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Minus second-order reflector by bullet-alike grating

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A polarization-independent bullet-alike reflection grating under second Bragg incidence is proposed, which can diffract the energy of TE-polarized light and TM-polarized light to -2nd order. Structural parameters can be obtained by using the finite element method, where efficiencies are 96.66% under TE polarization and 96.39% under TM polarization. Diffraction efficiencies of greater than 92% can be obtained in a 100 nm bandwidth (from 2710 to 2810 nm) for the -2nd order of both TE- and TM-polarized waves. After analysis, the grating has a large manufacturing tolerance and will have a good application prospect in the optical communication industry.

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1. Introduction

Periodic structures [1-5] can be diffractive optical elements [6-8], which modulate the amplitude and phase of incident light waves, and have high diffraction efficiency. Due to the fact that the grating can realize multiple functions such as polarization dispersion, beam splitting and phase, it has great application prospects in ultra-short [9-11], high-power laser system [12-15], polarizer [16-19] and terahertz element [20,21]. Many researchers have done a lot of research work for the application prospect of grating. High-efficiency polarization-independent diffraction was designed by transmission grating with a connecting layer. High efficiencies of 99.21% for TE polarization and 99.12% for TM polarization can be achieved with the optimized grating parameters [22]. *Sun et al.* designed unified beam splitter of fused-silica grating under the second Bragg incidence. By using the simplified modal method and rigorous coupled-wave analysis, theoretical results show that it is relatively easy for TM polarization to achieve high diffraction efficiency (>97%) while keeping the splitting ratio in the acceptable error region for a comparatively large tolerance of the duty cycle and relative depth [23]. *Cao et al.* designed high-efficiency polarization-independent wideband multilayer dielectric reflective bullet-alike cross-section fused-silica beam combining grating. The diffraction performance of the -1st order under different grating ridge structures is studied. Through testing the performance of the manufactured grating, it is verified that the grating is indeed feasible [24]. Modal method and rigorous coupled-wave analysis have been used to optimize the grating to achieve single-order high-efficiency transmission under Littrow mounting. The grating in this paper realize single-order efficient reflection function under second Bragg incidence by the finite element method. Compared with reported Ref. [24], planar light with a wavelength of 1550 nm is incident on the grating, and the grating reflects the energy of TE- and TM- polarized light into the -2nd order efficiently.

The method used in this paper to analyze the grating is the finite element method [25-29], which has the advantages of high efficiency and convenience in solving the problems of physical coupling and complex geometric structures. The finite element method divides the constructed model into finite, non-overlapping small units, and uses the variational principle to solve the equations, which greatly improves the accuracy of results. Its accurate calculation results provide theoretical support for grating analysis. After optimization by the finite element method, the diffraction result of the bullet-alike grating is obtained. The diffraction efficiency of -2nd order under TE polarization is 96.66%, and the diffraction efficiency under TM polarization is 96.39%. Analyzing the tolerance of the grating, within the bandwidth of 100 nm, the efficiency of -2nd order can be maintained above 92%.

2. Numerical design by the finite element method

Fig. 1 is a three-dimensional schematic diagram of the grating. It can be clearly seen from the Fig. 1 that the grating consists of three parts: the grating ridge, the Ag reflective layer, and the substrate. The material used for the substrate is fused silica, the height of the silver layer is expressed as h_3, and its height is 100 nm. The grating ridge of this grating is designed in the shape of a bullet head, the refractive index of the grating ridge is 1.45, and the groove is air with a refractive index of 1.00. The lower part is a rectangle, and its height is h_2. The upper part is trapezoidal, and its height is h_1, the width of the upper bottom is represented by a, and the width of the bottom is consistent with the width of the rectangle, represented by b. Based on the simulation of finite element method, the period d is set to 2780 nm. The duty ratio f_1 is expressed as b/d, and its value is 0.69. The duty ratio f_2 is expressed as a/d, and its value is 0.60. The heights h_1 and h_2 of the grating ridges are 0.76 μm and 1.7 μm, respectively. There are only three reflection diffraction orders which is 0th order, -1st order and -2nd order under second Bragg incidence when the grating period d is between λ and 2λ, where λ represents the wavelength of incident light. The polarization results of the grating are as following Table 1. Under TE polarization, the diffraction efficiencies of 0th, -1st, and -2nd orders are 0.006%, 0.006%, and 96.662%, respectively. Under TM polarization, the diffraction efficiencies of the 0th, -1st, and -2nd orders are 0.005%, 0.029%, and 96.394%, respectively. Part of the energy of TE- and TM-polarized waves is lost in the Ag reflective layer. From the diffraction results, most of the energy of the polarized light is reflected into the -2nd order, thus realizing the single-channel diffraction function of the grating.

