PIER Letters

(Received 2 April 2024, Accepted 27 May 2024, Scheduled 18 June 2024)

Controlling the Polarization Conversion and Asymmetric Transmission Properties of a Metasurface by Controlling the Chirality of its Unit Cell

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ABSTRACT: Chirality (mirror asymmetry) of the unit cell ensures the phenomenon of polarization conversion in a metamaterial/metasurface. In this paper, we control the polarization conversion and asymmetric transmission properties of a metasurface by controlling the chirality of its unit cells. Radio Frequency PIN diode switches are used to control the chirality. When the switches are turned OFF, the unit cells are chiral, and the metasurface successfully exhibits polarization conversion as well as asymmetric transmission for linearly polarized incident waves. When the switches are turned ON, the unit cells become achiral and lose both the above properties. The polarization conversion switching phenomenon is also observed for circularly polarized incident waves. A simple ultrathin metasurface is designed and fabricated to demonstrate these properties.

1. INTRODUCTION

Metasurfaces are the 2D equivalent of metamaterials. In metamaterials, the unit cell periodicity extends along all the three axes, whereas in a metasurface, the unit cell periodicity is confined to a single plane. In [1, 2], Caloz and Sihvola established an important relationship between chirality (mirror asymmetry) and polarization conversion. They showed that ensuring chirality of a metamaterial/metasurface unit cell guarantees the phenomenon of polarization conversion. This feature has been exploited by researchers in designing polarization conversion metasurfaces. The concept of asymmetric transmission for circularly polarized (CP) incident electromagnetic (EM) waves was first demonstrated by Fedotov et al. [3] for a planar chiral structure. By breaking the symmetry along the direction of EM wave propagation, a chiral metasurface can also exhibit asymmetric transmission for linearly polarized (LP) incident waves [4–24].

In [4], the authors design a broadband chiral cross-polarization converter in the terahertz frequency range. Zhao et al. utilize a diagonal split-ring resonator to design a broadband and high efficiency polarization converter which works within 8–11 GHz and 17–21 GHz in [6]. In [7, 8, 18], the authors utilize bi-layered chiral metasurfaces for designing polarization converters which work well up to 60° wave incidence. Dual-band polarization converters are presented in [5] and [12]. Multiple resonances of the unit cell geometry are utilized in [11] to produce a multiband polarization converter. The structure designed in [13] can manipulate the polarization of the incident wave in both transmission and reflection. Chiral polarization converters which work for both linearly polarized and circularly polarized light are presented in [15, 16, 22].

Many active microwave polarization conversion metasurfaces have also been presented in literature [19–21, 23]. In [19], two PIN diodes per unit cell are used to tune the polarization conversion operation bands.

The authors in [20] also utilize PIN diodes to switch the polarization conversion frequency bands by turning them on and off according to requirements. Zhao et al. design a metal-graphene metasurface for terahertz applications which can be tuned by controlling the Fermi energy in the graphene layers via a bias voltage [21]. The reconfigurable polarization converter designed in [23] uses PIN diodes to control the operation band, and it is used as a horn antenna cladding.

As seen from the above paragraph, the active polarization conversion metasurfaces use PIN diode switches or varactor diodes to shift, tune, or switch the polarization conversion bands of the structure on the fly. However, no attempts have been made at designing a switchable polarization conversion metasurface which can effectively toggle between a polarization conversion ON state and polarization conversion OFF state.

In this paper, we control the polarization conversion and asymmetric transmission properties of a metasurface by controlling the chirality of its unit cell. Radio frequency (RF) PIN diodes are connected to each unit cell of the metasurface. These PIN diodes are used as switches to control the chirality.

When the switches are turned OFF, the unit cells are chiral, and the metasurface can exhibit both polarization conversion and asymmetric transmission for LP incident waves. When the switches are turned ON, the unit cells become achiral and lose both the polarization conversion and asymmetric transmission properties. The metasurface then acts as an ordinary EM reflector.

