Control of Diffracted Magneto-Optical Enhancement in Ni Gratings

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The so-called diffracted magneto-optical (MO) effects, in which the MO responses of diffracted beams are measured in the off-specular geometry, have been utilized to change the amplitude and the sign of MO signals. An enhancement of MO effect of the first-order diffraction was found. In this paper, the rigorous coupled-wave analysis implemented as Airy-like internal reflection series was developed to simulate the diffracted longitudinal MO Kerr effect. We demonstrate that the enhancement of the MO effect is controllable for a certain diffraction order by adjusting the geometrical parameters of Ni gratings. Furthermore, it is believed that the absolute magnitude and the MO enhancement can be more effectively tuned by designing the grating profile and carefully selecting the gyrotropic materials.

Index Terms—**Diffraction, magneto-optical (MO) effect, Ni grating.**

I. INTRODUCTION

MAGNETO-OPTICAL (MO) materials are of importance in a number of applications for integrated optics. All kinds of MO structures were proposed to obtain the satisfactory MO effects based on different fundamentals, such as the magneto-photonic crystals [1]–[5] with defects and the bilayer system of a metallic film perforated with subwavelength-hole arrays in combination of a uniform magnetic film [6]. In these systems, the time-reversal symmetry is broken down and entails nonreciprocity [3], [7], [8] by exploiting the off-diagonal elements of the dielectric tensor in magnetic materials.

Besides the aforementioned schemes, the first work, in which the enhanced MO Faraday effect of the first-order diffraction was realized through a Co_2MnSi grating, was done by Kim *et al.* [9]. Subsequently, the enhancement of the MO Kerr effect was demonstrated [10]. In fact, this phenomenon was also illustrated elsewhere [11]–[14] before Kim *et al.* [9], [10] at both polar and longitudinal magnetization, however, they did not pay much attention to the significance of the observation.

The advantages of the diffraction-induced MO enhancement over other strategies are a considerable decrease in the thickness of devices, because it is not necessary to introduce the multilayered structures. In addition, the MO responses are highly tunable by changing the geometrical parameters of gyrotropic gratings as well as the applied magnetic field.

In this paper, a rigorous coupled-wave analysis (RCWA) implemented as the Airy-like internal reflection series (AIRS) is developed to elucidate the correlation between the MO enhancement and the structures of gratings, which is crucial to effectively apply this physical phenomenon to MO devices.

II. THEORY AND EXPERIMENTS

The RCWA implemented as the AIRS is developed to simulate the diffracted MO effects in the longitudinal configuration. The detailed derivation will be presented elsewhere. Concerning the basic idea of this algorithm, the readers might refer to [15]–[18]. What differs from the polar diffracted MO effects is that the tangential electric and magnetic fields are unable to be separated in the form of a second-order and a first-order differential equation, respectively, in the longitudinal diffracted MO effects, because of the different form of the permittivity tensor. Hence, the approach proposed in [15] was reformulated with coupled electric and magnetic fields for this case.

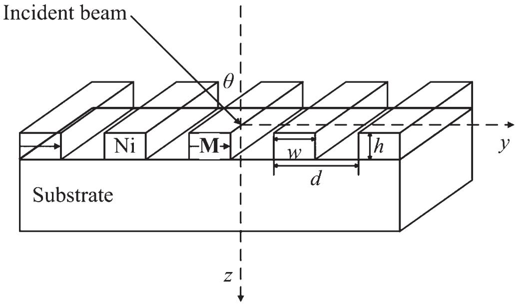

Fig. 1. Schematic figure of one-dimensional Ni gratings in the longitudinal magnetization.

In the simulation, the geometrical parameters of Ni gratings are from [11] and our experimental measurements. The material parameters are taken from the literatures [19], [20], [23]. For the isotropic Si and glass, $\varepsilon_{\text{Si}} = 15.06 - i0.155$ and $\varepsilon_{\text{glass}} = 2.123$ at a wavelength of 632.7 nm, respectively. For the anisotropic Ni, $\varepsilon_{xx} = -13.2 - i16.5$ and $\varepsilon_{xz} = -0.24 - i0.02$ at a wavelength of 635 nm. The schematics of the longitudinal configuration is presented in Fig. 1, where the Ni grating is identified by the depth h, the linewidth w, the period d and the magnetization $\boldsymbol{M}$.

A soft lithographic technique, the so-called two-polymer microtransfer molding [21], was used to fabricate the Ni grating on a glass substrate. The Kerr rotation was measured by using a photoelastic modulator (Hinds, PEM-90) [22] with an accuracy of $\sim 0.001^\circ$, where a He-Ne laser of 632.8 nm is the light source and a detecting system is equipped with a photomultiplier tube (Hamamatsu, R374) and two MgF_2 Rochon

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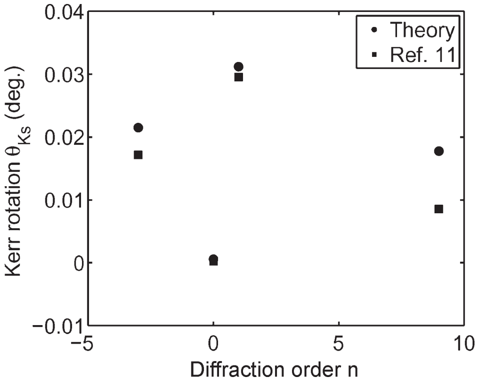

Fig. 2. Theoretical and experimental Kerr rotations of the zeroth-, the first-, the ninth-, and the third-order diffraction.

polarizers (Karl Lambrecht Corporation, MFRV5). The topography of gratings was observed by the atomic-force microscopy (AFM: PSIA, XE-100).

