Research Article

Terahertz broadband polarization converter based on the double-split ring resonator metasurface

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Abstract
A terahertz broadband polarization converter based on the metasurface of a double-split ring resonator is proposed. The structural parameters of this device have been optimized in numerical simulations. The results show that in the frequency range from 0.49 to 1.88 THz (bandwidth of 1.39 THz) the proposed device rotates incident linearly polarized waves through 90°. The polarization conversion rate is more than 80%. The coefficient of reflection for cross polarization is greater than 90% with a transmission loss of 1 dB. The surface current distribution of this structure was simulated and analyzed at three frequencies that give high conversion rates of the polarization. The mechanism underlying this high conversion rate is presented, and the dependence of the conversion rate on incident angle and polarization angle is stimulated and analyzed. The results show that the conversion performance of this device is good for incidence angles ranging from 0 to 30° and polarization angles ranging from − 10 to 10°. Compared with previous designs, the polarization converter has a simple structure and a broad operational bandwidth. It has potential applications in the field of terahertz polarization modulation.

Keywords Terahertz · Metasurface · Broadband · Double-split ring resonator · Polarization converter

1 Introduction

Terahertz technology has important applications in areas such as spectral analysis, [1, 2] imaging, [3, 4] safety inspection, [5, 6] and communication [7]. Most of the molecular vibration frequencies are in the terahertz band, so terahertz spectroscopy can be used as an important means of material recognition such as gunpowder, drug and so on. Terahertz waves have lower single-photon energy and are less damaging to biological cells, so they can be used in Human security field. Terahertz wave has a smaller wavelength and a wealth of spectrum resources, can be used as large capacity wireless communication field. The research on devices operating with terahertz waves, such as polarization converters, [8] filters, [9] and lenses, [10] is gradually garnering a lot of attention. In recent years, with the development of metamaterials, further research has been made on terahertz functional devices [11–13].

Our focus here is the polarization converter, which is a device that can alter the polarization state of an electromagnetic (EM) wave. Traditional polarization converters use dichromatic crystals or half-wave plates to alter the polarization state [14–16]. However, because of the specific characteristics of crystals, polarization devices have inherent drawbacks such as low conversion rates and narrow band widths. In contrast, with their artificially

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designed micro-structure units, metasurfaces can realize physical properties that natural materials cannot have that enable them to control the polarization and phase of EM waves [17–22]. Zhou and Yang proposed a bilayer chiral metamaterial that realizes cross polarization conversion and changes the resonance frequency by varying the structure of the unit [23]. Yong and co-workers proposed a reflective polarization converter with three adjacent resonance frequencies [24] . In the range from 0.65 to 1.45 THz, the reflected wave was orthogonally polarized at a polarization conversion rate of up to 80%. Wu and co-workers proposed a double-layer open-loop circularly polarized converter and analyzed its coefficient of transmission and surface current [25]. Li and co-workers proposed a Z-mode polarization converter with three resonance frequencies that can convert linear polarization to either cross polarization or circular polarization [26]. In the range from 0.44 to 0.76 THz, the polarization conversion rate of the reflected waves was up to 80%. In this paper, a terahertz polarization converter based on the hyper-surface of a double-open resonant ring is described that achieves an efficient polarization conversion over a wide band in the terahertz region of frequencies. When both incidence and polarization angles change in a certain frequency range, the converter maintains a high polarization transformation that offers a certain value in applications.

2 Designs and simulation

2.1 Structure design

The designed polarization converter consists of three layers (Fig. 1): the top layer is a resonant ring array structure made of gold, the intermediate dielectric layer is made of silicon dioxide, [27, 28] and the bottom layer is a metal plate. The geometric parameters of the unit structure are: $p = 100$ μm, $d_1 = 0.2$ μm, $d_2 = 44.5$ μm, $r_1 = 34.5$ μm, and $r_2 = 29.5$ μm. The electric field of the incident terahertz linearly polarized wave is along the *x* direction, and the wave vector *k* is directed in the negative direction of the *z* axis.

