Direct routing of intensity-editable multi-beams by dual geometric phase interference in metasurface

Abstract: Controlling spin electromagnetic waves by ultra-thin Pancharatnam-Berry (PB) metasurfaces show promising prospects in the optical and wireless communications. One of the major challenge is to precisely control over the complex wavefronts and spatial power intensity characteristics without relying on massive algorithm optimizations, which requires independent amplitude and phase tuning. However, traditional PB phase can only provide phase control. Here, by introducing the interference of dual geometric phases, we propose a metasurface that can provide arbitrary amplitude and phase manipulations on meta-atom level for spin waves, achieving direct routing of multi-beams with desired intensity distribution. As the experimental demonstration, we design two microwave metasurfaces for respectively controlling the far-field and near-field multi-beam generations with desired spatial scatterings and power allocations, achieving full control of both sophisticated wavefronts and their energy distribution. This approach to directly generate editable spatial beam intensity with tailored wavefront may pave a way to design advanced meta-devices that can be potentially used in many real-world applications, such as multifunctional, multiple-input multiple-output and high-quality imaging devices.

Keywords: circular polarization; geometric phase; metasurface; multifunctional.

1 Introduction

As the two-dimensional (2D) equivalence of metamaterials, metasurfaces have shown unprecedented abilities to manipulate the electromagnetic (EM) waves within sub-wavelength thickness that is far beyond what can be achieved by naturally occurring materials. Benefiting from the burgeoning capabilities for fabricating materials with accuracy geometries, metasurfaces consisting of subwavelength meta-atoms can elaborately tailor the amplitude, phase and polarization state of the interacting EM wavefront with the advantages of low profile, low loss, and simple fabrication, ranging from microwave to terahertz and optical regions [1–6]. Therefore, a plenty of applications have been implemented with metasurfaces, such as ultrathin metalens [3, 4, 7–10], invisibility cloak [11, 12], polarization converter [13, 14], and vortex beam generator [15–18], etc.

The explosive development of modern communication technology has drawn more attention to the design of miniaturized and integrated multifunctional devices that are compatible with nowadays compact systems. Due to the complexity and variety of application requirements, it is often necessary to implement integrated design with independent, arbitrary, and simultaneous control of multiple EM functionalities and the allocation of their radiation power intensities. Though conventional phase-only metasurfaces using addition theorem can realize superposition of the multiple independent EM beams [19], which have potential applications in multiple-input multiple-output (MIMO) communications, the power of each independent beam cannot be freely designed, inherently limiting their use in some applications. By employing optimization algorithms, this limitation can be somehow resolved so that the objective of simultaneously control over the beam propagation direction and power intensity allocation is consequently achieved [20]. Nevertheless, this method consumes large computing resource and time. Moreover, side-lobes are inevitably increased in the multi-beam
forming, which is difficult to overcome by such optimization algorithms.

Recently, by applying complex-amplitude addition theorem and introducing meta-atoms with independent amplitude and phase modulations, the propagation of EM wave can be completely tailored by amplitude-phase metasurface. Compared with phase-only metasurfaces, the major advantage of such metasurface is that better wavefront-shaping performances, e. g., ultra-low side-lobes or reduced speckle in hologram [21–25], can be directly achieved through theoretical formulas, without resorting to the complex and time-consuming optimizations. Due to these merits, the amplitude-phase modulation metasurfaces insure a wide range of applications such as high quality holography, synthesis of complex wave fields, and so on [21, 22]. The metasurface composing of C-shaped meta-atoms can arbitrarily control the power of each diffraction order or realize high-resolution holograms for linearly-polarized excitations [23–25]. By introducing lossy components, e. g., chip resistors or resistive film [26], to dissipate the unwanted energy, the metasurface with varying geometrical parameters can support both reflection amplitude and phase control [26], but this method could not be easily scaled to other frequencies, because the precise control of lossy values still remains challenging especially in much higher frequencies, e. g., in terahertz band. Moreover, while controlling circularly-polarized (CP) wave is essential for such as satellite communication, spin optics, etc., independently editing spatial radiation and their power intensities for CP wave have not been realized by thin-thickness reflective metasurface. Needless to say, it is still highly desirable to find accurate analytical method to achieve nimble metasurface designs with easy fabrication and flexible scalability.

