Anisotropic Reflective Metasurfaces for Manipulating Radiation Beams in Reflection

Hui Feng Ma*, Yan Qing Liu, Wen Xuan Tang, Qiang Cheng and Tie Jun Cui
State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing 210096, China.
Email: *hfma@seu.edu.cn

***Abstract*—We propose a kind of anisotropic metasurface, which is composed of orthogonal I-shaped structures and a grounded plane spaced by a dielectric substrate. The metasurface has capacity to manipulate the radiating characteristics of *x*- and *y*-polarized waves independently in reflection by changing the dimensions of each I-shaped structure. By designing homogeneous anisotropic metasurface, the linear-polarized incident plane waves can be converted to circular polarized reflected waves in a broad frequency band. By designing inhomogeneous anisotropic metasurface, the *x*- and *y*-polarized incident plane waves can be separated and radiated to two different directions. Moreover, the anisotropic metasurfaces also have some applications in reflector antenna by using a horn antenna as a feed, and the incident quasi-spherical waves generated by the feed can be manipulated to plane waves after reflected by the metasurface, whose polarizations, directions and number of beams of the reflected plane waves also can be controlled as desired.**

Keywords*—reflective metasurface; anisotropic; polarization; polarization beam sppliting.

I. INTRODUCTION

Metasurfaces having capacity to manipulate the reflections or refractions of incoming waves have been attracted more and more attentions in recent years, which was introduced by applying a series of metallic structures on the surface of two different medium to generate the discontinuous phase shifts, and the anomalous reflection and refraction will happen on this situation [1]. Many interesting works have been demonstrated based on such a metasurface [2-8], but the efficiency is usually low for these transmissive metasurfaces. The another kind of metasurface - reflective metasurface, which constructed by metallic structures placed on the top of a thin isolator or substrate with grounded plane on the bottom, usually has high efficiency in manipulating the reflection of incoming waves. By designing the gradient metallic structures on the top of isolator, the discontinuous phase shifts on the surface can be achieved to modulate the reflected waves. Many impressive works also have been proposed based on such reflective metasurfaces [9-21].

In this paper, we propose a kind of anisotropic reflective metasurface to manipulate the *x*- and *y*-polarized reflected waves independently with high efficiency, which metasurface is composed of a series of orthogonal I-shaped structures, so the phase responses of the reflected waves for both *x*- and *y*-polarized waves can be controlled independently by changing the dimensions of each I-shaped structure in both *x* and *y* directions, respectively. Based on this kind of anisotropic unit cells, a homogeneous anisotropic metasurface to convert the normally linear polarized incident waves to normally reflected circular polarized waves in a broad frequency band and a gradually inhomogeneous anisotropic metasurface to separate the orthogonal polarizations to different directions have been designed. Moreover, we will show that the metasurfaces can be fed by a horn antenna with quasi-spherical incident waves, and the reflected waves not only can be manipulated to plane waves with one or more radiation beams, but also the polarization states of each radiation beam can be designed as desired, which has a potential application in planar reflector antennas.

II. DESINGING OF ANISOTROPIC METASURFACE

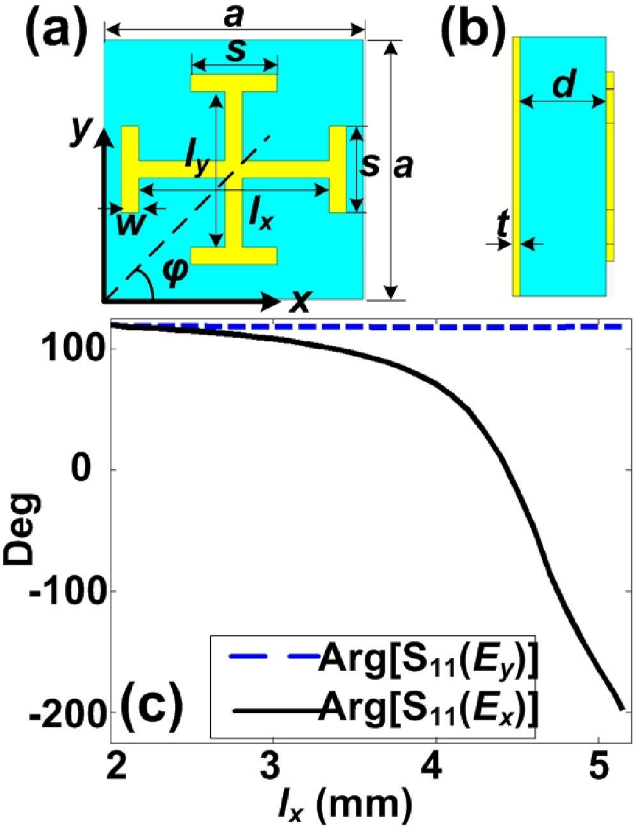

Fig. 1 The unit cell of anisotropic metasurface and its phase responses.