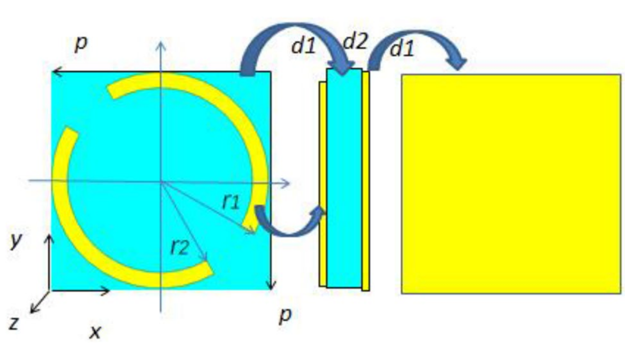

Fig. 1 Structural parameters of the polarization converter

2.2 Simulation results and analysis

The three-dimensional EM simulation software, CST MicroWave Studio Suite, was used to simulate this structure. Because of the anisotropy of the structure, the reflected wave has two polarization components: synclastic and cross. The ratio of the field magnitudes for the reflected polarized wave in the *x* direction and the incident polarized wave in the *x* direction is called the synclastic-polarization reflectivity, $r_{xx} = \frac{|E_{xr}|}{|E_{xi}|}$, corresponding to SZmax(2), Zmax(2) in the software. Similarly, the ratio of the field magnitudes for the reflected polarized wave in the *y* direction and the incident polarized wave in the *x* direction is called the cross-polarization reflectivity, $r_{yx} = \frac{|E_{yr}|}{|E_{xi}|}$, corresponding to SZmax(1), Zmax(2) in the software. Here, E_{xr} and E_{xi} denote the amplitudes of the reflected and the incident polarized waves along the *x*-axis respectively, and E_{yr} denote the amplitude of reflected polarized waves along the *y*-axis. The relationship between the polarization conversion ratio (PCR) and the phase difference of the reflected waves is

$$P_{PCR} = \frac{r_{yx}^2}{r_{xx}^2 + r_{yx}^2}, \quad (1)$$

$$\Delta\psi = \psi_{yx} - \psi_{xx}, \quad (2)$$

where ψ_{xx} (ψ_{yx}) denotes the phase of the reflected polarization terahertz wave from the *x* direction to the *x* (*y*) direction, and $\Delta\psi$ the phase difference between the *y*- and *x*-components of the wave.

The reflection characteristics of the double-opening resonant ring were simulated, and both coefficients of reflection r_{yx} and r_{xx} and the polarization conversion rate (PCR) were obtained (Fig. 2). The coefficient of reflection for cross-polarization r_{yx} is found to be within the frequency range of 0.49–1.88 THz (bandwidth of 1.39 THz) and has a value greater than 80%. The co-polarization and cross-polarization reflectance of the reflected wave can be obtained by the CST software, and then the phase difference of the reflected wave can be calculated according to Eq. (2). At the frequency of 0.4628 and 1.8974THz, the co-polarization reflectance and cross-polarization reflectance of the reflected wave are equal according to Fig. 2b, and the phase difference between the co-polarized and cross-polarized reflected waves is 90 degrees as shown in Fig. 3,

