Encapsulated polarization-selective splitting grating with metal-mirror-based features

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We design and optimize the sandwiched reflective polarization-selective grating in Littrow mounting. By using the modal method and the rigorous coupled-wave analysis, grating parameters are analyzed and calculated including grating groove depth, thickness of connecting layer, and so on. The grating device can diffract the transverse electric-polarized plane light only in the -1st diffractive order with high reflection efficiency of 97.91%. Meanwhile, for the transverse magnetic-polarized plane light, diffraction efficiencies in the 0th order and the -1st order correspond to 48.67% and 48.68%, respectively.

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1. Introduction

Diffraction gratings have an advantage of compact size, which are suitable for miniaturization and integration compared with conventional optical elements. Therefore, the diffraction gratings have attracted more and more attention in various optical systems [1-5]. For subwavelength gratings, two orders of the 0th and the -1st orders may be remained. The diffraction can be highly efficient [6]. High-efficiency gratings can be used for dense wavelength division multiplexing with advantages of parallel de-multiplexing. Furthermore, efficiencies of diffraction orders can be modulated by the grating parameters to act as beam splitters [7], which are widely used in optical information processing systems such as a coupler, an interferometer, and so on.

The modal method provides the explicit explanation for the analysis of grating propagation theory [8]. By interpreting the diffraction process, the simplified modal method can supply the coupled mechanism and theoretically evaluate the diffraction efficiency and sandwiched grating depth. Wang *et al.* have proposed a grating with a cover layer, which can reduce the Fresnel loss and achieve the near one hundred percent transmission efficiency [9]. Moreover, the sandwiched grating can keep the cleaning of the grating surface. Although modal method can provide the relative explanation, it cannot calculate the precise grating parameters. The rigorous coupled-wave analysis (RCWA) is an appropriate method to optimize the grating profile, which can calculate exact parameters of gratings [10,11].

With the RCWA and modal method, subwavelength gratings are widely investigated. Marchetti *et al.* designed high efficiency grating couplers and numerically demonstrated a coupling efficiency of -0.8 dB (83%), well matching the experimental value of -0.9 dB (81%) [12]. Xu *et al.* demonstrated an easy-to-fabricate SiNx-on-SOI transverse-electric (TE) mode grating coupler. A coupling coefficient of -2.5 dB and 1-dB-bandwidth of 65 nm were experimentally measured [13]. Ding *et al.* designed and fabricated an ultrahigh coupling efficiency fully etched grating coupler using subwavelength photonic crystals and bonded aluminum mirror [14]. Although gratings can work as high-efficiency elements and beam splitters, most reported gratings concentrate on one function. Feng *et al.* has been presented to obtain high efficiency for TE polarization and two-port output for transverse magnetic (TM) polarization with the reflexed structure of a simple grating [15].

In this paper, we design the sandwiched beam splitter by metal-mirror-based binary grating in Littrow mounting. The complicated grating structure involves the grating region to realize diffraction, the connecting layer to obtain wideband property, and metallic slab to reflect the incident wave. The grating device can diffract the TE polarization plane light in the -1st diffractive order with high efficiency and suppress TE polarization in the 0th-order. For TM polarization light, the diffraction efficiencies of the grating in the -1st order and the 0th order can nearly be 50/50 output. The wavelength range and angular bandwidth for operation are investigated with the optimized results. Therefore, for the further practical applications the metal-mirror-based grating has valuable effect for TE and TM polarizations.

2. Modal analysis and numerical design

Fig. 1 describes the schematic of the sandwiched metal-mirror-based grating. Parameters of the grating include the grating period of d, the grating groove depth of h_g, the connecting layer thickness of h_c, and the silver interlayer thickness of h_n. The Ag slab with its refractive index of n_m = 0.469-9.32i is located below the connection layer. The interior of the grating grooves is air with refractive index of n_1 = 1.0. Except for the Ag slab and the grating grooves, the other grating materials are fused silica with refractive index of n_2 = 1.45. The monochromatic plane wave irradiates the grating under the Littrow mounting. The incident plane wave length is represented by λ. Accordingly, the Littrow angle can be depicted by $\theta = \sin^{-1}(\lambda/2n_2d)$.

