$ Å). GGG (111) substrates are commercial substrates for optical isolators. GGG (110) is rare to obtain, however, it has an advantage for preparation of the films with in-plane magnetic anisotropy. Growth temperature was adjusted to be small lattice mismatch between the film and the substrate.

Manuscript received October 31, 2009; accepted January 17, 2010. Current version published May 19, 2010. Corresponding author: N. Adachi (e-mail: nadachi@nitech.ac.jp).

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Digital Object Identifier 10.1109/TMAG.2010.2041328

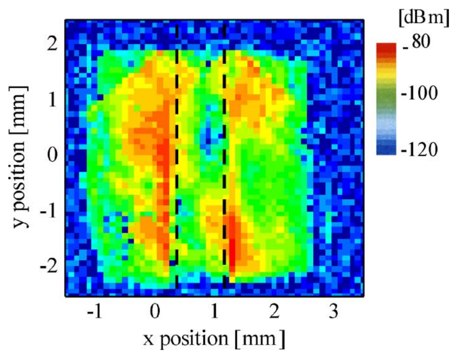

Fig. 1. MO imaging of the 14 GHz magnetic field distribution around Cu wire. Applied DC field was $\mathrm{H} = 286\ \mathrm{kA/m}$. Dashed lines correspond to the position of the Cu wire edge. The rectangle shape of green area is the area of the garnet film.

The lattice mismatch was determined by X-ray diffraction analysis using $\mathrm{Cu} - \mathrm{k}\alpha$ radiation. The compositions of the films were analyzed using an Energy Dispersive X-ray spectrometer (EDX).

The ferromagnetic resonances (FMR) at X band (9 GHz) and Q band (34 GHz) were measured by using electron spin resonance (ESR) spectrometer (Bruker E500). For the FMR measurements in high frequency region between 30 GHz and 315 GHz), gun diodes were used for generation of high frequency microwave and the microwave was introduced through light pipe to the specimen mounted in the center of pulsed magnet which generates high magnetic field. A detailed measuring system was described in the [8].

The detection of high frequency magnetic field via magneto-optical effect (Faraday effect) was achieved as follows; a garnet film with Au mirror is placed on a Cu conducting wire and high frequency signal was inputted into the wire from impedance analyzer. Then, the polarized infrared laser ($\lambda = 1.33\ \mu\mathrm{m}$) scan the garnet film. Experimental setup is described detail in [7]. According to the Ampère's law, magnetic fields are generated concentrically around the wire. The magnetic garnet onto the wire is partially magnetized by this magnetic field and the component of the magnetization parallel to the incident laser rotate the plane of polarization of the laser by Faraday effect. In the high frequency region above GHz, direct current (DC) magnetic field applies to the magnetic garnet film. Magnetic moment induced by ferromagnetic resonance can also rotate the plane of polarization. Fig. 1 shows an experimental result of 14 GHz magnetic field distribution generated around Cu wire. Although bright areas along the wire edge are inhomogeneous, it can be recognized that magnetic fields are generated around the wire. The detection of MO signals was measure up to 20 GHz.

III. Results and Discussions

From the EDX analysis, the prepared film composition x was determined to be approximately 1.0. Both (110) and (111) films show in-plane magnetic anisotropy. In-plane anisotropy means that the anisotropy field is parallel to the film plane. By using $\mathrm{Bi_1Lu_2Fe_5O_{12}}$ (110) film, high frequency magnetic fields generated around Cu wire were detected through the MO effects. The MO signals depending on the microwave frequencies at the various magnetic fields are shown in Fig. 2. The laser is focused on a certain position of the garnet film above the edge of the Cu wire and the microwave frequencies sweep up to 20 GHz, then, the MO signals are detected in the applied magnetic field. A sharp peak appears at each the MO spectrum. With increasing magnetic fields, the peak position shifts to the higher frequency region. The enhancement of the MO signals come from the induced magnetic moment due to ferromagnetic resonance of the magnetic garnet as discussed later.

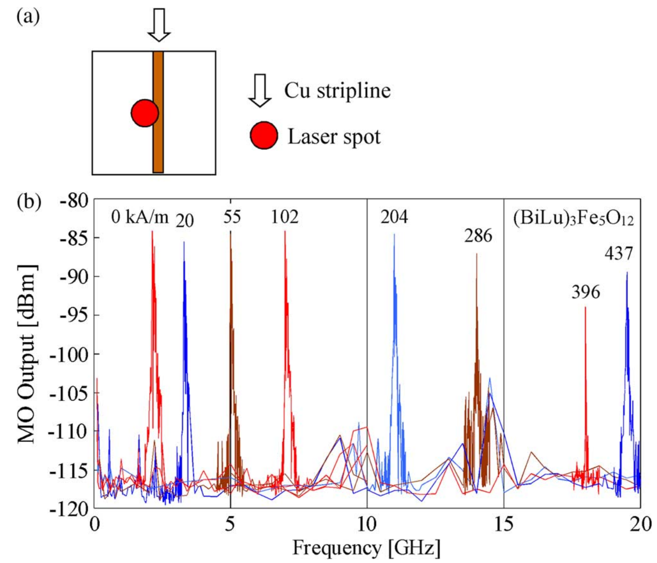

Fig. 2. (a) Schematic configuration of fixed laser spot and Cu wire. (b) Frequency dependence of the MO output signal at the various DC magnetic fields.