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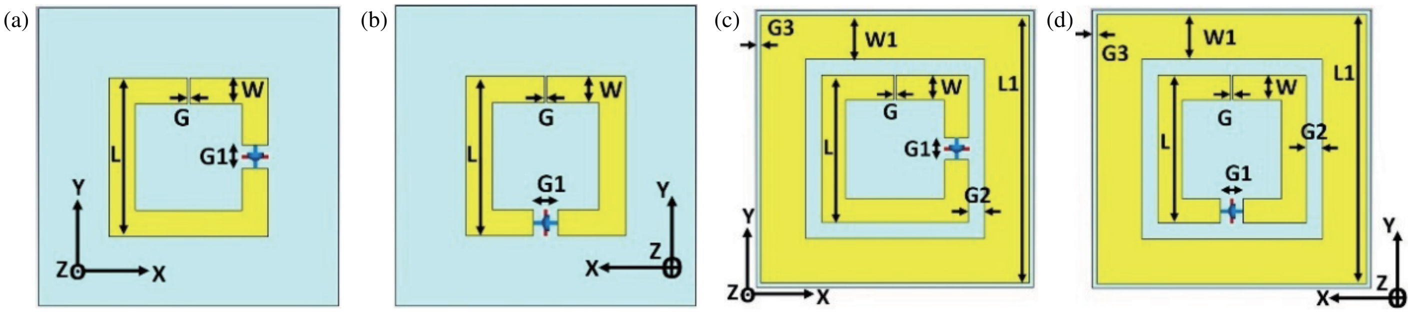

FIGURE 1. The two variants of the metasurface unit cell, (a) A and (b) B. The yellow regions are Copper and the sky-blue regions are Arlon AD-430 (lossy). $L = 14.465$ mm, $W = 2$ mm, $G = 0.15$ mm, $G1 = 2.3$ mm, $L1 = 26.3$ mm, $W1 = 4$ mm, $G2 = 1.917$ mm, $G3 = 0.35$ mm.

For the incidence of CP waves, the metasurface transmits a mixture of both co- and cross-polarized CP waves over certain frequency regions when the switches are OFF. When the switches are ON, both the co- and cross-polarization coefficients become negligibly small.

Using this switching principle, the metasurface can be used either as an asymmetric polarization converter (all switches OFF) or a standard reflector (all switches ON) for incident LP waves. For incident CP waves, the metasurface can be used either to produce a mixture of Right-Hand CP and Left-Hand CP waves (when the switches are OFF) or to reflect most of the incident CP wave (when the switches are ON). Therefore, instead of using the PIN diodes to change/shift the polarization conversion bands, we use the PIN diodes to change the fundamental property of the unit cell which is responsible for the polarization conversion, i.e., chirality. In doing so, we gain full control of the polarization conversion property of the metasurface and can switch it ON and OFF at will.

The switching property allows the metasurface to act either as an EM shield or as a polarization converter depending upon user requirements.

2. THEORY

Let us consider that a linearly polarized EM wave traveling along the z-direction is incident on a reciprocal chiral metasurface lying in the xy plane. When the wave is traveling along the $-z$-direction, we call it a forward wave and use E_x^f and E_y^f to denote x- and y-directed E-field orientations. Similarly, a wave traveling along the $+z$-direction is considered a backward wave with E_x^b and E_y^b used to denote the E-field orientations.

Let us assume that the metasurface unit cell has no symmetry. The forward and backward transmission matrices of the metasurface will then be given as follows:

$$T^f = \begin{bmatrix} T_{xx}^f & T_{xy}^f \\ T_{yx}^f & T_{yy}^f \end{bmatrix} \quad \text{and} \quad T^b = \begin{bmatrix} T_{xx}^f & -T_{yx}^f \\ -T_{xy}^f & T_{yy}^f \end{bmatrix} \tag{1}$$

T_{xx} and T_{yy} are the co-polarization transmission coefficients while T_{xy} and T_{yx} are the cross-polarization transmission coefficients. A metasurface having non-zero T_{xy} and/or T_{yx} can convert the polarization of the incident EM wave in transmission.

