Double-layer Metal Wire Based Artificial Electromagnetic Surface and its Application to Bessel Beam Microwave Lens

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Abstract **─** In this paper, a transmissive periodic metasurface based on double-layer metal wire structure is designed by combining gradient phase theory with Pancharatnam-Berry (P-B) phase theory to control scattering phase of electromagnetic wave. The proposed artificial electromagnetic medium lens can improve the cross-polarized wave conversion efficiency of the phase discontinuous metasurface and ensure the thickness of the lens is ultrathin relative to the working wavelength.

Index Terms **─** Metasurface, microwave lens, P-B phase, phase discontinuity.

I. INTRODUCTION

Metasurface derived from the concept of metamaterials. It is array structure with a thickness of sub wavelength and a periodic structure in a plane, which can be used to modify the electromagnetic characteristics (phase, amplitude, polarization, beam shape) of reflected or transmitted electromagnetic waves. In 2011, the concept of metasurface was first proposed by Yu [1]. They obtained abrupt changes in the amplitude and phase of transmission field through V-shaped metal resonant structure arrays of sub-wavelength size. The law of phase modulation was obtained to construct phase gradient metasurface in the optical band for abnormal refraction [2-5]. In the metal sub-wavelength V-shaped antenna, the phase change of incident wave is based on the surface plasmon resonance effect, not on the accumulation of optical path. Besides, they realized polarization wave plate [6], plane lens [7] and vortex wave front [8] through the spatial arrangement of the unit structure. Other research groups proposed new structures to construct metasurfaces for electromagnetic wave control. Nathaniel et al. realized highly efficient transmission-type anomalous refraction metasurface based on highly efficient transmission-type linear polarized rotating metamaterials [9]. Huang et al. achieved abnormal refraction under circularly polarized incident conditions through the spatial arrangement of short metal wire structural elements with different rotational directions [10].

In recent years, optical whirlpool wave plate based on metasurface, spherical aberration elimination, infinitely thin flat lens and axicon on communication wavelength have been studied. The research results of artificial electromagnetic metasurface in microwave band mainly focus on abnormal reflection, that is, one side of artificial electromagnetic surface is phase control unit, the other side is metal floor [11]. The focusing reflector was proposed with phase matching parabola distribution. The reflective phase gradient metasurface was realized by using the "H" structure design, which couples the vertical incident electromagnetic wave to the surface electromagnetic wave [12]. Based on the method of active device loading, a controllable 0-2π reflective phase artificial electromagnetic medium impedance surface was proposed [13]. It has been discovered that when the phase gradient of artificial electromagnetic surface can provide tangential wave vectors required by surface-like plasmon (SSP), the propagating wave and SSP can be efficiently coupled at specific frequencies in microwave band [14].

However, phase mutation is always accompanied by the change of polarization mode and most of the ultra-thin artificial electromagnetic surface can only affect the cross-polarization component. Therefore, the conversion efficiency of cross-polarization wave becomes the main factor restricting the practical application of ultra-thin artificial electromagnetic surface.

In this paper, by introducing phase discontinuity into the electromagnetic wave propagation interface, we can control the beam and realize reflection and transmission in any direction. The Pancharatnam-Berry (P-B) phase provides a theoretical basis to efficiently transform the circularly polarized wave. The cross-

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polarization phase is twice the rotation angle when it rotates along the geometric center at a certain angle.

II. THEORY ANALYSIS

A. Pancharatnam-Berry phase

In order to realize phase discontinuity at the interface of metasurface, the theory of Pancharatnam-Berry (P-B) phase is considered for circularly polarized incident electromagnetic waves. In microwave region, metals are ideal conductors without surface plasmon effect, so phase discontinuity cannot be achieved by using cross-polarized resonance in optical frequency [15]. However, we can still achieve phase discontinuity by converting circularly polarized incident wave into its cross-polarized wave, which generates P-B geometric phase by changing spatial polarization [16].

Here, a phase factor (PF) is introduced. When the polarization mode is changed from the initial state to the final state, the process can be conveniently expressed in the Poincare Sphere by introducing the PF. As is shown in Fig. 1, the two poles of the sphere represent right-handed and left-handed circular polarized waves respectively, while the equator corresponds to the linear polarized state. In other words, when the polarization mode of incident wave changes through spatial variation, its spatial phase also changes, because this process is a purely geometric change process. Through the variable of phase factor, we can quantify the relationship between the change of space-varying polarization mode and the change of phase.