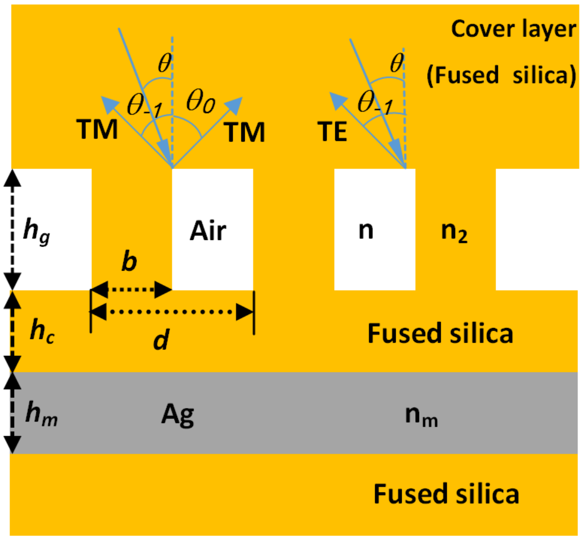


Fig. 1. (Color online) Schematic of the sandwiched polarization-selective splitting grating with metal-mirror-based features

The incident wave of the grating can be coupled into different propagating direction, which can be determined by the well-known grating equation:

$$n_{out}\sin(\theta_i) = n_{in}\sin(\theta) + i\lambda/d \tag{1}$$

In this equation, n_{out} is the refractive index of the export medium and n_{in} is the refractive index of the incident medium. θ_i depicts an angle of the *ith* diffractive order. When the thickness of the Ag plate is greater than 0.1μm, the metal plate can completely reflect the incident light.

In order to discuss the effect of diffraction splitter in physical process, the modal method is used. Due to the physical mechanism of two beam interference, the phase differences for both polarizations are accumulated. Moreover, the difference of phase difference can lead to the elimination of diffraction order. And the diffraction efficiencies can be determined by the phase differences for TE and TM polarizations. The following equations can be associated with the phase differences, which is denoted by [16]:

$$\Delta\varphi^{TE} = \frac{4\pi}{\lambda}\left(n^{TE}_{0\,eff}\text{-}n^{TE}_{1\,eff}\right)h_g \tag{2}$$

$$\Delta\varphi^{TM} = \frac{4\pi}{\lambda}\left(n^{TM}_{0\,eff}\text{-}n^{TM}_{1\,eff}\right)h_g \tag{3}$$

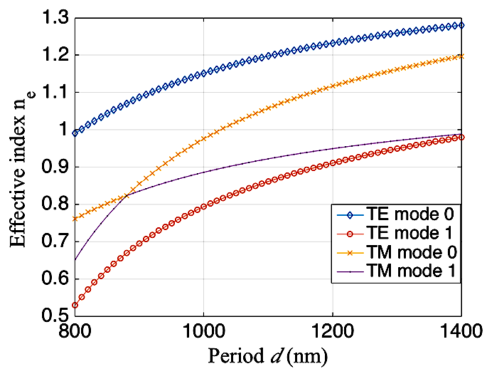
$$\eta^{TE}_{\text{-}1} = sin^2\left(\frac{\Delta\varphi^{TE}}{2}\right) \tag{4}$$

$$\eta^{TM}_{0} = cos^2\left(\frac{\Delta\varphi^{TM}}{2}\right) \tag{5}$$

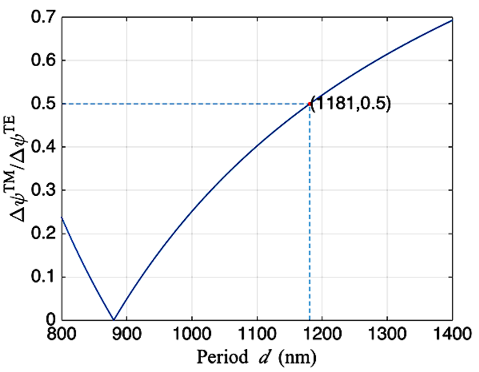
$$\eta^{TM}_{\text{-}1} = sin^2\left(\frac{\Delta\varphi^{TM}}{2}\right) \tag{6}$$