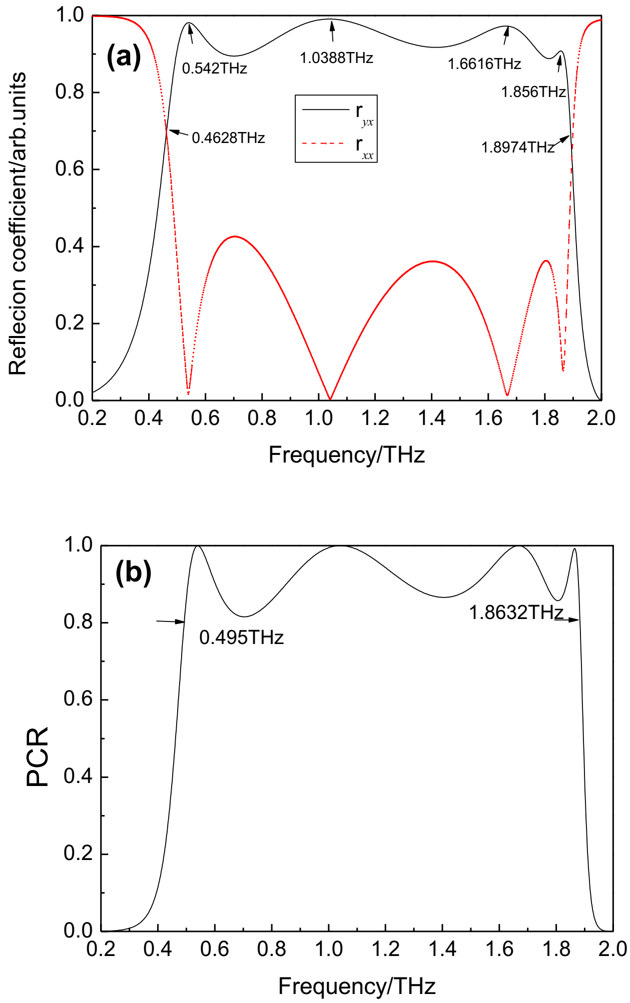

Fig. 2 **a** Reflectivity curves for cross and synclastic polarization r_{yx} and r_{xx}; **b** Polarization conversion rate of the polarization converter

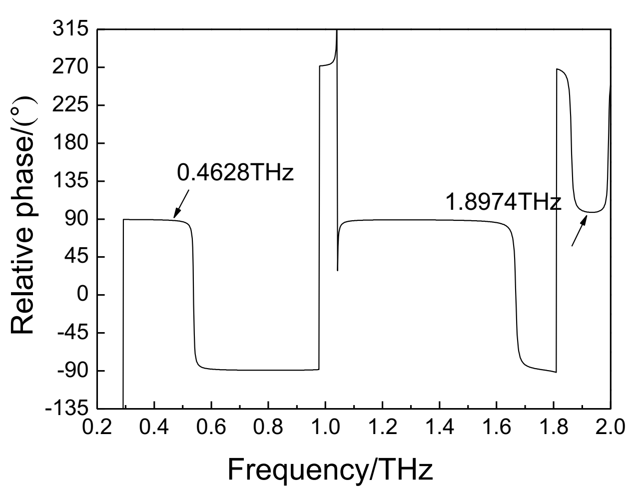

Fig. 3 Reflection phase difference of polarization converter

which indicate that linearly polarized waves are converted into circularly polarized waves.

3 Polarization conversion analysis

3.1 Symmetry analysis

To understand the mechanism underlying the polarization converter, certain coordinate transformations associated with specific symmetries help in the analysis. The coordinate plane formed by the x and y axes is rotated clockwise through 45° to obtain the u and v axes [Fig. 4a]. The polarization of an incident terahertz wave propagating in the y direction has two components corresponding to the u and v axes; its electric field is expressed mathematically as

$$\vec{E_i} = \frac{\sqrt{2}}{2}E_i e^{jkz}\hat{u} + \frac{\sqrt{2}}{2}E_i e^{jkz}\hat{v}, \tag{3}$$

The electric field of the reflected terahertz wave can be expressed as

$$\begin{aligned}\vec{E_r} = &\frac{\sqrt{2}}{2}[r_{uu}E_i e^{j(-kz+\varphi_{uu})} + r_{uv}E_i e^{j(-kz+\varphi_{uv})}]\hat{u} \\ &+ \frac{\sqrt{2}}{2}[r_{vv}E_i e^{j(-kz+\varphi_{vv})} + r_{vu}E_i e^{j(-kz+\varphi_{vu})}]\hat{v},\end{aligned} \tag{4}$$

where r_{ab} $(a,b=u,v)$ are the coefficients of reflection each defined as the ratio of the electric field magnitudes of the reflected polarized wave in the b direction and the incident polarized wave in the a direction, and similarly φ_{ab} denotes the phase difference between the same two waves.

The reflectivities associated with the two cross polarizations are almost 0. Therefore, the electric field of the reflected terahertz wave depends only on the two reflectivities of the synclastic polarization. Equation (4) then approximates to

$$\vec{E_r} = \frac{\sqrt{2}}{2}r_{uu}E_i e^{j(-kz+\varphi_{uu})}\hat{u} + \frac{\sqrt{2}}{2}r_{vv}E_i e^{j(-kz+\varphi_{vv})}\hat{v}, \tag{5}$$

with an associated phase difference of

$$\varphi_{diff} = \varphi_{uu} - \varphi_{vv} = \pi + 2k\pi (k \in z), \tag{6}$$

From the coefficients of reflection r_{uu} and r_{vv} calculated in the u–v coordinate system [Fig. 4b], the reflectivity for each synclastic polarization is above 95% with resonance peaks appearing at three frequencies 0.58 THz, 1.13 THz, and 1.69 THz. The phase difference for the terahertz waves incident along the directions u and v were calculated and plotted in