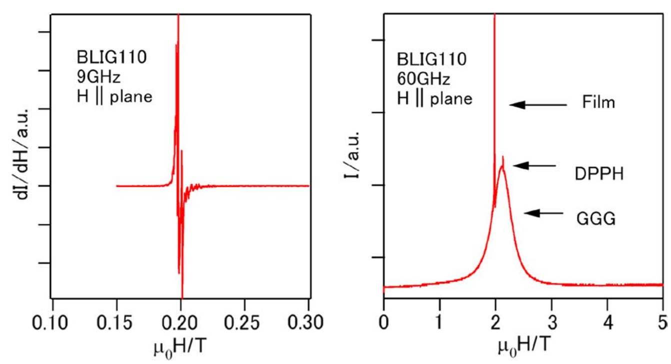

Fig. 3. FMR resonance spectra at (a) 9 GHz and (b) 60 GHz.

Fig. 3 shows the FMR spectrum of the (110) $\mathrm{Bi_1Lu_2Fe_5O_{12}}$ film measured at 9 GHz and at 60 GHz. In the low frequency of X and Q band, field modulation technique is possible to use. Then, the spectrum is described by differential curve of resonance spectrum. High frequency FMR measurements are only possible to measure by transmission mode because of measuring in a pulsed magnetic filed. For the marker of $\mathrm{g} = 2$ and the comparison of absorption intensity, $\mathrm{DPPH}(= 2.2 - \mathrm{diphenyl} - 1 - \mathrm{picrylhydrazyl})$ is spread on the film surface in the high frequency FMR measurements. At the (a) spectrum, fins structure accompanied with main large peak is observed. The splitting is caused by magnetostatic wave or spin wave. These modes are often observed in the high quality single crystal magnetic garnet. The modulation technique is effective to observe such fine structure. In the (b) spectrum, a broad peak appears with large and small sharp peaks. The large sharp peak is due to the

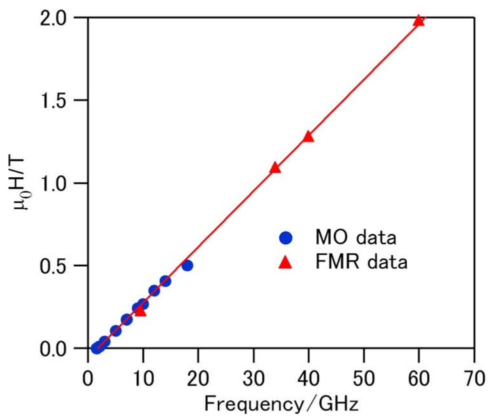

Fig. 4. Plots of resonance fields versus microwave frequencies (▲) and magnetic fields versus enhanced frequencies in the MO signals (•). The line is a guide to the eye.

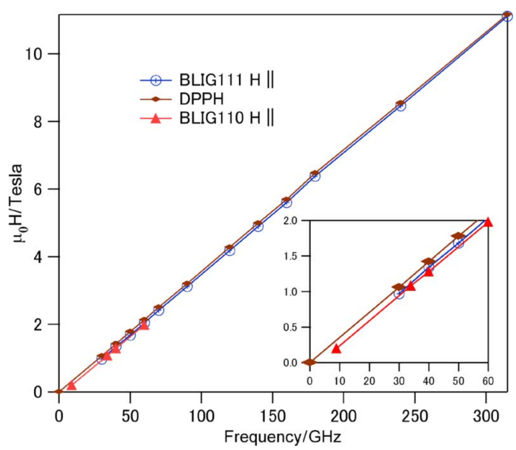

Fig. 5. Plots of resonance fields versus microwave frequencies of BLIG(100) (▲), BLIG(111) (∘) and DPPH (⧫).

