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Reflective terahertz tunable polarization controller*

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This paper proposes an optical device which can continuously change the polarization state of terahertz (THz) waves. The device consists of metal gate, anti-reflection coatings, liquid crystal and mirror. By changing the refractive index of liquid crystal in the interface between the metal gate and the mirror, the phase difference between two beams with orthogonal polarization is varied and a continuous phase shift is achieved. The phase shift of the device is calculated by using the finite difference time domain (FDTD) method, and the transmittance and reflectance are calculated by using the rigorous coupled wave analysis (RCWA) method. The results reveal that the structure can realize continuously tunable phase shift for THz wave at 1 THz.

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Terahertz (THz) technology has broad application prospects in biotechnology[1], spectroscopy[2], imaging[3], security[4] and other fields. The traditional THz quasi-optical devices, such as metal grid polarizer[5] and quartz wave plate[6,7], only have one function, and cannot be conveniently tuned nor integrated. Saito et al[8] achieved polarization switching function in the infrared band (2−11 μm) by changing the refractive index of liquid crystal in the middle of two high-resistivity silicon prisms according to the variations of external electronic field. Hsieh et al[9] achieved the tunable phase control by using the electronic field to vary the refractive index of liquid crystal layers between the fused silica. Wu et al[10] designed a THz switch controlled by magnetic field using the hollow Bragg fiber. Chen et al[11] designed a magnetron tunable phase shifter using the liquid crystal birefringence. The devices mentioned above are all transmission type, and they are unable to meet the needs for reflective THz applications.

The study of polarizer based on the metal gate structure has been reported. Zhao et al[12] designed a metal gate polarization splitter based on the effective index theory. This splitter reflects TE wave and transmits TM wave near 1550 nm, and the transmission extinction ratio is larger than 64 dB. J. J. Kuta et al[13] analyzed and calculated the transmission of metal gate based on different substrates in the visible and infrared ranges according to the rigorous coupled wave analysis (RCWA) theory. However, the above devices reported in the literature cannot be tuned. For applications of the terahertz technology, multifunctional and tunable devices can not only reduce the number of devices in system and reduce the insertion loss, but also extend the applications of the system. So the study of tunable devices is crucial for the development of the THz application technology.

This paper designs a THz quasi-optical polarization device which can be regulated continuously. It mainly consists of metal grid polarizer, liquid crystal and metal mirror. To realize tunable phase shift in the range of 0−2π, the refractive index of liquid crystal between the metal gate and metal mirror is continuously changed by the external electric field, so the phase difference between the two beams of the cross-polarized light is changed. This device uses the reflective structure, which is simple and easy to realize.

The structure of the polarization controller is shown in Fig.1. The high-purity silicon substrate forms the metal gate through ultraviolet lithography, metal deposition and metal stip. One germanium layer, which is below high-purity silicon layer, forms the anti-reflection coating together with the silicon layer. The liquid crystal material E7 is pressurized between two parallel copper electrodes. The liquid crystal is packaged by metal mirror together with copper electrodes. The metal gate cycle is much smaller than the wavelength (300 μm) of incident light. When one beam of THz wave propagates along the z direction, it splits at the metal gate. The TE wave (electric field in the y direction) is reflected, and TM wave (electric field in the x direction) is transmitted. The phase delay of TM wave can be controlled by adjusting the refractive index of liquid crystal, and a desired phase difference

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between two cross-polarized beams can be obtained.

The phase of TE and TM waves is detected in the same position, and the phase difference is:

$$\delta = \delta_0 + \frac{4\pi}{\lambda} dn \ , \tag{1}$$

where n is the refractive index of liquid crystal, d is the thickness of liquid crystal layer, and δ_0 is the phase difference between TE component and TM component of the incident light at the entrance. The refractive index n is changed continuously by adjusting the phase difference. Taking derivative to Eq.(1), we can obtain the change of phase difference at the exit point

$$\Delta\delta = \frac{4\pi}{\lambda} d\Delta n \ . \tag{2}$$

When $\Delta n=|n_o - n_e|$, $\Delta\delta$ is the phase tuning range of the device.

In this paper, the birefringence material is nematic liquid crystal E7. When we choose d = 468.75 μm and d = 937.50 μm, 180° and 360° phase delays can be achieved, respectively.

