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High Efficiency Asymmetric Transmission of Linearly Polarized Waves through a Three-Layered Chiral Metamaterial

Wenjiao Zheng

University of Shanghai for Science and Technology, Shanghai, China
Email: 1250483908@qq.com

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Abstract

In this paper, we propose a three-layered chiral metamaterial (CMM) that exhibits an asymmetric transmission effect for linearly polarized waves along forwardly and backwardly propagating in the microwave region, which not only realizes the asymmetric transmission effect of multi-frequency points for linearly polarized wave in microwave band, but also breaks through the limitation of single transformation from linear polarization to linear polarization. Numerical simulation results indicate that incident wave for linearly polarized waves will be converted and transmitted as a circularly polarized wave along the forward direction at 8.31 GHz. Moreover, the asymmetric transmission (AT) parameter Δ achieves 0.8 around 12 GHz, proving the existence of strong polarization conversion and diode-like function. The proposed CMM shows great potential applications in high performance linear polarization convertor and isolator in microwave frequency.

Keywords

Chiral Metamaterials, Asymmetric Transmission, Linearly Polarized, Polarization Conversion

1. Introduction

Metamaterials, as a kind of composite materials composed of subwavelength scale composites [1] [2], have been widely studied in recent years because of their unique electromagnetic properties [1] [3] [4] [5] [6] [7], such as negative refraction [4] [5] [6], polarization conversion [8], invisibility cloak [1] [3]. Recently, it was found that metamaterials with strong symmetry breaking can exhibit the propagation direction-dependent polarization sensitive [9] transmission effect, known as asymmetric transmission (AT), for both circular [10] [11] [12] and linear polarizations [8] [13] [14] [15] [16]. This effect is a polarization sensitive transmission effect asymmetric with respect to the direction of wave propagation [8] [9] [17]. The new effect in some ways resembles the famous non-reciprocity [18] [19] [20] of the Faraday effect in magneto-optic materials and nonlinear media but requires no magnetic field for its observation. In contrast to the non-reciprocal transmission, the diode-like AT effect [13] [14] [15] [16] [17] is reciprocal and fully satisfies Lorentz reciprocity theorem [21]. After systematically reviewing the research history of the AT effect, we found that chirality [22] [23] plays a crucial role in realizing the AT effect.

Chiral metamaterials (CMMs) are a subclassification of metamaterials, which have attracted the attention of many scholars since they were proposed by Pendry *et al.* in 2004 to achieve negative refraction [4]. A CMM structure does exhibit any mirror symmetry [8] and its mirror image cannot be superimposed on itself by any planar manipulation. CMMs can be designed to exhibit properties such as giant circular dichroism [24] [25], optical activity [2] [23] [26] and AT effect, which offer more possibilities for flexible control of electromagnetic waves [27]. Many polarization devices based on CMMs have been designed and reported, such as rotators, circular polarizers [10], and polarized converters [8] [12]. A large variety of CMMs structure unit cells were investigated that evoke a huge AT effect that firstly was obtained for circularly polarized waves [28] with various designs of CMMs including conjugated gammadions, split-ring structure [12], cut-wire structure, three-dimensional helix structure [7] [29] [30], L-shaped structure [31], omega-shaped particles and other novel structures. Asymmetric propagation of circularly polarized waves is achieved using structures so-called planar chiral metamaterials [25] [32] [33] that preserve symmetry along the direction of light propagation. Hence, strictly speaking, they are intrinsically achiral in three dimensions. Usually, the achievement of AT effect for linearly polarized [8] [17] waves acquires that the proposed structure possesses strong symmetry breaking both in the structure plane (considering it normal to the propagation) and along the propagation direction. Because of chirality [22], there can be cross coupling [2] [34] between electric and magnetic fields and polarization conversion between linearly to circularly polarized waves.

