Terahertz reflective nine-channel beam splitter under normal incidence

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A terahertz reflection beam splitter with a simple grating ridge under normal incidence is depicted in this paper. At a terahertz frequency of 2.5200 THz (correspondingly the wavelength λ = 118.83 μm), the terahertz reflection splitter grating can achieve a nine-port separation and has an excellent total diffraction efficiency which can reach 99%. For transverse electric (TE) polarization, the incident wave can be diffracted into the 0th, ±1st, ±2nd, ±3rd and ±4th orders for 10.03%, 11.87%, 9.75%, 12.85%, and 10.23%, respectively. For transverse magnetic (TM) polarization, the total diffraction efficiency of the terahertz reflection splitter grating reaches 99%. Through additional analysis of the energy distribution and the parameter tolerance, it is clear that the grating exhibits exceptional beam-splitting characteristics and stability.

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1. Introduction

With the development of technology, the application of multi-channel beam-splitting gratings in the optical field is becoming increasingly widespread, such as optical components [1-4], filters [5-7], and sensors [8-13]. Additionally, because of the distinctive attributes of the terahertz spectrum (frequency range from 0.1 to 10 THz), terahertz optical devices have become more and more popular in fields such as terahertz imaging [14-18], communication [19-21], and fiber lasers [22-25]. Therefore, terahertz beam-splitting grating has gained significant attention from researchers. Jiao et al. proposed a polarization beam splitter, which can achieve polarization splitting of TE and TM modes in the frequency range from 0.8 to 2.4 THz, and the transmittance can be maintained above 85% [26]. Liu et al. presented a terahertz reflective beam splitter that can output three channels with an efficiency of over 30% in 2.5200 THz [27]. Wang et al. designed a broadband terahertz beam splitter and the beam splitter can achieve even transmission through eight ports at the frequency of 0.54 THz [28]. Lin et al. presented a set of polarization-dependent terahertz reflective beam splitters under normal incidence, which can achieve efficient output from two-port to seven-port [29].

To expand the application of terahertz beam splitters, a terahertz reflection beam-splitting grating with an excellent output of nine-port is presented in this paper. A simple single-layer grating structure is selected in this paper and through optimizing the grating period, thickness of the grating ridge, and grating ridge duty cycle, a terahertz reflection beam splitter with outstanding total diffraction efficiency can be found under normal incidence. For TE polarization, the diffraction efficiencies are as follows: 10.03% for the 0th order, 11.87% for the ±1st order, 9.75% for the ±2nd order, 12.85% for the ±3rd order, and 10.23% for the ±4th order. Under TM polarization, the corresponding diffraction efficiencies are 15.79%, 7.34%, 12.73%, 12.95%, and 8.77% for the 0th, ±1st, ±2nd, ±3rd, and ±4th orders. The total diffraction efficiency for both TE and TM polarizations exceeds 99%.

The analysis of the distribution of electric and magnetic fields reveals the energy distribution of the beam-splitting grating. This paper also conducts a tolerance analysis of this structure. The proposal of this nine-port terahertz beam splitter enriches the research of gratings in the terahertz frequency of 2.5200 THz.

2. Structural design and optimization

To make the grating more suitable for industrial manufacturing, the structure of the grating ridge is a simple single-layer grating as shown in Fig. 1. The material of the grating ridge is polyethylene with a refractive index n_1 of 1.52 [30]. The material of the reflective layer is Al whose refractive index n_m is 303.95-375.61*i and Si with a refractive index n_2 of 3.42 is selected as the substrate material [31,32]. The grating groove is filled with air with a refractive index n_0 of 1.00. The thickness of the grating ridge layer is defined as h_1 and the thickness h_m of the reflective layer is set to 0.1 μm, which is enough for reflection [33]. The period of this beam splitter is identified as d as depicted in Fig. 1 and the duty cycle of the grating ridge of the terahertz beam splitter is defined as f_1 which equals d_1/d, where the d_1 means the width of the grating ridge. Given that the incident light is perpendicular to the grating, the 1st/2nd/3rd/4th orders, as well as the -1st/-2nd/-3rd/-4th orders, exhibit perfect symmetry. As such, only the 1st/2nd/3rd/4th orders will be discussed in the subsequent paper.

