URSI AP-RASC, Sydney, Australia, 17 – 22 August 2025

Dual Band Transmissive Circular Polarizer Based on Metamaterial Split Ring Resonator

Fatima Ghulam Kakepoto* (1), Farman Ali Mangi (2), Syed Muzahir Abbas (3)

(1) School of Physics, Provincial Key Laboratory of Solid-State Optoelectronic Devices, Zhejiang Normal University, Jinhua 321004, P.R. China

(2) Department of Physics & Electronics, Shah Abdul Latif University Khairpur, 66111, Sindh, Pakistan

(3) School of Engineering, Faculty of Science and Engineering, Macquarie University, NSW 2109, Sydney, Australia

*hina_kakepoto@zjnu.edu.cn

Abstract

This paper presents a dual band transmissive circular polarizer based on metamaterial split ring resonator (SRR) to achieve asymmetric transmission of linear-to-circular polarized waves across dual frequency bands. The designed structure achieves right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) waves at 16.13–16.80 GHz and 16.90–17.24 GHz, respectively. Notably, the axial ratio bandwidths are 3.72% and 14.77% at the dual band frequencies. Moreover, 5×5 array has also been analyzed. The observed giant circular dichroism (CD) is explored through surface current distributions. These features make it highly suitable for advanced polarization conversion applications. Overall, the design achieves axial ratio (AR) bandwidth of 18.49% across the 12–18 GHz frequency range.

1. Introduction

The metamaterials (MMs) have attracted significant attention for their special electromagnetic properties due to effective permittivity and permeability and demonstrate exceptional performance in controlling polarization, phase, and amplitude through the use of nanostructured units [1]. The linear cross-polarization converter using an anisotropic metamaterial is reported for the wide bandwidth of 6 GHz that covers the entire Ku-band [2]. Recently, the metamaterials have been proposed to convert linear-to-circular polarized waves. For example, twisted complementary split ring resonators, twisted U-shape split ring resonators with CP eigenmodes [3-4].

Multilayer metamaterial based broadband circular polarizers have found significant applications in optical communication systems [5]. Metamaterials, which are artificially engineered materials, have garnered considerable attention due to their unique electromagnetic properties. Early studies on metamaterials primarily explored simple unit cell designs with high symmetry [6]. Recent advancements have introduced bi-layered ultra-thin chiral metasurfaces, enabling asymmetric transmission in the Ku-band frequency range. Additionally, a wideband circular polarizer using metamaterial has been developed for the X-band. This novel structure demonstrates improved asymmetric transmission and efficiently converts linearly polarized (LP) wave into (RHCP) waves at specific frequencies. [7-9]. A reconfigurable polarization converter utilizing a metasurface integrated with liquid crystals (LC) has been introduced, enabling the generation of both LHCP and RHCP waves. Additionally, the proposed metamaterial structure demonstrates potential for radar cross-section reduction in advanced applications [10-11].

This paper introduces a dual band transmissive circular polarizer based on metamaterial split ring resonator (SRR) for microwave communication system. The asymmetric transmission mechanism is associated with the structural design, which is thoroughly explained. The introduced structure effectively generates RHCP waves with high transmission efficiency in the frequency range of 16.13–16.80 GHz and LHCP waves between 16.90–17.24 GHz. The good transmission and a broader AR bandwidth at dual-bands are the advantageous futures of the suggested structure, which are comparatively better than the majority of the published work. The structure's simplicity ensures ease of fabrication, making it well-suited for microwave device applications and scalable to higher frequency ranges.

2. Design and Operating Principle

The unit cell consists of perfect electric conductor (PEC) material on each side of Roger substrate. The unit cell and 5x5 array designs are shown in Fig. 1 (a) and (b). The parameter p represents periodicity, while t denotes the substrate thickness. The width of both SRRs is labelled a w, with their outer and inner radii identified as r_1 and r_2, respectively. The opening of the rings is indicated by D, the horizontal openings of the upper and bottom SRRs are represented by D_1 and D_2. The thickness dented by t_m of the top and bottom SRR layers. Each ring's central angle is uniformly described by θ. Additionally, the rings printed on the backside of the substrate are rotated by an angle ϕ relative to the rings on the front side.

