Asymmetric Transmission for Linearly Polarized Wave through Tunable Chiral Metasurface

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***Abstract*— Recent studies show that chiral metamaterials can be used in applications such as polarization conversion and asymmetric transmission (AT) without external magnetic field. Here we propose a tunable chiral metasurface for flexible control of the asymmetric transmission of linearly polarized electromagnetic (EM) wave at microwave frequencies with PIN diodes. By altering the applied biasing voltage, we manage to achieve the amplitude and phase manipulation of the transmitted waves dynamically. In addition, the operation frequency can also be tuned in a controlled manner.**

Keywords— chiral metamaterial; asymmetric transmission; tunable; coding material.

I. INTRODUCTION

The artificial chiral materials, owing to their special geometry, demonstrate extraordinary electromagnetic cross-coupling ability that is especially beneficial for applications such as polarization regulation and asymmetric transmission without external magnetic field [1,2]. Such materials show great advantages over non-reciprocal devices in terms of small volume, lightweight, low profile and easy integration.

To date, asymmetric transmission devices for circularly and linearly polarized electromagnetic waves have been successfully developed with the aid of chiral metamaterials, but their functionalities cannot be altered dynamically once the structural patterns are fixed [3-6]. Therefore, more efforts are demanded in the design of tunable, switchable or reconfigurable chiral metamaterials under external excitation. In the microwave region, the PIN diode is widely used in the design of active meta-atoms, where the 'on' and 'off' status provide different amplitude or phase responses in the spectrum of interest [7,8]. It can also be employed in the programmable metamaterials, which allows one to synthesize the radiation or scattering pattern in real time by controlling the coding sequences of the binary elements in free space.

In this paper, a tunable metasurface incorporated with the PIN diodes is put forward to realize asymmetric transmission of linearly polarized wave dynamically. For a certain polarized EM wave, it can be transformed differently when normally incident at opposite sides of the structure. Additionally, at a certain frequency, the phase difference of the meta-atom is approximately 180° when the integrated PIN diode is turned on or off, implying the possibility of digital chiral metasurface for asymmetric wave manipulation.

II. DESIGN AND CHARACTERIZATION

Fig. 1 shows the schematic diagram of the proposed chiral metasurface, which can convert the polarization for the transmitted waves. The inset in Fig. 1 presents a zoomed view of the unit cell comprising two split ring resonators mutually twisted by 65 degrees on both sides of the substrate. The geometrical dimensions of the unit cell are illustrated in Fig. 2. The commercial dielectric TF-1/2 with the permittivity of 10.2, the thickness of 2mm, and the loss tangent of 0.001 is adopted in this design. Two PIN diodes are installed across the slits of the rings. Both of them are connected by through-holes to ensure DC biasing at the same time. Straight feeding lines are deposited near the resonators to supply the operating voltage on the diodes. Notice that the feeding lines are perpendicular at the top and bottom surface so as to enhance the electromagnetic cross coupling of the unit.

Assuming an x-polarized wave is incident on the metasurface normally, the transmitted wave can be regarded as the combination of both x- and y-polarized components. The transmission property can be expressed by the Jones matrix [1]:

$$T_{lin}^{f}=\begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix}, T_{lin}^{b}=\begin{pmatrix} t_{xx} & -t_{yx} \\ -t_{xy} & t_{yy} \end{pmatrix}, \tag{1}$$

where the superscript 'f' and 'b' denote the forward and backward propagation, and the subscript 'lin' denotes linearly polarized wave. The asymmetric transmission parameter (AT) is used to describe the difference of the transmitted wave incident from opposite directions. For a linear polarization electromagnetic wave, we have

