Dual-band polarization angle independent 90° polarization rotator using chiral metamaterial

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Abstract: The polarization angle-independent, dual-band, 90° polarization rotator presented in this paper consisted of a bilayered chiral metamaterial composed of twisted capacity-loaded I-shaped electric field-coupled resonators in C4 symmetry. Simulated and measured results consistently demonstrated that the rotator exhibited extremely low loss and high polarization ratio under dual-band conditions. We also systematically investigated the dependence of the electromagnetic response of the loaded structure on the geometric parameters. The proposed simple, easily fabricated model of a chiral metamaterial may be used in further polarization rotator applications.

Keywords: chiral metamaterials, optical activity, ellipticity, polarization, C4 symmetry

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Precise polarization control of waves is becoming increasingly important in many scientific fields including biology, physics, chemistry and optics [1, 2, 3, 4, 5, 6, 7]. The optical activity, which is a measurement of the polarization rotation of a plane polarized electromagnetic wave travelling in a chiral optical medium [1, 4, 7, 8, 9], is crucial for many scientific and technical applications, such as polarization manipulation in photonic devices [3] and sensing enantiomers of chiral molecules [8]. Although optical activity has been found in natural materials such as DNA, sugar, and protein, as well as many other bio-molecules, the magnetoelectric effect in nature is generally weak, which limits the ability of practical applications. Metamaterials are a series of composite materials that can exhibit some special properties. Depend on these properties, we can obtain many applications [1, 10, 11]. Chiral metamaterials (CMMs) [1, 12], which are constructed from artificial sub-wavelength metallic cells, have recently been reported to exhibit strong optical activity. Therefore, many significant studies have focused on the design of chiral metamaterials with strong chirality, including rotating resonator, twisted cross conjugated gamma-dion, and double four-U structure. The experimentally observed strong chirality is theoretically supported by the model of coupling between bilayer structures [9, 13]. However, large ellipticity at resonant frequency remains an obstacle for application in polarization rotators, which calculate the difference between two polarized waves [7, 12, 13, 14, 15]. Strong inter-cell coupling is proposed to enhance optical activity,

providing a small gap [8]. However, the design freedom of this adjacent structure is significantly restrained, and the structure remains independent of the polarization angle.

In this paper, we experimentally and theoretically demonstrate a bilayer metamaterial structure with strong optical activity using capacity-loaded I-shaped electric field-coupled (ELC) resonators. On the basis of a semi-analytic coupled RLC resonator model, we qualitatively and quantitatively determined how the observed the electromagnetic response relates to the geometry of the proposed resonator.

The simulated and measured results consistently demonstrated that the polarizer can rotate the polarization angle of the incident wave by 90° in dual-band mode with high efficiency and low ellipticity. Because the present resonator possesses rotational C4 symmetry [12, 13, 14, 15, 16], the incident wave polarization is insensitive.

2 Physical model and theory description

The proposed twisted chiral metamaterial is illustrated in Fig. 1(a), in which two capacity-loaded I-shaped resonator pairs were arranged in C4 symmetry. All of the structures were printed on the substrate (Arlon-AD 350) with a relative permittivity of 3.5 and a loss tangent of 0.003. The dimensions of the unit cell were $r1 = 4$ mm, $r2 = 2.9$ mm, $w1 = 0.27$ mm, $g1 = 0.11$ mm, and $g2 = 1.2$ mm. Moreover, the slab thickness, h , was set to 1.524 mm. The resonator was made from copper with a thickness of 0.035 mm and possessed an electric conductivity of $\sigma = 5.8 \times 10^7$ S/m. Fig. 1(b) shows a photo of the fabricated rotator. The fabricated sample was composed of 20×20 cells (360×360 mm). Because the pair of twisted capacity-loaded ELC resonators did not possess a connected structure, they showed C4 rotation symmetry, which can produce polarization angle independent responses without asymmetric transmission [2].

After the unit cell of the polarization angle-independent, 90° polarization rotator was designed, which was based on the chiral metamaterial of the I-shaped resonator structure, Ansoft HFSS, a commercial full-wave finite-element-method (FEM) solver was used to evaluate the performance of the proposed chiral structure. The structure was placed periodically along the x and y axis, and incident wave propagation was applied to the z axis. The model was excited by the Floquet port using a vertical incidence of linearly polarized waves in the frequency range from 9.6 GHz to 16 GHz. Because the strong chirality of chiral metamaterials was theoretically supported by the cross-coupling model, the observed symmetric transmission can be explained by the co-polarized and cross-polarized transmission properties of the EM wave in the chiral structure. The transmission matrix T was defined as $E_i^t = T_{ij} \cdot E_j^i$, where E_j^i represents the input y -polarized electric field and E_i^t represents the transmitted x -polarized electric field [16]. Due to the C4 symmetry of the chiral metamaterial structures.

