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Quanchao Shi\textsuperscript{a}, Guangyu Nie\textsuperscript{a}, Zheng Zhu\textsuperscript{a}, Yang Liu\textsuperscript{b}, Jinhui Shi*\textsuperscript{a}

\textsuperscript{a}Key Laboratory of In-Fiber Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, China; \textsuperscript{b}Turbine Technology Institute, Harbin Turbine Company Limited, Harbin 150046, China

\section*{ABSTRACT}

We propose an ultrathin planar metamaterial with an abrupt phase change along its surface for beam manipulation. The metamaterial is composed of bilayered asymmetrical split ring apertures (ASRAs) on either side of a dielectric substrate. The proposed metamaterial relies on eight variable ASRAs in a super cell to modulate the phase of transmitted wave. Efficient beam direction manipulation for cross-polarization transmission has been achieved and co-polarization transmission has been completely suppressed. Numerical simulation results show that the linearly polarized incident wave can deflect in a designated direction passing through the ultrathin metamaterial. An intensity efficiency of 70\% and a deflection angle of 24° at 6.2GHz have been verified.

\textbf{Keywords:} Metasurface, phase discontinuities, beam manipulation, polarization transformation

\section*{1. INTRODUCTION}

Conventional optical components rely on phase changes accumulated through along the optical path and wavefront shaping can be realized by propagation through media with known refractive indices. Light propagation distance is larger than the wavelength to shape its wavefront. On the contrary, metamaterial\textsuperscript{[1]} manipulates light waves in subwavelength scale, and controls the spatial distribution of optical response with subwavelength resolution and the refractive indices varying from positive to negative\textsuperscript{[2]}. In this way many unusual light propagation phenomena such as negative refraction\textsuperscript{[1]}, invisibility cloaking\textsuperscript{[3]} and perfect lenses\textsuperscript{[4]} can be achieved. An ultrathin planar metamaterial, i.e., a metasurface\textsuperscript{[5,6]}, which is generally created by arrays of anisotropic light scatterers, opens the door to the manipulation of light beams by introducing abrupt phase discontinuity for scattering waves\textsuperscript{[7]}. As an example, the V-shaped antenna array is very typical which ensures that the amplitudes of scattering waves are all equal and the phase shift between two neighbor units is constant\textsuperscript{[7,14]}. Beam manipulation and phase modulation within an optically thin depth are favorable for various applications\textsuperscript{[12,13]}. Metasurfaces are usually made of arrays of optical antennas with subwavelength scales, which consist of reflect-arrays and transmit-arrays\textsuperscript{[8]}. Recently, metasurface produces abrupt phase discontinuity for scattering waves to modulate phase of transmitted waves, which is modified on a subwavelength scale and enables transmitted waves to refract at a predetermined deflection angle through an array of metamaterial units. A metasurface relies on resonating units\textsuperscript{[7]} to realize beam manipulation, and a phase shift that covers a range of 0-2π on the metasurface is required in order to realize anomalous deflector. The phase shift can be achieved by subwavelength metallic structures which are able to scatter incident wave into orthogonally polarized wave. The amplitude and phase of the transmitted wave can be controlled by turning the geometric parameters of optical antennas.

In this paper, we propose a bilayered gradient metamaterial composed of a dielectric spacer layer and two metallic layers that are perforated with asymmetrical split ring apertures (ASRAs). The geometries of two metallic layers are identical but arranged by a twist angle of 90°, and a bilayered gradient metamaterial can be used to realize beam shaping or beam steering. Simulation results indicate that the polarization state of incident light beam are fully transformed to orthogonal polarized by the twist angle when passing through the metamaterial. The orthogonal arrangement of ASRAs gives the metamaterial a chiral characteristic that promises highly efficient polarization conversion and co-polarization transmission\textsuperscript{[16,17]} are completely suppressed. The varied phase discontinuities along the metamaterial flexibly modify the wavefront of transmitted waves. An efficiency of 70\% and a deflection angle of 24° at 6.2GHz are verified by using CST commercial software.

*hrbeusjh@gmail.com; phone +86(0)451-82518226; fax +86(0)451-82518226

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2. BILAYERED GRADIENT METAMATERIAL

The schematic of the proposed gradient metamaterial for beam manipulation is shown in Figure 1. The metamaterial consists of a dielectric spacer layer and two metallic layers that are perforated with ASRAs. The dielectric layer has a thickness of \( t = 1.6 \text{mm} \) and a permittivity of \( \varepsilon = 2.65 \). The ASRAs of the two metallic layers are identical, but the back layer has a twist angle of 90° with respect to the front layer. In our system the metallic layer is considered to be a perfect electric conductor. As illustrated in Figure 2(a), a super cell consists of eight unit cells, which have a \( \pi/4 \) phase decrease from left to right of the metamaterial. The outer radius of unit cell is fixed at \( R = 6.4 \text{mm} \) while the inner radius is \( r = 5.6 \text{mm} \). The period is \( a = 15 \text{mm} \), \( L_x = 120 \text{mm} \). Each unit cell consists of two different arc slits corresponding to open angle \( \alpha \) and \( \beta \). The phase gradient is generated by varying the open angle of ASRAs along \( x \) direction on the metamaterial. In this work, the open angle \( \alpha \) is constant while \( \beta \) is variable along the \( x \) axis on the metamaterial. Figure 2(b) depicts the back layer of the metamaterial. Two layers of ASRAs rotate with respect to each other by a twist angle of 90°. Figure 2(c) illustrates a super cell with eight ASRAs. The incident plane waves polarized along the \( y \) axis are propagating along -\( z \) direction. Phase gradient is achieved by turning the open angle \( \beta \) of the ASRAs along \( y \) axis on the metamaterial. It obtains an additional phase when incident waves pass through the metamaterial and transmitted waves are refracted at a prescribed angle.

