A Linear-to-Circular Polarizer Using Split Ring Resonators

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Abstract **—** A transmission polarizer with one layer of splitting ring resonator to realize a linear-to-circular polarization rotator is presented. Based on the accurate design of anisotropic metamaterials, high conversion efficiency and 8 % frequency band are achieved. Microwave experiments were performed to realize these ideas successfully and results are in excellent agreement with numerical simulations.

Index Terms **—** Circularly polarized, linearly polarized, metamaterial, polarizer, and split ring resonators.

I. INTRODUCTION

Polarization is an important characteristic of electromagnetic (EM) waves and is often utilized in microwave and optical systems. It is always desirable to have full control of polarization in transmission and reflection of waves. Conventional methods to manipulate polarization include using optical gratings, dichroic crystals, or employing the Brewster and birefringence effects [1, 2]. Recently, metamaterials have been proposed to manipulate EM wave polarizations [3-8]. Metamaterials have drawn much attention recently due to its many fascinating properties, such as the negative refraction, the in-phase reflection, and the axially frozen modes, etc [9, 10]. A metamaterial reflector has been employed to manipulate the polarization state of an incident EM wave [6]. A near-complete cross polarization conversion has been achieved with anisotropic metamaterials. It is duo to the reflection phase difference in the two orthogonal polarizations. The disadvantage of the reflector polarizer is that the incoming and outgoing waves are difficult to separate. To overcome this, a metamaterial transmission polarizer has been proposed [7]. It can complete conversions from a linear polarization to a circular polarization and to its cross linear polarization effectively. Compared to the reflector polarizer, the incoming and outgoing waves in the transmission polarizer are naturally well separated, and therefore do not interfere with each other. However, in the transmission polarizer, it needs two (for the liner-to-circular polarizer) or four (for the liner-to-liner polarizer) pieces of substrate fixed with certain spacing. These substrates bring many reflections, which make the transmission efficiency of the polarizer restricted. Another alternative approach to the polarization conversion is by using a bilayered chiral metamaterials [8]. It is composed of a substrate coated on both surface with some enantiomeric patterns. In this polarization rotator, a 90° polarization rotation with high polarization conversion efficiency is obtained, but the bandwidth is only about 3 %.

In this paper, we propose a new transmission polarizer in which only one layer of splitting ring resonator (SRR) is fabricated. It completes the conversion from a linearly polarized wave to a circularly polarized wave successfully. The transmission efficiency of the polarizer can be controlled and the frequency band is extended to about 8%. Microwave experiments were performed and the results are in agreement with numerical simulations. Both the results of the simulations and the experiments show that highly efficient conversion from a linear polarization to a circular polarization has been accomplished.

II. NUMERICAL ANALYSIS

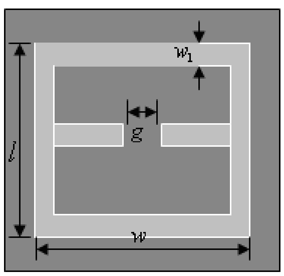
Figure 1 (a) shows the schematic diagram of one unit cell of the present polarizer. The

