Polarization Conversion and Splitting by Using Thin Reflective Anisotropic Metasurface

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Abstract— A kind of bi-reflective anisotropic metasurface has been proposed, which can manipulate the polarization states of the electromagnetic waves independently. The bi-reflective anisotropic metastufaces are made up of two mutually perpendicular I-shaped structures, which have capacities to control the vertical and horizontal polarizations by using each of I-shaped structures, respectively. Two typical devices of such reflective anisotropic metasurfaces have been proposed: polarization converters and polarization beam splitters. Polarization converters are designed by using homogenous anisotropic metasurfaces with thickness of $\lambda_0/10$, which can transform a linearly polarized incident wave into a circularly polarized wave in a broad frequency band. Polarization beam splitters are designed by using gradient anisotropic metasurfaces with thickness of $\lambda_0/15$, which can manipulate the vertical and horizontal polarizations to different directions independently. The full-wave simulated results of polarization converters and polarization beam splitters are calculated by using of CST, and good polarization conversion and splitting are clearly observed, which verify the capacities of such reflective anisotropic metasurfaces to manipulate the polarization states of electromagnetic waves.

1. INTRODUCTION

Reflective metasurface made up of an array of subwavelength structures has been attracted more and more attentions in recent years, which has a lot of potential applications such as mantle cloaking [1], controllable surface [2], absorbers [3] and so on [4]. The most of reflective metasurfaces are isotropic with the same responses for both TE-polarized and TM-polarized waves, which limits the ability to control the different polarizations of the electromagnetic waves. However, the anisotropic reflective metasurface provides a method to manipulate the TE-polarized and TM-polarized waves independently, which has much stronger ability to control electromagnetic waves.

Polarization converter is one of applications for anisotropic reflective metasurface to modulate the polarization states of electromagnetic waves [6]. However, the most of existing reflective polarization converters are narrow band. Many efforts have been made to expand the bandwidth by using multilayered structures [7, 8], but thicknesses of the structures are increased obviously.

Polarization beam splitter (PBS), which can separate two orthogonally polarized reflected waves two different directions, is another application for anisotropic reflective metasurface in both microwave and optical regions. Gradient periodic array placed on a top of grounded printed circuit board (PCB) are required for designing such reflective PBS. The isotropic metasurfaces are usually used to realize reflectarray antenna [9, 10], and the anisotropic metasurfacesare usually used to control the reflection of different polarizations [11, 12].

In this paper, we propose an anisotropic reflective metasurface to manipulate the different polarizations of the electromagnetic waves independently. The metasurface is made up of two mutually perpendicular I-shaped structures placed on a grounded PCB, which has capacity to control the vertical and horizontal polarizations by using each of I-shaped structures, respectively. Two above mentioned devices have been designed by such reflective anisotropic metasurfaces in the paper: polarization converter and polarization beam splitter. Polarization converter can transform a linearly polarized incident wave into a circularly wave in a broadband, which is designed by homogenous anisotropic metasurface. Polarization beam splitter can separate the vertical and horizontal polarizations to different directions independently, which is designed by gradient anisotropic metasurfaces. The full-wave simulations are calculated by using CST, and good polarization conversion and splitting are clearly observed from the simulation results, which demonstrate that these reflective anisotropic metasurfaces have good ability to control orthogonally polarized electromagnetic waves independently.

2. DESIGN AND SIMULATION

We start from the unit cell shown in Fig. 1(a), which is composed of two mutually perpendicular I-shaped structures fabricated on grounded printed circuit board (PCB) of F4B, whose relative permittivity is 2.65 and loss tangent is 0.001. Figs. 1(b) and (c) are the electric-field distributions of unit cell at 10 GHz, which show that the x directional I-shaped structure is only excited by x-polarized waves as shown in Fig. 1(b) and the y directional I-shaped structure is only excited by y-polarized waves as shown in Fig. 1(c). Hence the responses of horizontal (x) and vertical (y) polarizations can be controlled independently by each of I-shaped structures.

