Broadband high-efficiency grating of total internal reflection etched in fused silica for high-power lasers

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Diffraction properties of total internal reflection (TIR) grating etched in fused silica under second Bragg angle incidence are investigated. The grating profile parameters are optimized using the rigorous coupled-wave analysis (RCWA). With the optimized results, diffraction efficiencies of 99.68% and 99.87% can be obtained for TE and TM polarizations in the reflected -2nd order, respectively. The presented gratings under second Bragg angle incidence have advantages of high efficiency of TIR, high damage threshold of fused silica and important broadband property for operation, which should be useful elements for numerous optical applications, especially for high-power laser systems.

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1. Introduction

High-density gratings can show various new diffraction properties, which were widely reported in numerous optical information processing systems. For some subwavelength gratings, there are only two diffraction orders remained in transmission and reflection: the 0th and -1st orders. With the design of the grating profile parameters such as grating depth, period, and duty cycle, efficiencies in the two diffracted orders can be optimized as novel optical elements [1-3]. A deep-etched grating was fabricated with high efficiency and low polarization-dependent loss used for dense wavelength division multiplexing [4]. Using rigorous coupled-wave analysis (RCWA) [5], a 50/50 beam splitter was designed for not only TE or TM polarization but also TE and TM polarizations [6], which can be fabricated by inductively coupled plasma technology and well explained based on modal method. Diffraction properties of high-density gratings are polarization-dependent according to vector theory, which are different from conventional low-density gratings. A novel highly efficient polarizing beam splitter grating was proposed with broadband range around the wavelength of 1550 nm used in communication [7]. However, for transmission gratings mentioned above, amount of energies are reflected. To improve the efficiency, sinusoidal- [8] and triangle-groove [9] gratings were designed based on average differences of the grating mode indices in the grating region.

A new class of reflection gratings was reported with high efficiency based on total internal reflection (TIR) [10]. With suitable grating parameters, such gratings can realize efficiencies of more than 97% for both TE and TM polarizations at a wavelength of 1550 nm [11]. Also, a two-port beam splitter was recently proposed based on TIR and efficiencies can reach nearly 50%*2 = 100% in the 0th and -1st reflected orders [12]. For a grating with three diffracted orders under second Bragg angle incidence, the splitting property was studied using the modal method [13] for transmission grating [14] etched in fused silica with high damage threshold [15]. To our knowledge, no one presented high-efficiency grating under second Bragg angle incidence based on TIR.

In this paper, diffraction properties of total internal reflection grating are investigated under second Bragg angle incidence. To obtain high efficiency in the -2nd reflected order, grating period and depth are optimized using RCWA. The wavelength range and angular bandwidth are given for operation in practice. Important advantages of high efficiency, high damage threshold and broadband property for operation are shown.

2. Optimization of the high-efficiency grating

The TIR grating is shown in Fig. 1, which is illuminated by a plane wave with wavelength of λ under second Bragg angle of $\theta_i = \sin^{-1}(\lambda/(n_1 d))$, where n_1 is the refractive index of fused-silica substrate and d is the grating period. The refractive index of groove is n_2=1 for the air. With deep-etched depth of h, the grating can show high efficiency. Under second Bragg angle incidence, there are three diffracted orders in reflection for TIR grating. The -2nd order is reflected at angle of $\theta_{-2} = \sin^{-1}(\lambda/(n_1 d))$, which is symmetrical to the 0th order. And the -1st order is reflected along normal direction.

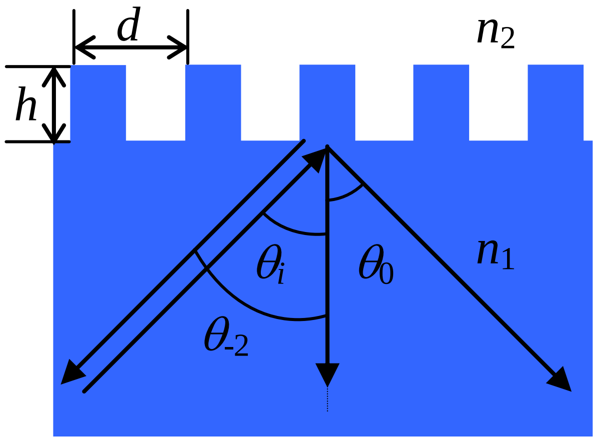


Fig. 1. (Color online) Schematic of a high-efficiency grating based on TIR under second Bragg angle incidence (n_1 and n_2 refractive indices of fused-silica and air, respectively, d period, h depth, θ_i incident angle, θ_0 and θ_{-2} diffraction angles of the 0th and -2nd reflection orders in fused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