$|T_{xx}| = |T_{yy}|$ and $|T_{xy}| = |T_{yx}|$ [7]. In other words, the amplitude properties remained invariant when the coordinate rotated along the z -axis. Thus, for simplicity, we only studied $|T_{xx}|$ and $|T_{yx}|$. The fabricated prototype was measured

Fig. 1. (a) Unit cell of the bilayered chiral metasurface. (b) The photography of the fabricated sample. (c) The I-shaped resonator structure and the equivalent RLC circuit. (d) The simplified equivalent RLC circuit of the I-shaped resonator.

using an Agilent vector network analyzer (E8362C) and two double ridged broad-band horns antenna (ETS Model 3115) as transmitting and receiving antenna.

Fig. 2 shows both the simulated and measured transmission spectra with an x-polarized incidence wave propagating along the z direction, which is expressed by $|T_{xx}|$ and $|T_{yx}|$. The simulated results showed that the designed structure can resonant at 11.11 GHz and 15.22 GHz. At 11.11 GHz, the simulated $|T_{yx}|$ is -0.5166 dB, and the $|T_{xx}|$ is -65.9 dB. At 15.22 GHz, the $|T_{yx}|$ is -0.5314 dB, and the $|T_{xx}|$ is -41.8729 dB. When $|T_{yx}|$ reached the maximum, $|T_{xx}|$ was almost the minimum. Thus, according to the numerical data, the cross polarization conversion ratio (PCR) [15, 16] was more than 99.9% at 11.11 GHz and 15.22 GHz. The measured PCR at 11.11 GHz and 15.22 GHz was also more than 99%. As illustrated in Fig. 2(a), the measured $|T_{yx}|$ and $|T_{xx}|$ were -0.65 dB and -33.83 dB at 11.11 GHz, and the $|T_{yx}|$ and $|T_{xx}|$ were -0.924 dB and -45.58 dB at 15.22 GHz. To obtain a full understand of the optical activity of our structure and its ability to create cross-polarization transmission, one must analyze the transmission results for circularly polarized waves [17]. These data can be directly calculated from the linearly polarized transmission results [18] according to the following equation:

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

Because the structure of the proposed chiral metamaterial was C4 symmetry, the $T_{-+} = T_{+-}$, $T_{++} = T_{yy} - i \cdot T_{xy}$, $T_{--} = T_{yy} + i \cdot T_{xy}$. From these calculations, we obtained the right-handed circular polarized wave (RCP) (T_{++}) and left-handed circular polarized wave (LCP) (T_{--}) [18, 19]. The polarization rotation angle θ and its ellipticity angle η are given as follows:

$$\theta = -\frac{1}{2} [\arg(T_{++}) - \arg(T_{--})], \quad \eta = \frac{1}{2} \arctan\left(\frac{|T_{++}| - |T_{--}|}{|T_{++}| + |T_{--}|}\right) \quad (2)$$

Fig. 2. (a) The simulated and measured transmission coefficient of the $|T_{xx}|$ and $|T_{yx}|$ of chiral metasurface. (b) The polarization rotation angle calculated from simulated and measured data. (c) The ellipticity calculated from the simulated and measured data.

The polarization rotation angle θ , which was calculated from the simulated and measured results, is shown in Fig. 2(b). At 11.11 GHz and 15.22 GHz, the simulated value of θ was 89.92° and 89.97° . Meanwhile, the measured optical activity (θ) was 89.45° and 87.82° , respectively. The ellipticity, η , which was calculated from simulated and measured results, is shown in Fig. 2(c). At 11.11 GHz and 15.22 GHz, the simulated ellipticity, η , was 0.97° and 0.9° , respectively. The measured ellipticity was 0.93° and -3.12° , respectively. Thus, the presented 90° polarization rotator, which was based on the proposed chiral metamaterial of I-shaped resonators, provided excellent performance with extremely high PCR and low transmission loss. Hence, the transmitted wave was almost completely linearly polarized, and the polarization angle of rotation was nearly 90° . The measured results are consistent with the simulated results.

