Proposed method of three-channel division by covered multilayer model

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In this paper, a triple-layer grating splitter with three-port output is designed. Under normal incidence of light at 800 nm wavelength, the diffraction efficiency of 0th order and ±1st orders under TE polarization are 32.87% and 32.86%, respectively. The diffraction efficiency of 0th order and ±1st orders under TM polarization are 31.98%, respectively. The results show that the total diffraction efficiency is more than 95% under TE polarization and TM polarization. Through the combination of rigorous coupled-wave analysis (RCWA) and simulated annealing algorithms (SAA), the calculation and optimization of each parameter of the grating is carried out to make the diffraction efficiency of the grating meet the conditions. Finally, the effects of incident wave characteristics and grating parameters on diffraction efficiency are discussed.

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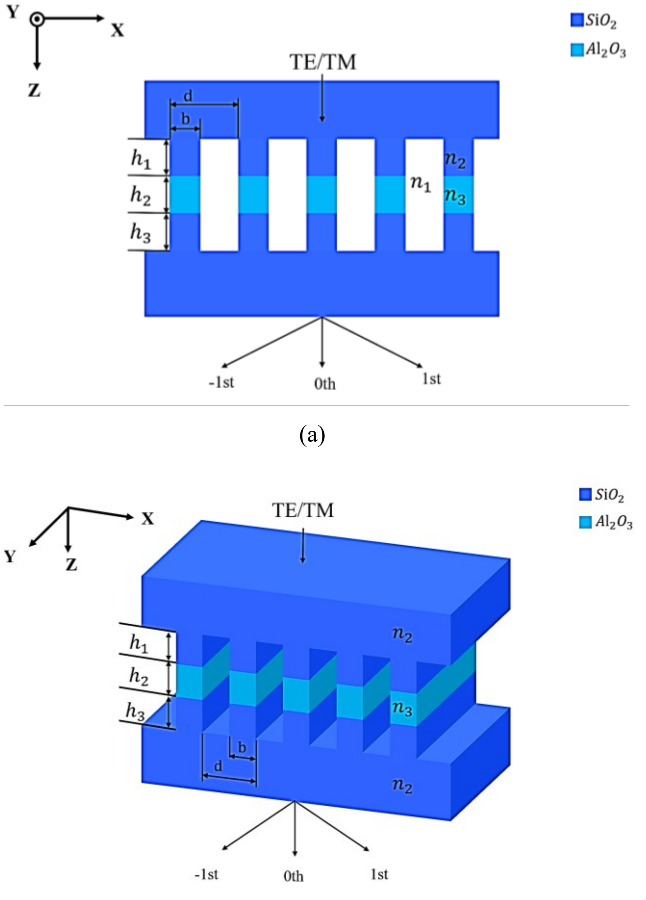
1. Introduction

In recent years, the optoelectronic industry has developed rapidly, and beam splitters have played an important role in the development of optoelectronic information technology. As a common optical element, beam splitter [1-5] can evenly divide the incident light into multiple energies for output. Due to the advantages of good diffraction efficiency, compact structure, wide working spectrum, and lightweight, the grating beam splitter is widely used in the fields of optical communication [6,7], optical storage [8,9], displacement measurement [10,11] and laser processing [12,13], which has attracted many scholars' attention. Huang et al. proposed an enhanced newly high-efficiency dual-function beam splitter of the grating [14]. Xiong et al. proposed a reflective two-port beam splitter grating with zeroth order suppressed [15]. Liu et al. proposed a triple-channel reflective beam splitter in a terahertz band with a connecting layer under second Bragg incidence and achieved beam splitter obtained 97.47% for TE polarization and 91.27% for TM polarization [16]. Fang et al. proposed a zero-order offset dual port reflection grating. Under normal incident light with a wavelength of 1550 nm, the grating can output at ±1st order for TE and TM polarizations. In addition, the efficiency of the 0th order reflected light is less than 1% [17].

