Multi-Band Tunable Chiral Metamaterial for Asymmetric Transmission and Absorption of Linearly Polarized Electromagnetic Waves

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Due to the importance of chiral materials in realizing many exotic phenomena, a chiral metamaterial incorporated with active components of PIN diodes for the flexible control of asymmetric transmission (AT) of linearly polarized electromagnetic (EM) waves at microwave frequency is proposed. A transfer-matrix approach and full-wave simulations for cascading anisotropic impedance sheets is applied to analyse the physical mechanism of the structure, enabling the device with optimal multi-band AT effect. The experimental results demonstrate that the robust real-time controls of polarization conversion and AT effect for the linearly polarized waves can be achieved by altering the applied biasing voltage, giving rise to the tunability in three frequency bands of 9–10.5 GHz, 11–11.8 GHz, and 12.2–12.8 GHz. Furthermore, the tunable absorption can also be achieved, making it a good candidate in intelligent EM systems.

1. Introduction

Metamaterial or metasurface refers to a new type of electromagnetic (EM) material with the subwavelength structures whose equivalent permittivity and permeability can be artificially designed and controlled. They have shown promise for many exotic phenomena and exhibit various potential applications, such as negative refractive index, perfect lens, stealth invisibility, magnetic surface, and polarization rotation.[1–7] In recent years, substantial attention has been paid to chiral metamaterials, whose geometry property lacks any planes of mirror symmetry. The chiral metamaterials are classified into two-dimensional and three-dimensional symmetries and have exhibited novel phenomena like negative refractive index,[8,9] optical activity,[10–14] circular dichroism,[15,16] etc.[17–20] Furthermore, the interesting feature of the chiral metamaterial, discovered in 2006 by Fedotov et al., is the asymmetric transmission (AT) of the EM waves incident from opposite directions or having different handedness of circular polarization.[21] Different from non-reciprocity of magneto-optic Faraday effect, this directional asymmetric response does not require the magnetic field for its observation. EM waves propagating in the opposite direction interact with the mirror image of the original structure, showing reversed sense of twist in opposite directions of perception. Various chiral metamaterials with AT effect for circularly polarized incident waves have been investigated,[22,23] and the first demonstration of AT effect for linearly polarized waves was reported by Menzel et al. in 2010.[24] Moreover, the distinct properties of chiral materials make them promising candidates for a series of applications in polarization manipulation, biological detection, self-assembled applications, optical display, optical force, polarization sensitive imaging, and nonlinear optics.[20,25–32] Nevertheless, most of the existing chiral metamaterials contain only passive components,[33–37] and a few experiments have been reported that achieved reconfigurable chirality and controllable EM properties.[38,39] In the microwave frequencies, active elements such as positive-intrinsic-negative (PIN) diodes[38,40–43] and varactors[44–47] have been widely used to achieve dynamic controls of the meta-atoms by outer bias voltages at real time.
Moreover, multi-band active chiral metamaterials can be more useful in the conditions where multi-modes or different functions are desired. In this paper, a tunable chiral metasurface incorporated with PIN diodes is put forward to realize active control of AT effect for the linearly polarized waves. The unit cell consists of bi-layered twisted split-ring resonators (SRRs) which are in the conjugate-symmetry arrangement along the diagonal of the substrate, and both of them are incorporated with PIN diodes. Such a distribution of metallic resonators breaks the mirror symmetry in the direction perpendicular to the plane of the structure, thereby inducing strong chirality around the resonant frequencies and realizing AT effect for the linearly polarized waves only.[34] A transfer-matrix approach and full-wave simulations for cascading anisotropic impedance sheets is applied to analyse the physical mechanism of the structure, enabling the device with optimal multi-band AT effect. Moreover, the electric fields and surface current distributions are simulated to further analyze the origin of AT effect. We experimentally demonstrate the robust real-time controls of multi-band polarization conversion, AT effect and other parameters for the linearly polarized waves in the microwave region can be achieved by altering the applied biasing voltage. Our design is a good example of achieving active controls for metamaterials, and the proposed structure can be further integrated into compact devices.

