A Mechanically Reprogrammable Pancharatnam-Berry Metasurface

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Article

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Abstract

Metasurfaces have enabled the realization of several optical functionalities over an ultrathin platform, fostering the exciting field of flat optics. Traditional metasurfaces are achieved by arranging a layout of static meta-atoms to imprint a desired operation to the impinging wavefront, but their functionality cannot be altered. Reconfigurability and programmability of metasurfaces are the next important step to broaden their impact, adding customized on-demand functionality in which each meta-atom can be individually reprogrammed. However, programmable metasurfaces to date can only reconfigure 2 or 4 phase levels per meta-atom at best, hindering the overall functionality performance. Here, we demonstrate a mechanical metasurface platform with controllable rotation at the meta-atom level, which can implement continuous Pancharatnam-Berry phase control of circularly polarized waves. As the proof-of-concept experiments, we demonstrate metalensing, focused vortex beam generation, and holographic imaging in the same metasurface template, exhibiting versatility and superior performance. Such dynamic control of electromagnetic waves using a single, low-cost metasurface paves an avenue towards practical applications, driving the field of reprogrammable intelligent metasurfaces for a variety of applications.

Introduction

As one of the most rapidly expanding frontiers of modern photonics, metasurfaces hold the promise for a wide range of applications due to their compact physical size and unconventional optical functionalities^{1–9}. These flat and miniaturized devices usually consist of an array of optically thin meta-atoms (plasmonic or dielectric structures) with spatially varying geometrical parameters and subwavelength separations aimed at imprinting on the incoming optical wavefront a functionality of choice through tailored local interactions. Upon a prescribed interaction, meta-atoms can precisely sculpt the phase^{10–12}, amplitude^{13–15} and polarization^{16–18} local response of the scattered fields, and thus enabling metadevices with superior functionalities^{19–24}. The further development of this field entails not only endeavors to optimize the static metasurface performance for certain functionalities^{1,5,25,26}, but most importantly techniques for tunable/reprogrammable metasurfaces that can be flexibly controlled on demand and in real time^{27–30}. Active control, although challenging, is a key route to increase the density of optical components and functionalities enabled by the metasurface. In early studies, the most commonly used method for reprogrammability consisted in integrating tunable materials into the meta-atoms and, thus, the functionalities of metasurfaces could be tuned or switched utilizing the response to external stimuli, such as optical pump^{31–33}, heating^{34–36} and bias voltage^{37,38}, etc. However, dynamic metasurfaces demonstrated so far have been typically limited to simultaneous tuning of a large portion of the meta-atoms, being able to switch among a limited number of operations.

Recently, reprogrammable metasurfaces emerged as an ideal platform for arbitrary customized functionalities, where each meta-atom can be individually reconfigured^{39–47}. By judicious designs, several reprogrammable metasurfaces have been experimentally realized, enabling dynamic

functionalities including projection display⁴⁵, holographic imaging^{40,41,43}, special beam steering^{41,42,46,48}, etc. Moreover, digital and real-time features promote several system-level applications that can hardly be achieved by static metasurfaces, such as space-time-coding^{47,49}, intelligent autonomous self-adaptive systems^{44,50,51}, and dynamic optimization of wireless communication channels^{52–54}. Despite this progress, the degrees of freedoms for active tuning have been mostly limited to 2 or 4 phase levels per meta-atom, i.e., the reprogrammability was limited to a locally controllable abrupt phase by a step of π or $\pi/2$ at best. These limitations introduce two major problems in practical applications: from the perspective of diffraction optics, the roughly discontinuous phase distributions unavoidably introduces undesired diffraction orders, reducing the efficiency and performance; from the information perspective⁵⁵, a limited number of phase levels per meta-atom fundamentally limits the amount of information that can be processed by a metasurface of given size. Extending the tuning capability of meta-atoms would undoubtedly improve the metasurface performance, particularly for diffraction-limited applications such as high-quality focusing and vortex beam generation. At the same time, these efforts may improve the information capacity of metasurfaces for complex and precise wavefront control, such as holographic imaging. However, major challenges exist in achieving these goals, and there is still plenty of work to do in order to advance the paradigm of efficient reprogrammable metasurfaces.

In this article, we propose and demonstrate a reprogrammable metasurface platform based on mechanical control for quasi-continuous Pancharatnam-Berry (PB) phase tunability operating at microwave frequencies. PB phase, also known as geometric phase, is a robust control method for incident circularly polarized waves, which is determined by the rotation angle of meta-atoms^{2,19,20}. Figure 1a schematically shows our reprogrammable PB metasurface platform, which consists of 20×20 supercells covering an area of $870 \times 870 \text{ mm}^2$. Each supercell, as shown by Fig. 1b, is composed of a stepping motor, a set of transmission gears, and an array of 4×4 PB meta-atoms. The reprogrammable function is enabled by mechanically rotating each PB meta-atom to achieve the desired phase control, enabling a continuous and arbitrary phase control pattern over the entire surface without introducing particular complexity in the system. In principle, this metasurface platform can be employed for on-demand generation of a large variety of functionalities in real time. As proof-of-concept experiments, we demonstrate metalensing, focused vortex generation, and holographic imaging using the same metasurface, exhibiting superior performance and real-time tunability.

