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Polarizing beam splitter of total internal reflection fused-silica grating under second Bragg angle incidence

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We describe a high-efficiency polarizing beam splitter (PBS) of deep-etched fused-silica grating based on total internal reflection (TIR) under second Bragg angle incidence. Efficiency can reach 98.27% for TE-polarized wave in the -2nd order and 99.15% for TM-polarized wave in the 0th order, and extinction ratio can reach 2.257×10^3. As an excellent optical material, fused silica can stand with high laser power. TIR grating can realize high efficiency by reflecting all the energy without transmission. It is the first time to present PBS grating based on TIR under second Bragg angle incidence etched in fused silica.

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1. Introduction

The polarizing beam splitter (PBS) plays an important role in numerous optical systems [1-3], which can split an incident beam into two orthogonally polarized beams. Most conventional PBSs are based on birefringent crystals or multilayer coatings, which are bulky or expensive, respectively. For high-density gratings, it indicates that polarization-dependent diffraction properties [4] will appear when the period is near the incident wavelength or subwavelength. And deep-etched gratings can show high efficiency [5]. It is desirable that a simple high-density deep-etched grating can work as a PBS. According to the grating equation, if the grating period is no larger than the incident wavelength, there are only two diffracted orders existed: the 0th and -1st orders. Based on transmission case, a series of novel optical elements including high-efficiency polarization-independent gratings [6], polarizing beam splitter [7, 8] and two-port beam splitter gratings [9] can be obtained by optimizing grating parameters such as period, depth and duty cycle.

With increase of the grating period, three diffracted orders may appear: 0th order, -1st order and -2nd order. High-efficiency element, 1×2 beam splitter and 1×3 beam splitter can still be realized under second Bragg incidence [10]. Also, a new class of high-efficiency gratings has been reported based on total internal reflection (TIR) [11, 12]. All the incident energy will be diffracted in the reflected orders without transmission, provided that the total reflection condition is met for the incident angle. Furthermore, such gratings optimized can show high efficiency for TE and TM polarization, which can be used for dense wavelength division multiplexing [13]. Recently, high-efficiency two-port beam splitter has been reported based on TIR grating, which can work as a 50/50 beam splitter for not only TE or TM polarization but also both TE and TM polarization with the optimized grating profiles [14].

In this paper, we describe a novel PBS of TIR fused-silica grating under second Bragg angle incidence for a wavelength of 800 nm. In order to achieve high extinction ratio and efficiency, the grating period and depth are optimized using the rigorous couple-wave analysis (RCWA) [15]. Diffraction properties are investigated for the wavelength range and angular bandwidth. It is the first time that PBS grating is introduced based on TIR under second Bragg angle incidence.

2. Optimization of the PBS grating based on TIR under second Bragg angle

Fig. 1 shows a fused-silica PBS grating based on TIR under second Bragg angle, where n_1 and n_2=1 are refractive indices of fused silica and air, respectively, d is the grating period, and h is the depth. The PBS grating is illuminated by an incident plane wave of wavelength λ at second Bragg angle of $\theta_i = \sin^{-1}(\lambda/(n_1 d))$, which can split TE and TM polarization into the -2nd and 0th orders, respectively. Extinction ratios C_0 and C_{-2} for the 0th and -2nd orders are defined by

$$C_0 = \eta_0^{TM} / \eta_0^{TE} \quad \text{and} \quad C_{-2} = \eta_{-2}^{TE} / \eta_{-2}^{TM} . \quad (1)$$

The extinction ratio C of such a PBS grating is the minimum of C_0 and C_{-2} in the two diffracted orders. In order to meet total reflection condition, the period should satisfy

$$\frac{\lambda}{n_1} < d < \frac{\lambda}{n_2} . \quad (2)$$

Three diffracted orders are permitted in this paper. According to grating equation, the period should be in the range

$$\frac{\lambda}{n_1} < d < \frac{2\lambda}{n_1}. \quad (3)$$

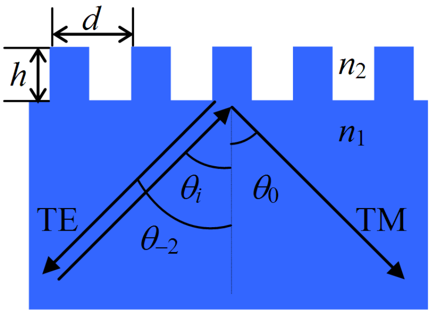


Fig. 1. (Color online) Schematic of a PBS grating based on TIR under second Bragg angle incidence (n_1 and n_2 refractive indices of fused-silica and air, respectively, d period, h depth, θ_i incident angle, θ_0 and θ_{-2} diffraction angles of the 0th and -2nd reflection orders in fused silica, respectively).

