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Modeling of magneto-optical properties of lamellar nanogratings

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Abstract

Optical and magneto-optical (MO) properties of the MO nanometer-size gratings (nanogratings) are modeled using improved rigorous couple wave analysis (RCWA). The improvements include S-matrix propagation algorithm and Fourier factorization rules and lead to necessary numerical precision for the modeled quantities. The rigorous model is compared with effective medium approximation (EMA), used for simple description of the grating parameters, and the areas of differences are discussed. Dependence of optical and MO elements of permittivity tensor on the fill factor is presented together with comparison to the EMA. Basic polar, longitudinal, and transverse MO configuration are studied.

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1. Introduction

Magneto-optical (MO) materials find wide applications in optical communications as isolators, in areas of magnetic sensors, and recording media. However, there is limited amount of natural and synthesized materials with appropriate optical and magneto-optical properties. One promising approach is to tune optical and MO properties is nanostructurization of common MO materials using periodic patterning. The simplest method is to pattern (or self-assemble) the materials to produce lamellar gratings with the period much smaller than the light wavelength. We can obtain the effective MO medium with desired properties by appropriate choice of materials and grating fill factor and optimize the structure using advanced modeling.

Moreover, efficient modeling combined with MO ellipsometric measurement enable us to characterize properties of the objects by parameters obtained from effective medium approximation (EMA) [1,2]. Also optical functions of such grating can be specified, which leads to better understanding of the nanoscale structures and allows the study of nanosize quantum effects introduced by existence of quantum well or dots in the structure [3,4]. However, EMA cannot be generally used for arbitrary structure or conditions [5]. The limits of the EMA applicability will be discussed later.

In this paper two models of subwavelength gratings represented by effective media are compared. First, a simple EMA model, uses zero-order approximation of the effective parameters assuming that only the zero diffraction order can be found in the grating [6–9]. Second one is based on the following virtual experiment: The reflectivity and ellipsometric data obtained from the rigorous grating model are fitted to the response from an effective layer described by appropriate parameters. Particularly, the one-dimensional lamellar grating consisting of cobalt stripes on the silicon substrate is used for modeling.

2. Theory

Fig. 1 shows schematically the one-dimensional binary lamellar grating, which is modeled in this paper. We use the plane of the incidence being perpendicular to the stripes and models based on monochromatic plane waves.

In rigorous modeling the rigorous coupled wave analysis (RCWA) is used for description of the electromagnetic field in a periodic grating [10]. This method is based on Fourier series representation of the electromagnetic field and material parameters. Slower convergence for transverse magnetic TM, or *p*-polarized incident light in the highly absorbing gratings was improved by representing the permittivity tensor according

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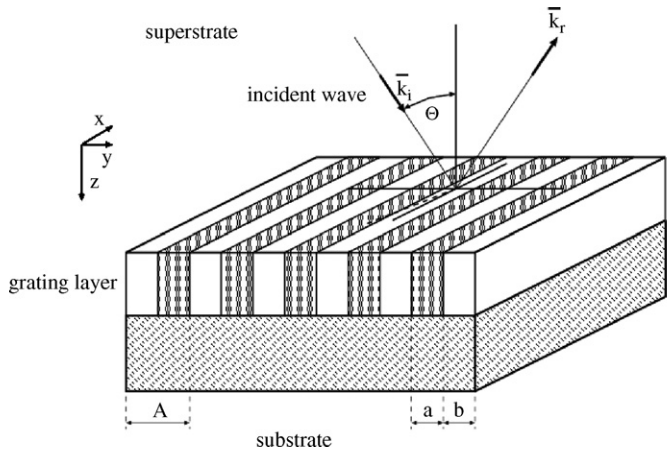

Fig. 1. Structure of one-dimensional lamellar grating. Polar, longitudinal, and transverse MO configuration corresponds to magnetization direction along *z*, *y*, and *x* axis, respectively.

