Sandwiched connecting-layer-based polarizing beam splitter with improved efficiency and extinction ratio

HAO PEI, BO WANG*, WENHUA ZHU, SUFANG YIN, LI CHEN, LIANG LEI, JINYUN ZHOU
School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510006, China

A transmission polarizing beam splitter (PBS) is described and designed by a sandwiched grating with a connecting layer at a central wavelength of 800 nm. The novel grating is analyzed and designed by modal method and rigorous coupled-wave analysis. Compared with the reported surface-relief PBS gratings, the proposed grating extinction ratio, fabrication tolerance and incident spectrum band width can be improved greatly.

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1. Introduction

Polarization state of the incident beam can be controlled by polarizing beam splitters which play important roles in the optical system [1-3]. Gratings are found to have polarization-dependent properties when periods can be comparable to the incident wavelength of the incident light [4]. The performance of a polarizing beam splitter (PBS) includes the efficiency, the incident wavelength and angular bandwidths, and the extinction ratios. Conventional PBSs become increasingly unable to meet the some requirements of optical applications, especially extinction ratio [5], size, and bandwidth property [6]. In order to further improve the performance of PBSs, surface-relief grating [7,8] and sandwiched grating [9,10] have been discussed. A dielectric layer between a metal layer and the grating layer is used to achieve broader reflection bandwidth. Zheng *et al*. have reported a metal-mirror-based reflecting polarizing beam splitter grating with wide bandwidth [11]. Clausnitzer *et al*. have experimentally fabricated a transmission grating with a cover layer [12]. The cover layer can realize the suppression of the Fresnel reflection loss at the grating-air interfaces. In the process of fabrication, the cover fused silica and grating were cleaned under the condition of high-pressure. Then the grating surface and cover-layer surface were activated by oxygen plasma. Wang *et al* [13] proposed a transmission PBS by a sandwiched grating, where the optimized efficiencies for transverse electric (TE) polarization in the -1st order and transverse magnetic (TM) polarization in the 0th order are 93.07% and 99.26%, respectively. Although the efficiency for TM polarization is very high, the efficiency for TE polarization needs to be further improved. For the optimized sandwiched PBS under different incident wavelengths, efficiencies more than 90% can be obtained for 33 nm spectral bandwidths. From the results, the efficiency for TE polarization and incident wavelength bandwidth are required to be further enhanced.

In this paper, a novel transmission PBS grating is presented. The duty cycle of the grating and the grating period are optimized based on the modal method [14], which well reveals the diffraction process in the grating. The modal method has been proved to provide good guideline for PBS gratings [15]. Diffraction efficiencies are obtained by using rigorous coupled-wave analysis (RCWA) [16]. With improved merits, the PBS based on a sandwiched grating with a connecting layer should be interesting in practical application.

2. Modal analysis and numerical design

Fig. 1 shows the schematic of a sandwiched transmission PBS grating with a connecting layer. The PBS grating is under Littrow mounting with its incident angle of $\theta_i = \sin^{-1}(\lambda/2n_1d)$ at an incident wavelength of 800 nm. The first layer of the grating is covering layer, where its refractive index is $n_1 = 1.45$. The second layer of the grating is grating region. The depth of the grating is h_g and the grating duty cycle is the ratio of width b to period d. The refractive index of grating ridge is $n_1 = 1.45$ and the refractive index of grating groove is $n_2 = 1.00$. The third layer is the connecting layer of h_c and its refractive index is $n_1 = 1.45$. The refractive index for the substrate is $n_3 = 2.00$. In this paper, many parameters should be optimized: duty cycle, period, depth, and thickness of connecting layer.