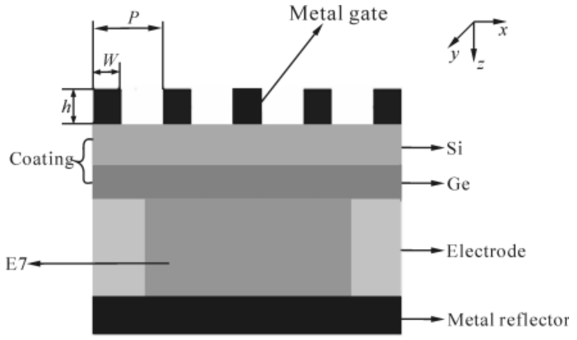
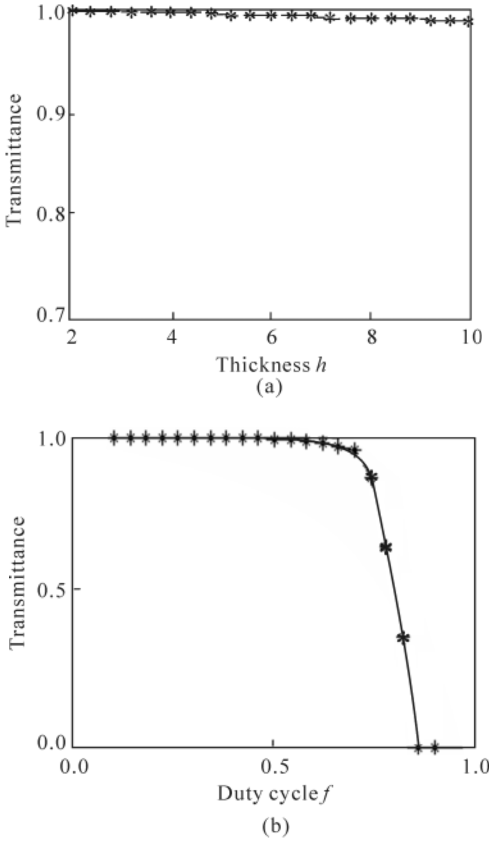


Fig.1 Top view of the THz tunable phase retarder

In this paper, the transmission characteristics of the aluminum gate are calculated using the RCWA theory. When the cycle of the metal gate is much smaller than the incident wavelength, the influence of the variation of cycle P on polarization extinction ratio can be ignored. The transmittance of TM wave decreases with the metal gate thickness h increasing, and also decreases with the increasing of duty cycle f ($f=W/P$), as shown in Fig.2. But the TE wave is almost unaffected. When the cycle of the metal gate is P=10 μm, the distance between two electrodes is 3 μm, the duty cycle is f< 0.4, and the thickness is h < 5 μm, the polarizer works better.Thus, the transmission polarization extinction ratio is $\rho_P=10\lg(T_{TM}/T_{TE})$ = 22.86 dB.

We use the anti-reflection coating structure to enhance the transmittance of TM wave, as shown in Fig.3.



(a)

(b)

Fig.2 Influence of metal gate on the TM wave transmittance: (a) The relationship between transmittance and thickness; (b) The relationship between transmittance and duty cycle

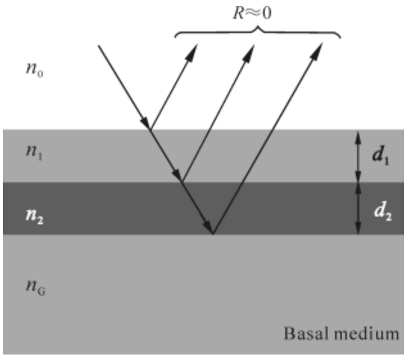


Fig.3 AR coating

We take the thicknesses of Si and Ge as d_1=22 μm and d_2=1875 μm, respectively. The range of the liquid crystal's refractive index is 1.62−1.78. The reflectivity is about 1% according to the calculation and the absorption coefficient of Si and Ge to electromagnetic wave near 1 THz is tiny[14-16], so the absorption loss can be neglected.

Using manual processing methods to control the liquid crystal orientation surface is called surface anchoring. Surface anchoring in different ways will produce different surface arrangements[17]. The methods commonly used are polyimide (PI) friction method and ultraviolet orientation method. Both methods can make the liquid crystal orientation parallel to the surface. When there is an electric field, the orientation of liquid crystal molecules will align along the electric field lines.

The material used in this paper is the nematic liquid crystal E7. The orientation of the liquid crystal molecules tends to the direction of y. When the electric field is applied in the x direction, with the voltage increasing, the director of liquid crystal rotates from y-axis to x-axis, and the refractive index changes from n_o to n_e. The effective refractive index $n_z(\theta)$ of the liquid crystal is determined by the following equation

$$\frac{1}{n_z^2(\theta)}=\frac{\sin^2(\theta)}{n_e^2}+\frac{\cos^2(\theta)}{n_o^2} , \tag{3}$$

where θ is the torsional angle of liquid crystal molecules, which is controlled by voltage, and n_e=1.79 and n_o=1.62 are the refractive indices of liquid crystal for extraordinary and ordinary lights, respectively.

