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Magneto-optical spectroscopy by the polarization modulation method using a multi-channel spectrometer

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In the conventional magneto-optical (MO) spectrometer, MO spectra are measured for each wavelength using monochromatic light, resulting in a long measurement time of more than 1 h. To shorten the measurement time, we propose an MO spectrometer using a multi-channel spectrometer combined with the polarization modulation method, by which both Faraday rotation and Faraday ellipticity spectra can be simultaneously obtained in several minutes from three optical spectra measured with linearly, left- and right-circularly polarized lights. In this study, a measurement of Faraday rotation and Faraday ellipticity spectra of a bismuth-substituted neodymium iron garnet thin film was demonstrated.
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1. Introduction

Since British scientist Michael Faraday discovered the Faraday effect in 1845,[1] which is the magneto-optical (MO) effect in the transmission configuration, various magneto-optical materials have been researched and developed. Nowadays, the MO effect is widely applied to optical isolators, MO recording media etc.[2–7]

The measurement of the MO effect is indispensable for the evaluation of magnetic materials because information on the electronic structures of the materials are obtained as well as the magnitude of the MO effect. There are several methods for quantitative measurement of the MO effect, such as an orthogonal analyzer method, a rotational analyzer method, a Faraday cell method, and a polarization modulation method.[8–17] However, in order to measure the MO spectrum by those methods, the MO spectra had to be measured for each wavelength using a spectrometer while applying a magnetic field. Therefore, for example, the measurement time of 1–2 h was necessary for the visible region. Saito et al. succeeded in shortening the measurement time to several minutes by combining a multi-channel spectrometer with a conventional Faraday cell modulation method, which can measure an MO spectrum in a single magnetic field sweep with an accuracy of 0.004 degrees.[18,19] However, Faraday rotation and Faraday ellipticity spectra had to be measured individually using different optical setups.

In this study, we combined a multi-channel spectrometer with the polarization modulation method[17,20,21] in which rotation and ellipticity spectra can be simultaneously obtained from three spectra measured for linearly and left- and right-circular polarization. By using the polarization modulation method, it is possible to measure the rotation angle and the ellipticity with the same optical setup in addition to a short measurement time of several minutes. In this paper, we report on the MO spectrometer for the visible light region, and the calibration method for Faraday rotation and Faraday ellipticity.

2. Experimental methods

Figure 1 shows a schematic of the MO spectrometer utilizing the polarization modulation method. A 100 W halogen lamp (TH4-100, Olympus Co., Inc.) was used as a light source, and a multi-channel spectrometer (USB2000 + VIS-NIR, Ocean Optics Inc.) having a detection range of 350–1000 nm, with a 2048-element linear silicon CCD array detector, was used as a light detector. For the MO measurement, collimating lenses (L1, L2, L3), pinhole, polarizer (Pol.), perforated electromagnet (EM), and an analyzer (Ana.) were used. A quarter wave plate (QW) was used to carry out the polarization modulation method. The QW will be rotated by a stepping motor (DS102, Suruga Seiki). The transmission axis of analyzer (α) forms an angle of 45° with the polarizer, and the QW will be set to −45°, 0° and +45° with the polarizer for the measurement.

White light emitted from the light source is converted to parallel light by a combination of a pinhole and collimator lens, and then converted to linearly polarized light by a polarizer and passes through a quarter wavelength plate and a sample. The transmitted light from the sample passes through an analyzer and is then focused by a collimating lens on the end of the optical fiber connected to the multi-channel spectrometer.

The procedure of measurement of the Faraday rotation and Faraday ellipticity spectra is as follows. While applying a magnetic field to the sample, the optical axis of the QW was set to −45°, 0° and +45°, corresponding to left-circularly, linearly and right-circularly polarized light, respectively. Those three polarized light intensity spectra were measured, and Faraday rotation angle (θ_F) and Faraday ellipticity angle (η_F) are calculated by the following equations,[17]

$$\theta_F \approx \frac{1}{2}\left\{\frac{2I_{0°} - (I_{45°} + I_{-45°})}{(I_{45°} + I_{-45°})}\right\}, \tag{1}$$

$$\eta_F = -\frac{(I_{45°} - I_{-45°})}{(I_{45°} + I_{-45°})}, \tag{2}$$

where $I_{-45°}$, I_0 and $I_{45°}$ are light intensities when the optical axis of the QW is −45°, 0° and 45°. The units of the values obtained by Eqs. (1) and (2) are radians. In this article we convert them to angles for discussion. The exposure time of spectrum measurement was 1 ms, and 100 times of averaging were taken for noise reduction. In addition, MO spectra also measured for magnetic fields of +2.5 and −2.5 kOe were averaged. Total measurement time will not exceed 2 min, including applying magnetic fields, rotating the QW, and the