$$AT_x = \left|t_{yx}\right|^2 - \left|t_{xy}\right|^2 = -AT_y. \tag{2}$$

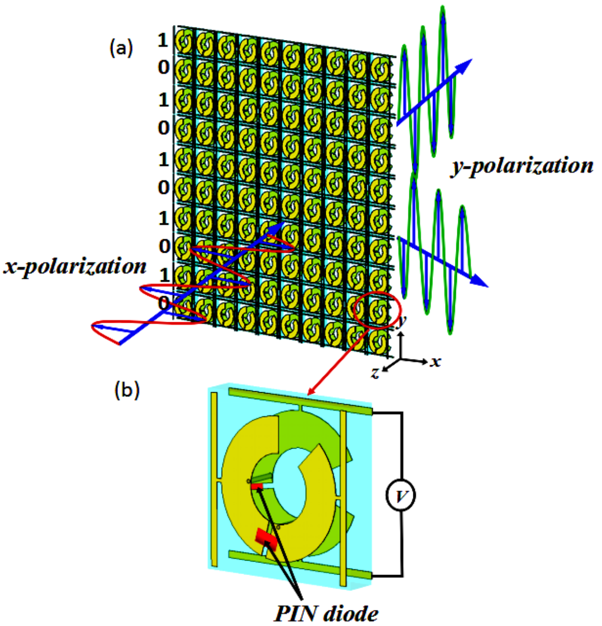

Fig.1. (a)The schematic diagram of the proposed chiral metasurface. (b)The unit cell of the structure.

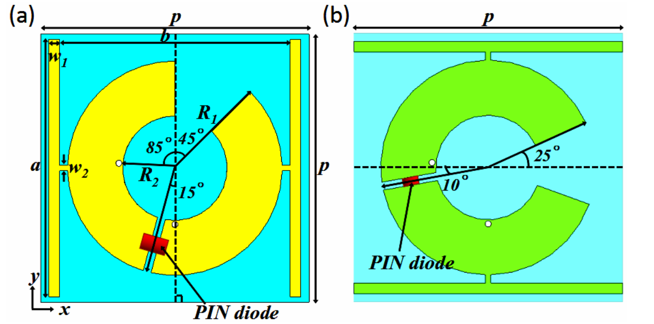

Fig.2. (a)Top view of the first layer. The geometric parameters are: p=10mm, a=9.6mm, b=8.6mm, w1=0.4mm, w2=0.2mm, R1=4mm, R2=1.95mm (b)Perspective of the bottom layer.

III. SIMULATION RESULTS

In this paper, the commercial full-wave package CST is used to simulate the reflection and transmission properties of the proposed metasurface. The PIN diode is chosen as SMP1320_040LF, with the equivalent resistance, inductance, and capacitance nearly invariable under either positive or zero biasing voltages. The numerical results show that when the diode is turned on or off, the meta-atom demonstrates a relatively high polarization conversion rate for the incident x-polarized wave, as can be observed in Fig. 3. It can be seen that with sufficient positive voltage for the PIN diode, the element has a large cross-polarization transmittance for the x-polarized wave in the frequency range from 10.5 to 11.8GHz, with T_{yx} reaching a peak value of 0.88 at f=11.19GHz. However, in the case of zero biasing voltage, the bandwidth for cross polarization conversion of the x-polarized wave is red shifted to 9.5 to 10.8GHz, with T_{yx} approaching 0.86 at 9.8GHz. It can be seen that in the two states the meta-atom share the same transmission amplitude but a phase difference of nearly 180° near 10.728GHz, making it suitable to serve as the binary element of coding metamaterials for wave manipulation of cross-polarized waves.

The asymmetric transmission parameter is calculated based on the simulation results from Eq. (2), as illustrated in Fig. 4. The structure has a prominent asymmetric effect in 'on' and 'off' states. The maximum values of AT_x (AT_y) in the two states are close to 0.7. For better illustration of the asymmetric transmission characteristics, the energy distribution around the chiral elements in the two states is provided in the figure 5 and 6 respectively. There is a great difference in the transmittance for x-polarized wave incident from forward and backward directions.