As an efficient way to control CP waves, geometric phase (or Pancharatnam-Berry (PB) phase) can impart an additional phase shift of $2\sigma \theta$ once the meta-atom is rotated by an angle of $\theta$, where the sign $\sigma = \pm 1$ denotes different spin waves [10, 15, 27–30]. The most appealing feature of PB phase is its simple design strategy that only a single meta-atom with different rotation angles can achieve full phase coverage required for complex wavefront manipulations [10, 15]. However, traditional geometric elements have identical amplitude but opposite phase responses for excitation of different spins, which cannot provide arbitrary, independent, and decoupled phase and amplitude behaviors at the meta-atom level. Here, we show that the metasurfaces composed of dual geometric phases are capable of providing direct spatial-power-editing for versatile functionalities without relying on optimization algorithm. Specially, the meta-atom can achieve a free combination of reflection amplitude from 0 to 1 and reflection phase of 0 to 360° based on the analytical method of dual geometric phase interference. To give the experimental verifications, we propose two functional devices for directly routing the far-field and near-field EM behaviors in microwave region: the first metasurface can simultaneously control the propagation directions of multiple beams and the power allocation of each scattered beam; the second bi-foci metasurface can achieve independent control of the position and power of each focal spot. The two prototypes are fabricated and measured, which validates the good performances of our proposals.

### 2 Theoretical concept and element design

As schematically shown in Figure 1, the metasurfaces with independent control of the spatial wave functions and desired power allocation of multiple scattering wavefronts can be achieved under the illumination of CP incidence. The first one (shown in Figure 1A) can realize free and independent control of scattering directions and power level (denoted by $A_1$, $A_2$, and $A_3$) of multiple beams, whereas the second one (shown in Figure 1B) can realize desired focal spots with

![Figure 1: Schematic of the proposed reflective metasurface with arbitrary and independent control of spatial and powers of the wavefront under normal CP wave excitation. (A) The reflective beams with independent and distinct powers can be controlled to arbitrary directions. (B) Two-foci with different powers generated by the metasurface.](image-url)
different powers (denoted by $B_1$ and $B_2$). Here, we assume that the incident source is right-handed circularly polarized (RCP) wave, and the corresponding radiation property for left-handed circularly polarized (LCP) incidence will be discussed in the next section.

In order to simultaneously and independently manipulate the spatial power intensity allocation of the scattering fields, the amplitude and phase responses of each pixel of a metasurface should be totally decoupled and arbitrarily tailored. Therefore, designing proper realistic meta-atom is the key point to get the devices with desired spatial-intensity-editable scattering power. Here, we consider a metasurface particle composed of dual geometric phases, interpreted by two simple independent metallic rod structures, as shown in Figure 2. We utilize the meta-atom that is a triple-layer structure consisting of top metallic layer, a bottom metallic plane and a middle dielectric layer. By carefully tuning the structural anisotropy of each rod in the metasurface particle to achieve near-unity reflective amplitude for two orthogonal linearly-polarized incidence but with a 180° phase difference, the geometric phase will be induced, imparting an additional phase shift of $2\sigma\theta$ once the meta-atom is rotated by an angle of $\theta$ under the normal illumination of CP wave, where the parameter $\sigma = \pm 1$ corresponding to RCP and LCP waves [27–30], respectively. As shown in Figure 2A and B, the relative additional phase shifts of a single rod-structured meta-atom caused by the geometric phase are twice the rotation angle ($2\sigma\theta_1$ and $2\sigma\theta_2$) for CP incidence, but the reflective amplitude always keeps near unity. Here, for a single rod-structured meta-atom, the normally incident electric field of CP incidence can be defined as 

$$\begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix} = \frac{1}{\sqrt{2}} \left(1 - i\sigma\right) T$$