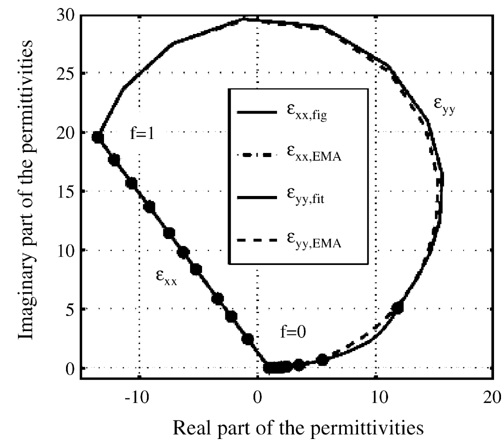

Fig. 2. Dependence of the diagonal effective permittivity tensor elements on the fill factor. Dashed and solid lines represent fitted ordinary ε_{xx} and extraordinary ε_{yy} permittivities, respectively.

to the Fourier factorization rules [11]. Boundary conditions, stating that the tangential components of the field vectors at interfaces are preserved, are realized using the scattering matrix algorithm [12], which allows numerically stable computations of deeper gratings. Rigorous modeling uses fitting of the modeled reflectivities, ellipsometric angles, and MO Kerr angles for the TE (transverse electric, or *s*-) and TM (transverse magnetic or *p*-) polarized incident light.

The effective relative permittivity tensor of lamellar MO subwavelength grating is used in the following form:

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ -\varepsilon_{xy} & \varepsilon_{yy} & \varepsilon_{yz} \\ -\varepsilon_{xz} & -\varepsilon_{yz} & \varepsilon_{zz} \end{bmatrix}. \quad (1)$$

The diagonal tensor components ε_{xx} and ε_{yy} represent the ordinary and extraordinary permittivities corresponding to the grating symmetry. For the polar, longitudinal, and transversal magnetic configuration the off-diagonal elements ε_{xy}, ε_{xz}, and ε_{yz} in (1) are nonzero. The polar magnetization direction is perpendicular to the sample surface (*z* axis), the longitudinal one is in the plane of sample and in the plane of incidence (*y* axis), and the transverse MO configuration corresponds to the magnetization perpendicular to the plane of incidence (*x* axis).

3. Results and discussions

This section deals with the numerical modeling of optical and MO response from the 100 nm height cobalt stripes on the silicon substrate at the chosen wavelength $\lambda = 633$ nm. Optical and MO properties of silicon and cobalt are characterized using the relative permittivity $\varepsilon_{Si} = 15.0634 + 0.1521i$ [13] and $\varepsilon_{Co} = -13.0449 + 19.0400i$ [14], and for the off-diagonal element of the cobalt permittivity tensor $\varepsilon_{off,Co} = 0.9271 + 0.2072i$ [15]. The space period of the stripes is $\Lambda = 5$ nm to ensure validity of the effective medium approximation. The plane of incidence is perpendicular to the stripes.

First, the diagonal components of the effective permittivity tensor is considered. The simple EMA model gives the approximate form of the diagonal permittivity tensor elements [6]:

$$\varepsilon_{xx} = f\varepsilon_{Co} + (1-f)\varepsilon_{air}, \quad \varepsilon_{yy} = \frac{\varepsilon_{Co}\varepsilon_{air}}{f\varepsilon_{air} + (1-f)\varepsilon_{Co}}, \quad (2)$$

where $f = a/\Lambda$ denotes the fill factor of the grating. Fig. 2 shows dependence of the ordinary and extraordinary permittivity tensor elements on the fill factor. The values well correspond to the values obtained from (2).

Good agreement between the simple EMA and rigorous modeling was obtained, indicating that the grating can be modeled by the effective medium. The differences between the simple model (2) and the data obtained from fit of rigorous model correspond to effects of higher-order evanescent waves. Differences increases with increasing grating period Λ [8].

For the polar MO geometry ($\varepsilon_{xy} = \varepsilon_{off,Co}$ and $\varepsilon_{xz} = \varepsilon_{yz} = 0$), the simple EMA gives following form of off-diagonal (ε_{xy}) element [6]:

$$\varepsilon_{xy} = \frac{f\varepsilon_{xy,Co}\varepsilon_{air}}{f\varepsilon_{air} + (1-f)\varepsilon_{Co}}, \quad (3)$$

The dependence of the off-diagonal element of permittivity tensor ε_{xy} on the fill factor is shown in Fig. 3. Good agreement with the EMA values confirms the applicability of the formula (3).