Comparing with other 90° polarization rotator in recent years, this chiral metamaterial could improve the optical activity and circular dichroism. The results of polarization conversion depicted in Table I. Ye [1] and Song [6] could just achieve single band polarization rotation, the point of the 90° polarization rotation

wasn't the resonant point. Huang [7] proposed a SRRs structure which could get dual-band cross-polarization rotation but produced very low transmission efficiency and polarization rotation angle, the polarization of incident wave and incident angle were insensitive. Shi [15] proposed a 90° polarization rotator based on electric-field-coupled resonators, which could get insensitive incident wave and incident angle, but the polarization conversion ratio and polarization transmission efficiency just reached 90% and 95%, respectively. So the polarization conversion ratio and polarization transmission efficiency need improving in the following study.

Table I. Comparison of the 4-I structure of 90°-polarization rotator and 90°-polarization rotator in recent years

90°-polarization rotator	based on the metallic wire pairs of enantiomeric patterns [1]	Wide-angle 90°-polarization rotator [6]	based on split ring resonators array [7]	based on electric field coupled resonators [15]	based on 4-I structure
Optical activity (deg)	86	90	Close to 90	89.1	89.97
Polarization transmission efficiency	90%	Not the maximum polarization transmission	94.4% 93.3%	95%	98%
Polarization transformation frequency	Single band	Single band	Dual band	Dual band	Dual band
Polarization sensitivity	insensitive	insensitive	sensitive	insensitive	insensitive

This chiral metamaterial improved the optical activity to 89.97°, PCR reached 96.5%, transmission efficiency was 98% and the polarization rotation point is the maximum transmission point exactly. Hence, this structure reached higher optical activity and transmission efficiency, it also realized angle independent 90° polarization rotation.

3 Discussion

To understand the relationship between optical activity, ellipticity of the proposed metamaterial and the intra-cell capacitive loading of the I-shaped ELC resonators, a semi-analytic coupled RLC resonator model was proposed, as shown in Fig. 1(c). Since the distance between the inter cells was much greater than the coupling gap inside the cell, the RLC model was simplified by considering only the dominated capacitive loading. Therefore, in this part, we only discuss the planar layers. The resistor elements were ignored for the sake of simplicity. Due to the symmetry of the proposed resonator, we obtained a simplified RLC circuit model, which is shown in Fig. 1(d). C_1 and C_2 are the coupling capacity inside the unit cell, and C_1 is inversely proportional to the gap width, g_1 . Because the coupling length of

the gap between C_2 is much smaller than that of C_1 , C_2 is much smaller than C_1 . According to the theory of resonant circuits, we obtained expressions for the resonance frequencies f_1 and f_2 as follows:

$$f_1 = \frac{\sqrt{L_1 C_1 + L_2 C_1 + L_1 C_2 + \sqrt{(L_1 C_1 + L_2 C_1 + L_1 C_2)^2 - 4L_1 L_2 C_1 C_2}}}{2\pi\sqrt{2L_1 L_2 C_1 C_2}} \quad (3)$$

$$f_2 = \frac{\sqrt{L_1 C_1 + L_2 C_1 + L_1 C_2 - \sqrt{(L_1 C_1 + L_2 C_1 + L_1 C_2)^2 - 4L_1 L_2 C_1 C_2}}}{2\pi\sqrt{2L_1 L_2 C_1 C_2}} \quad (4)$$

To further elaborate the chiral response of the twisted capacity-loaded I-shaped inter-molecular coupling, we examined the value of C_1 of the I-shaped resonator with a gap width of g_1 and a length of $r_1 - g_2$. Using a coplanar strip capacitance formula [20], C_1 can be expressed as:

$$C_1 = \varepsilon_0 \varepsilon_{eff} \left\{ 1.15 \left(\frac{t}{g_1} \right) + 2.8 \left(\frac{w_1}{g_1} \right)^{0.22} \right\} (r_1 - g_2), \quad \varepsilon_{eff} = 1 + q(\varepsilon_0 - 1) \quad (5)$$

ε_{eff} and ε_0 are the effective dielectric constant and absolute dielectric constant of the substrate, respectively, q is the correction factor, which relates to the presence of the other resonator on two sides, t represents the thickness of the strip, $(r_1 - g_2)$ is the effective length of the coupling capacitance, and w_1 is the width.