Due to the important applications of AT effect [7] [17] [28] [29] [32], from microwave to terahertz, many structures with AT effects have been proposed to improve the value of AT parameters and broaden the operating frequency band [11] [14] [15] [35]. In this study, we propose a three-layered CMM structure to achieve AT effect for linearly polarized waves. The structure proposed in this study is composed of three layers of metal sheet with different shapes and two layers of media, which not only realizes the AT effect of multi-frequency points for linearly polarized wave in microwave band, but also break through the limitation of single transformation from linear polarization to linear polarization. The linearly polarized wave is converted into circularly polarized wave at 8.31 GHz and the AT parameter of linearly polarized wave at 12 GHz reaches 0.8.

2. Metamaterial Structure

The unit cell of proposed three-layered CMM structure is shown in Figure 1, which consists of a T-shaped metal sheet, a metal grating, a strip metal sheet connecting two rectangular metal strips, and two dielectric substrates. The period of the structure in x and y directions is P, and the total thickness of the medium layer is h. When the structure is observed against the Z-axis, the T-shaped sheet in Figure 1(a) is the top metal, and the metal sheet in Figure 1(c) is the bottom metal. The following geometrical parameters for the unit cell in the simulation: P = 8.2 mm, h = 1.775 mm, t = 0.015 mm, L_1 = 5.83 mm, L_2 = 0.95 mm, L_3 = 6.8 mm, L_4 = 4 mm, L_5 = 2.2 mm, W_1 = 0.85 mm, W_2 = 0.95 mm, W_3 = 0.55 mm, W_4 = 0.8 mm, W_5 = 0.55 mm, a = 0.5 mm, b = 8 mm, s = 1.05 mm. A Rogers RO3010 board with a relative permittivity of 11.2 and a dielectric loss free was utilized as the substrate. The metal layer is 15 um thick copper.

3. Theoretical Analysis

Jones matrix T is applied to describe the propagation properties of linearly polarized waves in CMMs. The T-matrix is a frequency-dependent Jones matrix [7] which describes the complex amplitudes of the incident to the transmitted fields. Assuming that a linearly polarized wave incidents on the metamaterial structure

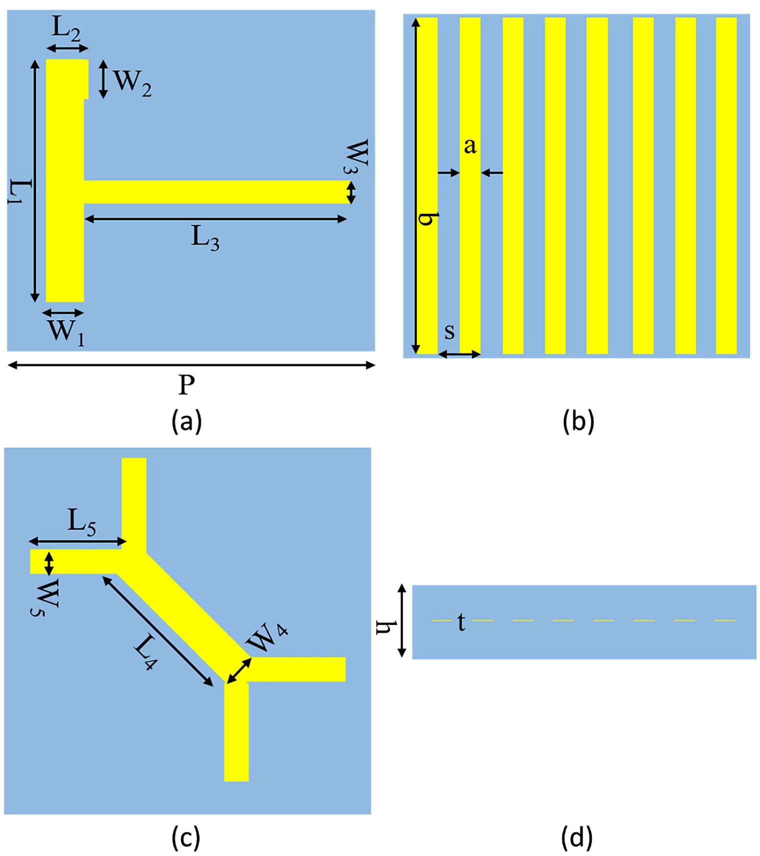

Figure 1. Schematic of three-layered CMMs. (a) Top metal and structural parameters. (b) Middle metal. (c) Bottom metal. (d) The side view of the structure.