2. Theory and Method

The schematic diagram of the proposed chiral metamaterial which is an array of artificial structures for the AT effect of linearly polarized waves is shown in Figure 1a. The structure of the unit cell is described in Figure 1b–d, as we can see, it consists of two stacked SRRs that are mutually twisted by $\alpha$, on both sides of the dielectric substrate. Each SRR has a split angle of $\alpha$, and a slit with a width of $w$, across which the PIN diode (we choose SMP1320_040LF) is installed. Straight feeding lines are deposited near the resonators on the bottom side of the substrate to supply the operating voltage for the diodes. Metallic vias are deposited near the positive and negative electrodes of the PIN diodes so as to ensure the DC biasing on both sides of the substrate at the same time. The metallic structures on both sides of the substrate are nearly in the conjugate-symmetry arrangement along the diagonal (highlighted by the auxiliary blue dashed line), so as to achieve the AT effect for the linearly polarized EM waves only.[34] The commercial dielectric F4BM with the relative permittivity of 3, thickness of $h$, and the loss tangent of 0.0015 is adopted in this design. The metallic layers are made of copper with the thickness of $t = 0.035$ mm and conductivity of $5.8 \times 10^7$ S/m.

The transmission feature of the linearly polarized wave propagating through the chiral metamaterial can be illustrated by Jones matrix. Assuming a linearly polarized wave normally incidents on the metasurface along the -z direction, the transmitted wave can be regarded as the combination of both x- and y- polarized components. The Jones matrix links the incident fields to the transmitted fields can be expressed as[24,33]

$$E_t = T_{lin} E_i = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} E_i$$

where the vectors $E_i$ and $E_t$ denote the incident and transmitted electric field, and the matrix $T_{lin}$ represents the transmission
matrix along the forward propagation direction. The matrix $T_{\text{lin}}$ consists of $2 \times 2$ elements, and the element $T_{ij}$ is the transmission coefficient of the $i$-polarization for a $j$-polarized incident wave ($i, j = x, y$). Since it does not involve non-reciprocal component in the medium, the reciprocal theorem is applied, the transmission matrix $T_{\text{lin}}^b$ for backward propagation (along $+z$ direction) can be derived as

$$T_{\text{lin}}^b = \begin{pmatrix} T_{xx} & T_{xx}^* \\ T_{xy} & T_{yy} \\ \end{pmatrix}$$

The AT parameter is used to describe the difference of the transmitted energy of a certain polarized incident wave propagating in the opposite directions. For a linearly polarized EM wave, we have

$$AT_{\text{lin}}^x = |T_{yx}|^2 - |T_{yx}^*|^2 = AT_{\text{lin}}^y$$

where $AT_{\text{lin}}^x$ and $AT_{\text{lin}}^y$ represent the AT parameters of the x- and y- polarized EM waves, respectively.

Usually, to obtain AT effect for linear polarization only, the transmission matrix elements should satisfy the following conditions:

$$|T_{xy}| \neq |T_{yx}|$$

$$T_{xx} = T_{yy}$$

and specific structure asymmetry (i.e., conjugate symmetry) should be applied on the three-dimensional unit cell to ensure the satisfactory solution.

To explore the design procedure, a general solution by cascading anisotropic impedance sheets is proposed. The equivalent circuit (EC) model based on the transmission-line theory is presented in Figure 1e. Here, we define the sheet admittance tensor $Y_s$ in a general form as

$$Y_s = \begin{bmatrix} Y_{xx} & Y_{xy} \\ Y_{yx} & Y_{yy} \end{bmatrix}$$

where the subscriptions indicate the $x$- or $y$- polarization.

Considering the meta-sheets rotated counterclockwise by an arbitrary in-plane rotational angle $\theta$ along the $z$-axis, the sheet admittance tensor $Y_s(\theta)$ can be derived as

$$Y_s(\theta) = R^{-1}(\theta) \cdot Y_s \cdot R(\theta)$$

where, $R(\theta)$ is the rotation matrix written as

$$R(\theta) = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$$

For a two-layered metasurface, the transfer matrix illustrating the transmission features that includes the properties of each stacked layer and the dielectric segments between the consecutive layers can be written as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} I & 0 \\ n \cdot Y_{\text{lin}} & I \end{bmatrix} \cdot \begin{bmatrix} \cos(\beta d) I & -j \sin(\beta d) \eta_{12} n \\ j \sin(\beta d) \eta_{21}^{-1} n \cos(\beta d) I & \eta_{21} \cdot Y_{\text{lin}} \end{bmatrix} \cdot \begin{bmatrix} I & 0 \\ n \cdot Y_{\text{lin}} & I \end{bmatrix}$$