In this paper, we propose an efficient transmission three-port grating based on the vertical incidence of an 800 nm light wave. In the design of grating structure parameters, the rigorous coupled-wave analysis (RCWA) [18-21] and simulated annealing algorithm (SAA) [22-24] are combined to obtain the optimal parameters of the grating. In addition, the finite element method (FEM) [25,26] is used to verify the results of RCWA calculation, and the electric field distribution of the grating is obtained. The optimized grating has high diffraction efficiency. For TE polarization, the 0th order diffraction efficiency is 32.87%, the ±1st order diffraction efficiency is 32.86%, and the total efficiency is 98.59%; For TM polarization, the 0th order diffraction efficiency and ±1st order diffraction efficiency are both 31.98%, and the total diffraction efficiency is 95.94%. The diffraction efficiencies of the three ports in TE polarization and TM polarization are more than 31%. The results show that both TE polarization and TM polarization have high diffraction efficiency and good uniformity.

2. Grating structure and parametric analysis

Fig. 1 shows a three-port transmission grating based on vertical incidence. SiO_2 is used in both incident and outgoing media, while air is used in the grating groove. The grating ridge is composed of three layers of a rectangular structure with Al_2O_3 in the middle. When the incident wavelength is 800 nm, the refractive indices of SiO_2 and Al_2O_3 are $n_2 = 1.45$ and $n_3 = 1.76$, respectively. In the three-channel transmission grating structure, d is the grating period, b is the width of the grating ridge, the duty cycle of the grating is $f = \frac{b}{d}$, h_1 and h_3 are the thickness of SiO_2, h_2 is the thickness of Al_2O_3, so the thickness of the grating ridge is $h_1+h_2+h_3$. When the incident light with the wavelength of 800 nm is perpendicular to the incident light, the energy of the incident light diffracts to 0th order and ±1st order respectively after passing through the grating.



(a)

(b)

Fig. 1. Two-dimensional (a) and three-dimensional (b) diagrams of three-port grating under normal incidence (color online)

In order to obtain the optimized structural parameters, RCWA and SAA are combined in this paper. k_{xi} is the wave vector component in the x direction, and $k_0 = \frac{2\pi}{\lambda}$ can be determined by the Floquet theorem:

$$k_{xi} = k_0\left(-i\frac{\lambda}{d}\right), \tag{1}$$

moreover

$$k_{2,zi} = \begin{cases} +k_0\sqrt{n_2^2 - (\frac{k_{xi}}{k_0})^2}, k_0 n_2 > k_{xi}, \\ -jk_0\sqrt{(\frac{k_{xi}}{k_0})^2 - n_2^2}, k_{xi} > k_0 n_2. \end{cases} \tag{2}$$

To calculate the diffraction efficiency of the grating, we need to solve the electric field vector of the grating region in Maxwell equations by matching the magnetic field component and the tangential electric field component at the grating boundary:

$$DE_{ti} = T_i T_i^* Re\left(\frac{k_{2,zi}}{k_0 n_1}\right), \tag{3}$$

where T_i is the normalized electric field of the ith order transmission, and DE_{ti} is the change of the transmissivity of the grating with the ith order. The diffraction efficiency under TM polarization is:

$$DE_{ti} = \frac{T_i T_i^* Re\left(\frac{k_{2,zi}}{n_2^2}\right)}{\frac{k_0}{n_1}}, \tag{4}$$

In the formula (5), η_i is the diffraction efficiency of ith order, η_{av} is the average diffraction efficiency of all channels, η_i calculated by the rigorous coupled-wave program, $2N+1$ is the number of optical channels.

$$\eta_{av} = \frac{1}{2N+1}\left(\sum_{i=-N}^{N}\eta_i\right). \tag{5}$$

The diffraction efficiency calculated by RCWA is substituted into the cost function:

$$\Phi = \frac{\sum_{i=-N}^{N}(\eta_i - \eta_{av})^2}{\sum_{i=-N}^{N}\eta_i}. \tag{6}$$

Because the grating designed in this paper is polarization independent, the cost function of TE polarization and TM polarization must be considered at the same time. Take the average value of the two cost functions, so the formula should be expressed as:

$$\Phi_{av} = \frac{1}{2}(\Phi_{TE} + \Phi_{TM}). \tag{7}$$

RCWA is used to calculate the diffraction efficiency of grating parameters within a certain range, set an appropriate interval within this range, and compare Φ_{av}. When Φ_{av} of a group of parameters is the minimum value within this range, this parameter is the optimal parameter within this range.

Under the condition of the wavelength of 800 nm, in order to obtain the highest diffraction efficiency and good uniformity, the optimal parameters are obtained through multiple optimization and calculation, as shown in Table 1.