According to the elastic deformation theory of liquid crystal continuum[18], with external electric field, the director of liquid crystal changes from the original equilibrium to another equilibrium through splay, twist and bend. To obtain the distribution of the director of liquid crystal molecules under external electric field[19], Wang et al used differential iteration method[20] for calculating the Freedericksz change. Wu et al[21] used the finite element method for calculating the variation of the director of 5CB liquid crystal with voltage variation.

The changes of refractive index of liquid crystal are calculated based on Kahn's theory[22]. Birefringence of liquid crystal depends on voltage variation. The threshold voltage can be expressed as

$$v_{\rm th}=\pi\frac{L}{d}\left(\frac{k_3}{\varepsilon_a\varepsilon_0}\right)^{\frac{1}{2}} , \tag{4}$$

where L is the distance between electrodes, and d is the thickness of liquid crystal layer. k_3=17.1 pN is the bending elastic constant, and ε_a=13.8 is dielectric anisotropy of liquid crystal. According to Eq.(4), the threshold voltages are 7.5 V and 3.75 V for d=468.75 μm and d=937.50 μm, respectively.

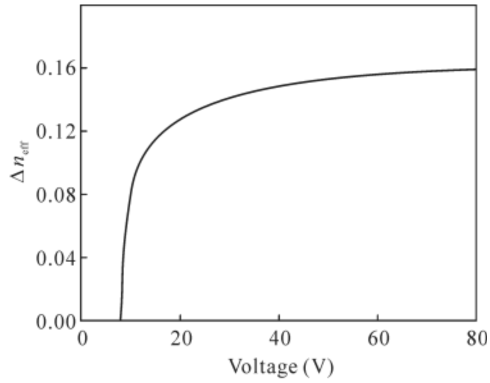
For $0< v-v_{\rm th}< v_{\rm th}$, the changes of effective refractive index of liquid crystal can be expressed as

$$\Delta n_{\rm eff}(v)=(n_e-n_o)\frac{n_o}{n_e}\left[\left(1+\frac{n_o}{n_e}\right)\left(\frac{v-v_{\rm th}}{v_{\rm th}}\right)\right] , \tag{5}$$

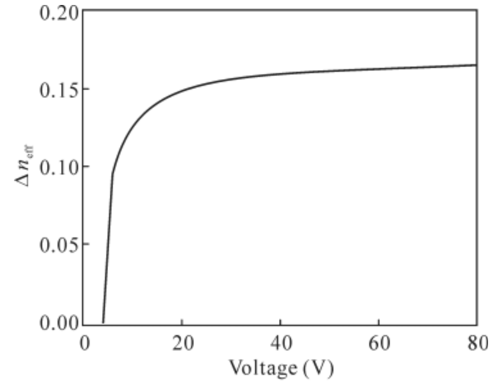
and for $v-v_{\rm th}> v_{\rm th}$,

$$\Delta n_{\rm eff}(v)=(n_e-n_o)\left[1-\frac{2}{v}\left(\frac{k_3}{\varepsilon_a\varepsilon_0}\right)^{\frac{1}{2}}\frac{L}{d}\right] . \tag{6}$$

The relationship between the changes of refractive index of liquid crystal and voltages is shown in Fig.4. When the voltage increases from the threshold voltage to 80 V, the refractive index of liquid crystal changes from 1.62 to 1.78.



(a) d=468.75 μm



(b) d=937.50 μm

Fig.4 Relationship between refractive index of liquid crystal and voltage

Thus, after reflection by the device, the variation of phase difference between TM and TE wave is

$$\Delta\delta=\frac{4\pi}{\lambda}d\Delta n_{\rm eff}(v) . \tag{7}$$

Since $\Delta n_{\rm eff}$ changes from 0 to 0.16, the device with the thickness of liquid crystal d = 468.75 μm can achieve a continuous phase change of 180° for a beam of wave at 1 THz frequency. When d = 937.50 μm, it can achieve a continuous phase change of 360°.

Using RCWA, we calculate the relationship between the reflectivity of TM wave and the refractive index of liquid crystal for normally incident TM polarized light, as shown in Fig.5. In the range of the refractive index of liquid crystal, the reflectivity of TM wave is close to 100%, which means the amplitudes of TM and TE waves at the front surface of device are approximately equal.