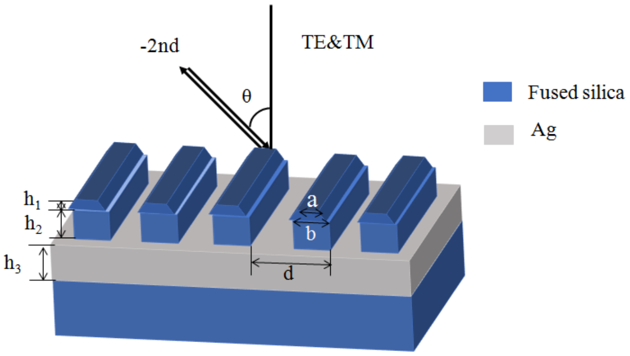
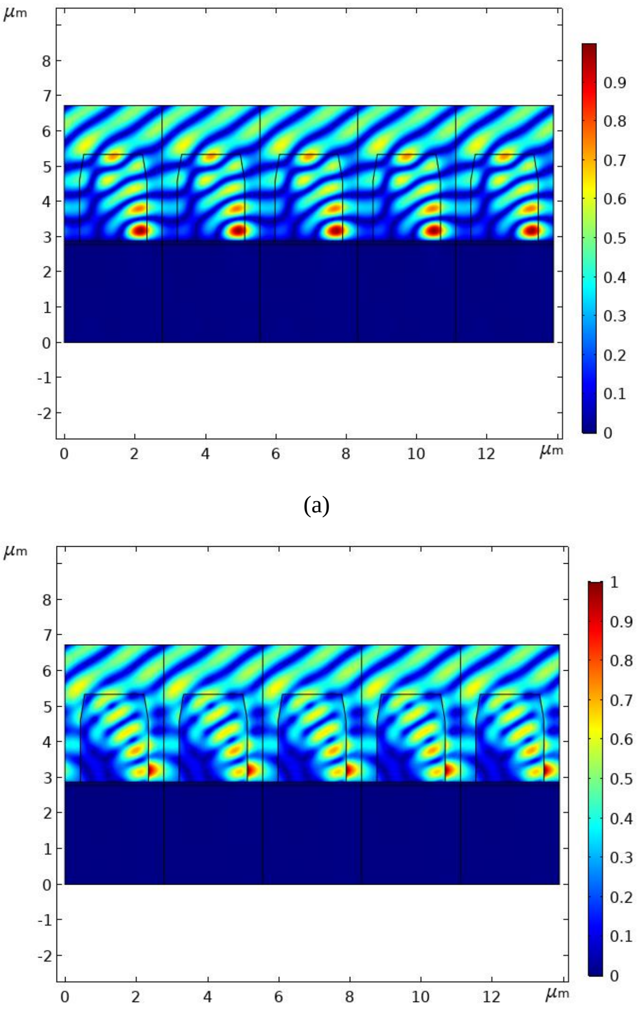


Fig. 1. The three-dimensional schematic diagram of the grating under second Bragg incidence at an incident wavelength of 1550 nm (color online)

Table 1. Diffraction efficiencies of bullet-alike grating with d=2780 nm, f_1=0.69, f_2=0.60

	h_1/μm	h_2/μm	-2nd	-1st	0th
TE	0.76	1.70	96.662%	0.006%	0.006%
TM	0.76	1.70	96.394%	0.029%	0.005%

After the grating model is established, based on the finite element method, the normalized electric field diagram is obtained [30]. A beam of polarized light with a wavelength of 1550 nm enters the grating under second Bragg incidence. Under TE polarization, energy is transmitted inside the grating layer, reaching a peak at the bottom right end of the grating ridge, and then reflected by the Ag layer out of the grating. Under TM polarization, since the light irradiates the grating at the second Bragg angle, the distribution of energy in the grating also shows an angle-related regularity.



