High-Efficiency Phase and Polarization Modulation Metasurfaces

Huan Zhao, Xinke Wang, Baogang Quan, Shutian Liu,* and Yan Zhang*

Use of metasurfaces to control the characteristics of electromagnetic waves is an emerging trend at present. Multifunctional metasurfaces, which can modulate multiple wave parameters, greatly reduce the complexity and enrich the functionality of optical systems. Herein, a high-efficiency multifunctional metasurface for operation in the terahertz band is proposed and demonstrated. Use of a trilayer structure allows the working efficiency to reach 85% at the designed operating frequency. The phase and polarization states of the transmitted waves are modulated individually via subtle adjustment of the geometric parameters of each layer. Two terahertz-band vector beam generators are demonstrated based on the proposed metasurface. The two devices individually generate radial and azimuthal terahertz vortex beams that can carry arbitrary orbital angular momentum. The experimental results demonstrate the validity of the proposed approach. This method represents a route toward easy fabrication of high-performance phase and polarization modulation metasurfaces that can improve the information-carrying capabilities of terahertz systems and offers benefits for structured light generation, optical information security, and optical communication applications.

1. Introduction

Metasurfaces, which are artificial aperiodic planar structures, are composed of subwavelength antennas. These structures can control the wavefronts of electromagnetic waves easily by simply adjusting the geometric parameters and the distributions of their antennas.[1–5] The most common metasurface structures can modulate the phase and/or amplitude of specifically polarized light; for example, a metal split-ring structure is generally used to control the phase and/or amplitude of linearly polarized light[6–8] and a bar structure is used to modulate the phase of circularly polarized light based on the Pancharatnam–Berry phase mechanism.[9–12] However, simultaneous discretionary control of the phase and polarization states of light is essential for these multifunctional metasurface devices. Birefringent metasurfaces, which are composed of dielectric materials, can control the phase and polarization of a wave with high transmission efficiency.[13–20] This type of structure has different effective refractive indexes along the two orthogonal principal axes, which means that the phase of the transmitted wave can be modulated individually by varying the geometric dimensions of the structures along the two principal axes. Rotation of the two principal axes of the structure can cause polarization change in the waves scattered from each unit. Therefore, it is possible to control the phase and polarization states of the light scattered by each unit individually by selecting the appropriate dimensions and rotation angles. Complex vector beam generation and full-polarization holograms[13] have been demonstrated using silicon birefringent metasurfaces. The working efficiency of these metasurfaces can reach almost 85%. However, fabrication of dielectric metasurfaces for the large-wavelength band is quite difficult because the height of the dielectric structure must be greater than the relatively large wavelength to achieve a sufficiently large phase modulation range. For a terahertz wave, for which the wavelength is several hundred micrometers, the height of the silicon metasurface structure should also be several hundred micrometers and the width should only be several tens of micrometers[21–23] which could prove challenging in the structural fabrication process. The diatomic metasurface, in which each unit cell is composed of two identical bar antennas, is another approach intended to enable full control of the phase and polarization states that is based on the detour phase method.[24–30] By adjusting the displacement of the diatomic unit cell relative to the periodic structure, the phases of scattered waves...
can be modulated. Rotation of each antenna in the cell allows the polarization states of the scattered waves to be adjusted. Vector beam generation\textsuperscript{[13,28]} and full-polarization holograms\textsuperscript{[20,26,27,30,31]} have also been demonstrated using all-dielectric pillar or reflective bilayer metal structures. However, the diatomic metasurface operates for first-order diffraction, which represents a barrier to carry out measurements in the terahertz band. Furthermore, the chromatic dispersion that results from different wavelengths having different diffraction angles will present difficulties for broadband applications.

In this article, we propose and experimentally demonstrate a high-efficiency trilayer metasurface for individual phase and polarization control. Based on the proposed structure, we design and realize two terahertz-band vector beam metasurface devices that can generate vortex beams with different orbital angular momentum and polarization states. The designed devices operate in transmission mode and have operating efficiency of $\approx85\%$. The two devices are fabricated using conventional UV lithography and a subsequent lift-off technique. The performances of the fabricated devices are then measured using an in-house-built terahertz focal plane imaging system. The experimental results verify the high efficiency and robustness of the devices. It is therefore believed that the proposed high-efficiency trilayer metasurface will provide a new approach to the fabrication of multifunctional metadevices and enable full wavefront control.