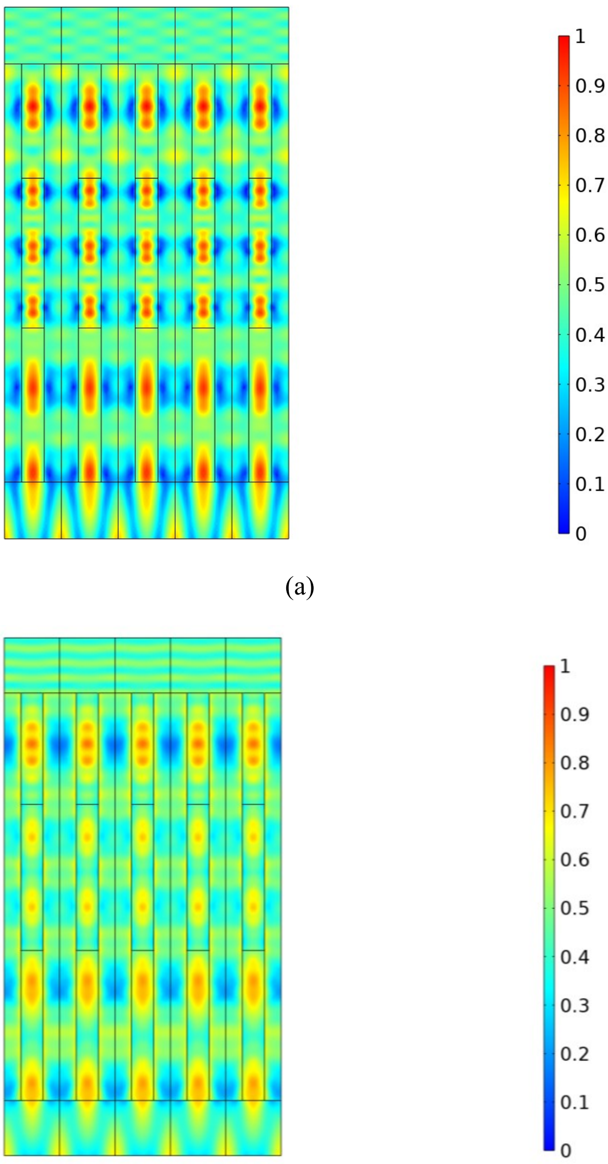
Table 1. The optimized parameters of three-port grating under normal incidence

λ	d	f	h_1	h_2	h_3
800 nm	1022 nm	0.4	2.064 µm	2.700 µm	2.780 µm

When the incident wavelength is 800 nm, the optimal parameters of the grating structure are duty cycle f = 0.4, grating period d = 1022 nm, and the thickness of grating grooves h_1 = 2.064 µm, h_2 = 2.700 µm, and h_3 = 2.780 µm. When the grating parameters are the optimal parameters, the diffraction efficiencies of the 0th order and ±1st order under TE polarization are 32.87% and 32.86%, respectively. Under TM polarization, the diffraction efficiencies of 0th order and ±1st order are both 31.98%. The total diffraction efficiency is 98.59% under TE polarization and 95.94% under TM polarization. This shows that the structure has high diffraction efficiency and good uniformity, and has polarization independent characteristics. In order to ensure the accuracy of the calculation results, the finite element method (FEM) will be used to verify the calculation results of RCWA. The diffraction efficiencies calculated by FEM and RCWA are shown in Table 2. Fig. 2 is the normalized field strength diagram of the grating under two kinds of polarization. Under the effect of TE polarization, the energy is mainly output from the substrate below and directly below the grating ridge. Under the effect of TM polarization, the energy is mainly output directly below the grating ridge.

Table 2. The efficiencies of gating under the optimized parameters based on RCWA and FEM

Theory	η_0^{TE} (%)	η_0^{TM} (%)	$\eta_{\pm1}^{TE}$ (%)	$\eta_{\pm1}^{TM}$ (%)
RCWA	32.87	31.98	32.86	31.98
FEM	32.72	31.95	32.92	31.98



(a)

(b)

Fig. 2. The normalized electric field distribution with λ=800 nm, d=1.022 µm, f=0.4, h_1=2.064 µm, h_2=2.700 µm, h_3=2.780 µm: (a) TE polarization and (b) TM polarization (color online)

