Broadband asymmetric transmission characteristics based on metamaterial in terahertz region

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Abstract. In this paper, a multi-layered terahertz metamaterial has been proposed, which consisted of dual-layered substrate and three 6-shaped meta-layered. Numerical results reveal that the structure realizes broadband asymmetric transmission of linearly polarized wave. In particular, this structure realizes a maximum of 0.95 for asymmetric transmission at 6.7THz. Based on the electric fields, we have analyzed the wave conversion of linearly polarized wave and the mechanism of asymmetric transmission effect.

Key words: Metamaterial; Asymmetric transmission; Terahertz; Polarization conversion

1 INTRODUCTION

Terahertz (THz) wave between millimeter wave with visible light, is refers to the frequency in the 0.1 ~ 10 THz and the relevant wavelength in the 0.03 ~ 3 mm of the electromagnetic (EM) wave. Terahertz wave with unique characteristics, such as transient, broadband, coherence and low energy, occupies a very special place in the electromagnetic spectrum. However, for a long time due to the lack of effective production and the test method of terahertz radiation, the terahertz frequencies of electromagnetic wave is rarely used in the field of research and application, which has been called “the terahertz gap (THz gap)” in the electromagnetic spectrum. In addition, researchers have pursued the applications in the terahertz region, for instance, THz communications [1], biomedicine [2], chemistry [3] and THz imaging [4].

In recent years, the terahertz metamaterials research has made a series of important theories and achievement, which can be widely used in absorber [5], polarization deflector [6], filters [7]. The metamaterials are artificial man-made composite materials, which do not exist in nature. The metamaterials have many peculiar features, for instance, polarization rotation [8] asymmetrical transmission [9], optical activity, circular dichroism. Using metamaterials to control the propagation of electromagnetic waves became one of the hot spots of current research. In 2006, Fedotov et al [10] first
proposed chiral metamaterial can produce effect of asymmetric transmission (AT) in microwave. They used aperiodic array of metal array structure, and observed that the circular polarized wave has possessed asymmetric transmission effect. Huang et al [11] proposed double SRR structure, which achieves the asymmetric transmission in microwave, and can control the x-polarized and y-polarized wave in 2012. Thus, we believe the chirality structure can not only control wave transmission, also the polarization of the wave.

In 2015, a three-dimensional structure of chirality is proposed in infrared wavelength by Kenanakis et al [12]. However, the structure is complicated, and in the narrow-band the maximum asymmetric transmission value is only 0.3. In 2019, Dai et al [13] proposed a chiral metamaterial structure with asymmetric transmission characteristics in the terahertz band, and the maximum polarization conversion rate was only 0.81. With the development of society, researchers have proposed many asymmetric transmission metamaterial structures [14]. However, the value of asymmetric transmission coefficient is relatively low in THz region using these structures. Thus, designing a new structure to realize the THz band of high value and broadband asymmetric transmission is very necessary, and important.

In this work, chiral metamaterial structure with three metal layers is proposed, which can realize asymmetric transmission. And in the process of electromagnetic wave transmission this structure also realizes the polarization conversion. Simulation results show that this structure has an asymmetric transmission coefficient value greater than 0.8 in the frequency range of 4.78-7.07 THz. Especially at 6.7 THz, the asymmetric transmission parameter of this structure reaches a maximum value of 0.95, and the polarization conversion ratio (PCR) can also reach 98%.

2. DESIGN AND ANALYSIS METHOD

As shown in figure 1, the proposed chiral structure is designed, which composed of three metal layers, two dielectric substrates. The dielectric substrate is chosen silica glass with a permittivity of 2.1, and the thickness of \( d = 4 \) \( \mu \)m. The three metal layers are the silver with the “6” shaped, which can be described by Drude dispersion model [9]. The three silver layers have the same thickness of \( t = 4 \) \( \mu \)m. From Fig. 1(a), the schematic diagram of the metamaterial unit cell with side length \( a = 16 \) \( \mu \)m. The parameters of “6” shaped resonator are \( l_{1} = 8 \) \( \mu \)m, \( l_{2} = 14 \) \( \mu \)m, \( w_{1} = 2 \) \( \mu \)m \( w_{2} = 4 \) \( \mu \)m. This unit cell structure, no matter how to rotate and displace within the space, cannot superpose itself. To study the electromagnetic (EM) response of this structure, we adopt finite element method of CST MICROWAVE STUDIO (Computer Simulation Technology, Germany). Among the simulation boundary settings, periodic boundary condition is applied in the x and y directions, and the EM wave propagating along the z direction.

