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Improving the performance of high-efficiency element and beam splitter based on total internal reflection grating

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We describe the dual-function device of high-efficiency element and beam splitter grating. In order to improve the efficiency, total internal reflection (TIR) grating is introduced. With the grating parameters optimized using rigorous coupled wave analysis (RCWA), high efficiency of 99.58% can be obtained for TE polarization in the -1st order and 50/50 output can be achieved for TM polarization in the -1st and 0th orders. The presented dual-function grating device has advantages of high efficiency of TIR, high damage threshold of fused silica, and good groove shape tolerance of the total reflection energy during fabrication.

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Keywords: Rigorous coupled-wave analysis, Total internal reflection, High efficiency, Beam splitter

1. Introduction

High-density gratings are widely used in various optical information processing systems, which can show novel diffraction properties, such as high efficiency [1,2], polarization property [3-5] and so on. Theoretical and experimental methods can be employed to design and fabricate a series of diffraction optical elements based on high-density deep-etched gratings, including high-efficiency element and beam splitter. High-efficiency element has been optimized using rigorous coupled-wave analysis (RCWA) [6] based on total internal reflection (TIR) grating [7] for dense wavelength division multiplexing application [8]. Also, transmission grating was etched in fused silica with high efficiency at a wavelength of 1550 nm with inductively coupled plasma technology [9]. Compared with metal wire-grids, phase gratings have no absorption, which can show high damage threshold. High-efficiency grating etched in fused-silica can be used in femtosecond laser pulse compressor [10] and chirped pulse amplification system [11]. Furthermore, beam splitter based on phase grating has advantages of high efficiency and uniformity without multiple refraction and reflection of multilayer coatings. Reflective 50/50 output dielectric diffraction grating was reported for interferometer, which should be suitable for high-power laser systems [12]. Wideband [13] and high-efficiency [14] two-port beam splitter were presented based on binary fused-silica grating for not only TE or TM but also both TE and TM polarizations.

High-density deep-etched phase gratings reported above can function as high-efficiency element or beam splitter. It is desirable that a simple grating can realize several functions. A novel dual-function grating has been designed and fabricated, which can show high efficiency of 95% for TE polarization and two-port output of (49%*2)=98% for TM polarization at a wavelength of 1550 nm [15]. The reported dual-function grating element is based on transmission and the efficiency can be improved further based on TIR. All the incident energy can be diffracted in the reflection region regardless of the grating groove shape, which can lead to the maximum efficiency of nearly unity without transmission for TIR grating.

In this paper, we presented improving the performance of high-efficiency element and beam splitter based on TIR. In order to obtain high efficiency in the -1st order for TE polarization and uniformity in the -1st and 0th orders for TM polarization, TIR grating parameters are optimized using RCWA. The wavelength range and angular bandwidth are investigated for operation. Analysis indicates that efficiency can be improved further for dual-function grating device based on TIR.

2. Optimization using RCWA

Fig. 1 shows the schematic of a dual-function grating device based on TIR with the usual duty cycle of 0.5, which is the ratio of the grating ridge width to the period of d. The grating can be etched in the excellent optical material of fused silica with refractive index n_1 = 1.45332 for laser wavelength of 800 nm and n_2 = 1 for air. The incident wave with wavelength of λ illuminates the grating with depth of h under Littrow mounting, which corresponds to an incident Bragg angle of $\theta_i = \sin^{-1}(\lambda/(2n_1 d))$. As a dual-function device, TE polarization can be diffracted with high efficiency in the -1st reflection order and TM polarization can be diffracted with good uniformity in the -1st and 0th reflection orders in Fig. 1.