The phenomenon of asymmetric transmission occurs when $|T_{xy}^f| \neq |T_{xy}^b|$ and $|T_{yx}^f| \neq |T_{yx}^b|$. This is also evident from (1), which gives us $|T_{xy}^b| = |T_{yx}^f|$ and $|T_{yx}^b| = |T_{xy}^f|$. The degree of asymmetry is measured using the asymmetric transmission parameter Δ. For linearly polarized waves, $\Delta^x = |T_{yx}^f|^2 - |T_{yx}^b|^2$ and $\Delta^y = |T_{xy}^f|^2 - |T_{xy}^b|^2$ respectively. It should also be noted that $\Delta^x = -\Delta^y$.

Now, let us assume that the same EM wave is incident on an achiral metasurface whose unit cells are mirror symmetric about a plane. The forward and backward transmission coefficients of such a metasurface will be given as:

$$T^f = \begin{bmatrix} T_{xx}^f & 0 \\ 0 & T_{yy}^f \end{bmatrix} \quad \text{and} \quad T^b = \begin{bmatrix} T_{xx}^f & 0 \\ 0 & T_{yy}^f \end{bmatrix} \tag{2}$$

Interestingly, both T_{xy} and T_{yx} turn out to be zero. Therefore, the metasurface has lost both its polarization conversion and asymmetric transmission properties.

It is clear from the above paragraphs that we can control the polarization conversion as well as asymmetric transmission property of the metasurface by switching between a chiral unit cell having no symmetry and an achiral unit cell with planes of symmetry. This will be demonstrated in the following sections.

3. UNIT CELL DESIGN AND CHARACTERISTICS

The metasurface unit cell consists of an Arlon AD-430 dielectric substrate ($\varepsilon_r = 4.3$, $\tan\delta = 0.002$ and thickness $= 1.6$ mm) with metallic (copper) patterns etched on both the top and bottom surfaces of the substrate. The simulations of the unit cell are performed in CST Studio Suite. The unit cell has periodic boundary conditions (PBCs) set on all four sides in the xy-plane. The characteristics of the metasurface are studied within 4.25–5.75 GHz, i.e., a portion of the microwave C band.

Two different types of unit cells (A and B) are presented. The primary component in both is a split ring resonator (SRR) with two split gaps. The wider gap (G1) has an RF PIN diode switch attached across it. The narrower gap (G) is present to facilitate the biasing of the PIN diode switch. The unit cell geometries are shown in Fig. 1.

The PIN diode switch is represented by a lumped element in CST. In the ON state, the lumped element consists of an inductance (0.6 nH) and resistance (2.1 Ω), while in the OFF state, it consists of the same inductance and a capacitance (0.13 pF). The values of the inductance, capacitance, and resistance are taken from the data sheet of the actual RF PIN diode used with the fabricated metasurface, *Infineon BAR64-02V*. This PIN diode switch can be utilized efficiently up to 6 GHz.

The first unit cell, A, consists of the SRR + PIN diode combination on both the top and bottom surfaces of the substrate. This is a chiral unit cell with no symmetry when the switches are OFF and an achiral unit cell with a plane of symmetry along the *yz*-plane when the switches are ON. The second unit cell, B, is a replica of the first unit cell with a larger square ring surrounding the SRR. It behaves like unit cell A in both states of the switch.

The metasurface responses are expressed in terms of the transmittance values, which relate directly to the power of the transmitted co/cross-polarized EM waves.

3.1. Transmittance Curves of the Metasurface

Figure 2 shows the cross-polarization transmittance curves when the PIN diode switches are turned OFF. Unit cells A and B, being chiral in nature, have high values for $|T^f_{xy}|^2$ (or $|T^b_{yx}|^2$). This suggests that A and B are capable of polarization conversion. Moreover, they are also capable of asymmetric transmission since $|T^f_{xy}|^2 - |T^f_{yx}|^2$ has appreciable magnitudes for both A and B. These observations align with the theory discussed in Section 2.

