Dual-function grating element under total internal reflection and second Bragg angle mounting

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We present dual-function grating element under total internal reflection (TIR) and second Bragg angle mounting. There are three diffracted orders which are different from most reported Littrow mounting or normal incidence. Grating profile parameters are optimized in order to obtain high efficiency for TE polarization and good uniformity for TM polarization using rigorous coupled wave analysis (RCWA). The fabrication tolerance is investigated, which should be useful guideline for manufacture such a dual-function grating element. The diffractive optical element has novelty of dual-function grating, high efficiency of TIR, and new incidence mounting of second Bragg angle.

(Received December 20, 2011; accepted April 11, 2012)

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

1. Introduction

High-density deep-etched gratings are widely investigated for their novel and useful properties. For theoretical simulation of diffraction properties, Maharam *et al.* have described formulation for stable and efficient implementation of binary gratings using vector method of rigorous coupled-wave analysis (RCWA) [1] and the physical mechanism of transmission gratings can be well explained by the modal method [2]. For their experimental fabrication, Wang *et al.* have reported optimized condition for etching high-density gratings in fused silica, under which deep-etched gratings can be obtained with inductively coupled plasma (ICP) technology [3]. Base on presented theoretical and experimental methods, many diffractive optical elements can be designed, optimized and fabricated as high-efficiency element, polarizing beam splitter (PBS), two-port beam splitter, three-port beam splitter and so on.

For high-efficiency element, Wang *et al.* exhibited a transmission grating etched in fused silica, which could be used in dense wavelength division multiplexing [4]. Zhang *et al.* introduced reflection grating based on total internal reflection (TIR), where the efficiency could be improved greatly for both TE and TM polarizations [5]. Due to high damage threshold of fused silica, Cao *et al.* reported a polarization-independent wideband grating, which could be used in high-power femtosecond laser systems [6]. For polarizing beam splitter, Wang *et al.* etched a fused-silica grating to split different polarized beams with high extinction ratio [7]. In order to improve the efficiency of PBS, sinusoidal- [8] and triangular-groove [9] shape gratings were introduced. Also, a PBS with high efficiency and extinction ratio can be obtained with a metal-mirror-based grating [10]. For beam splitter, Wang *et al.* presented wideband two-port beam splitter grating, which could be used for not only TE or TM polarization but also both TE and TM polarizations [11]. Feng *et al.* fabricated a polarization-independent two-port beam splitter at a wavelength of 1310 nm [12]. If the incident wave normally illuminates a high-density grating, a three-port beam splitter can be presented. Feng *et al.* designed and fabricated such a beam splitter with theoretical numerical simulation of RCWA and physical mechanism of modal method and experimental holographic recording and ICP etching [13].

Most reported elements can fulfill just one function by high-density deep-etched gratings. Feng *et al.* presented a novel dual-function grating element, where high efficiency could be obtained for TE polarization and two-port beam splitter could be achieved for TM polarization [14]. Furthermore, conventional output was obtained in the -1st, 0th and 1st orders under normal incidence or Littrow mounting. Zheng *et al.* introduced transmission gratings under second Bragg angle incidence for high-efficiency element, two-port and three-port beam splitters [15]. To our knowledge, no one studied TIR grating under second Bragg angle incidence for dual-function grating.

In this paper, we presented dual-function grating element under TIR and second Bragg angle mounting. The grating profile parameters are optimized in order to obtain high efficiency for TE polarization in the -2nd order and two-port beam splitter in the -2nd and 0th orders for TM polarization. The diffraction properties are investigated by numerical results using RCWA. The new element involves dual-function element, TIR, and second Bragg mounting.

2. Optimization of the dual-function element

Fig. 1 shows a TIR grating etched in fused silica with refractive indices of n_1 =1.45332 for 800 nm laser wavelength and n_2 for air, where d is the period, h is the depth, and duty cycle of the ratio of ridge width to the period is 0.5. As a dual-function element, TE polarization is diffracted in the reflection -2nd order with high efficiency and TM polarization is divided into the -2nd and 0th orders with good uniformity. The grating is illuminated by a plane wave with wavelength of λ under second Bragg angle incidence of $\theta_i = \sin^{-1}(\lambda/(n_1 d))$, which is different from conventional Littrow mounting or normal incidence.

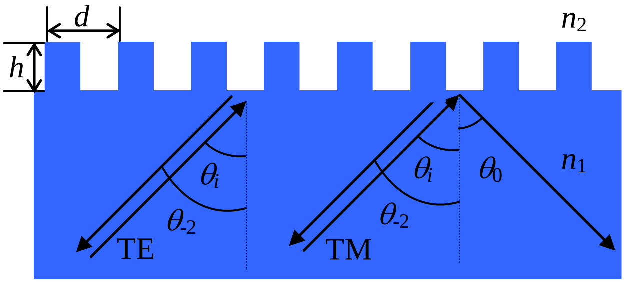

Fig. 1. (Color online) Schematic of a dual-function grating element under TIR and second Bragg angle mounting (n_1 and n_2 refractive indices of fused silica and air, respectively, d period, h depth, θ_i incident angle, θ_0 and θ_{-2} diffraction angles of the 0^{th} and -2nd reflection orders in fused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