Submitted On: Nov. 21, 2012
Accepted On: Mar. 30, 2013

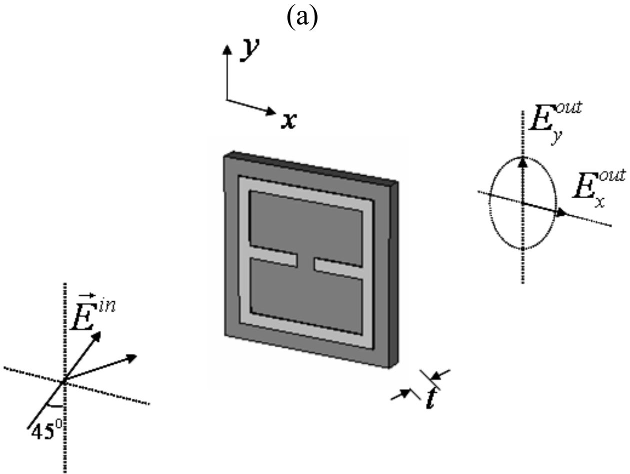
dimension of the unit cell is 11 × 11 mm^2. The dielectric constant of the substrate is ε_r = 2.65 and its thickness t is 1 mm. The SRR with 0.1 mm thick is coated on one side of the substrate. Both the length l and width w of the SRR are 9 mm. The width of the wires is w_1 = 0.75 mm. The air gap g between two adjacent cut-wires is 1.2 mm. The incident wave $\vec{E}^{in}$ normally impinged on the sample can be decomposed into two modes with the electric fields along the x axis and the y axis ($\vec{E}^{in} = \hat{x}E_x^{in} + \hat{y}E_y^{in}$, as shown in Fig. 1 (b)). The incident wave is linearly polarized with,

$$\left|E_x^{in}\right| = \left|E_y^{in}\right| \quad (1)$$

$$\arg\left(E_x^{in}\right) = \arg\left(E_y^{in}\right). \quad (2)$$



(a)



(b)

Fig. 1. (a) Unite cell of the polarizer and (b) the schematic picture of the polarization state of the incident and transmitted waves.

The transmitted wave is $\vec{E}^{out} = \hat{x}E_x^{out} + \hat{y}E_y^{out}$. For the two wave modes, the transmission coefficients T_x and T_y are defined as,

$$T_x = \left|E_x^{out}\right| / \left|E^{in}\right| \quad (3)$$

$$T_y = \left|E_y^{out}\right| / \left|E^{in}\right|. \quad (4)$$

The axial ration p and phase difference of the transmitted wave are defined as [11],

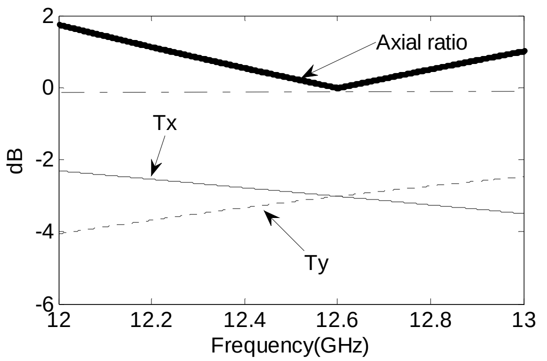
$$p = 20\log\left(\left|E_x^{out}\right| / \left|E_y^{out}\right|\right) \quad (5)$$

$$phase\ difference = \left|\arg\left(E_x^{out}\right) - \arg\left(E_y^{out}\right)\right|, \quad (6)$$

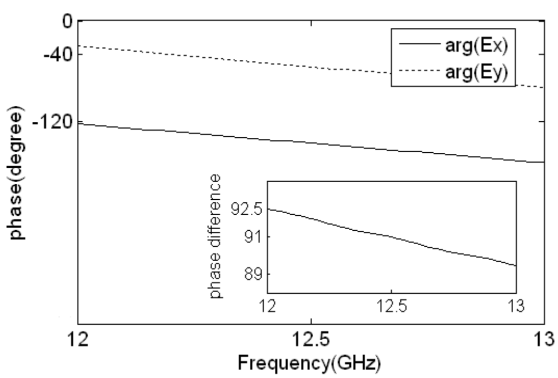
when p = 0 and *phase difference* = $\pi/2$, the transmitted wave becomes circularly polarized wave. The transmission coefficients T_x and T_y represent the conversion efficiency of the polarizer. If we are able to control T_x and T_y to be close to -3 dB, nearly all the energy will be transmitted and no wave will be reflected.