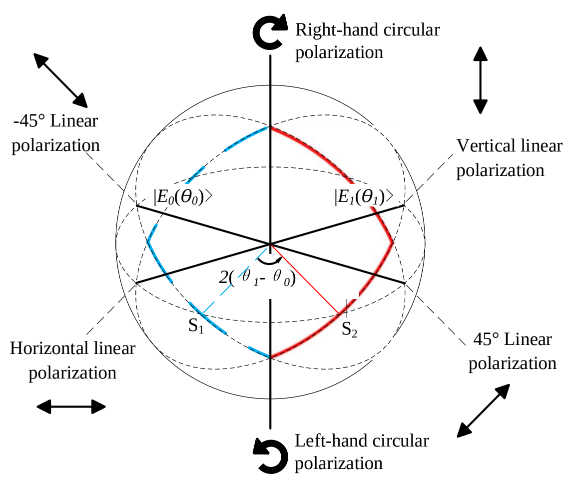


Fig. 1. Polarization representation on Poincare Sphere.

Assuming that the polarization mode varies between the poles of Poincare Sphere, any desired phase change (from 0 to 2π) can be achieved for any polarization rotation. When the incident wave is a circularly polarized wave, the transmission field can be described as:

$$\left|\overrightarrow{E_{out}}\right. = \sqrt{\eta_E}\left|\overrightarrow{E_{in}}\right. + \left(\sqrt{\eta_R}^{\pm i2\theta}\left|\vec{R}\right. + \sqrt{\eta_L}e^{\mp i2\theta}\left|\vec{L}\right.\right), \qquad (1)$$

η_E, η_R and η_L represent the coupling efficiency of polarization order, R and L represent the right-handed and left-handed polarization states. t_x and t_y denote as the transmission factors of the two linear polarization components, respectively. φ is the phase difference between the two transmission factors. For circularly polarized incident wave, the transmitted electric field contains two components. One component keeps the original rotation direction and the other component is cross polarized field, which is the key to the construction of hyperlens by using phase discontinuity.

B. Bessel beam metasurface

For an axle prism with a beta angle, the phase delay must increase linearly with the increase of the distance from center point. The use of artificial electromagnetic metasurface instead of traditional phase control elements will make it possible to achieve high-performance convergent lens with light weight and small volume. In this method, the control of the incident wavefront will no longer depend on cumulative phase of electromagnetic wave propagation, but on the phase shift obtained by scattering on the sub-wavelength ultra-thin array.

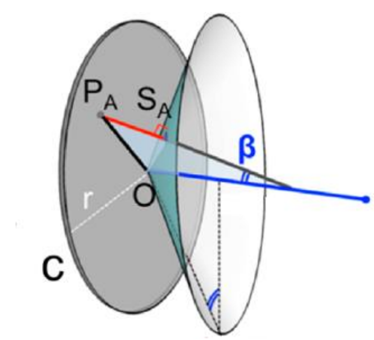


Fig. 2. Plane lens and its equivalent prism.

The plane lens and its equivalent prism is shown in Fig. 2. The phase shift of PA (x, y) at any point on the lens should satisfy the following equation:

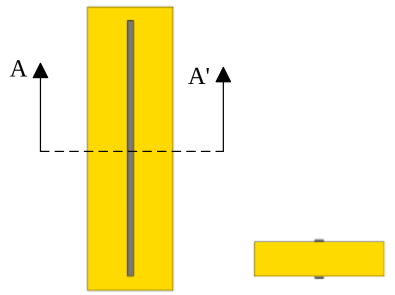
$$\varphi_A(x,y) = \frac{2\pi}{\lambda}\overline{P_AS_A} = \frac{2\pi}{\lambda}\sqrt{x^2+y^2}\sin\beta \qquad (2)$$

Based on the structure of split ring resonator (SRR) unit, we construct the phase profile of the lens and obtain a microwave lens with 25×25 unit by taking beta=10°.

III. DESIGN AND RESULTS

A. Double-layer metal wire structure

The double-layer metal wire structure is shown in Fig. 3. Metal wires are arranged at the same position on both sides of the dielectric plate. The structure is used to simulate the silicon dielectric metasurface. When electromagnetic waves are irradiated on the structure, magnetic resonance will occur between the two metal.



(a) Orthographic (b) AA' profile

Fig. 3. Metal wire array unit from different perspectives.