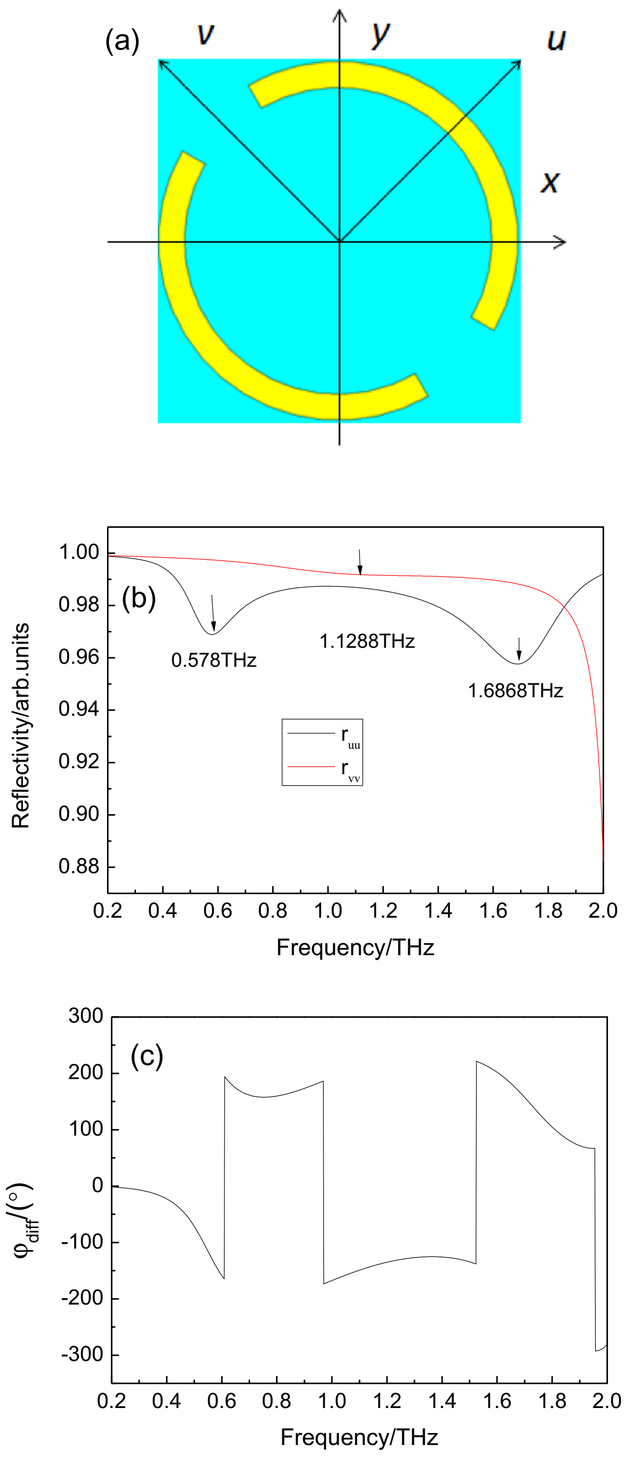

Fig. 4 **a** Definition of *u* and *v* axes; **b** Reflectivity of co-polarization; **c** Phase difference of co-polarization

Fig. 4c. Within the range 0.97 to 1.52 THz, the phase difference ranges from – 180° to – 140°, in which incident linearly polarized terahertz waves are converted into right-handed elliptically polarized terahertz waves. Within the ranges 0.61–0.97 THz and 1.52–1.96 THz, the phase difference ranged from 150 to 220°, in which incident linearly polarized terahertz waves are converted into left circularly polarized terahertz waves, with a phase transition occurring near the resonance points. This conforms with condition (6) in that the polarization direction of the reflected terahertz wave rotates 90°. The calculation shows that the polarization conversion rate of the polarization converter is over 90% in the range 0.49 to 1.88 THz.

3.2 Analysis of polarization conversion mechanism based on surface current

To understand the conversion mechanism of the polarization converter, a simulation analysis was performed concerning the current distribution of the top and bottom metal plates at the three resonance frequencies 0.58 THz, 1.13 THz, and 1.69 THz. Figure 5a–c shows the distribution of the surface current between the metal base plate and the double-open resonant ring element structure at these frequencies (Fig. 6).