and corresponding radiated electric field can be expressed as

$$\begin{bmatrix} E_{o1} \\ E_{o2} \end{bmatrix} = \frac{1}{\sqrt{2}} e^{i2\theta_1} \left[1 - i\sigma\right] T,$$

where $E_{i1}$ and $E_{i2}$ ($E_{o1}$ and $E_{o2}$) are the two orthogonal linear polarized field components of the incident (radiated) electric field [31]. As shown in the Figure 2C and D, an X-shaped meta-atom combining two rectangular rods has been proposed in reflective geometry for CP waves, where the orientation angles of the two rods are denoted by $\theta_1$ and $\theta_2$, respectively. Under the illumination of normal CP incidence, the abrupt phase change caused by the single rod structure is attributed to the resonant modes of the arm. For the X-shaped metasurface with dual geometric phase interference, each geometric phase component (one arm of the X-shaped structure) can be regarded as an independent electric dipole approximately. Thus, the whole X-shaped

![Figure 2](image-url)
structure can be modelled by the resonances of each arm. Overall, the co-polarized reflection performance of the meta-atom can be calculated by the interference of dual geometric phases (two independent electric resonances), whose superposition can be written as (the reflection of a single rod structure is assumed as 1 for simplicity):

\[
\begin{bmatrix}
E_{o1} \\
E_{o2}
\end{bmatrix}
= e^{i2\phi_1} + e^{i2\phi_2} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i\sigma \end{bmatrix},
\]

where \(\sigma\) is the angular difference between orientation angles of the two rotated rods. If parameters \(A\) and \(\varphi\) are defined as co-polarized reflection amplitude and phase of the X-shaped meta-atom for the CP incidence, they can be represented as \(A = 2\cos \alpha\) and \(\varphi = \sigma(\theta_1 + \theta_2) = \sigma(\theta_2 + \alpha),\) respectively. From the above equation, we can infer that when the parameter \(\alpha\) is changed between 60° and 90°, the reflection amplitude of the meta-atom can be changed between 0 (e.g., \(\theta_1 = 0°\) and \(\theta_2 = 90°\)) and 1 (e.g., \(\theta_1 = 15°\) and \(\theta_2 = 75°\)), therefore achieving the flexibly tuning of amplitude responses. At the same time, the phase responses of the meta-atom can be tuned by simultaneously changing the angle \(\theta_1\) and \(\theta_2\). As the examples to show the meta-atom’s ability in controlling the amplitude and phase responses, we investigate the influence of the parameter \(\alpha\) and \(\theta_1\) on the reflection performance of the meta-atom. The central working frequency of the proposed meta-atom operates at 8.6 GHz. The optimized physical parameters of the metasurface element is \(l = 9.5\) mm and \(w = 0.3\) mm, and period length \(D\) of 10 mm. The dielectric spacer has a relative permittivity of 3.55 + 0.0027\(i\) and its thickness \(h\) is 3.048 mm. Figure 2E shows the theoretical and simulated results of amplitude and phase responses with \(\theta_1 = 9.5\) mm and \(\theta_2 = 30°\) fixed to be 30° but a varying parameter \(\alpha\). Here, the simulated results are calculated using commercial software CST Microwave Studio™. It is obvious that the amplitude will be continuously reduced from one to zero as \(\alpha\) is increased from 60° to 90°, whereas the phase shift is slightly changed around \(\sigma \alpha\). On the other hand, the reflective amplitude constantly retains nearly one when the parameter \(\alpha\) is fixed to be 60° and parameter \(\theta_1\) is changed from 0° to 180°. In this case, the phase shift satisfies \(\Delta \varphi = 2\sigma \theta_1\), as shown in Figure 2F. Meanwhile, the absorption retains low values as the parameters \(\alpha\) and \(\theta_1\) changing. The above simulated results agree with the theoretical predictions, despite a little difference which is due to the mutual coupling (this term is neglected in the theoretical derivation for simplicity and straightforwardness) between the two geometric phase elements in simulation. Therefore, once the distributions of amplitude \(A\) and phase \(\varphi\) are determined, the distribution of parameter \(\alpha\) can be obtained. Then, the distribution of parameter \(\theta_1\) is calculated to compensate the phase shifts caused by parameter \(\alpha\) and finally realize the required phase distribution \(\varphi\) on the metasurface aperture. By tuning the parameters of \(\alpha\), \(\theta_1\), and \(\theta_2\), X-shaped meta-atom can achieve arbitrary assembly of phase and amplitude, providing possibilities in freely designing the power ratio of the wavefronts of the reflective metasurface in each independent spatial channel. Although the aforementioned theory is based on the premise of normal incidence, we have also studied influence of the oblique incidence on the reflection magnitude and phase responses of the proposed meta-atom. When the incident angle is smaller than 30 degree, the Eq. (1) can be used to design the amplitude-phase metasurface approximately. As the incident angle increases larger than 30 degree, the equation cannot be satisfied. More details can be found in Section I of the Supplemental Material.