The structure is periodically arranged horizontally and vertically, and the scattering parameters are obtained by irradiating the structure with left-handed circular polarization wave. From the results in Fig. 4, it can be seen that at 9.8 GHz, the cross-polarization transmission coefficient of the periodic structure is as high as 0.85, i.e., the cross-polarization conversion rate is 72%. At the same time, the co-polarization transmission coefficient is only 0.25, i.e., the co-polarization transmission rate is only 6.25%. Therefore, in the transmission wave, most of the energy transferred from the left circularly polarized wave is called the cross polarized wave. According to the principle of PB phase introduced above, the S_{21} phase value of the cross-polarized wave is the abrupt phase introduced by the structure to the incident electromagnetic wave.

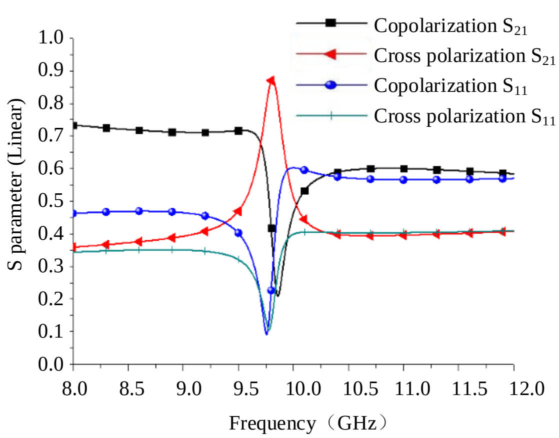


Fig. 4. S parameter simulation results of double-layer metal wire structure.

The unit size of the structure is only 3 mm×10 mm, which is insensitive to oblique incidence. Hence, when the electromagnetic wave was introduced as oblique incidence, the same results can be obtained. When the incident angle is changed from 0° to 60°, the cross polarization conversion coefficients are all above 0.85 (Fig. 5). This indicates that when the size of the unit is much smaller than the wavelength, the electromagnetic response characteristics are insensitive to the incident angle, so the electromagnetic wave control process can be realized in a wide angle.

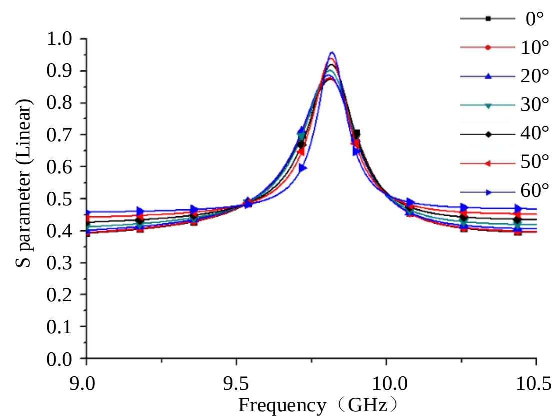


Fig. 5. Oblique incidence cross polarization conversion coefficient of double-layer metal wire structure.

If the right-handed circular polarization wave is used to irradiate, the parameters and simulation settings of the structure remain unchanged. The scattering parameters are obtained as shown in Fig. 6. It can be seen that the structure has the same polarization conversion effect for the left-handed circular polarization wave and the right-handed circular polarization wave.

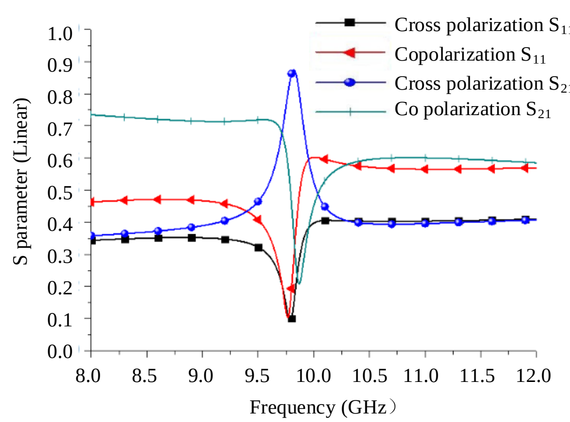
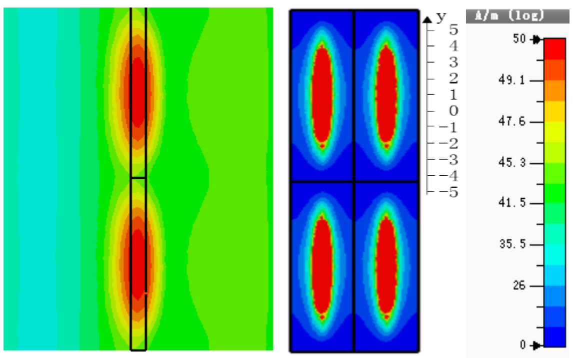


