Total internal reflection fused-silica grating for splitting polarized femtosecond beams

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We described a PBS grating based on total internal reflection (TIR) to realize high efficiency. The grating period and depth are optimized using rigorous coupled wave analysis (RCWA) for a femtosecond laser wavelength of 800 nm. Efficiencies can reach unity for both TE-polarized wave in the 0th order and TM-polarized wave in the -1st order. Based on TIR, all the incident energy can be reflected without transmission regardless of grating tooth shape. The presented TIR PBS can stand with high laser power systems without absorptions of metal or complicated structures of multilayer coatings.

1. Introduction

The polarizing beam splitter (PBS) is used in numerous optical systems [1-3], which can separate two orthogonal polarized wave beams into different propagation directions. Conventional PBSs of birefringent crystals are not suitable for integration, and those of multilayer structures are expensive for complicated coatings. Moreover, the important property of high damage threshold is not easy to achieve. With the development of microfabrication, several works reported surface-relief phase gratings as PBSs [4-6]. Recently, a novel rectangular transmission fused-silica PBS grating was proposed [7], which not only has broadband wavelength range for operation but also can stand with high laser power [8]. In order to improve the efficiencies, a transmission PBS grating is designed with triangular-groove [9]. In most of the applications, high extinction ratio and diffraction efficiency are necessary for a PBS with good performance.

Based on the phenomenon of total internal reflection (TIR), Marciante *et al.* reported a new class of high-dispersion diffraction gratings [10]. If the angle of incidence meets the total reflection condition, energy will be concentrated in the reflection waves. Also, the first experimental realization of TIR gratings showed high efficiency with low polarization-dependent loss [11]. Zhang *et al.* [12] optimized the TIR grating period and depth using the rigorous coupled-wave analysis (RCWA) [13] for dense wavelength division multiplexing application. Such TIR gratings can realize the reflection efficiency of nearly unity.

In this paper, we described a fused-silica PBS grating based on TIR for a wavelength of 800 nm used in femtosecond laser. Profiles parameters optimized are given by numerical calculation using RCWA in order to achieve high extinction ratio and reflection efficiency. The wavelength range and angular bandwidth are investigated for operation. Most importantly, total reflection efficiencies are independent of grating tooth shape, which can facilitate the fabrication of such TIR PBS gratings.

2. Design optimization of the TIR fused-silica grating for PBS

Fig. 1 shows a PBS grating based on TIR, where d is the grating period and h is the depth. The duty cycle f is defined as the ratio of the grating ridge width to the period. We consider the PBS a deep-etched fused-silica grating with refractive indices $n_1 = 1.45332$ and $n_2 = 1$. The grating is illuminated by a plane wave under Littrow mounting at an incident angle of $\theta_i = \sin^{-1}(\lambda/(2/d/n_1))$, where λ is the wavelength of incidence in vacuum. As can be seen from Fig. 1, TE- and TM-polarized waves are diffracted in the 0th and -1st reflection orders, respectively.
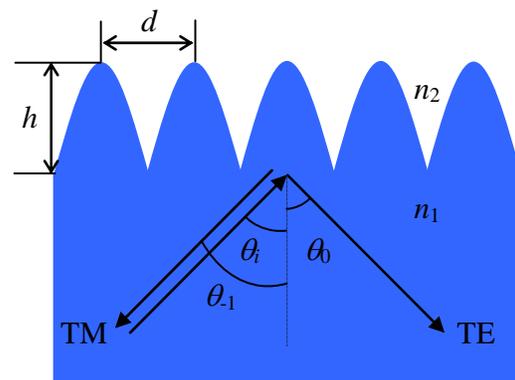
Fig. 1. (Color online) Schematic of a TIR PBS grating (n_1 and n_2 refractive indices of fused-silica and air, respectively, d period, h depth, θ_i incident angle under Littrow mounting, θ_0 and θ_{-1} diffraction angles of the 0th and -1st reflection orders in fused silica, respectively).

According to the grating equation and total reflection

condition, the period should satisfy an inequity [10]

$$n_1 > \frac{\lambda}{2d} > n_2 \qquad (1)$$

The period of such a TIR PBS grating etched in fused silica is limited within 276-400 nm for a femtosecond laser wavelength of 800 nm. Since all the light will be reflected for a TIR grating regardless of grating tooth shape, we take the usual rectangular grating as a mode in this paper. Diffraction properties of the TIR PBS grating are investigated by numerical calculation using RCWA. Fig. 2 shows efficiency of the PBS grating versus period and depth for the incident wavelength of 800 nm with duty cycle of 0.5. Design optimization can be obtained in order to achieve a TIR PBS grating with high reflection efficiency. As can be seen from Fig. 2, reflection efficiencies of both TE-polarized wave in the 0th order and TM-polarized wave in the -1st order can nearly reach unity with the prescribed grating period of 359 nm and etched depth of 1.020 μm. The best performance can be obtained for a PBS grating based on TIR under the profile parameters optimized.