In order to assess the uniformity of diffraction efficiency, we will use the uniformity formula. When the diffraction efficiency is high and the uniformity is close to 100%, the performance of the grating beam splitter is better. The uniformity formula is expressed as:

$$U = \left(1 - \frac{E_{max} - E_{min}}{E_{avg}}\right) \times 100\%. \tag{8}$$

The E_{max} is the maximum value of 0th order and ±1st order under TE polarization and TM polarization, while E_{min} is the minimum value. E_{avg} in the formula is the average diffraction efficiency of 0th order and ±1st order. By substituting the diffraction efficiencies of the three ports previously obtained into the above formula, it can be concluded that the uniformity of the diffraction efficiency under TE polarization is 99.4%, and the uniformity of the diffraction efficiency under TM polarization is 99.9%. It can be seen that the grating beam splitter in this paper has high diffraction efficiency and excellent uniformity, which shows that the grating splitter has excellent performance.

3. Analysis and discussions

It is assumed that after the optimization of grating parameters, the light with a wavelength of 800 nm is incident vertically. In reality, it is not guaranteed that the light is vertically incident because the wavelength of the incident light will change constantly. When the characteristics of the incident light change, the diffraction efficiency of the grating will also change. It is necessary to consider the influence of the deviation of the incident wavelength and incident angle on the performance of the grating. Fig. 3 depicts the relationship between the diffraction efficiency of the grating and the incident wavelength. It can be seen from the figure that for TE polarization when the incident wavelength is between 785 nm and 807 nm, the zero-order and first-order diffraction efficiencies are higher than 30%. For TM polarization, when the incident wavelength is between 780 nm and 820 nm, the zero-order and first-order diffraction efficiencies are higher than 30%. In conclusion, the bandwidth of TM polarization is wider than that of TE polarization, and the grating has higher diffraction efficiency in the above wavelength range.

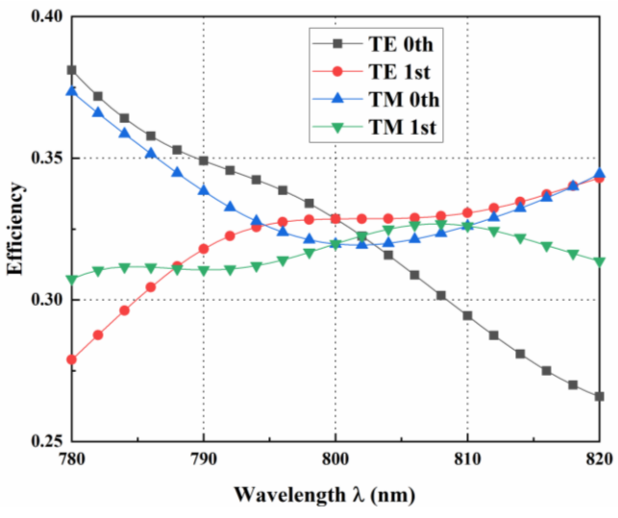


Fig. 3. The efficiency corresponding to the incident wavelength for both TE and TM polarizations under normal incidence, where d=1.022 μm, f= 0.4, h_1= 2.064 μm, h_2= 2.700 μm and h_3=2.780 μm (color online)

Fig. 4 shows the relationship between the incident angle and the diffraction efficiency of the grating. When the incident angle is between -0.03 rad and 0 rad, the diffraction efficiency under TE polarization and TM polarization is higher than 30%, that is, between -1.72° and 0°. This shows that the grating maintains a high diffraction efficiency in the above incidence angle range. When the incident angle is 0, the two diffraction efficiency curves of TE polarization and TM polarization are very close.

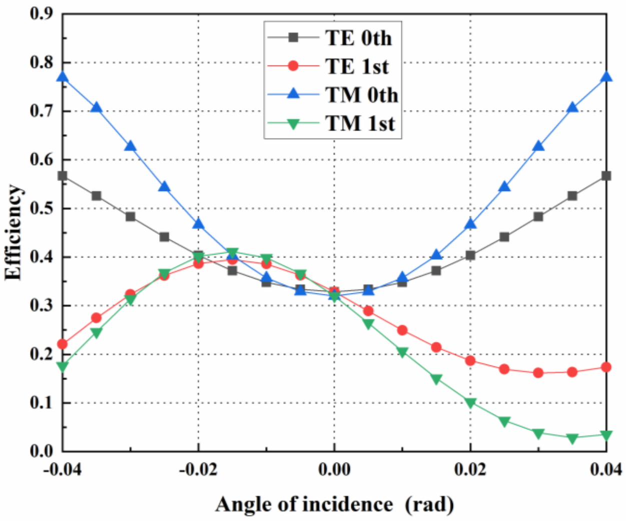


Fig. 4. The diffraction efficiency corresponding to the incident angle for the incident wavelength of 800 nm with the optimized grating profile parameters, where d=1.022 μm, f = 0.4, h_1=2.064 μm, h_2=2.700 μm, and h_3=2.780 μm (color online)