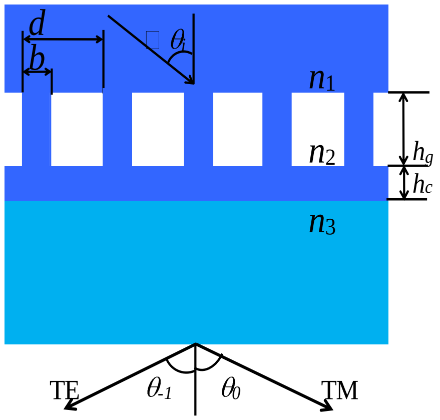


Fig. 1. (Color online) Schematic of the transmission polarizing beam splitter of a sandwiched grating with a connecting layer

The analysis of the transmission grating and calculation of the grating period are based on modal method, which can facilitate the optimization greatly. According to modal method, the efficiency will be decided by the phase difference. If the phase difference is an odd-numbered multiple of π, the incident wave will be mainly diffracted into the -1st order, if the phase difference is an even-numbered multiple of π, high efficiency can be obtained in 0th order. Effective indices can be achieved by the equation for TE polarization [14]:

$$F(n_{eff}^{\ 2}) = \cos\beta b \cos\gamma g - \frac{\beta^2+\lambda^2}{2\beta\gamma}\sin\beta b \sin\gamma g = \cos\alpha d \quad (1)$$

and for TM polarization, the equation can be expressed as:

$$F(n_{eff}^{\ 2}) = \cos\beta b \cos\gamma g - \frac{n_2^4\beta^2+n_1^4\gamma^2}{2n_1^2 n_2^2\alpha\beta}\sin\beta b \sin\gamma g = \cos\alpha d \quad (2)$$

where

$$\alpha = k_0 \sin\theta_i, \beta = \sqrt{n_1^2 - n_{eff}^2}, \gamma = k_0\sqrt{n_2^2 - n_{eff}^2}, k = 2\pi/\lambda \quad (3)$$

According to Eqs. (1)-(3), effective indices can be obtained with different periods. Fig. 2 shows the effective index versus grating period with a duty cycle of 0.3 under Littrow mounting. For TM polarization, high efficiency can be obtained with the same effective indices and no phase will be accumulated for the period of 530 nm. Moreover, extinction ratio is an important performance index of the PBS. In this design, extinction ratios C_0, C_{-1}, and C can be defined as:

$$C_0 = 10\log\left(\frac{\eta_0^{TM}}{\eta_0^{TE}}\right), C_{-1} = 10\log\left(\frac{\eta_{-1}^{TE}}{\eta_{-1}^{TM}}\right), C = \min\{C_0, C_{-1}\} \quad (4)$$

C_0, C_{-1}, and C are in the units of dB.

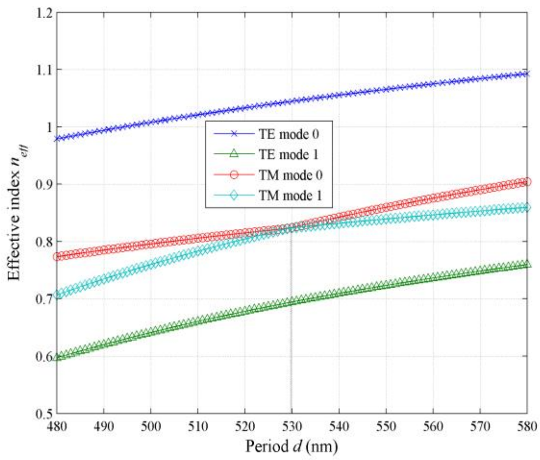
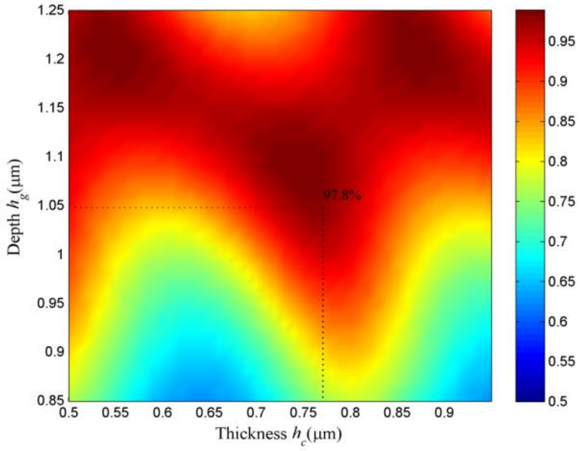


