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Ultra-broad band and dual-band highly efficient polarization conversion based on the three-layered chiral structure

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HIGHLIGHTS

- We proposed and investigated a novel multi-layered structure.
- Numerical simulations based on different algorithm prove the related results.
- The design achieves highly efficient asymmetric effect with extremely broad bandwidth.
- The structure also realizes the multi-band dispersionless 90° polarization angle.
- The reason of high amplitude is analyzed based on the Fabry-perot like resonance.

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ABSTRACT

In the paper, a novel three-layered chiral structure is proposed and investigated, which consists of a split-ring resonator sandwiched between two layers of sub-wavelength gratings. This designed structure can achieve simultaneously asymmetric transmission with an extremely broad bandwidth and high amplitude as well as multi-band 90° polarization rotator with very low dispersion. Numerical simulations adopted two kinds of softwares with different algorithms demonstrate that asymmetric parameter can reach a maximum of 0.99 and over than 0.8 from 4.6 to 16.8 GHz, which exhibit magnitude and bandwidth improvement over previous chiral metamaterials in microwave bands (S, C, X and Ku bands). Specifically, the reason of high amplitude is analyzed in detail based on the Fabry-perot like resonance. Subsequently, the highly efficient polarization conversion with very low dispersion between two orthogonal linearly polarized waves is also analyzed by the optical activity and ellipticity. Finally, the electric fields are also investigated and further demonstrate the correctness of the simulated and calculated results.

1. Introduction

Chiral metamaterial, as an artificial structure, exhibits many novel properties such as negative refraction index [1], optical activity [2], circular dichroism [3], linear-to-circular polarization conversion [4,5], sub-diffraction imaging [6,7] and invisibility cloak [8] and so on. In 2006, Fedotov et al. [9] first observed and demonstrated the asymmetric transmission (AT) phenomenon only to circularly polarized wave in planar chiral structure, which becomes a hot topic of research. Then lots of efforts have focused on the AT only for circularly polarized waves before 2010 [10–12]. In 2010, simultaneously achieving AT phenomenon of both linearly and circularly polarized waves is reported by Menzel et al. through a novel structure with lack mirror symmetry [13]. Subsequently, an increasing number of sophisticated structures that could be used to achieve AT effect for linearly or circularly polarized wave in microwave, terahertz and even optical frequency regions have been reported [14–21,24,25]. However, to the authors' knowledge, all of the proposed chiral structure with the AT effect can only operate in narrow frequency range [21] or low magnitude [24], which restricts its application seriously. Therefore, a novel chiral structure that can possess simultaneously ultra-broad band, dual-band and high magnitude AT effect is highly desirable.

In this work, ultra-board band, dual-band and high amplitude AT to linearly polarized waves is achieved simultaneously through a novel three-layer chiral structure which consists of a split-ring resonator sandwiched between two layers of sub-wavelength gratings. What is more, the structure exhibits multi-band 90° polarization rotator with very low dispersion. The Computer Simulation Technology (CST) microwave studio based on frequency-

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domain finite-integration technology (FIT) and Ansoft High Frequency Structure Simulator (HFSS) based on finite element method (FEM) are adopted simultaneously to simulate and evidence the perfect effect of the proposed chiral structure. Numerical simulations show that asymmetric parameter can reach a maximum of 0.99 and over than 0.8 from 4.6 to 16.8 GHz, which exhibit magnitude and bandwidth improvement over previous chiral metamaterials in microwave bands. Specifically, the reason of high amplitude is analyzed in detail based on the Fabry-perot like resonance and the polarization conversion with very low dispersion between two orthogonal linearly polarized waves is also analyzed by the optical activity and ellipticity. The electric fields are also investigated and the simulated results are coinciding with the calculated ones.

2. Basic theory

The transmission coefficient of linearly polarized wave can be written adopting the Jones matrix, which is demonstrated through this work [13,22]:

$$\begin{pmatrix} T_x^f \\ T_y^f \end{pmatrix} = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix}\begin{pmatrix} I_x^f \\ I_y^f \end{pmatrix} = \begin{pmatrix} \delta & \gamma \\ \beta & \delta \end{pmatrix}\begin{pmatrix} I_x^f \\ I_y^f \end{pmatrix} = T_{lin}^f\begin{pmatrix} I_x^f \\ I_y^f \end{pmatrix} \tag{1}$$

The superscript f and subscript lin indicate the propagation EM wave along forward $(+z)$ direction and the specific linear base, respectively. According to the reciprocity theorem, the backward $(-z)$ propagation can be derived as:

$$\begin{pmatrix} T_x^b \\ T_y^b \end{pmatrix} = \begin{pmatrix} \delta & -\beta \\ -\gamma & \delta \end{pmatrix}\begin{pmatrix} I_x^b \\ I_y^b \end{pmatrix} \tag{2}$$

The superscript b indicates the propagating EM wave along backward $(-z)$ direction. According to (Eqs. (1) and 2), if $I_x^f = I_x^b \approx 0$ (y-polarized incident wave) and $\delta \approx 0$, nearly all transmitted energy corresponds to the non-diagonal (cross-polarized) elements, resulting in a strong AT if these elements are significantly different in magnitude. In the ideal case, one must obtain $\beta = 1$ and $\gamma = 0$ [14,15]. Therefore, the diodelike phenomenon requires the diagonal components of the Jones matrix to be zero, and one of the non-diagonal elements to be zero while the other is unity. For the purposes of this study, we design and demonstrate the three-layered chiral structure.