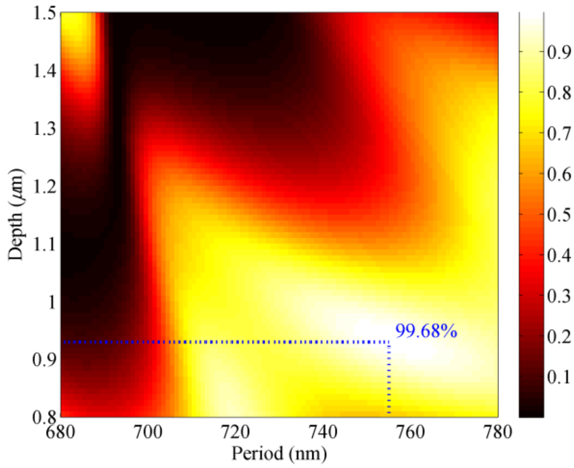
The incidence mounting meets total reflection condition $\frac{n_2}{n_1} < \sin\theta_i < 1$. With the incident second Bragg angle of $\theta_i = \sin^{-1}(\lambda/(n_1 d))$ for the above equation , the period should satisfy

$$\frac{\lambda}{n_1} < d < \frac{\lambda}{n_2}. \quad (1)$$

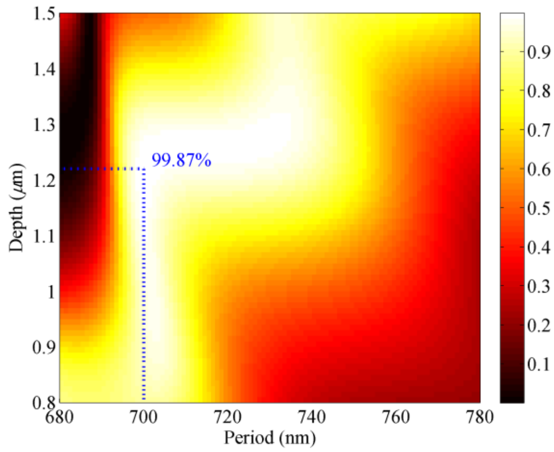
Furthermore, since there are three reflected orders, the period should be in the range

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

The refractive index of fused silica is n_1 = 1.45332 for an incident laser wavelength of 800 nm. With the two simultaneous equations given above, the period should be in the range of 551-800 nm. Using RCWA, efficiencies can be studied with various grating profile parameters. Fig. 2 shows diffraction efficiency in the -2nd order 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. In Fig. 2, the efficiency can reach 99.68% for TE polarization with optimized d = 755 nm and h = 0.93 μm and 99.87% for TM polarization with optimized d = 700 nm and h = 1.22 μm.



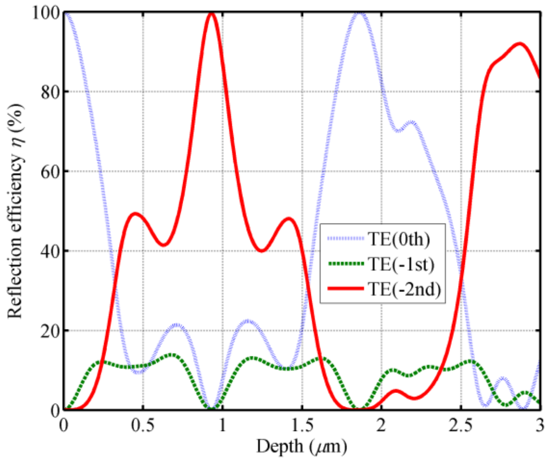
(a)