Equation (4) shows diffraction efficiency of TE polarization in the -1st order based on the modal method. Analogously, Eqs. (5) and (6) denote diffraction efficiencies in the 0th order and the –1st orders for TM polarization, respectively. In Eq. (4), when the phase difference meets the odd-numbered of π, the efficiency in the -1st order can reach to the maximum value. In Eqs. (5) and (6) in order to achieve uniform power distribution in the -1st and the 0th orders for TM polarization, the phase difference should be the odd-numbered multiple of π/2.

For ease of fabrication, the groove depth should be as low as possible. So the corresponding $\Delta\varphi^{TM}/\Delta\varphi^{TE}$ is 1/2. First, we assume that the incident wave length λ is 1550 nm, and for convenience of fabrication, the duty cycle f of grating is assumed to be 0.5. Effective refractive indices of two propagating modes for both polarizations varying with grating period are shown in Fig. 2 (a). Fig. 2 (b) shows the corresponding phase difference ratio of TM polarization to TE polarization. When grating period d is 1181 nm, the ratio of $\Delta\varphi^{TM}/\Delta\varphi^{TE}$ is 1/2. For TE and TM polarizations, the results of each effective refractive index can be calculated: n^{TE}_{0eff} =1.2265, n^{TE}_{1eff} =0.90226, n^{TM}_{0eff} =1.1067, and n^{TM}_{1eff} =0.94463. In purpose of obtaining the high efficiencies of TE and TM polarizations, the various parameters should be considered by RCWA. For the polarization-selective splitting grating, the efficiency of each port is a very significant index either to the TE polarization or the TM polarization.



(a)

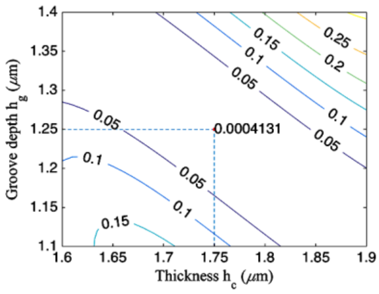


(b)

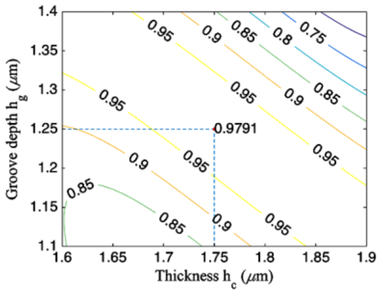
Fig. 2. (Color online) (a) Effective refractive indices of propagating modes and (b) Phase difference ratio of TM polarization to TE polarization versus the grating period for both polarizations with duty cycle of 0.5 at a wavelength of 1550 nm under Littrow mounting

3. Results and discussion

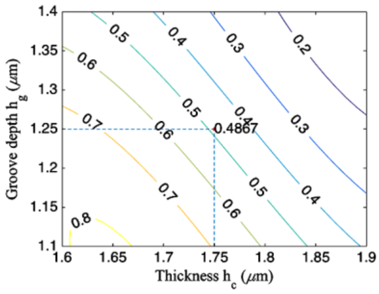
According to RCWA method, we use numerical calculation to optimize the grating groove depth h_g and thickness of connecting layer h_c. Figure 3 shows efficiency versus grating depth layer and thickness of connecting layer with the grating duty cycle of 0.5 and grating period of 1181nm for working wavelength of 1550 nm under Littrow mounting. The four figures show diffraction efficiencies of TE and TM polarizations in the 0th order and the -1st orders. When grating groove depth h_g is 1.25 μm and connecting layer thickness h_c is 1.75 μm, the diffraction efficiency for TE polarization in the -1st order can reach 97.91%. For TM polarization, the diffraction efficiencies in the 0th order and the -1st order corresponding to 48.67% and 48.68%, respectively.



