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Broadband and high-efficiency circular polarizer based on planar-helix chiral metamaterials

Jiang Wang,^{1,a)} Zhongxiang Shen,² and Wen Wu¹

¹*School of Electronic and Optical Engineering, Nanjing University of Science and Technology, 200 Xiaolingwei Avenue, Nanjing 210094, China*

²*School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*

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We reveal a broadband and high-efficiency circular polarizer based on chiral metamaterials composed of an array of planar helices, which can effectively reject the incident left-hand circularly polarized (LCP) wave, while allowing the right-hand circularly polarized (RCP) wave to pass through it. The physical mechanism of the proposed circular polarizer is explained with the aid of the current distributions under the excitations of LCP and RCP waves. Microwave experiments are performed to verify this idea, and measured results are in good agreement with the numerical ones. Experimental results show that a fractional bandwidth of 75.6% for the transmittance of the LCP wave lower than 0.2 can be obtained. Moreover, the proposed circular polarizer exhibits a high transmittance of over 0.9 for the RCP incident wave and a high circular polarization selection efficiency of over 0.95. The proposed circular polarizer will be potentially very useful for satellite and optical communications. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4990142>]

Polarization is a fundamental property of electromagnetic waves due to its inherent sensitivity in many phenomena, especially when the waves interact with matter. Controlling the polarization state of an incident wave is of great importance for a variety of applications.^{1–3} Polarization-selective devices function as spatial filters for electromagnetic waves of different polarization states.^{4–7} Linear polarizers can be easily achieved by utilizing a grid surface of parallel metal vanes arranged closely together,⁸ which can select a wanted direction of the linearly polarized wave from un-polarized waves. Different from the linear polarizer, circular polarizers can entirely reject one handedness of a circularly polarized wave, while simultaneously allowing the opposite one to pass through it without much attenuation. Such devices find widespread applications in optical communications, photography, and remote sensing.⁹ Up to now, circular polarizers have been extensively studied at microwave, terahertz, and optical frequencies.^{9–12}

Classical circular polarizers are basically designed using bended wires, and each unit cell consists of two $3\lambda/8$ orthogonal arms connected by a $\lambda/4$ arm along the propagation direction.^{12–14} The characteristics of those configurations depend on the length of the $\lambda/4$ arm, and thus, their performance deteriorates sharply with a change in the incident angle. Although the $\lambda/4$ arm was replaced by a parallel L-shape strip to achieve a planar structure,^{15,16} the transmission loss is extremely large and its application may be limited in practical systems. Additionally, an ultra-thin chiral metamaterial absorber was employed to achieve the circular polarization selection.¹⁷ Due to its extremely thin profile and subwavelength resonant characteristic, the bandwidth of this circular polarizer is inherently narrow. Another technique for designing circular polarizers is cascading two linear-to-circular

polarization converters with the separation of a linear polarizer.^{18,19} However, such circular polarizers are usually constructed using many layers, which results in a more difficult fabrication process and high cost.

Recently, one kind of twisted metamaterial based on closely spaced twisted broadband bianisotropic gold nanorod arrays was reported.^{20,21} Unfortunately, the extinction ratio and operation band of planar metamaterials are very limited and cannot meet the requirements of practical applications. To overcome these limitations, helical metamaterials were explored to realize a broadband circular polarizer.^{22–25} Later, several helix-like structures were proposed to improve the selection performance.^{26–28}

In this paper, we present a kind of planar-helix²⁹ chiral metamaterial to realize a broadband and high-efficiency circular polarizer, which not only has a high-contrast bianisotropic response analogous to helical metamaterials but also reduces the fabrication difficulty. The electric current distributions along the planar-helix under the excitations of left-hand circularly polarized (LCP) and right-hand circularly polarized (RCP) waves are carefully investigated to better understand the circular polarization selection mechanism. After that, the unique characteristic of the proposed circular polarizer is verified through both numerical simulations and experimental measurements. The results show that high rejection and transmission for LCP and RCP waves, respectively, as well as high circular polarization selection efficiency (CPSE) can be obtained over a broad frequency band.

