Mutual Conversion and Asymmetric Transmission of Linearly Polarized Waves Based on Metamaterial

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Abstract—**In this paper, we propose a simple bilayered chiral matamaterial (CMM) consisting of two layers of split oval ring resonators by twisted angle of 90°. Numerical simulated results demonstrate that the proposed structure can realized a mutual polarization conversion and dual-band asymmetric transmission of linearly polarized waves in two opposite directions. The structure can convert the linearly polarized (LP) waves to its cross-polarized waves at 12.4 GHz and 14.6 GHz, respectively. The bandwidth of polarization conversion ratio (PCR) over 80% can be achieved from 12.5 to 17.7 GHz.**

Keywords—metamaterial; asymmetric transmission; dual-band; polarization conversion

I. INTRODUCTION

Polarization is one of important characteristics of electromagnetic (EM) waves, and plays an irreplaceable role in many classical physical effects [1]. Manipulation of EM polarization states has been greatly used for potential applications including microwave communications, astronavigation and the manufacture of antennas [2]. It is highly desirable to have full, flexible manipulation of polarization. However, the efficiency of polarization conversion by conventional methods using optical gratings and dichroic crystals is low and large thickness is needed, which is a non-negligible drawback for the application in practice [3-5].

Recently, metamaterials (MMs) have attracted enormous amount of interest due to many fascinating EM properties [6]. This kind of materials has many potential applications, such as perfect absorber [7], high-impedance surfaces (HIS) [8], and invisible cloaking [9]. The so-called materials have opened up a flexible route to control polarization states of EM waves [10-13]. As an important part of MMs, chiral metamaterials (CMMs) with non-mirror images present numerous fascinating properties. In 2006, Fedotov *et al.* [11] firstly observed the asymmetric transmission (AT) phenomenon for circularly polarized (CP) waves in planar CMMs. This phenomenon is quite useful in realizing nonreciprocal EM devices in microwave frequency such as isolators and circulators. The AT effect in CMMs can be well explained by de Hoop reciprocity as revealed by the Jones matrix formulation [15, 16]. Many designs have been proposed to achieve AT for either linearly polarized (LP) waves or CP waves [17-21]. In 2014, Cheng *et al.* [19] designed a CMM based on bilayer twisted split-ring resonator (SRR) to realize AT for CP waves. Meanwhile, many structures have also been proposed to enhance AT and accomplish cross-polarization conversion, such as L-shaped structures [17], twisted cut-wire arrays [20], and split ring apertures [21]. In spite of the described advantages, the aforementioned structures are multilayered, or the AT strongly depends on wave frequency and suffers from narrow bandwidth, which extremely impedes their practice applications. In the previous papers, the periodically arranged oval ring patterns enables the broadband and high-efficiency reflective cross-polarization conversion [22], and the Lorentz-theory approach can be used to explain AT [16, 23, 24]. Therefore, it is possible for us to design a CMM that can simultaneously achieve broadband and enhanced AT for LP waves.

In this paper, we propose a simple planar CMM that is composed of bilayered twisted oval ring resonators and a sandwiched dielectric spacer layer. The proposed scheme can achieve mutual polarization conversion between two orthogonal LP waves. The simulated results demonstrate that the CMM enables a dual-band AT of incident LP waves at normal incidence. The bandwidth of polarization conversion ratio (PCR) over 80% can be achieved from 12.5 to 17.7 GHz.

This paper is organized as follows. In Section Ⅱ, CMM structure is designed to realize the AT effect and polarization conversion. Section Ⅲ presents the simulated results of the designed CMM. Conclusions are drawn in Section Ⅳ.

II. Design of the Metamaterial

The schematic illustrate of the proposed CMM is shown in Fig. 1. Each unit consists of two spatially separated metallic oval ring patterns, which are structurally identical by twisted angle of 90°. The geometrical parameters of the structure are given by p = 9.0 mm, a = 3.9 mm, b = 3.1 mm, m = 2.8 mm, n = 2.8 mm, and the slit gap w = 0.3 mm. The dielectric substrate is selected as Roger with a relative permittivity of 3.48 and a dielectric loss tangent of 0.001. The thicknesses of dielectric substrate and metallic patterns are t = 1.2 mm and t_n =0.002 mm, respectively.

