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Tunable multi-band chiral metamaterials based on double-layered asymmetric split ring resonators

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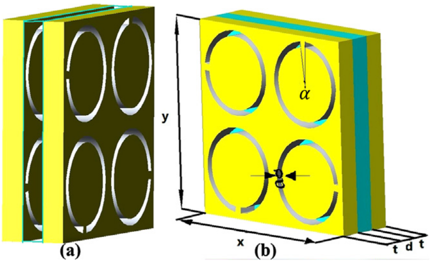
HIGHLIGHTS

- A chiral metamaterial based on double-layered asymmetric Au film with hollow out split ring resonators (SRRs) on both side of the polyimide is presented.
- The correct geometric parameters are given by optimization for structure.
- The larger optical activities and five negative refraction bands of the LCP wave and the RCP wave account for 22% and 25% of total visible light region are obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

We have numerically demonstrated chiral metamaterials based on double-layered asymmetric Au film with hollow out design of split ring resonators on either side of the polyimide. Multiple electric dipoles and magnetic dipoles resulted from parallel and antiparallel currents between the eight split ring resonators. Multi-band circular dichroism is found in the visible frequency regime by studying the transmission properties. Huge optical activity and the induced multi-band negative refractive index are obtained at resonance by calculating the optical activity and ellipticity of the transmitted E-fields. Chirality parameter and effective refractive index are retrieved to illustrate the tunable optical properties of the metamaterials. The underlying mechanisms for the observed circular dichroism are analyzed. These metamaterials would offer flexible electromagnetic applications in the infrared and visible regime.

1. Introduction

Metamaterials with negative refraction have drawn significant attention since Smith et al. successfully prepared such metamaterials in the laboratory in 2000 [1]. Recently, increasing attention has been focused on chiral metamaterials (CMMs) owing to their attractive electromagnetic (EM) properties, such as their large optical activity, strong circular dichroism (CD) effect, negative refractive index (NRI), and asymmetric transmission effect [2–11]. CMMs with self-polarization and cross-polarization between electromagnetic fields can achieve NRI depending on their chirality, whether or not the permittivity and permeability are negative. Furthermore, they can exhibit strong optical activity and lower loss of the electromagnetic wave (EMW) transmission [3].

Recently, negative refraction CMMs have shown large optical activities (e.g., $\theta = 130°$) [12], high-frequency regions (3×10^{14} Hz) [13], lower loss (FOM = 4.2) [14], and high negative refraction value ($n = -180$) [15]. Chirality is the lack of the internal mirror symmetry of a molecule or artificial structure. Optical activity is a major characteristic of CMMs. In nature, optical activity is caused

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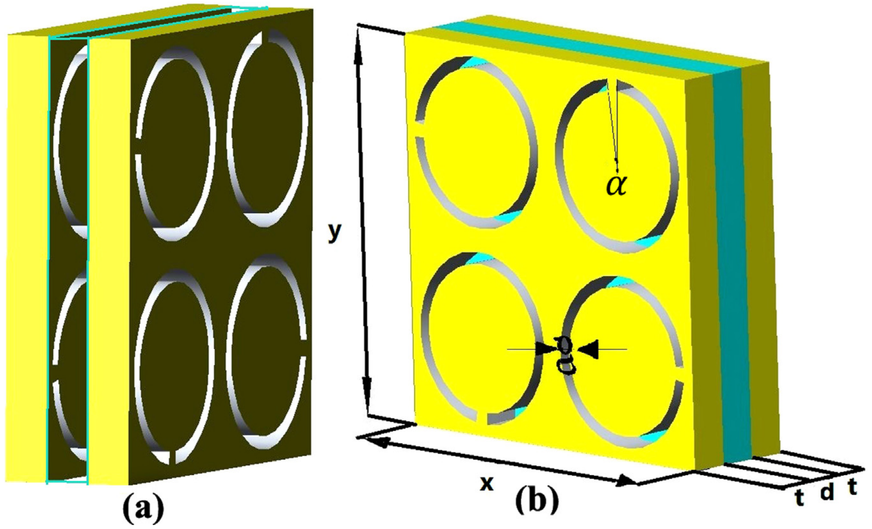

Fig. 1. The unit cell of the chiral metamaterial (CMM): (a) Perspective view of the structure includes hollowed-out split ring resonators in front and back. (b) Full dimensions of the three-layered structure composed of Au layer, polyimide layer and Au layer another, $x=y=500$ nm, the metal layer thickness is represented by t, the dielectric layer thickness is represented by d, the width of the rings is represented by g (between outer radius and minus inner radius), and the angle of splits is represented by α. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

by the intrinsic spiral feature of chiral molecules or the spiral arrangement of its atomic molecules. The optical activity of a natural chiral medium is caused by the intrinsic helical characteristics of molecules or the spiral alignment of atoms, and the root of the rotation is circular birefringence, and strength is very weak. For artificial CMMs, optical activity is caused by the optical spatial dispersion of structural chirality. Compared with nature, CMMs have higher optical activities and chiralities [3,12,16,17].

