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Terahertz angle-insensitive 90° polarization rotator using chiral metamaterial

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ABSTRACT

We design and study a kind of gammadion-like chiral metamaterial (CMM), which uniaxially exhibits exceedingly strong optical activity and circular dichroism. The optical activity obtained by the proposed CMM rises to about 2280°/λ, which is much larger than that of the previously reported planar designs. Due to the giant chirality, the present CMM can realize negative refractive index easily at the resonant frequencies. The most fascinating property of the present CMM is that it can function as a 90° polarization rotator for wide incident angles, thereby holding great promise for future devices.

1. Introduction

Negative refractive index metamaterials (NRIMs) with many unusual physical properties and effects may lead to important applications in superlens [1], extraordinary transmission [2], slow light devices [3], and cloaking [4,5]. However, the conventional NRIMs were generally achieved by making the permittivity ε and permeability μ simultaneously negative [6–8]. Although the negative permittivity can be easily obtained, it is not the case for the permeability, especially in the optical region [9,10]. Recently, Tretyakov and Pendry [11,12] each proposed an alternative route to realize negative refractive index by chiral metamaterials (CMMs). Since then, CMMs have gained much interest, and many theoretical and experimental works have been proposed [13–19]. In fact, besides for the negative refractive index, CMMs also possess a lot of other intriguing properties, such as strong optical activity [20–22], circular dichroism [23,24], and even the prospect of a repulsive Casimir force [25,26]. For all the aforementioned cases, a strong chirality is desired.

By definition, the unit cells of CMMs lack any planes of mirror symmetry, the cross coupling between the magnetic field and electric field therefore occurs around the resonant frequency. Consequently, the degeneracy of the right-handed and left-handed circularly polarized (RCP, +/LCP, −) waves is broken, i.e., the refractive indices of the RCP and LCP waves are different. The chiral parameter κ is used to characterize the strength of cross coupling, where $\kappa=(n_+-n_-)/2$, n_+ and n_- are the refractive indices of the RCP and LCP waves, respectively. According to the previous theoretical work [12], if the chiral parameter κ is large enough, negative refractive index will be obtained in CMMs. In other words, the CMMs do not require simultaneously negative permittivity and permeability. Therefore, the geometry of CMMs will be much simpler, and it is also much easier to realize negative refractive index for CMMs. So far, some kinds of CMMs have been proposed, for instance, twisted cross-wires [17], twisted rosettes [18], conjugated gammadion [27] and four "U" split ring resonators [28,29]. Although the CMMs mentioned above can also realize negative refractive index and optical activity, none of them can function as a 90° polarization rotator, in which case, the polarization plane of a linearly polarized electromagnetic wave will be rotated by 90°.

Recently, He and Ye [30] proposed a 90° polarization rotator using the fourfold-rotational (C_4) cut-wire-pairs. However, as well as the other works, the CMM was investigated only for normal incidence, and the electromagnetic properties of a planar CMM at oblique incidence have not yet been studied. In this paper, we study a kind of gammadion-like CMM that operates at terahertz bands and exhibits much larger optical activity than the previously reported planar CMMs. The present CMM possesses giant chirality and can realize negative refractive index more easily. It can function as a 90° polarization rotator for wide incident angles, thus enabling extensive practical applications.

2. Theory and simulations

Fig. 1 shows the schematic of the considered CMM in this work. The unit cells consisting of bilayer gammadion-like resonant pairs are conjugatedly arranged on the opposite sides of an MgF_2 board. The metamaterial structure possesses C_4 symmetry along the z axis. The dimensions of the unit cell are shown in the captions of Fig. 1.

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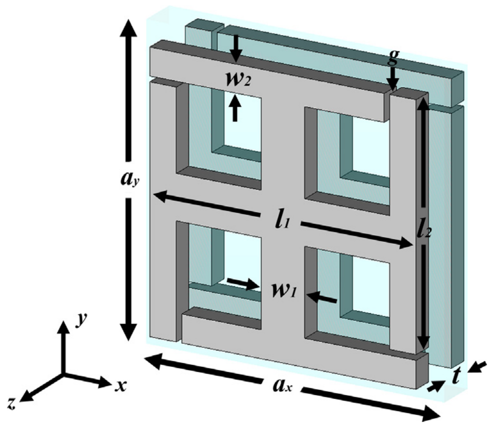

Fig. 1. Scheme of a unit cell of the gammadion-like CMM. The geometry parameters are given as follows: $a_x = a_y = 560$ nm, $l_1 = 500$ nm, $l_2 = 440$ nm, $w_1 = 82$ nm, $w_2 = 50$ nm, $g = 10$ nm and $t = 75$ nm. The thickness of silver is 40 nm.

We have performed full-wave simulations to study the electromagnetic behaviors of the gammadion-like CMM by using the CST Microwave Studio. The simulations were achieved by the frequency domain solver that implemented a finite integration technique. In the simulations, the unit cell boundary conditions were applied to the x and y directions and absorbing boundary conditions were applied to the z direction. A linearly polarized electromagnetic wave is incident on the CMM. The optical constants of silver in the frequency range of our simulations are described by the Drude model with plasma frequency $w_{pl} = 1.37 \times 10^{16}\ s^{-1}$ and collision frequency $w_{col} = 8.5 \times 10^{13}\ s^{-1}$ [31]. MgF_2 is treated as lossless dielectric with permittivity $\varepsilon = 1.9$ [8].