![Figure 1. Schematic of the metamaterial with anomalous refraction for the cross-polarization](image1)

![Figure 2. Schematic of the gradient metsurface. The (a) front and (b) back view of a super cell. (c) The stereogram of a super cell.](image2)

In figure 3, we obtain the spectra of transmission coefficient and phase of the metamaterial with an array of a constant unit cell, in which \( \alpha = 160° \) and \( \beta = 70° \). There are two transparent windows in the frequency range of 5-10GHz, in which the polarization states of transmitted waves are changed to be orthogonal to the incident one and the phase is varied from 0 to -4\( \pi \). Next, we will design the gradient metamaterial at the first transmission window of 6.2GHz. Table 1 shows the open angles of eight ASRAs. The first four ASRAs provide a phase shift of \( \pi \) from left to right for cross-
polarized wave corresponding to $\beta = 0°, 50°, 70°$ and $150°$. The rest four ASRAs are formed by mirroring the first four ASRAs with respect to the y axis, therefore a phase shift of $2\pi$ can be obtained. Transmission amplitude and phase of each element in the gradient metamaterial at 6.2 GHz are shown in Figure 4.

![Figure 3](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 3. Transmission spectrum (black square dots) and phase (red circular dots) from a bilayered gradient metamaterial perforated with a periodic array of ASRAs with $a = 15\text{mm}$, $\alpha = 160°$, $\beta = 70°$.

In this paper, the phase gradient along the interface is constant, so it follows the generalized Snell’s law of refraction [6],

$$\sin(\theta_i) n_i - \sin(\theta) n_t = \frac{\lambda}{2\pi} \frac{d\phi}{dx}$$  \hspace{1cm} (1)

Where $\theta_i$ ($\theta$) is the angle of refraction (incident), and $\lambda$ is wavelength of operate wave, while $n_i$ ($n_t$) is refractive index of the media on the transmission (incident) side of the metamaterial, $\phi$ is the phase discontinuity along the surface of the metamaterial, $d\phi/dx$ is the component of the phase gradient parallel to the plane of incidence along the x axis, which is used to deflect the transmitted wave away from the z axis. In free space, $n_t = 1$ and $n_i = 1$, the deflection angle is determined by the gradient of phase discontinuity at normal incidence (i.e. $\sin(\theta_i) = 0$). In this case, the refraction angle $\theta_i$ can be obtained by:

$$\theta_i = \arcsin \left( \frac{\lambda}{L_x} \right) = 23.8°$$  \hspace{1cm} (2)

![Figure 4](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 4. Transmission amplitude (black square dots) and phase (red circular dots) of each element in the gradient metamaterial at 6.2 GHz. The open angles of the periodic ASRAs are shown in Table 1.
Table 1. Open angles $\alpha_n$ and $\beta_n$ of our proposed metamaterial

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3. SIMULATION RESULTS

We demonstrate the theoretical predictions of beam manipulation for the bilayered metamaterials by using CST commercial simulation software. In the simulation, the periodic boundary conditions along the x axis and the y axis are applied. The metamaterial is expected to have a super cell length of $L_z = 120 \text{mm}$ along the x axis. The incident y-polarized waves are plane waves, propagating along $-z$ direction. Figure 5(a) and 5(b) present the distributions of the calculated $E_x$ of transmitted waves in the $x$-$z$ plane for incident y-polarized waves without and with the metamaterial. For no metamaterial, no polarization conversion occurs, thus no $x$-polarized transmitted wave is found. However, when the incident y-polarized waves pass through the proposed gradient metamaterial, a giant polarization conversion is observed. The polarization state of the transmitted wave is orthogonal with respect to the incident wave and also a deflection of $x$-polarized transmitted wave is produced. In this case, the y-polarized waves cannot be allowed to pass through the bilayered gradient metamaterial. Due to the imperfect design, the transmitted field is not a plane wave. As shown in Figure 5(b), the incident beam is propagating through the metamaterial with a deflection angle of about 24° with respect to the $z$ axis.

![Figure 5. Distributions of the calculated $E_x$ of the transmitted waves in the $x$-$z$ plane for incident y-polarized waves (a) without and (b) with the bilayered gradient metamaterial.](image)

The near-field simulation obviously shows anomalous refraction phenomena. In order to further determine the deflection angle and the transmission efficiency, we also detect intensities of the transmitted wave at different angles under normal incident wave. We set a series of probes every 1 millimeter along the $x$ direction and measure the transmission intensities. Figure 6 shows the intensity profile of the transmitted wave at different angles. The results indicate that one intensity peak is obtained at an angle of 24° with an efficiency of 70%. All of results confirm the ability of the bilayered gradient metamaterial to manipulate the propagation direction and the polarization state of the transmitted beam.
4. CONCLUSION

In conclusion, we propose a bilayered gradient metamaterial that is composed of two layers of variable ASRAs arranged by a twist angle of 90°. Orthogonal arrangement of the gradient metamaterial realizes the polarization transformation and a deflection of the cross-polarization wave due to lateral gradient phase change. The proposed metamaterial achieves a $2\pi$ range of phase shift, leading to an ability of highly efficient beam manipulation. The simulation results show an efficiency of 70% and a deflection angle of 24° at 6.2GHz for the transmitted beam. Therefore, the bilayered gradient metamaterial is feasible to be used for some optical devices such as beam focusing, polarization converters and other functionalities.

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