We use the commercial software CST Microwave Studio to simulate the unite cell shown in Fig. 1. The SRR is modeled as perfect electrically conducting material. Along the x and y axes, periodic boundary conditions are applied. The calculated transmission coefficients and the axial ratio of the transmitted wave are shown in Fig. 2 (a). It can be seen from this figure that both the transmission coefficients of T_x and T_y are close to -3 dB in the frequency range 12 GHz - 13 GHz, which is a direct evidence of small loss and little reflections of the polarizer. The axial ratio of the transmitted wave is below 2 dB in this frequency range. Meanwhile, an obvious zero value in the axial ratio can be observed around 12.6 GHz, which indicates that the two wave modes of the transmitted waves have equal amplitudes. The phases of the two modes of the transmitted wave obtained using CST calculations are shown in Fig. 2 (b). The phase difference between the E_x^{out} and E_y^{out} is also shown in the same figure. It can be seen from this figure that in the frequency range of 12 GHz - 13 GHz near 90^o phase difference in the two orthogonal components is achieved. These simulated results confirm a fact that in the frequency range of 12 GHz - 13 GHz the linearly polarized wave is conserved to a circularly polarized wave by the transmission polarizer. The bandwidth can reach to 8 %.

The conversion efficiency (defined as $\sqrt{\left(E_x^{out}\right)^2 + \left(E_y^{out}\right)^2} / E^{in}$) is plotted in Fig. 3. It can be seen from this figure that the conversion efficiency of the polarizer exceeds 99 % in the frequency range of 12 GHz - 13 GHz and reaches its maximum value at around 12.6 GHz, which shows that highly efficient conversion from a linearly polarized wave to a circularly polarized wave has been accomplished.



(a)



(b)

Fig. 2. (a) The simulated transmission and axial ration of the transmitted wave and (b) the simulated phase difference of the two wave modes of the transmitted wave.

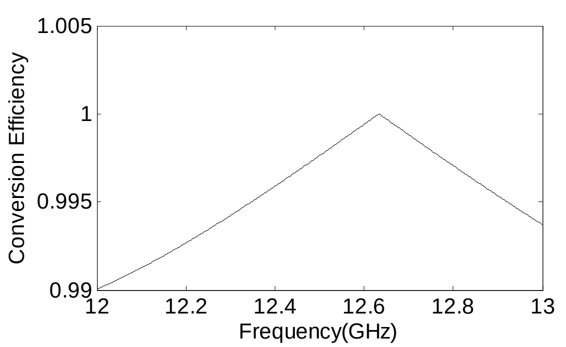
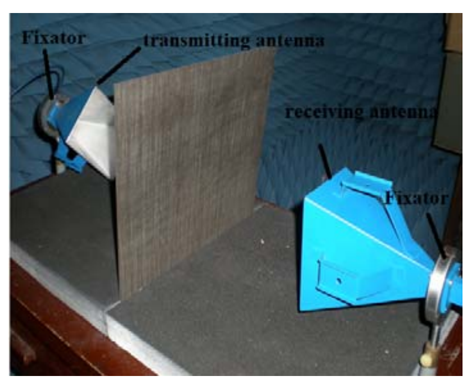


Fig. 3. The conversion efficiency of the polarizer.

III. EXPERIMENT VALIDATION

In order to confirm this expected behavior experimentally, we have fabricated a sample composed of 30 × 30 unit cells (see Fig. 4 (a)). The picture of the experimental setup is shown in Fig. 4 (b). The reflection and transmission waves were measured using a pair of horn antennas connected to the vector network analyzer (Agilent E83638). The horns antennas was fixed on a fixator, which had angle calibration to ensure that horn alignments were at the exact angles. The electric field of the transmitting antenna was polarized to the direction illustrated in Fig. 1 (b), which had a 45^o angle with respect to the vertical direction, so that the electric fields of the two modes for incident waves were related by $|E_x^{in}| = |E_y^{in}|$ and arg (E_x^{in}) = arg (E_y^{in}) and. A calibration was conducted by removing the sample and having the receiving antenna aligned at the same direction with the transmitting antenna. Then we rotated the receiving antenna from 0^o to 90^o to achieve the E_x^{out} and E_y^{out} of the transmitted wave. All the measurements were performed in an anechoic chamber.