2. Results and Discussion

2.1. Metasurface Design

Figure 1 shows the operation of the designed metasurface, which can modulate the phase and polarization states of scattered waves simultaneously. The metasurface is constructed from designed unit cells. Each cell is composed of three metal structured layers and two dielectric spacer layers. The top and bottom metal layers in each single unit cell are an orthogonal pair of metagrating arrays that are used to carry out polarization modulation. The middle metal layer is a split-ring antenna array that is used to carry out phase modulation. The incident light beam is circularly polarized, which means that the beam components along each linear direction all have the same amplitude. The first metal layer is a metagrating that serves as a linear polarizer. When an illuminating wave is incident downward onto the metasurface, the circularly polarized wave will be changed into a linearly polarized wave with a polarization direction that lies perpendicular to the direction of the metagrating. The wave with its specific linear polarization will then be transformed into a wave with cross-polarization of the initial linear polarization by the metal split ring antenna in the second layer. The phase of the converted cross-polarized wave can be modulated by varying the opening angle of the antenna. Finally, the modulated cross-polarized light passes through the final metagrating layer and the polarization state remains unchanged. The first and third metal layers also act as cavity mirrors. Careful adjustment of the thickness of the dielectric spacer layers will cause constructive interference to occur at a predefined frequency, causing the structure to have high transmission. As a result, light can be output with the desired phase modulation and polarization direction. Through optimal arrangement of the cells, output light with arbitrary phase and polarization state distributions can be achieved. As shown in Figure 1, if the top and bottom metagrating layers have radial and azimuthal distributions, respectively, then a vector beam with radial polarization will be obtained. However, because of the relative phase delay of the left circularly polarized wave, the generated vector beam will have a vortex phase distribution with a topological number of $+1$. To realize a vector beam with a plane phase distribution, the antenna array should provide a vortex distribution with a topological number of $-1$, thus ensuring that the total phase distribution of the output wave is constant. This approach based on individual phase and polarization state modulation can be used to generate structured light with more complex phase and polarization distributions.

Figure 2a shows a schematic of a unit cell for the designed metasurface. The metagrating and the split ring antenna are both made from gold (Au). The Au layer thickness is 100 nm. The two dielectric spacer layers are made from polyimide (PI), and the PI layer thickness is selected to be 40 $\mu$m to support constructive interference at a preset frequency of 0.37 THz. Figure 2b–e shows top views of the complete unit cell, the top metagrating layer, the split ring layer, and the bottom metagrating layer, respectively. The period of the unit cell $P$ is set at 200 $\mu$m. The width $a$ and period $b$ of the metagrating are 10 and 20 $\mu$m, respectively. The azimuth angles of the top metagrating and the bottom metagrating with respect to the x-axis are $\theta_0$ and $\theta'=-90^\circ$, respectively. By adjusting the angle $\theta$ of each unit cell, the...
transmitted wave’s polarization state can be adjusted to be along the $\theta$ direction. The outer and inner radii of the split ring antenna, $R$ and $r$, are optimized to be 90 and 70 $\mu$m, respectively. The angle between the axis of symmetry of the antenna and the $x$-axis is $\theta - 45^\circ$. When the circularly polarized wave passes through the top metagrating, a linearly polarized wave with a polarization angle of $\theta - 90^\circ$ will be generated and will then be incident on the antenna layer. In the antenna layer, the angle between the axis of symmetry of the antenna and the polarization direction of the incident light is arranged to be $45^\circ$, which enables excitation of both the symmetric and antisymmetric modes of the split ring antenna. A cross-polarized wave can be scattered using these two modes, i.e., the re-emitted wave will have a polarization angle of $\theta$. The phase of the re-emitted wave can be controlled by varying the opening angle $2\alpha$ of the split ring antenna. Because the bottom metagrating has an azimuth angle of $\theta - 90^\circ$, re-emitted waves from the antenna with a polarization angle of $\theta$ can pass through it freely. In summary, the polarization angle of the transmitted wave can be set at $\theta$ by varying the azimuth angles of the metagratings, and the phase of the transmitted light can be adjusted by varying the opening angle $2\alpha$ of the split ring antenna.

