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Wideband femtosecond polarizing beam splitter grating with orthogonally diffractive directions

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We describe gratings etched in fused silica for splitting femtosecond polarized beams, where TE- and TM-polarized waves are diffracted in two orthogonal directions. Grating duty cycle and depth are directly optimized with two-wave interference of the excited modes. Efficiencies are calculated using rigorous coupled-wave analysis, which coincides well with predictions of the modal method. Optimized polarizing beam splitter grating shows wide wavelength range and angular bandwidth from diffraction properties. For high optical quality of fused silica, the presented PBS grating with orthogonally diffractive directions should be useful in femtosecond laser high power systems.

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1. Introduction

Polarizing beam splitters (PBSs) are used in numerous optical systems [1-3], which can generate different polarized states. In most of the applications, a PBS should present compact size, high extinction ratio, high efficiency, broad wavelength range and wide angular bandwidth for operation. Conventional PBSs utilize birefringent crystals and multilayer structures, which are bulky and expensive, respectively. The important property of high damage threshold is not easy to achieve. High-density gratings show polarization-dependent diffractive properties. Many PBSs with high efficiency are proposed based on surface-relief gratings [4-6]. A novel rectangular transmission fused-silica PBS phase grating was fabricated [7], which not only has broadband wavelength range for operation but also can stand with high laser power [8].

Optical properties of high-density deep-etched gratings can be calculated by rigorous methods that directly solve vector Maxwell's equations, such as rigorous coupled-wave analysis (RCWA) [9]. Optimized grating profiles can be obtained to work as PBSs using RCWA. Numerical calculation process will cost much time and the physical mechanism taking place inside the grating region can not be understood easily from their numerical treatment. Recently, Clausnitzer *et al*. adopted the modal method [10-12] to investigate these high-efficiency dielectric rectangular transmission gratings [13] and polarization-dependent diffraction [14]. Feng *et al*. analyzed diffraction process and optimized dual-function beam splitter, which can function as high-efficiency grating for TE polarization and two-port beam splitter for TM polarization [15].

In this paper, femtosecond PBS fused-silica gratings are proposed to separate TE- and TM-polarized beams into orthogonal directions. Modal method is employed to optimize grating profiles, especially the grating duty cycle and depth. Efficiencies are calculated using RCWA, which correspond well with predictions of modal method. For high optical quality of fused silica, the presented PBS grating can stand with high power of femtosecond laser systems.

2. Optimization base on modal method

Fig. 1 shows a transmission fused-silica grating for splitting polarized beams with orthogonal directions, where d is the grating period, b and g are the ridge with refractive index of n_2 and groove with $n_1 = 1$ widths, respectively, and h is the depth. The duty cycle f is defined as the ratio of the grating ridge width to the period. A incident wave with wavelength of λ illuminates the PBS grating under Littrow mounting with incident angle of $\theta_i = \sin^{-1}(\lambda/(2/d/n_1))$. As shown in Fig. 1, TE- and TM-polarized waves are diffracted in the -1st and 0th orders, respectively. In order to realize TE-and TM-polarized waves are diffracted in the orthogonal directions. The incident angle should be 45°, which means a period of 566 nm for femtosecond laser wavelength of 800 nm.

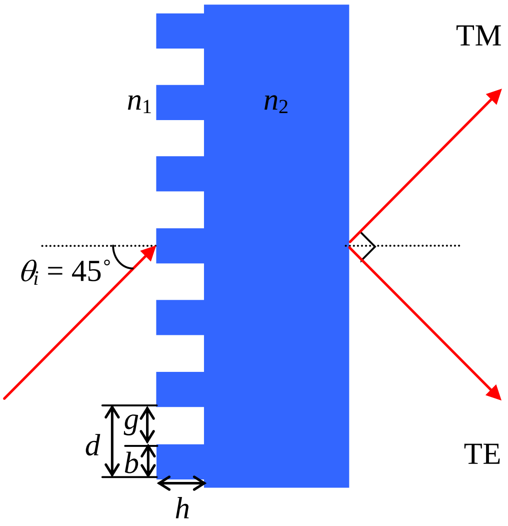


Fig. 1. Schematic of a polarizing beam splitter grating with orthogonally diffractive directions.