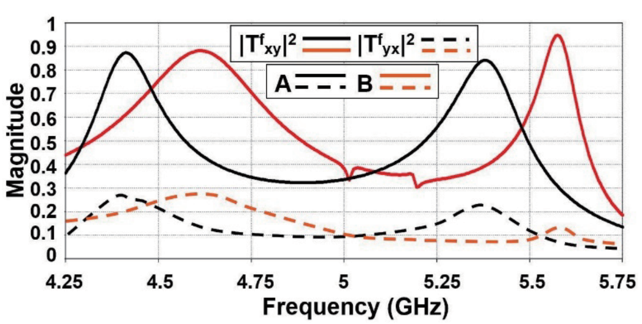

FIGURE 2. The cross-polarization transmittance plots for the unit cell variants when the PIN diode switches are OFF.

Since the $|T^f_{yx}|^2$ curves have relatively low magnitudes throughout the observed region, we focus only on the $|T^f_{xy}|^2$ curves. The co- and cross-polarization transmittance curves for both the ON and OFF switch states of A and B are plotted in Fig. 3.

There is a dramatic change in $|T^f_{xy}|^2$ between the two states of the switch. For the ON condition, $|T^f_{xy}|^2$ decreases nearly to zero for both A and B. The co-polarized transmittance curves, $|T^f_{yy}|^2$, remain relatively low for both the ON and OFF conditions of the switch. It indicates that there is only cross-polarized transmission when the switches are OFF, and there is negligible transmission (mostly reflection) when the switches are ON.

In summary, for the switch OFF condition, an incident EM wave with E^f_y is transmitted as an EM wave with E^f_x. However, for the switch ON condition, E^f_y is reflected by the metasurface with negligible cross-polarized and co-polarized transmission. The polarization conversion property of the metasurface is therefore lost when the switches are ON. This also leads to a loss of the asymmetric transmission property since both the cross-polarization transmission coefficients are negligible. These observations also align with the theory discussed in Section 2.

The simple SRR pair of unit cell A is enough to demonstrate the polarization conversion switching properties. However, unit cell B converts the polarization across a wider frequency region than A. The addition of the square ring on the top and bottom of B is responsible for this increased polarization conversion range.

3.2. Physical Mechanism

Chiral unit cells are mirror asymmetric in nature. This implies that they can never be mapped to their mirror image via translations or rotations. As discussed in [1] and [2], chiral unit cells also exhibit magnetoelectric coupling, which is better known as bianisotropy. Bianisotropy is the dependence of the induced electric and magnetic responses of a structure on both the incident electric and magnetic fields. In chiral metasurfaces, a part of the electric and/or magnetic responses of the surface are perpendicular to the incident electric and magnetic field excitations. This leads to the emergence of cross-polarized field components. These components give rise to the phenomenon of polarization conversion.

When the PIN diodes are turned OFF in the proposed metasurface unit cell, the unit cell is chiral in nature. Based on the explanation in the above paragraph, the metasurface in this condition is capable of polarization conversion.

When the PIN diodes are turned ON, they represent a low impedance path, and the incident EM wave sees a structure which is symmetric about the yz-plane. Due to this symmetry of the unit cell, the incident fields can no longer excite surface responses that are perpendicular to them. This leads to the extinction of the polarization conversion phenomenon.

3.3. Scalability

To demonstrate that the phenomenon described in this paper does not depend on the specific unit cell dimensions chosen, we scale the entire unit cell B by a factor of 1.5. The same PIN diode switches are connected across the SRR gaps. The cross-polarization transmittance curves of the scaled metasurface are shown in Fig. 4 for both the ON and OFF conditions of the switches. The nature of the transmittance curves is the same as Fig. 3 for both switch states. The operating frequency region has simply shifted down (reduced) by a factor of around 1.5.