along the forward (+*z*) direction, the transmitted wave can be considered as a combination of both *x*- and *y*-polarized components. The Jones matrix *T* that relates the incident to transmitted fields can be described as [36]:

$$E_t^f = T_{lin}^f E_i^f = \begin{pmatrix} T_{xx}^f & T_{xy}^f \\ T_{yx}^f & T_{yy}^f \end{pmatrix} E_i^f = \begin{pmatrix} A & B \\ C & D \end{pmatrix} E_i^f \tag{1}$$

For the sake of convenience, we replaced T_{ij} by *A*, *B*, *C*, *D*. Where the vectors E_i and E_t denote the incident and transmitted electric field, and the T_{lin}^f represents transmission matrix along the forward propagation direction. The matrix element T_{ij} is the transmission coefficient of the *x*-polarization for a *y*-polarized incident wave ($i, j = x, y$). The transmission matrix T_{lin}^b for backward (−*z*) propagation can be derived as [36]:

$$E_t^b = T_{lin}^b E_i^b = \begin{pmatrix} T_{xx}^b & T_{xy}^b \\ T_{yx}^b & T_{yy}^b \end{pmatrix} E_i^b \tag{2}$$

According to the reciprocity theorem, *i.e.* $T_{ii}^f = T_{ii}^b$, $T_{ij}^b = -T_{ji}^f$, the transmission matrix T_{lin}^b can be simplified as:

$$T_{lin}^b = \begin{pmatrix} A & -C \\ -B & D \end{pmatrix} \tag{3}$$

Furthermore, the total transmittances for *x*- and *y*-polarized incident wave along the forward propagation direction can be written as:

$$t_x^f = \left|T_{xx}^f\right|^2 + \left|T_{yx}^f\right|^2 \tag{4a}$$

$$t_y^f = \left|T_{yy}^f\right|^2 + \left|T_{xy}^f\right|^2 \tag{4b}$$

The asymmetric transmission of the linearly polarized waves is usually characterized by the parameter Δ, which is defined as the difference between the transmittances in two opposite propagation directions

$$\Delta^x = \left|T_{xx}^f\right|^2 + \left|T_{yx}^f\right|^2 - \left|T_{xx}^b\right|^2 - \left|T_{yx}^b\right|^2 = \left|T_{yx}^f\right|^2 - \left|T_{xy}^f\right|^2 = -\Delta^y \tag{5}$$

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

$$\left|T_{yx}^{f(b)}\right|^2 \neq \left|T_{xy}^{f(b)}\right|^2 \tag{6}$$

When a circularly polarized wave is incident normally along the forward direction, the transmission matrix T_{cir} of the circularly polarized wave can be obtained by the transformation of the Jones matrix T_{lin} of the linearly polarized wave (we omit the superscript *f* for simplification here):

$$T_{cir} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2} \times \begin{pmatrix} (A+D)+i(B-C) & (A-D)-i(B+C) \\ (A-D)+i(B+C) & (A+D)-i(B-C) \end{pmatrix} \tag{7}$$

In order to guarantee the AT effect of circularly polarized waves, the following relationship need to be satisfied:

$$\Delta^+ = \left|T_{-+}\right|^2 - \left|T_{+-}\right|^2 = -\Delta^- \neq 0 \tag{8}$$

Obviously, an ideal diodelike asymmetric transmission should be that in one direction the transmission is unity while in the opposite direction the transmission is zero. This requires that two diagonal components and one of the off-diagonal components of the T matrix are nearly zero while the other off-diagonal component is unity.