$$Y_s = Y_s + Y_{\text{lin}} + 1/R_{\text{eff}}$$

$$Y_{\text{lin}} = 1/j \omega L_{\text{eff}}, \ Y_{\text{C}} = j \omega C_{\text{eff}}$$

where $\beta$ is the propagation constant, $d$ is the thickness of the substrate, $\eta_{ij}$ is the wave impedance of the substrate, $R_{\text{eff}}$ is the total equivalent resistance, $L_{\text{eff}}$ is the total equivalent inductance, and $C_{\text{eff}}$ is the total equivalent capacitance. The tunability of $Y_s$ is caused by the change of the PIN diodes’ parameters, and $I$ or $n$ is the identity or the 90° rotation matrix of

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \ n = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

The scattering parameters (S-parameters) are defined as the ratios of the scattering electric fields to the incident electric field.
Table 1. Dimensions of the unit cell.

| Dimensions | a  | b  | c  | w1 | h  | a1 | a2 |
|------------|----|----|----|----|----|----|----|
| Value (mm) | 16 | 15.4 | 15.4 | 0.2 | 3 | 3.2 | 7 |

Considering a general case that the EM wave contains both x- and y-components, the S-parameter matrix should be written as

$$\begin{bmatrix}
S_{xx}^{m} & S_{xy}^{m} \\
S_{yx}^{m} & S_{yy}^{m}
\end{bmatrix}$$

(13)

where $(m)$ represents the region of the scattered (incident) field, while the first (second) superscript indicates the polarization state of the scattered (incident) wave.

Assuming that the metasurface is generally located among the media with wave impedance given by $\eta_1$ and $\eta_2$, respectively, the formula relating the S-parameters with the transfer matrix of metasurface can be given as

$$\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix} = \begin{bmatrix}
-I B \cdot n \eta_2 + A \\
I n \eta_1 D \cdot n \eta_2 + C
\end{bmatrix}^{-1} \begin{bmatrix}
I B \cdot n \eta_2 + A \\
I n \eta_1 D \cdot n \eta_2 - C
\end{bmatrix}$$

(14)

where $\eta_1 = \eta_2 = \eta_0$, where $\eta_0$ is the wave impedance of free space.

The ideal AT effect for the linearly polarized incident waves has the following properties

$$S_{21} = e^{i \alpha} \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \quad S_{12} = e^{i \alpha} \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

(15)

and the undesired polarization is completely reflected

$$S_{11} = e^{i \alpha} \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix}, \quad S_{22} = e^{i \alpha} \begin{bmatrix} -1 & 0 \\ 0 & 0 \end{bmatrix}$$

(16)

where $\alpha$ is the arbitrary phase change of the component.

To achieve a good performance of AT effect, the specific objective function is to minimize the value of

$$|S_{xx}^{21} - T_{xx}|^2 + |S_{xy}^{21} - T_{xy}|^2 + |S_{yx}^{21} - T_{yx}|^2 + |S_{yy}^{21} - T_{yy}|^2$$

(17)

where $T$ is the transmission coefficient of the cascaded sheet admittance and $S_{21}$ is the desired transmission coefficient.

Figure 3. a) Real part of the sheet admittance $Y_{xx}$, b) imaginary part of the sheet admittance $Y_{xx}$, c) real part of the sheet admittance $Y_{xy}$, and d) imaginary part of the sheet admittance $Y_{xy}$ in three special working states (0 A, 20 µA, and 5 mA), respectively.
3. Fabrication

The commercial dielectric F4BM is a copper-clad board suppressed with glass fiber cloth, polytetrafluorethylene resin and polytetrafluoroethylene film, which has a wide dielectric constant.