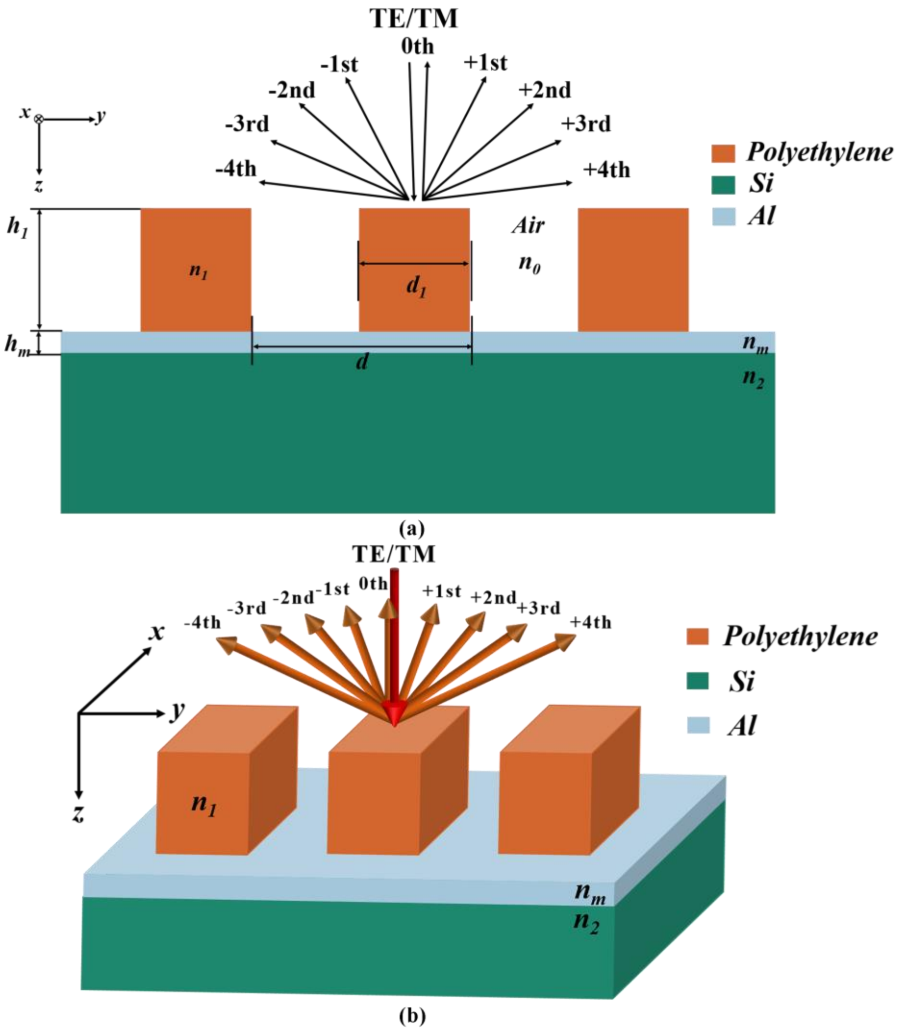

Fig. 1. The (a) two-dimensional and (b) three-dimensional schematic diagram of a nine-channel terahertz reflection beam splitter at normal incidence (color online)

The rigorous coupled-wave analysis (RCWA) [34, 35] and simulated annealing algorithm (SAA) [36, 37] can analyze and optimize the grating structure precisely. For the nine-port terahertz reflective beam splitter in this paper, the cost function which is also applicable to a beam splitter with (2N+1) ports can be expressed as follows:

$$\Phi = \frac{\sum_{i=-N}^{N}(I_i - I_{av})^2}{\sum_{i=-N}^{N} I_i}, \tag{1}$$

where the term I_i symbolizes the diffraction efficiency of the ith order, and I_{av} denotes the average efficiency for the (2N+1)-port beam splitter, given by:

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

The calculation of I_i is performed by the RCWA and the N equals 4 in this paper. Since the optimal parameters can be calculated by Eq. (1) for only one single polarization, to obtain the optimal parameters of the beam splitter for both polarizations, the cost function needs to be rewritten as:

$$\varphi = \frac{\varphi_{TE}+\varphi_{TM}}{2}, \quad (3)$$

where φ_{TE} and φ_{TM} are the cost functions for TE polarization and TM polarization, respectively.