4. Simulation Results and Discussion

Figure 2 shows the simulated results of four transmission matrix elements of the designed structure for propagations in forward (+*z*) and backward (−*z*) directions in the frequency range of 7 to 13 GHz. Since the structure does not exhibit any symmetry, the cross-polarization transmission coefficient T_{yx} is different from T_{xy}, and the co-polarization transmission coefficient T_{xx} does also not coincide with T_{yy}, indicating the presence of the AT effect for linearly polarized waves.

In Figure 2(a) and Figure 2(c), it can be observed that the transmitted cross-polarized and co-polarized wave present the same amplitude, about 0.64, the phase difference between them is about −89.8˚ at 8.31 GHz, when the *x*-polarized wave is incident along the forward direction. It can be easily concluded that the transmitted electromagnetic wave should be left-handed circularly polarized wave in this circumstance. In the case of incident *y*-polarized wave, the transmitted amplitude of co-polarized and cross-polarized wave is about 0.23, with a phase

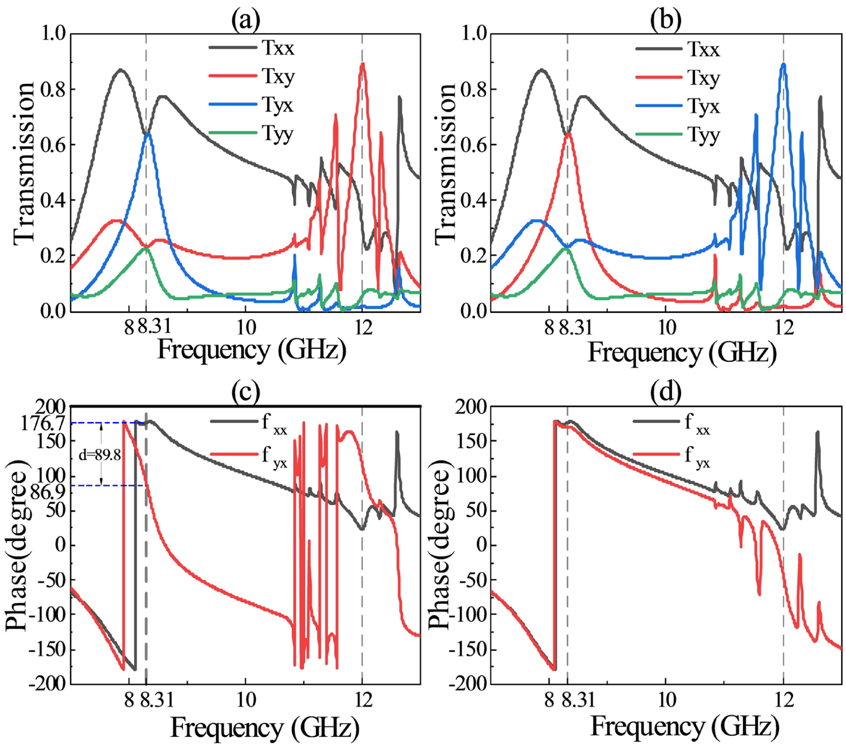

Figure 2. The transmission coefficients when linearly polarized waves propagate in the forward (+*z*) (a) and backward (−*z*) (b) directions. The cross-polarization transmission phase in the forward (+*z*) (c) and backward (−*z*) (d) directions.

difference of about 84.5˚. The transmitted electromagnetic wave should nearly be right-handed circularly polarized wave (not shown here due to its small amplitude). Figure 2(b) and Figure 2(d) depict that this conversion effect of linearly polarized waves to circularly polarized waves is not achieved regardless of incident *x*-polarized or *y*-polarized wave along the backward direction. In conclusion, we realize the conversion of transmitted electromagnetic waves from linearly polarized to circularly polarized waves along the forward direction at 8.31 GHz.

