Asymmetric Electromagnetic Wave Polarization Conversion through Double Spiral Chiral Metamaterial Structure

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***Abstract*-This paper presents the design, simulation and measurement of a chiral metamaterial with double spiral unit cell structure that can be used to convert the polarization states of linearly polarized electromagnetic (EM) wave. The metamaterial is composed of a dielectric slab sandwiched by a double spiral metallic structure. By full-wave EM simulations and free space measurements, a strong polarization conversion of linearly polarized EM wave has been demonstrated in the microwave band. Moreover, the polarization conversion is asymmetric due to the chirality of the structure, therefore the structure could allow propagation of linearly polarized EM wave along one direction, while almost no propagation along the opposite direction. The proposed chiral metamaterial structure could find applications in designing polarization control devices.**

I. INTRODUCTION

Chirality is a geometric concept, indicating lack of geometric symmetry between the substance and its mirror image and lack of chance of overlapping via both translation and rotation operations. Chiral structures can be found in natural materials; however their chirality is rather weak. Recently, chiral metamaterial structures have been proposed and exotic electromagnetic (EM) properties have been experimentally validated including negative refraction characteristics [1]. With the rapid progress in the study of the electromagnetic properties of chiral metamaterial, some of its other inherent exotic features are constantly revealed, and experimentally verified, such as the optical activity [2], nonlinearity, circular dichroism [3]. Polarization is an important characteristic of electromagnetic wave. It is always desirable to have full control of the polarization states of EM waves in many applications. Since the mirror symmetry of chiral metamaterial is broken either in the propagation direction or in the perpendicular plane, it leads to the interaction of electromagnetic wave radiation with the structural chirality in the metamaterial. These chiral structures could be utilized to control the polarization states of EM waves. In particular, asymmetric EM propagations have been realized with particularly designed chiral metamaterial associated with the conversion between two independent linear polarizations [4-8].

In our previous work, we established a theoretical analysis on a kind of bilayered metamaterial structure with specific structure asymmetry that enables the asymmetric EM wave propagation only for linear polarization. We also proposed and experimentally verified a kind of chiral metamaterial structure that has substantial asymmetric propagation for a certain linearly polarized EM wave, but none for circular polarizations [9].

In this paper, we propose a chiral metamaterial structure composed of a dielectric slab sandwiched by a double spiral metallic structure which can achieve strong asymmetric polarization conversion for linearly polarized EM wave. We will demonstrate that the chiral metamaterial can achieve cross-polarization conversion with an efficiency of over 90% for a certain linearly polarized EM wave. Such phenomenon is more interesting in the application for designing polarization control devices. We will present the design, simulation and measurement of the chiral metamaterial structure, and validate its strong polarization conversion ability with transmission measurement in the microwave band (X band).

II. THEORETICAL ANALYSIS

Asymmetric transmission of EM waves in the chiral metamaterial is usually caused by the partial polarization conversion of the incident EM radiation into one of the opposite polarization, which is asymmetric for the opposite directions of propagation [10]. To analyze such phenomenon we consider an incoming plane wave propagating along the negative z direction, with electric field as

$$E^{in}(r,t)=\begin{pmatrix} I_x \\ I_y \end{pmatrix} e^{i(-kz-\omega t)}, \qquad (1)$$

where ω, k, I_x, I_y represent the frequency, wave vector, and complex amplitudes, respectively. The transmitted electric field through the slab can be then described as

$$E^{trans}(r,t)=\begin{pmatrix} T_x \\ T_y \end{pmatrix} e^{i(-kz-\omega t)}. \qquad (2)$$

To understand better the cross-polarization conversion due to the chirality of the metamaterial structure, we invoke the transmission matrix expression for the EM fields, which relates the incident and the transmitted electric fields in terms of linearly polarized components. The subscripts i and j correspond to the polarization base states of the transmitted and incident waves, which could be either x or y linear polarization (assuming EM wave propagates along $-z$ direction). The transmission matrix element includes information of both the amplitude $|t_{ij}|=|E_i^{trans}|/|E_j^{inc}|$, and phase