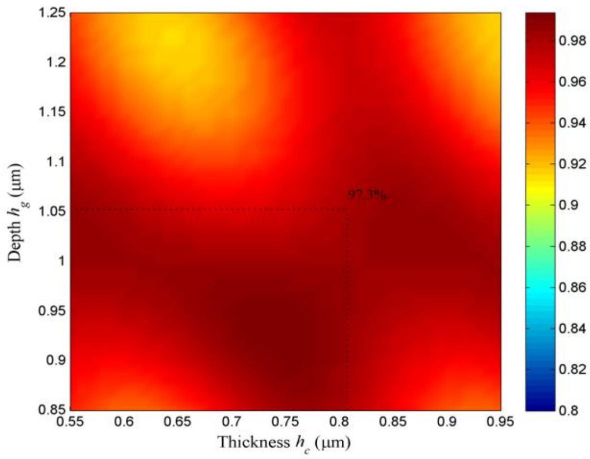
Fig. 2. (Color online) Effective index versus grating period with a duty cycle of 0.3 under Littrow mounting

3. Results and discussion

According to RCWA, simulation is employed to optimize the depth h_g and thickness of connecting layer h_c in order to achieve high efficiencies for TE polarization in the -1st order and TM polarization in the 0th order. Fig. 3 shows efficiency versus grating depth and thickness of connecting layer with the special duty cycle of 0.3 and period of 530 nm at the incident wavelength of 800 nm under Littrow mounting. For the optimization, the grating depth is 1.05 μm and the thickness of connecting layer is 0.77 μm, efficiencies are 97.8% and 97.3% for TE polarization in the -1st order and TM polarization in the 0th order, respectively.

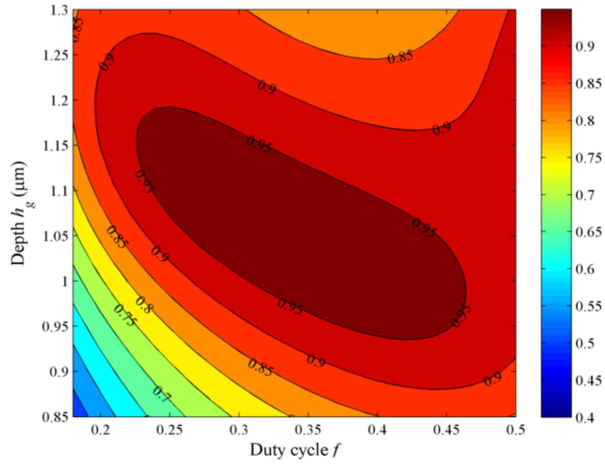


(a)

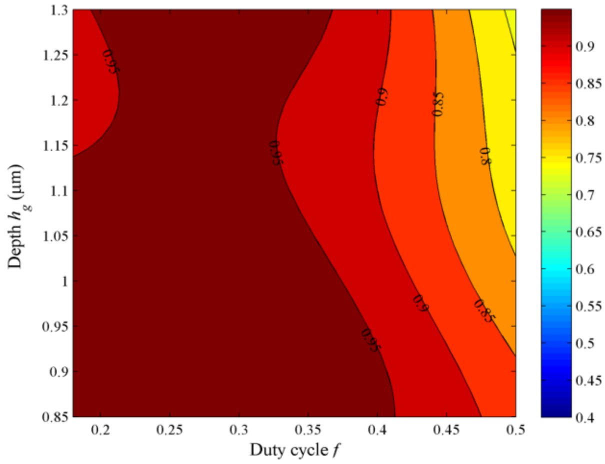


(b)

Fig. 3. (Color online) Efficiency versus grating depth and thickness of connecting layer at an incident wavelength of 800 nm under Littrow mounting (a) TE polarization in the -1st order and (b) TM polarization in the 0th order.