The optimization parameters for the grating structure are acquired by minimizing the value of φ. In addition, to obtain a nine-port beam splitter, the grating period d and working wavelength λ should meet the following criteria, which have been pointed out in reference [38]:

$$4\lambda \leq d \leq 5\lambda. \quad (4)$$

At a terahertz frequency of 2.5200 THz whose wavelength is approximately 118.83 μm, the optimized structural parameters for the grating period, grating ridge thickness, and grating ridge duty cycle are presented in Table 1. Under these conditions, the diffraction efficiency of the grating at all orders is also shown in Table 1. It can be found that the grating exhibits excellent total diffraction efficiency for both polarizations.

Table 1. Parameters and diffraction efficiency of nine-channel terahertz reflective beam splitter after optimization

Diffraction Efficiency						
TE Polarization	4th	3rd	2nd	1st	0th	Total
	10.23%	12.85%	9.75%	11.87%	10.03%	99.43%
TM Polarization	4th	3rd	2nd	1st	0th	Total
	8.77%	12.95%	12.73%	7.34%	15.79%	99.37%

Structural Parameters					
Wavelength λ(μm)	**n_1**	**n_2**	**h_1(μm)**	**d(μm)**	**f_1**
118.83	1.52	3.42	901.8	516.3	0.22

To make the beam splitter more practical, further data analysis is conducted in this paper. The tolerance values of period d, duty cycle f_1, and grating ridge thickness h_1 are discussed emphatically. Moreover, due to the same diffraction efficiency as 1st/2nd/3rd/4th and -1st/-2nd/-3rd/-4th orders, in the following discussion, only 1st/2nd/3rd/4th orders of the reflection efficiency will be discussed. The thickness h_1 of the grating ridge is a factor that affects reflection efficiency.

As illustrated in Fig. 2, the reflection efficiency of each order differs depending on h_1. When h_1 falls within the range of 899.37 μm to 906.4 μm, the reflection efficiencies of the 0th, 1st, 2nd, 3rd, and 4th orders for both polarizations surpass 7%.

It is necessary to discuss the grating period d. Because the diffraction efficiency of each order will change if the value of grating period d alters. Fig. 3 shows the influence of the grating period on the reflection efficiency of the beam splitter grating under TE and TM polarization. When the grating period is in the range of 514.77 μm to 520.2 μm, the diffraction efficiencies of each order under both polarization conditions exceed 7%.

Besides, the diffraction efficiency of the terahertz reflective beam splitter will be affected by the width d_1 of the grating ridge and the influence of width d_1 can be transformed into duty cycle f_1. Therefore, the duty cycle has been further analyzed in the paper. As illustrated in Fig. 4, for TE polarization, the reflection efficiencies of the 0th, 1st, 2nd, 3rd, and 4th orders are greater than 7%, when the duty cycle f_1 changes between 0.214 and 0.221. For TM polarization, when the duty cycle is within the range of 0.216 to 0.223, the efficiency of each order exceeds 7%.

