Optik 125 (2014) 1316–1319

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

A numerical parameter study of chiral metamaterial based on complementary U-shaped structure in infrared region

Yang Liu[a,b], Yongzhi Cheng[a,*], Zheng Ze Cheng[c]

[a] School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
[b] School of Science, Wuhan Institute of Technology, Wuhan 430074, China
[c] School of Electronic and Information Engineering, Hubei University of Science and Technology, Xianning 437100, China

ARTICLE INFO

Article history:
Received 5 April 2013
Accepted 5 August 2013

PACS:
42.25.Bs
78.20.−e

Keywords:
Optical activity
Circular dichroism
Negative refractive index
Complementary U-shaped structure

ABSTRACT

In this paper, the optical properties of the chiral metamaterial (CMM) with complementary U-shaped structure assembly have been investigated numerically in infrared frequencies. Here, we systematically study the dependence of CMM's optical properties to the structural parameters. The giant optical activity, circular dichroism (CD), and high negative refraction can be obtained by properly selecting the parameters, respectively. CMMs will also lead to many applications in photonic devices due to their strong polarization effect and CD effect.

1. Introduction

Electromagnetic (EM) metamaterials (MMs) are new fascinating artificial materials with ability to manipulate beams of light in surprising ways, which is basically composed of subwavelength metallic resonators held together in a dielectric [1]. Recently, increasing attention has been focused on the chiral metamaterials (CMMs) due to their attractive EM (optical) properties such as giant optical activity, strong circular dichroism (CD) effect, negative refractive index (NRI) and asymmetric transmission effect [2–11]. CMMs are artificial materials that lack any planes of mirror symmetry, so that there is cross-coupling between the electric and magnetic fields at the resonance. The strength of cross-coupling is characterized by the chiral parameter $\kappa = (n_+ - n_-)/2$ [12], which is connected to the refractive index $n_\pm = \sqrt{\varepsilon\mu} \pm \kappa$, $n = \sqrt{\varepsilon\mu}$, where ε and μ are the relative permittivity and permeability of the CCMs; n_+ and n_- represent the refractive indices of the right-handed circularly polarized (+, RCP) and left-handed circularly polarized (−, LCP) waves, respectively. At the same time, both RCP and LCP waves have the same impedance of $z = \sqrt{\mu/\varepsilon}$.

Owing to its intriguing properties (such as the giant optical activity and CD effect), which possess great potential application to many areas of science, such as analytical chemistry and molecular biology. To realize the larger optical activity, CD effect and negative refractive property, various enantiomeric forms or similar bi-layer chiral structure, such as Twisted-Rosettes [13,14], Twisted-Crosswires [15,16], Four-U-SRRs [17–19], and Conjugate-Swastikas [20], complementary structure [21,22] and other novel structures [23–29] have been proposed and investigated widely. Nearly all these CMMs structure can achieve negative refractive index or stronger CD effect at resonance, and optical activity at off-resonance.

In the present work, we used the finite difference time domain (FDTD) method to systematically study the complementary U-shaped structure CMMs, which has been shown experimentally that negative refractive index and huge optical activity occur at microwave frequency [22]. Dependence of geometrical parameters are examined to explore strong optical activity, CD effect and negative refractive index in the infrared frequencies. With endowed richer EM (optical) properties, CMMs not only support negative refraction generatiqqwaaon, but also lead to many applications in photonic devices due to their strong optical activity (polarization rotation effect) and CD effect.

2. Physical model and numerical method

Babinet's principle would be applied to the MMs design, resulting in both a complementary spectral response and fields

* Corresponding author. Tel.: +86 15872388449; fax: +86 027 87547337.
E-mail address: cyz0715@126.com (Y. Cheng).

0030-4026/$ – see front matter.
http://dx.doi.org/10.1016/j.ijleo.2013.08.012

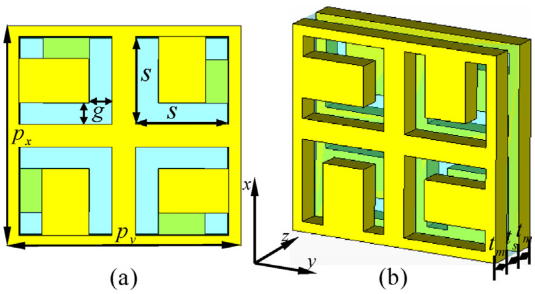

Fig. 1. Schematic diagram of the unit cell of the proposed complementary structure.

[21,30–32]. Generally, unit cell of U-shaped CMMs that is formed by four of these pairs, wherein the pairs are rotated by 0°, 90°, 180°, and 270° with respect to the EM wave propagation direction [17,33]. Fig. 1 shows the schematics of the construction of the unit cell of the CCMM. It indicates that the four twisted copper pair and continuous wires are patterned on the opposite sides of a dielectric membrane [22]. The spacer is selected as polyimide with the relative dielectric constant of 3.5 and a low loss tangent of 0.003, and the gold is described by the frequency dependent Drude model with plasma frequency $w_p = 1.37 \times 10^{16}\ \mathrm{s^{-1}}$ and scattering frequency $\gamma = 2.04 \times 10^{14}\ \mathrm{s^{-1}}$ [13].