According to modal method [10], the incident wave can excite a discrete set of modes when propagating through the grating region. In this case of high-density deep-etched grating for PBS, modal method simplifies the complex diffraction process to a two-beam interference of the first two modes with effective indices n_{eff}^0 and n_{eff}^1. The accumulated phase difference $\Delta\varphi$ at the grating-substrate interface can be expressed as follows:

$$\Delta\varphi = \frac{2\pi}{\lambda}\left|n_{eff}^0 - n_{eff}^1\right| h . \tag{1}$$

The efficiency in the 0th order may be written as

$$\eta_{0th} = \cos^2\frac{\Delta\varphi}{2} . \tag{2}$$

And the efficiency in the -1st order can be represented by

$$\eta_{-1st} = \sin^2\frac{\Delta\varphi}{2} . \tag{3}$$

Fig. 2 shows effective indices of excited modes with different duty cycle under Littrow mounting for a incident femtosecond laser wavelength of 800 nm and n_2 = 1.45332. It indicates that effective indices of excited two modes depend on the duty cycle for TE- and TM- polarized waves.

For optimized duty cycle of 0.22, two modes with the same effective indices 0.823 are excited for TM polarization, while two modes with different effective indices of 1.009 and 0.722 are excited for TE polarization. No phase difference is accumulated for TM polarization, which will always be diffracted in the 0th order. For TE polarization, phase difference varies with grating depth. For optimized depth of 1.394 μm, phase difference of near π can be obtained and efficiency will be diffracted in the -1st order.

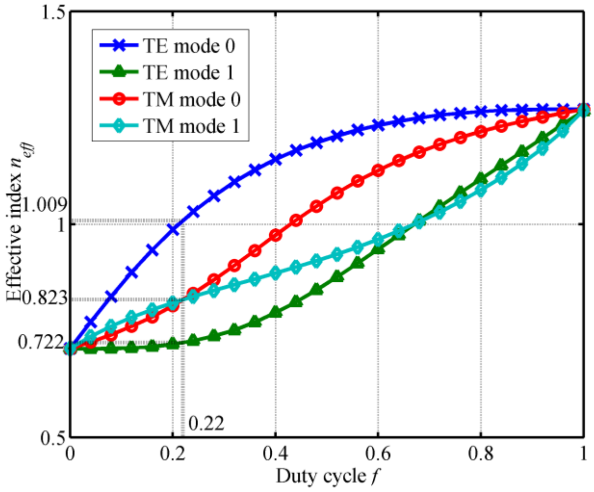
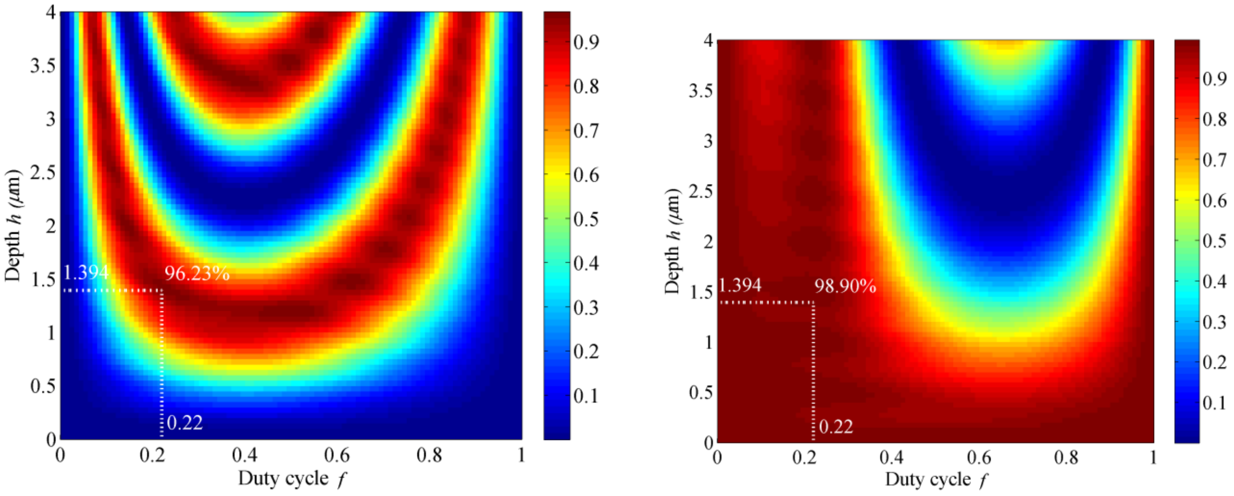