Furthermore, it is also possible to shift the operating frequency bands to the left or right by adjusting and tuning the widths and gaps of the SRR and square ring of unit cell B, which is not discussed since the main aim of this paper is to highlight the polarization conversion switching property of the metasurface.

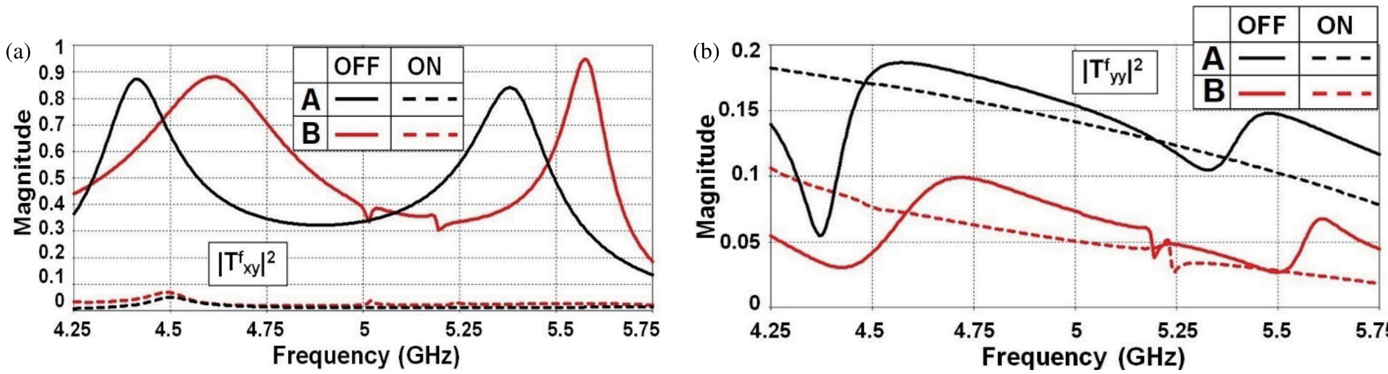

FIGURE 3. The effects of turning the switches ON and OFF on the (a) cross-polarized and (b) co-polarized transmittance values of unit cells A and B.

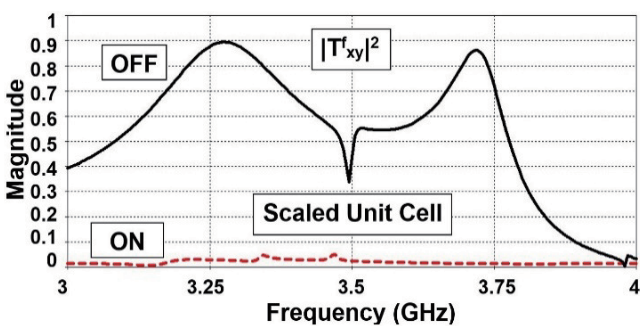

FIGURE 4. Cross-polarization transmittance curves of a 1.5 times scaled version of unit cell B for the switch OFF and switch ON conditions.

4. FABRICATION AND MEASUREMENTS

A 10×10 metasurface is fabricated with the unit cells of B. The *Infineon* PIN diodes are soldered across the wider gaps (G1) of the SRR splits of each unit cell. The fabricated prototype is presented in Fig. 5(a). Each PIN diode is switched ON using 10V DC and a bias current of 1 mA. The total current supplied to the metasurface is 200 mA for the 200 SRR structures (100 on top and 100 at the bottom). A variable voltage source is used for this purpose. The inset of Fig. 5(a) contains an expanded view of a unit cell of the bottom surface with biasing wires in place. The biasing wires are connected to the two terminals of the PIN diode. The smaller split gaps of width G (see Fig. 1) prevent the two terminals of the PIN diode from being at the same potential (shorting). Such biasing wires are connected to all the unit cells before the structure response is measured.