The simulation has been performed based on the standard finite difference time domain (FDTD) method. The periodic boundary conditions are applied to the x and y directions and the absorbing boundary conditions to the z direction as well. In the actual simulations, a linearly polarized EM wave (electric field in the x direction) is incident on the CMMs and two linear transmission coefficients T_{xx} and T_{yx} are measured, where the first subscript indicates the transmitted field polarization (x-or y-polarized), and the second indicates the incident field polarization. The transmission coefficients of RCP wave and LCP wave can be expressed as $T_{++/--} = T_{xx} \pm iT_{yx}$ [15]. Here, due to the fourfold rotational symmetry, circular polarization conversion is absent, and the cross coupling transmission T_{+-} and T_{-+} are usually very small, thus negligible [22]. The detailed calculations were used to determine reflection and transmission coefficients from a single unit cell. Circular dichroism Δ and polarization azimuth rotation angle θ can be calculated by $\Delta = |T_{--}| - |T_{++}|$ and $\theta = [\arg(T_{--}) - \arg(T_{++})]/2$[22]. The ellipticity η can be calculated by $\eta = \arctan[(|T_{++}| - |T_{--}|)/(|T_{++}| + |T_{--}|)$, which defines the difference of polarization state of transmitted and incident waves, and also measures the CD effect. The complex effective parameters n, ε and η, and κ can be retrieved from the simulated transmission and reflection using the retrieval procedure for CMM [33,34].

3. Simulation results and discussion

3.1. Dependence of gap width g of the complementary U-shaped structure

Firstly, structures with different gap width g (g was selected as 10 nm, 20 nm, 40 nm and 80 nm) were calculated, and the other parameters were fixed as: $p_x = p_y = 500$ nm, $s = 200$ nm, $t_s = 50$ nm, $t_m = 50$ nm. There is no diffraction effect, since the geometry dimension of the unit cell of this CCMM is much smaller than the operating wavelength (<λ/10). The simulated circular dichroism Δ and polarization azimuth rotation angle θ, and the retrieved real part of refractive index n are presented in Fig. 2. It indicates that the functional frequency regions will blue-shift with the increase of g, which can be interpreted by L–C resonance circuit theory [35]. It can be observed that the Δ and the negative n will be up to maximal value of 7.2 dB and −2.5 when $g = 10$ nm, respectively. The absolute value of Δ is smaller 3 dB across the entire frequency region, when $g = 40$ nm, where the θ is up to maximal value of 73° with $\Delta = 0$ as shown in Fig. 2(b). It's mean that the CCMM can rotate a linearly polarized incident wave a certain angle θ at this frequency. As shown in Fig. 2(b) and (c), the θ of the middle of two resonance frequencies and the negative n will decrease with increase of the width g, which mainly originate from the weak of coupling effects between two sets of complementary structure. The coupling effects between the two complementary U-shaped structures in each pair are crucial for optical activity and negative index properties. Generally, the structural parameters of the complementary CMM will strongly influence the coupling effects, especial the thickness of the dielectric substrate and the width g of U-shaped slot. The coupling effects will weaken with the increase of the g gradually. It indicates that functional frequency region, optical activity, and negative refractive index can be tunable significantly by changing the gap width g of complementary U-shaped structure.

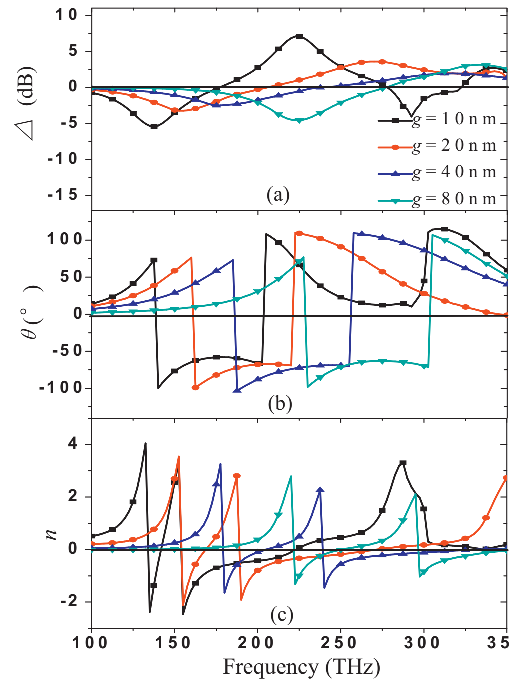

Fig. 2. Dependence of gap width g: (a) circular dichroism Δ, (b) polarization azimuth rotation angle θ, and (c) real part of refractive index n.

3.2. Dependence of lattice size s of the complementary U-shaped structure

We simulated structures with different lattice size s ($s = 120$ nm, 150 nm, 190 nm, 230 nm), while $g = 40$ nm and kept the other parameters unchanged. The corresponding numerical calculation results of Δ, θ, and n are presented in Fig. 3. It can be found that the functional frequency regions will red-shift remarkably with the increase of s, which is contrary to the case of the change of g. It is also can be interpreted by L–C resonance circuit theory. The Δ is up to maximal value of 19 dB for the lattice size s of 230 nm and the maximal negative n is −2.1, respectively. As the lattice size s increases, the Δ and the negative n will increase, and the θ will decrease gradually, respectively. It should be noticed that the θ can be up to −90° with $\Delta = 0$ when $s = 120$ nm, which indicates that the designed CCMM can be used as a 90°-polarization rotator in infrared region in this case. As shown in Fig. 3(c), we also can see that the magnitude change of the n is not remarkable, which is due to the coupling effects. We can conclude that the functional frequency region, optical activity, and circular dichroism effect can be