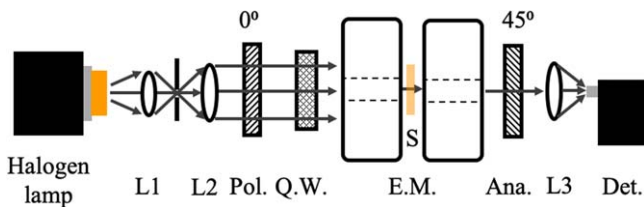© 2019 The Japan Society of Applied Physics

Fig. 1.   (Color online) Magneto-optical multi-channel spectrometer using polarization modulation method.

calculations. A bismuth-substituted neodymium iron garnet, $Nd_{0.5}Bi_{2.5}Fe_5O_{12}$ (Bi:NIG), thin film with a thickness of 200 nm prepared on a $Gd_3Ga_5O_{12}$ (GGG) substrate with (111) orientation by the metal-organic decomposition (MOD) method[22–24] was used as a sample.

3.   Calibration of MO spectrometer

Figure 2 shows intensity spectra measured for $I_{-45°}$, $I_{0°}$ and $I_{45°}$, They exhibit broad spectral structures between 400 and 1000 nm in wavelength, which is determined by the spectrum of the light source, the sensitivity of the multi-channel spectrometer, and the optical absorption of the Bi:NIG thin film. It can be seen that those light intensities changed depending on the wavelength and the polarization state of the light, which was caused by the Faraday effect of the Bi:NIG thin film. Since the wavelength range beyond 800 nm is outside the wavelength range of the polarizing plate and the QW, MO spectrometer in the wavelength range of 400 to 800 nm is discussed in the following. It should be noted that both rotation angle and ellipticity cannot be accurately measured at wavelength of <480 nm for the garnet film, because there is huge optical absorption.[25] Although the polarization modulation method should obtain quantitative MO values in principle, it is considered that an accurate value could not be obtained due to deviations from ideal characteristics of optical elements. Therefore, calibration is required to obtain an accurate rotation angle and ellipticity angle. It will be described in the following part.

3.1.   Calibration method for Faraday rotation
To calibrate Faraday rotation angles, several spectra were measured and calculated with rotating the transmission axis of analyzer from 45° to 40°–50° with 1° step without setting the sample as shown in Fig. 3. This result indicated that the
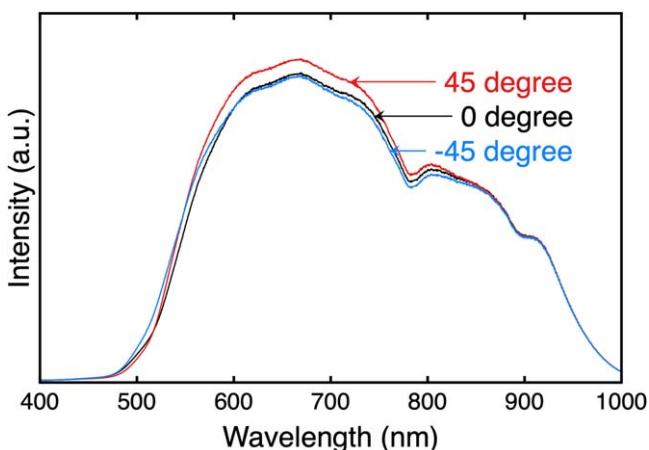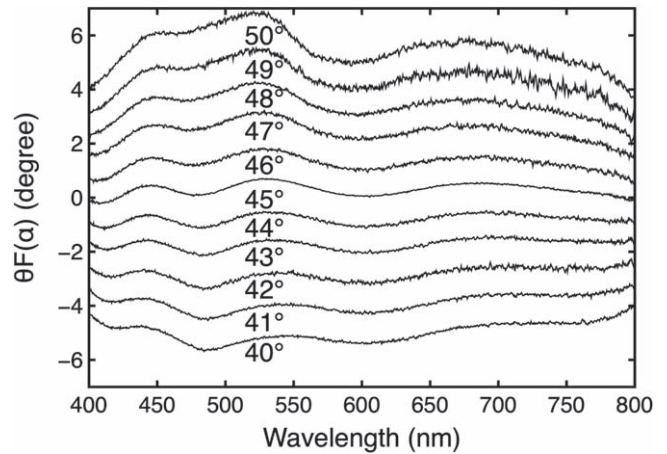