The unit cell of anisotropic metasurface - orthogonal I-shaped structure is shown in Fig. 1, which is a sandwiched structure composed of orthogonal I-shaped structures as shown in Fig. 1(a) and a grounded-plane spaced by a dielectric substrate as shown in Fig. 1(b). The dimensions of structure are a=6mm, s=2mm, w=0.2mm, d=3mm, t=0.018mm, l_{s1} and l_{s2}, in which l_{s1} and l_{s2} are changeable independently in both x and y directions to obtain the reflection phases of two orthogonal linearly-polarized waves, respectively. Figure 1(c) show that the reflected phase of E_x can be adjusted independently by changing the length of the l_x to obtain the phase changes covering from 130° to -200°, which has no influence to the reflected phase of E_y. Similarly, the reflected phase of E_y also can be adjusted independently by changing the length of l_y without any influence to the reflected phase of E_x. Hence, we can conclude that the reflected phases of E_x and E_y can be adjusted independently by changing the l_x and l_y, respectively. We should remark here that the reflected efficiency of the metasurface is very high, reaching nearly 100%.

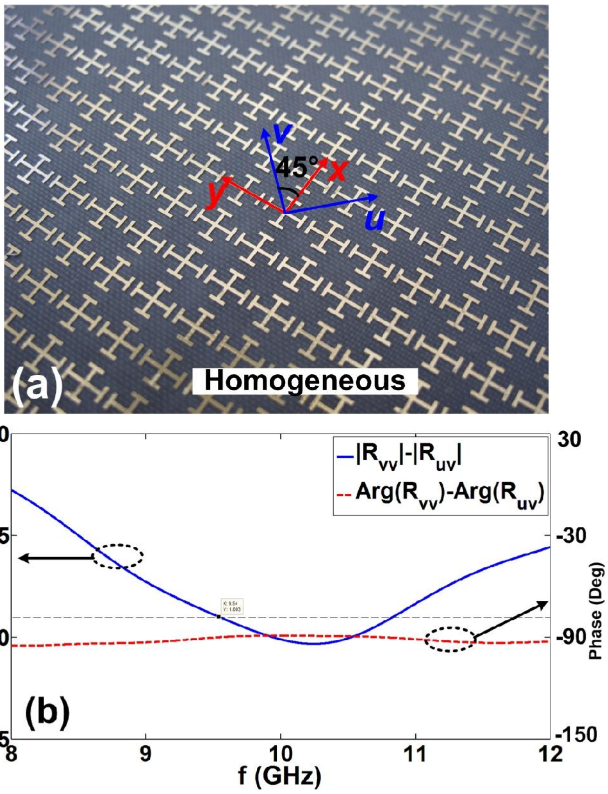

Fig. 2 The homogeneous anisotropic metasurface to realize broadband circular-polarized reflected waves. (a) The photograph of the homogeneous anisotropic metasurface. (b) The measurement results.

The metasurface can be constructed by homogeneous unit cells as shown in Fig. 2(a), which can manipulate the linearly-polarized incident plane waves to circular-polarized reflected waves in a broad frequency band with high performance [18]. The lengths of the l_x and l_y are different with l_x=3.6mm and l_y=4.4mm, respectively. To obtain circular-polarized reflected waves, the angle between the electric-field vector of linearly-polarized incident waves and x axis should be equal to φ=45° with normal incidence, so the total electric-field vector can be decomposed to be equal E_x and E_y. The phase dispersions for both E_x and E_y are similar, and the reflected phase difference can maintain as 90° in a broad frequency band with fixed l_x and l_y, so the linearly-polarized incident waves can be converted to circularly-polarized reflected waves in a broad frequency band. Two linearly-polarized horn antennas are used in measurement, in which one horn is used as emitter to generated v-polarized incident plane waves and another is used as receiver to receive both v-polarized and u-polarized reflected waves, respectively, as shown in Fig. 2(a). We should notice that the receiver and emitter of the horn antennas are put away from the designed metasurface to satisfy the far-field condition. The measurement results are shown in Fig. 2(b), which show that the magnitude errors between the reflection of E_v and E_u are less than 1dB from 9.5GHz to 10.8GHz and the phase difference is always equal to 90°. Hence, we can conclude that the good circular-polarized waves have been achieved in a broad frequency band from 9.5GHz to 10.8GHz.