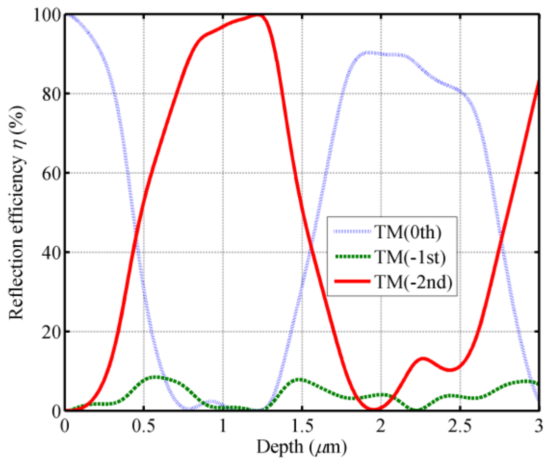
(b)

Fig. 2. (Color online) Diffraction efficiency in the -2nd order 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, (b) TM polarization.

Fabrication tolerance should be considered for etching TIR grating to realize high efficiency under second Bragg angle incidence. The etched grating depth can modulate the efficiency of the three orders in diffraction. Deep-etched grating is necessary to obtain high efficiency in numerous applications. High efficiency can be obtained in the -2nd orders for TE and TM polarizations with the optimized depth. Fig. 3 shows efficiency of a TIR grating versus depth under second Bragg angle incidence with the duty cycle of 0.5 for the wavelength of 800 nm. It indicates that high efficiency can be obtained for TE polarization with etched depth h = 0.93 μm and for TM polarization with etched depth h = 1.22 μm for the optimized period. Efficiencies of the -1st and 0th orders are not higher than 0.13% for TE and TM polarizations with the optimized depth and period. The efficiency may fall with deviation of depth from the optimized results. In Fig. 3, efficiencies of larger than 90% can still be achieved with etched depth range of 0.88-0.99 μm for TE polarization and 0.81-1.33 μm for TM polarization, which will be a good guideline to fabricate such high efficiency gratings.



(a)

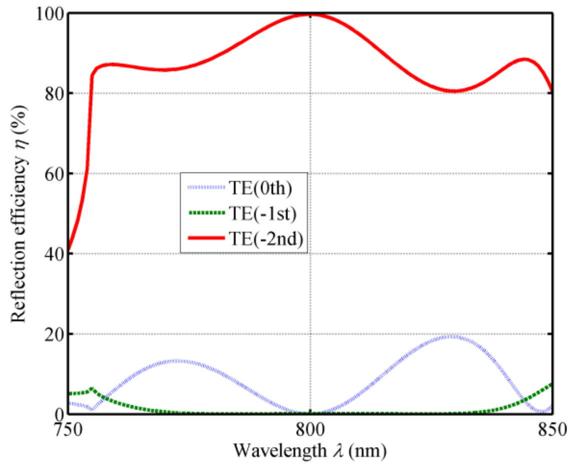


(b)

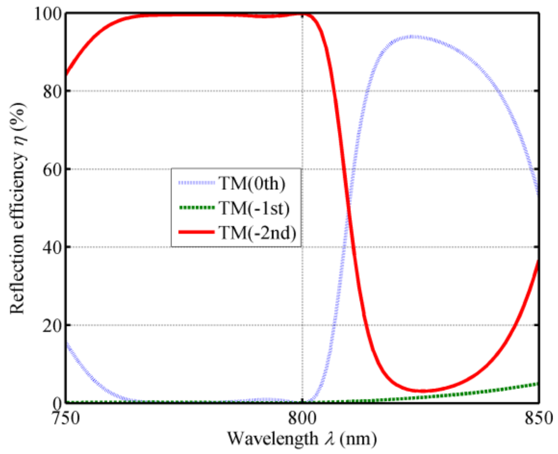
Fig. 3. (Color online) Diffraction efficiency of a TIR grating versus depth under second Bragg angle incidence with the duty cycle of 0.5 for the wavelength of 800 nm: (a) TE polarization and d = 755 nm, (b) TM polarization and d = 700 nm.

3. Wavelength range and angular bandwidth properties

With the optimized grating parameters, high efficiency can be achieved by a simple grating based on TIR under second Bragg angle incidence. In practical applications, the broadband property is of vital importance for operation. The diffraction efficiency may be not so high when the incident wavelength and angle deviate from the designed conditions. The wavelength and angular bandwidth can be investigated for the optimized results. Fig. 4 shows efficiency versus incident wavelength under second Bragg angle incidence with duty cycle of 0.5 for the optimized grating. Efficiencies larger than 90% can be achieved with wavelength range of 782-814 nm for TE polarization and 754-805 nm for TM polarization. In Fig. 4, the optimized grating indicates broadband property with high efficiency.