$\arg(t_{ij}) = \arg(E_i^{trans} / E_j^{inc})$, then the EM wave transmission perpendicularly propagating through a slab of metamaterial structure can be described by the so-called complex Jones matrix ***T*** as

$$\begin{pmatrix} E_x^{trans} \\ E_y^{trans} \end{pmatrix} = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix} \begin{pmatrix} E_x^{in} \\ E_y^{in} \end{pmatrix} = T_{lin}^{f} \begin{pmatrix} E_x^{in} \\ E_y^{in} \end{pmatrix}. \tag{3}$$

The superscript *f* and subscript *lin* indicate the forward propagation (along -*z* direction) and a special linear base, respectively. If the medium does not contain magneto-optical material, the reciprocity theorem can be applied and the transmission matrix for T_{lin}^{b} propagation in the backward direction (+*z* direction) can be derived as [11]

$$T_{lin}^{b} = \begin{pmatrix} t_{xx} & -t_{yx} \\ -t_{xy} & t_{yy} \end{pmatrix}. \tag{4}$$

When the propagation direction is reversed, the off-diagonal elements t_{xy} and t_{yx} not only interchange their values, but also get an additional 180^0 phase shift.

We can also define the polarization conversion ratio (PCR) for *x* or *y* polarization as

$$PCR_y = t_{xy}^2 / (t_{yy}^2 + t_{xy}^2), \tag{5}$$

$$PCR_x = t_{yx}^2 / (t_{xx}^2 + t_{yx}^2), \tag{6}$$

If there is no absorption and reflection, we could have $t_{xy}^2 + t_{yy}^2 = t_{yx}^2 + t_{xx}^2 = 1$ and thus the *PCR* can be further reduced to $PCR_y = t_{xy}^2$ and $PCR_x = t_{yx}^2$.

III. DESIGN AND CHARACTERISTICS

The proposed chiral structure is designed to work at 8 - 12 GHz, composed of a dielectric substrate sandwiched by two thin copper layers. The dielectric substrate is chosen as FR4 (a glass-reinforced epoxy printed circuit board) with a permittivity of 4.6, loss tangent of 0.01, and thickness of 1 mm. The top and bottom copper layers have the same thickness of 17 µm. Fig. 1(a) shows the schematic diagram of the metamaterial unit cell with side length *a* = 12 mm, while the whole slab sample is composed of 16 × 17 unit cells. The right part of Fig. 1(a) indicates metallic patterns on the top and bottom copper layers. The patterns on top and bottom layers are two copper rings with gaps respectively, which have inner and outer radii of r_1 = 3.5 mm and r_2 = 4 mm. The gap angle corresponding to the ring center is $\theta = 135^0$. The point p_1 indicates center of the unit cell and the p_2 and p_3 points indicates centers of two copper rings on the top layer. If the p_1 point is set as the origin of *x* - *y* plane, p_3 and p_2 will have coordinates of (1 mm, 1 mm) and (-1 mm, -1 mm), respectively. The cooper rings on top and bottom layers with same position in *x* direction and *y* direction are connected through one metallic via hole of radius of 0.5 mm and form a double spiral structure. The twisted metallic patterns form a chiral structure and have strong strength to convert polarization of EM wave due to the electric and magnetic mutual couplings between them. Fig. 1(b) shows the photograph of the fabricated sample. The orientation of the incident wave is indicated in fig. 1(c) for forward (along –*z* direction) or backward (along +*z* direction) propagation.