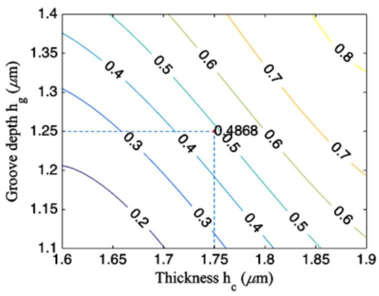
(a)



(b)



(c)



(d)

Fig. 3. (Color online) Diffraction efficiency versus grating depth and thickness of the connecting layer with the grating duty cycle of 0.5 and grating period of 1181nm at working wavelength of 1550 nm under Littrow mounting: (a) TE polarization in the 0th order, (b) TE polarization in the -1st order, (c) TM polarization in the 0th order, (d) TM polarization in the -1st order

Fig. 4 presents the reflective efficiency versus the grating duty cycle with grating period of 1181nm at a working wavelength of 1181 nm under the Littrow mounting. As shown in Fig. 4, owing to different duty cycle, the reflection efficiency will change to some extent. When the duty cycle is within the range of 0.49-0.51, for TM polarization light in the -1st order and the 0th order, the diffraction efficiencies are higher than 45%. And the diffraction efficiency of TE polarization in the -1st order can exceed 97.88%. In industrial manufacturing, a certain industrial tolerance should be considered. The duty cycle range of 0.49-0.51 for both TE and TM polarizations in each diffractive order can satisfy the performance requirements.

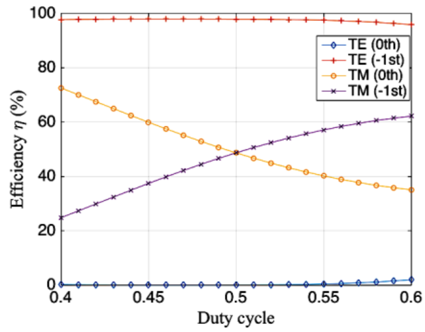


Fig. 4. (Color online) Efficiency versus grating duty cycle for the sandwiched grating with the optimized parameters at the working wavelength of 1550 nm under the Littrow mounting

In addition to considering the tolerance of duty cycle, the tolerance of grating period should also be considered. Fig. 5 shows the diffraction efficiency with the different grating period. It can be found that good grating efficiency can be obtained for grating period range of 1171-1191 nm by using RCWA. When the grating period is within the range between 1171nm and 1191nm, for TM polarization light in two order, the diffraction efficiencies of the grating are higher than 45%. And the diffraction efficiency of TE polarization in -1st order can exceed 97.86%. The grating of the grating period has a relatively wide tolerance, which is beneficial to the actual industrial production.

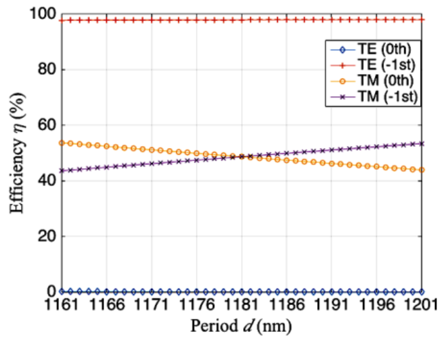


Fig. 5. (Color online) Diffraction efficiency versus grating period with the grating duty cycle of 0.5 at the working wavelength of 1550 nm under Littrow mounting

The incident wavelength of spectral bandwidth can be studied by using the RCWA method. Because of the different incident wavelengths, the diffraction efficiency of the sandwiched grating is also different. High efficiency can be obtained within a wide range of incident wavelength for both TE and TM polarizations. Fig. 6 shows the efficiency with different incident wavelengths for the optimized grating parameters using RCWA. In Fig. 6, for the incident wavelength range of 1544-1556 nm, for TM polarization light in two order, the diffraction efficiencies of the grating are higher than 45%. And the diffraction efficiency of TE polarization in the -1st order can exceed 97.64%.