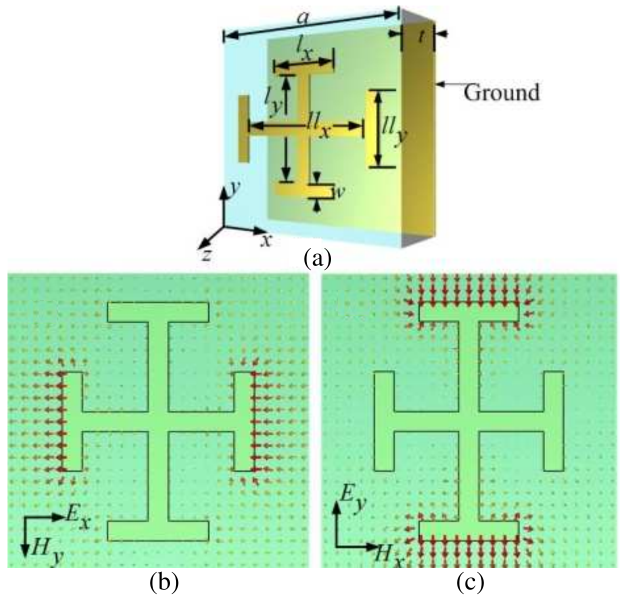
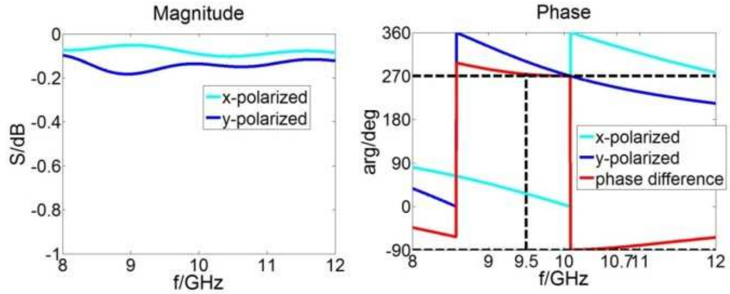


Figure 1: Unit cell of metasurface and its electric-field responses. (a) The structure of the unit cell. (b) Electric-field distributions under x-polarized waves. (c) Electric-field distributions under y-polarized waves.

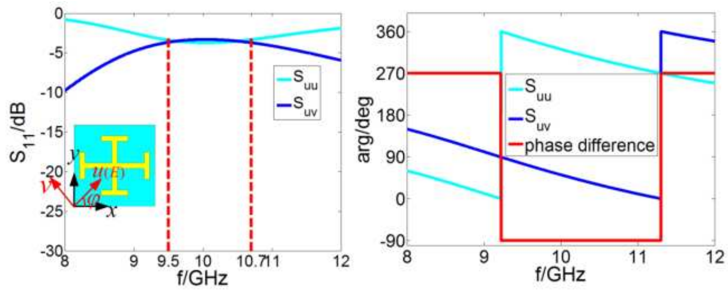
The first device realized by reflective metasurface is polarization converter, which is made up of homogenous periodic units as shown in Fig. 1(a). The linearly polarized incident waves can be converted into circularly polarized waves in a broadband after reflected by the metasurface. The dimensions of unit cell are $a = 6\,\text{mm}$, $w = 0.4\,\text{mm}$, $lx = lly = 2\,\text{mm}$, $ly = 3.6\,\text{mm}$, $ll_x = 4.4\,\text{mm}$ and $t = 3\,\text{mm}$. We assume that the linearly polarized incident waves propagate along $-z$ direction, which are reflected by metasurface as shown in Fig. 1(a). The magnitudes and phases of S_{11}-parameter for both x- and y-polarized incident waves are demonstrated in Fig. 2. The simulated results show that the magnitudes of S_{11}-parameter for both x-and y-polarized waves are nearly 0dB with total reflection as shown in Fig. 2(a), while the phase difference between x- and y-polarized reflected waves is $-90°$ or $270°$ from 9.5 GHz to 10.7 GHz as shown in Fig. 2(b). We define a new local coordinate system of uvw, and the angle between the u axis and x axis is $\varphi = 45°$ as shown in Fig. 3(a). In order to transform a linear-polarized incident waves to a circular-polarized reflected waves, the linear-polarized waves are illuminated to the metasurface along the $-z$ axis with u polarization. Hence total electric field of E can be decomposed to $E_x = E\cos\varphi$ and $E_y = E\sin\varphi$ with $|E_x| = |E_y|$ for $\varphi = 45°$. From the simulation results shown in Fig. 2, we can obtain that the magnitudes of reflected electric-field vectors of E_{rx} and E_{ry} are equal, i.e., $|E_{rx}| = |E_{ry}|$, while phase difference between E_{rx} and E_{ry} is $\arg(E_{ry}) - \arg(E_{rx}) = 270°$ or $-90°$ from 9.5 GHz to 10.7 GHz, which imply that such linear-polarized incident waves can be transformed into circular-polarized reflection waves in a broad frequency band from 9.5 GHz to 10.7 GHz. We define the S_{uu} and S_{uv} are the reflection coefficients of u-polarized and v-polarized reflection waves compared to the u-polarized incident waves, and the full-wave simulated results magnitudes and phase differences of S_{uu} and S_{uv} are shown in Figs. 3(a) and 3(b), respectively. The results show that the magnitudes of S_{uu} and S_{uv} are nearly equal from 9.5 GHz to 10.7 GHz, i.e., $|S_{uu}| = |S_{uv}|$, while the phase difference between the S_{uu} and S_{uv} is $-90°$ shown in Fig. 3(b), which imply that the circular-polarized reflected waves are achieved.