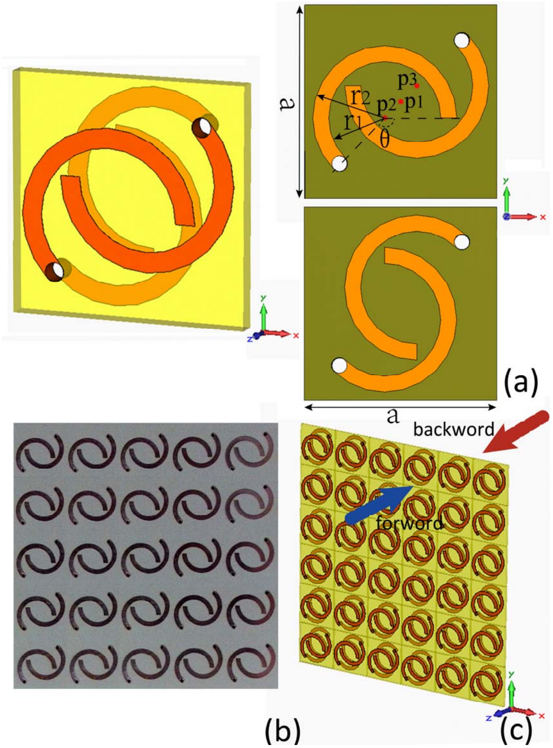


Figure 1. (a) The schematic of chiral metamaterial unit cell. (b) Photograph of fabricated sample slab. (c) Its orientation with the incident wave.

The proposed metamaterial slab has been analyzed through full-wave electromagnetic simulations with commercial software (CST Microwave Studio™) based on finite-difference time-domain method. The simulation is carried out upon the unit cell as shown in Fig. 1(a). Open boundary conditions are employed along the propagation direction, and unit cell boundary conditions are used along the directions perpendicular to the propagation direction. Therefore, the structure is assumed to be periodic and infinite along the directions that are perpendicular to the propagation direction. After the parameters study and optimization through the simulations, a sample slab (with outer dimension of 200 × 220 mm^2) is fabricated by printed circuit board technique and characterized through free space electromagnetic transmission measurement in a microwave anechoic chamber. Two linearly polarized horn antennas with Teflon lenses are used to emit and receive microwave signal, and a vector network analyzer (Agilent N5244A) is employed to measure the transmission. In the experiment, transmission measurement is calibrated to the case where the sample is left as hollow (as the unit transmission). By rotating the transmitting or receiving horn antenna 90° around the main radiation direction to generate and receive EM waves with different linear polarizations (either *x*-polarization or *y*-polarization), all the four components of the electromagnetic wave transmission (the complex Jones matrix) for different polarizations have been measured.