The thermal expansion coefficient of the material is (the typical value under the temperature of 0–100 °C when the dielectric constant is 3.0) : x- direction: 12 ppm / °C; y- direction: 15 ppm / °C; z- direction: 95 ppm / °C. Volume resistance is: under normal condition: ≥6 × 10¹⁰ Ω·cm; under humid condition: ≥1 × 10¹³ Ω·cm. The stripping force of copper foils is: under normal condition: ≥18 N/cm; under humid condition and high temperature of 260 °C: ≥15 N/cm.

The material can be processed with Printed Circuit Broad (PCB) technology, and the hole metalization should be treated with sodium naphthalene solution activation or plasma. The temperature of Hot Air Leveling should be within 253 °C, and cannot repeat, moreover, the hot spray is required.

The picture of the fabricated sample is displayed in Figure 2, which contains 15 × 18 unit cells and the DC power supplying module. The thickness is 3mm, which is 1/10 of the propagation wavelength.

4. Results and Discussion

The optimized geometrical dimensions of the unit cell are presented in Table 1. The calculated sheet admittances $Y_{xx}$ and $Y_{yy}$ of the first layer of the SRR in three special working states (0 A, 20 µA, and 5 mA) are shown in Figure 3, demonstrating the dependence on the working states of PIN diodes and operating frequencies.

The performance of the cascaded SRRs are simulated by CST (see Supporting Information), results of the cross-polarization transmittance amplitude $T_{xy}$ for the normally incident plane waves along the forward direction, obtained by continuously regulating the current of PIN diodes. As we can see, the experimental and simulated results show good agreement with each other. Some deviations between experimental and simulated results are mainly caused by the manufacturing errors of the specimens and the PIN diodes. There is a large modulation range for the cross-polarization transmittance amplitude $T_{xy}$ within the frequency band of 9–13 GHz. When the PIN diodes operate in the current of 0 A, the existence of the metallic vias leads to the increase of $|T_{xy}|$ at around 13 GHz. From 11 GHz to 14 GHz, it also exhibits a peak of about 0.51 at 12.6 GHz, and reaches its minimum value of 0.08 at 11.4 GHz. Nevertheless, $|T_{xy}|$ is above 0.7 from 9.1 GHz to 10.3 GHz, and exhibits a peak of about 0.83 at 9.7 GHz. From 11 GHz to 14 GHz, it also exhibits a peak of about 0.51 at 12 GHz and a peak of about 0.68 at 13 GHz. Nevertheless, $|T_{xy}|$ is below 0.3 within the frequency bands of 11–11.8 GHz and 12.2–12.6 GHz, and reaches its minimum value of 0.08 at 11.4 GHz and 0.13 at 12.3 GHz, respectively. As the current increases, $|T_{xy}|$ becomes smaller in the frequency bands of 9.1–10.2 GHz, while becomes larger in the frequency bands of 11–11.8 GHz and 12.2–12.6 GHz. As the current gets to 20 µA, $|T_{xy}|$ decreases to the minimum value of below 0.6 in the frequency band.

Figure 4. The simulation results of cross-polarization transmittance amplitude $T_{xy}$ of the structure when the PIN diodes operate in the current of a) 0 A, b) 20 µA, and c) 5 mA. S1: The SRRs; S2: The SRRs with vias; S3: The structure with a single side of biasing feeding lines; S4: The complete structure.
of 9.1-10.3 GHz, and increases to above 0.3 at 11.4 GHz and 12.3 GHz. When the current further increases to 5 mA, more frequency bands appear (9–9.8 GHz, 11.5–11.9 GHz, and 12.1–12.5 GHz) with high amplitude, exhibiting three peaks of about 0.8, 0.75, and 0.73 at the frequency of 9.2 GHz, 11.8 GHz, and 12.3 GHz, respectively.

While other three parameters depend weakly on the working states of the PIN diodes. The largest modulating range of the copolarization transmittance amplitude $|T_{xx}|$ is from 0.15 to 0.33 at about 11.7 GHz, and the largest modulating range of the copolarization transmittance amplitude $|T_{yy}|$ is from 0.15 to 0.25 at about 12.3 GHz, as shown in Figure 5f,g. Moreover, the values of $|T_{xx}|$ and $|T_{yy}|$ are approximately equal, which indicates that the AT effect for the circularly polarized waves is well suppressed.