(a)



(b)

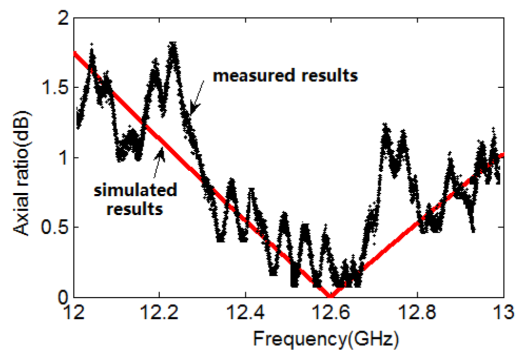
Fig. 4. (a) The top view of the fabricated sample and (b) the picture of the experimental setup.

The measured axial ratio of the electric field is shown in Fig. 5 (a). For circular polarization, the amplitude of the electric field is supposed to be invariant and in our measurement the variation is less than 2 dB. The measured phase difference between the E_x^{out} and E_y^{out} components is shown in Fig. 5 (b). It can be seen from this figure that the phase difference is also around 90^o. For the sake of comparison, the simulated results of the axial ratio and phase difference are also plotted in Fig. 5. It can be seen from this figure that although the measured result deviates from the simulated result in some frequencies (in fact, it revolves around the simulation result), it also indicates a fact that a full conversion from a linearly polarized wave to a circularly polarized wave is achieved. The deviations between the simulated value and the measured result are mainly due to the fact that, in the simulated model, the unit cells are periodically arranged and the substrate is infinite, while, in the experiment, the sample is composed of 30 × 30 unit cells and its size is only 33 × 33 cm^2, which is slightly larger than the aperture of the horn antenna. The small size of the sample results is due to the fact that some diffracted wave from the transmitting antenna reaches the receiving antenna directly. If we increase the size of the sample, the deviation between the simulated value and the measured result will be reduced.

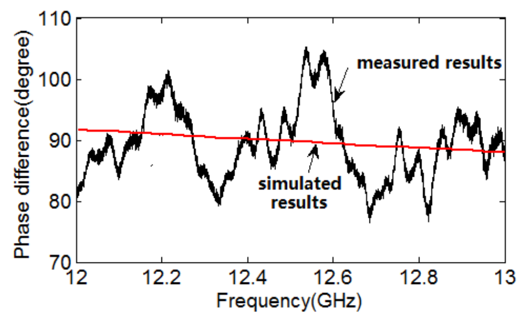
IV. THE APPLICATION OF THE POLARIZER TO A HORN ANTENNA

To demonstrate the function of the metamaterial as a circular polarizer, we integrate the polarizer to a conventional horn antenna. The aperture of the horn antenna is 19.05 mm × 9.525 mm. It radiates a linearly polarized wave at 12.6 GHz. We arrange the structure periodically on the aperture of the antenna, as shown in Fig. 6. The horn needs to be rotated 45^o to the x-axis to make sure that the electronic field has the same component along the x and y directions.

The simulated normalized radiation pattern of the integrated horn antenna is shown in Fig. 7. The simulation frequency is 12.6 GHz. For the sake of comparison, the radiation pattern of the conventional horn antenna is also plotted in this figure. It can be seen from this figure that the novel integrated horn has almost the same gain with the conventional horn, but it radiates a left handed circularly polarized (LHCP) wave. The gain-difference between the LHCP wave and the right handed circularly polarized (RHCP) wave of the integrated horn is 21.9 dB in the E-plane, and 20.3 dB in the H-plane.



(a)



(b)

Fig. 5. (a) The measured axial ration of the transmitted wave and (b) the measured phase difference of the transmitted wave.