In order to improve the efficiency, TIR conditions should be met under second Bragg angle incidence, where the period can vary within the range of $\dfrac{\lambda}{n_1} < d < \dfrac{\lambda}{n_2}$. Only three diffracted orders are remained under second Bragg angle mounting: -2nd order, -1st order, and 0th order, which correspond to a period of $\dfrac{\lambda}{n_1} < d < \dfrac{2\lambda}{n_1}$. Thus, the grating period is limited within the range of 551-800 nm. Efficiencies of the three diffracted orders can be investigated using RCWA to optimize the grating profile parameters. Fig. 2 shows the contour of efficiency for different grating period and depth with duty cycle of 0.5 at a wavelength of 800 nm under second Bragg angle incidence. In Fig. 2, efficiencies change with the grating parameters for TE and TM polarizations. With the optimized period of 748 nm and etched depth of 2.73 μm, efficiency of 97.02% can be obtained for TE polarization in the -2nd order and efficiencies of 49.20% in the -2nd order and 49.57% in the and 0th order can be achieved for TM polarization.

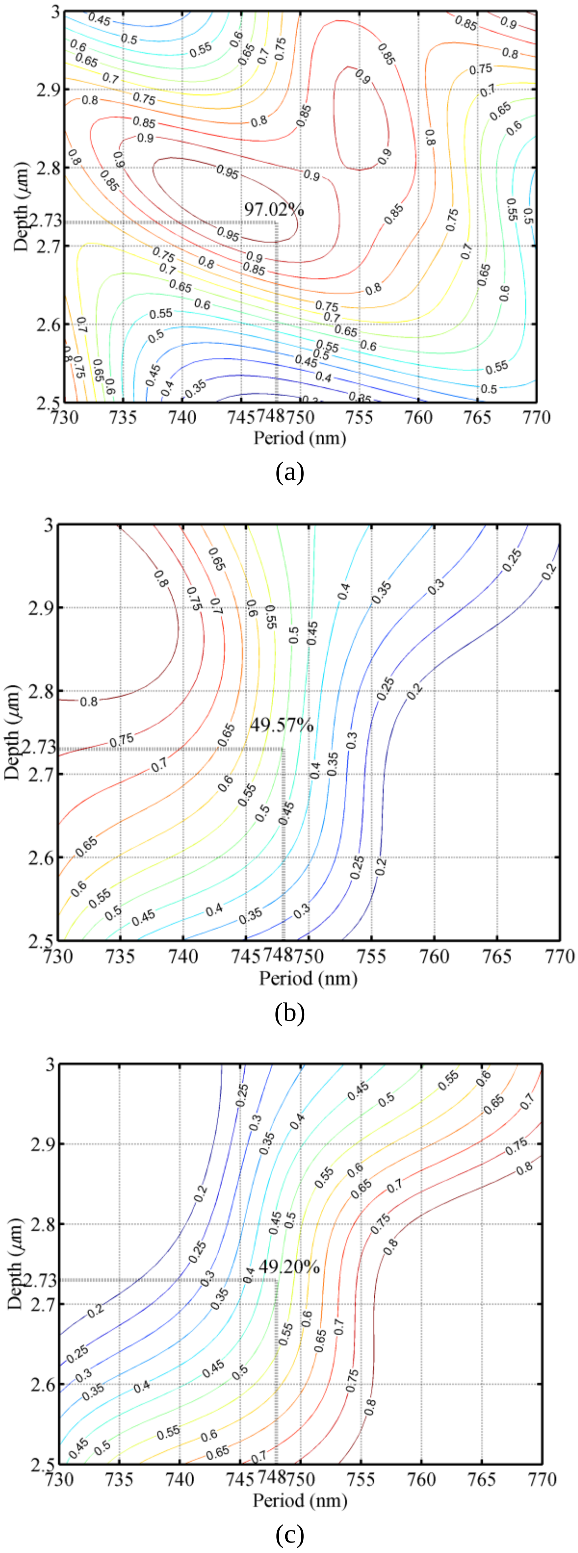

Fig. 2. (Color online) The Contour of the efficiency of a TIR grating versus grating period and depth with the duty cycle of 0.5 for the wavelength of 800 nm under second Bragg angle mounting: (a) TE polarization in the -2nd order, (b) TM polarization in the 0th order, (c) TM polarization in the -2nd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

The fabrication tolerance should be taken into account during manufacture process. With the deviation of etched depth from the optimized result, efficiency and uniformity may decrease. Fig. 3 shows the efficiency versus etched depth with the period of 748 nm and duty cycle of 0.5 at the wavelength of 800 nm under TIR and second Bragg angle mounting. In Fig. 3, efficiencies larger than 90% can be obtained for TE polarization in the -2nd order and efficiencies larger than (45%*2) = 90% can be achieved for TM polarization in the -2nd and 0th orders with the etched depth range of 2.69 μm-2.80 μm, which should be a useful guideline for fabrication of such a dual-function grating element.