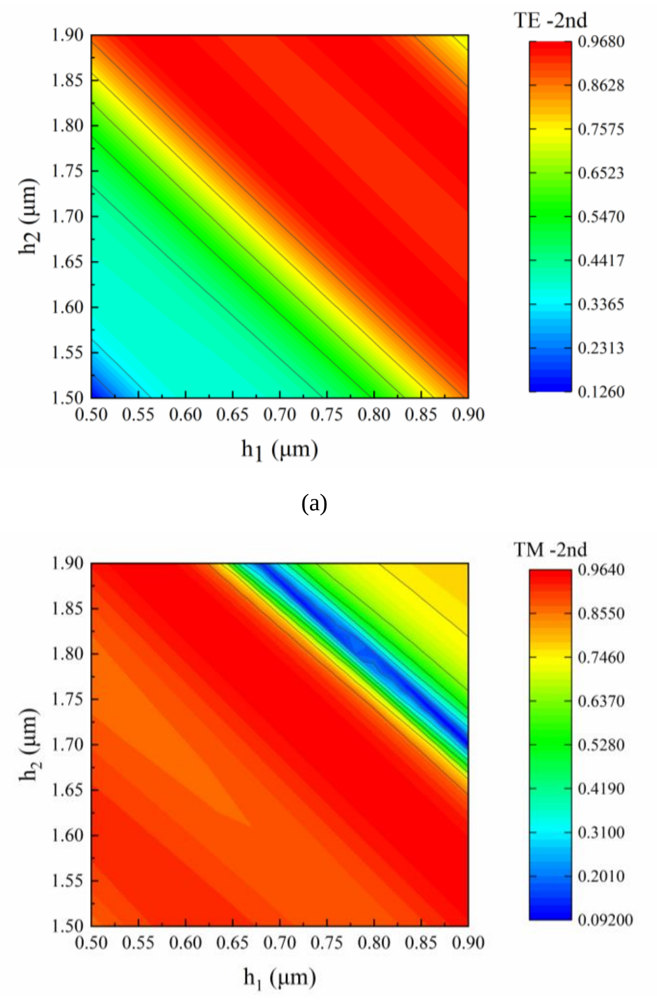
(a)

(b)

Fig. 2. Normalized field magnitude distribution of bullet-alike grating under second Bragg incidence for (a) TE polarization and (b) TM polarization (color online)

3. Results and discussion

In the process of grating being used, the diffraction efficiency is the most direct factor to judge the performance of the grating [31-35]. Next, the influence factors of the grating diffraction efficiency will be simulated and analyzed. Fig. 3 describes the changes in the diffraction efficiency of -2nd order under two polarizations when h_1 and h_2 are changed. When h_1 is in the range of 0.74-0.78 μm and h_2 is in the range of 1.68-1.74 μm, the efficiency of -2nd order is higher than 90%. When h_1=0.76 μm and h_2=1.7 μm, the grating produces a good single-order diffraction effect, and its diffraction efficiency is greater than 96%.



(a)

(b)

Fig. 3. Contour of the diffraction efficiencies of -2nd order versus groove depth h_1 and h_2 for (a) TE polarization and (b) TM polarization (color online)

In addition to the effect of the height of the grating layer, the period of the grating will also affect the diffraction efficiency. Therefore, the period is very important in the manufacturing process of the grating. Fig. 4 can clearly indicate the influence of the period on the diffraction efficiency. The fact that the reflection efficiencies of 0th order and -1st order under two polarizations are very close to 0% expounds the grating has a strong inhibitory effect on these two orders. The period is between 2710 nm and 2810 nm, and the diffraction efficiency of -2nd order under both polarizations is above 92%.

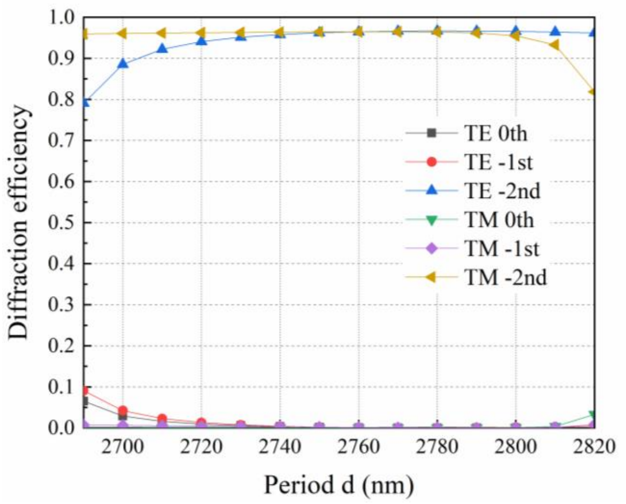


Fig. 4. The efficiency corresponding to the period with duty cycle f_1 of 0.69 and duty cycle f_2 of 0.60 (color online)

In the design of this grating, the incident light condition is that the wavelength is 1550 nm under second Bragg incidence. It is necessary for us to discuss the incident conditions. Fig. 5 shows the effect of incident angle on diffraction efficiency at three different wavelengths. When the wavelength is 1550 nm and the incident angle is in the range of 33.0-34.5°, the diffraction efficiency under the two polarizations is higher than 90%. When the wavelength is 1530 nm and the incident angle is in the range of 30.5-36.0°, the diffraction efficiency under TE polarization is higher than 90%. When the wavelength is 1570 nm and the incident angle is in the range of 32.5-36.5°, the diffraction efficiency under TM polarization is higher than 90%.

