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Researches on the guide-mode resonance of the planar polymer sub-wavelength grating

Feng Li*, Xiaofeng Cui, Guowen Kuang, Huaming Wu, Yiqing Gao

Key Laboratory of Nondestructive Test (Ministry of Education), Nanchang Hangkong University, Nanchang 330063, People's Republic of China

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ABSTRACT

In this paper, a planar polymer sub-wavelength grating whose period structure is modulated by different refractive index is proposed. The guided mode resonant of the proposed grating is analyzed with effective medium theory and the eigenvalue equation of the thin film waveguide, and the reflectance properties of the grating are simulated with rigid coupled-wave analysis. The reflectance property shows obvious polarization dependent. The influences of the grating period, thickness and the incident angle on the resonant wavelength are also analyzed. It is shown that the resonant wavelength shows redshift with the increase of grating period, dual resonant peaks occur when the grating thickness is of some certain values, and the resonant peak of normal incidence will split into 2 peaks on the condition that oblique incidence. This planar polymer sub-wavelength grating may find application in filters, polarization elements, reflectors and so on.

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1. Introduction

Diffraction gratings are common optical elements in science and engineering. They serve as wavelength separation device [1], dispersion element [2], filter [3], coupler [4] etc. and can be seen applications in many communication instrument, measuring and detection equipment, optical pick-up head and so on. Gratings with sub-wavelength periodic structure have become one of the most popular research focuses because of their unique characteristics such as high diffraction efficiency and polarization dependent. Sub-wavelength grating has three typical periodic structures. They are surface relief [5], embedded [6], and gradient refractive index [7,8]. MEMS technologies such as lithography, ion beam etching, coating etc. usually are employed to fabricate these periodic sub-wavelength structures. Besides, ion modified and doping usually participate into the fabrication of the periodic sub-wavelength structure of gradient refractive index [9]. Most of these structures are fabricated on the substrates that are made by inorganic materials such as silicon or silica. Especially for the structure of gradient refractive index, photosensitive glass or Ge-doped silicon is the material that is used frequently [10].

Recently, photosensitive polymer has been employed to fabricate many kinds of micro-optical elements such as micro lens array [11], photonic crystals [12], optical waveguide [13], and diffraction grating [14] and so on. Photosensitive polymer not only possesses the features of high electro-optic coupling coefficient and low relative permittivity, but also has the advantages of light mass, low cost and easy processing. Otherwise, some polymer materials have interesting nonlinear optical properties such as photo induced refractive-index variation. By controlling the exposure dose distribution, different index profile can be realized in the polymer film, so that the photosensitive polymer has been employed to fabricate many kinds of micro-optical elements as mentioned above. Undoubtedly, photosensitive polymer becomes the candidate material for fabricating the planar polymer sub-wavelength grating.

Planar polymer sub-wavelength grating has plane surface and its periodic structure is modulated by refractive index in its own volume. As far as the fabrication methods for planar diffraction gratings using photosensitive polymer are concerned, double beam interference exposure is a kind of conventional method [15]. One-step writing process is used to fabricate a planar waveguide including a Bragg grating structure in bulk polymethylmethacrylate (PMMA) [16]. By using of proton beam writing or femtosecond laser, refractive index modification periodic structure forms in the relative thin polydimethylsiloxane (PDMS) film without development processes [17]. Sub-wavelength structure in the visible region with period of 150 nm fabricated in polymer with waveguide-mode interference lithography technique has been reported [18]. Therefore, the fabrication process of the planar polymer grating is relative simple compared to that of the grating on the organic substrate. In addition, planar polymer sub-wavelength grating is

* Corresponding author. Tel.: +86 079183953461.
E-mail address: lifengnchu@163.com (F. Li).

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easily to be integrated with other optical elements due to its plane surface.

In this paper, the resonance wavelength of a planar polymer sub-wavelength grating with single layer is analyzed with the eigenvalue equation of the thin film waveguide, and the reflectance properties of the grating is simulated with rigid coupled-wave analysis. The polarization characteristic and the influences of the grating period, the grating thickness and the incident angle on the position of the resonant wavelength are discussed in detail.

2. Theory

A model for planar polymer grating is illustrated in Fig. 1. It is supposed that there are two different refractive-index values in one period of the grating, denoted as n_1 and n_2 respectively. n_c and n_s are denoted as the refractive index of the cover and the substrate respective. H and Λ are denoted as the grating thickness and the grating period respectively. τ is used to denote the width of the part with refractive n_2 in one period, so that the duty factor of the grating is written as $\rho=\tau/\Lambda$. The wavelength of the incident light is λ.