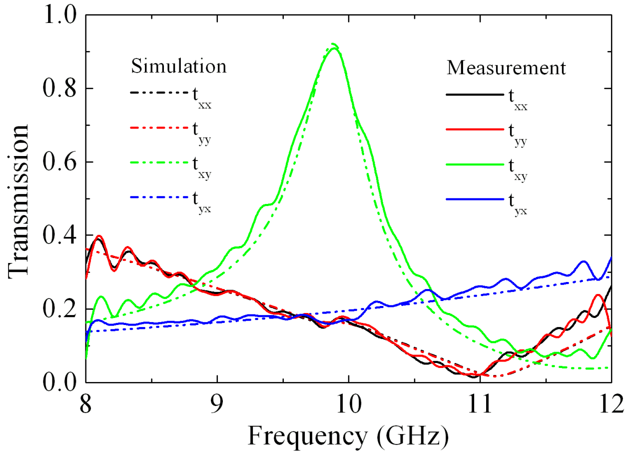


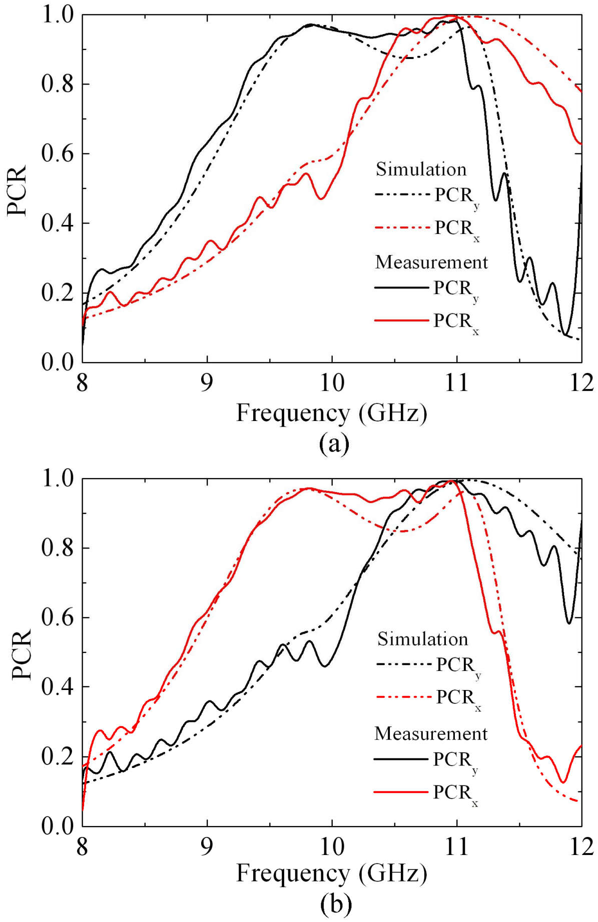
Figure 2. The measurements (solid lines) and simulations (dashed lines) of the four transmission matrix elements of the slab for forward propagations.

Fig. 2 shows the simulated and measured results of the four transmission matrix elements of the slab. The measurements and simulations agree with each other quite well across the whole frequency range. As the frequency increases, the cross-polarization transmission t_{xy} experiences a resonant peak and reaches a maximum of around 0.9 at the frequency of 9.88 GHz, while the cross-polarization transmission t_{xy} maintains around 0.2 and the co-polarization transmission t_{xx} and t_{yy} are very close to each other across whole frequency range.

According to Eq. (5) and Eq. (6), PCR is calculated for both *x*- and *y*-polarized incident EM wave for forward and backward propagations. As illustrated in Fig. 3, the PCR parameter for *y*-polarized incident wave reaches around 0.95 from 9.8 GHz to 11 GHz, indicating that the *y*-polarization converts mostly to *x*-polarization after transmission through the slab, while PCR parameter for *x*-polarized incident wave reaches the maximum of 1 at approximate 11GHz, corresponding precisely to the resonance at which t_{xx} and t_{yy} tend to zero. Either polarization experiences a pure polarization conversion when propagates through this metamaterial slab. The PCR parameters for opposite propagations show strong asymmetric characteristics due to the chirality of the structure.

The PCR parameter for linear polarization in the proposed structure leads to a strong asymmetric transmission. As a result the total transmission for a certain linear polarized wave is quite different along opposite directions. We measured both the forward and backward total transmissions (including both the co- and cross-polarizations) for *y*-polarized wave, and the result is shown in Fig. 4. The forward transmission reaches above 0.85, while the backward transmission is below 0.1 at around 9.88 GHz.

To look into the mechanism of the polarization conversion that is associated with the chiral metamaterial, we have analyzed the distribution of electric energy density of top and bottom copper layers and mid-plane of dielectric substrate and the surface current distribution of top and bottom cooper rings of *y*-polarized incident wave at 9.88 GHz. Through careful analysis of Fig. 5 and the dynamic graphics of surface current across whole phase, following phenomenon can be observed. The incident *y*-polarized wave induces a strong electric field in the gaps of the top cooper layer (Fig. 5(a)). Surface currents are mainly distributed in parts of top and bottom rings that having overlap with each other. Surface currents on top and bottom parts of the cooper rings with overlap to each other are in opposite directions across whole phase (Fig. 5(d) and (e)).