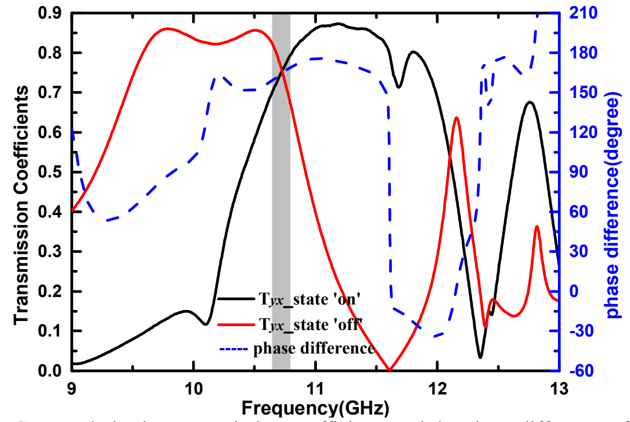

Fig.3. Cross-polarization transmission coefficients and the phase difference of x-polarized incident waves propagating in forward direction in two states.

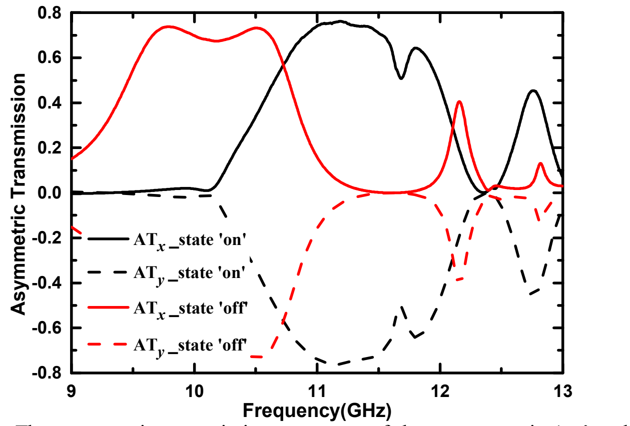

Fig.4. The asymmetric transmission parameter of the meta-atom in 'on' and 'off' states for x- and y-polarized waves.

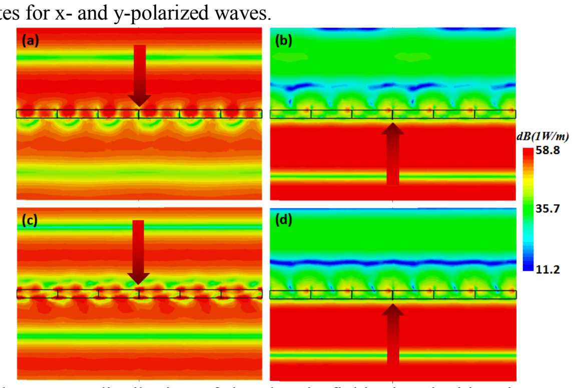

Fig.5. The energy distribution of the electric field when incident in opposite directions in 'on' state at 10.728GHz (first row) and 11GHz (second row) respectively. (a)(c) Forward incidence. (b)(d) Backward incidence.

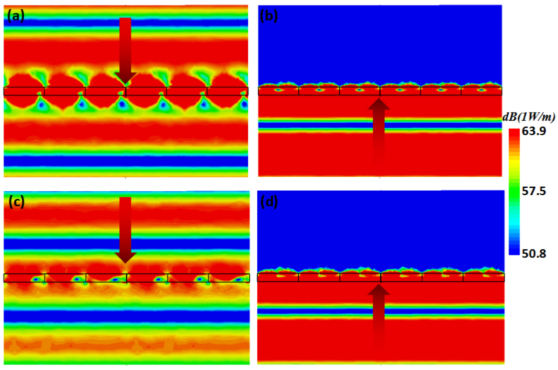

Fig.6. The energy distribution of the electric field when incident in opposite directions in 'off' state at 10.5GHz (first row) and 10.728GHz (second row) respectively. (a)(c) Forward incidence. (b)(d) Backward incidence.

IV. Conclusion

In conclusion, we propose an active chiral metasurface with tunable asymmetric transmission bandwidth for linearly polarized waves depend on the biasing status of the PIN diodes in the element. The phase difference of the element can approach 180 degrees at a certain frequency, which makes it possible for asymmetric and flexible control of EM waves in the future.

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