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Polarization-selective beam splitter by a sandwiched grating

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We describe a polarization-selective beam splitter by a sandwiched grating, which can fulfill the high efficiency element for TE polarization and the two-port output for TM polarization. The modal method and the rigorous coupled-wave analysis (RCWA) are employed together to optimize the polarization-selective beam splitter. According to the modal method, the grating duty cycle and period are discussed to analyze the physical mechanism of such a dual-function element. Using RCWA, grating depth and thickness of the covering layer are accurately optimized to design such a polarization-selective beam splitter. With the optimized grating duty cycle, period, depth and covering layer thickness, TE polarization can be mainly diffracted in the –1st order and two-port output can be achieved for TM polarization in the 0th and the –1st orders. The polarization-selective beam splitter should be a useful element in a variety of applications with advantages of high efficiency, wideband property, and dual functions based on a sandwich grating.

Keywords: modal method, rigorous coupled-wave analysis (RCWA), sandwiched grating, high efficiency, beam splitter.

1. Introduction

High-efficiency gratings are key elements in numerous optical information processing systems such as high-power systems, optics communications and so on. Binary gratings with high density have been extensively studied in the resonance domain with periods comparable to incident wavelengths [1–3]. With optimized grating parameters using a rigorous coupled-wave analysis (RCWA) [4], such gratings can show high efficiency in the –1st order by cancellation of the 0th order, which also can be well explained based on the modal method [5]. A highly efficient deep-etched transmissive grating was designed and fabricated for a femtosecond laser wavelength of 800 nm [6]. The input chirped pulse can be compressed with a pair of the fabricated gratings instead of the prism pair to compensate the group velocity dispersion. Furthermore, a free-space diffraction grating was presented for use in dense wavelength division multiplexing (DWDM) systems [7]. With the optimized region, the efficiencies that can be obtained are more than 95% for TE polarization and above 80% for TM polarization. DWDM can be realized through a high-efficiency grating with advantages of parallel demultiplexing, low polarization-dependent loss, and stable performance.

A beam splitter can also play an important role in optical computing, interferometry, and metrology. Conventional beam splitters are based on multilayer coatings, which have disadvantages of the complicated fabrication procedure, thermal deformation, and low diffraction efficiency. Therefore, a new type of a beam splitter has been reported based on binary phase gratings, which has the advantage of simple structure, stable performance, and high efficiency. A transmissive beam splitter was designed and fabricated for both TE and TM polarizations [8]. The two-port beam splitter at a wavelength of 1310 nm has advantages of compact size, high efficiency, and polarization independence. Moreover, a 50/50 beam splitter used for laser interferometers can be applied to gravitational wave detectors [9]. Such a two-port beam splitter can avoid a critical thermal lensing effect without light absorption. Compared with metal gratings, 50/50 beam splitter gratings etched in fused silica can sustain high-power lasers. An all-dielectric 50/50 beam splitter has been designed and fabricated with the multilayer stack structure for laser interferometers [9].

Both high-efficiency gratings and beam splitters are useful elements in numerous optical systems [10, 11]. It would be attractive that a phase grating can fulfill the two functions. In this paper, a polarization-selective beam splitter is presented based on a sandwiched grating, which can act as a high-efficiency element for TE polarization and a beam splitter for TM polarization. RCWA [4] and the modal method [5] are used to optimize the sandwiched grating parameters, including grating duty cycle, period, depth, and thickness of the covering layer. Such a transmission sandwiched grating can have advantages of high efficiency, wideband property, and dual functions, which can be used in the chirped-pulse amplification [1], femtosecond pulse compressor [6], and high-power laser interferometer [9].

2. Sandwiched grating for polarization-selective beam splitter

Figure 1 shows a polarization-selective beam splitter by a sandwiched grating. The grating with the period of d and depth of h_g can be based on excellent optical material of fused silica with the refractive index $n_2 = 1.45332$ for an incident wavelength of 800 nm. The covering layer is a thin slab of fused silica with the thickness of h_c, which can also affect the efficiency distribution. The incident condition meets the Littrow mounting with a Bragg incident angle of $\theta_i = \sin^{-1}(\lambda/(2n_1d))$ from air with the refractive index of $n_1 = 1$ and the wavelength of λ. For TE polarization, the incident energy can be mainly diffracted into the –1st order with high efficiency. For TM polarization, the two-port output can be obtained in the 0th and the –1st orders with uniformity. The sandwiched grating can work as a dual-function element for TE and TM polarization, respectively.