The angular stability of the metasurface is also tested. Depending upon the incident E-field orientation of the EM wave, we can have either a TE oblique incidence or a TM oblique incidence. The field orientations for both are shown in Fig. 5(b). Two wideband TEM horn antennas are used to measure the transmittance values of the fabricated metasurface.

The measured transmittance values for the ON and OFF conditions of the PIN diode switches are plotted in Fig. 6. The peak magnitudes of the transmittance during the switch OFF state have decreased and slightly shifted in frequency (with respect to the simulated results) because of the additional impedance introduced by the presence of the soldering metal used to place the PIN diodes and connect the biasing wires.

Since the polarization conversion phenomenon occurs for the forward incidence of an EM wave with y-directed E-field orientation, we only measure the angular stability of the metasurface for TE oblique incidence. This is shown in Fig. 7.

The polarization conversion and asymmetric transmission switching phenomena occur quite distinctly even for an incident angle of 60°. At $\theta = 60°$, the polarization conversion bands start becoming narrower, and this trend continues for higher angles of incidence.

5. CIRCULARLY POLARIZED INCIDENT WAVES

We now examine the response of the metasurface (designed with unit cell B) when the incident EM wave is CP, i.e., either Right-Hand (RHCP) or Left-Hand CP (LHCP). Only the simulated response for CP incident will be presented in this paper.

T_{RR} and T_{LL} refer to the co-polarized transmission coefficients for RHCP and LHCP incidence while T_{LR} and T_{RL} refer to the cross-polarized transmission coefficients for RHCP and LHCP incidence. The simulated responses for RHCP and LHCP incidence are plotted in Fig. 8.

The same trend is seen for CP incidence, i.e., the cross-polarization transmittance has significant non-zero values for the switch OFF condition and values very close to zero for the switch ON condition. This can be understood intuitively if we recall that CP waves can be represented as a combination of linearly polarized incidence waves.

However, there is a difference between the LP and CP responses. For LP incidence, the main source of transmission (when the switches are OFF) is cross-polarized transmission, as seen from Fig. 3. For the CP case, the co-polarized transmittance magnitudes are larger than the cross-polarized transmission magnitudes on an average. There are also certain frequency regions where the co- and cross-polarized transmission coefficients have comparable magnitudes. This is around 4.5 GHz in Fig. 8(a) and around 4.625 GHz in Fig. 8(b). Here, the metasurface transmits both co- and cross-polarized CP waves with similar power levels.

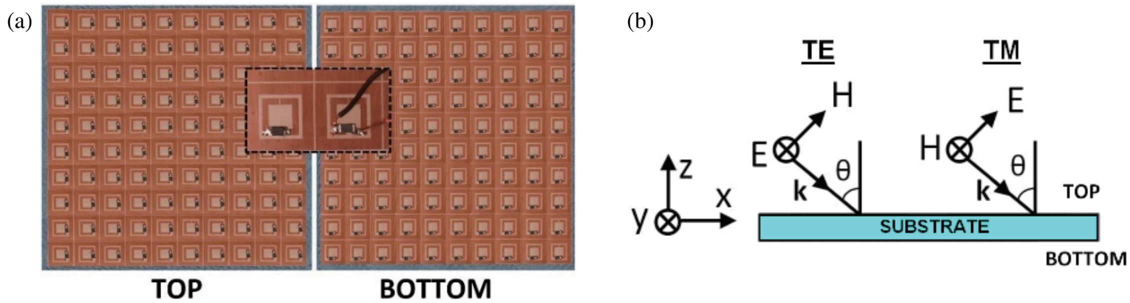

FIGURE 5. (a) Fabricated metasurface. (b) TE and TM incidence field orientations.