In addition, due to the influence of the processing technology, there will always be deviations in the actual process of making the grating, which will affect the actual parameters of the grating. To ensure that the total diffraction efficiency of the grating exceeds 90% while also ensuring good uniformity at the same time. It is necessary to study the influence of grating structure parameters on diffraction efficiency. Fig. 5 shows the relationship between the grating period and diffraction efficiency. It can be seen from the figure that for TE polarization when the grating period is between 1018 nm and 1026 nm, the diffraction efficiencies of the zero-order and the first-order are more than 30%. For TM polarization, when the grating period is between 1010 nm and 1026 nm, the diffraction efficiencies of the zero-order and the first-order are more than 30%. Fig. 6 shows the relationship between the duty cycle of the grating and the diffraction efficiency. It can be seen from the figure that the duty cycle also has a great impact on the diffraction efficiency. When the duty cycle is between 0.36-0.41, the zero-order and first-order diffraction efficiencies are still more than 30% for TM polarization. When *f*=0.4, the diffraction efficiency of the grating is the best. The thickness of each layer of the grating ridge will also affect the diffraction efficiency. Fig. 7 shows the relationship between the thickness of each layer of the grating ridge and the diffraction efficiency. It can be seen from the figure that for TM polarization, the range of diffraction efficiency over 30% is larger than that of TE polarization.

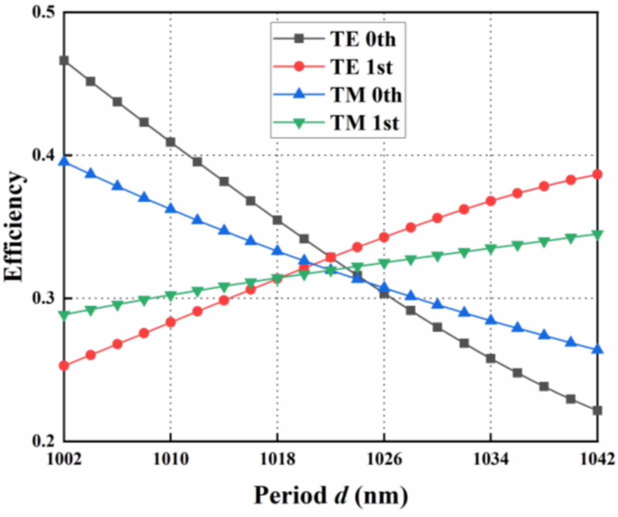


Fig. 5. The efficiency corresponding to period under normal incidence, where f=0.4, h_1= 2.064 μm, h_2= 2.700 μm and h_3=2.780 μm (color online)