(a)

(b)

Figure 3. PCR for linear polarization determined by measured (solid lines), and simulated (dashed lines) data for (a) forward and (b) backward propagations.

The result demonstrates clearly that when a *y*-polarized wave at 9.88 GHz normally incidents into the structure along the $-z$ direction, the wave is strongly coupled to the slab by inducing a strong electric field in the gaps of the top SRR layer; meanwhile due to significant mutual coupling between the top and bottom metallic rings through the overlap parts, *y*-polarized wave is converted mostly to *x* polarization when it pass through the structure. The backward propagation can be understood in a similar manner.

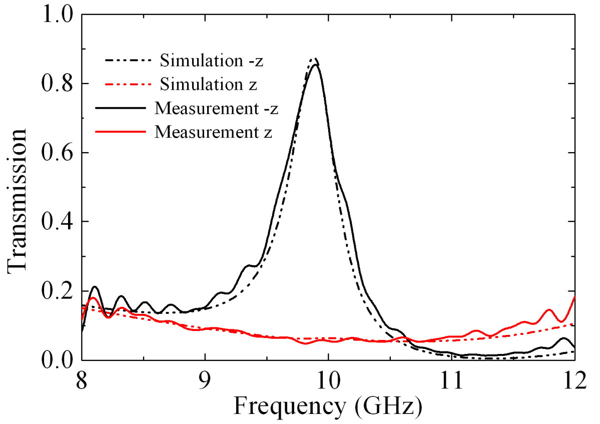


Figure 4. Measured (solid lines), calculated (dashed lines) total transmission for *y*-polarized incident wave for forward and backward propagations.

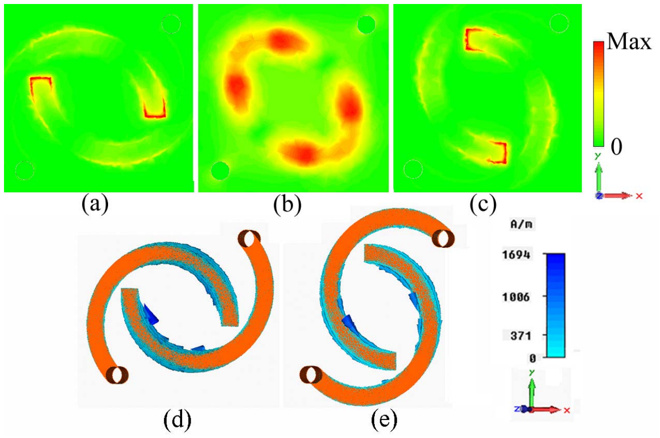


Figure 5. Distribution of electric energy density of (a) top copper layer (b) mid-plane of dielectric substrate (c) bottom copper layer and distribution of surface current of (d) upper cooper rings and (e) bottom cooper rings for *y*-polarized incident EM wave at 9.88GHz.

IV. CONCLUSIONS

In summary, we propose a chiral metamaterial structure composed of a dielectric slab sandwiched by a double spiral metallic structure that could achieve strong polarization conversion for linearly polarized EM wave. After analyzing and optimizing the metamaterial structure through full-wave EM simulations, we fabricate and test the structure at the microwave band. The experimental results have confirmed the strong polarization conversion and asymmetric transmission ability. We believe that such structure could find applications in designing polarization control devices. By scaling down the proposed metamaterial structure, the concept could also be utilized to function at other frequency bands, such as millimeter, sub-millimeter wave or even terahertz band.

ACKNOWLEDGMENT

This work is partially supported by the National Nature Science Foundation of China (60990322, 60990320, 60801001, 61101011), the Key Grant Project of Ministry of Education of China (313029), the Ph.D. Programs Foundation of Ministry of Education of China (20100091110036, 20120091110032), and partially supported by Jiangsu Key Laboratory of Advanced Techniques for Manipulating Electromagnetic Waves.

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