(a)

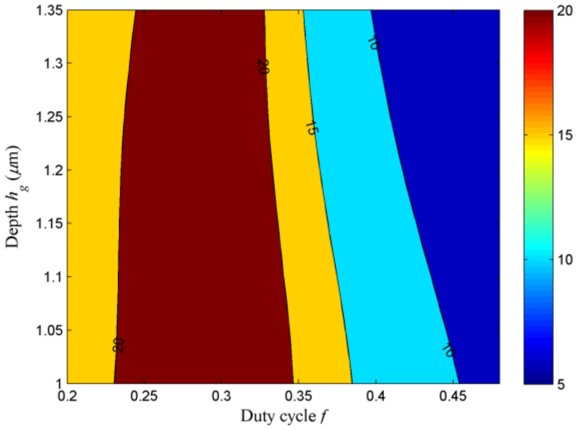


(b)

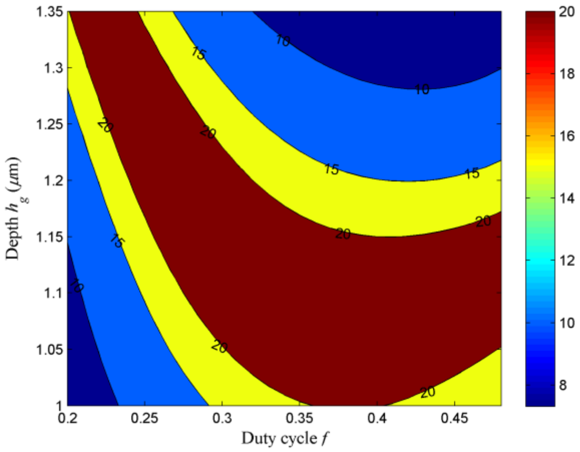
Fig. 4. (Color online) Efficiency versus grating depth and duty cycle at an incident wavelength of 800 nm under Littrow mounting (a) TE polarization in the -1st order and (b) TM polarization in the 0th order.

For the design of the transmission PBS by a sandwiched grating with a connecting layer, wide fabrication tolerance, incident wavelength and angular bandwidths are desirable. Fig. 4 shows efficiency of the transmission grating versus grating depth and duty cycle at an incident wavelength of 800 nm. In Fig. 4, efficiencies more than 90% can be obtained within the duty cycle range of 0.25-0.39 and the grating depth range of 1.03-1.17 μm for two polarizations.

Moreover, the extinction ratio is an important performance index of the PBS, which can be calculated by the Eq. (4). Figure 5 shows the extinction ratios versus the grating depth and duty cycle with the optimized grating parameters. In Fig. 5, when the grating depth changes from 1.01 μm to 1.19 μm, C_{-1} and C_0 are higher than 15 dB within a duty cycle range from 0.29 to 0.42.



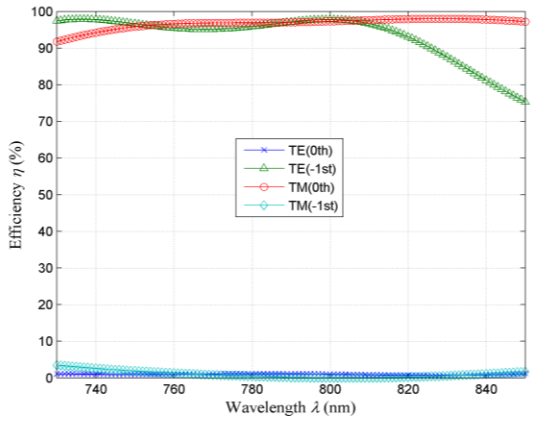
(a)