(a)

(b)
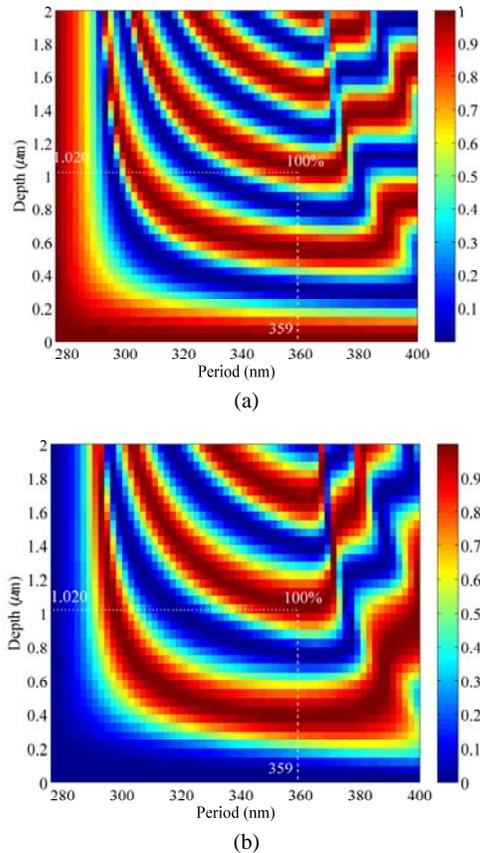
Fig. 2. (Color online) Reflection efficiency of a TIR grating versus grating period and depth with the duty cycle of 0.5 for the wavelength of 800 nm under Littrow mounting: (a) TE polarization in the 0th order, (b) TM polarization in the -1st order.

Fig. 3 shows reflection efficiency and extinction ratio versus grating depth with the optimized period of 359 nm and the usual duty cycle of 0.5 for the incident wavelength of 800 nm under Littrow mounting. As shown in Fig. 3, for a grating depth of 1.020 μm, efficiencies of TE-polarized in the 0th order and TM-polarized wave in the -1st order both reach the maximum~100%, respectively, while efficiencies of TE-polarized wave in the -1st order and TM-polarized wave in the 0th order are the minimum~0. The extinction ratio of 2.20×10^4 can be obtained with the optimized grating parameters.

(a)

(b)
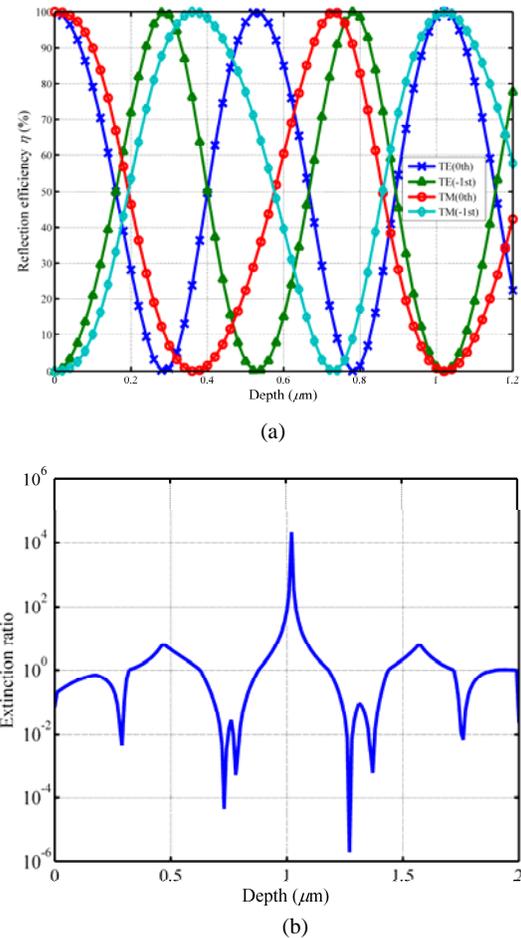
Fig. 3. (Color online) Reflection efficiency (a) and extinction ratio (b) of a TIR PBS grating versus depth with the optimized period of 359 nm and duty cycle of 0.5 for the wavelength of 800 nm under Littrow mounting.