It is known that the RCP wave and LCP wave are the two eigensolutions of the electromagnetic wave in chiral materials, and the four corresponding transmission coefficients, T_{++}, T_{+-}, T_{-+}, and T_{--}, which characterize the response of the CMMs, can be converted from the four linear copolarization and cross-polarization transmission coefficients, T_{xx}, T_{xy}, T_{yx}, and T_{yy}, by the following equation [17]:

$$\begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2} \times \begin{pmatrix} (T_{xx}+T_{yy})+i(T_{xy}-T_{yx}) & (T_{xx}-T_{yy})-i(T_{xy}+T_{yx}) \\ (T_{xx}-T_{yy})+i(T_{xy}+T_{yx}) & (T_{xx}+T_{yy})-i(T_{xy}-T_{yx}) \end{pmatrix},$$

where T_{++} and T_{--} are the transmission coefficients for the RCP and LCP waves, respectively. The cross coupling transmission T_{+-}, and T_{-+} can be neglected as they are near zero at normal incidence. For the circular reflection coefficients R_{++}, R_{+-}, R_{-+}, and R_{--}, a similar expression also exists.

For a CMM, there are two important properties. One is called optical activity, arising from the transmission-phase difference between the two circularly polarized waves, and it is characterized by the polarization azimuth rotation angle θ, which is calculated by the formula:

$$\theta = [\arg(T_{--}) - \arg(T_{++})]/2,$$

The other is called circular dichromism which refers to the difference between the transmission spectrums of two circularly polarized waves. It is revealed by the ellipticity η defined as:

$$\eta = \arctan[(|T_{--}|^2 - |T_{++}|^2)/(|T_{--}|^2 + |T_{++}|^2)]/2.$$

3. Results and discussions

3.1. The simulation results at normal incidence

Fig. 2(a) shows the simulated transmission spectra. There are two resonances in the transmission spectrums. One resonance is a peak that occurs around $f = 73.7$ THz and the other one corresponds to a dip around $f = 78.4$ THz. At the resonant frequencies, the transmission of RCP and LCP waves are significantly different. Around the frequency of 73.7 THz, the transmission of the LCP wave is higher than that of the RCP wave, while it reveres around the frequency of 78.4 THz.

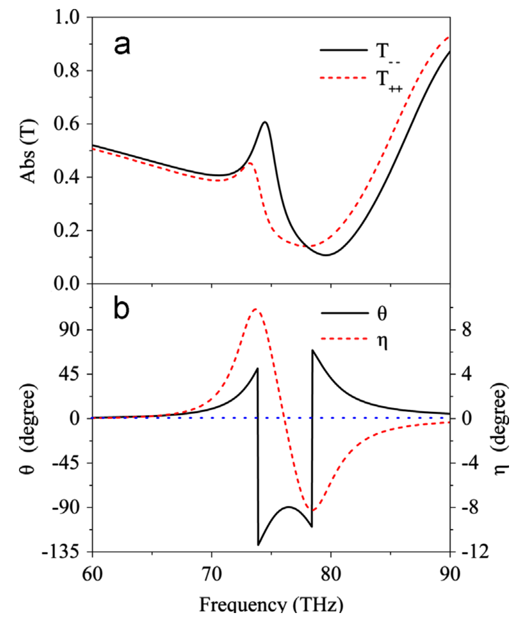

Fig. 2. Simulation results for the CMM. (a) The transmission spectrums for RCP and LCP waves. (b) The polarization azimuth rotation angle θ and ellipticity η.

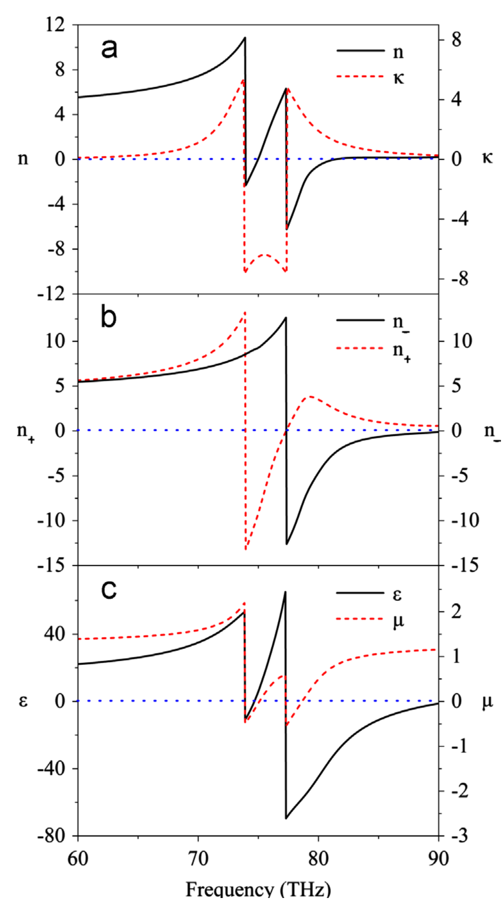

Fig. 3. Retrieved effective parameters of the CMM. (a) The real parts of the average refractive index n and chiral parameter κ. (b) The real parts of refractive indices for the RCP and LCP waves. (c) The real parts of the permittivity ε and permeability μ.