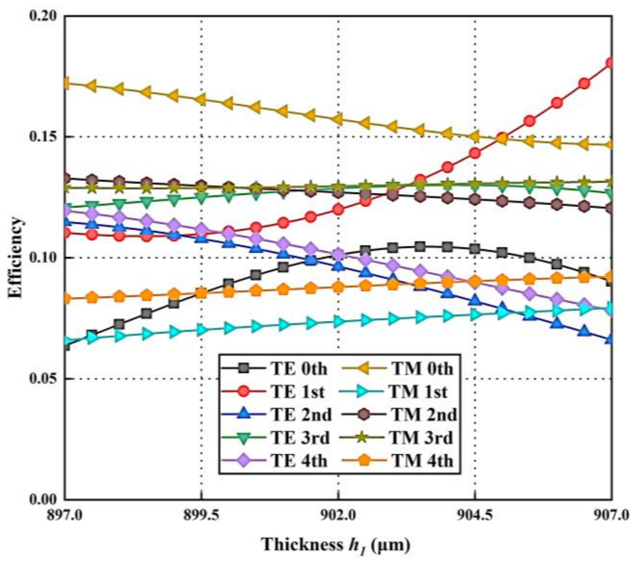

Fig. 2. The relationship between the efficiency of each order and the thickness h_1 of the grating ridge (color online)

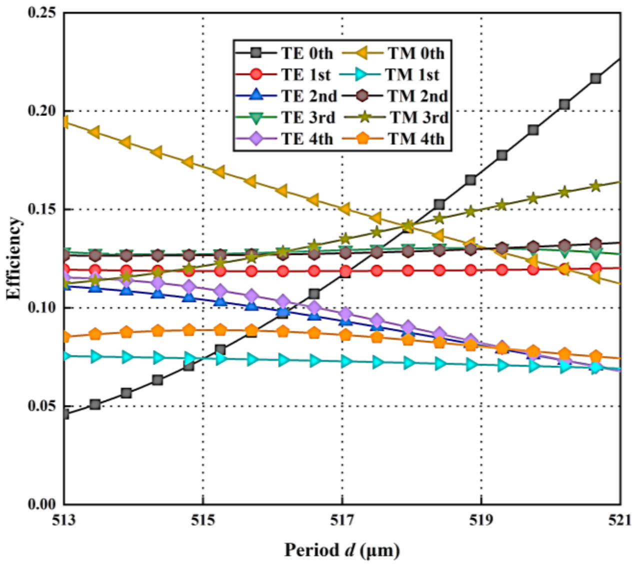

Fig. 3. The relationship between the efficiency of each order and the grating period d (color online)

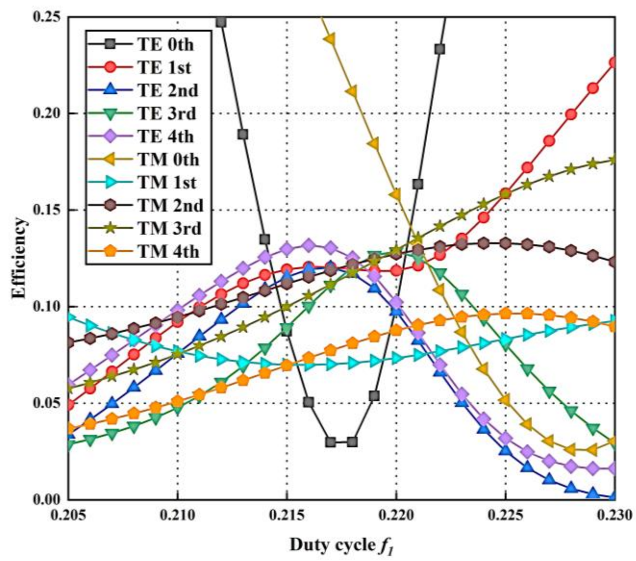

Fig. 4. The relationship between the efficiency of each order and the duty cycle f_1 of the grating ridge (color online)

3. Analysis and discussions

In order to visualize the energy inside the grating, it is necessary to obtain the electromagnetic field distribution of the grating in the paper. Firstly, due to the periodicity of the grating structure, Fig. 5 takes three grating periods as an example. In addition, the distribution of electromagnetic fields also exhibits periodicity and the energy distribution in Figs. 5 (a) to (f) is symmetrically distributed because of the normal incidence. As demonstrated in Fig. 5, which consists of six figures, Figs. 5 (a), (c), and (e) are the $|H_x|$, $|E_y|$, and $|H_z|$ components of the electromagnetic field distribution for TE polarization. Figs. 5 (b), (d), and (f) are the $|E_x|$, $|H_y|$, and $|E_z|$ of the electromagnetic field distribution for TM polarization, respectively.