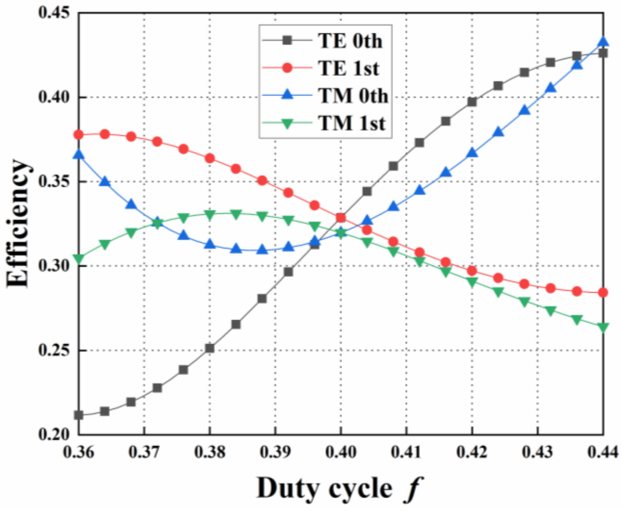
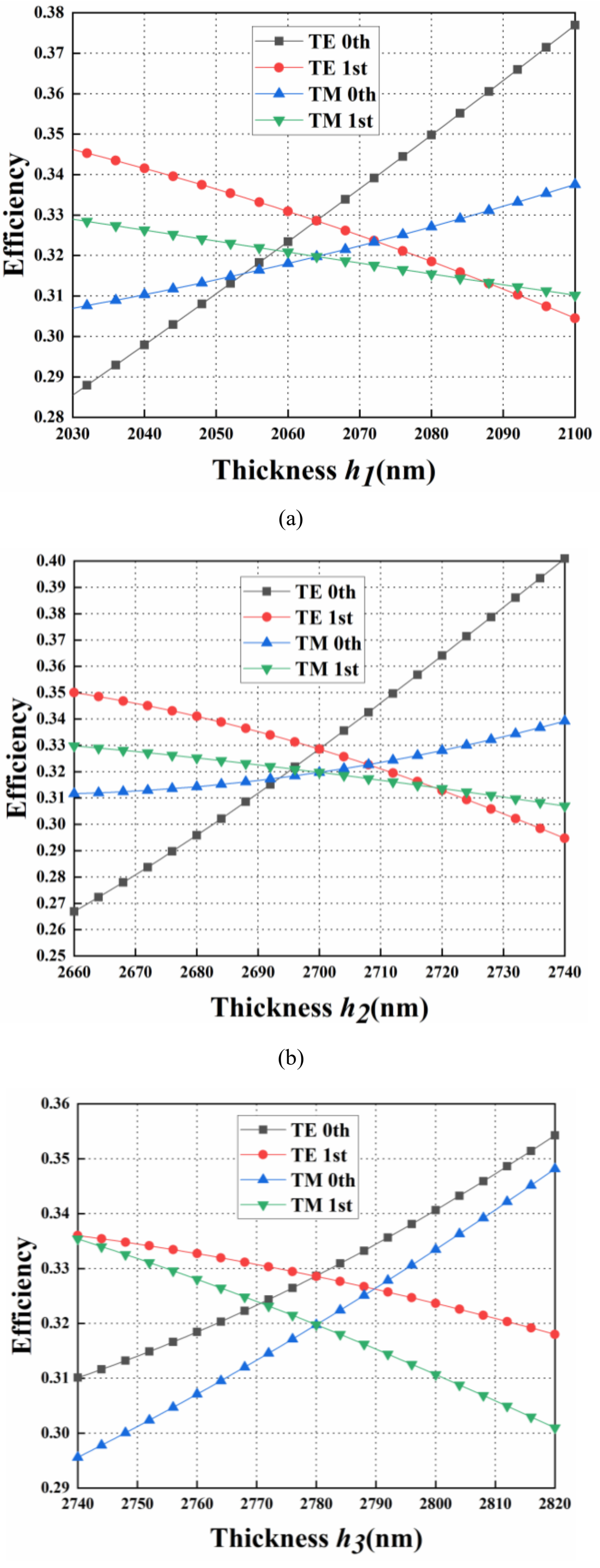


Fig. 6. The efficiency corresponding to duty cycle under normal incidence, where d= 1.022 μm, h_1= 2.064 μm, h_2= 2.700 μm and h_3=2.780 μm (color online)



(a)

(b)

(c)

Fig. 7. Efficiencies in orders for the grating versus thicknesses of the grating ridge under normal incidence with λ=800 nm, period d=1.022 μm, and duty cycle f=0.4: (a) thickness h_1, (b) thickness h_2, (c) thickness h_3 (color online)

4. Conclusion

A transmission three-layer grating splitter with high diffraction efficiency and good uniformity is proposed in this paper. The optimal parameters of the grating are calculated by rigorous coupled wave analysis and simulated annealing method, and the results are verified by finite element method to ensure the accuracy of the parameters. For TE polarization, the diffraction efficiencies of 0th order and ±1st order are more than 30%, which are 32.87% and 32.86%, respectively. For TM polarization, the diffraction efficiencies of 0th order and ±1st order are 31.98%. At the same time, the influence of incident light characteristics and grating structure parameters on the diffraction efficiency of the grating is also analyzed. The results show that the grating has high diffraction efficiency. The total diffraction efficiency is 98.59% under TE polarization and 95.94% under TM polarization. At the same time, the uniformity is very close to 100%, 99.4% under TE polarization and 99.9% under TM polarization. Finally, the influence of the thickness of each layer of the grating ridge on the diffraction efficiency is discussed.

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