Fig. 3.   Rotation spectra measured for $\alpha = 40°$–$50°$.

rotation angles varied with the angle of the analyzer, however, those values deviated from the expected values and resulted in the wavy shaped spectra. One of the reasons why the spectrum of $\alpha = 45°$ does not reach y=0° is due to an error in the angular relationship between the polarizer, the analyzer and the wave plate. On the other hand, with regard to the spectral shape, it is considered that the deviation of the phase characteristic of the wave plate from the ideal value is a major factor. However, those errors are expected to be canceled by averaging values measured with positive and negative magnetic fields. In this case we do not apply any magnetic field, these errors still exist in the spectra of Fig. 3 so we will eliminate them in the next part.

To obtain a calibration curve for Faraday rotation spectra, the spectrum measured with the angle of analyzer of 45° was subtracted from other spectra as shown in Fig. 4, which are equivalent to Faraday rotation of −5–5°, respectively. It can be seen that the spectral shape became smooth, but these 10 spectra in Fig. 4 do not show accurate values (y = −5°, −4°, …4°, 5°). For this reason, a process of rotation angle calibration is required. From those spectra, a calibration curve corresponding to an angle of one degree was determined using the least squares method. Use the rotation angle in Fig. 4 as the vertical axis when $\alpha = 40$–$50°$, and the standard value as the horizontal axis (x = −5, −4, …4, 5),
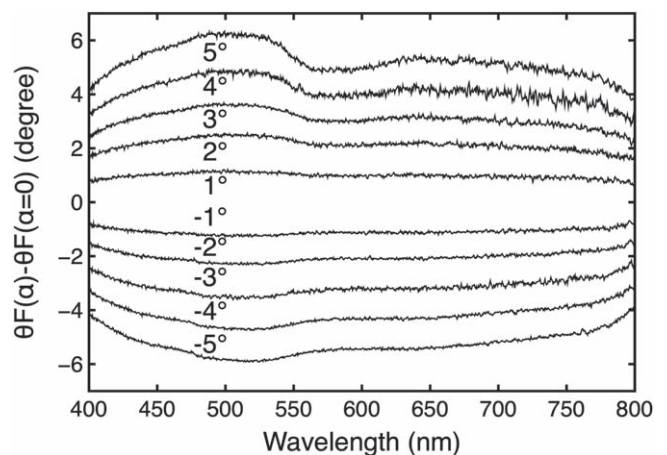

Fig. 2.   (Color online) Light intensity spectra measured with angles of the $\lambda/4$ plate of −45°, 0° and 45°.

Fig. 4.   Rotation spectra for $\alpha = 40°$–$50°$, from which the spectrum for $\alpha = 45°$ was subtracted. And these spectra could be seen as the angle of rotation $\theta_F = -5°$–$5°$.
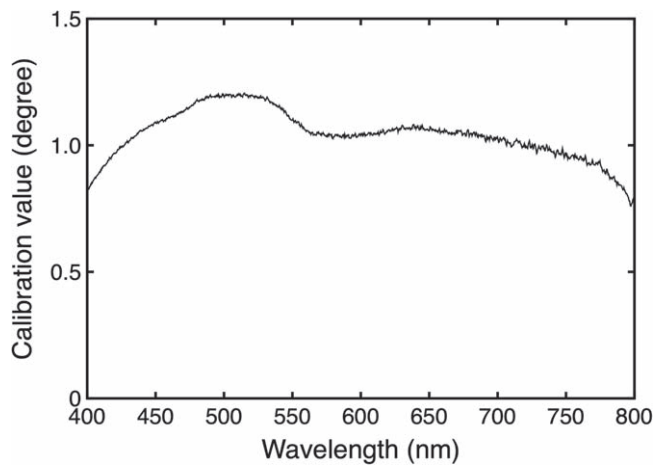
Fig. 5. Calibration spectrum corresponding to per 1° rotation angle. It can be seen that the rotation angle obtained in the experiment differed by this deviation.