Moreover, the cross-polarization transmittance amplitude $|T_{xy}|$ is much lower than $|T_{yx}|$ in the whole frequency band, and is totally suppressed below 0.22, as is shown in Figure 5h. Due to the reciprocity theorem, the transmission difference among

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**Figure 5.** Simulated a–d) and measured e–h) results of the amplitudes of transmission Jones matrix under the normal incidence in the forward propagation situation.
Figure 6. Measured results of the energy ratio of transmission, reflection as well as absorption for the x-polarized incident waves in three special states. a–c) Forward propagation when the PIN diodes operate in the current of (a) 0 A, (b) 20 µA, and (c) 5 mA. d–f) Backward propagation when the PIN diodes operate in the current of (d) 0 A, (e) 20 µA, and (f) 5 mA.

The energy ratios of transmission, reflection and absorption for the x-polarized incident waves in the forward and backward situations are calculated by

\[
\text{Transmission} = |T_{yx}|^2 + |T_{xx}|^2 \quad (18)
\]

\[
\text{Reflection} = |R_{yx}|^2 + |R_{xx}|^2 \quad (19)
\]

\[
\text{Absorption} = 1 - |T_{yx}|^2 - |T_{xx}|^2 - |R_{yx}|^2 - |R_{xx}|^2 \quad (20)
\]

where \(R_{xx}\) and \(R_{yx}\) represent the co-polarization and the cross-polarization reflectance of the x-polarized incident wave, respectively.

Figure 6 presents the experimental results under three special states (0 A, 20 µA, and 5 mA), as we can see, the transmitted energy exhibit a great difference between the forward and backward propagation situations. When the PIN diodes operate in the current of 0 A, the transmitted energy is higher than 50% for the forward propagation situation within the frequency band of 9.2–10.2 GHz (the peak reaches up to 75%), and below 5% for the backward propagation situation, demonstrating a significant AT effect for the x-polarized waves. When the current is switched to
Figure 7. Measured results of controlled chirality of the proposed metamaterial in three special working states. a) Polarization rotation azimuth angle $\theta$, b) ellipticity $\eta$, c) PCR, and d) AT parameter for the $x$-polarized incident waves. The green shadows in the pictures show the stable chirality and PCR, while the blue shadows indicate the adjustable feature.

20 $\mu$A, the AT effect gets weak, as the transmitted energy becomes lower than 40% in the forward situation and also lower than 10% in the backward situation. When the current further increases to 5 mA, more frequency bands appear (9–9.8 GHz, 11.5–11.9 GHz, and 12.1–12.5 GHz) with high transmittance in the forward propagation situation, while remains low in the backward propagation situation.

Then we consider the three parameters (transmission, reflection and absorption) together. In the forward propagation situation, the three parameters can be dynamically controlled by the operating current of the PIN diodes. Especially, when the PIN diodes operate in the current of 20 $\mu$A, as is shown in Figure 6b, the absorption is higher than 70%, while the reflection and transmission is lower than 25% for the forward propagation situation in the frequency band of 10–12.5 GHz. While in the backward propagation situation, the reflection energy remains above 60%, the transmission and absorption energy remain below 30% whatever the state is.

The polarization rotation angle $\theta$ and the ellipticity angle $\eta$ of the transmitted wave can be calculated according to the following equations\(^{[33]}\)

\[
\begin{align*}
\begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} &= \frac{1}{2} \begin{pmatrix} T_{xx} + T_{yy} + i(T_{xy} - T_{yx}) & T_{xx} - T_{yy} - i(T_{xy} + T_{yx}) \\ T_{xx} - T_{yy} + i(T_{xy} + T_{yx}) & T_{xx} + T_{yy} - i(T_{xy} - T_{yx}) \end{pmatrix} \\
\theta &= -\frac{1}{2} \left[ \arg(T_{++}) - \arg(T_{--}) \right] \\
\eta &= \frac{1}{2} \arcsin \left( \frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2} \right)
\end{align*}
\]  

where “+” and “−” denote the right-handed (RCP) and left-handed (LCP) circularly polarized waves, respectively. The rotation angle $\theta$ quantifies the strength of optical activity and is defined by the rotation of the polarization plane as the wave propagates through the chiral metamaterial. The ellipticity angle $\eta$ quantifies the polarization state of an EM wave as the ratio of the semiminor to semimajor of the polarization ellipse.