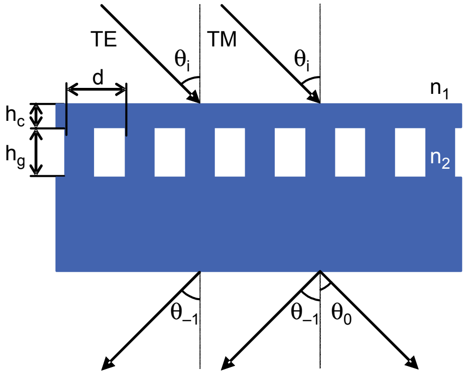

Fig. 1. Schematic of a sandwiched grating for a polarization-selective beam splitter (n_1 – refractive index of air, n_2 – refractive index of fused silica, d – period, h_g – grating depth, h_c – thickness of the covering layer, θ_i – incident angle, θ_0 and θ_{-1} – diffraction angles of the 0th and the –1st orders, respectively).

The polarization-selective beam splitter is designed by a sandwiched grating. There are four grating parameters to be optimized: duty cycle, period, depth, and thickness of the covering layer. Conventional optimization process is based on numerical calculation using RCWA [4], which will involve too much time with so many parameters. However, the modal method [5] can be introduced to optimize the polarization-selective beam splitter effectively. Most importantly, the propagation process to form such a dual-function element can be well explained by the modal method.

The grating duty cycle and period can be optimized based on the modal method [5]. The duty cycle is defined as the ratio of the grating ridge width to the period. The grating can be recorded by holographic interference for forming a grating pattern and fabricated by inductively coupled plasma technology for etching in the fused silica. After the recording exposure, different developing time can lead to different duty cycle. The excessive and insufficient developing time can affect the grating duty cycle. When the efficiency reaches the maximum and uniformity during developing, the usual duty cycle of 0.5 can be obtained by such an appropriate developing time. The usual parameter of 0.5 can be chosen for the grating duty cycle for simple fabrication. The incident wave may excite two modes in the grating region, which have different effective indices for different modes. Phase difference between two modes can be accumulated after propagating the same grating depth, which will further affect the diffraction efficiency. If the phase difference meets an odd-numbered multiple of π, high efficiency can be obtained in the –1st order. For an odd-numbered multiple of $\pi/2$, the two-port output can be obtained. The phase difference can be determined by the effective indices difference and the grating depth. With the same propagation depth, the effective indices difference for TE polarization should be 2 multiple of TM polarization. The eigenvalue equations have been given for both TE and TM polarizations based on the modal method [5], which can be used to calculate the effective