The material selected for the design is dielectric Roger RT/duroid 5880, permittivity εr=2.2 and loss tangent of 0.0009. The geometry dimensions of the structure are defined as follows: px=8mm, py=10mm, t=0.787 mm, w=1.87mm, r_1=1.4mm, r_2=3.4mm, D_1=2.4mm, D_2=1.57mm, t_m=0.01mm, θ=270°, and ϕ=290°.

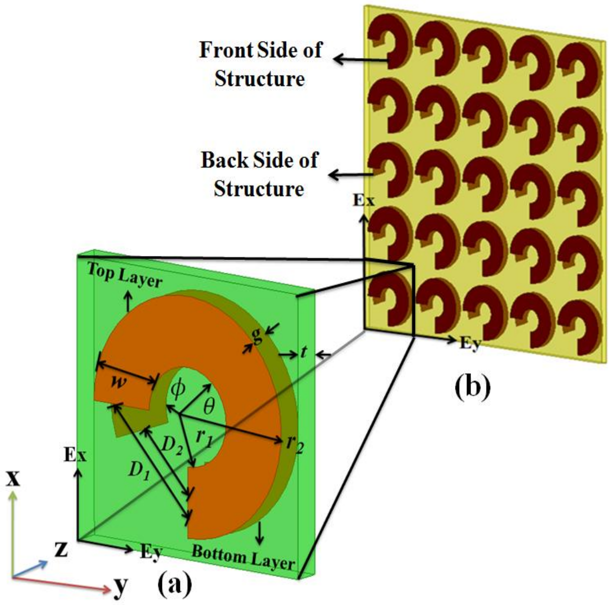

Figure 1. (a) the unit cell structure, (b) the 5x5 array of the structure.

The designed structure was simulated as a 5×5 array, maintaining the same parameters covering an area of 40mm × 40mm. The transmission properties were analyzed with ANSYS HFSS software, exhibiting a strong circular dichroism (CD) effect. The structure incorporates a bi-layered Split Ring Resonator (SRR) to generate circularly polarized (CP) waves in response to an incident x-polarized wave. The SRR elements effectively enable linear-to-circular polarization conversion.

3. Results and Discussion

The transmission coefficients co- and cross- polarizations (T_{xx} and T_{xy}) are obtained from the simulated results as 1.73dB, 3.59dB, 4.21dB, 6.37dB, and 7.78dB, 3.07dB, 2.44dB, 1.33dB are achieved at f_1=16.13GHz, f_2=16.80GHz, f_3=16.90GHz, and f_4=17.24GHz as shown in Fig. 2. The calculated phase difference is to be 111.99°, 109.07°, -255.38°, and -285.52° at f_1, f_2, f_3, and f_4 as denoted in Fig. 3. The AR is obtained as 0.7, 1.0, 1.22, and 1.78 at f_1, f_2, f_3, and f_4 as shown in Fig. 4. The AR bandwidths are extracted which are broaden at 16.13–16.80 GHz, BW=3.72% and 16.90–17.24 GHz, BW=14.77%, respectively. The RHCP and LHCP waves demonstrate high transmission in the frequency ranges of 16.13–16.80 GHz and 16.90–17.24 GHz, respectively. The simulated result shows that the amplitudes of T_{xx} and T_{xy} are nearly identical at the distinct frequencies, ranging from 16.13–16.80 GHz, and 16.90–17.24 GHz. It is evident that both co- and cross-polarization waves are efficiently transmitted and successfully changed into circularly polarized waves.

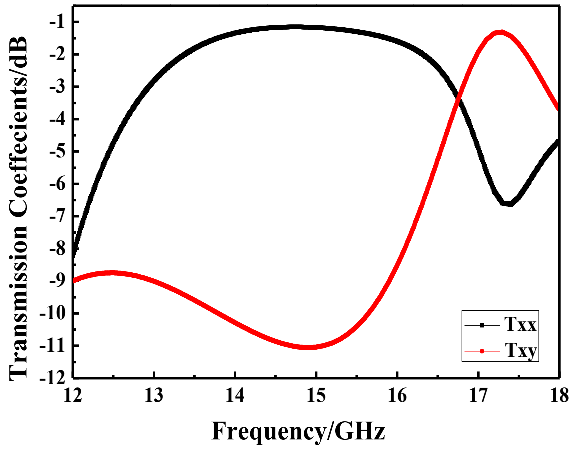

Figure 2. Transmission coefficients versus frequency.

