Electrically thin asymmetric chiral metamaterial circular polarizer

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Abstract

In this paper, we numerically and experimentally demonstrate an asymmetric chiral metamaterial circular polarizer constructed by using four double-layered U-shaped split ring resonators, each mutually rotated by 90°. The sizes of the electrically and magnetically excited rings are different, which allows for equalizing the orthogonal components of the electric field at the output interface with ±90° phase difference. As a result, left hand circular polarization and right hand circular polarization are obtained in transmission at 5.1 GHz and 6.4 GHz, respectively.

1. Introduction

The chirality concept in metamaterials has attracted significant attention since Pendry predicted that a chiral route can be used in order to obtain negative refraction [1]. A chiral metamaterial (CMM) is not identical to its mirror image, *i.e.*, it cannot be brought into congruence with its mirror image unless it is lifted off the substrate [2]. For such materials, at the resonance frequencies, cross-coupling between the electric and magnetic fields exists and, therefore, right-hand circularly polarized (RCP) and left-hand circularly polarized (LCP) waves encounter different transmission coefficients [3].

In this paper, we demonstrate an asymmetric chiral metamaterial structure, in which C_4 symmetry is broken in order to equalize the magnitudes of the orthogonal components of the electric field with ±90° phase difference at the output interface [4]. Modifying the sizes of the electrically excited split ring resonators (SRRs) allows for higher transmission along the x direction. After optimizing the design by using numerical methods, we obtain LCP transmission at 5.1 GHz, as well as RCP transmission at 6.4 GHz.

2. Structure

We started the analysis with numerical simulations using CST Microwave Studio, which is based on the finite integration technique. The boundaries along the x and y directions are chosen to be periodic, whereas the boundary along the z direction is absorbing. The response of the CMM is studied by excitation using plane waves propagating in the $-z$ direction.

The proposed CMM is demonstrated in Fig.1 and the geometrical parameters are given as: $a_x = a_y = 15$ mm, $s_1 = 6$ mm, $s_2 = 4.2$ mm, $w_1 = 0.7$ mm, $w_2 = 0.5$ mm, $d = 2.6$ mm, and $t = 1.5$ mm. The SRRs are made of 30 µm thick copper and the substrate is FR-4 with a relative permittivity of 4.0 and a loss tangent of 0.025. The proposed design is electrically thin since $t / \lambda = 0.024$ and 0.03 at 5.1 GHz and 6.4 GHz, respectively. Moreover, the transverse periodicity is electrically small since a_x / λ corresponds to 0.255 and 0.3 for 5.1 GHz and 6.4 GHz, respectively.

For the experiments, the structure is fabricated to be composed of 15 × 15 unit cells. In the experiments, transmission coefficients are measured using a HP-8510C network analyzer and two

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standard gain horn antennas positioned at a 50 cm distance. In the simulations and experiments, linear transmission coefficients along the x (T_{xx}) and y (T_{yx}) [5] polarizations are studied in order to characterize the behavior of the CMM.

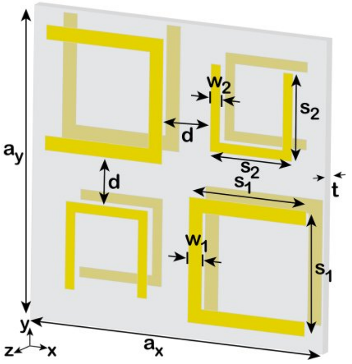

Fig. 1: Geometry of the simulated and fabricated CMM unit cell

The proposed design produces circularly polarized waves at the output interface only if the incident wave is linearly polarized in the x direction. Since the CMM lacks C_4 symmetry, the transmitted wave is not equivalent for other polarization directions. In other words, introducing an asymmetry limits the polarization of the incident field, while demonstrating the desired polarization conversion behavior.

3. Results and Discussions

The ratio $|T_{yx}| / |T_{xx}|$ and the phase difference $\angle (T_{yx}) - \angle (T_{xx})$ are demonstrated in Fig. 2(a) and (b), respectively. The peaks in Fig. 2(a) corresponds to the largest coupling between the top and bottom layers, so that transmission along the y polarization is largest. However, as Fig. 2(b) demonstrates, at those peak points the phase difference is not equal to ±90°. Briefly, the optimization aims to coincide $|T_{yx}| / |T_{xx}| = 1$ and $\angle (T_{yx}) - \angle (T_{xx}) = \pm 90°$ simultaneously. In this case, maximum conversion efficiency is achieved since both criteria for circular polarization are satisfied at the same frequency. The operation frequencies are marked as X and Y in Fig. 2(a) and 2 (b).

