Real Time Magneto-optical Imaging using Liquid Crystal Modulator

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Polarization modulation technique has been applied for magneto-optical (MO) imaging to measure MO values quantitatively. In this paper, we report on a real-time MO imaging using the polarization modulation method with a liquid crystal modulator. Measurements of MO images and hysteresis Kerr loop of patterned Bi,Ga substituted yttrium iron garnet film were demonstrated by using the technique. A frame rate of 1 s was achieved in this experiment.

Key words: magneto-optical imaging, garnet thin film, real time measurement, liquid crystal modulator

1. Introduction

Recent years, quantitative and real time measurements are one of the most important issues in the magneto-optical (MO) imaging to study dynamics of magnetic properties in magnetic materials. We have recently developed an MO microscope using a polarization modulation technique, and demonstrated that quantitative MO measurements are possible with this technique[1-3]. In this technique, quantitative images of MO rotation and ellipticity can be obtained by using three images taken with three different polarized lights; *i.e.*, the linearly polarized light (LP), the right-circularly polarized light (RCP) and the left-circularly polarized light (LCP). However, there is a drawback that it takes a several seconds at least for measurements because of a procedure to modulate optical polarization states by mechanical rotation of a quarter wave plate. In order to realize a real time MO imaging at the video rate (30 frames/sec) using this technique, an optical modulator that works faster than 30 ms is required. In this study, we used a liquid crystal modulator (LCM), which can switch the optical polarization state only by changing an AC voltage applied to the device. In this paper, we report on introduction of LCM to the MO microscope and MO imaging for a patterned Bi,Ga-substituted yttrium iron garnet (YBFGO) thin film[4].

2. MO microscope

Figure 1 shows an optical setup for the MO microscope used in this experiment. In order to utilize the optical modulation method with a polarizer, an LCM and an analyzer were installed with an optical axis of $\pi/4$, 0 and 0, respectively. An objective lens with a long working distance (Mitsutoyo, G Plan APO ×50) was employed. Digital images of 640 × 480 pixels are taken by a high speed CCD camera (Hamamatsu, C9300-201) with a 12-bit A-D converter, which can directly transfer 160 digital images/sec to RAM in the computer. A halogen lump was used as a light source, and wavelength was selected by using interference filters.

We prepared an LCM employing a commercially available liquid crystal (ZLI-4792) and ITO-coated glass plates. The retardation was varied by an application of AC voltage of 0 - 10 V with a frequency of approximately 100 Hz to the LCM in this experiment. The voltages corresponding to the LCP, the LP, the RCP were determined by measuring an extinction ratio of a maximum intensity $I_{\min}$ and a minimum intensity $I_{\max}$, of the output light. Figure 2 shows extinction ratios for a wavelength of 550 nm. Maxima and a minimum in Fig. 2 correspond to the circularly polarized lights and the linearly polarized light, respectively. It should be noted that these voltages varies with wavelengths. In this experiments, an ideal extinction ratio was not obtained due to phase-shift of the light suffered by optical elements such as a beam splitter, lenses, window, etc.

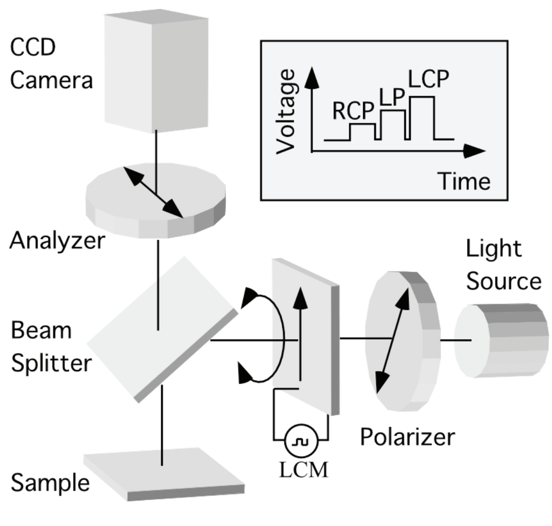

Fig. 1 MO microscope using a liquid crystal modulator. Polarization state of the light can be controlled by applying voltage to the LCM.