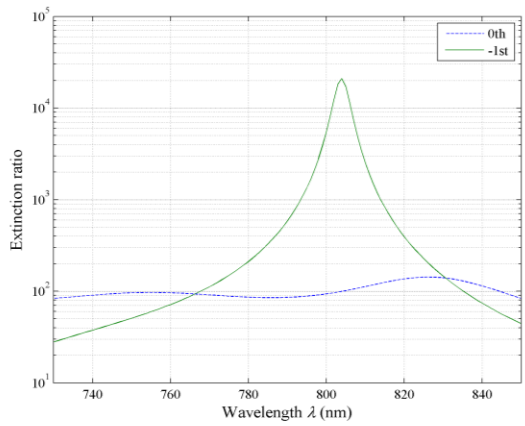
(b)

Fig. 5. (Color online) Extinction ratios (unit: dB) of the (a) -1st order and (b) 0th order versus the grating depth and duty cycle with the optimized grating parameters

Fig. 6 shows the efficiency and extinction ratio versus the incident wavelength under Littrow mounting with the optimized grating parameters. In Fig. 6 (a), the efficiency for TE polarization in the -1st order and TM polarization in the 0th order more than 95% can be obtained for 70 nm spectral bandwidths within the wavelength range of 745-815 nm. In Fig. 6 (b), the extinction ratios larger than 100 can be for 62 nm spectral bandwidths within 771-833 nm.



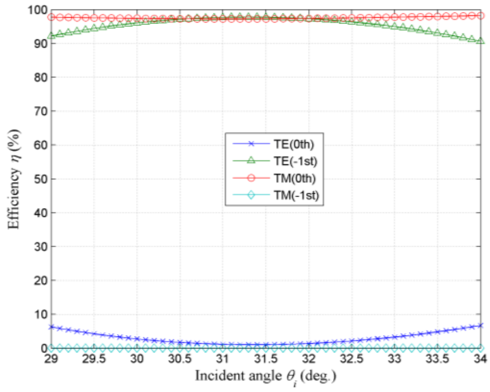
(a)



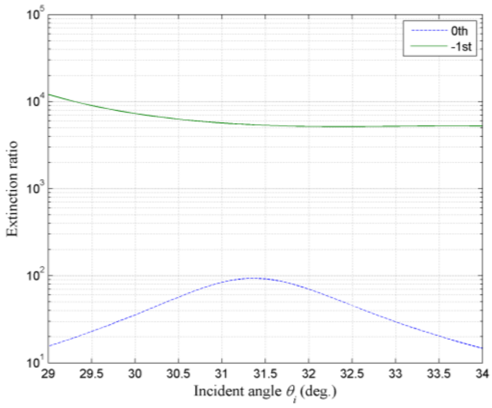
(b)

Fig. 6. (Color online) (a) Efficiency and (b) extinction ratio versus incident wavelength under Littrow mounting with the optimized grating parameters.

For different incident angles, figure 7 shows efficiency and extinction ratio versus incident angle for the incident wavelength of 800 nm with the optimized grating parameters. In Fig. 7 (a), efficiencies more than 95% can be obtained for both TE and TM polarizations within the incident angle range of 29.6-33.1°. In Fig. 7 (b), the extinction ratio is very high in the -1st order with a broad incident angle range.



(a)



(b)

Fig. 7. (Color online) (a) Efficiency and (b) extinction ratio versus incident angle for the incident wavelength of 800 nm with the optimized grating parameters.

4. Conclusion

In conclusion, a novel transmission PBS grating is proposed by the sandwiched structure. With grating parameters optimized by using modal method and RCWA, the polarizing beam splitter can exhibit efficiencies of 97.8% and 97.3% for TE polarization in the -1st order and TM polarization in the 0th order, respectively. Moreover, under Littrow mounting, extinction ratios can be larger than 100 for 62 nm spectral bandwidths within 771-833 nm. A good tolerance for grating fabrication is achieved with the parameters for the proposed design.

Acknowledgements

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*Corresponding author: wangb_wsx@yeah.net