Polarization conversion ratio (PCR) is defined as the ratio of the cross-polarization transmittance to the total transmittance, which can be calculated by

\[
\begin{align*}
\text{PCR}_x &= \frac{|T_{xy}|^2}{(|T_{xy}|^2 + |T_{xx}|^2)} \\
\text{PCR}_y &= \frac{|T_{yx}|^2}{(|T_{yx}|^2 + |T_{yy}|^2)}
\end{align*}
\]  

The measured results of polarization rotation azimuth angle $\theta$, ellipticity $\eta$, PCR and AT parameter in three special working states are presented in Figure 7. As we can see in Figure 7a, when the PIN diodes operate in the current of 0A, $\theta$ is about ±90° within the frequency bands of 8.6–10.6 GHz, 12 GHz, and 12.6–13.2 GHz. Meanwhile, a high PCR of over 0.9 can be achieved within the three frequency bands in Figure 7c, and the AT parameter also exhibits three peaks in Figure 7d. On the contrary, $\theta$ is about 0° at 11.4 GHz and −20° at 12.3 GHz. Meanwhile, a low PCR of 0.15 is achieved at 11.4 GHz and 0.45 at 12.3 GHz, and the AT parameter gets to its minimum value of approximate 0. When changing the working status of the PIN diodes, the controllable performance can be obtained. At about 11.4 GHz and 12.3 GHz, $\theta$ can be turned from −10° to −90° and −20° to −90°, resulting in a large adjustability of PCR from 0.15 to 0.85 and 0.45 to 0.9, respectively. The AT parameter can also be turned from 0.1 to 0.54 and 0.02 to 0.51, respectively. Nevertheless, at about 9 GHz, $\theta$ has...
Figure 8. Simulated surface currents distributions for the x-polarized plane waves incident along the forward direction (first hit the top layer), when the PIN diodes operate in the current of a) 0 A at 9.8 GHz, b) 20 µA at 9.8 GHz, and c) 5 mA at 11.5 GHz. Simulated surface currents distributions for the x-polarized plane waves incident along the backward direction (first hit the bottom layer), when the PIN diodes operate in the current of d) 0 A at 9.8 GHz, e) 20 µA at 9.8 GHz, and f) 5 mA at 11.5 GHz. The highlighted red arrows indicate the parallel or anti-parallel currents that contribute to the EM cross-coupling effect. The highlighted blue dotted arrows indicate the induced electric or magnetic dipoles by the currents.

the value of about ±90°, indicating that the structure can achieve a giant chirality. Accordingly, the PCR remains above 0.9. Meanwhile, the AT parameter can be turned from 0.33 to 0.6, and the tunability of the absorption instead of chirality for forward incident waves is the main factor. Figure 7b shows the ellipticity angle \( \eta \) of the metasurface, which indicates the polarization status of the output waves. When the operating current is 0 A, \( \eta \) achieves different values from −44° to 35°, indicating that the transmitted wave can be elliptically or linearly polarized. Especially, at about 8.7 GHz, 10.2 GHz, and 11.9 GHz, the ellipticity angle is about 0° and the polarization rotation angle is about ±90°, indicating that the pure polarization conversion for the linearly polarized waves can be realized. When changing the working status of the PIN diodes, the controllable value of \( \eta \) can also be obtained, and the maximum modulation range is from −25° to 30° at about 11.2 GHz. Nevertheless, it maintains 0° at 11.8 GHz in different working states, indicating that the output wave is always linearly polarized but rotated by an angle of \( \theta \) with respect to the incident wave. The tunability of chirality above suggests that we can get the desired polarized EM waves and AT parameters in real time.