For an incident wavelength of 800 nm with refractive index of n_1 = 1.45332, the grating period of 551-800 nm is considered in the optimization. Diffraction efficiencies of the 0th, -1st and -2nd orders can be widely investigated for different grating parameters using RCWA. Fig. 2 shows diffraction efficiency of TE polarization in the -2nd order and TM polarization in the 0th order versus grating period and depth for the incident wavelength of 800 nm with duty cycle of 0.5 under second Bragg angle incidence. In Fig. 2, efficiencies can be obtained for TE polarization with 98.27% in the -2nd order and TM polarization with 99.15% in the 0th order. Therefore, such TIR grating can split two polarized waves into different propagation directions with high efficiency under second Bragg angle incidence.

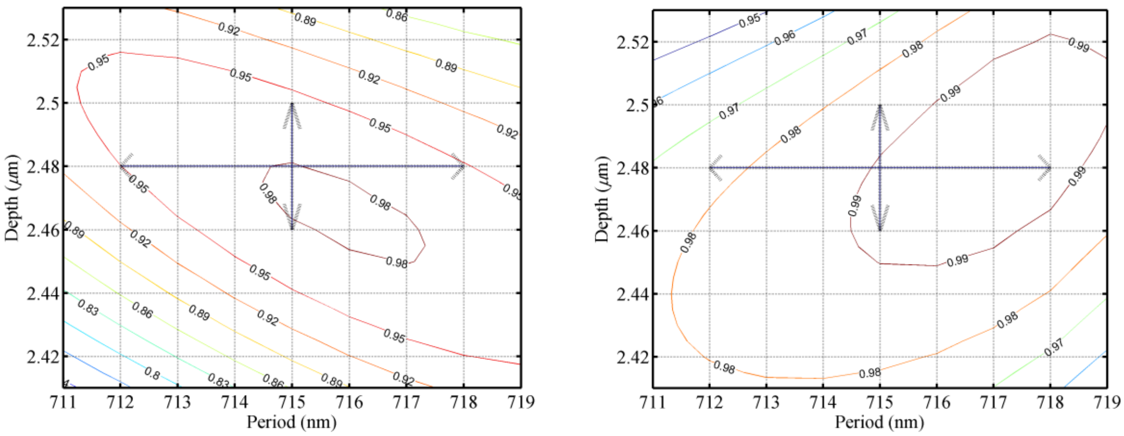


Fig. 2. (Color online) Diffraction efficiency of a TIR grating versus grating period and depth with the duty cycle of 0.5 for the wavelength of 800 nm under second Bragg angle incidence: (a) TE polarization in the -2nd order, (b) TM polarization in the 0th order.

Fig. 3 shows the contour of the PBS grating extinction ratio versus grating period and depth under second Bragg angle incidence with duty cycle of 0.5 for the incident wavelength of 800 nm. With the optimized grating period of 715 nm and depth of 2.48 μm, the extinction ratio can reach 2.257×10^3. The efficiency and extinction ratio of the PBS grating will fall with deviations of the period and depth from optimized parameters. However, Fig. 2 indicates that efficiencies of TE-polarized wave in the -2nd order and TM-polarized wave in the 0th order are more than 90% within the range of 712 nm$<d<$718 nm and 2.46 μm$<h<$2.50 μm.