The longitudinal MO configuration characterized by $\varepsilon_{xz} = \varepsilon_{off,Co}$, $\varepsilon_{xy} = \varepsilon_{yz} = 0$ gives the same values of the diagonal permittivity tensor as for the polar configuration. The form of the off-diagonal permittivity tensor component using simple EMA model is in the form [6]:

$$\varepsilon_{xz} = f\varepsilon_{xz,Co} + (1-f)\varepsilon_{air}. \quad (4)$$

Fig. 3 shows dependence of the off-diagonal permittivity tensor on the fill factor. Exceptional linear dependence for the longitudinal configuration corresponds to special direction of the longitudinal magnetization perpendicular to the grating lamellas.

The fitting process has to be changed for the case of transversal configuration. In the practical measurements, the permittivity tensor elements can be obtained from two measurements: The

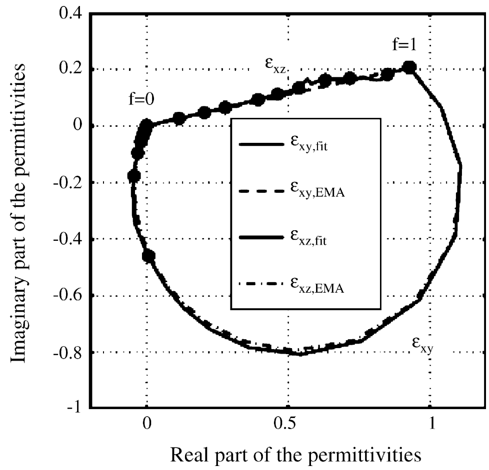

Fig. 3. Dependence of the off-diagonal effective permittivity tensor element on the fill factor for polar and longitudinal MO configurations. Solid and dashed lines represent rigorous and EMA values of the off-diagonal permittivity tensor elements in the complex plane plot.

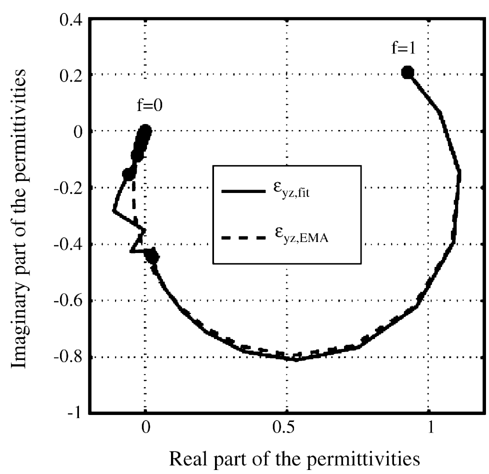

Fig. 4. Same as in Fig. 3 for transverse MO configuration.

measurement without applying external field, which is sensitive to the diagonal elements and the measurements with external field, where the non-zero off-diagonal element can be obtained by estimating relative changes in TM polarization reflectivity. Denoting the presence of the external field by **M**, the relative difference of TM polarization reflection coefficient $r_{34,\Delta}$ can be written in the form:

$$r_{34,\Delta} = \frac{r_{34,M} - r_{34,0}}{r_{34,0}}. \quad (5)$$

EMA value of the off-diagonal effective permittivity tensor element can be obtained from formula [6]:

$$\varepsilon_{yz} = \frac{f\varepsilon_{yz,\mathrm{Co}}\varepsilon_{\mathrm{air}}}{f\varepsilon_{\mathrm{air}} + (1-f)\varepsilon_{\mathrm{Co}}}, \quad (6)$$

Fig. 4 shows fill factor dependence of the off-diagonal permittivity tensor element.

4. Conclusions

The presented results show usability of the simple EMA model for the description of subwavelength gratings on the wide range of the fill factor values. Larger disagreement between simple model and rigorous data was obtained for large values of the grating period Λ, for which the simple zero-order approximation EMA does not properly describe light propagation in a absorbing periodic system. The difference between EMA and the rigorous data is caused by influences of higher orders that affect distribution of the field inside structure although they cannot be measured in far field.

Fill factor dependencies of the off-diagonal elements of the effective permittivity tensor show interesting development of values, which can hardly be reached by the simple natural materials (Figs. 3 and 4). This property is promising for the future applications, where new MO materials can be designed by the subwavelength gratings.

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