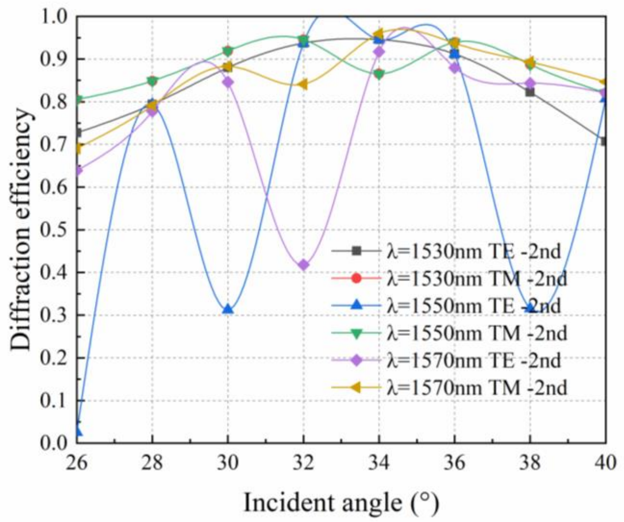
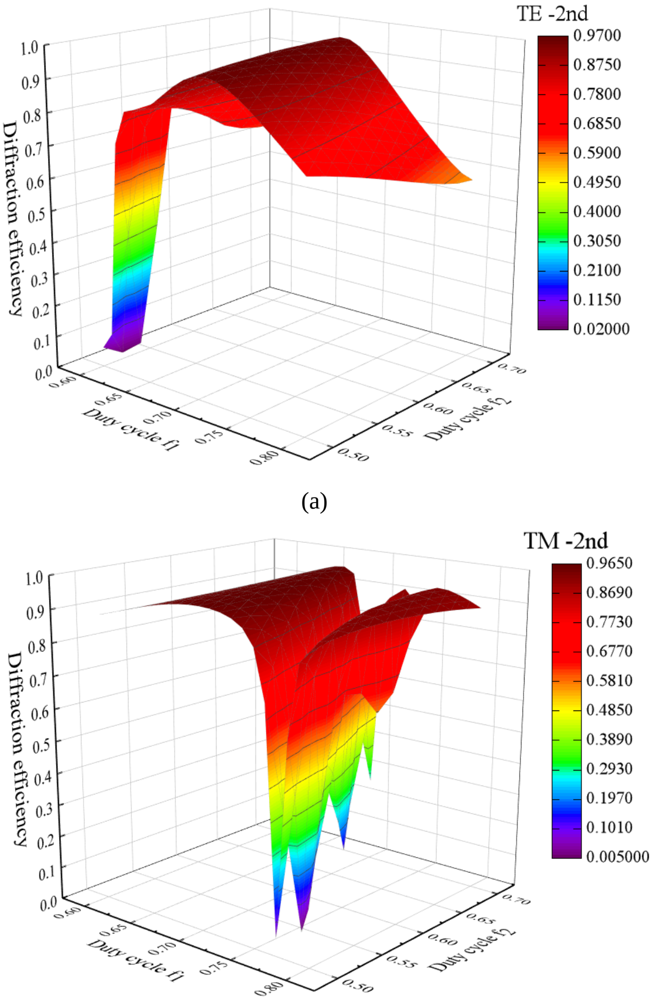


Fig. 5. The efficiency of -2nd order corresponding to the incident angle at three different wavelengths (color online)

For tolerance of duty cycle shown in Fig. 6, the reflection efficiency in each small area is clear at a glance. By filtering the data, when the duty ratios f_1 and f_2 are in the range of 0.67-0.71, 0.54-0.66, respectively, the reflection efficiency of the -2nd order under TE polarization is higher than 90%. When the duty cycles f_1 and f_2 are in the range of 0.62-0.69 and 0.50-0.68, respectively, the reflection efficiency of the -2nd order under TM polarization is higher than 90%.



(a)

(b)

Fig. 6. Contour of the diffraction efficiencies of -2nd order versus duty cycle f_1 and f_2 for (a) TE polarization and (b) TM polarization (color online)

4. Conclusion

In conclusion, a fused-silica bullet-alike reflection grating used in the -2nd order under second Bragg incidence is designed. Since the finite element theory has a more accurate and efficient simulation analysis on the grating ridge in the shape of the bullet-alike, the diffraction effect of the optimized grating can be obtained. The reflection efficiency of the -2nd order under TE polarization and TM polarization is 96.66% and 96.39%, respectively. The energy distribution inside the grating can be seen from the normalized electric field diagram. The paper also analyzes the incident characteristics and manufacturing tolerances of the grating. Diffraction efficiencies of greater than 92% can be obtained in a 100 nm bandwidth (from 2710 to 2810 nm) for the -2nd order of both TE- and TM-polarized waves. f_1 is in the range of 0.67-0.69, f_2 is in the range of 0.54-0.66, and the second-order reflection efficiency is above 90%. The results show that the grating has a large process tolerance, which indicates that the polarization-independent bullet-alike grating will have applications in many fields.

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