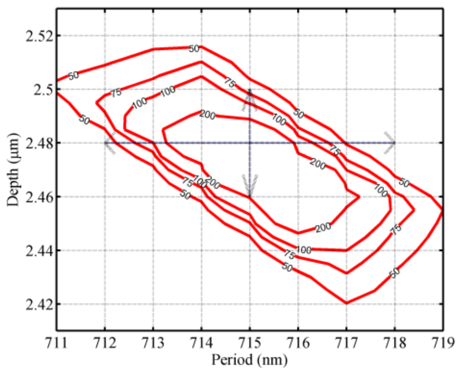
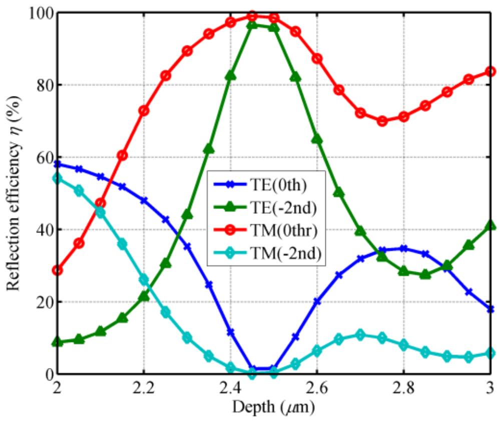
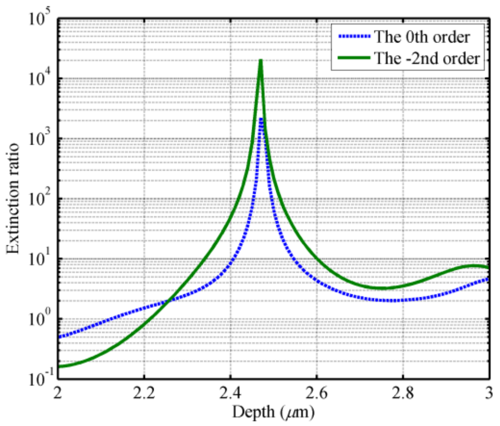


Fig. 3. (Color online) Extinction ratio contour of the TIR PBS grating versus period and depth under second Bragg angle incidence with duty cycle of 0.5 for the wavelength of 800 nm.

The deep-etched grating may show high efficiency, which is different from the shallow-etched surface-relief grating. Diffraction efficiency of the three orders can be modulated by the grating depth. Fig. 4 shows efficiency and extinction ratio of the -2nd and 0th orders versus grating depth with the period of 715 nm and duty cycle of 0.5 for the incident wavelength of 800 nm under second Bragg angle incidence. In Fig. 4, efficiencies of TE-polarized wave in the 0th order and TM-polarized wave in the 2nd order both reach high efficiency for a grating depth of 2.48 μm, while efficiencies of TE-polarized wave in the 0th order and TM-polarized wave in the -2nd order are not higher than 0.10%. Also, with the optimized grating parameters, high extinction ratio can be achieved.



(a)

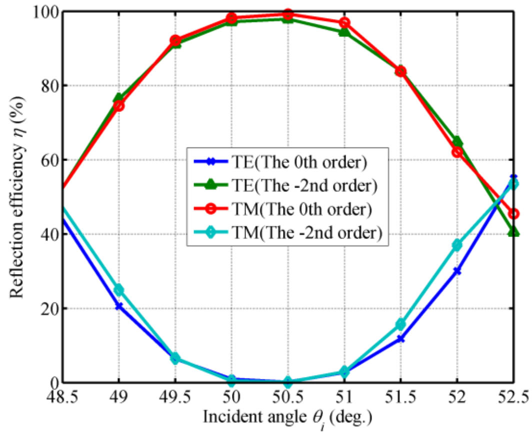


(b)

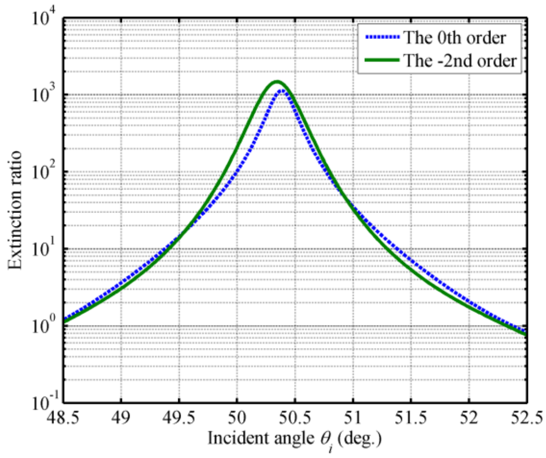
Fig. 4. (Color online) Diffraction efficiency (a) and extinction ratio (b) of a TIR PBS grating versus depth under second Bragg angle incidence with the period of 715 nm and duty cycle of 0.5 for the wavelength of 800 nm.

