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Broadband asymmetric transmission and polarization conversion of a linearly polarized wave based on chiral metamaterial in terahertz region

De-jun Liu, Zhong-yin Xiao *, Xiao-long Ma, Kai-Kai Xu, Jiang-yao Tang, Zi-hua Wang

School of Communication and Information Engineering, Key Laboratory of Special Fiber Optics and Optical Access Networks, Shanghai University, Shanghai 200072, China

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A novel chiral metamaterial consisting of double L resonators on two sides of the dielectric substrate is proposed in this paper. The structure can realize broadband asymmetric transmission and polarization conversion of a linearly polarized wave in the terahertz band. The polarization conversion ratio of the linearly polarized wave is more than 80% across a wide frequency range from 2.65 THz to 5.58 THz. Furthermore, the structure realizes three bands polarization angle independent 90° polarization rotator. In addition, optical activity and chirality parameter changing with frequency are studied in detail. The physical mechanism of the polarization conversion is also analyzed by the electric field distributions.

1. Introduction

Chiral metamaterials (CMMs) have attracted many researchers' attention since Pendry et al. [1] used them to realize negative refraction in 2004. Many new properties are found in the chiral metamaterial, such as optical activity, circular dichroism and asymmetric transmission (AT). Asymmetric transmission was first found in a planar chiral metamaterial by Fedotov et al. [2] in 2006, which quickly becomes a hot topic [3–9]. In recent years, control and manipulation of electromagnetic polarization states based on planar chiral metamaterials has been investigated. Compared with the traditional polarization manipulation devices, chiral metamaterial polarization rotators or convertors have many advantages such as the flat profile, high conversion efficiency, and scalability [10,7]. Chiral metamaterials can manipulate electromagnetic waves in different polarization states, such as linearly polarized, circularly polarized and elliptically polarized states. More recently, multilayered metallic meander-line grating [11], twisted split ring resonators (SRRs) [12] and asymmetric U-shaped SRR structure [13] have been reported to control the polarization states in the microwave or infrared regions. Therefore, a metamaterial with the properties of broadband, multi-band, and high polarization conversion efficiency is still very desirable, especially in the terahertz band [14–26].

In this paper, a bi-layered chiral structure based on non-C4 (four-fold rotational) symmetry is proposed. The structure consists of double *L* resonators on two sides of the dielectric substrate, which realizes high-efficiency, broadband polarization conversions and asymmetric transmission of a linearly polarized wave in the terahertz band. The polarization conversion ratio of the linearly polarized wave is more than 80% across a wide frequency range from 2.65 to 5.58 THz. Owing to

* Corresponding author.
E-mail address: zhyxiao@shu.edu.cn (Z.-y. Xiao).

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non-C4 symmetry of the structure, optical activity and chirality parameter changing with frequency are studied in detail. It is found that the structure realizes three bands polarization angle independent 90° polarization rotator. The physical mechanism of the polarization conversion is also analyzed by the electric field distributions. We believe that the designed chiral metamaterial can also be used in other frequency bands, such as the microwave band and optical frequency regions.

2. Theoretical analysis

To better understand the effective parameters of chiral metamaterial, assuming a time harmonic field with $e^{j\omega t}$ dependence, the constitutive equation of a chiral medium can be expressed as [27]:

$$\begin{pmatrix} D \\ B \end{pmatrix} = \begin{pmatrix} \varepsilon_0\varepsilon_r & -j\kappa/c \\ j\kappa/c & \mu_0\mu_r \end{pmatrix} \begin{pmatrix} E \\ H \end{pmatrix} \tag{1}$$

where ε_0 and μ_0 are the permittivity and the permeability of vacuum, c is the speed of light in free space, ε_r and μ_r are the relative permittivity and the relative permeability of the chiral metamaterial, respectively, and κ is the chirality parameter.

When a linearly polarized wave passes through the chiral metamaterial, the transmitted electric field can be described as $E_t(r, t) = (T_x, T_y)^T e^{i(kz-wt)}$. The complex amplitudes of the incident and the transmitted waves can be represented by the T matrix [4]:

$$\begin{pmatrix} T_x \\ T_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} I_x \\ I_y \end{pmatrix} = T_{lin}^{f} \begin{pmatrix} I_x \\ I_y \end{pmatrix} \tag{2}$$

where T_{xx} and T_{yx} are the transmission coefficients of the transmitted waves polarized on x and y directions for a x-polarized incident wave. Similarly, T_{yy} and T_{xy} are the transmission coefficients of the transmitted waves polarized on y and x directions for a y-polarized incident wave.

Considering non-C4 symmetry of the proposed structure, we use T matrix to express the transmission coefficients of a circularly polarized wave [5,28]:

$$T_{\pm}^{x} = T_{xx} \pm i * T_{yx}, \qquad T_{\pm}^{y} = T_{yy} \pm i * T_{xy} \tag{3}$$

where $T_{\pm}^{x}$ and $T_{\pm}^{y}$ represent the transmission coefficients of a right-handed and a left-handed circularly polarized waves of the proposed chiral metamaterial in the case of x-polarized and y-polarized waves, respectively.

The polarization plane of a linearly polarized wave will rotate when it passes through a chiral medium, which is called optical activity. Mathematically, it is defined as the polarization azimuth rotation angle [29,6]:

$$\theta_{x,y} = \frac{1}{2}\left[\arg(T_{+}^{x,y}) - \arg(T_{-}^{x,y})\right]. \tag{4}$$

The other property of chiral media is the circular dichroism which arises from the different absorption for right-handed and left-handed circularly polarized waves. The circular dichroism can be measured by the ellipticity (η), which can be expressed as:

$$\eta_{x,y} = \frac{1}{2}\sin^{-1}\left[\left(\left|T_{+}^{x,y}\right|^2 - \left|T_{-}^{x,y}\right|^2\right) / \left(\left|T_{+}^{x,y}\right|^2 + \left|T_{-}^{x,y}\right|^2\right)\right]. \tag{5}$$

In addition, the effective chirality parameter (κ) can be written as:

$$Re(\kappa^{x,y}) = \left[\arg(T_{+}^{x,y}) - \arg(T_{-}^{x,y})\right]/2k_0 d \tag{6}$$

$$Im(\kappa^{x,y}) = \left[\ln\left|T_{-}^{x,y}\right| - \ln\left|T_{+}^{x,y}\right|\right]/2k_0 d \tag{7}$$

where d is the thickness of the chiral medium, $k_0 = \omega/c$ is the free space wave number.

Optical activity in the natural material is generally very weak. However, a chiral metamaterial can possess a large polarization azimuth angle (θ) and a small ellipticity (η), which is very important for many field applications such as polarizer, isolator and circulator.

3. The designed structure and simulation

Fig. 1 shows the unit cell of the designed chiral metamaterial, which is composed of two metallic gold double L resonators on two sides of a dielectric substrate. The dielectric substrate is made of silica with relative permittivity 2.1, and the substrate thickness is $d = 4\ \mu$m. Periodic boundary conditions are applied in the x and y directions, and absorbing boundaries are applied in the z direction. Numerical simulations are performed with the CST Microwave Studio.