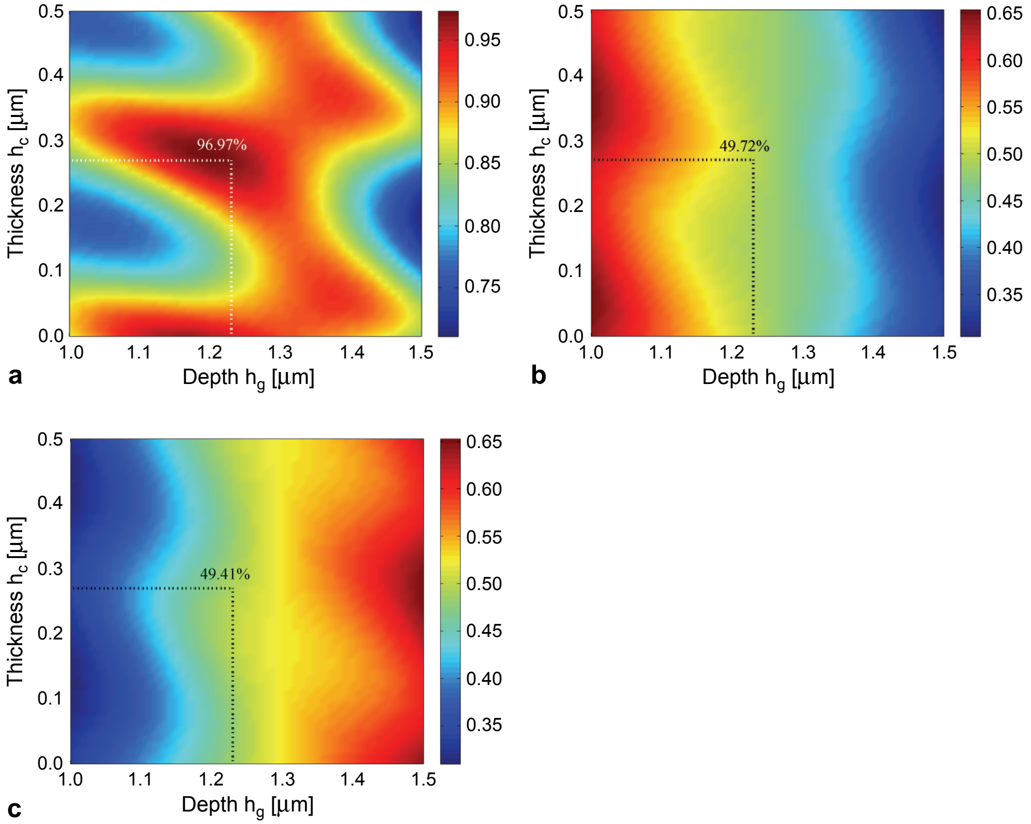

Fig. 2. Contour of efficiency versus the sandwiched grating depth and thickness of the covering layer with the duty cycle of 0.5 and period of 607 nm under Littrow mounting for the wavelength of 800 nm: TE polarization in the –1st order (**a**), TM polarization in the 0th order (**b**), TM polarization in the –1st order (**c**).

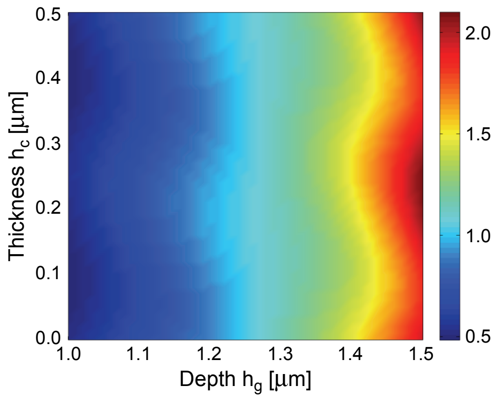

Fig. 3. Contour of the efficiency ratio between the –1st order and the 0th order versus depth and thickness of the covering layer based on a sandwiched grating for TM polarization.

indices of excited modes. According to equations of the modal method that effective indices meet, an optimized grating period of 607 nm should be chosen.

There are four parameters to be optimized for such a sandwiched grating, including duty cycle, period, depth, and thickness of the covering layer. Parameters of grating duty cycle and period have been chosen after the physical mechanism was analyzed based on the modal method [5]. Therefore, only two grating parameters are left: the depth and covering layer thickness, which can be optimized using RCWA [4]. The enhanced transmittance matrix approach for numerical calculation can realize the stable implementation of RCWA, which can be used to investigate the efficiency by the developed codes in this paper. Figure 2 shows the contour of efficiency versus the sandwiched grating depth and thickness of the covering layer with the duty cycle of 0.5 and period of 607 nm under Littrow mounting for the wavelength of 800 nm. It indicates that the sandwiched grating can show high efficiency of 96.97% for TE polarization in the –1st order and the two-port output of 49.72% and 49.41% for TM polarization in the 0th and –1st orders with the optimized grating depth of 1.23 μm and covering layer thickness of 0.27 μm. Figure 3 shows the contour of the efficiency ratio between the –1st order and the 0th order versus the depth and thickness of the covering layer based on a sandwiched grating for TM polarization. With the optimized grating parameters, the two-port output can be achieved with good uniformity in the diffracted two orders.

3. Properties for incident conditions

A polarization-selective beam splitter can be obtained by a sandwiched grating with the optimized grating parameters. Figure 4 shows the diffraction efficiency versus the grating depth with the duty cycle of 0.5, period of 607 nm, and the connecting layer thickness of 0.27 μm for the wavelength of 800 nm under Littrow mounting. The etched grating can modulate the phase difference, which will affect the efficiencies