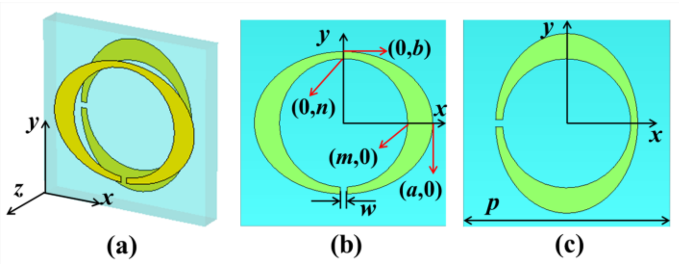

Fig. 1. Schematic of the planar CMM. (a) A unit cell in CMM, (b) the view of the front layer, and (c)the view of the back layer.

It is evident that the mirror image of the proposed CMM does not coincide with that seen from the back side, the mirror symmetry is broken along the direction of propagation, which ensures existence of AT for LP waves due to chiral property [9]. And due to the asymmetric of the CMM, the phase responses of the CMM to the x-polarized or y-polarized transmitted waves are quite different. Thus, by optimizing the structural parameters, the polarization conversion can be obtained.

III. Prepare Your Paper Before Styling

Numerical simulations were performed with CST Microwave Studio and the metallic pattern was copper (with a conductivity of 5.8 × 10^7 S/m). The periodic boundary conditions are applied in the x and y directions, and open in the z direction.

To better understand the cross-polarization conversion based on the chirality of MM structure, we apply complex Jones matrices **T** matrix to analytically solve the polarization properties of the CMM. The T matrix connects the generally complex amplitudes of the incident and transmitted fields [1].

$$\begin{pmatrix} t_x \\ t_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} I_x \\ I_y \end{pmatrix} \tag{1}$$

The AT of the LP waves is usually characterized by the parameter Δ, which is defined as the difference between the transmittances in the opposite propagation directions [1].

$$\Delta_{lin}^{(x)} = \left|t_{yx}^{f}\right|^2 - \left|t_{xy}^{f}\right|^2, \Delta_{lin}^{(y)} = \left|t_{xy}^{f}\right|^2 - \left|t_{yx}^{f}\right|^2 \tag{2}$$

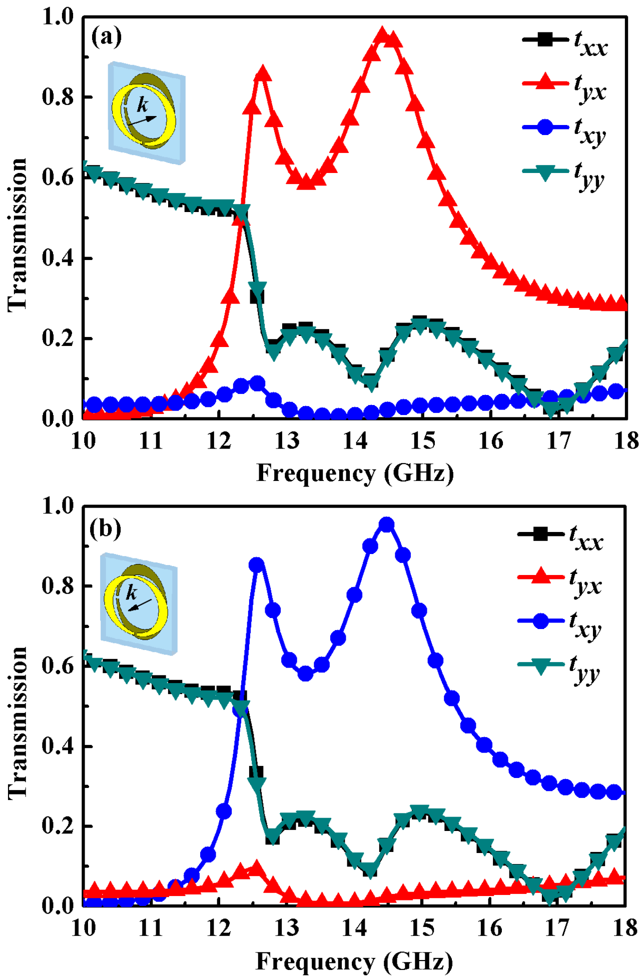

Fig. 2. Simulated transmission spectra for (a) forward and (b) backward LP incident waves, respectively.