In Fig. 5a and c, the incidence of the polarized terahertz waves is along the *u* axis; for Fig. 5a, the distribution of the surface current corresponds to the 0.58THz resonance frequency. In Fig. 5b, a double dipole resonance occurs at this point. Moreover, the current on the double-open resonant ring structure induces a reverse current on the bottom metal plate, forming a magnetic resonance. For Fig. 5c, the incidence of the polarized terahertz wave is along the *u* axis direction. From the surface current distribution at the resonance frequency of 1.69 THz, a double dipole resonance occurs. At the same time, the current on the double-opening resonant ring structure induces a syntropy current on the bottom metal plate, forming an electrical resonance.

Viewing the surface current distribution [Fig. 5b] at the resonance frequency of 0.58 THz generated when a polarized terahertz wave is incident along the *v* axis, a quadrupole resonance occurs. Again, the current on the double-split-ring resonator structure induces a reverse current on the bottom metal plate, forming a magnetic resonance. The resonant ring can be regarded as a *LC* resonant circuit. Let L_1, L_2, $L_{3,}$ and L_4 denote the equivalent inductance of each part of the split-ring resonator, and C_1 and C_2 the equivalent capacitance of the two openings of the resonant ring. The polarization converter now produces different reflected wave phases for the incident *u* and *v* polarized waves, and the phase difference of the reflected wave alters the polarization of the terahertz wave.