3. Diffraction properties of the optimized PBS grating

Using RCWA, the wavelength range and angular bandwidth can be investigated with the optimized PBS grating. Fig. 5 shows efficiency and extinction ratio versus the incident wavelength under second Bragg angle incidence with duty cycle of 0.5 for the optimized grating period of 715 nm and depth of 2.48 μm. In Fig. 5, efficiencies of TE and TM polarization are obtained higher than 90% within the range 795-804 nm when the incident wavelength is around the central 800 nm, and extinction ratios in the -2nd and 0th orders are higher than 77 and 10, respectively.



(a)



(b)

Fig. 5. (Color online) Diffraction efficiency (a) and extinction ratio (b) versus incident wavelength under second Bragg angle incidence with duty cycle of 0.5 for the optimized grating period of 715 nm and depth of 2.48 μm.

Fig. 6 shows efficiency and extinction ratio versus the angle of incidence with the same profile parameters optimized as Fig. 5. TE- and TM-polarized waves are incident upon the PBS grating at an angle of near 50.34˚, which is the second Bragg angle incidence mounting for a wavelength of 800 nm. In Fig. 6, within the range 49.45˚-51.26˚, reflection efficiencies of TE- and TM-polarized waves are higher than 90%, and extinction ratios in the -2nd and 0th orders are higher than 11 and 12, respectively.

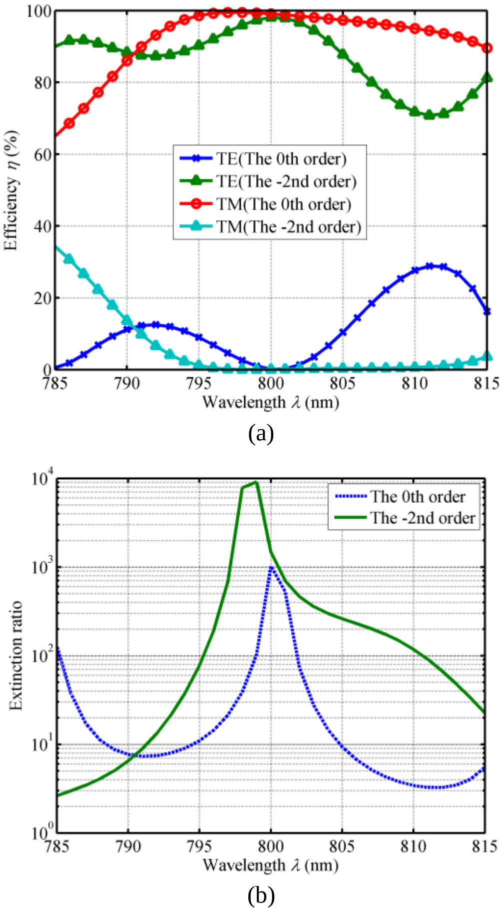


Fig. 6. (Color online) Diffraction efficiency (a) and extinction ratio (b) versus incident angle for an incident wavelength of 800 nm with the same optimized grating profile parameters as Fig. 5.

4. Conclusions

In conclusion, we have presented a novel fused-silica PBS grating based on TIR under second Bragg angle incidence with duty cycle of 0.5 for a laser wavelength of 800 nm. With the optimized period of 715 nm and depth of 2.48 μm, high efficiency and extinction ratio can be obtained to split different polarized beams. The maximum extinction ratio can reach 2.257×10^3 with optimized grating parameters. Within the range of 712 nm$<d<$718 nm and 2.46 μm$<h<$2.50 μm, high efficiency and extinction ratio can still be obtained. For the incident wavelength and angle for operation, the presented PBS grating can split two orthogonal polarized beams into different diffracted orders. The novel presented PBS grating based on TIR under second Bragg angle incidence should be a useful optical element etched in fused silica.

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