Fig. 7. (Color online) Ellipticity spectra for angles of ±45°. And the envelope curve and approximation curve are also plotted.

then the slope of the curve in each wavelength will be the calibration value shown in Fig. 5. From this result, it is understood that the obtained spectrum shape has wavelength dependence, indicating the necessity of the calibration. Through the above calibration of measurement, by using the calibration value and spectrum of rotation angle, we are using a standard deviation to confirm the resolution of this system. To confirm the measurement resolution, setting the analyzer to 46°, measuring and calculate the rotation angle. Then, after calibration, the spectrum should match to $y = 1$. However, the rotation angle measured in the experiment has a deviation with respect to the theoretical value, so we calculated the standard deviation from the experimental value and it is smaller than 0.01° in the range of 500 to 600 nm. So, we can obtain a measurement resolution of 0.01° for the Faraday rotation angle in the range of 500 to 600 nm, with an averaging of 1000 spectra and the exposure time of 1 ms.

3.2. Calibration method for Faraday ellipticity

An optical setup for a calibration of ellipticity is shown in Fig. 6, where a sapphire plate with a thickness of 0.297 cm is used as a multi-order plate.[26,27] The sapphire was set between a sample and the analyzer. Ellipticity spectra were measured without setting a sample when the optical axis of the sapphire plate of ±45° with the polarizer with 45°.

Measured spectra are shown in Fig. 7. It can be seen maxima and minima values are appeared alternately and they were symmetric for signs. The envelope curve is providing calibration functions corresponding to the ellipticity of ±45°. Consequently, a calibration curve corresponding to per 1°

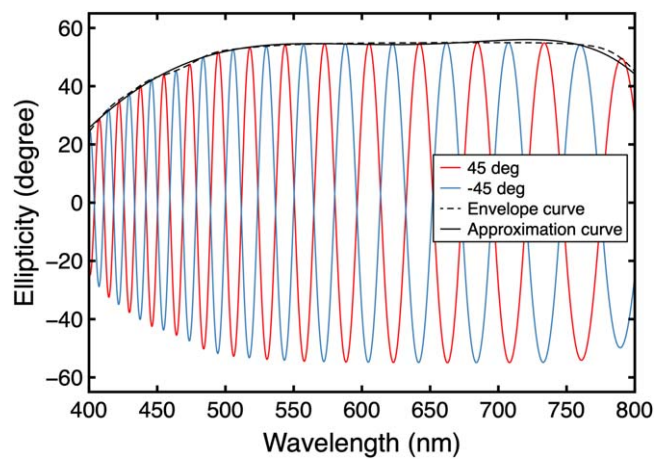ellipticity was obtained as shown in Fig. 8, it is obtained by normalizing the approximate curve of Fig. 7. This calibration spectrum also exhibited wavelength dependence due to the same reason for the Faraday rotation. The correct ellipticity values can be obtained by dividing the experimental values by the calibration value.

4. MO spectra of Bi:NIG thin film

Faraday rotation and Faraday ellipticity spectra of a Bi:NIG thin film were measured with averaging of 100 and 1000 times, are shown in Fig. 9, together with Faraday rotation spectra measured with a conventional MO spectrometer using the differential detection technique. Faraday rotation angle of 3.95° was obtained at a wavelength of 525 nm, and Faraday ellipticity of 12.17° was obtained at 490 nm. From Fig. 9, the shape of these MO spectra are consistent with a typical MO response of Bi: NIG that had been reported.[28–30] The Faraday rotation angles were consistent with that measured by the conventional method, except for a wavelength range shorter than 480 nm. In the range shorter than 480 nm, the Faraday rotation angles decreased and the noise level increased. The reason is due to a low transmittance of the Bi:NIG thin film, resulting that the signal to noise (S/N) ratio decreased. We consider that the S/N ratio could be improved by decreasing the stray light during the measurement.