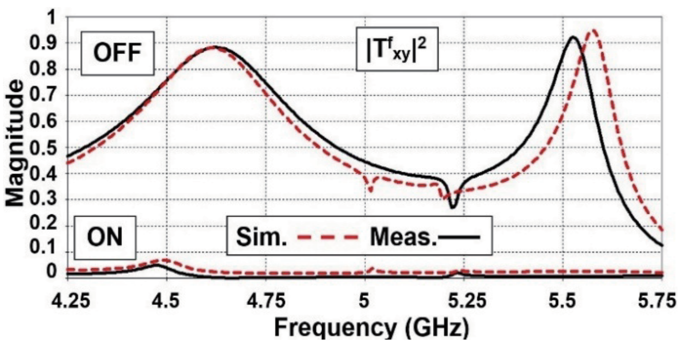

FIGURE 6. Comparisons between the simulated and measured switch conditions.

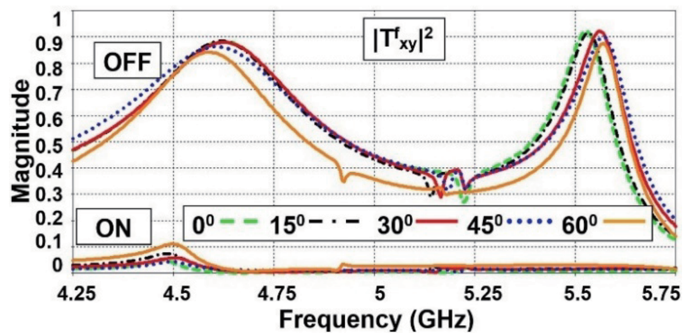

FIGURE 7. Measured angular stability of the fabricated metasurface for the ON and OFF conditions of the PIN diode switches.

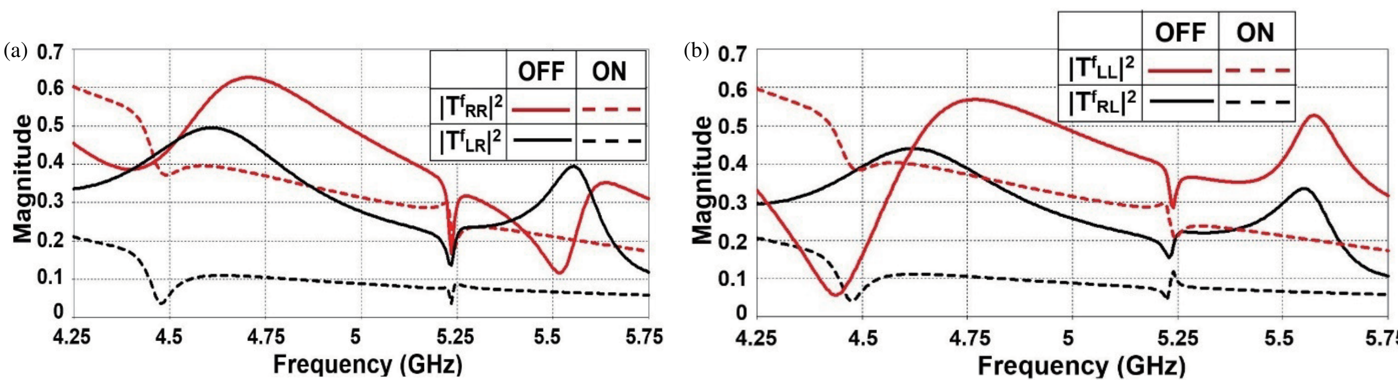

FIGURE 8. Simulated co- and cross-polarization transmittance curves for the normal incidence of (a) RHCP wave and (b) LHCP wave.

When the switches are ON, the cross-polarized transmittances remain low throughout the studied frequency range, and the co-polarized transmittance values show a decreasing trend with increasing frequency.

6. CONCLUSION

In this paper, we control the polarization conversion and asymmetric transmission properties of a metasurface by controlling the chirality of its unit cells. The chirality is controlled by using switchable PIN diodes. This phenomenon is also noticed for a scaled version of the original unit cell. The polarization conversion switching property is also present when the incident EM wave is circularly polarized. The metasurface operates well even for an incident wave angle of 60°.

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