In Figure 2(a), the cross-polarization transmission coefficient T_{xy} reaches 0.9 near 12 GHz, while the co-polarization transmission coefficient T_{xx} is about 0.3, and T_{yy} and T_{yx} are close to zero. In this passband, the forward incident *y*-polarized waves are almost all transformed to *x*-polarized waves, while the incident *x*-polarized waves are blocked. Obviously, the situation in Figure 2(b) is opposite to that in Figure 2(a) at the same frequency, where the incident *x*-polarized wave is almost completely converted and transmitted as *y*-polarized wave, while the incident *y*-polarized wave is completely blocked. Figure 3 shows the surface current distributions, which further explain the mechanism of this phenomenon (The red, purple and black arrows represent the prominent current directions in the top, middle and bottom metal structure respectively). Figure 3(a) and Figure 3(b) show the surface current distributions of the incident *x*-polarized wave along the forward and backward directions respectively. When the *x*-polarized wave is incident along the forward direction, the surface current intensity is very weak, where it does not occur that cross coupling between electric field and magnetic field, and the transmitted field intensity is very weak. However, when the *x*-polarized wave is incident along the backward direction, there are several groups of parallel and antiparallel currents in the structure, which result in induced electric dipoles and magnetic dipoles, respectively. Due to the presence of electric and magnetic dipole moments, induced electric fields and magnetic fields will be generated with components along the *x* (E_1, H_1) and *y* (E_2, H_2) directions. Since the incident electric field is in the *x* direction, H_1 paralleling to the incident field is cross-coupled [34] [37], which makes the majority of incident *x*-polarized waves converted into *y*-polarized waves. Similarly, the component of E_2, which is along the *y* direction, perpendicular to the incident electric field direction also contributes to the polarization conversion. Figure 3(c) and Figure 3(d) show the surface current distributions of the *y*-polarized wave incident along the forward and backward directions respectively, whose circumstances are just contrary to Figure 3(a) and Figure 3(b). The *y*-polarized wave is incident in the forward direction, almost all of which are converted and transmitted as *x*-polarized wave. When the electromagnetic wave is incident in the backward direction, it does not generate that polarization conversion. All above are greatly consistent with the transmission coefficient results shown in Figure 2.

The results of total transmission coefficient calculated through Equation (4)