3 Multiple beams with independent power intensity control

For the multi-beam devices, each beam can be regarded as a communication channel. Independent control of amplitude and phase responses of each meta-atom is the key step for realizing complete control of the powers in each channel. Assume a plane wave illuminating the metasurface, the scattering pattern from the reflective metasurface can be calculated as:

\[
E_{total}(\theta, \varphi) = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn}^\theta(\theta, \varphi) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}^\theta e^{i\varphi_{mn}} e^{ikD \sin \theta [\cos \theta (m-1) + \sin \theta (n-1) + \sin 2\varphi]}\]

where \(\theta\) and \(\varphi\) is the elevation and azimuth angles in spherical coordinate system, respectively. The \(E_{total}(\theta, \varphi)\) is the superposition of the secondary scattering fields from \(M \times N\) elements in the direction \((\theta, \varphi)\). The integers \(M\) and \(N\) represent the columns and rows of elements in the proposed metasurface. The \(A_{mn}^\theta\) and \(\varphi_{mn}\) are the amplitude and phase responses of the \(mn\)-th element located at \((m, n)\), respectively. The wavenumber \(k = 2\pi/\lambda\) is related to the working wavelength \(\lambda\), and \(D\) is the periodicity of each
element. In order to generate the multiple beams or functions, the mixed amplitude pattern and phase pattern on the metasurface aperture can be obtained by the complex-amplitude addition theorem [19]:

\[
A_{m}^{n} = |A_{1}^{mn}e^{j\varphi_{r}^{mn}} + A_{2}^{mn}e^{j\varphi_{r}^{mn}} + \ldots + A_{i}^{mn}e^{j\varphi_{r}^{mn}}| 
\]

\[
\varphi_{r}^{mn} = \text{arg}(A_{1}^{mn}e^{j\varphi_{r}^{mn}} + A_{2}^{mn}e^{j\varphi_{r}^{mn}} + \ldots + A_{i}^{mn}e^{j\varphi_{r}^{mn}}) 
\]

where \(A_{i}^{mn}\) and \(\varphi_{r}^{mn}\) represent the amplitude and phase responses of \(mn\)-th element that is required to generate \(i\)-th beam (or \(i\)-th function).

We first demonstrate a practical application by utilizing the proposed X-shaped meta-atoms to generate double beams with independent control of the radiation direction and power. The reflective metasurface composed of \(30 \times 30\) elements is shined by normal RCP incidence with central frequency set as 8.6 GHz. By applying constant phase gradient pattern to meets the equation of frequency set as 8.6 GHz. By applying constant phase elements is shined by normal RCP incidence with central and power. The reflective metasurface composed of 30 beams with independent control of the radiation direction ing the proposed X-shaped meta-atoms to generate double beam (or \(\lambda\)

\[
A_{1}^{mn} = 1 \quad \text{and} \quad A_{2}^{mn} = 0.707\quad \text{(The power ratio is the square of the amplitude ratio). Thus, the final amplitude and phase profile (shown in Figure 3B) can be obtained from Eqs. (3) and (4), and for RCP incidence (\(\sigma = +1\)), the spatial distributions of geometric parameters \(\alpha^{\sigma}\) and \(\beta^{\sigma}\) can be consequently calculated from Eq. (1), as shown in Figure 3C.}