The simulation is carried out using the commercial software Lumerical FDTD Solutions. The operating frequency is set at 0.37 THz. First, the appropriate geometric parameters of each layer structure, i.e., $P$, $R$, $r$, $a$, and $b$, and the thicknesses of each part of the layer structure are optimized. The simulated transmission spectra of the proposed antenna with an opening angle of $8^\circ$ are shown in Figure 3a. The incident wave is left circularly polarized and the angle $\theta$ is set at $90^\circ$, which means that the polarization state of the transmitted cross-polarized light is oriented along the $y$-axis. The results show that the cross-polarized light has a maximum transmission of 0.97 at the desired operating frequency of 0.37 THz, whereas the corresponding polarized component always has transmission of less than 0.02 over the entire frequency range under consideration. This means that the structure with the optimized geometric parameters can act as a polarizer to filter the desired polarized light at the preset working frequency. After optimization of the other parameters, we scanned the opening angle of the split ring antenna from $0^\circ$ to $180^\circ$. The amplitude and phase of a transmitted wave with $\gamma$-polarization are shown in Figure 3b. The phase of the desired polarized wave changes by $220^\circ$ when the opening angle changes from $0^\circ$ to $180^\circ$. Four split ring antennas with different opening angles are used to realize phase modulation of the cross-polarized wave with steps of $45^\circ$ while also maintaining high transmission of more than 0.85. The opening angles of selected antennas #1 to #4 are $120^\circ$, $95^\circ$, $65^\circ$, and $8^\circ$, respectively. By changing the axis of symmetry of each of these antennas from $\beta - 45^\circ$ to $\beta + 45^\circ$, another four antennas numbered #5 to #8 are obtained that can maintain the same transmission as antennas #1 to #4, whereas the phase modulation ranges between $180^\circ$ and $360^\circ$. The transmission and phase modulation characteristics of these eight structures are shown in Figure 3c,d, respectively, as the green starred lines; the results show that the transmission is more than 0.85 for each of the eight structures, and the phase modulations are plotted over the full $360^\circ$ range at steps of $45^\circ$, which means that the eight selected structures can modulate the phase of the transmitted cross-polarized light over a $2\alpha$ range with a working efficiency exceeding 85%. To provide a further demonstration of the individual phase and polarization state modulation properties of the proposed structure, several cells are built with different metagrating directions. The transmission and phase modulation characteristics of these structures are shown in Figure 3c,d, respectively. The incident wave is always left circularly polarized, and the values of the angle $\theta$ are set at $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$, respectively. The transmission
of the desired polarized wave (Ecross) exceeds 0.75 in all cases while the phase modulation ranges from 0° to 360° with steps of 45°. The corresponding results for the background wave (Esame) are also shown in the figures as dashed lines. The transmission for the background wave is less than 0.05 and the phase modulation characteristics show no regularity, which means that the desired phase modulation can only be achieved for a transmitted wave with the desired polarization. Optimal arrangement of these eight split ring antennas and the azimuth angles of the metagratings in each cell allows the phase and polarization states of the transmitted waves to be modulated individually point-by-point, thus enabling the generation of structured light with complex polarization and phase distributions.

2.2. Experimental Results and Discussion

Two high-efficiency terahertz-band vector beam generators are designed to demonstrate the individual phase and polarization state modulation properties of the proposed tri-layer metasurface. Each device has 75 unit cells arranged in the radius direction and a total area of 2 × 2 cm². Usually, the circular or azimuthal subwavelength gratings can be used to generate azimuthally or radially polarized beams when illuminated by circularly polarized waves. However, because of the relative phase delay of the circularly polarized beam, the generated vector beams will have a vortex phase distribution that is not always desirable. Because the proposed approach can modulate the phase and polarization states of the transmitted waves individually, a vector beam with an arbitrary phase distribution can be generated.