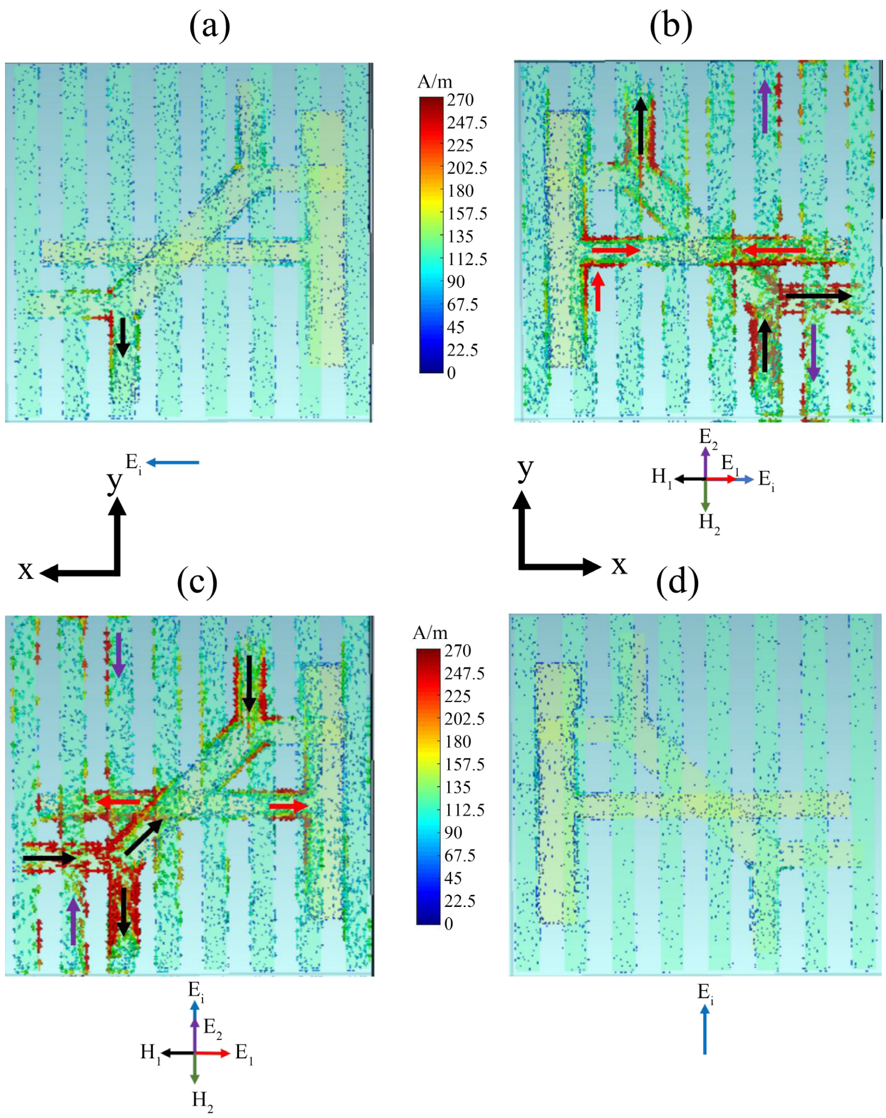

Figure 3. Surface current distributions of the resonance of 12 GHz. The x-polarized (a) and y-polarized (c) waves incident along the (+z) direction. The x-polarized (b) and y-polarized (d) waves incident along the (−z) direction.

for linearly polarized waves are illustrated in Figure 4(a) and Figure 4(b). The large difference between t_x and t_y and the alternation of peak values well prove that the proposed three-layered CMMs structure achieves the selectivity of incident linearly polarized waves [38] and the diode-like function [18]. In order to qualify the AT effect of the CMMs structure, the AT parameter Δ calculated through Equation (5) is shown in Figure 4(c) and Figure 4(d). It is evident that the structure exhibits strong AT effect for linearly polarized waves around the frequency of 12 GHz. Additionally, it is observed that the all values for Δ^x and Δ^y are placed oppositely. The existence of opposite peaks for Δ^x and Δ^y also substantiate that in the forward direction, one polarization (x- or y-polarized) is allowed while the other (y- or x-polarized) polarization is forbidden and in the backward direction this situation is reversing. Figure 4(d) shows the role of the