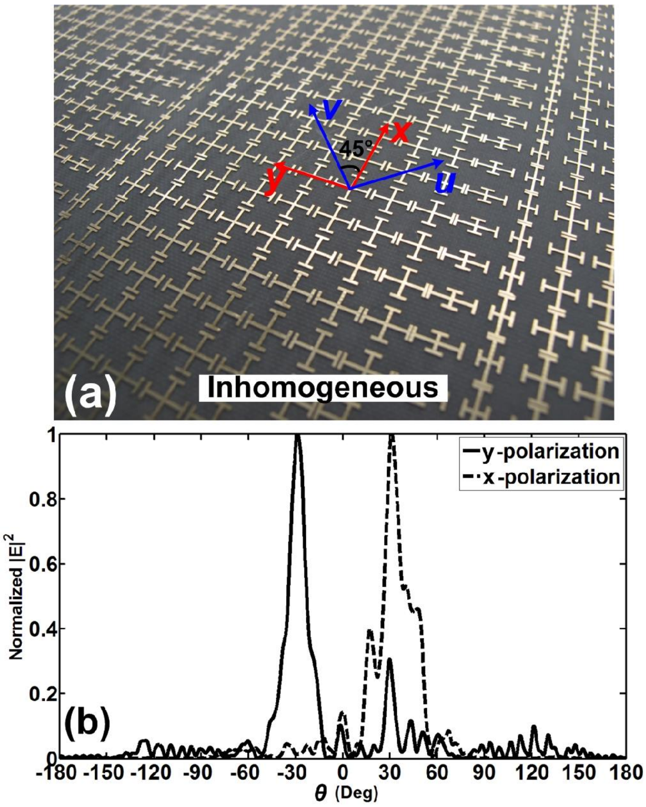

Fig. 3 The inhomogeneous anisotropic metasurface to separate the x- and y-polarized waves to different directions. (a) The photograph of the inhomogeneous anisotropic metasurface. (b) The measurement results.

The metasurface also can be designed by inhomogeneous unit cells as shown in Fig. 3(a), which can separate x- and y-polarized reflected waves to different directions [19]. By designing the l_x and l_y gradually increased and decreased along the y axis, the x- and y-polarized waves will be separated and reflected to different directions after manipulated by the inhomogeneous anisotropic metasurface. In measurement, a rectangular horn antenna is placed in front of the metasurface as an excitation with v-polarized incident plane waves as shown in Fig. 3(a). We notice that the horn antenna is also put away from the metasurface to satisfy the far-field condition.

The far-field measurement results clearly show that both x- and y-polarized waves are separated and radiated to two different directions of $\theta=30^\circ$ and $\theta=-30^\circ$ as shown in Fig. 3(b).

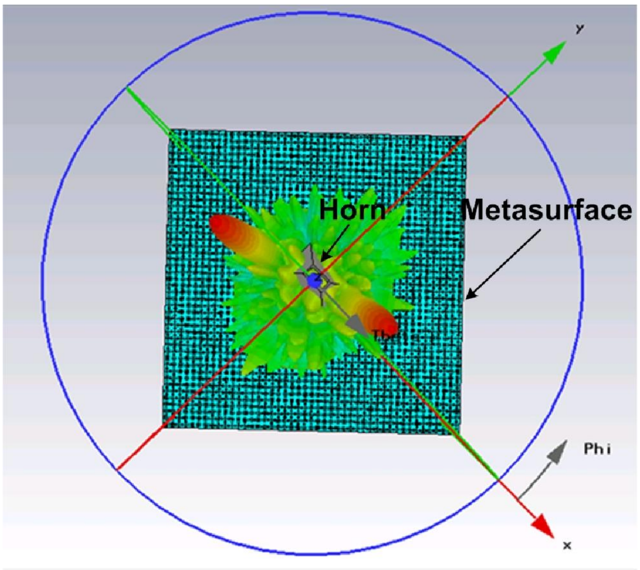

Fig. 4 The anisotropic metasurface fed directly by a linearly-polarized horn antenna.

Furthermore, in order to make such anisotropic metasurface have potential applications in reflector antenna, we use a horn antenna as an excitation directly, which is placed near to the metasurface. Hence, the incident waves generated by the horn antenna will be quasi-spherical waves instead of plane waves. By designing the anisotropic metasuface, the quasi-spherical incident waves also can be manipulated to plane waves after reflected by the anisotropic metasurface. In addition, the number of the reflected beams and their polarization states also can be designed as desired as shown in Fig. 4.

