AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **106**, 093103 (2009); doi: 10.1063/1.3247972
View online: http://dx.doi.org/10.1063/1.3247972
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/106/9?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **106**, 093103 (2009)

Diffracted magneto-optical Kerr effect of a Ni magnetic grating

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(Received 25 August 2009; accepted 19 September 2009; published online 3 November 2009)

We report the results of a joint experimental and theoretical investigation focused on the magneto-optical (MO) properties of one-dimensional magnetic grating structure made of Ni. It was found that the longitudinal Kerr rotation of the second-order diffracted beam is nearly three times larger than that of the zeroth-order beam. The calculational results further confirmed the experimental ones, and almost perfectly reproduced the measured hysteresis loops of the longitudinal MO Kerr rotation, elucidating the origin of the enhanced MO rotation.

 [doi:10.1063/1.3247972]

I. INTRODUCTION

Recently, remarkable magneto-optical (MO) properties of magnetic photonic crystals (MPCs) (Ref. 1) have become the subject of considerable attention because of the potential application to information technology, which requires the solutions for heavy traffic of optical communications, high-density storage, and ultrahigh-speed computing. Apart from the technical aspects, there has also been a tremendous interest in their fundamental physics. Under an external magnetic field, for instance, the optical properties of MPCs can be tuned.[1,2] More specifically, the off-diagonal components of the complex dielectric tensor are altered and, in turn, the MO response is modified in ferromagnetic materials. Such systems have been extensively studied since the time-reversal symmetry breaks down and the nonreciprocity is entailed in the system.[1] They are expected to be a good candidate for efficient MO devices, since the weakness of MO effects can be overcome by light localization in the vicinity of the defects with a consequent increase in the mean optical path length, and thus MPCs require a greatly reduced propagation distance to occupy a large footprint.[3,4] At the same time, there are remarkable interests in understanding, modeling, and controlling the magnetization reversal of magnetic microstructures and nanostructures as functions of shape (stripes, squares, circular dots, elliptic dots, etc.), aspect ratio, and interparticle separation.

In decades, the urge toward the discovery and/or the fabrication of enhanced MO media was mainly concentrated on MPCs.[5–7] Inoue *et al.*[8] also investigated theoretically the MO Faraday effect of discontinuous magnetic media with a one-dimensional (1D) array structure to understand the experimentally observed enhancement in Faraday rotation from porous magnetic media.[9] Moreover, the micromagnetic properties of periodically arranged magnetic wires, dots, and holes in magnetic films have received significant attention.[10,11] However, unlike Kim and co-workers,[12–14] who have reported that the MO effect of the first-order diffracted beam is enhanced, compared to the undiffracted one, they paid little attention to the significance of their observation. It was predicted that in some exotic structures, the MO Kerr rotation close to 45° and a high reflectance (higher than 95% reflection) can be achieved at a certain wavelength.[15] In order to measure the micromagnetic properties of periodic structures based on magnetic/nonmagnetic films, the MO diffraction technique is better suited, which possesses a high sensitivity required to monitor the magnetization changes in thin films and very small elements of different shapes.[11,16]

In this report, the measurement results of the longitudinal Kerr rotation of a 1D Ni magnetic grating are presented. The fabricated 1D magnetic gratings consist of alternating arrays of magnetic and nonmagnetic regions. The longitudinal Kerr rotation of the second-order diffracted beam, as well as that of the first-order one, is enhanced, compared to the zeroth-order one.

II. EXPERIMENTAL

In order to fabricate a 1D magnetic Ni grating structure on a glass substrate, we employed a soft lithography technique, the so-called two-polymer-microtransfer molding.[17] This technique is proven to have a number of advantages, including low cost, capability for nonperiodic three-dimensional (3D) structures, a wide range of material compatibility, and flexibility in design.

The magnetic domain structure has been investigated by using a magnetic force microscopy (MFM) system, which is basically a scanning-probe microscope (Park systems, XE-100) equipped with a magnetic tip (Nanosensors). The magnetic tip scanned the sample in the noncontact mode to obtain the surface morphology and then a second scan was carried out at a constant height above the surface so that the magnetic and the topographic signals were well separated. In