According to the effective medium theory, the grating can be regarded as uniform anisotropic media on the condition that $\Lambda<\lambda$, and the first order of approximation of the effective refractive index is

$$n_{\text{eff}} = \begin{cases} \sqrt{(1-\rho)n_1^2+\rho n_2^2}, & \text{TE} \\ \sqrt{n_1^2 n_2^2 / \left[(1-\rho)n_2^2+\rho n_1^2\right]}, & \text{TM} \end{cases} \tag{1}$$

The eigenvalue equation of thin film waveguide for TE wave is

$$\tan(\kappa H)=\frac{\kappa(\gamma+\delta)}{\kappa^2-\gamma\delta} \tag{2}$$

In this equation, κ, γ and δ are the wave numbers along the z-axis in the grating, cover and substrate, respectively. They are written as

$$\begin{cases} \kappa=\sqrt{n_{\text{eff}}^2 k_0^2-\beta^2} \\ \gamma=\sqrt{\beta^2-n_c^2 k_0^2} \\ \delta=\sqrt{\beta^2-n_s^2 k_0^2} \end{cases} \tag{3}$$

where k_0 is the wave number in the vacuum, and β is the propagation constant in the waveguide. In the grating layer, because of diffraction, the propagation constant in the grating layer is written as

$$\beta=k_0\left(\frac{n_c\sin\alpha-i\lambda}{\Lambda}\right), \quad i-0,\pm1,\pm2,\ldots \tag{4}$$

in which i represents the diffraction orders. If the propagation constant β in the grating layer satisfies Eq. (2), guided-mode resonances occur.

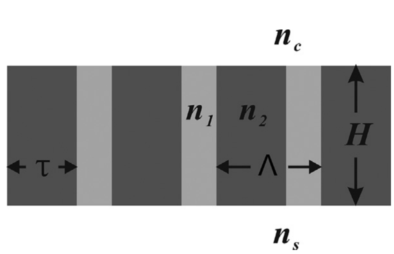

Fig. 1. Period structure of the planar polymer grating.

3. Calculations and results

As can be seen from Eq. (4) that β is related to the incident wavelength and angle, the refractive index of the cover and the diffractive order and the grating period. In order to obtain symmetric reflected spectra, n_c and n_s are adopted to be equal with each other. The refractive index of polymer ranges usually from 1.3 to 1.7. Taking SU-8 polymer as an example, different refractive index increase can be obtained by means of different photo-thermal processes. In the near infrared region, the refractive index of SU-8 polymer can be taken to be constant. Reflectance for TE and TM waves are calculated with RCWA and the results are shown in Fig. 2. Refractive index distribution along x-axis is supposed to be rectangular. In the calculation, 1.550 and 1.605 are adopted for n_1 and n_2, respectively, $\rho=0.5$, $H=1.5$ μm, $\Lambda=1$ μm, $n_c=n_s=1$, and the incident angle is zero. There are only 0 order forward and backward diffractive waves for sub-wavelength grating. Due to the differences of the effective refractive index and the eigenvalue equation between TE and TM waves, the reflectance properties show obvious polarization dependent.

Submitting the values of n_1, n_2, n_s, n_c and ρ into the equations from Eqs. (1)–(4) and assuming $\lambda=1.550$ μm and $\Lambda=1.1625$ μm, the grating thickness is solved to be $H=0.4464$ μm. With these parameters, the zero-order diffractive efficiency of the reflected light for TE incident wave is calculated with RCWA and the dash curve in Fig. 3 shows the results. Because the calculated result for the grating thickness is not the most accurate value for the resonant wavelength calculated with RCWA. The sharp resonant appeared at $\lambda=1.53579$ μm exhibits a shift $\Delta\lambda=14.21$ nm from the designed wavelength $\lambda=1.550$ μm.

Many factors such as the distribution of the refractive index, the grating depth, the grating period the incident angle etc. have

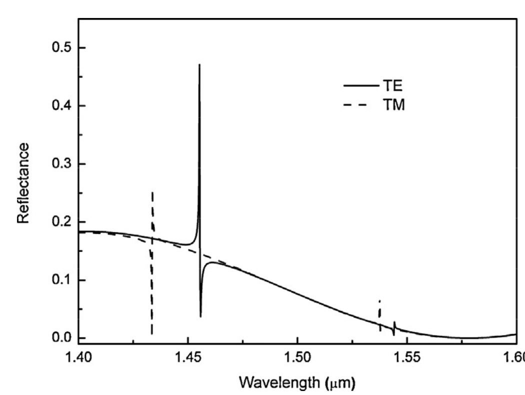

Fig. 2. The reflectance property of the planar polymer grating shows obvious polarization dependent.

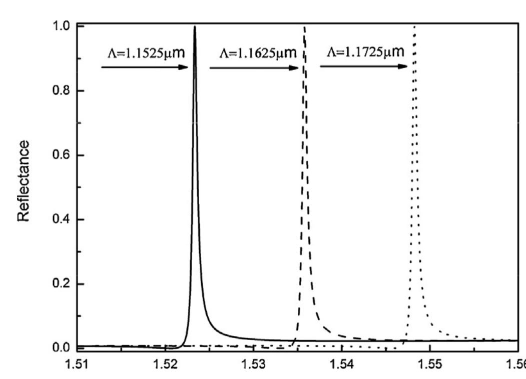

Fig. 3. The resonant wavelength exhibits redshift with increase of the grating period.

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