Figure 1(a) schematically depicts the proposed circular polarizer, which consists of an array of one dimensional dielectric slab printed with several strips on both sides; two adjacent strips are connected by a metallized via-hole. Meanwhile, Fig. 1(a) also clearly shows that the proposed circular polarizer can effectively reflect the LCP incident wave back into the entrance space without changing its sense, while

^{a)}Electronic mail: wangjiang923@126.com

FIG. 1. Schematic diagram of the proposed circular polarizer. (a) 3-D view of the circular polarizer and its function. (b) Perspective, (c) front, and (d) back views in the x - z plane, and (e) y - z plane views of a unit cell. The metallic strips inside and behind the substrate are denoted by shadow.

it allows the RCP wave to pass through the structure. Structural details of a unit cell of the proposed circular polarizer are sketched in Figs. 1(b)–1(e). It is clear that the unit cell is a planar-helix chiral structure analogous to a traditional helical metamaterial. Intuitively, two pairs of metallic strips are printed on both sides of a substrate, with the front and backside adjacent strips connected through a metallized via-hole. It should be mentioned that the titled adjacent strips are implemented to produce the required helix pitch along the propagation direction. All strips are arranged according to a certain rule to form a structure of handedness. In this design, a right-handed two-turn planar-helix chiral metamaterial is formed. As manifested in Figs. 1(c)–1(e), the thickness and length of the substrate are denoted by t and l and periods are denoted by P_x and P_y along the x - and y - directions, respectively. Likewise, the length and width of strips are denoted by l_s and w_s , respectively. Furthermore, the metallic via-holes have the same diameter d , and the angle between two adjacent strips is marked as θ . It should be pointed out that the reflection and transmission behavior of the proposed circular polarizer is predicted using the full-wave electromagnetic simulation software *ANSYS HFSS*. Moreover, periodic boundary conditions (*Master* and *Slave*) are imposed along the x - and y -directions to characterize the infinitely large structure. It may also be mentioned that the excitation of the Floquet port with two orthogonal modes is employed to represent the incident wave. By setting the same amplitude and $\pm 90^\circ$ phase difference between two modes, the LCP and RCP incident waves can then be simulated.

For the frequency selective surfaces (FSSs) of reflection type, the incident linearly polarized wave will be rejected when the effective lengths of metal strips are close to half a wavelength.³⁰ Similar to FSS, in planar-helix chiral metamaterials, strong magnetoelectric coupling gives rise to an appreciably different response for LCP and RCP waves. Specifically, when a LCP wave propagating along the z -direction strikes on the planar-helix chiral metamaterials, strong interaction will occur because the rotation of electric vectors of the LCP wave is exactly the same as the helix one. This effect will produce strong resonances that in turn cause a reflection response for the incident LCP wave. To realize the resonance, the effective total length of the one-turn planar-helix and the effective pitch related to the designed wavelength should meet the following equations:²⁹

$$\lambda = 2(t\sqrt{\epsilon_r} + l_s\sqrt{(\epsilon_r + 1)/2}), \quad (1)$$

$$\lambda/4 = 2l_s \sin(\theta/2), \quad (2)$$

where ϵ_r is the relative permittivity of the substrate. In contrast, there is no resonance occurring on the planar-helix for the rotation of the electric vector opposite to the handedness of the planar helix, and therefore, the RCP wave can pass through the structure without much reflection. Thereby, the circular polarization selection property can be realized by the proposed planar-helix chiral metamaterial.

Figure 2 shows the simulated transmission spectra of LCP and RCP waves for the proposed circular polarizer. It is obvious that the circular polarizer features distinct transmittance for LCP and RCP waves. More specifically, the transmission level of the LCP wave is relatively low, below 0.2 from 10 to 23 GHz, representing a fractional bandwidth of 78.8% with respect to the center frequency of 16.5 GHz. Meanwhile, a high transmittance of around 0.9 for the RCP wave can be obtained in the entire frequency band. Therefore, the proposed circular polarizer can effectively reject the LCP wave, while simultaneously allowing the RCP wave to pass through the structure. Furthermore, three transmission zeros can be found at $f_1 = 11.2$ GHz, $f_2 = 17.1$ GHz, and $f_3 = 22.2$ GHz, facilitating bandwidth broadening with high selectivity of circular polarization selection response.