The theoretical three-dimensional (3D) far-field scattering patterns generated by the spatial amplitude and phase pattern (Figure 3B) is shown in Figure 4A for RCP incidence, where the axis \(u = \sin(\theta) \times \cos(\phi)\) and \(v = \sin(\theta) \times \sin(\phi)\), representing angular coordinate. We also perform full-wave simulations to verify the design theory using commercial software CST Microwave Studio™ (open add space boundary condition). It is obvious that the scattering power of the beams with deflection angle \(\theta_{r} = -15^\circ\) is 3 dB higher than that of the beam with \(\theta_{r} = 15^\circ\) in both theoretical and simulated 3D far-field scattering patterns. In order to give a detailed comparison, we also plot in Figure 4C the corresponding 2D normalized scattering patterns in xoz plane, where good agreements are observed between the simulated result and the theoretical prediction.

We have also investigated the case of metasurface shined by LCP incidence. The theoretical and simulated normalized 3D far-filed scattering patterns for LCP incidence are presented in Figure 4D and E, respectively. The corresponding 2D normalized scattering patterns in xoz

![Figure 3: Design process to obtain the proposed reflective metasurface for independently controlling the radiation direction and powers of the beams. (A) The phase distributions for the desired beams. (B) The corresponding amplitude and phase distributions with the parameters \(A_{1}^{mn} = 1\) and \(A_{2}^{mn} = 0.707\). (C) The calculated distributions of geometric parameters \(\alpha^{\sigma}\) and \(\beta^{\sigma}\) for \(\sigma = 1\).](image-url)
The scattering power of the beams with deflection angle $\theta = -15^\circ$ is 3 dB lower than that of the beam with $\theta = 15^\circ$ along the z-axis. Obviously, the spatially power allocation is opposite between RCP and LCP incidence. This can be understood by the conjugate relationship between the phase responses of geometric phase element for LCP and RCP incidence [28–30], where macroscopically speaking, the beam will be deflected by angle with the same value yet opposite constant linear gradient if the spin of the incidence is changed to its orthogonal one. So we only consider cases operated with RCP incidence in the rest part of the paper while the performance for LCP incidence can be easily obtained by the inherent feature of geometric phase metasurface.

Applying complex-amplitude addition theorem, arbitrary scattering beams with independent powers can be generated from a metasurface simultaneously. Without loss of generality, we have designed a reflective metasurface with more complex functions that has three spatial radiation beams with different powers. The radiation directions $(\theta, \phi)$ of the three beams are $(10^\circ, 0^\circ)$, $(15^\circ, 180^\circ)$ and $(20^\circ, 90^\circ)$, respectively, with the radiation power ratio set as 1:2:3. To achieve this objective, we set the parameters normalized as: $A_{1}^{\alpha\theta} : A_{2}^{\alpha\theta} : A_{3}^{\alpha\theta} = 1 : 1.41 : 1.73$. The design process of metasurface for generating three beams is similar to that presented above for generating two beams. The spatial amplitude and phase distributions for generating these three beams shined by RCP incidence are shown in the left panels of Figure 5A while the corresponding distributions of geometric parameters $\alpha^{\phi}$ and $\theta^{\phi}$ are shown in right panels. The theoretical 3D scattering pattern (Figure 5B) is in agreement with the numerically simulated result (Figure 5C), and three scattering beams can be obtained with different spatial direction and power. The high side-lobes in the simulations are mainly caused by the distortion of the reflection characteristics attributed to imperfect unit cell boundary condition in the real metasurface. By using optimization algorithms [5, 32, 33], the high side-lobes may be well suppressed and we may even obtain more sophisticated radiation patterns, such as flat-top beam, cosecant squared beam and so on. Besides, the spin-decoupled metasurface with independent phase tuning of the RCP and LCP by introducing propagation phases may provide more degrees of freedom in controlling the amplitude and phase responses [16, 34–37].