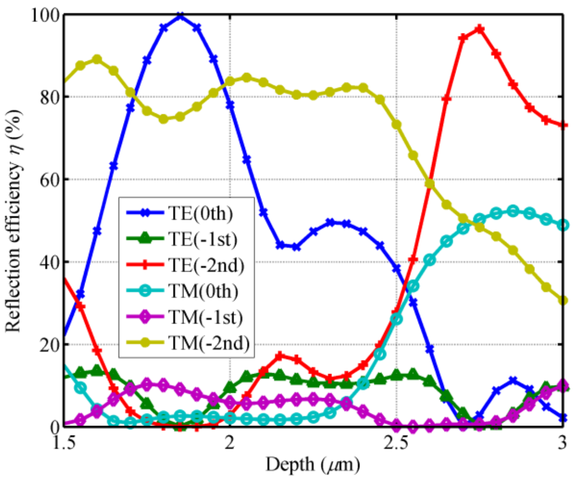

Fig. 3. (Color online) Reflection efficiency of a TIR grating versus depth with the optimized period of 748 nm and duty cycle of 0.5 for the wavelength of 800 nm under second Bragg angle mounting.

3. Reflection efficiency with incident wavelength and angle

The reflection efficiencies of the three orders for the incident wavelength and angle can be investigated using RCWA. Fig. 4 shows the efficiency versus incident wavelength with the optimized period of 748 nm, depth of 2.73 μm for the duty cycle of 0.5 under second Bragg angle incidence. Efficiencies vary with the incident wavelength for TE and TM polarizations in the three orders. High efficiency for TE polarization in the -2nd order and good uniformity for TM polarization in the -2nd and 0th orders can be obtained with the central wavelength of 800 nm.

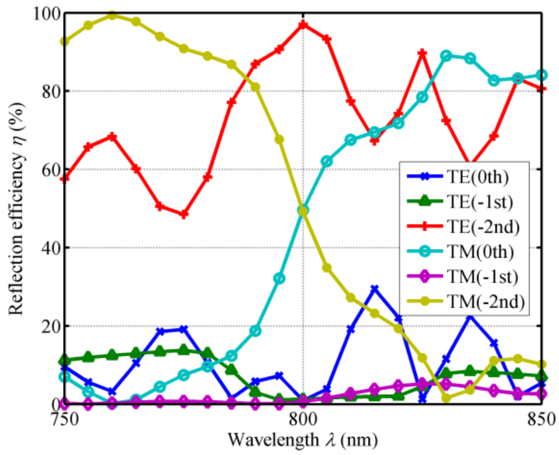

Fig. 4. (Color online) Reflection efficiency versus incident wavelength under second Bragg angle mounting, duty cycle f = 0.5, period d = 748 nm and depth h = 2.73 μm.

Fig. 5 shows the efficiency versus incident angle with the same optimized period and depth as Fig. 4 at a wavelength of 800 nm. The incident angle varies near the second Bragg angle. The efficiency and uniformity may be not as good as the optimized results with deviation of the incident angle. Under the second Bragg angle incidence, the dual-function grating element can be obtained by diffracting TE polarization with high efficiency and TM polarization with good uniformity.

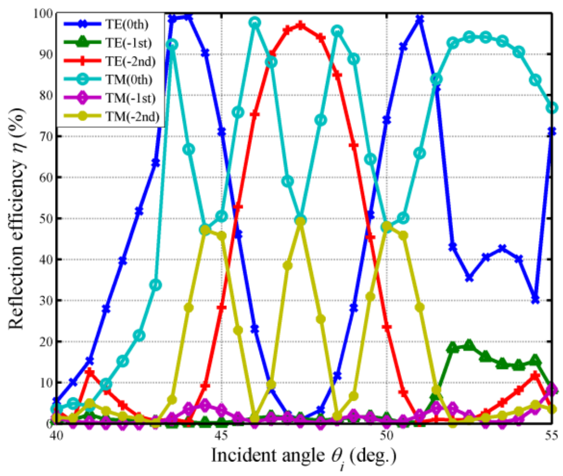

Fig. 5. (Color online) Reflection efficiency versus incident angle for a wavelength of 800 nm with the same optimized grating profile parameters as Fig. 4.

4. Conclusions

Dual-function grating element can be optimized under TIR and second Bragg angle mounting. Grating parameters are investigated using RCWA for the duty cycle of 0.5 at a wavelength of 800 nm. With the optimized grating period of 748 nm and etched depth of

2.73 μm, efficiency of 97.02% for TE polarization can be obtained in the -2nd order and efficiencies of 49.20% in the -2nd order and 49.57% in the 0th order can be achieved for TM polarization. High efficiency and good uniformity can be obtained for the central wavelength of 800 nm and second Bragg angle incidence. The presented diffractive optical element can show merits of dual-function grating, novel design of second Bragg angle mounting, and high efficiency of TIR. The dual-function grating element should be useful in numerous optical information processing systems.

Acknowledgements

This work was supported by Educational Commission Foundation (100068) of Guangdong Province and National Natural Science Foundation (11147183) of China.

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