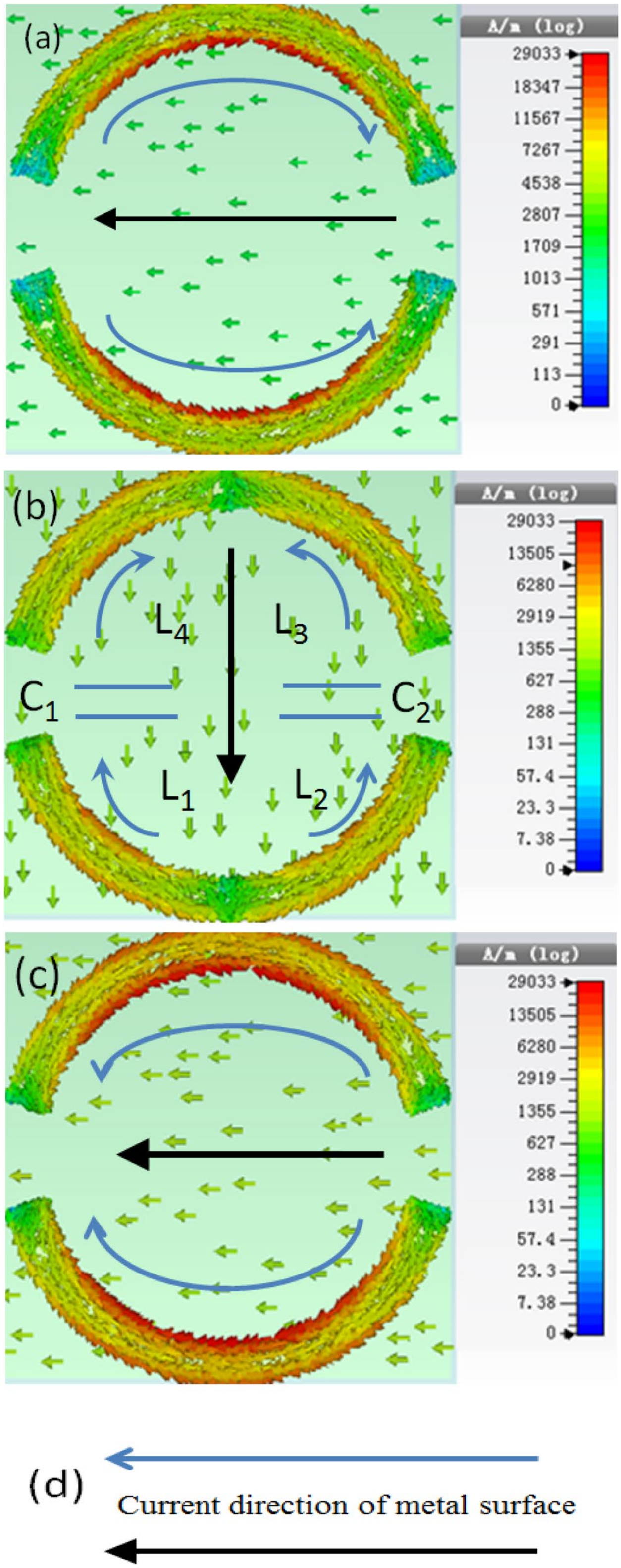

Fig. 5 Current distributions at the top and bottom metal plates at resonance frequencies: **a** 0.578 THz; **b** 1.1288 THz; **c** 1.6868 THz; **d** Illustration showing current directions

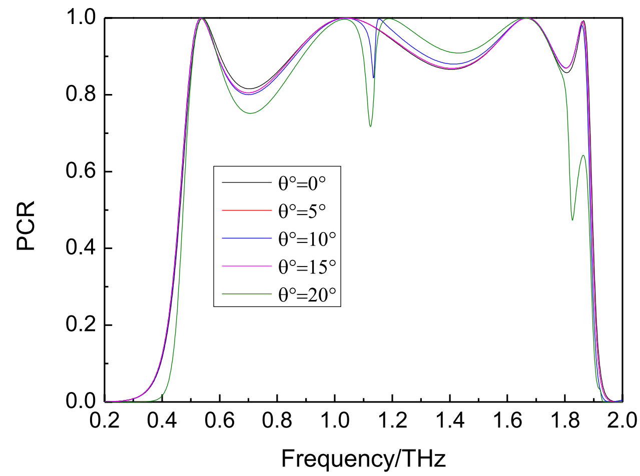

Fig. 6 Relationship between PCR and incident angle

4 Relationship between polarization conversion rate and incidence and polarization angles

4.1 Polarization conversion rate versus incidence angle

The relationship between the polarization conversion rate and the incidence angle is an important index in evaluating the performance of the polarization converter. By varying the incidence angle in simulations, the polarization conversion rate may be examined. When terahertz waves are incident at 0–20°, the polarization conversion rate of the polarization converter within the range 0.49–1.88 THz rises above 70%. At 20°, the polarization conversion rate is above 80% in the frequency ranges 0.49–1.11 THz and 1.14–1.81 THz.

4.2 Polarization conversion rate versus polarization angle

The dependence of the polarization conversion rate on polarization angle from– 15 to 15° was also studied (Fig. 7). When the frequency is between 0.49 and 1.88 THz, the polarization angle lies between– 10 and 10°, and the polarization conversion rate rises above 70%.

5 Conclusion

A wide-band polarization converter based on a double-open resonant ring was designed and simulated, and its polarization conversion mechanism was analyzed both theoretically and numerically. The simulation results show that the polarization conversion rate is greater than 80%

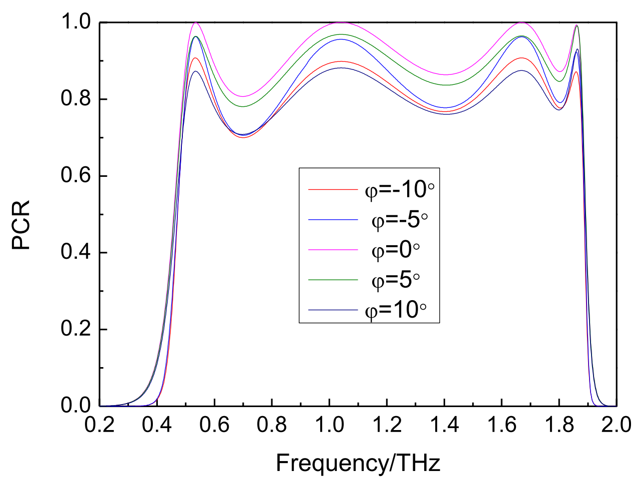

Fig. 7 Relationship between PCR and polarization angle

within the range 0.49–1.88 THz (bandwidth of 1.39 THz). The structure exhibits a good polarization conversion performance for incident angles between 0 and 20°; the polarization angle ranges from– 10 to 10°. Simulating the surface current distribution of the polarization converter has enabled the polarization conversion mechanism of the converter to be analyzed so that its function can be understood better. This polarization converter has potentially broad applications in terahertz communications, sensing, and imaging.

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