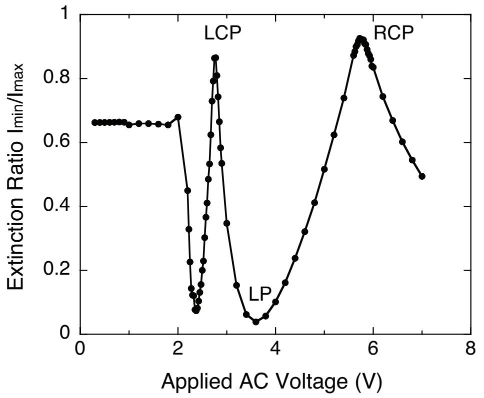

Fig. 2 An extinction ratio I_{min}/I_{max} for a wavelength of 550 nm depending on an AC voltage applied to the LCM.

A physical explanation of the MO imaging using LCM is analyzed by Jones matrix method. The output $\boldsymbol{E}_2$ light is obtained by using matrices of an analyzer $\boldsymbol{A}$, a sample $\boldsymbol{S}$, an LCM $\boldsymbol{J}_Q$, a polarizer $\boldsymbol{P}$ and an input light $\boldsymbol{E}_1 = (E_x, E_y)$,

$$\begin{aligned}\boldsymbol{E}_2 &= \boldsymbol{A}\boldsymbol{S}\boldsymbol{J}_Q\boldsymbol{P}\boldsymbol{E}_1\\ &= \frac{1}{4\sqrt{2}}\begin{pmatrix}1 & 1\\ 1 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_K + i\eta_K\sin\theta_K & -\sin\theta_K + i\eta_K\cos\theta_K\\ \sin\theta_K - i\eta_K\cos\theta_K & \cos\theta_K + i\eta_K\sin\theta_K\end{pmatrix}\\ &\qquad \begin{pmatrix}e^{i\delta/2}+e^{-i\delta/2} & e^{i\delta/2}-e^{-i\delta/2}\\ e^{i\delta/2}-e^{-i\delta/2} & e^{i\delta/2}+e^{-i\delta/2}\end{pmatrix}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\begin{pmatrix}E_x\\ E_y\end{pmatrix}\end{aligned} \quad (1)$$

where θ_K is Kerr rotation, η_K is Kerr ellipticity and δ is a retardation. As a consequence, an intensity of the output light $I(\delta) = |\mathbf{E}_1|^2$ measured by a CCD camera is obtained as a function of θ_K, η_K and δ,

$$I(\theta_K,\eta_K,\delta) = \left|\sin\theta_K - i\eta_K\cos\theta_K + e^{i\delta}\left(\cos\theta_K + i\eta_K\sin\theta_K\right)\right|^2 I_0/4 \quad (2)$$

where I_0 is the intensity of the input light. Kerr rotation θ_F and Kerr ellipticity η_F, can be calculated from three images taken with three different optical polarization states of $\delta = 0$, $\pi/2$ and $-\pi/2$, corresponding to LP, LCP and RCP, respectively, as follows;

$$\theta_K \approx -\frac{1}{2}\sin^{-1}\left\{\frac{2I(0) - [I(0) + I(-\pi/2)]}{(1-\eta_F{}^2)[I(\pi/2) + I(-\pi/2)]}\right\}, \quad (3)$$

$$\eta_K \approx -\frac{1}{2}\left\{\frac{I(\pi/2) - I(-\pi/2)}{I(\pi/2) + I(-\pi/2)}\right\} \quad (4)$$

In order to obtain MO images, three polarization images for LCP, LP and RCP are sequentially measured by applying AC voltages to the LCM as shown by an inset in Fig. 1. Those images are captured with a delay time of 200 ms after each voltage corresponding to LCP, LP and RCP, and are immediately transferred to the memory on the computer. MO images for rotation and ellipticity are constructed with MO values obtained for each pixel by using equation (3) and (4). In this experiment, although the delay time of 200 ms was required to measure images, we consider that the delay time will be shortened as small as 10 ms by using other fast response LCM devices.

3. MO images of patterned Bi,Ga:YIG film

3.1 Hysteresis measurements

Our technique gives us a quantitative MO values in principle. Therefore, once MO images are acquired for a sequence of magnetic field swinging between negative and positive magnetic saturation, hysteresis curves at any pixel point can be visualized. As an example, MO images measured with a magnetic field of 750 and -750 Oe and hysteresis curves of an array of patterned Bi-, Ga-substituted yttrium garnet ($YBi_2Fe_4GaO_{12}$) thin films prepared on a glass substrate with a pattern size of 50 μm × 50 μm and thickness of 400 nm are shown in Fig. 3 and Fig. 4. MO images shown in Fig. 3 were obtained with an averaging of 100 images taken with an exposure time of 60 ms for each image to reduce noise. Magnetic contrast is clearly obtained even though reflectivity of the dot and the glass are different. It should be noted that it is difficult to obtain quantitative MO values as shown in Fig. 3 in the crossed polarizer technique which measure only differences in the light intensity, because change in the intensity depends on the reflectivity. Figure 4 shows magnetic field dependences of Kerr rotation for a garnet dot measured with wavelength of 500 and 550 nm and the glass substrate measured with 500 nm. Clear hysteresis loop was observed for the garnet pattern and those saturation values correspond to MO spectrum measured by MO spectrometer, while no signal was obtained for the glass substrate.