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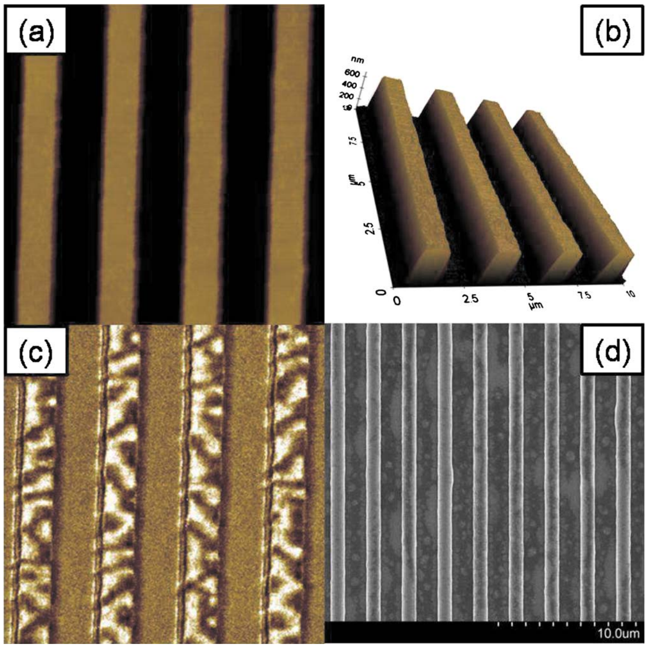

FIG. 1. (Color online) (a) AFM, (b) 3D AFM, (c) MFM, and (d) SEM images of a Ni magnetic grating. The AFM and the MFM images were taken from the same scan area (10×10 μm^2) and position.

our measurement, the MFM images were obtained by using the interleave mode at a lift scan height of 50 nm. The magnetic tip was coated with a Co alloy (40-nm-thick) on the tip side and with Al (30-nm-thick) on the detector side, and the tip radius was typically less than 50 nm.

The longitudinal Kerr rotation was measured at a 45° incidence by using a photoelastic modulator (PEM) method.[18] We could measure the Kerr rotation with an accuracy of ~0.001° by using a PEM (Hinds, PEM-90) at an operating frequency of 50 kHz and with a pair of crystal polarizers whose extinction ratio is better than 10^{-5}. A He–Ne laser of 632.8 nm wavelength was used as a light source and a detection system equipped with a photomultiplier tube (Hamamatsu, R374) was employed. For the polarizing optics, two MgF_2 Rochon polarizers (Karl Lambrecht Corporation, MFRV5) were used. The external magnetic field was applied perpendicularly to the undiffracted and the diffracted beams using an electromagnet capable of a maximum field of ±5 kOe.

III. RESULTS AND DISCUSSION

As shown in Fig. 1, the atomic force microscopy (AFM), the MFM, and the scanning electron microscopy (SEM) studies reveal that a well-defined 1D magnetic grating was fabricated. The AFM and the MFM images were taken on the same 10×10 μm^2 area at room temperature. By comparing the AFM and the MFM images, it is clear that the topography and the magnetic contrast are well separated. The groove depth is 0.6 μm as can be seen in the AFM image [see Fig. 1(b)]. The corresponding MFM image in Fig. 1(c) shows alternating magnetic and nonmagnetic states in the sample with the same periodicity of 2.6 μm, matching with the topological one [see Fig. 1(b)]. Figure 1(c) exhibits the MFM

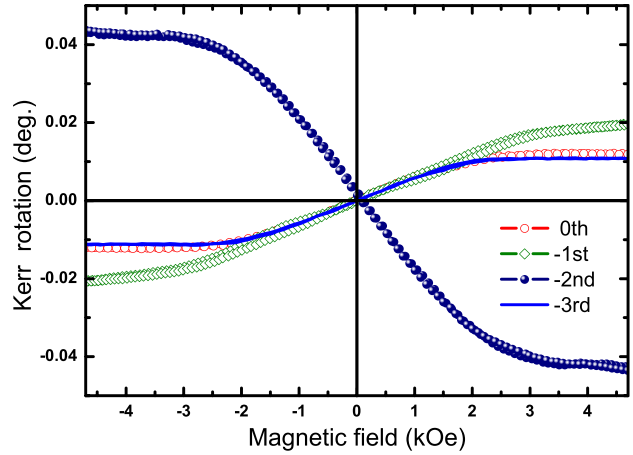

FIG. 2. (Color online) Hysteresis loops of the longitudinal Kerr rotation. Lines are guide to the eyes only.

image for the remanent magnetization of 1D magnetic grating. The image also clearly resolves two different magnetic domains within a single magnetic stripe. It should be noted that the MFM contrast within a ferromagnetic Ni stripe is due to the stray field from the end parts of the in-plane magnet. As seen in Fig. 1(c), the domain structure in the demagnetized state can be described as simple domains. The simple domains are defined as the spin configuration having a single spin direction. It is well known that the domain walls are not only perpendicular or parallel to the stripes but make intermediate angles in the ferromagnetic Ni grating system.

The hysteresis loops of the longitudinal Kerr rotation for the zeroth-order, the first-order, and the second-order diffracted beams have been measured and are displayed in Fig. 2. The magnetic field was applied perpendicular to the groove direction. It can be seen that the shape of the loops is independent of the diffraction order n, while the Kerr rotation, both its magnitude and sign, strongly depend on n. Interestingly, as can be seen in Fig. 2, a nearly three-times enhanced Kerr rotation and the inversion of sign are observed for the second-order diffracted beam. It should be noted that rather large MO enhancement (about 30 times) was observed by us[12–14] for the first-order diffracted beam of a Co_2MnSi magnetic grating. The difference in the enhancement factor is discussed as follows.