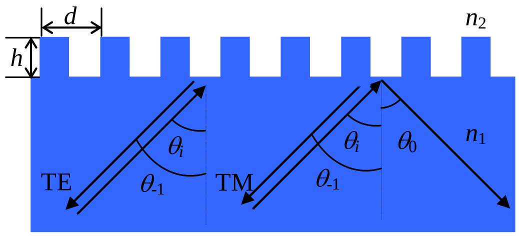
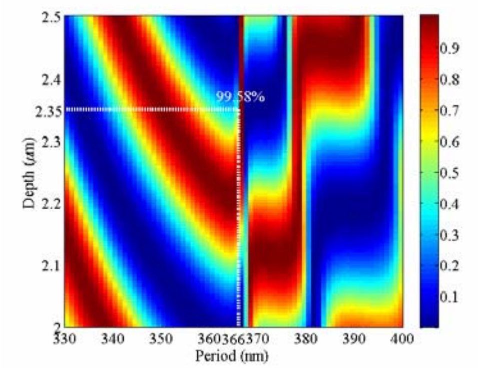
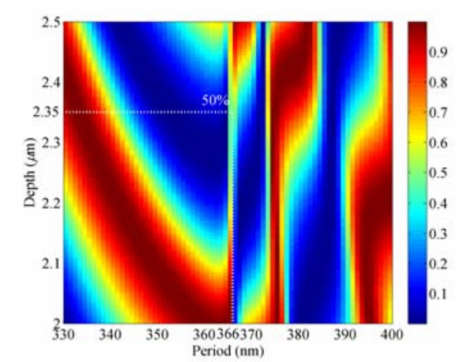


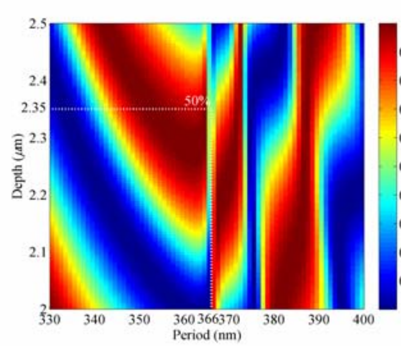
Fig. 1. (Color online) Schematic of a high-efficiency element and beam splitter based on TIR grating (n_1 and n_2 refractive indices of fused-silica and air, respectively, d period, h depth, θ_i incident angle under Littrow mounting, θ_0 and θ_{-1} diffraction angles of the 0th and -1st reflection orders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



(a)



(b)



(c)

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 -1st order, (b) TM polarization in the 0th order, (c) TM polarization in the -1st order.

In order to design the presented dual-function grating device, RCWA can be applied to optimize the grating groove parameters. The period should meet an inequity of $n_1 > \frac{\lambda}{2d} > n_2$ according to grating equation and TIR. For an incident wavelength of 800 nm, the period is limited within 276-400 nm. Numerical results of diffraction efficiencies can be widely investigated for TE and TM polarizations in the -1st and 0th reflection orders using RCWA. Fig. 2 shows the reflection efficiency of a TIR grating versus grating period and depth with the usual duty cycle of 0.5 for the wavelength of 800 nm under Littrow mounting. In Fig. 2, with the optimized period of 366 nm and depth of 2.35 μm, efficiency of TE polarization in the -1st order can reach 99.58%, and efficiencies of 50/50 output can be obtained for TM polarization in the two diffracted orders.

Fig. 3 shows efficiency of a TIR PBS grating versus etched depth with the optimized period of 366 nm and usual duty cycle of 0.5 for the wavelength of 800 nm under Littrow mounting. It indicates that efficiency can be modulated by the etched grating depth for TE and TM polarizations in the two diffracted orders. With the optimized depth of 2.35 μm, for TE polarization, high efficiency can be obtained in the -1st order, and for TM polarization, the incident energy can be split into the -1st and 0th orders with good uniformity.