To obtain a deeper understanding of the mechanism and effect of capacitive loading, a parametric study of the proposed resonator was performed, as shown in Fig. 3 and Fig. 4, respectively. The initial values of the unit cell were fixed and were identical to those described in section 2.

Fig. 3 depicts the transformation spectra when the gap width g_1 was varied from 0.07 mm to 0.2 mm. As g_1 decreased, the resonant frequencies decreased toward low frequencies. When g_1 was equal to 0.07 mm, the designed rotator operated at 11.09 GHz and 15.16 GHz. When g_1 was equal to 0.11 mm, the designed structure operated at 11.11 GHz and 15.22 GHz. When $g_1 = 0.2$ mm, the maximum of $|T_{yx}|$ was obviously misaligned with the minimum of $|T_{xx}|$.

The corresponding simulated optical activity and ellipticity at different values of g_1 are shown in Fig. 3(b) and (c), and the results are summarized in Table II. At all three resonant frequencies, the simulated optical activity θ was greater than 89.45° , and the simulated ellipticity η was less than 3° .

When g_1 decreased, the value of C_1 and C_2 increased, and the resonant frequency decreased. These results are consistent with the results under RLC-lumped mode. Without strong capacitive loading, for example, when $g_1 = 0.2$ mm, the optical activity and ellipticity were acceptable at the resonant frequencies but possessed low PCR.

Fig. 4(a) depicts the transformation spectra when the length g_2 was varied from 0.8 mm to 1.6 mm. The resonant frequency increased toward high frequencies as g_2 increased. When g_2 was equal to 1.6 mm, the designed rotator resonated at 11.78 GHz and 15.8 GHz. When g_2 was equal to 1.2 mm, the designed structure operated at 11.11 GHz and 15.22 GHz. When $g_2 = 0.8$ mm, the maximum of $|T_{yx}|$ was obviously misaligned with the minimum of $|T_{xx}|$.

Fig. 3. The simulations for different size of $g1$ (a) Transformation of wave (b) Optical activity (c) Ellipticity

Table II. Comparison of optical activity and ellipticity in $g1$

	$g1 = 0.07$ mm		$g1 = 0.11$ mm		$g1 = 0.2$ mm	
Frequency (GHz)	11.09	15.16	11.11	15.22	11.64	15.74
Optical activity (deg)	89.93	89.9	89.93	89.97	89.9	89.93
Ellipticity (deg)	1.51	0.97	-0.97	0.9	1.46	-1.3

Table III. Comparison of optical activity and ellipticity in $g2$

	$g2 = 0.8$ mm		$g2 = 1.2$ mm		$g2 = 1.6$ mm	
Frequency (GHz)	10.58	14.4	11.11	15.22	11.78	15.8
Optical activity (deg)	89.89	89.86	89.93	89.97	89.74	89.89
Ellipticity (deg)	-1.02	1.39	-0.97	0.9	1.31	1.16

The corresponding simulated optical activity and ellipticity at different values of $g2$ are shown in Fig. 4(b) and (c), and the results are summarized in Table III. At all three resonant frequencies, the simulated optical activity θ was greater than 89.7° , and the simulated ellipticity η was less than 1.5° .

When g_2 decreased, C_1 and C_2 increased, and the resonant frequency also decreased, which is consistent with the results of the RLC-lumped circuit. Due to the strong capacitive loading of C_2 , for example, when $g_2 = 0.8$ mm, the resonant tank of L_1 , C_2 dominated the RLC circuit. The optical activity and ellipticity was acceptable at resonant frequencies with low PCR.

Fig. 4. The simulations for different size of g_2 (a) Transformation of wave (b) Optical activity (c) Ellipticity

4 Conclusion

In this paper, we demonstrated a dual-band polarization angle-independent 90° polarization rotator. The proposed structure was based on the chiral metamaterial of the I-shaped resonator structure in C_4 rotation symmetry. The proposed two-layer metasurface exhibited higher efficiency (approximately 98%) and higher PCR (99.6%) in cross-polarization transmission. This bilayer chiral metamaterial provided excellent 90° rotation at 11.11 GHz and 15.22 GHz in the present experiment. At the same time, the observed strong cross-polarization was due to the strong optical activity, indicating that the polarization rotation angle was nearly 90° and the ellipticity angle was nearly 0° . Lastly, we qualitatively and quantitatively explained how the electromagnetic response scaled with the geometrical parameter of the proposed resonator. Due to the aforementioned properties, the proposed 90° polarization rotator may be used in antenna applications and telecommunication applications.

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