Journal of Magnetism and Magnetic Materials 347 (2013) 47–50

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magneto-optical effects of transparent magnetic diffraction gratings

Atsushi Syouji [a,b,*], Hiroki Tominaga [a]

[a] Graduate School of Medicine and Engineering, University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan
[b] Japan Science and Technology Agency (JST) PRESTO, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan

ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form
17 July 2013
Available online 31 July 2013

Keywords:
Magneto-optics
Bismuth-substituted yttrium-iron-garnet
Diffraction

ABSTRACT

Magneto-optical effects of transparent magnetic diffraction gratings composed of bismuth-substituted yttrium-iron-garnet ($Bi_2YFe_5O_{12}$) were investigated. The off-diagonal components of the dielectric tensor of the grating are imaginary and real numbers for the light with 450 nm and 532 nm wavelengths, respectively. From precise observation of the first-order transmitted diffraction beam from the grating, the intensity imbalance and relative phase shift caused by the off-diagonal components are clearly observed to be 0.021 and 0.012 rad, respectively.

1. Introduction

Faraday effects, Kerr rotation, magneto-birefringence, and magneto-circular dichroism (MCD) are well known as magneto-optical effects associated with macroscopic materials. In contrast, micro-structures exhibit alternative magneto-optical effects because the scale of their structures is comparable to that of the electric field of light. Magneto-photonic crystals are one of the most effective materials for the application of micro-structural magneto-optical effects. [1–4]. Following these investigations, some authors have studied the capabilities of magneto-photonic crystals, for example, a junction circulator comprising three waveguides coupled with a magneto-optical cavity [5], analogs of the quantum-Hall-effect edge state, [6] and a one-way edge mode [7].

Diffraction features can also be modulated by an external magnetic field. The diffracted magneto-optic Kerr effect (D-MOKE), which is a transverse magneto-optical Kerr effect for a reflected diffraction beam from a magnetic metal grating, has recently attracted much attention [8,9]. Because the effect can be estimated accurately using the Rayleigh perturbation approximation [10,11], the D-MOKE is an interesting tool to investigate magnetization information and dynamics. A magnetization reversal mechanism [12], hysteresis loops [13], and the pattern of a spin valve system [14] have been investigated using a ferromagnetic metal grating. In addition, the vortex spin structure [15] domain formation during the reversal process [16], as well as the domain wall motion and pinning mechanism [17] have been examined in ferromagnetic permalloy arrays of circular, elliptical, triangular, and square rings.

Because magnetic metals have large off-diagonal components in the dielectric tensor, the magneto-optical effects of reflected diffraction beams are observed with high intensity. However, the effects of transmitted diffraction beams are more applicable, even though the off-diagonal components of transparent magnetic materials are generally small. In the present study, to investigate the magneto-optical effects of transmitted diffraction beams, the intensity imbalance and relative phase shift are precisely studied. Here, the gratings are composed of bismuth-substituted yttrium-iron-garnet (Bi:YIG), which is well known as a transparent magnetic material exhibiting strong Faraday effects and MCD in the visible and near-infrared region.

For simplicity, two-dimensional scattering is considered using an infinitely long one-dimensional transparent magnetic dielectric thin wire as the scattering material, although light scattering by a magnetic particle has been precisely studied [18]. A thin wire with a substantially smaller radius than the wavelength of light is aligned in the z direction. The x-polarized $(E_x, 0, 0)$ light propagating along the y-axis illuminates the wire, and an external magnetic field is also applied to the wire along the z direction to form the Voigt configuration. Photo-induced polarization $\left(\vec{p}\right)$ inside the wire is written as,

$$\vec{p} = \varepsilon_0 \begin{pmatrix} \varepsilon_{xx}-1 & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon_{xx}-1 & 0 \\ 0 & 0 & \varepsilon_{zz}-1 \end{pmatrix} \begin{pmatrix} E_x \\ 0 \\ 0 \end{pmatrix}, \quad (1)$$

* Corresponding author at: Graduate School of Medicine and Engineering, University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan.
Tel.: +81 55 220 8348.
E-mail address: ashohji@yamanashi.ac.jp (A. Syouji).

0304-8853
http://dx.doi.org/10.1016/j.jmmm.2013.07.053

with the vacuum dielectric constant ε_0. Here, when each component of the dielectric tensor is a pure real number, the tensor is considered to be a rotation matrix, and the polarization therefore rotates in the x–y plane. If the wires are arrayed, the polarization rotation causes diffraction beam intensity imbalance. When the off-diagonal components of the tensor are pure imaginary numbers, the photo-induced polarizations circulate because the y component of the photo-induced polarization P_y is phase delayed due to the imaginary number i. Consequently, the circulating photo-induced polarizations cause a diffraction beam phase shift for the wire array. We are easily able to select pure real numbers or pure imaginary numbers as the off-diagonal components by only slightly changing the incident light wavelength because the off-diagonal components of the Bi:YIG [19] are more sensitive than those of ferromagnetic metals [20].

The magnetic diffraction grating was fabricated using the metallo-organic decomposition (MOD) method [21] together with the replica method. After the MOD solution with a chemical composition ratio of Bi:Y:Fe=2:1:5 (Kojyundo Chemical Laboratory Co., Ltd.) was spin-coated onto the (111) surface of a gadolinium gallium garnet (GGG) substrate, the solution was replicated on a plastic grating with 1000 grooves/mm by pressing. By baking at 700 °C for 3 h, a diffraction grating composed of Bi:YIG ($Bi_2YFe_5O_{12}$) was obtained. Here, a high Bi-substituted Bi:YIG crystal was adopted to obtain higher magneto-optical effects [22]. Fig. 1 is an image of an atomic force microscopy (AFM) measurement. A grating structure with grooves 20 nm in height and a period of 1 μm was confirmed.