Fig. 2 depicts the simulated transmission spectra for the forward and backward propagating EM waves. As shown in Fig. 2(a) and 2(b), there are two peaks of cross-polarized transmission t_{yx} that can reach 0.86 and 0.95 at resonance frequencies of 12.6 GHz and 14.4 GHz, respectively, while the magnitude of t_{xy} remains lower than 0.1 from 11.0 GHz to 17.0 GHz. It is clear that there is a big difference between t_{yx} and t_{xy} at the resonance frequencies, and the co-polarized transmission t_{xx} and t_{yy} are equal to each other. According to the Jones matrix formulation [16, 23, 24], a strong AT can be obtained when $t_{xx} = t_{yy}$, and $|t_{yx}| \neq |t_{xy}|$. From the simulated results, these two conditions are well satisfied.

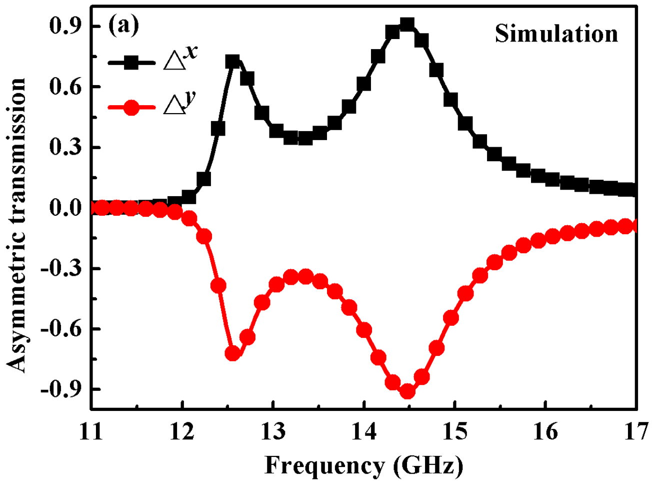

Fig. 3. Simulated AT parameters.

As clearly seen in Fig. 3, the simulated AT transmission parameter Δ for forward x-polarized waves and backward y-polarized waves is presented. The Δ^x and Δ^y show two opposite peaks at two pass bands. The AT parameters are 0.73/-0.73 and 0.91/-0.91 for Δ^x/Δ^y at resonance frequencies of 12.6 GHz and 14.4 GHz, respectively.

$$\begin{pmatrix} t_{++} & t_{+-} \\ t_{-+} & t_{--} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} t_{xx}+t_{yy}+i(t_{xy}-t_{yx}) & t_{xx}-t_{yy}-i(t_{xy}+t_{yx}) \\ t_{xx}-t_{yy}+i(t_{xy}+t_{yx}) & t_{xx}+t_{yy}-i(t_{xy}-t_{yx}) \end{pmatrix} \quad (3)$$

where + and – denote right-handed and left-handed circularly polarized (CP) waves, respectively. The polarization rotation azimuth angle θ and its ellipticity angle η are given as follows.

$$\theta = -\frac{1}{2}[\arg(t_{++}) - \arg(t_{--})] \quad (4)$$

$$\eta = \frac{1}{2}\arcsin\left(\frac{|t_{++}|^2 - |t_{--}|^2}{|t_{++}|^2 + |t_{--}|^2}\right) \quad (5)$$