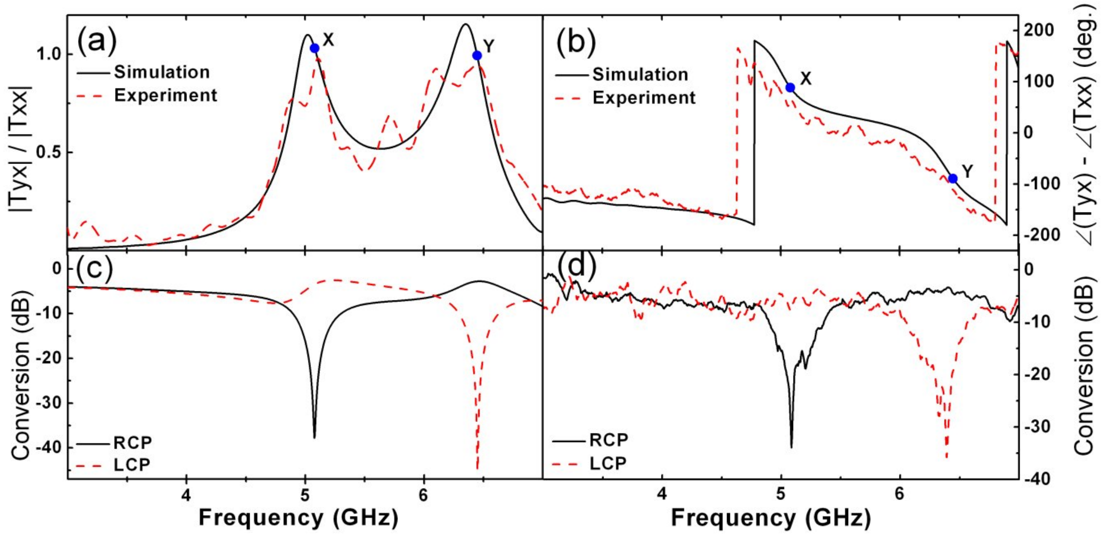

Fig. 2: (a) The ratio of the magnitudes and (b) the phase difference of T_{yx} and T_{xx}, (c) the simulated and (d) experimental circular conversion coefficients valid for an x-polarized incident wave.

It has been mentioned that the proposed CMM lacks C_4 symmetry. Therefore, the eigenwaves of the system are not circularly polarized waves, but elliptical waves. In that case, the transmission

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coefficients should be calculated in terms of the eigenwaves of the system. However, at this point we define circular conversion coefficients, which indicate the weight of RCP and LCP waves at the output interface, in order to simplify our disccussion. We have asserted that the structure works as a circular polarizer only when the incident field is linearly polarized in the x direction. In this case, we can assume that $E_y = 0$, which also cancels the effects of T_{xy} and T_{yy}. Under this assumption, for an x-polarized incident field, we can retrieve the circular conversion coefficients to RCP (C_+) and LCP (C_-) waves using $C_{\mp} = T_{xx} \pm iT_{yx}$ [5]. The result of the retrieval corresponds to the weight of each component (RCP and LCP) at the farfield. However, as a result of our assumption, these circular conversion coefficients would not be valid if the incident wave has an electric field component along the y direction.

Numerically and experimentally retrieved circular conversion coefficients are shown in Fig. 2(c) and 2 (d), respectively. It is observed that at 5.1 GHz, the conversion to RCP is minimum, which explains the conversion to LCP at this frequency. Similarly, at 6.4 GHz the conversion to LCP is minimum, which leads to the transmission of an RCP wave to the farfield. Moreover, the resonances observed at Fig. 2 (c) corresponds to the points X and Y given in Fig. 2(a) and (b), which demonstrate the operation frequencies of the structure.

Numerical surface current analysis reveals that, at 5.1 GHz the currents on the SRR pairs are parallel leading to parallel magnetic dipole moments at this frequency. On the contrary, at 6.4 GHz, the currents are antiparallel, creating magnetic dipole moments in opposite directions.

The major advantage of the design is being electrically very thin. In addition, the fabrication process is an advantage since the proposed structure is planar. Also, the frequency of operation can be modified in the fabrication stage by changing the size of the structure. On the other hand, narrowband operating frequency is a drawback of the design. Additionally, the power incident on the CMM is not completely converted to circular polarization; however, half of the incident power is lost.

4. Conclusion

To summarize, an asymmetric chiral metamaterial structure, operating as a circular polarizer, composed of four U shaped SRR pairs is designed. Due to illumination by an x-polarized incident wave, LCP and RCP waves are obtained in the vicinity of 5.1 GHz and 6.4 GHz, respectively. The proposed design can be utilized as an electrically thin circular polarizer for microwave applications. As a future study, the ideas utilized in this study can be adapted for terahertz and optical applications.

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