To gain insight into the nature of the polarization selection mechanism, the electric current distributions along the planar-helix under the excitation of LCP and RCP waves at the above three frequencies are carefully investigated, as shown in Fig. 3. It can be clearly seen from Figs. 3(a)–3(c)

FIG. 2. Simulated transmission spectra of the LCP and RCP waves for the proposed circular polarizer.

FIG. 3. Snapshots of electric current distributions along the planar-helix for the three resonant frequencies: f_1 , f_2 , and f_3 . (a)–(c) present the excitation of the LCP wave. (d)–(f) present the excitation of the RCP wave.

that under the excitation of the LCP wave, due to the fact that the length of the one-turn helix is close to the integer multiples of a half-wavelength, strong induced currents will be generated along the planar-helix and correspondingly can radiate the LCP wave. By properly controlling the effective helix pitch, the radiated and incoming LCP waves will interact with each other in the propagation direction so that no outgoing wave can be transmitted. It is therefore similar to band-stop FSS. In comparison, it is noted from Figs. 3(d)–3(f) that there is hardly any surface current induced on the helix under the excitation of the RCP wave for these three frequencies, which indicates that the helix does not interact with the RCP wave. Consequently, the RCP wave can pass through the structure with little reflection. Additionally, these three depicted modes [Figs. 3(a)–3(c)] closely resemble standing waves, which means that the positions of their current nodes change only slightly with time. The number of nodes increases from one to three as the frequency increases from the lower order mode to the high order mode. The superposition of these three modes leads to a broad-band response with three transmission zeros for the LCP wave.

To verify the functionality of the proposed configuration, a sample of $100\text{ mm} \times 100\text{ mm}$ containing an array of 27×20 unit cells is fabricated using the standard printed circuit board and plated through-hole technologies. The fabrication involves two types of structures in general. The first is the main dielectric slabs printed with periodic strips with

two adjacent strips connected by a metallized via-hole. The substrate used is Rogers 5880 with $\epsilon_r = 2.2 + i0.002$, which has a smaller imaginary part of its complex permittivity and hence absorbs less energy. In addition, the metallic strips have a thickness of 0.017 mm , which is much greater than the skin depth of copper at microwave frequencies, and therefore, copper is considered to be a perfect electrical conductor. Another part is the comb-structure with a total length of 105 mm , which is employed to support all the dielectric slabs at an equal spacing along the y -direction. The depth of these periodic slots is 5 mm in the comb with a width of 10 mm . The photograph of our assembled circular polarizer is shown in Fig. 4, and its physical dimensions are designed as: $l = 10\text{ mm}$, $t = 3.175\text{ mm}$, $d = 0.5\text{ mm}$, $l_s = 3.55\text{ mm}$, $w_s = 0.6\text{ mm}$, $p_x = 3.72\text{ mm}$, $p_y = 5\text{ mm}$, and $\theta = 80^\circ$. These values are consistent with those obtained from Eqs. (1) and (2), which illustrates the validity of these design formulas.

Since most antennas of circular polarization cannot operate over a broad frequency band with the axial ratio close to 1, their radiation beam is no longer circularly polarized when the frequencies are away from the center frequency. Alternatively, the measurement is carried out using two horn antennas of linear polarization with a vector network analyzer, and the distance from the antenna to the sample is set to 1 m to meet the far-field condition. Then, the transmission matrix for circularly polarized waves can be extracted subsequently by post-processing four transmittances of T_{xx} , T_{xy} , T_{yx} , and T_{yy} as follows:²⁸

$$\begin{pmatrix} T_{rr} & T_{rl} \\ T_{lr} & T_{ll} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} (T_{xx} + T_{yy}) + i(T_{xy} - T_{yx}) & (T_{xx} - T_{yy}) - i(T_{xy} + T_{yx}) \\ (T_{xx} - T_{yy}) + i(T_{xy} + T_{yx}) & (T_{xx} + T_{yy}) - i(T_{xy} - T_{yx}) \end{pmatrix} \quad (3)$$

where the former and latter subscripts correspond to the polarization of the transmitted and incident waves and the subscripts r and l represent the RCP and LCP waves, respectively.