III. Results and Discussion

To verify the validity of the RCWA implemented as the AIRS for the longitudinal MO configuration, the simulation results, together with the experimental ones from [11], are shown in Fig. 2. This Ni grating has a lattice parameter of $d = 20\ \mu$m, a linewidth of $w = 4\ \mu$m, and a groove depth of $h = 20$ nm. The incident angle was fixed to 45° with the s-polarization. Since the Kerr hysteresis loops of the ninth and negative third-order diffraction are not saturated with the increase of the magnetic field, the maxima of the Kerr rotation are taken to compare with the calculated ones. It was found that the agreement between the theory and the experiment is rather satisfactory. This deviation increases as changing the diffraction order to higher ones. And the maximum deviation of them is comparable to the experimental accuracy. Obviously, the MO Kerr rotation of higher diffraction orders is more sensitive to minor effects. It is worth noting that the Kerr rotation of the first order is enhanced considerably compared with others, which is identical to the findings of Kim *et al.* [9], [10].

To explore the possibility to enhance the Kerr rotation of higher orders instead of the first order, a Ni grating was fabricated. The topography of the grating was measured by AFM and obtained the geometric parameters: $d = 2.6\ \mu$m, $w = 1.1\ \mu$m, and $h = 600$ nm. The Kerr rotations, both experimental and theoretical, of various orders are displayed in Fig. 3. As shown in it, there are no obvious discrepancies between the theory and experiment. It was found that the Kerr rotation of the negative second order is the largest, nearly three times the zeroth one, instead of the negative first one as usual, which suggests that the enhancement of MO Kerr rotation is controllable by adjusting the geometric parameters of gratings.

The diffracted MO enhancement is defined as the amplification A^n

$$A^n = \left|\frac{\theta_{Ks}^n}{\theta_{Ks}^0}\right| \tag{1}$$

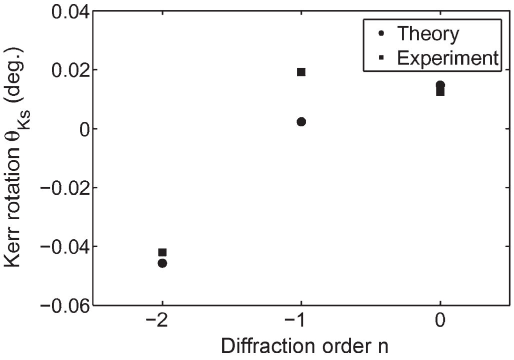

Fig. 3. Theoretical and experimental Kerr rotations of the zeroth-, first-, and seocnd-order diffraction.

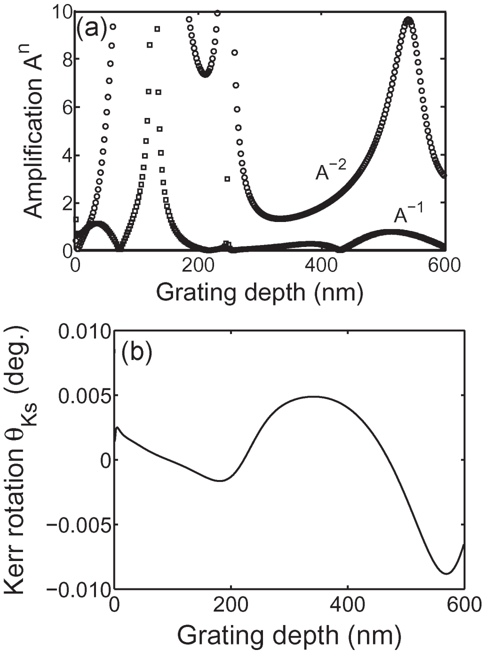

Fig. 4. (a) Amplification A^n and (b) Kerr rotation of the zeroth-order diffraction as a function of grating depth.

where θ_{Ks}^n and the θ_{Ks}^0 are the Kerr rotation of the nth and zeroth-order diffraction with s-polarized incidence, respectively.

Besides the filling factor of gratings, the groove depth is considered as one of the most important parameters. It can be supposed that the effects from the lateral edges become more and more remarkable with the increase of the groove depth. These effects give greater contributions to the higher order diffraction than the lower one. To elucidate it, the depth-dependent amplification is displayed in Fig. 4(a).

It can be clearly seen that $A^{-1} \geq A^{-2}$ when the grating depth $h \leq 20$ nm. With increasing h, the relationship between A^{-1} and A^{-2} is definitely reversed. Considering that there is no remarkable fluctuation in the Kerr rotation of the zeroth order, as shown in Fig. 4(b), it is suggested that the Kerr rotation of the negative second order can be amplified dramatically with increasing groove depth h. Particularly, the amplification can be huge at a certain value of the grating depth, which is ascribed to the satisfaction of resonance conditions. Therefore, we are ought to be careful to design the structure of gratings in order to utilize the diffracted MO enhancement.

IV. CONCLUSION

The RCWA implemented as the AIRS was developed to investigate the diffracted MO effects from one-dimensional Ni gratings in the longitudinal magnetization, which can be easily extended to two-dimensional arrays and/or other MO configurations, such as the polar or the longitudinal magnetization. By comparing the theoretical and experimental Kerr rotations, we realize that there exists a good consistency for all diffraction orders, which fully verifies the proposed algorithm and provides an efficient tool to design the gratings.

In this work, it was found that the amplification A^n is strongly dependent on the grating depth h. The value of A^n can be controlled by choosing the proper thickness of gratings. The larger thickness is beneficial to enhance the Kerr rotation of higher orders. Moreover, it is believed that the absolute magnitudes and the MO amplification can be improved further by elaborately selecting the grating structures and the gyrotropic materials.

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