CD (Δ) refers to one of the main physical parameters for characterizing the absorption of the RCP wave (+, right circular polarization wave) and the LCP wave (−, left circular polarization wave):

$$\Delta = |T_{++}| - |T_{--}| \tag{1}$$

The polarization azimuthal rotation angle (θ) refers to the angle of rotation with respect to the plane of polarization:

$$\theta = \frac{\arg(T_{--}) - \arg(T_{++})}{2} \tag{2}$$

The ellipticity (η) refers to the difference of polarization state of transmitted and incident waves, and also measures the CD effect. It is caused by electromagnetic coupling between two layers of the CMM:

$$\eta = \frac{1}{2}\arctan\left(\frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2}\right) \tag{3}$$

Here, T_{++} refers to the transmission coefficient of the RCP wave and T_{--} refers to the transmission coefficient of the LCP wave. Using the retrieval methods for CMMs [18], we can obtain the effective impedance (Z_{eff}), the refractive index of the RCP and LCP waves ($n_{\pm}$), and the effective refractive index (n_{eff}) of the chiral medium:

$$Z_{eff} = \sqrt{\frac{(1+R)^2 - T_{++}T_{--}}{(1-R)^2 - T_{++}T_{--}}} \tag{4}$$

$$n_{\pm} = \frac{-j}{k_0 d}\ln\left[\frac{1}{T\pm\pm}\left(1 - \frac{Z_{eff}-1}{Z_{eff}+1}R\right)\right] \tag{5}$$

$$n_{eff} = (n_{+} + n_{-})/2 \tag{6}$$

Here, κ_0 refers to the wave number in free space, and d refers to the equivalent thickness of the chiral structure. The effective impedance and equivalent refractive index are the basis for obtaining the effective chiral parameter (κ_{eff}) and effective permittivity (ε_{eff}):

$$\kappa_{eff} = (n_{+} - n_{-})/2. \tag{7}$$

$$\varepsilon_{eff} = n_{eff}/Z_{eff}. \tag{8}$$

In this work, we used the finite difference time domain (FDTD) method to systematically study the complementary split ring shaped CMM. In this context, it has been shown that an NRI and a large optical activity occur at infrared and visible light frequencies. The geometrical parameters are examined to explore the strong optical activity, CD effect, and NRI at these frequencies. Endowed with these rich EM (optical) properties, CMMs may lead to many applications in photonic devices on account of their strong optical activity (polarization rotation effect) and CD effect.

2. Physical model and mechanism analysis

Babinet's principle was applied to the design of the metamaterial, resulting in both a complementary spectral response and fields [19–22]. We created a chiral structure in an array of conjugated bilayer metal split ring resonators, as shown in Fig. 1(b), where the conjugated bilayer metal split ring resonator is depicted as yellow, and the dielectric layer is depicted as blue. The unit size of the chiral structure is $x=y=500$ nm. The CMM consists of three layers (i.e., Au/polyimide/Au). The metal layer thickness is represented by t, the dielectric layer thickness by d, the width of the ring by g (outer radius minus inner radius), and the angle of cut by α. The location of the cut rotates by 90° from ring to ring. The dielectric constant of the polyimide is 3.5, and the loss tangent is tan $\tan\delta=0.003$. Gold can be described by Drude dispersion model as follows: $\varepsilon = 1 - \omega_p/\omega(\omega + i\omega_\gamma)$. The plasma frequency is $\omega_p = 1.37\times10^{16}\ \mathrm{s}^{-1}$, and the collision frequency is $\omega_\gamma = 2.04\times10^{14}\ \mathrm{s}^{-1}$ [23].

The current density distributions and electric field distributions were obtained from numerical simulations at nine resonance frequencies where strong optical activity occurs, as shown by Fig. 2.