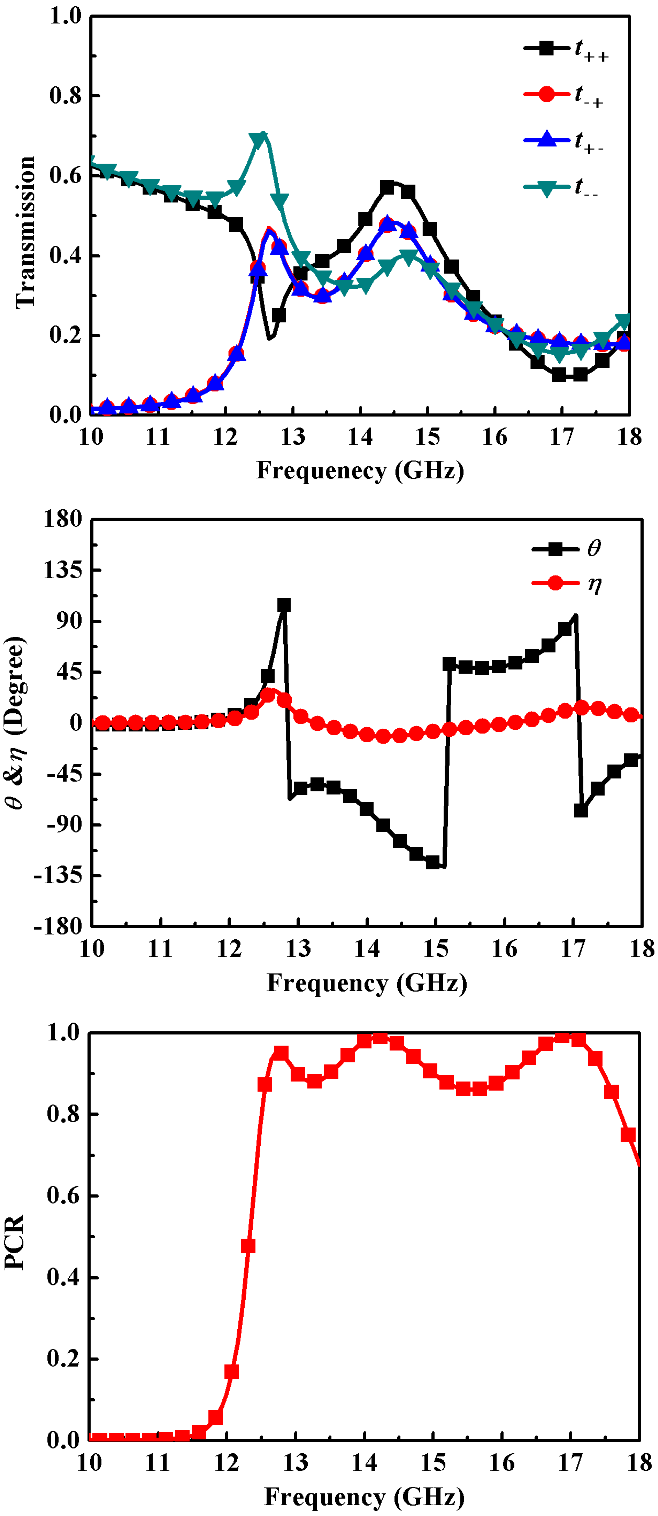

Fig. 4. (a) Calculated transmission spectra of CP waves. (b) Polarization rotation azimuth angle θ and its ellipticity angle η of the transmitted wave. (c) Simulated polarization conversion ratio.

Fig. 4(a) shows the transmission spectra of CP waves. Obviously, the values of t_{++} are different from that of t_{--}. As aforementioned, the circular polarization coefficient t_{+-} is extremely identical with t_{-+} at all frequencies, thus no AT of CP wave occurs. In Fig. 4(b), the transmitted wave is nearly linearly polarized in the frequencies of 12.6-17.5 GHz, since the ellipticity is close to zero, accompanied by larger than ±45° of polarization rotation angle. The polarization conversion ratio (PCR) (PCR = $t^2_{yx} / (t^2_{yx} + t^2_{xx})$) of transmitted waves is also checked for the *x*-polarized incident wave as shown in Fig. 4(c). The bandwidth of PCR over 80% can be achieved from 12.5 to 17.7 GHz for simulation, indicating that the CMM holds broad-band properties and more than half of the energy of *x*-polarized waves is converted. In this broad bandwidth, the *x*-polarized incident waves for the forward propagation can pass through the CMM and then convert to *y*-polarized waves while the *y*-polarized incident waves are blocked.

IV. Conclusion

In summary, we have numerically proposed a dual band AT and polarization conversion for LP waves in a CMM. The CMM is constructed by two separate layers of oval ring resonators with a twist angle of 90°. The simulated results show that the CMM can realize a dual-band polarization conversion for LP waves in 10-18 GHz. The bandwidth of PCR over 80% can be achieved from 12.5 to 17.7 GHz. We think that with the simple geometry by scaling the structural parameters, the proposed CMM is benefited in designing polarization controlled devices.

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