The second device realized by metasurface is polarization beam splitter (PBS), which is made up of inhomogeneous gradient unit cells. The metasurface is designed gradually changed along the x direction with a phase discontinue of $\phi(x)$, which can make the reflection waves deflected with



(a) (b)

Figure 2: The simulated results of S_{11} parameters for x- and y-polarized waves. (a) Magnitudes. (b) Phases and phase difference.



(a) (b)

Figure 3: The simulated magnitudes and phase differences of S_{uu} and S_{uv}, in which S_{uu} and S_{uv} are the reflection coefficients of u-polarized and v-polarized reflection waves compared to the u-polarized incident waves. (a) Magnitudes. (b) Phases and phase difference between S_{uu} and S_{uv}.

an angle of θ as shown in Fig. 4(a). The relationship between $\phi(x)$ and θ can be defined as:

$$\phi(x) = \phi(x_0) - k \cdot x \cdot \sin\theta \tag{1}$$

where k is the wave number in free space, and $\phi(x_0)$ is the phase at location of $x = x_0$, which can be a constant.

In order to realize the required phase discontinue in Eq. (1) by using metasurface, we first investigate the phase responses of S_{11}-parameter of the unit cell by changing its dimensions as shown in Fig. 4(b). From the simulation results, 360° phase shift for y-polarized reflected waves can be obtained by changing the l_y from 2 mm to 5.1 mm, while the phases of x-polarized reflected waves will not be affected by changing the l_y. Similarly, 360° phase shift for x-polarized reflected waves also can be obtained by changing the l_x from 2 mm to 5.1 mm, while the phases of y-polarized reflected waves will not be affected by changing the l_x. Hence, the l_x and l_y can be adjusted to obtain different reflected phases of x-polarized and y-polarized waves independently, which imply that the deflection of x-polarized and y-polarized reflected waves can be controlled independently. We remark that the meta-structures are fabricated on the grounded PCB of F4B, whose thickness is 2 mm.

Based on above discussions, we designed a PBS, which can deflect x-polarized and y-polarized reflected waves to the different directions of θ_x and θ_y in xz plane, respectively. According the Eq. (1), the $\phi_x(x)$ and $\phi_y(x)$ should be designed independently to control the x- and y-polarized waves:

$$\phi_x(x) = \phi_x(x_0) - k_0 \cdot x \cdot \sin\theta_x, \tag{2}$$
$$\phi_y(x) = \phi_y(x_0) - k_0 \cdot x \cdot \sin\theta_y. \tag{3}$$

In which θ_x and θ_y are deflection angles for x- and y-polarized waves, respectively. We define that θ_x (or θ_y) is positive (or negative) for reflected beam deflected clockwise (or anticlockwise)to z axis in xz plane, respectively. The and of the designed PBS are demonstrated in Figs. 5(a) and 5(b), respectively, in which $\phi_x(x_0) = \phi_y(x_0) = 0$ and $\theta_y = -\theta_x = 30°$. From the simulation results shown in Fig. 4(b), the dimensions of the unit cells can be obtained to satisfy the Eqs. (2) and (3), and one period of the designed gradient anisotropic metasurface is demonstrated in Fig. 5(c), in which $l_x(l_y)$