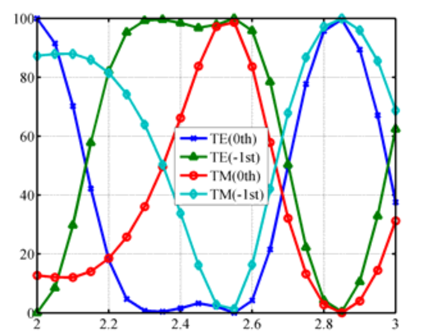


Fig. 3. (Color online) Reflection efficiency of a TIR grating versus depth with the optimized period of 366 nm and duty cycle of 0.5 for the wavelength of 800 nm under Littrow mounting.

3. Diffraction properties for incident wavelength and angle

The high-efficiency element and beam splitter grating is designed for the incident wavelength of 800 nm and Littrow mounting. Efficiencies in the two orders will change if the incident conditions deviate from the prescribed parameters. Fig. 4 shows the efficiency versus incident wavelength under Littrow mounting with the usual duty cycle of 0.5, period of 366 nm, and depth of 2.35 μm. The efficiency in the -1st order for TE polarization may not be so high and for TM polarization efficiencies in the two orders will not be so uniform with the variation of the incident wavelength. For the incident wavelength of central 800 nm, such high-efficiency element and beam splitter can be obtained with high efficiency and uniformity for operation.

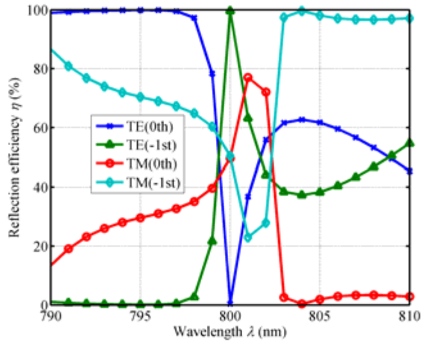


Fig. 4. (Color online) Reflection efficiency versus incident wavelength under Littrow mounting, duty cycle f = 0.5, period d = 366 nm and depth h = 2.35 μm.

Fig. 5 shows the efficiency versus the incident angle for a wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4. For the incident wavelength of 800 nm, the Littrow mounting corresponds to a Bragg angle of 48.76˚. When the TE and TM polarizations are incident upon the grating near Bragg angle, performance will decrease from the optimized results. In Fig. 5, efficiency larger than 90% in the -1st order for TE polarization and efficiencies larger than (45%*2) = 90% in the both -1st and 0th orders for TM polarization can be achieved within the incident angle range of 48.26 ˚-49.27 ˚.

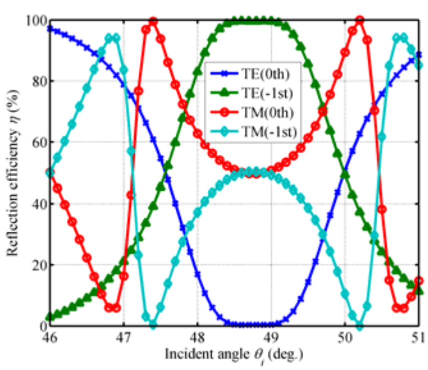


Fig. 5. (Color online) Reflection efficiency versus incident angle for a wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4.

4. Conclusions

High-efficiency element and beam splitter can be realized based on the phase grating. In order to improve the performance of such a dual-function device, TIR grating is optimized using RCWA. For the usual duty cycle of 0.5 and incident wavelength of 800 nm under Littrow mounting, the presented TIR grating can obtain a high efficiency of 99.58% in the -1st order for TE polarization and nearly 50/50 output in the -1st and 0th orders for TM polarization with the optimized period of 366 nm and depth of 2.35 μm. Diffraction properties indicate that high efficiency can still be achieved with the central wavelength of 800 nm and angle near the Littrow mounting. The novel dual-function device of high-efficiency element and beam splitter has advantages of high efficiency. And most importantly, all the energy can be reflected without transmission regardless of the grating groove shape, provided that TIR condition is met for the incident condition. The presented high-efficiency and beam splitter based on TIR should be promising and highly efficient device in a variety of laser system applications.

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