(a)



(b)

Fig. 4. (Color online) Diffraction efficiency versus incident wavelength under second Bragg angle incidence with duty cycle of 0.5 for the optimized grating: (a) TE polarization, d = 755 nm and h = 0.93 μm, (b) TM polarization, d = 700 nm and h = 1.22 μm.

Fig. 5 shows efficiency versus incident angle for an incident wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4. Efficiencies will fall when the incident wave illuminates the TIR grating near the second Bragg angle for a wavelength of 800 nm. High efficiency of larger than 90% can still be achieved with the incident angle range of 45.98-47.66° for TE polarization and 51.25-52.45° for TM polarization.

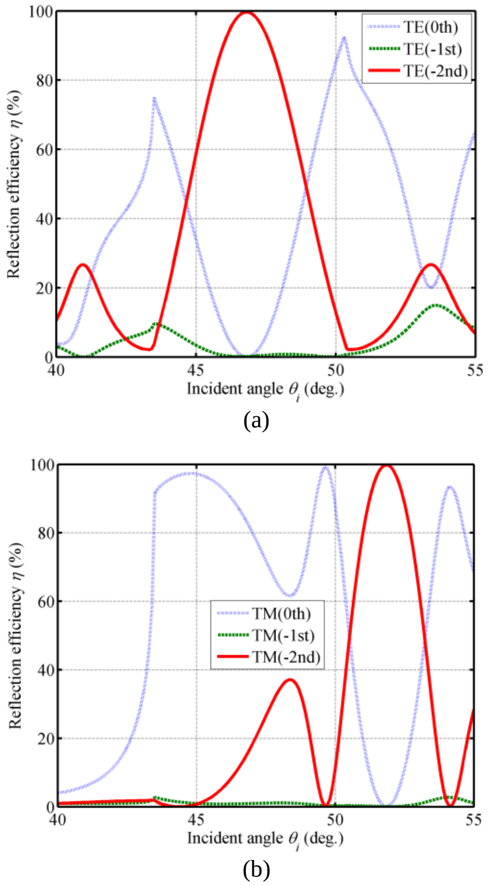


Fig. 5. (Color online) Diffraction efficiency versus incident angle for an incident wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4: (a) TE polarization, (b) TM polarization.

4. Conclusions

For the transmission curve, the reflection to the -1st order is relatively small, which can be explained by reflections [16] of excited modes in the grating groove top and bottom. The incident wave will excite two modes in the grating region according to modal method. Fresnel-reflection will be formed for each mode in the grating-air and grating-substrate interfaces. Due to such reflections of two modes, the efficiency of transmission will be reduced. It indicates that the reflection behavior will mainly be dominated by the 1st mode. Therefore, for the transmission curve, the reflection to the -1st order is relatively small and the reflection to the 0th order is high to some extent. And excited modes by TE polarization are different from TM polarization, which will lead to the different reflection for two polarizations. To solve the problem of suppressing reflection, a sandwiched grating or a grating with triangular grooves may be applied instead of a usual surface-relief grating with rectangular grooves. In this paper, a new good method is presented to obtain high efficiency by total internal reflection under second Bragg angle incidence.

In conclusion, diffraction properties are investigated for TIR grating under second Bragg angle incidence based on which novel high-efficiency gratings are proposed for a laser wavelength of 800 nm. Efficiencies of 99.68% for TE polarization can be obtained with optimized period of 755 nm and depth of 0.93 μm. For TM polarization, efficiencies can reach 99.87% with optimized period of 700 nm and depth of 1.22 μm. The Wavelength range for operation indicates that broadband property is shown for the optimized high-efficiency gratings. The presented Broadband high-efficiency grating can be fabricated by holography recording technique and inductively coupled plasma dry etching method. For high efficiency of TIR, high damage threshold of fused silica and broadband wavelength range, the new and novel presented TIR grating under second Bragg incidence should be useful in high-power laser systems.

Acknowledgements

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