Results

Design of the reprogrammable metasurface. In order to empower the metasurface with well-controlled programmability, 400 commercial stepping motors are utilized to respectively control the 20×20 supercells. Each stepping motor is equipped with an addressed circuit for the power supply (terminal voltage of 5 V) and rotation control. The step angle is 5.625° , corresponding to 64 steps per turn. The maximum response frequency is $\geq 1000 \text{ pps}$ and the maximum starting frequency is $\geq 500 \text{ pps}$, respectively (see Supplementary 1 for details). The rotation step number (clockwise or counterclockwise)

is controlled by digital signals from a host computer with full addressability (see

Supplementary 2 for details). As shown in Fig. 1b, a three-layered gear set is utilized to transmit the torque from the motor to the PB meta-atoms: the first layer consists of the main gear attached to the output shaft of the stepping motor; the middle layer consists of four gears that connect the first and last layer; the bottom layer consists of 16 gears connecting with the PB meta-atoms one by one. The rotation ratio is 7/8, i.e., the rotation of each PB meta-atom consists of 56 steps per turn. In the experiments, considering the transmit load and accuracy of rotation angles, the rotation speed of PB meta-atoms is set to about 2 s per turn. For reference, a Supplementary Video is provided to show the controllable rotations.

Different from traditional static metasurfaces, the meta-atoms of the proposed reprogrammable metasurface are discretely arranged to avoid possible obstructions during their rotation. Thus, the resonance is designed to be strongly localized inside each PB meta-atom to suppress crosstalk. With the overall performance taken into consideration, a circle shaped metal-insulator-metal structure, as schematically shown in Fig. 2a, is chosen as the meta-atom to manipulate PB phase in reflection at an operating frequency of 7 GHz. The PB meta-atom consists of two Archimedean spirals with the same geometric parameters, which are C2 rotation-symmetric with each other along the normal axis. Both the spirals and the bottom metallic film are made from 35 μm thick copper. They are fabricated using standard printed circuit board technology over a 3 mm thick FR4 substrate, with relative permittivity of 4.2 and a loss tangent of 0.025. The radius of the meta-atom is $R = 4.8$ mm and the center distance between adjacent meta-atoms along x and y directions is about 10.7 mm, leaving a minimum distance of about 1.1 mm to ensure smooth rotation of each meta-atom. By carefully optimizing the meta-atom dimensions, such meta-atom could efficiently convert the incident right- and left-handed circular polarization (RCP and LCP) to reflected RCP and LCP, respectively⁵⁶. In principle, when this meta-atom is rotated by an angle θ , the phase of reflectances R_{rr} and R_{ll} are expected to follow a phase gradient of 2θ and -2θ , respectively, where the subscript r and l stands for RCP and LCP. Such geometric dependent phase behavior is also known as the PB phase response^{2,19,20}.

Experimental verification of PB phase controllability. Since the PB meta-atom can be rotated by 56 steps per turn, our metasurface enables quasi-continuous PB phase control over 28 levels. As schematically shown by the pink and sky-blue dials in Fig. 2a, the reflectance R_{rr} and R_{ll} have a phase control resolution of $\pi/14$ and opposite phase gradients. To experimentally characterize the metasurface, an experimental setup is established by a vector network analyzer (VNA, Agilent N5230C) and two broadband horn antennas (see Methods). Figures 2b and 2c illustrate the normalized amplitude of measured R_{rr} and R_{ll} , respectively, where the amplitude peak around the target working frequency of 7 GHz can be obtained in both spectra. $|R_{rr}|$ has a maximum amplitude of 0.91 at 6.925 GHz and $|R_{ll}|$ has a maximum amplitude of 0.7 at 6.55 GHz. Notably, the spectra are quite different from each other, and such phenomena can be attributed to the broken mirror-symmetry induced by the chiral geometry of the meta-atom, at the basis of the PB phase response. The red and blue circles in Figs. 2d and 2e illustrate the measured phase response of R_{rr} and R_{ll} , respectively, as we simultaneously rotate all meta-atoms from 0 to π . Clearly, the phase variation of R_{rr} and R_{ll} has respectively a positive and negative gradient versus the rotation angle.

Loading [MathJax]/jax/output/CommonHTML/jax.js nearly fitted results, where the fitting gradient of R_{rr} and R_{ll} is

1.9624 and -2.0665 , respectively, which agree well with the theoretical value. These results experimentally verify the PB phase controllability of the proposed metasurface platform.