Furthermore, to better understand the physical origin of the AT effect, the surface currents at typical frequencies and working states are depicted in Figure 8 for the forward and backward situations, respectively. As we can see in Figure 8a, when the PIN diodes operate in the current of 0 A and a forward x-polarized incident wave impinges on the structure, it is evident that the intense currents can be induced at the resonant frequency of 9.8 GHz. The currents are concentrated on the bias feeding lines, along edges of the SRRs, around the PIN diodes, and through the metallic vias. Due to the conjugate symmetry of the metallic structures on both sides of the substrate, the induced currents on the top and bottom layers can be paralleled or anti-parallel (highlighted by the red arrows). Therefore, the electric dipole resonance along the y-direction induced by the parallel currents and the magnetic dipole resonance along the x-direction induced by the anti-parallel currents can be excited. The coupled electric and magnetic fields finally lead to a polarization rotation at
the resonant frequency, namely a $y$-polarized transmitted wave. When the PIN diodes operate in the current of 20 $\mu$A, as shown in Figure 8b, the currents distribution is similar to the first situation but much sparse than that in Figure 8a due to the absorption of the structure, as a result, the transmitted amplitude is low. When the PIN diodes operate in the current of 5 mA, the intense currents can also be induced at the resonant frequency of 11.5 GHz, as depicted in Figure 8c. Nevertheless, the distribution is different from the first situation in Figure 8a, the current through the vias is not that intense, which indicates that the metallic vias have little contributions to the chiral response. The paralleled and anti-paralleled currents finally result in the transmission and polarization conversion of the $x$-polarized incident waves.

However, the resonant feature of the unit cell is quite different when the incidence is inverted to the backward direction. As is illustrated in Figure 8d–f, the $x$-polarized incident wave first hits the bottom layer, the paralleled and anti-paralleled currents cannot be well-induced on the metallic rings due to its sensitivity to the polarization, thus resulting in a comparably weak cross-coupling effect and low transmission for the $x$-polarized incident waves.

In order to have a better observation of the polarization conversion and AT effect, simulated electric fields in three different working states (0 A, 20 $\mu$A, and 5 mA) at the frequency of 9.8 GHz is plotted along the xoz-plane in Figure 9. As we can see in Figure 9a,e, when the PIN diodes operate in the current of 0 A and 5 mA, most of the $x$-polarized incident waves can be transmitted and converted into the $y$-polarized waves at the resonant frequencies in the forward propagation situation. On the contrary, when the $x$-polarized EM wave incident from the backward direction, as is shown in Figure 9b,f, there is a low transmission without polarization rotation. The significant difference between the field distribution of the forward and backward condition
indicates the high AT effect for the linearly polarized waves. Nevertheless, when the diodes operate in the current of 20 µA, as is shown in Figure 9c,d, the x-polarized EM wave cannot be well transmitted and converted into the y-polarized wave in both forward and backward conditions, and the co-polarization transmittance is also very low, resulting in a rather low AT effect.

5. Conclusion

We proposed an active chiral metamaterial that can achieve tunable AT effect for linearly polarized waves depending on the biasing status of the PIN diodes. The simulated and experimental results show the robust controlling performance of multi-band cross-polarization transmission, optical activity, as well as AT effect. At around 9 GHz, the structure exhibits a high PCR larger than 90% and can be used as an amplitude-adjustable polarization converter. Moreover, due to the tunability of both absorption and chirality, at around 11.5 GHz, it is possibly used as a reflection-absorption-transmission switcher. Our design can be further engineered in a programmed manner[43] and is a good candidate for amplitude-modulated communication systems. Moreover, due to its functionality of polarization conversion, it can work as a radome to decrease the interference of in-band copolarization transmission signals and increase the isolation between the antennas. The proposed design can also be scaled for other frequency bands, such as terahertz and optical range, where tunable materials such as graphene,[21] semiconductors,[19] vanadium dioxide (VO2),[50] etc, are available.

6. Experiment

The measurement is carried out in a microwave anechoic chamber to minimize the reflections as well as to avoid interference from the environment. The transmission and reflection coefficients for the sample at normal incidence were measured by a network analyzer (Agilent N5230C). The two ports were connected to two linearly polarized standard gain horn antennas, working as the EM wave emitter and receiver, respectively. The voltage and current of the PIN diodes can be precisely controlled by a DC voltage source.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

asymmetric transmission, chiral metamaterials, tunable systems

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