Fig.1 The schematic of chiral metamaterial unit cell, (a) front view (b) right view (c) perspective view

For linear polarized wave vertical incidence to structure, we introduce the transmission coefficient matrix [15] to analyze transmission mechanism. From which we can know that \( \mathbf{T}_{xx}^{\prime} = \mathbf{T}_{xx}^{b}, \mathbf{T}_{yy}^{\prime} = \mathbf{T}_{yy}^{b}, \mathbf{T}_{xy}^{\prime} \neq \mathbf{T}_{xy}^{b} \). Here, \( T \) denotes the transmission coefficient, the superscripts \( f \) and \( b \) indicate the normal incidence and reverse incidence, respectively, and the subscripts \( x \) and \( y \) denote the polarization directions of waves, respectively. For asymmetric transmission, we can use the formula \( \Delta_{lin}^{x}=|T_{yx}|^{2} - |T_{xy}|^{2} = -\Delta_{lin}^{y} \) to calculate. The optical activity of chiral metamaterials is mainly characterized by
two parameters: azimuth rotation angle $\theta$ and ellipticity $\eta$. Under the Stokes formula [16] the $\theta$ and $\eta$ can be expressed as:
\[
\theta = \frac{1}{2} \tan^{-1} \left( \frac{2|T_{xx}||T_{yx}| \cos \varphi}{|T_{xx}|^2 + |T_{yx}|^2} \right), \quad \eta = \frac{1}{2} \sin^{-1} \left( \frac{2|T_{xx}||T_{yx}| \sin \varphi}{|T_{xx}|^2 + |T_{yx}|^2} \right)
\]

For the mutual conversion effect between polarized waves, the polarization conversion rate (PCR) is introduced to calculate, which indicates the efficiency of the electromagnetic wave from one polarization form to another polarization form. The PCR of x-polarized and y-polarized waves can be defined as $PC$ $R_x = |T_{yx}|^2/(|T_{xx}|^2 + |T_{yx}|^2)$ and $PCR_y = |T_{xy}|^2/(|T_{yy}|^2 + |T_{xy}|^2)$ [17].

3 NUMERICAL RESULTS AND DISCUSSION

The transmission coefficient of a linearly polarized wave through the chiral structure is simulated. Fig.2 shows the simulated transmission coefficient for the backward and forward propagating EM waves. From the Fig.2(a), when the EM waves propagate along the $-z$ direction (backward), the cross-polarized $T_{xy}$ has two transmission peaks at 5.21 THz and 6.74 THz with the maxima of 0.97 and 0.98, respectively. At the same time the cross-polarization $T_{yx}$ is integrally constrained, with the transmission below 0.1. The co-polarized transmission $T_{xx}$ coincides with $T_{yy}$ almost, and both of them are restrained to being below 0.15 at each resonance. It is obvious that the cross-polarization transmission $T_{xy}$ and $T_{yx}$ have huge difference. This difference will inevitably lead to the AT effect and high polarization conversion efficiency. And the co-polarization and the cross-polarization transmission coefficient satisfy the conditions $|T_{xy}| \neq |T_{yx}|, |T_{xx}| = |T_{yy}|$. As shown in Fig.2(b), when the EM waves propagate along the $+z$ direction (forward), the cross-polarization transmission $T_{xy}$ produces a transmission peak with maxima of 0.97 at 5.20 THz and 0.98 at 6.72 THz. The changes of $T_{xx}$ and $T_{xy}$ are common with coefficients $T_{xx}$ and $T_{xy}$ of the forward transmission. Compared to two pictures, we can find that the electromagnetic wave through the structure along different directions, the cross-polarization transmission coefficients is different. As a result, the AT effect is formed. So, we can conclude that when the y-polarization (x-polarization) wave along $+z$ ($-z$) direction incident to this structure, the polarization wave is converted to the x-polarization (y-polarization). However, when y-polarization (x-polarization) is along the opposite direction through this structure, it is difficult to produce polarization conversion.