The AT of linearly polarized waves is usually characterized by the AT parameter Δ, which is defined as the difference between the transmitted coefficients of cross-polarized waves [13,22]:

$$\Delta_{lin}^x = |\beta|^2 - |\gamma|^2 = -\Delta_{lin}^y \tag{3}$$

Total transmission of x-polarized and y-polarized waves can be expressed as:

$$T_x = |\delta|^2 + |\beta|^2, \quad T_y = |\gamma|^2 + |\delta|^2 \tag{4}$$

And polarization conversion ratio (PCR) can be used to describe the polarization conversion of linearly polarized waves. The PCR of x-and y-polarized waves can be defined as [23]:

$$\mathrm{PCR}_x = |\beta|^2 / \left(|\delta|^2 + |\beta|^2\right)$$

$$\mathrm{PCR}_y = |\gamma|^2 / \left(|\delta|^2 + |\gamma|^2\right) \tag{5}$$

3. The designed structure and simulation

The unit cell of the proposed chiral structure is composed of two sub-wavelength grating and split-ring resonator printed on two sides of dielectric substrates. Schematic diagram of this structure with all geometric parameter is depicted in Fig. 1. For convenience, we decompose the chrial structure into three components: layer A, layer B and layer C, shown in Fig. 1(d). Layer A is a sub-wavelength grating which is transparent to y-polarized wave while blocking x-polarized wave. Layer B is constructed by a substrate and spilt-ring resonator, while layer C is composed of a substrate and sub-wavelength grating which are parallel to y-axis. Simulations of the structures are achieved with CST microwave studio based on FIT. In our simulations, we apply periodic boundary conditions in the x and y directions while open condition along the z direction.

The structure parameters are as follow: $_{ax}=a_y=8.6$ mm, $w=0.5$ mm, $p=1.2$ mm, $g=3.8$ mm, $c=1$ mm, $r=4.2$ mm, $d=3.6$ mm. The dielectric substrate is made of the Rogers RO3003 with a relative permittivity of 3.0 and a dielectric loss tangent of 0.0013. The metallic layers on both sides of substrate are copper with a thickness of 17 μm.

4. The results and discussion

4.1. Mechanism of high AT amplitude in a three-layered chiral structure

At the first step, we studied the transmission and reflection coefficients of layer B, bi-layer AB, layer C and multi-layer ABC, the results are shown in Fig. 2(a), (b), (c) and (d), respectively. As previously mentioned, layer A is a sub-wavelength grating paralleled to x-axis, which is transparent to y-polarized wave while blocking x-polarized component. So, most of the incident y-polarized wave can pass through it, while x-polarized wave will be near-thoroughly reflected, when the linearly polarized waves illuminate the layer A. From Fig. 2(a), we can see that cross-polarized t_{xy} has two resonant peaks of 0.43 and 0.49 at frequency of 12.5 GHz and 20.2 GHz, respectively. At the same time, the co-polarized transmission coefficient t_{yy} is 0.44 and 0.52 at the same resonance frequency. Accordingly, we can say that the transmitted y-polarized wave (t_{yy}) is comparable with the converted x-polarized component (t_{xy}). Similarly, the refection coefficients (r_{yy}, r_{xy}) all have two resonance frequencies, and the co-polarized reflection coefficient r_{yy} can achieve a minimum of 0.25, while the cross-polarized reflection parameter r_{xy} can reach a maximum of 0.74 at the same resonance frequency about 12.4 GHz. The larger difference between the reflection coefficients means that fewer reflection wave (r_{yy}) will pass through the layer A, while most of them (r_{xy}) will be reflected by the layer A and contribute to finally converting to the x-polarized wave. In Fig. 2(b), the co-polarized transmitted wave remains higher amplitude over the entire frequency range, and cross-polarized wave achieves high transmission of 0.73 and 0.80 at the resonance peaks of 8.3 and 15.3 GHz, respectively. In contrast to single layer B, the amplitude of cross-polarized transmitted wave has been significantly enhanced. For the reflection waves, the co-polarized reflection can reach a minimum of about zero (0.00014). Similarly, the cross-polarized reflection wave does not exceed 0.05 over the entire frequency range. Seen from Fig. 2(c), the reflection coefficient of y-polarized wave is near unity and the transmitted component of x-polarized wave t_{xx} always remains high amplitude (larger than 0.85), which means that x-polarized component can well pass layer C, while y-polarization will be near-unity reflected by it. In Fig. 2(d), we can see that the cross-polarized transmitted wave t_{xy} achieves a maximum of 0.994 at the frequency of 10.5 GHz, and higher than 0.8 from 4.3 to 17.1 GHz. Meanwhile, the reflection wave r_{yy} drops to zero at two resonance frequencies of 10.5 and 15.6 GHz, respectively. Thus, we can see that most of y-polarized incident wave