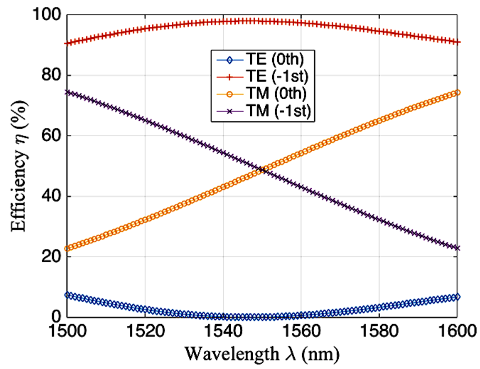


Fig. 6. (Color online) Diffraction efficiency versus incident wavelength for the sandwiched beam splitter by metal-mirror-based binary grating in Littrow mounting

Similarly, the difference of incident angle will affect the diffraction efficiency. Fig. 7 shows the reflective efficiency with different incident angles for the optimized grating parameters. The Littrow angle can be represented by $\theta=\sin^{-1}(\lambda/2n_2d)$. With the previous optimized results of $\lambda = 1550$nm, $n_2 = 1.45$ and $d = 1181$nm, the angle is 26.91° under the Littrow mounting.

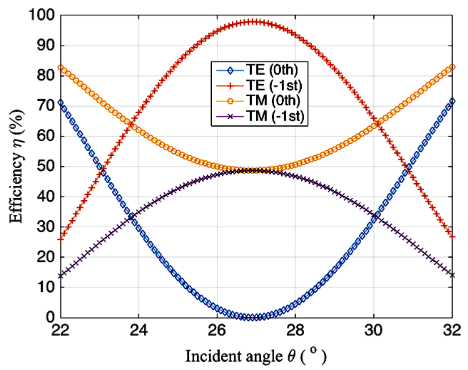


Fig. 7. (Color online) Diffraction efficiency versus incident angle for a wavelength of 1550 nm with the optimized grating profile parameters

Fig. 7 shows the reflective efficiency with different incident angles for the optimized grating parameters. In

Fig. 7, when the incident angle is in the range of 25.6 - 28.3°, for TM polarization light in two order, the diffraction efficiencies of the grating are higher than 45%. And the diffraction efficiency of TE polarization in the -1st order can exceed 90.8%. Based on the above optimization calculation, the grating has good operation range for the incident angle.

4. Conclusion

In conclusion, we design and optimize the sandwiched polarization-selective splitting grating with metal-mirror-based features. According to phase differences of the modal method for TE and TM polarizations, an optimized grating period of 1181 nm can be chosen with the duty cycle of 0.5. The grating groove depth and thickness of the connecting layer are numerically optimized accurately using the RCWA. With the grating groove depth of 1.25 µm and connecting layer thickness of 1.75 µm for the incident wavelength of 1550 nm under Littrow mounting, the efficiency of TE polarization in the -1st order can reach 97.91%. For TM polarization, the diffraction efficiencies in the 0th order and the -1st order corresponding to 48.67% and 48.68%, respectively. For different incident wavelength and angle, the bandwidth for operation can be exhibited to some extent. For incident wavelength, the bandwidth is 14 nm. For incident angle, the bandwidth is 2.7^{o}. The proposed metal-mirror-based grating presents an access to improve performance for polarization-selective splitting grating, which can satisfy the requirements of different optoelectronic devices.

Acknowledgements

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