To elucidate the underlying physics of the MO enhancement in Ni grating, we have compared these results with the calculated data. The diffracted MO effects of Ni grating were calculated using the rigorous coupled-wave approach by solving the time-harmonic Maxwell's equation with Bloch wave expansion of the electric and the magnetic fields, the Fourier expansions of the periodic permittivity tensor, and the Airy-like internal reflection series.[19] Since a detailed description on the calculational procedure can be found elsewhere,[20,21] only a brief one is mentioned here. The permittivity of Ni and glass were taken from Refs. 22 and 23, corresponding to wavelengths of 635 and 632.4 nm, respectively. The glass has a permittivity of $\varepsilon_{\mathrm{glass}}=2.123$ and $\varepsilon_{\mathrm{Ni}}$ for Ni is given as a function of external magnetic field,[24] namely,

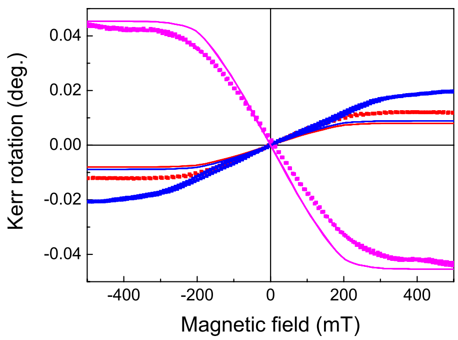

FIG. 3. (Color online) Experimental (symbols) and theoretical (solid lines) Kerr rotation in the zeroth-order (red), the first-order (blue), and the second-order (magenta) diffraction beams for the *s*-polarized incidence.

$$\varepsilon_{\mathrm{Ni}} = \begin{pmatrix} \varepsilon_{xx} & -ifm_z & 0 \\ ifm_z & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix},$$

where $\varepsilon_{xx}=\varepsilon_{yy}=\varepsilon_{zz}=-13.2-(i16.5)$, f is the linear MO constant to be $f=0.02-i0.24$, and m_z is the z component of the unit magnetization vector $m=M/M_s$ (M_s is the saturation magnetization). The values of magnetization were extracted from the micromagnetic simulation employing object oriented micromagnetic framework (OOMMF).[25] In the simulation we assumed that the magnetic domains are perfectly two-dimensional. In other words, the domain walls are perpendicular to the magnetic stripes. The geometrical parameters were obtained by AFM to be the grating period $d=2.6$ μm, the thickness $h=600$ nm, and the width of Ni stripe $w=1.2$ μm.

The theoretical hysteresis loops, together with the experimental ones, are presented in Fig. 3, for the zeroth-order, the first-order, and the second-order diffractions. As can be seen in Fig. 3, the overall agreement between the experiment and the theory is excellent. It was suggested that the MO enhancement strongly depended on the depth of grating or groove.[20,26] The MO enhancement factor can be estimated by the aspect ratio p/d of the grating periodicity p to the grating depth d. We have already observed a significant enhancement (almost 30 times) in the Kerr rotation of the first-order diffracted beam compared to the zeroth-order one in a magnetic grating fabricated by a selective-area annealing of amorphous Co_2MnSi film.[14] The groove depth of the Co_2MnSi grating was about 0.009 μm, while that of the present Ni grating is 0.6 μm. This large value of groove depth leads to a slight enhancement for the first-order and the inversion of sign for the second-order. This result confirms, even with a metallic grating, the finding in Refs. 20 and 26 that the MO enhancement is reduced as the groove depth increases.

IV. SUMMARY

In summary, the AFM and the MFM studies reveal that the obtained 1D magnetic grating has an array-type structure with a significant magnetic contrast. We observed a considerably enhanced MO Kerr rotation for the second-order diffracted beam, compared to the zeroth-order. The calculated hysteresis loops of the longitudinal MO Kerr rotations, in which the values of the magnetization were extracted from the OOMMF simulation, almost completely reproduce the experimental ones. Since the MO enhancement strongly depends on the grating depth, i.e., the smaller the grating depth the more enhanced MO effect, the enhancement factor of 3 is significantly smaller than that of Co_2MnSi magnetic grating, whose groove depth is about 0.009 μm, with respect to a groove depth 0.6 μm of Ni grating.

ACKNOWLEDGMENTS

This work was supported by the NRF through the Quantum Photonic Science Research Center, Seoul, Korea, and MEST, Korea. This work was also supported by the Korean Research Foundation grant funded by the Korean Government (MEST) (Grant No. KRF-2008-005-J00703).

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