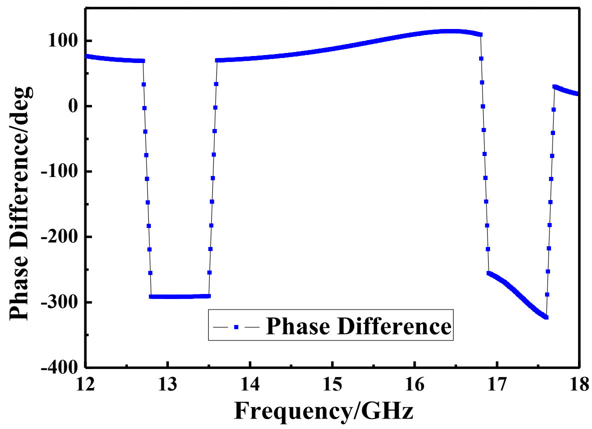

Figure 3. Phase difference versus frequency.

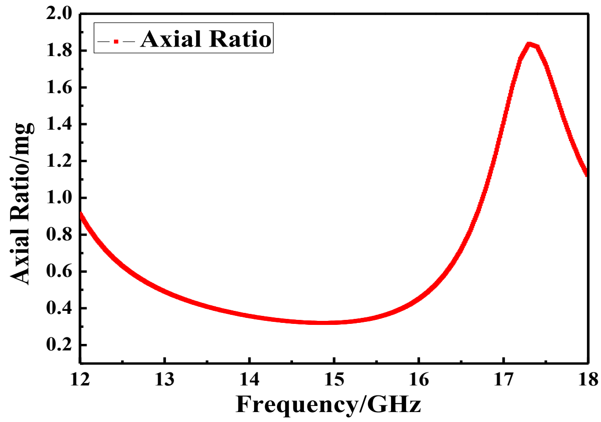

Figure 4. Axial ratio versus frequency.

The geometric parameter of the structure can be expressed by the resonant frequency f_r. The RLC resonant circuit and an inductor-capacitor make up the design's electrical equivalent circuit. The diagram of the equivalent RLC electrical circuit and is represented in Fig. 5.

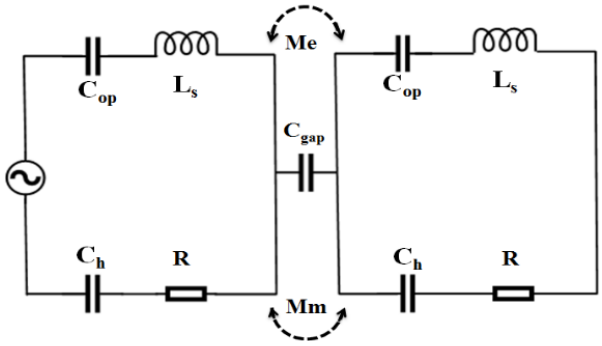

Figure 5. Dual Band transmissive circular polarizer's equivalent RLC circuit.

The capacity C_{op} denotes the horizontal opening space of the SRR and ring associated with the solenoid mentioned by L_s. Where C_h represents the capacity produced between horizontal rings. The mutual capacitance generated by C_{gap}. The applied metal of rings with inductance. The resonant frequency (f_r) of an SRR is determined by the LC resonance formula.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

Here, *L* and *C* represent the inductance and capacitance of the SRR, respectively. The capacitance (*C*) is influenced by the geometry of the gap (D_2) and the dimensions of the ring.

$$C = \varepsilon_0 \varepsilon_r \frac{wt}{D_2} \quad (2)$$

Here, "*w*" represents the width of the metallic SRR, "*t*" denotes the thickness of the substrate, and "D_2" is the gap between the rings. Additionally, ε_0 and ε_r correspond to the permittivity of free space and the substrate, respectively.