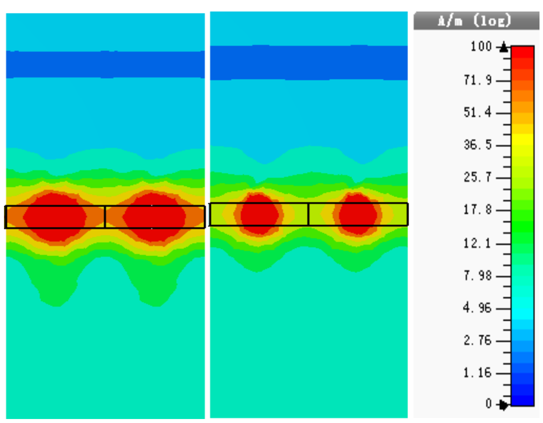
Fig. 6. S parameter simulation results of the structure irradiated by right-handed circularly polarized wave.

In the upper and lower metal structures, there are surface currents flowing in opposite directions. These two parts of the surface current and the displacement current between the two layers of metal will form a loop, which constitutes the magnetic response of the structure. A magnetic field monitor is applied around the structure to obtain the magnetic field distribution of the double-layer metal wire structure at 9.8 GHz. As is clearly seen from Fig. 7, the section of the magnetic response generated by the structure under the irradiation of the left circularly polarized wave on z-o-y plane. It can be seen that at 9.8 GHz, there is a strong magnetic field in the position of the metal strip on the structure, and the magnetic field intensity takes the form of strong in the middle and weak at both ends. Figure 8 depicts the corresponding magnetic field distribution on the x-o-z plane when y=0 and y=3mm. The results demonstrate that the magnetic field in the center of the structure is the strongest and extends gradually to both ends.



(a) Side view (b) Front view

Fig. 7. Simulation of magnetic field distribution in double-layer metal wire structure.

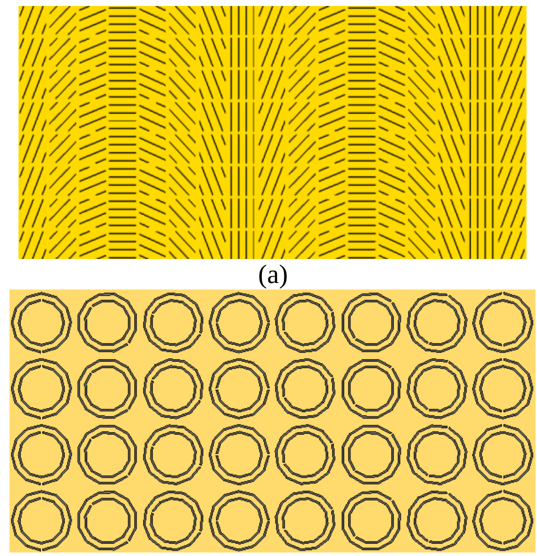


(a) y = 0 (b) y = 3 mm

Fig. 8. Cross section of magnetic field distribution in double-layer metal wire structure.

B. Double-layer metal wire array metasurface

Eight rotating elements are combined to form a new unit, which is periodically arranged and irradiated by left-handed circular polarization wave. Metasurface with double-layer metal wire array structure and the SRR structure metasurface are depicted in Fig. 9. When the incident wave is perpendicular to the incident wave, the angle of the incident wave deflects. From the generalized refraction law formula, when the cell spacing is 10 mm, the abrupt phase of the phase difference between adjacent elements is 45°, and the incident angle is 0°, the emission angle is 23°. The deflection of electromagnetic wave propagation direction was observed by an electric field monitor. The results of the electric field monitor show that when the structure is illuminated vertically by a left-handed circular polarized wave, the angle between the transmitted wave and the observed wave is 18.4° and the energy of the transmitted wave is high.



(a)

(b)

Fig. 9. (a) Metasurface with double-layer metal wire array structure. (b) SRR structure metasurface.