The first device is used to generate a focused azimuthal polarized beam under illumination by an incident wave with left circular polarization. To realize azimuthal polarization modulation, the directions of the top and bottom metagratings are set to be oriented along the azimuthal and radial directions, respectively. When the left circularly polarized wave is incident on the structure in the upward direction and then passes through the top metagrating layer, a radially polarized vortex beam with a topological charge of +1 is generated, and this beam then impinges on the split ring antenna array. To realize a focused beam without the topological charge, the phase modulation of the split ring antenna layer should have a −1 order vortex phase distribution.
and a lens phase distribution. The phase modulation characteristics of the first device are shown in Figure 4a. The designed focal length is 10 mm. The phase distribution shows the superposition of the lens phase and the vortex phase distribution with a topological charge of −1. The corresponding polarization state distribution is shown in Figure 4b, where all polarization directions are oriented along the azimuthal direction. The second device is used to generate a focused radially polarized vortex beam with a topological charge of +2 under illumination by an incident wave with left circular polarization. In this situation, the phase modulation of the split ring antenna layer is represented by the superposition of the +1 order vortex phase and a lens phase, as shown in Figure 4c. The polarization state distributions, thus verifying the robustness of the incident left circularly polarized wave in the experiment and can be improved using an appropriately designed broadband terahertz quarter-wave plate. All the experimental results showed that the fabricated devices can generate used to demonstrate the working efficiency of the fabricated device, which is composed of periodic antenna #1 with an angle θ of 90°. The measured transmission characteristics are also shown in Figure 3a for comparison with the simulation results; the red line represents the transmission of the desired polarized wave, which is polarized along the y-axis. The peak of the transmission spectrum is seen to occur at 0.36 THz with a value of almost 0.9. The transmission of the background wave, which is polarized along the x-axis, is less than 0.1. These results show that the fabricated device can achieve the preset function well.

To demonstrate the performances of the fabricated vector beam generators, the amplitude and phase distributions of a transmitted terahertz field at 0.37 THz along the x- and y-axes are measured on the focal planes of the devices, which are located 10 mm away from the actual devices. The measured results are shown in Figure 5. The first device generates a focused azimuthally polarized beam. The simulated amplitude and phase distributions of the fields $Ex$ and $Ey$ are shown in the first row of Figure 5a. The corresponding experimental results are shown in the second row of Figure 5a. The results show that the amplitude distributions for $Ex$ and $Ey$ are oriented along the y-axis direction and x-axis direction, respectively, in accordance with the $Ex$ and $Ey$ components of the azimuthally polarized light. The results also show that phase distributions for $Ex$ and $Ey$ have obvious phase gradients of π in the y- and x-directions, respectively. The second device generates a focused radially polarized vortex beam with a topological charge of +2. The simulated and measured amplitude and phase distributions for $Ex$ and $Ey$ are shown as the first and second rows, respectively, in Figure 5b. The distributions show that the amplitudes and phases of $Ex$ and $Ey$ have two singularities in the x- and y-directions, which means that the vortex beam is radially polarized. There is a slight tilt in the amplitude distribution that can be attributed to the lack of purity of the incident left circularly polarized wave in the experiment and can be improved using an appropriately designed broadband terahertz quarter-wave plate. All the experimental results showed that the fabricated devices can generate their as-designed vectorial beams with the expected phase and polarization state distributions, thus verifying the robust
individual phase and polarization state modulation capabilities of the designed metasurfaces. The experimental operating efficiency is calculated by dividing the total transmitted light intensity by the total incident light intensity, which gives an efficiency of 85% at a working frequency of 0.37 THz. Although the bilayer reflection metasurfaces have high working efficiency,\cite{34,35} use of the reflection mode is inconvenient for practical applications. When compared with existing transmission trilayer metasurface devices, for which the operating efficiencies range between 80% and 90\%,\cite{36,37} the designed vortex beam generator achieves the average efficiency value and also offers the advantage of individual phase and polarization control of the wavefront.

### 3. Conclusions

We designed and experimentally demonstrated a high-efficiency trilayer metasurface structure to enable individual modulation of the phase and polarization states of transmitted waves. The designed metasurface comprises three metal structural layers and two dielectric spacer layers, where the top and bottom metal layers are orthogonal metagratings and the middle metal layer is a split ring antenna array. By adjusting the antenna’s opening angle and the azimuthal direction of the metagrating, the phase and polarization states of the transmitted wave can be modulated with efficiency of more than 85\%. Two vector beam generation devices based on the proposed metasurface have been demonstrated. One of the devices can generate a focused azimuthally polarized beam and the second can generate a focused radially polarized vortex beam with a topological charge of \( +2 \).