III. CONCLUSIONS

In this paper, we propose an anisotropic orthogonal I-shaped structure to construct the anisotropic reflective metasurfaces. The reflected phases of the x- and y-polarized waves can be manipulated independently by such anisotropic unit cells. We designed both homogeneous and inhomogeneous anisotropic metasurfaces to realize broadband circularly-polarized reflected waves and separated x- and y-polarized waves to different directions for incident plane waves. Otherwise, we also propose a potential application of the anisotropic metasurface in reflector antenna by using a horn antenna as a feed. The simulation results show that the quasi-spherical waves emitted from the horn antenna also can be manipulated to plane waves, and the number of the reflected beams and their polarization states also can be controlled.

REFERENCES

[1] N. Yu, et al. "Light propagation with phase discontinuities: generalized laws of reflection and refraction," Science, vol. 334, pp. 333–337, 2011.

[2] X. Yin, Z. Ye, J. Rho, Y. Wang, and X. Zhang, "Photonic spin hall effect at metasurfaes," Science, vol. 339, pp. 1405–1407, 2013.

[3] J. Lin, et al. "Polarization-controlled tunable directional coupling of surface plasmon polaritons," Science, vol. 340, pp. 331–334, 2013.

[4] L. Huang, et al. "Three-dimensional optical holography using a plasmonic metasurface," Nat. Commun. Vol. 3, 2155, 2013.

[5] F. Aieta, et al. "Aberration-free ultrathin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces," Nano Lett., vol. 12, pp. 4932–4936, 2012.

[6] X. Ni, S. Ishii, A. V. Kildishev, and V. M. Shalaev, "Ultra-thin, planar, Babinetinverted plasmonic metalenses," Light: Sci. Appl.,vol. 2, pp. e72, 2013.

[7] N.Yu, et al. "A broadband, background-free quarter-wave plate based on plasmonic metasurfaces," Nano Lett., vol. 12, pp. 6328–6333, 2012.

[8] A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, "Planar Photonics with Metasurfaces," Science, vol. 339, pp. 1232009–1232009, 2013.

[9] S. Sun, et al. "Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves," Nat. Mater. Vol. 11, pp. 426–431, 2012.

[10] A. Pors, M. G. Nielsen, R. L. Eriksen, and S. I. Bozhevolnyi, "Broadband focusing flat mirrors based on plasmonic gradient metasurfaces," Nano Lett., vol. 13, pp. 829–834, 2013.

[11] X. L. Li, et al. "Flat metasurfaces to focus electromagnetic waves in reflection geometry," Opt. Lett., vol. 37, pp. 4940–4942, 2012.

[12] S. Sun, et al. "High-efficiency broadband anomalous reflection by gradient metasurfaces," Nano Lett. Vol. 12, pp. 6223–6229, 2012.

[13] M. Pu, et al. "Broadband anomalous reflection based on gradient low-Q metasurface," AIP Adv., Vol. 3, 052136, 2013.

[14] Y. Li, B. Liang, Z. Gu, X. Zou and J. Cheng, "Reflected wavefront manipulation based on ultrathin planar acoustic metasurfaces," Sci. Rep. vol. 3, 2546, 2013.

[15] A. Pors, O. Albrektsen, I. P. Radko and S. I. Bozhevolnyi, "Gap plasmon-based metasurfaces for total control of reflected light," Sci. Rep., vol. 3, 2155, 2013.

[16] M. Farmahini-Farahani and H. Mosallaei, "Birefringent reflectarray metasurface for beam engineering in infrared," Opt. Lett., vol. 38, pp. 462–464, 2013.

[17] A. Pors, and S. I. Bozhevolnyi, "Plasmonic metasurfaces for efficient phase control in reflection," Opt. Express, vol. 21, pp. 27438–27451, 2013.

[18] H. F. Ma, G. Z. Wang, G. S. Kong and T. J. Cui, "Broadband circular and linear polarization conversions realized by thin birefringent reflective metasurfaces," Opt.l Mater.l Express, vol. 4, pp. 1717-1724, 2014.

[19] H. F. Ma, G. Z. Wang, G. S. Kong and T. J. Cui, "Independent controls of differently-polarized reflected waves by anisotropic metasurfaces," Sci. Rep., vol. 5, 9605, 2015.

[20] J. Perruisseau, "Dual-Polarized and Polarization-Flexible Reflective Cells With Dynamic Phase Control", IEEE Trans. Antennas Propag., vol. 58, pp. 1494–1502, 2010.

[21] T. Niu, et al. "Terahertz reflectarray as a polarizing beam splitter", Opt. Express, Vol. 22, pp. 16148-16160.