The performance comparison of single-layer metal wire array metasurface and the designed metasurface is demonstrated in Table 1. As can be concluded from the chart, the designed double-layer metal wire array metasurface can realize high transmittance efficiency of cross polarized waves by introduced magnetoresistance.

Table 1: Performance comparison of single-layer metal wire array metasurface and the designed metasurface

Structure	**Efficiency**
Single Layer	20%
Double Layer	72%

Full-wave simulation is carried out by using Lumerical FDTD (Fig. 10). Left-circular polarization wave is used to illuminate the lens, and its effect on electromagnetic wave convergence is studied. The near-field results of the convergent lens are obtained. According to the results, when the convergent lens is illuminated by the left-handed circular polarization wave, a non-diffracting Bessel beam with concentrated energy is generated on the other side of the lens. The maximum energy is achieved at z=200 mm, which means, the focal length of the convergent lens is 200 mm.

The phase change of the structure is gradient change rather than uniform change, and the discrete phase change leads to the difference between the control effect and calculation of the final electromagnetic wave. When simulating metasurface, finite elements are selected to simulate the infinite periodic structure. For this structure, every element has been trimmed after rotation, so there is a small error between the simulation results and the calculation of the generalized refraction law formula.

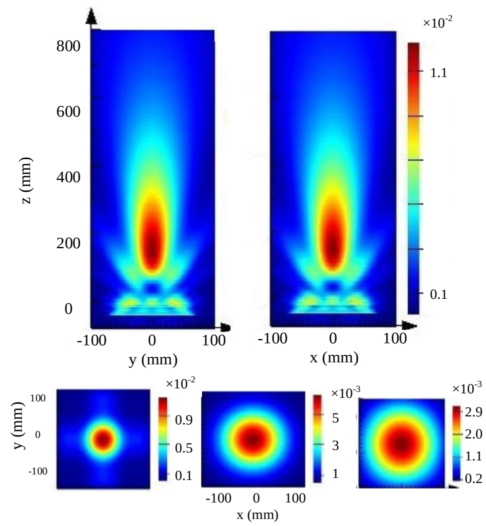


Fig. 10. FDTD results of double metal wire structure.

In the microwave anechoic chamber shown in Fig. 11, the circularly polarized horn is used as the transmitting antenna and the cross polarized horn is used as the receiving antenna. The metasurface is placed in front of the receiving horn and the receiving pattern is tested.

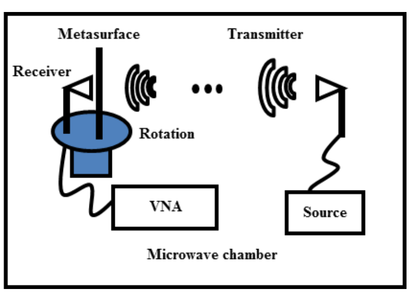


Fig. 11. Measurement setup of the designed metasurface.

In Fig. 12, when the incident wave is irradiated to the structure at 19° incidence angle, the receiving antenna obtains the maximum test level. In other words, when the incident wave is incident vertically, a transmission wave with an angle of 19° from the normal line will be generated, which is only slightly different from the calculated result of 23°.

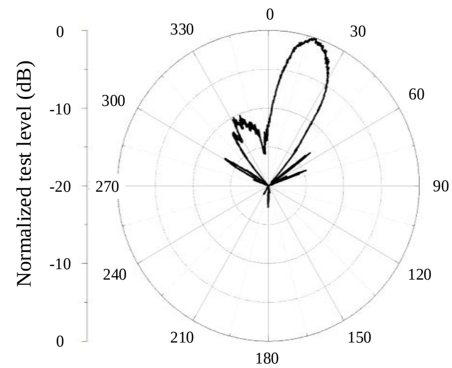


Fig. 12. Measurement results of double-layer metal wire array metasurface.

IV. CONCLUSION

In this paper, based on the generalized refraction law and P-B phase principle, an artificial electromagnetic surface with deflection effect and a Bessel beam theory for convergence of electromagnetic waves are designed by using the double-layer metal wire array unit structure. The unit used to form microwave lens has high efficiency in the X wave band to achieve efficient manual control of electromagnetic wave transmission, which will be a good candidate for electromagnetic wave regulating device application.

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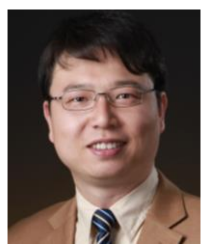

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