3. Diffraction properties of the optimized fused-silica PBS grating

With the profile parameters optimized, the wavelength range and angular bandwidth for operation are investigated using RCWA. Fig. 4 shows the reflection efficiency and extinction ratio of the optimized TIR PBS grating versus the incident wavelength under Littrow mounting. For practical applications, wideband wavelength is of great

significance [14]. As can be seen from Fig. 4, reflection efficiencies of TE polarization in the 0th order higher than 91.07% are obtained for 40-nm spectral bandwidths (within the range 777-817 nm) when the PBS is used for femtosecond laser wavelengths. Within the same wavelength range, efficiencies of TM polarization in the -1st order are no less than 93.73%. Extinction ratios higher than 100 are obtained for incident wavelengths of 793-805 nm around central 800 nm.
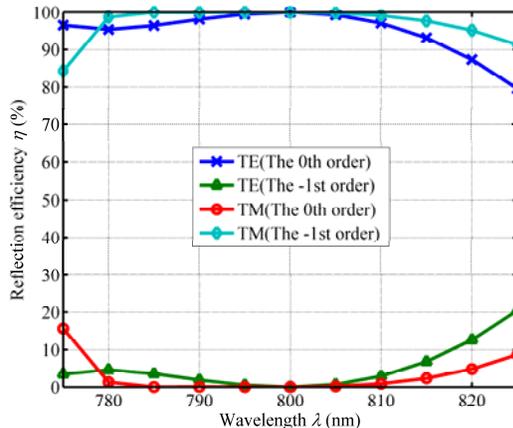
(a)
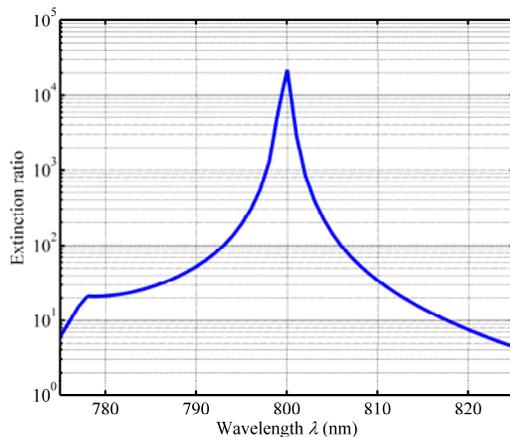
(b)

Fig. 4. (Color online) Reflection efficiency (a) and extinction ratio (b) versus incident wavelength under Littrow mounting, duty cycle f = 0.5, period d = 359 nm and depth h = 1.020 μm.

Fig. 5 shows the reflection efficiency and extinction ratio versus the angle of incidence with the same profile parameters optimized as Fig. 4. TE- and TM-polarized waves are incident upon the PBS grating at an angle of near 50.06°, which is the Bragg angle for a wavelength of 800 nm under Littrow mounting. As shown in Fig. 5, over a 5.21° window (within the range 47.52°-52.73°), reflection efficiencies of TE-polarized wave in the 0th order and those of TM-polarized wave in the -1st order are higher than 98.84% and 90.06%, respectively. Extinction

ratio values higher than 100 are obtained at an incident angle of 49.17°-50.96° near the Bragg angle.
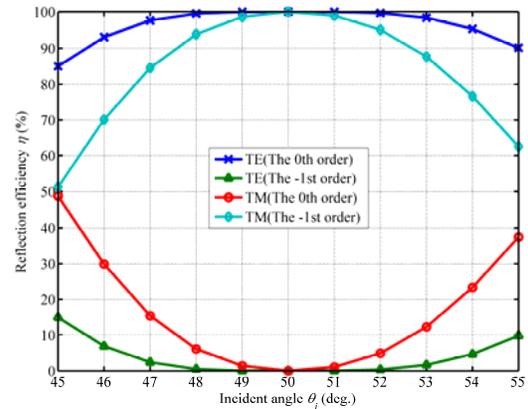
(a)
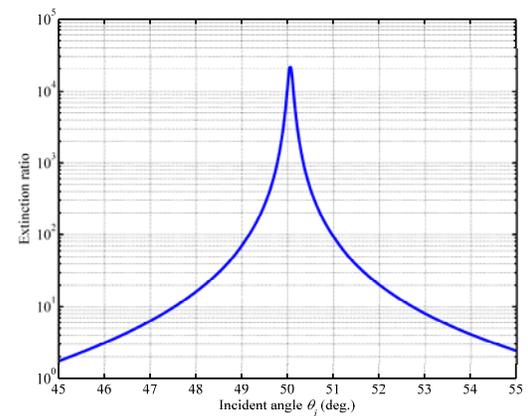
(b)

Fig. 5. (Color online) Reflection efficiency (a) and extinction ratio (b) versus incident angle for a wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4.

4. Conclusions

We have presented a novel TIR PBS grating etched in fused silica for a femtosecond laser wavelength of 800 nm. With the optimized period of 359 nm and depth of 1.020 μm, high reflection efficiency and extinction ratio can be obtained. The maximum efficiency can nearly reach unity within the angle and wavelength for operation. The fused silica is an ideal optical material with high optical quality which has a wide transmitting spectrum ranging from deep ultraviolet to far infrared. Especially, it is reported to stand with high laser power [8]. A transmission fused-silica grating with high efficiency for TE polarization has been fabricated to compress femtosecond pulse [15]. As a reflection PBS grating, without absorptions of metal or complicated structures of multilayer coatings, the presented high-efficiency TIR PBS grating etched in fused silica should be useful in numerous optical information processing systems.

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