For Fig. 5 (a), it is notable that the $|H_x|$ component of TE polarization exhibits a distinct feature: the energy distribution in the grating ridge is concentrated along the mid-line, contrasting the energy distribution on both sides. The energy distribution for the $|E_x|$ component of TM polarization and the $|H_y|$ component of TM polarization is similar to Fig. 5 (a) of the $|H_x|$ component of TE polarization, which is also mainly distributed at the mid-line of the grating ridge. For Fig. 5 (c), the $|E_y|$ component of TE polarization, the energy is evenly distributed in the grating ridge. Additionally, the energy distribution is mainly distributed on both sides of the grating ridge for the $|H_z|$ component of TE polarization. Similarly, the energy distribution for the $|E_z|$ component of TM polarization is the same as Fig. 5 (e) of the $|H_z|$ component of TE polarization.

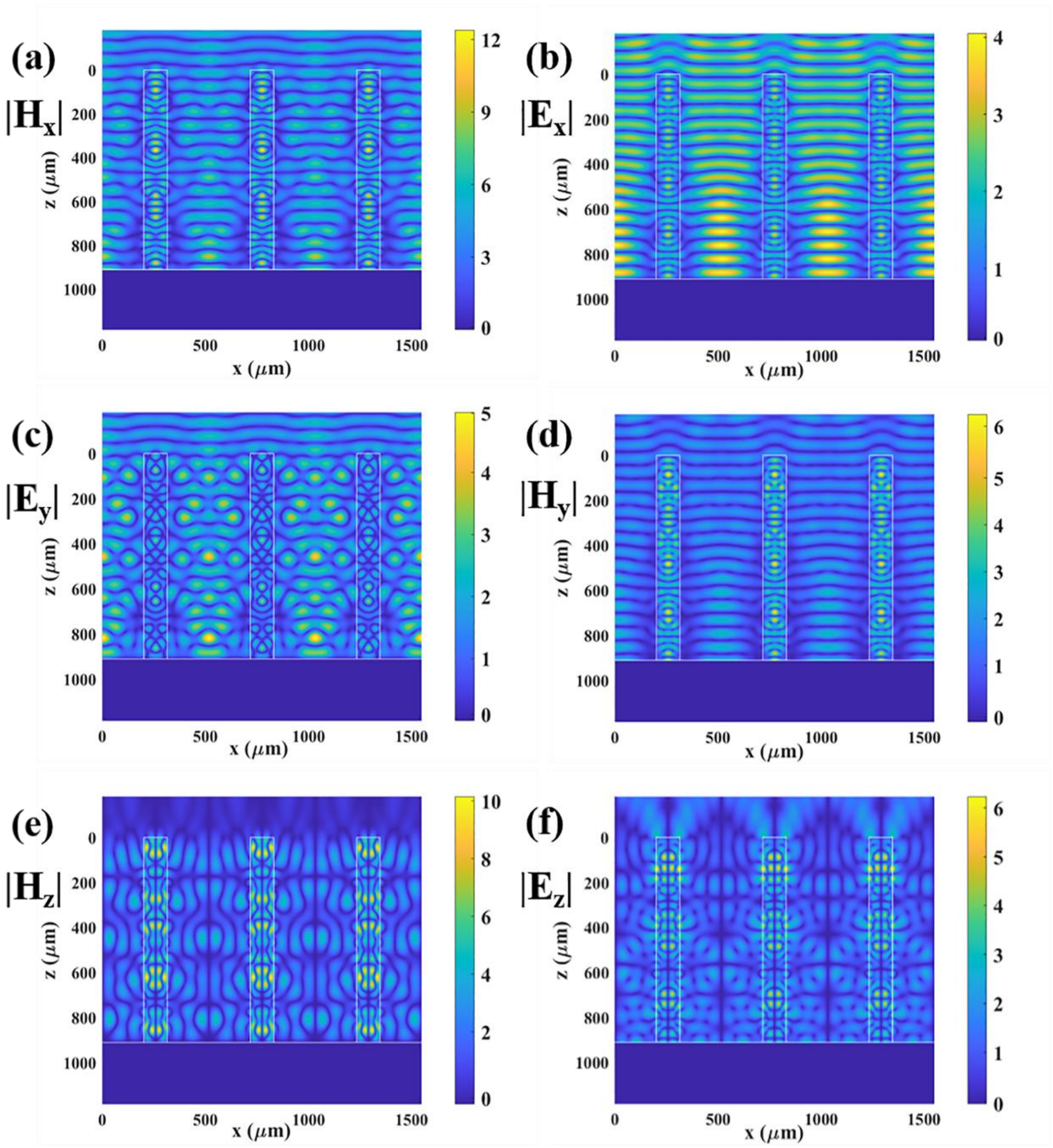

Fig. 5. The electromagnetic field distribution diagrams of (a) $|H_x|$, (c) $|E_y|$, and (e) $|H_z|$ components for TE polarization and (b) $|E_x|$, (d) $|H_y|$, and (f) $|E_z|$ components for TM polarization (color online)

The incident light frequency is 2.5200 THz whose wavelength λ is approximately 118.83 μm. However, in practical applications, the change of the wavelength λ has a significant influence on the grating performance. Therefore, the relationship between the wavelength λ of incident light and the diffraction efficiency of each order is presented in Fig. 6. When the incident wavelength λ changes between 118.43 μm and 119.05 μm, the reflection efficiencies under both polarizations are greater than 7% in the 0th, 1st, 2nd, 3rd, and 4th orders.