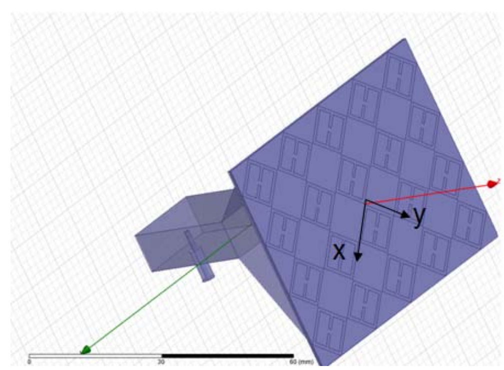
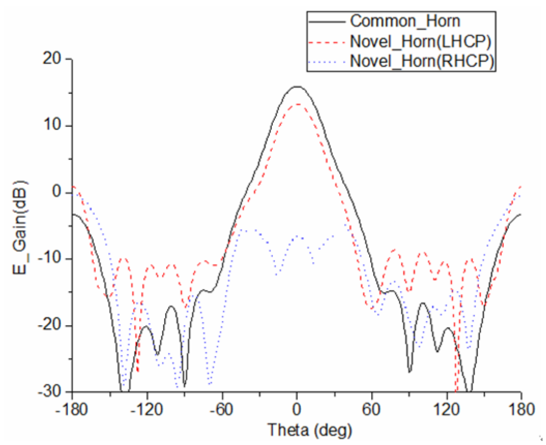
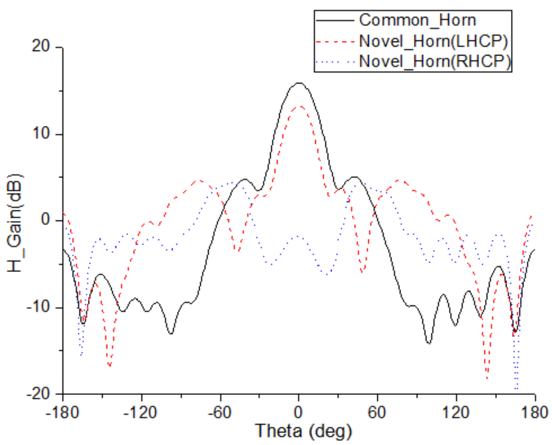


Fig. 6. The schematic picture of the polarizer integration to a horn antenna.



(a)



(b)

Fig. 7. (a) The simulated radiation patterns in the E-plane at 12.6 GHz and (b) the simulated radiation patterns in the H-plane at 12.6 GHz.

The simulated axial ratio of the integrated horn in both E- and H-planes are shown in Fig. 8. The axial ratio is bellow 3 dB from about -10° ~10° at 12.6 GHz and the 3 dB angle band covers the main lobe. The results in the presented simulations demonstrate the function of the metamaterial as a circular polarizer. It can turn a conventional horn antenna, which radiate linearly polarized wave into a circularly polarized antenna.

V. CONCLUSION

This paper presents a new transmission polarizer with one layer of SRR to realize a linear-to-circular polarization rotator. Both the simulated and the measured results show that highly efficient conversion is achieved. Due to its thin thickness and high polarization conversion efficiency, the present polarizer may have potential applications in many situations and will find broad applications in various radio frequency and optical devices.

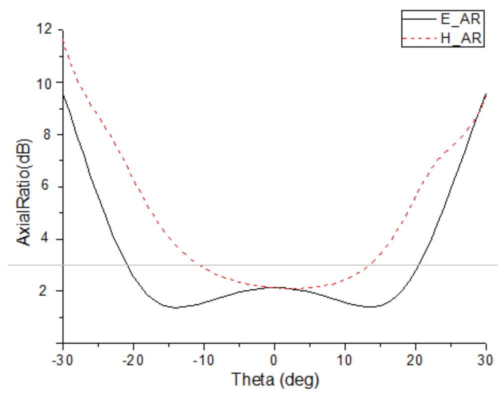


Fig. 8. The axis ratio of the circular polarized horn at 12.6 GHz.

ACKNOWLEDGMENT

This work was supported by National Natural Science Foundations of China (No. 61001039 and 61231003), and also supported by the Fundamental Research Funds for the Central Universities.

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