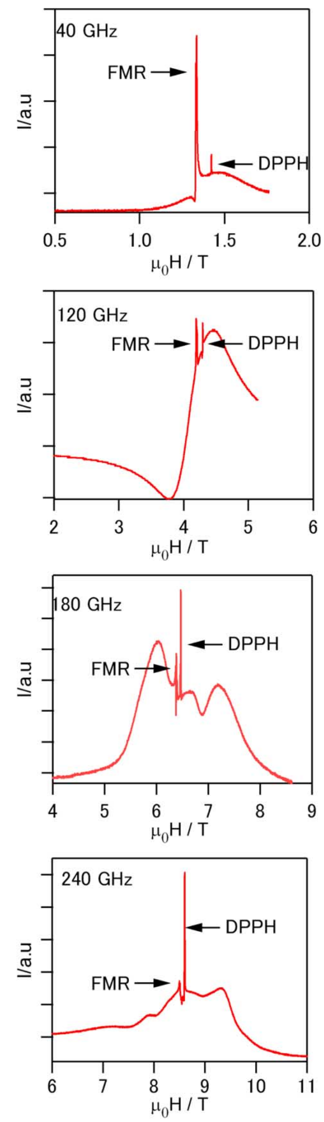

Fig. 6. FMR spectra of BLIG (111) film in the magnetic field parallel to the plane in high magnetic frequency region.

FMR of the magnetic garnet and the small sharp peak is due to the electron paramagnetic resonance (EPR) of the DPPH. The broad peak comes from EPR of the GGG substrate. In the low magnetic field, the EPR spectrum of the substrate is too broad to detect. High field measurements make possible to trace the signal of such broad resonance.

Fig. 4 shows the plots of resonance fields versus microwave frequencies and magnetic fields versus enhanced frequencies in the MO signals (see Fig. 2). Both frequency relations are in good agreement with each other. This is the evidence that the enhancement of the MO output signals shown in Fig. 2 caused by magnetic resonance.

Although the MO measurements up to the 60 GHz region are now in progress, the FMR measurements have already been possible in TeraHz region in pulsed high magnetic field at the present stage. Fig. 5 shows the experimental plots of resonance fields versus microwave frequencies. The (111) $Bi_1Lu_2Fe_5O_{12}$ film was used for the FMR measurements up to 315 GHz. According to the Kittel's equation, the relation between frequency and FMR resonance field is expressed as follows:

$$f_0 = \frac{\gamma}{2\pi}\sqrt{(H_r + H_A)\left(H_r + H_A + \frac{I_s}{\mu_0}\right)} \tag{1}$$

where f_0 is microwave frequency, H_r is resonance magnetic field, H_A is anisotropy field, I_s is saturation magnetization, γ: is gyromagnetic ratio $(-2\pi \mathrm{g}\mu_\mathrm{B}/\mathrm{h})$ and μ_0: vacuum permeability. Due to the existence of the anisotropy energy, the resonance fields deviate from the paramagnetic resonance relation. When the anisotropy field is in in-plane, resonance appears in lower magnetic field than that of DPPH (the marker of $\mathrm{g} = 2$.) As described before, both (110) and (111) $Bi_1Lu_2Fe_5O_{12}$ films show in-plane magnetic anisotropy and anisotropy field affect the lower resonance field than that of DPPH. In the high frequency region, the resonance fields are almost in promotion to the frequencies.

The resonance peaks were surely recognized in the resonance spectra of high frequency measurements. Strange to say, however, the resonance intensity extremely decreases at the frequencies above 100 GHz. The FMR spectra of (111) $Bi_1Lu_2Fe_5O_{12}$ film at several frequencies are shown in Fig. 6. At the 40 GHz, the large sharp peak is due to the FMR of the film. At the 120 GHz, the height of the intensity of FMR peak becomes almost the same as that of the DPPH EPR peak. At the 180 GHz, the height of the DPPH peak becomes much larger than that of FMR and the FMR peak almost disappears at 240 GHz while DPPH peak becomes extremely high. Although the absolute resonance intensities are difficult to estimate, the FMR of the film and EPR of DPPH were measured at the same time and with the same specimens. Then, the decreasing of the peak intensity ratio $\mathrm{I_{FMR}/I_{EPR}}$ indicates the decreasing the resonance intensity of FMR of the film. About the EPR spectrum of GGG substrate, fine resonance structure seems to appear in the high frequency region. The behaviors of these resonances are complex and it is not clear to understand at the present. From the point of view of detection of high frequency magnetic field using MO effect of magnetic garnets, the induced magnetic moment is necessary to enhance the MO effect. Decreasing of the FMR intensity above 100 GHz gives a possible frequency region for magnetic field sensor using garnet materials. As far as the large and sharp resonances less than 100 GHz are concerned, the garnet material is considered to be attractive material for high field magnetic sensor device.

Acknowledgment

This work was supported by the Strategic Information and Communications R&D Promotion Programme (SCOPE) of the Ministry of Internal Affairs and Communications of Japan.. The authors would like thank to staff members of the Institute of Molecular Science for FMR measurements at X and Q band.

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