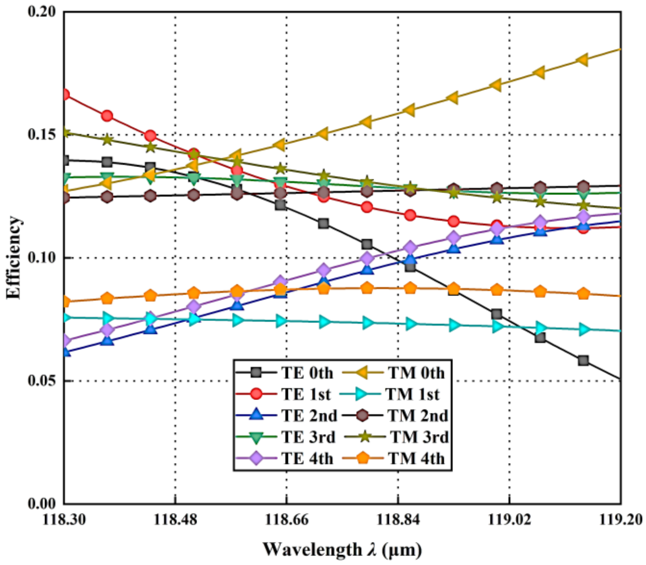

Fig. 6. The relationship between the efficiency of each order and the wavelength λ under normal incidence (color online)

4. Conclusion

In this paper, a terahertz reflection beam-splitting grating with a simple grating ridge is proposed. The optimization parameters of the grating are obtained through RCWA and SAA, and the terahertz reflection beam splitter can achieve a uniform and efficient output of 9 channels for TE polarization and TM polarization under these optimization parameters. Meanwhile, the structural parameters of duty cycle f_1, grating period d, and grating ridge thickness h_1 are further analyzed in Sec. 2. The results indicate that the grating has satisfactory tolerance performance. In Sec. 3, the electromagnetic field distributions of the incident light for both polarizations are presented. These analyses can assist with the design of a nine-port terahertz reflection beam splitter. In conclusion, the grating structure presented in this paper is simple and easy to fabricate. It is believed that the proposed nine-port beam splitter can guide the future manufacturing of nine-channel gratings in the terahertz frequency of 2.5200 THz with similar structures.

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