$$L = \mu_0 \mu_r \frac{2\pi r_{avg}}{w} \quad (3)$$

Where, r_{avg} is expressed as the average radius of the SRR, "*w*" is the width of the strip, μ_0 and μ_r are shows as the permeability of free space and permeability of substrate. The effective inductance (L_{eff}) and capacitance (C_{eff}) of the SRR can be tuned to shift the resonance frequency:

$$f_r = \frac{1}{2\pi\sqrt{L_{eff} C_{eff}}} \quad (4)$$

Where tuning the gap (D_2) or adjusting the strip width (*w*) impact both inductance (L_{eff}) and capacitance (C_{eff}) of the SRR.

The polarization transformation behavior and asymmetric transmission characteristics are analyzed through the surface current distributions on the SRR surfaces. These current distributions illustrate the resonance effects of the design at f_1=16.13GHz, f_2=16.80GHz, f_3=16.90GHz, and f_4=17.24GHz, as depicted in Fig. 6 (a)-(d). The strong optical activity and circular dichroism (CD) effects are attributed to the interaction between electric and magnetic fields. In-phase currents correspond to the electric response, while anti-phase currents result in a magnetic response.

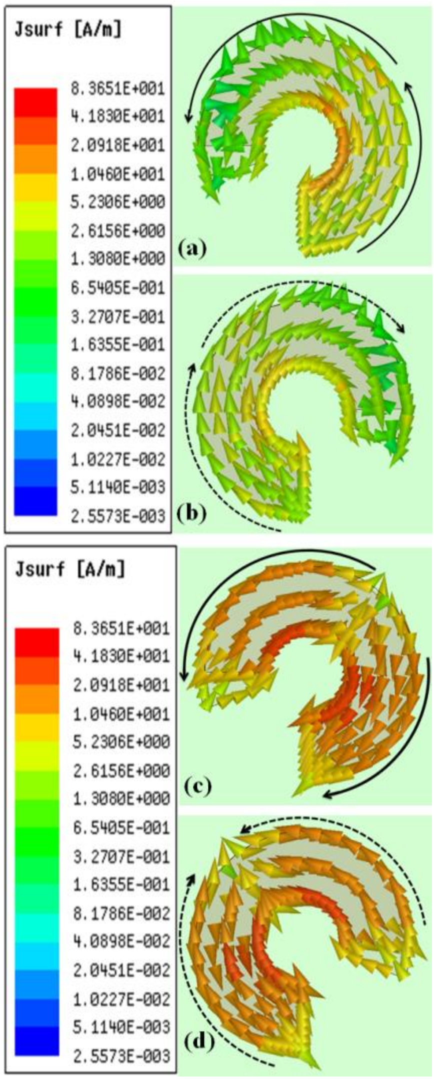

Figure 6. (a) and (b) the distributed surface current at 16.13–16.80 GHz, and (c) and (d) at 16.90–7.24 GHz.

The current distributions at f_1=16.13GHz, f_2=16.80GHz, f_3=16.90GHz, and f_4=17.24GHz, are represented by solid and dashed arrows in Fig. 6 (a)-(d). Fig. 6 (a) and (b) show that the currents on the top and bottom layers flow in the same direction, indicating a symmetric resonance mode. Conversely, Fig. 6 (c) and (d) demonstrate that the current on the top layer flows in the opposite direction at a lower frequency, revealing an asymmetric resonance mode.

4. Conclusion

This paper presents a method for constructing a dual band transmissive circular polarizer based on a metamaterial split ring resonator (SRR) design to demonstrate LP-to-CP wave. The proposed structure is presented to realize a significant circular dichroism (CD) effect. Notably, the axial ratio bandwidths are 3.72% and 14.77% at the dual-band frequencies. The design demonstrates high transmission efficiency across the operating frequency bands. Furthermore, by adjusting the geometry of the implemented SRR, the structure's bandwidth can be enhanced. This design is also scalable, making it suitable for use in higher-frequency arrays in the terahertz and optical regions. The proposed structure's excellent performance makes it a promising candidate for practical applications, including antenna systems, remote sensors, and optical devices.

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