![Fig.2](image-url)

**Fig.2** Transmittances for propagating waves: linear polarization incident wave along backward ($-z$) direction (a), linear polarization incident wave along forward ($+z$) direction (b)

To better understand the characteristic of the AT effect, we calculate the AT parameters $\Delta_{\text{lin}}$ and $\Delta_{\text{lin'}}$ of linear polarization wave along the $-z$ direction. The results are displayed in Fig. 3(a).
This converted results in Fig. 3(b) is the polarization conversion ratio when the wave propagates in the -z direction. It is obvious that the PCR of the x-polarized wave can reach 98% at the resonance points, and is greater than 90% in the range of 4.64 THz to 8.29 THz. Meanwhile, for y-polarized wave, the PCR is less than 20% in the range of 4.64 THz to 7.6 THz. These results indicate that when the x-polarized wave passes through the chiral structure, it can be completely converted to y-polarized wave. For the y-polarized wave, the polarization conversion effect is not good. This also illustrates the asymmetric transmission effect from another aspect.

The azimuth rotation angle $\theta$ and ellipticity $\eta$ are shown in Fig. 4 for x-polarization and y-polarization wave. As shown in Fig. 4(a) the $\theta$ of y-polarized wave is less than $40^\circ$ in the whole frequency range, while at 5.3 THz, 6.3THz and 8.3THz the $\theta$ of x-polarized wave has three peaks, which is $89.77^\circ$, $89.63^\circ$ and $89.84^\circ$, respectively. In the frequency range from 4.64 THz to 8.29 THz, the $\theta$ is greater than $80^\circ$, and $T_{xy}$ is also greater than 0.5. Therefore, we believe that the $\theta$ of x-polarized waves will lead to a high cross-polarization transmission coefficient $T_{xy}$.

Fig. 4 (b) shows the $\eta$ of linearly polarized waves. The $\eta$ of y-polarized waves and x-polarized waves is less than $45^\circ$ in the whole frequency range, indicating that they cannot achieve circular polarized wave state. This has something to do with the proposed structure. Similarly, the different $\theta$ of x-polarized wave and y-polarized wave also indicate that asymmetric transmission and polarization conversion can be carried out.

To further analyze asymmetric transmission and polarization deflection, we analyze the distribution of electric field when the incident wave is –z direction. Fig. 5 shows the polarization states at different
frequencies when the incident waves are x-polarized wave and y-polarized wave. As can be seen from the figure, when the incident wave is y-polarized wave, the y-polarized wave is inhibited at the two resonance frequencies. While the incident wave is x-polarized wave, this structure allows x-polarized wave to propagate widely. The electric field direction of the y-polarized wave is deflected by 180°, while the electric field direction of the x-polarized wave is deflected by 90°. It can be seen from the figure that the electric field intensity of x-polarized wave has almost no difference between the incident direction and the exit direction, indicating that x-polarized wave can pass through the structure well. This also explains that the transmission amplitude can reach 0.97 at the resonance frequency. The distribution of electric field is basically consistent with the results of numerical analysis. So, this structure can realize asymmetric transmission and polarization conversion.

**Fig.5** The electric field distribution of x polarized wave and y polarized at 5.2 THz and 6.7 THz, respectively

4. CONCLUSION
In summary, a new chiral structure composed of three ‘6’ shaped metal layers, and two dielectric layers substrates is proposed. We analyze the transmission coefficients and asymmetric transmission coefficients for linearly polarized wave. The result shows that the chiral structure can achieve broadband asymmetric transmission, and the maximum asymmetric transmission is obtained at 6.7 THz. This structure can realize high PCR in terahertz region. In order to understand the physical mechanism of asymmetric transmission, we analyze the distribution of electric field at resonance frequencies, and the results are consistent with the conclusion mentioned above. We believe that the structure will enrich the potential application in novel polarization-controlled devices, such as antenna radome, imaging systems and radiometer.

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