The measured results of the proposed circular polarizer are plotted in Figs. 5–7, which show a good agreement with the simulated ones, while some small discrepancies between experiments and simulations are mainly attributed to the tolerances in the fabrication and characterization. It is clearly

FIG. 4. Photograph of the fabricated circular polarizer. The insets show the enlarged view of the comb and the front and back sides in the x - z plane of several unit cells.

seen in Fig. 5 that the level of the transmitted LCP wave ($|T_{ll}|$) is below 0.2 from 10.2 to 22.6 GHz, representing a fraction bandwidth of 75.6% with respect to the center frequency of 16.4 GHz, which represents a slight degradation compared to the simulated one. Moreover, three transmission poles in the measured spectrum of $|T_{ll}|$ are observable at frequencies of 11.7, 17.1, and 21.9 GHz, respectively, as previously discussed. Furthermore, Fig. 5 also exhibits that the cross-transmittance of the RCP wave ($|T_{rl}|$) in the entire frequency band is relatively small, which indicates that the circular polarization conversion does not take place in the

FIG. 5. Transmission spectrum of the LCP wave.

FIG. 6. Transmission spectrum of the RCP wave.

proposed structure. Accordingly, the proposed planar-helix chiral metamaterial acts as an obstacle to the LCP incident wave and prevents it from propagating, which can be demonstrated by the inset in Fig. 5.

Correspondingly, the spectrum of the transmitted RCP wave is shown in Fig. 6. One can clearly see that an extremely high and flat transmittance of around 0.9 for the RCP wave ($|T_{rr}|$) can be obtained when the RCP wave passes through the metamaterial, which sufficiently demonstrates that the proposed circular polarizer is almost transparent to the RCP wave. Meanwhile, the cross transmittance of $|T_{lr}|$ is also relatively low, which is similar to the situation of $|T_{rl}|$ under the LCP incident wave. Additionally, the inset of Fig. 6 clearly reveals that the electric vectors of the RCP wave do not interact with the planar-helix, and thus, the RCP wave can pass through the structure without much attenuation.

In order to clearly highlight the superior performance of our proposed circular polarizer, the circular polarization selection efficiency (CPSE) is utilized and can be described as

$$\text{CPSE} = \frac{|T_{rr}|^2 - |T_{lr}|^2}{|T_{rr}|^2 + |T_{lr}|^2} \quad (4)$$

Figure 7 shows the CPSE of the proposed circular polarizer. It is clear that a selection window with very sharp roll-off performance can be observed, which demonstrates that the proposed circular polarizer has a higher selectivity for the filtering response. Moreover, a remarkably stable and high CPSE of around 0.95 can be obtained, from 10.5 to 22.5 GHz, which is consistent with the $|T_{lr}|$ results. Furthermore, it is noted that the CPSE decreases dramatically outside the operating band because the planar-helix is no longer a resonator under the excitation of the LCP incident wave. Therefore, the LCP wave can also pass through the structure, and then, the selectivity will no longer exist. As a result, the proposed circular polarizer can efficiently reject the LCP incident wave while simultaneously allowing the RCP wave to pass through the structure with high selectivity.

In conclusion, we have experimentally demonstrated a circular polarizer based on planar-helix chiral metamaterials, which exhibits a high-contrast and broadband circular polarization selection. The electric current distributions along the planar-helix have been thoroughly investigated to reveal the circular polarization selection mechanism. A prototype of the proposed circular polarizer has been fabricated, and all measured results are in good agreement with the simulated

FIG. 7. CPSE of the proposed circular polarizer.

ones, which validates the proposed design concept. The proposed circular polarizer features a highly selective filtering response of high rejection and transmission for LCP and RCP waves, respectively, as well as high CPSE, which makes it very useful in a variety of exciting applications for polarization control. It may also have great potential to act as an integrated broadband circular polarizer for real-time full-Stokes polarization detection.

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