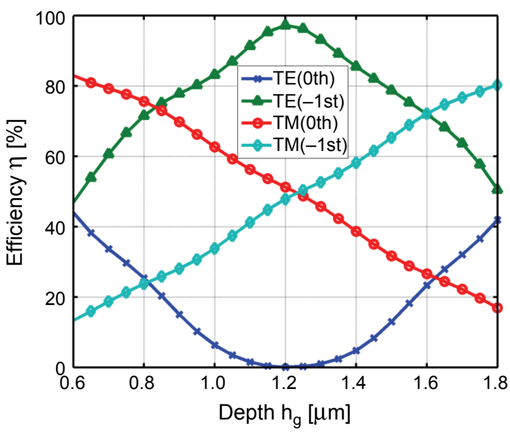

Fig. 4. Diffraction efficiency versus grating depth with the duty cycle of 0.5, period of 607 nm, and the connecting layer thickness of 0.27 μm for the wavelength of 800 nm under Littrow mounting.

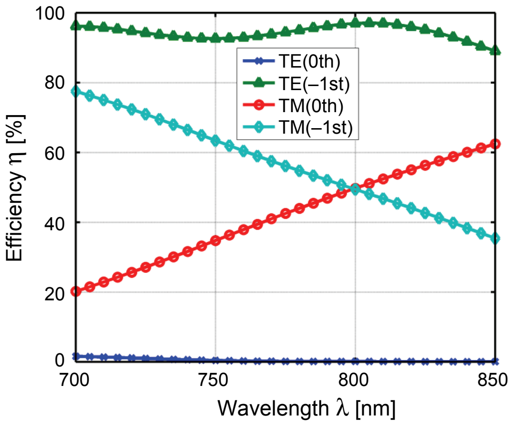

Fig. 5. Diffraction efficiency versus incident wavelength under Littrow mounting with the optimized grating parameters.

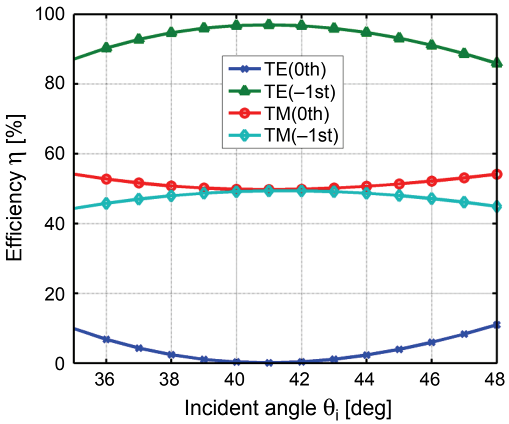

Fig. 6. Diffraction efficiency versus incident angle for a wavelength of 800 nm with the optimized grating profile parameters.

of two orders for TE and TM polarizations. With the optimized grating depth of 1.23 μm, the high efficiency and the two-port output can be achieved for TE and TM polarizations, respectively. For practical applications, it is necessary to investigate the incident wavelength and angular bandwidths. Figure 5 shows the diffraction efficiency versus the incident wavelength under Littrow mounting with the optimized grating parameters. In Figure 5, the efficiency bandwidth of 1 dB can be obtained for TE polarization within the incident wavelength range of 547–1018 nm. And the efficiencies bandwidth of 3.5 dB in both diffracted orders can be achieved within 783–817 nm. Figure 6 shows the diffraction efficiency versus the incident angle for a wavelength of 800 nm with the optimized grating profile parameters. With the deviation of the incident angle from the Littrow mounting, the efficiency will be reduced to some extent. The efficiency bandwidth of 1 dB can still be obtained within the incident angle range of 34–49° for TE polarization in Fig. 6. The two-port output of efficiencies bandwidth of 3.5 dB can be obtained within the range of 36–48° in the diffracted two orders for TM polarization.

4. Conclusions

In conclusion, a polarization-selective beam splitter is presented based on a sandwiched grating, where a dual-function grating element can be fulfilled for TE and TM polarizations. The modal method and RCWA can be used to optimize such a polarization-selective beam splitter effectively. With the optimized grating duty cycle of 0.5, period of 607 nm, depth of 1.23 μm, and covering layer thickness of 0.27 μm, the efficiency of 96.97% can be obtained in the –1st order for TE polarization. And the two-port output of 49.72% and 49.41% can be achieved in the 0th and –1st orders for TM polarization. It indicates that the high efficiency can be obtained with the wideband property under Littrow mounting from diffraction properties. The polarization-selective beam splitter by a sandwiched grating should be a useful element in numerous optical applications with the advantages of high efficiency, wideband property, and dual functions.

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