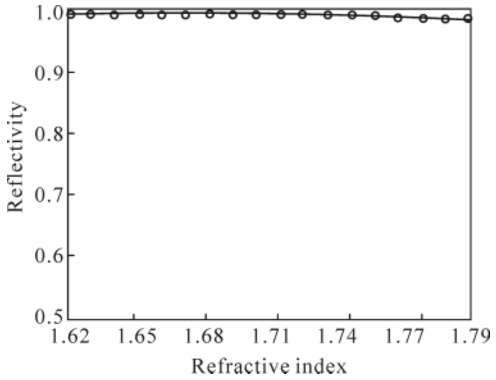
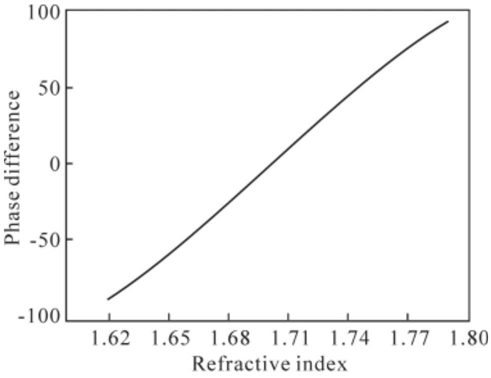
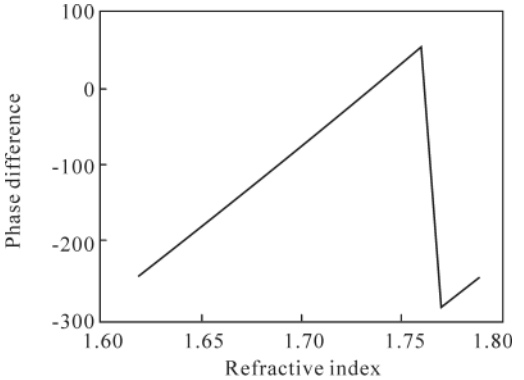


Fig.5 Reflectivity of TM wave versus refractive index of liquid crystal

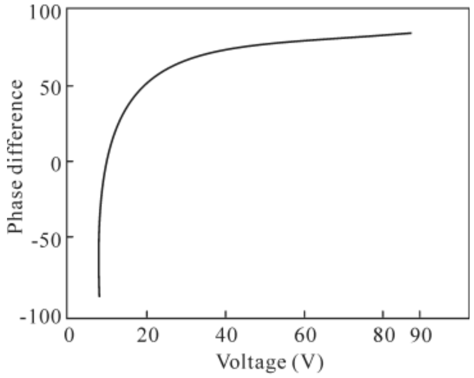
The phase delays of liquid crystal layers with different thicknesses are calculated using FDTD method. Fig.6 shows the phase difference between TE and TM waves under different thicknesses of liquid crystal layer. When *d* = 468.75 μm and voltage changes from 7.5 V to 80 V, the phase difference changes continuously from -86.9835° to 84.5369°, thus the range is 171.5204°. When *d* = 937.50 μm and voltage changes from 3.75 V to 80 V, the phase difference changes from -242.6865° to 116.1389°, and the range is 358.8254°. That is to say, by changing the strength of external electric field, continuously tuned polarization can be obtained.



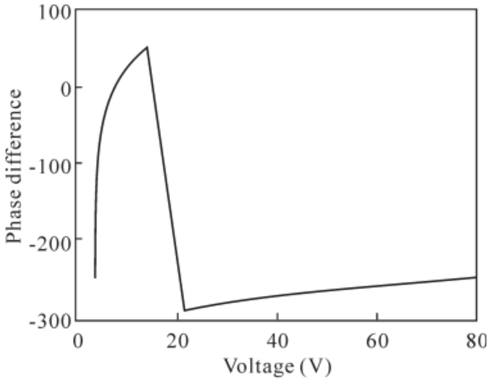
(a) Phase difference vs. refractive index for *d*=468.75 μm



(b) Phase difference vs. refractive index for *d*=937.50 μm



(c) Phase difference vs. voltage for *d*=468.75 μm



(d) Phase difference vs. voltage for *d*=937.50 μm

Fig.6 Dependence of phase difference between TE and TM waves on refractive index and voltage for *d*=468.75 μm and *d*=937.50 μm

In conclusion, a reflective THz polarization controller is designed. By changing the refractive index of liquid crystal, the phase difference between two orthogonally polarized beams is varied, and continuous phase shift is achieved. The phase shift of the device is calculated using FDTD method, and the transmittance and reflectance are calculated using RCWA method. The results show that this device can achieve continuously tunable phase shift from -86.9835° to 84.5369° and from -242.6865° to 116.1389° for the wave at 1 THz frequency.

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