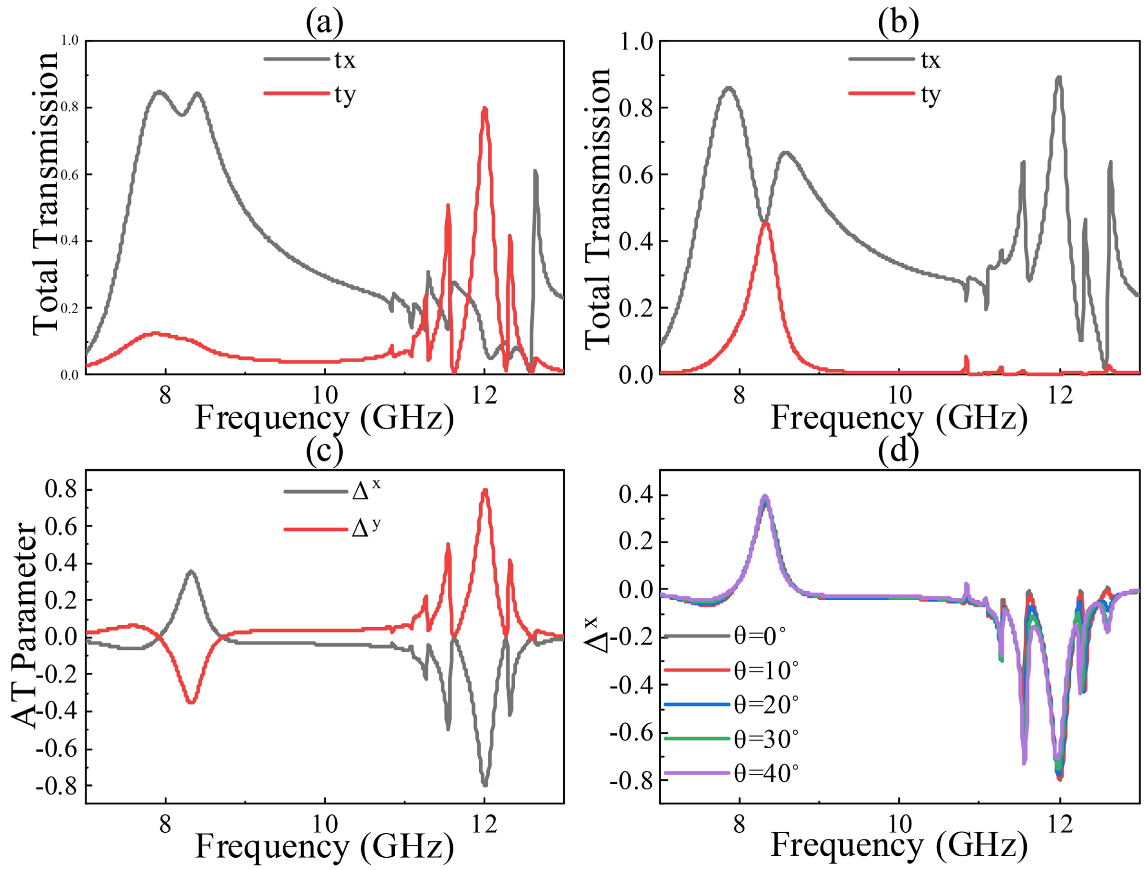

Figure 4. Total transmission coefficient of the x-polarized and y-polarized incident waves along the forward (a) and backward (b) directions. (c) The AT parameter Δ^x and Δ^y for *x*-polarized and *y*-polarized incident waves respectively. (d) Calculated AT parameter Δ^x at different angles.

incident angle on the AT spectrum of the proposed CMMs. From the plot, we can see that the peak value changes only slightly within a certain range of incident angles, and the position of the peak hardly changes, which shows that the proposed CMMs structure allows incident waves do not have to be normal incidence, but it still reaches a better AT effect.

5. Conclusion

In conclusion, we present a CMM unit cell based on a three-layered metal and two media structure, which can achieve the transformation of linearly polarized waves to circularly polarized waves and a high AT parameter which characterizes the AT effect. The simulation results confirm that the incident wave for the *x*-polarized and *y*-polarized will be converted and transmitted as left-handed circularly polarized and right-handed circularly polarized wave respectively along the forward direction at 8.31 GHz. There is no conversion like this along the backward direction. Moreover, there exist four peaks of the AT parameter, and the peak value achieves 0.8 associating with a giant AT effect around 12 GHz, which is attributed to the structural anisotropy of the CMM, making it possible for practical application [38]. The surface current distributions demonstrate this point well, which the forward incident *y*-polarized waves are almost all transformed to *x*-polarized waves, while the incident *x*-polarized waves are blocked, and the incident *x*-polarized wave is almost completely converted and transmitted as *y*-polarized wave, while the incident *y*-polarized wave is completely blocked. The strong polarization transformation in such structure could also make it a significant candidate in designing microwave wave plate or other polarization control devices.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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