Fig. 2. Effective indices of the first two modes versus the grating duty cycle with period of 566 nm for the femtosecond laser wavelength of 800 nm.

3. Diffraction efficiency calculated using RCWA

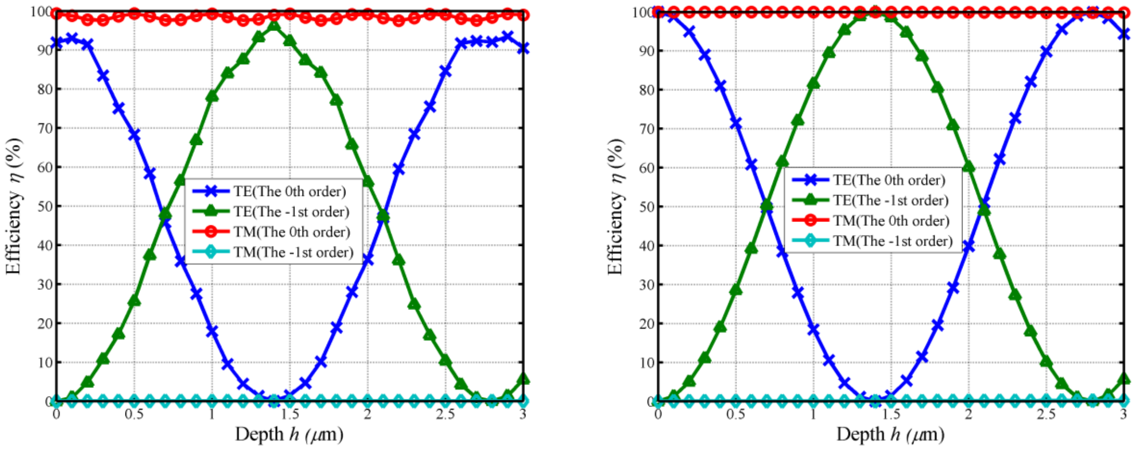
Fig. 3 shows numerical calculated diffraction efficiency using RCWA [9] with different duty cycle and depth under Littrow mounting for the incident wavelength of 800 nm. As can be seen from Fig. 3, with optimized duty cycle of 0.22 and depth of 1.394 μm, efficiencies of TE- and TM-polarized waves can reach 96.23% and 98.90%, respectively. With the optimized duty cycle and depth, the presented PBS grating can separate TE polarization in the -1st order and TM polarization in the 0th order efficiently.



(a) (b)

Fig. 3. Diffraction efficiency of a PBS grating with orthogonally diffractive directions for different profile parameters with period of 566 nm and incident wavelength of 800 nm: (a) TE polarization; (b) TM polarization.

Fig. 4 (b) shows diffraction efficiencies of TE- and TM-polarized waves calculated based on an interference of the two modes (Eqs. (2, 3)). Comparing Fig. 4(a) with Fig. 4 (b), numerical results using RCWA coincide well with simulations based on modal method.