Figure 5. Simulated and experimental results for the transmitted Ex and Ey fields of the designed metasurface devices. a) Amplitude and phase distributions on the focal plane of the first device, which can generate a focused azimuthally polarized beam. b) Amplitude and phase distributions on the focal plane of the second device, which can generate a focused radially polarized vortex beam with a topological charge of \( +2 \).
4. Experimental Section

Fabrication of the Designed Metasurface Devices: We fabricated the designed metasurface devices using conventional UV lithography, thermal evaporation, and lift-off techniques. Specifically, we first carried out the regular lithography and subsequent lift-off processes to obtain the bottom metal metagrating layer on a 500 μm-thick high-resistance silicon substrate, and then spin coated the PI on the metagrating layer four times. After each spin coating, we carried out gradient baking of the sample to turn the PI into its solid state and obtained an exactly 10 μm-thick PI layer. After four cycles of coating and baking, a 40 μm-thick PI spacer was obtained. Then, we repeated the regular lithography and subsequent lift-off steps again to obtain the middle layer, a metal split ring antenna array, with high-precision alignment with the bottom metagrating layer. We then repeated the coating and baking cycles to obtain another 40 μm-thick PI spacer layer on top of the metal split ring antenna array. Finally, we completed another regular lithography and subsequent lift-off stage to obtain the top metal metagrating layer. Microscopic images of the fabricated surface are shown in Figure 6. Because of the trilayer arrangement of the structure, the middle and bottom layers were indistinct in these images; therefore, we have provided a video in the Supporting Information that shows the structure of the device by varying the focal length.

Experimental Setup: The terahertz focal plane imaging system shown in Figure 7 was used to characterize the performance of the designed structure. A Ti:sapphire regenerative amplifier was used to produce 100 fs ultrashort laser pulses with a spot diameter of 8 mm, a central wavelength of 800 nm, and a repetition rate of 1 kHz. The laser beam with its average power of 900 mW was divided into two parts, which were then used as the pump (880 mW) and probe (20 mW) beams for generation and detection of the terahertz waves, respectively. The pump beam impinged on a 1 mm-thick (110) ZnTe crystal to generate the required terahertz beam via the optical rectification effect. The horizontally polarized (x-polarized) terahertz beam (diameter: 24 mm) was passed through a terahertz polarizer to maintain its polarization, and then passed through a terahertz quarter-wave plate to generate a left circularly polarized light beam at the designed working frequency of 0.37 THz, which then impinged on the structure. The scattered terahertz beam was detected using another (110) ZnTe crystal. In the probe’s optical path, a half-wave plate and a polarizer were used to modulate the probe beam polarization. In the sensor crystal, the probe beam polarization was modulated using the terahertz field via the Pockels effect, and the reflected probe beam was captured using the imaging unit. A Wollaston prism was used to split the probe beam into two beams with orthogonal polarizations, and two images of the sensor crystal were then projected into the charge-coupled device (CCD) camera. The terahertz complex field was extracted using the balanced electro-optic detection technique. By varying the optical path difference between the terahertz beam and the probe beam, 100 temporal images were captured at each time delay within a short time window of 17 ps. The amplitude and phase information at the different frequencies

![Figure 6. Microscopic images of the fabricated metasurface. a) Top metagrating layer, b) middle C-shaped-antenna layer, and c) bottom metagrating layer. The scale bar in each image represents 50 μm.](image)

![Figure 7. Schematic of the experimental setup. PBS: polarized beam splitter; M: mirror; L: lens; PM: parabolic mirror; TP: THz polarizer; TQWP: THz quarter-wave-plate; MS: metasurface sample; P: polarizer; HWP: half-wave-plate; BS: beam splitter; WP: Wollaston prism; CCD: charge-coupled device.](image)
were extracted by performing Fourier transforms on the temporal signals that occurred at each pixel. Finally, the linearly polarized terahertz fields Ex and Ey were extracted at 0.37 THz.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
This work was supported by the National Natural Science Foundation of China (grant nos. 11874132, 1174243, and 11774246), the National Key R&D Program of China (no. 2019YFC1711905), the Beijing Talents Research Funds (grant no. 00820531120017), China (grant nos. 11874132, 1174243, and 11774246), the National Key R&D Program of China (no. 2019YFC1711905), the Beijing Talents Research Funds (grant no. 00820531120017).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
metasurfaces, phase modulation, polarization modulation, vector beams

Received: July 7, 2021
Revised: October 13, 2021
Published online: December 22, 2021

[1] N. F. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, Z. Gaburro, Science 2011, 334, 333.
[2] F. Aieta, P. Genevet, M. A. Kats, N. F. Yu, R. Blanchard, Z. Gaburro, F. Capasso, Nano. Lett. 2012, 12, 4932.
[3] N. F. Yu, F. Aieta, P. Genevet, M. A. Kats, Z. Gaburro, F. Capasso, Nano. Lett. 2012, 12, 6328.
[4] J. P. Tetienne, B. S. Kawasaki, F. Capasso, Adv. Photon. 2021, 3, 2100199.