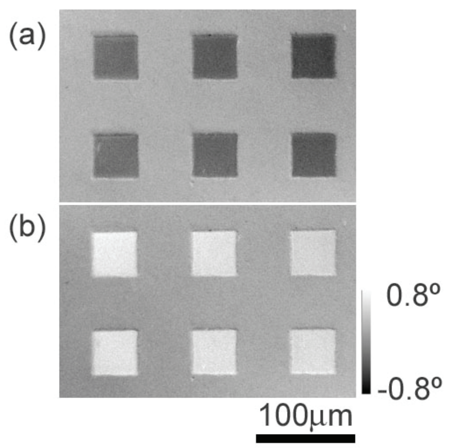

Fig. 3 Kerr rotation images of patterned YBFGO thin films measured with a wavelength of 500 nm and magnetic field of (a) 750 and (b) -750 Oe. Dimension of a dot is 50 μm × 50 μm and thickness of 400 nm.

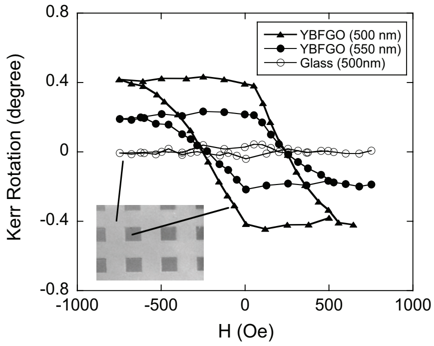

Fig. 4 Magnetic field dependences of Kerr rotation for a garnet dot measured with wavelength of 500 and 550 nm and a glass substrate measured with 500 nm.

3.2 Real-time MO imaging

Although our technique is more complicated than the conventional cross polarizer technique, a real-time measurement becomes possible by utilizing the LCM and the software developed in this study. Figure 5 shows a result of the real time measurement of Kerr rotation images of the patterned garnet dot shown previously. In order to increase the frame rate, we simplified equation (2) assuming $I_{\mathrm{RCP}} \approx I_{\mathrm{LCP}}$ as expressed by

$$\theta_K \approx \frac{I(0) - I(\pi/2)}{2I(\pi/2)}. \qquad (5)$$

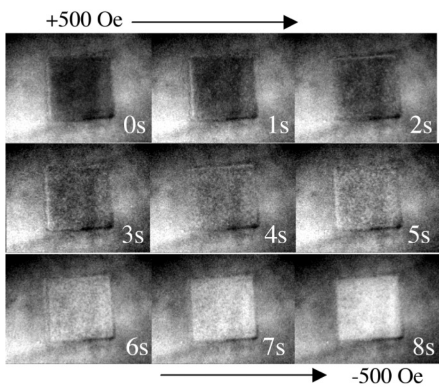

Fig. 5 MO images of patterned BYFGO thin films with 50 μm × 50 μm measured with various magnetic fields. The frame rate of 1 s was achieved.

In this measurement, optical images are captured with an exposure time of 20 ms and were averaged on 10 images for each circular polarization image to reduce shot noise. As a result, MO-images become possible to be displayed with a rate of approximately 1 frame/sec. We are optimistic to improve the frame rate to the video-rate by appropriate selection of a fast response LCM.

4. Conclusions

An MO microscope using a polarization modulation with an LCM has been developed. A physical explanation of our technique that MO images can be constructed from three images for different polarization states, LP, LCP and RCP, produced by the LCM has been described. Using the microscope, MO images and hysteresis curves have been successfully obtained for patterned Bi,Ga-substituted magnetic garnet film. For real time MO measurement, a frame rate of 1 s was achieved.

Acknowledgements This work has been supported in part by 21st COE project "Future Nano Materials" of TUAT, and the Grant-in-Aid for Scientific Research (No.16360003) from the Japan Society for Promotion of Science.

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Received May 17, 2006; Revised June 21, 2006; Accepted June 22 2006