The experimental setup for the diffraction beam intensity imbalance measurement is shown in Fig. 2(a). A 450-nm diode laser perpendicularly irradiates the magnetic diffraction grating, which was polarized perpendicular to the grating grooves. A pair of conjugated first-order diffraction beams was detected by a pair of photo diodes. The grating was subjected to an external magnetic field using an electric magnet modulated by a sinusoidal AC field with a frequency of 0.5 Hz and strength of ±130 mT. The field was parallel to the grating grooves. An optical chopper was used to improve the signal-to-noise ratio. Signals were analyzed by a lock-in amplifier (NF Corporation, LI5640).

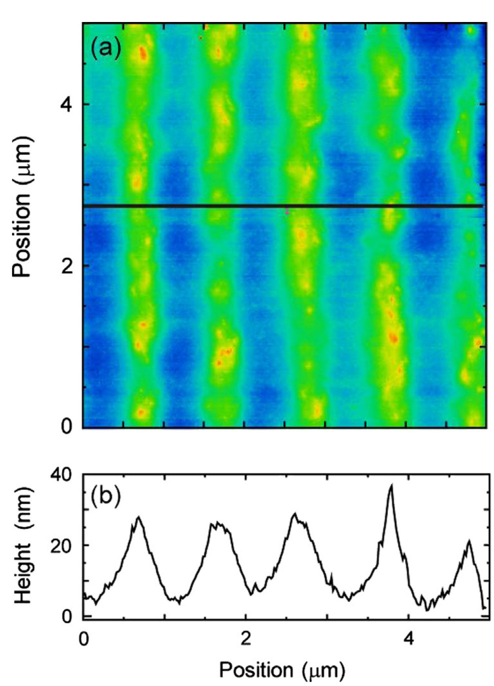

Fig.1. (a) AFM image of the magnetic diffraction grating composed of Bi:YIG. (b) Cross-sectional profile of the image.

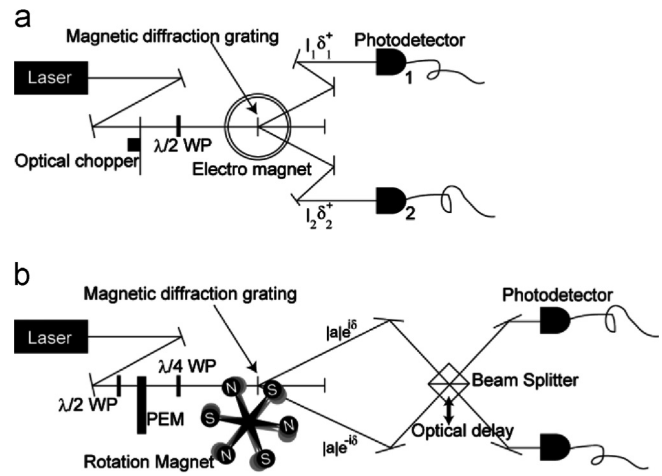

Fig. 2. Setup for (a) diffraction beam imbalance measurements using a magnetic diffraction grating composed of Bi:YIG. The wavelength of the laser is 450 nm and (b) diffraction beam phase shift measurements. The wavelength of the laser is 532 nm. The beam splitter placed on the piezo stage causes an optical delay. WP: waveplate. PEM: photo-elastic modulator.

The experimental setup for the diffraction beam phase-shift measurement is shown in Fig. 2(b). The grating is perpendicularly illuminated by a 532-nm vertical single mode laser (Coherent Scotland, Ltd., Sapphire 532 nm, 50 mW, CDRH YM). After being generated, the two first-order conjugated diffraction beams are interfered with each other using a non-polarized beam splitter, and each is then detected by a photo diode. The beam splitter was placed on a piezo stage (Piezosystem, Jena PX 100 SG, controlled by an NV 40/1 CLE voltage amplifier) to provide an optical delay. The magnetic field applied to the grating was periodically flipped with a rotating permanent magnet to avoid air fluctuation due to the Joule heating of the electric magnet. The magnetic field intensity was ±100 mT, and the flipping repetition rate was 120 Hz. To eliminate the effects of the optical path movements due to the magnetic force, the subtraction signals of parallel and perpendicularly polarized light are detected by placing a photo-elastic modulator (PEM) in front of the sample, the polarizations of which are opposite to the grating grooves. Here, the parallel-polarized light beams must not exhibit magneto-optical effects. The obtained signals are analyzed by double lock-in amplifiers synchronized with the PEM and the rotating magnet.

The diffraction beam imbalance signals are shown in Fig. 3(a) as a function of time, together with the magnetic field strength. Fig. 3 (b) is the diffraction beam intensity hysteresis curve. The intensity imbalance is clearly observed to be synchronized with the magnetic field. Assuming I_1 and I_2 are the two conjugated first-order diffraction beam intensities without magnetic field modulation, and ${\delta_1}^+, {\delta_2}^+, {\delta_1}^-$ and ${\delta_2}^-$ are the modulation ratios of light intensity due to the off-diagonal components, the peak-to-peak detected signal can be written as

$$A=(I_1\delta_1^+-I_2\delta_2^+)-(I_1\delta_1^--I_2\delta_2^-), \tag{2}$$

and the average signal is

$$A_0=I_1(\delta_1^+ + \delta_1^-)/2-I_2(\delta_2^+ + \delta_2^-)/2 \tag{3}$$

here, the subscripts and the superscripts are the detector number and magnetic field direction, respectively. In contrast, when a neutral density (ND) filter with optical density (OD)=f is placed before one detector, the detected signal and the average signals