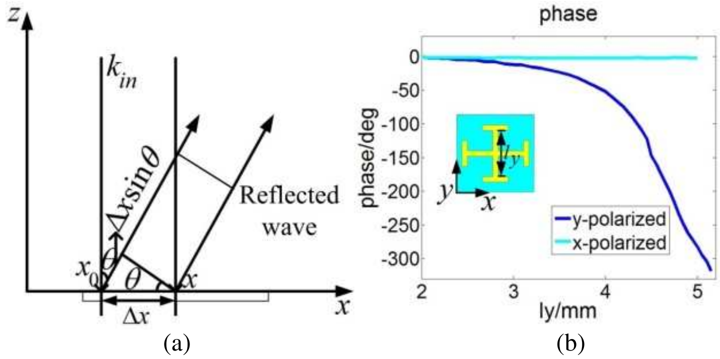


Figure 4: (a) The sketch of incident plane waves and reflected waves deflected by reflective metasurface. (b) The reflective phase responses of unit cell for both x- and y-polarized waves by varying the length of l_y at 10 GHz.

are decreased (increased) gradually from left to right. The red dots shown in Figs. 5(a) and 5(b) are the decreased phase realized by using actual unit cell, which show good agreements with the calculations. A further full-wave simulation has been made by using CST to show the performance of our designed PBS. A plane wave illuminates to the metasurface along $-z$ direction with normal incidence, whose electric-field vector is polarized with an angle of $\varphi = 45°$ to the x axis as shown in Fig. 5(c). Hence both x- and y-polarized electric vectors can be achieved by decomposing the total electric vector. The simulation results of near electric field distributions in Figs. 5(d) and 5(e) show that the reflected waves are clearly separated to two different directions: x-polarized (horizontal polarized) wave is deflected to $-30°$ and y-polarized (vertical polarized) wave is deflected to $30°$, which have good agreements with the theoretical expectation.

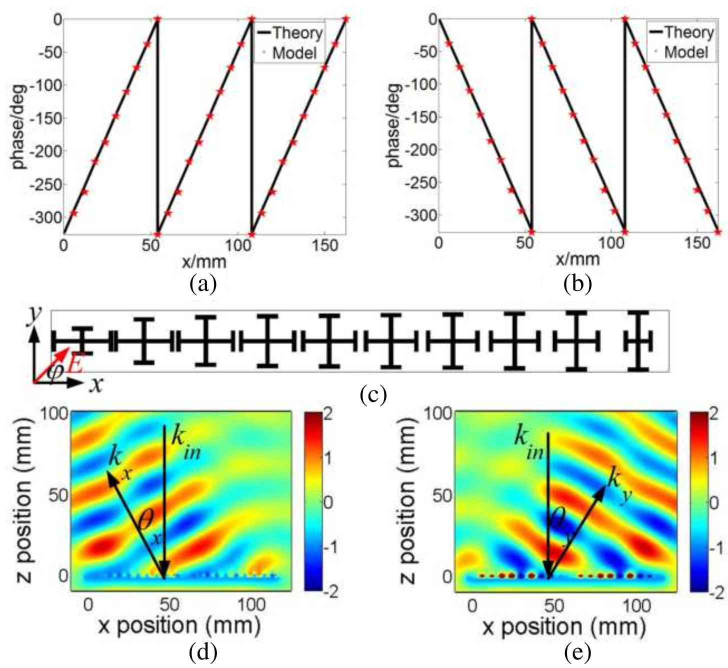


Figure 5: The phase shifts generated by one period of metasurface along x direction (a) for x-polarized waves and (b) for y-polarized waves. (c) One period of designed metasurface. (d) The near electric-field distribution of x-polarized reflected waves at 10 GHz. (e) The near electric-field distribution of y-polarized reflected waves at 10 GHz.

3. CONCLUSIONS

In this work, we proposed a kind of reflective anisotropic metasurface, which can manipulate the vertically and horizontally polarized waves independently. Two functional devices have been proposed based on such metasurfaces: broadband polarization converter and polarization beam splitter. Polarization converter is made up of homogeneous anisotropic metasurface with thickness of $\lambda/10$, which can transform linear polarized incident waves to circular polarized waves in a broad frequency band from 9.5 GHz to 10.7 GHz. Polarization beam splitters are made up of gradient anisotropic metasurface with thickness of $\lambda/15$, which can deflect horizontally and vertically polarized reflected waves to different directions with angle of $\theta_x = -30°$ and $\theta_y = 30°$. The metasurfaces are designed and simulated, which show good performances of broadband polarization conversion and polarization beam splitting.

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