(a) (b)

Fig. 4. Diffraction efficiency as a function of the grating depth with duty cycle of 0.22, period of 566 nm, and for the wavelength of 800 nm: (a) using RCWA; (b) based on a two-beam interference of the two modes (Eqs. (2, 3)). (a) and (b) are similar to each other.

4. Diffraction properties of PBS grating with orthogonally diffractive directions

In practical applications, it is desirable for the PBS grating to have wide wavelength range and angular bandwidth for operation. Fig. 5 shows efficiency versus incident femtosecond laser wavelength around 800 nm under Littrow mounting.

It indicates that efficiencies of TE-polarized wave in the -1st order and TM-polarized wave in the 0th order are near or higher than 90% for 203-nm spectral bandwidths (within the range 699 nm - 902 nm) , respectively.

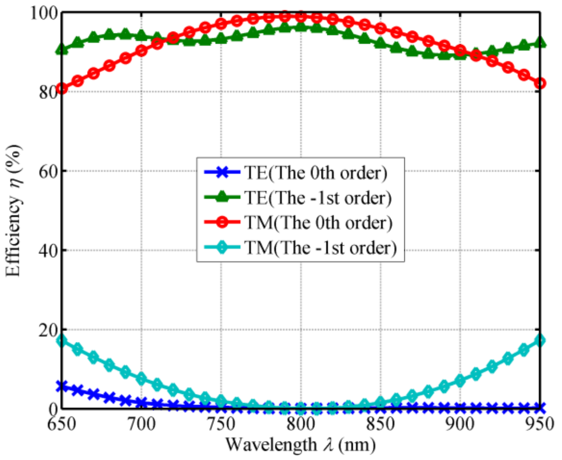


Fig. 5. Diffraction efficiency versus incident wavelength under Littrow mounting, duty cycle f = 0.22, period d = 566 nm and depth h = 1.394 μm.

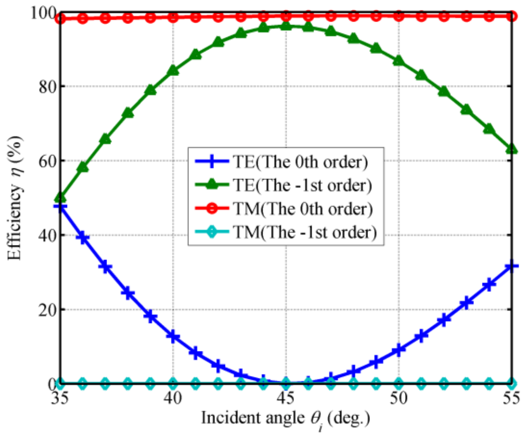


Fig. 6. Diffraction efficiency versus incident angle for a wavelength of 800 nm with the same optimized grating profile parameters as Fig. 5.

Fig. 6 shows efficiency versus incident angle around Littrow mounting with the optimized grating profiles. As can be seen from Fig. 6, TE- and TM-polarized waves are separated with efficiencies high than 90% in the -1st and 0th orders over a 7.59° window (within the range 41.43° - 49.02°), respectively. Efficiency will decrease when the incident wavelength and angle deviate from the designed parameters. However, within a wide wavelength range and angular bandwidth, the presented PBS grating still shows high efficiency.

5. Conclusions

Fused-silica gratings with orthogonally diffractive directions are introduced for splitting femtosecond polarized waves. Optimized results of duty cycle 0.22 and depth 1.394 μm are given based on modal method. Efficiencies calculated using RCWA correspond well with predictions of the modal method, which provide a useful guideline for design and fabrication of grating as novel optical element easily and effectively. The optimized PBS grating shows wide incident wavelength range and angular bandwidth. The fused silica is an ideal optical material with high optical quality which can stand with a high laser damage threshold. The presented PBS fused silica gratings should be useful elements in numerous femtosecond laser high power systems.

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