5. Conclusion

We proposed the MO spectrometer using the multi-channel spectrometer and the polarization modulation method. Measurements of the Faraday rotation and Faraday ellipticity
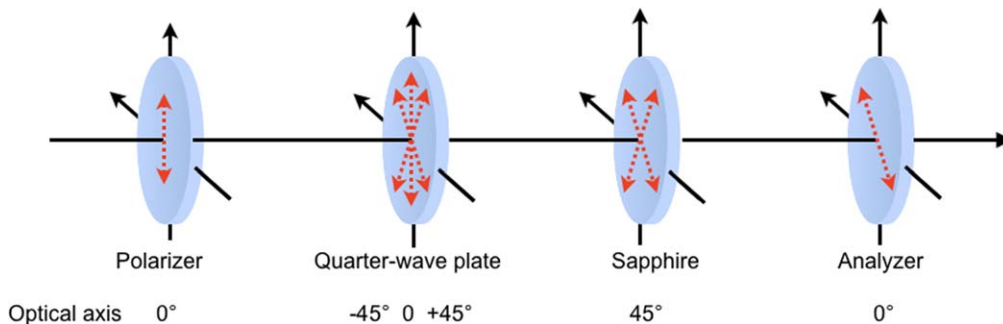

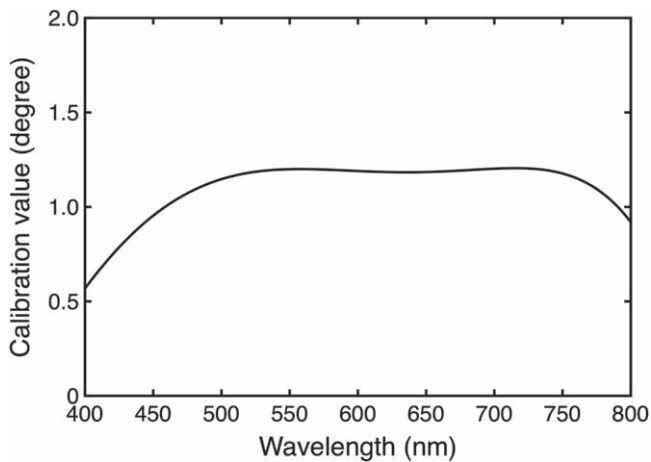**Fig. 6.** (Color online) A diagram of the calibration for Faraday ellipticity.

Fig. 8. Calibration spectrum corresponding to per 1° ellipticity angle. It is obtained from the approximate curve in Fig. 7 after normalization.
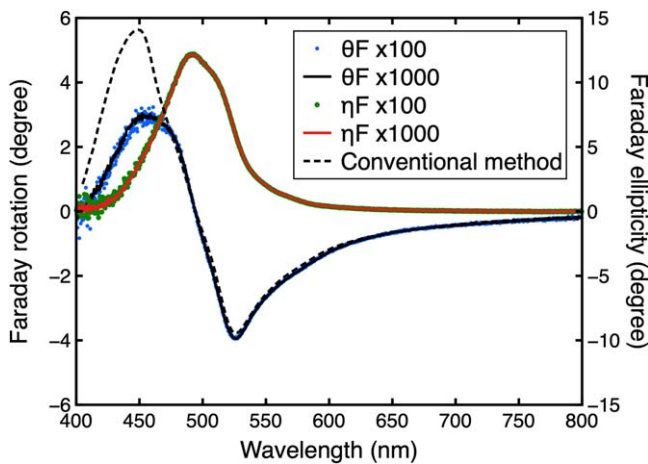

Fig. 9. (Color online) Calibrated Faraday rotation and Faraday ellipticity spectra of Bi:NIG thin film. Faraday spectra measured by the conventional method is also plotted.

spectra were performed for the visible light region. It was shown that the measurement time of the MO spectrum can be shortened from the usual 1–2 h to 2 min by using the proposed MO spectrometer. Calibrations of Faraday rotation and Faraday ellipticity were demonstrated. The resolution of Faraday rotation approximately 0.01° was obtained with an averaging of 1000 spectra and the exposure time of 1 ms. Finally, it should be noted that measurement range is limited to 400–800 nm in this study due to the wavelength range of the polarizing films. We except that the measurement range could be expanded to 350–1100 nm by using the polarizing prisms, and moreover, near-infrared and ultraviolet regions could be measured by changing the multi-channel spectrometer.

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