To experimentally validate the design principle and the proposed metasurface capable of achieving independently editable amplitude and phase tuning, the metasurfaces with three scattering beams is fabricated by standard printed circuit board (PCB) technique. PCB techniques have been widely used for fabricating flat microwave samples in industrial engineering, which can provide precise control of the pattern shapes and layer alignment with a fabrication error of about $\pm 0.05$ mm for dielectric thickness and about $\pm 0.02$ mm for the width of metallic patterns. The PCB technique can ensure a precise sample fabrication in microwave region. The photograph of the fabricated metasurface is shown in Figure 5D, with enlarged view of the metasurface.
elements shown in the inset. We have measured the scattering patterns of the sample in a standard microwave chamber and all the measured results of the fabricated sample are calibrated to a same-sized copper slab. The details of the measurement setup can be obtained in Section II of the Supplemental Material. The measured 2D normalized scattering patterns in $xoz$ plane and $yoz$ plane are compared with simulated results in Figure 5E. The measured results are roughly in agreement with the simulation results, taking into account of the fabrication and measurement tolerances. As for the cross-polarized components, only a single dominating output beam is observed in the far-field region due to that the meta-atom can only manipulate the reflection phases of the co-polarized components. In addition, the total efficiency of the reflected beams from the metasurface (defined by the ration of co-polarized reflection to input energy) is about 33.4% in the simulation and about 31.8% in the measurement. Therefore, by the proposed theory and the X-shaped particle, the functions of independent scattering beams with distinct power levels can be integrated onto a single reflective metasurface for CP incidence.

4 Intensity-editable bi-foci metalens

In order to further demonstrate the feasibility of the proposed theory in controlling the spatial scatterings and power allocation of the EM wave arbitrarily and independently, we have designed a bi-foci metalens that can transform the CP incidence into two focal spots with controllable spatial focusing performance and desirable powers, as schematically shown in Figure 1B.

The spatial phase distribution on the lens aperture to achieve a single-focus metalens with the pre-designed focal length $F_0$ can be obtained by [38]:

\[ \beta = \tan^{-1} \left( \frac{y - y_0}{x - x_0} \right) \]

\[ \theta = \tan^{-1} \left( \frac{z - z_0}{r} \right) \]

Where $(x_0, y_0, z_0)$ is the center of the lens, $r$ is the distance from the point $(x, y)$ on the aperture to the focal point. The required amplitude, phase and geometric parameters $A^{\sigma}(\theta, \phi)$ distributions for the desired triple-beams metasurface are shown in Figure 5A. The theoretical and corresponding simulated 3D normalized scattering pattern for the RCP incidence at 8.6 GHz are shown in Figure 5B.

The photograph of the fabricated sample is shown in Figure 5D. The inset shows the enlarged view. The theoretical, simulated and measured 2D normalized scattering pattern for the RCP incidence in the $xoz$ and $yoz$ planes at 8.6 GHz is shown in Figure 5E.
\[ \varphi(x_{mn}, y_{mn}) = \frac{2\pi}{\lambda_0} \sqrt{(x_{mn} - x_i)^2 + (y_{mn} - y_i)^2 + F_i^2 - F_i^2}, \]

here, \( \lambda_0 \) is the free-space wavelength at the operational frequency. The location of \( mn \)-th element is represented by parameter \((x_{mn}, y_{mn})\). The parameter \( x_i \) or \( y_i \) is the displacement of the \( i \)-th focal spot from the lens center along \( x \)- or \( y \)-axis, respectively. The focal length of the two foci is denoted by \( F_i \) \((i = 1 \text{ and } 2)\), respectively. Then, from the Eqs. (3)–(5), we can calculate the total spatial amplitude and phase distributions required for designing bi-foci metalens, which is given as:

\[
A_{mn} = A_{mn}^{1m} e^{j\alpha_{mn}} \left( \sqrt{(x_{mn} - x_1)^2 + (y_{mn} - y_1)^2 + F_1^2 - F_1^2} \right) + A_{mn}^{2m} e^{j\theta_{mn}} \left( \sqrt{(x_{mn} - x_2)^2 + (y_{mn} - y_2)^2 + F_2^2 - F_2^2} \right),
\]

\[
\varphi_{mn} = \arg \left( A_{mn}^{1m} e^{j\alpha_{mn}} \left( \sqrt{(x_{mn} - x_1)^2 + (y_{mn} - y_1)^2 + F_1^2 - F_1^2} \right) + A_{mn}^{2m} e^{j\theta_{mn}} \left( \sqrt{(x_{mn} - x_2)^2 + (y_{mn} - y_2)^2 + F_2^2 - F_2^2} \right) \right).
\]

The proposed metalens consists of \( 40 \times 40 = 1600 \) X-shaped elements. Here, the focal length of the two foci are both set as \( F_1 = F_2 = 200 \text{ mm} \), with \((x_1, y_1) = (0 \text{ mm}, 104 \text{ mm})\) and \((x_2, y_2) = (0 \text{ mm}, -104 \text{ mm})\). We define the power allocation as \( I_1 : I_2 = 1 : 2 (A_1^{mn} : A_2^{mn} = 0.707 : 1) \), thus the spatial amplitude and phase distributions for generating these focal spots can be consequently calculated, as shown in the first column of Figure 6A. Then, the spatial distributions of geometric parameters \( \alpha_{mn} \) and \( \theta_{mn} \) can be obtained, as shown in the second column of Figure 6A, which are implemented by realistic X-shaped meta-atoms to form the proposed meta-lens. The fabricated meta-lens by the PCB technique is depicted in Figure 6B, where the inset shows the enlarged view of the meta-atoms.

The simulated \( E \)-field power profiles on the focal plane and \( xoz \)-plane at 8.6 GHz are shown in Figure 7A and B, respectively. Two focal spots located at \((0 \text{ mm}, 104 \text{ mm})\) and \((0 \text{ mm}, -104 \text{ mm})\) are observed with pre-designed power levels, which are consistent with the theoretical values. To experimentally verify the focusing performance, two orthogonal linearly-polarized \( E \)-fields reflected from the metalens are mapped by a 3D field-scanning system with dipole probes to detect pixel by pixel in a pre-designed plane, and then the two orthogonal linearly-polarized components are transformed into CP \( E \)-filed. The moving step is set as 5 mm, the area of the measured plane is \( 300 \times 300 \text{ mm} \), and the distance between the measured plane and the metasurface is about 200 mm. The details of the measurement setup of the 3D field-scanning system can be obtained in Section II of the Supplemental Material. The measured RCP \( E \)-field power profile on the focal plane is shown in Figure 7C.
clearer comparison, the simulated and measured normalized 2D field powers scanned along the line of \( x = 0 \) mm in the focal plane are plotted in Figure 7D. Good agreements are observed between the measured and simulated results and they are both consistent with the theoretical prediction, clearly validating that the spatial positions and powers of focal spots can be generated and controlled independently.

5 Conclusion

In summary, we have proposed a method to design the spatial-intensity-editable metasurface supporting independent manipulation of multiple spatial wave functions and their power allocations under CP excitation. Assisted with the interference of dual geometric phases, the reflection amplitude and phase responses can be controlled freely and independently by the X-shaped meta-atom. Two proof-of-concept designs working in the microwave region have been fabricated and experimentally demonstrated as illustrations. The wave functions are not limited to reflection operation and what have been achieved herein, and actually, transmissive geometry and much complex spatially power allocations may be readily designed by the proposed method, which may have potential applications in high-quality imaging (e.g., realizing the suppression of the zero-order and increasing the fidelity) and wireless communication techniques. In particular, considering the dramatic progresses made by optical geometric phase metasurface [10–15], it is also quite promising to extend the design method to higher frequency bands, such as terahertz and optical region, stimulating the advanced processing of EM waves and novel meta-devices.

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