Rotation distribution design for reprogrammable optical functionality. Since each supercell can be individually controlled, the metasurface yields a variety of optical functionalities by designing the rotation distribution over the surface. We define the metasurface as the xy -plane and its center the origin of our coordinate system. In order to experimentally characterize the performance, a broadband antenna is coaxially mounted at $(0, 0, 2100 \text{ mm})$ as a feeding source, and a waveguide probe is used to scan the electric field distribution (see Method). Since the wave emitted by the antenna is not a plane wave as it reaches the metasurface, we should compensate its phase to make it collimated (see Supplementary 3 for details). Notably, thanks to the quasi-continuous phase controllability, our metasurface can flexibly work under various incident wavefronts, since the functionality distortion produced by a non-planar incident wavefront can be easily compensated. Such flexibility is quite important in practical applications, especially in scenarios in which the feeding antenna can hardly be placed in the Fraunhofer region of the metasurface^{43,47}. Once the desired phase distribution for certain target functionality is obtained, the corresponding rotation distribution can be calculated by dividing by 2 or -2 , according to the target polarization handedness. In the following, we choose RCP as target operating polarization to demonstrate several representative functionalities, including metalensing, focused vortex beam generation and holographic imaging.

Metalensing. We first investigate the functionality of a metalens using the proposed metasurface. Figure 3a illustrates the required rotation profile for a metasurface focusing the impinging wave at $(0, 0, 600 \text{ mm})$ at an operating frequency of 7 GHz. The measured electric field intensity ($|R_{rr}|^2$) in the xy -plane at $z = 600 \text{ mm}$ is shown in Fig. 3b, where a highly symmetric focal spot can be obtained. The horizontal cut of the focal spot is shown in Fig. 3c showing a full-width at half-maximum (FWHM) $\sim 42 \text{ mm}$. Notably, the numerical aperture of the demonstrated metalens is about 0.587, corresponding to a diffraction-limited FWHM of $\sim 36.5 \text{ mm}$ at 7 GHz. We remark that the generated focal spot is quite close to the diffraction limit, indicating the excellent performance of our quasi-continuous phase control. The programmability of our surface enables scanning the focus off-axis. Figures 3d and 3g present the desired rotation profiles for focusing at $(-80, 0, 600 \text{ mm})$ and $(120, 0, 600 \text{ mm})$, respectively. The measured electric field intensities and the horizontal cuts of the focal spots are shown in Figs. 3e,h and 3f,i, respectively, shown to perform very well in terms of their focusing and scanning capabilities. These high-quality and compact focal spots experimentally verify the accuracy of the phase realization of our proposed metasurface.

Focused vortex generation. Electromagnetic fields with a phase profile $e^{il\varphi}$ carry orbital angular momentum (OAM), where φ is the azimuthal coordinate in the transverse plane and l is the topological charge. To corroborate the generality of the proposed metasurface, we demonstrate reprogrammable focused vortex generations in Fig. 4. These vortices are designed to coaxially focus at $(0, 0, 600 \text{ mm})$, thus their target rotation angle distribution is the one in Fig. 3a plus $l/2$ times the azimuthal angle.

Loading [MathJax]/jax/output/CommonHTML/jax.js distribution across the surface to generate focused vortex

beams of topological charges $l = 1, 2, 3, 4$, respectively. Figures 4b,f,j,n illustrate the measured electric intensity ($|E_r|^2$) distributions of the vortex beams, respectively, at the focal plane $z = 600$ mm. As expected, these intensity distributions exhibit doughnut shapes, and the central dark area of the vortices is larger for increased topological charge. Figures 4c,g,k,o illustrate the corresponding measured phase distributions, where the azimuthal angle dependence clearly reveals the vortex nature of the focused beams. To quantitatively analyze the quality of the vortex beams, we extracted and integrated the complex amplitudes to get the amplitude $|S_n|$ of each OAM (see Supplementary 4 for details). Figures 4d,h,l,p respectively illustrate the corresponding normalized $|S_n|$ as a function of l from -6 to 6 . Clearly, the target OAM component of each measurement is the strongest, while the other OAM components are quite weak, indicating the high purity of the generated vortex beams. These results experimentally illustrate the large reprogrammability and at the same time high efficiency of our metasurface in tailoring the impinging fields at will.

Holographic imaging. Metasurface holography has become a well-established approach to address inverse engineering problems for electromagnetic waves. In order to further explore the wavefront control capability of our programmable metasurface, we apply it to construct computer-generated holographic images in Fig. 5. In our demonstration, the Chinese sentences “天津大学” (Tianjin University) and “董永刚” (Datong Yungang) were generated in the image plane at $z = 600$ mm. The required rotation profile for each word, as shown in Figs. 5a-d and 5i-l, is calculated by a modified Gerchberg-Saxton algorithm^{56,57} (see Supplementary 5 for details). To confirm the functionality, we calculated the holography imaging by considering the meta-atoms as point sources with ideally designated hologram phase profiles. The calculated results are shown in Supplementary 5, which comply well with the target sentences. To experimentally demonstrate these holographic images, we rotate the meta-atoms according to the required rotation profile and measured the corresponding electric intensity ($|E_r|^2$) distribution. Although the holograms have only 20×20 pixelated phase points, the generated holographic images, as shown in Figs. 5e-h and 5m-p, are of very high-quality and in good agreement with calculations, indicating the excellent wavefront control capability of the proposed reprogrammable metasurface platform.

Discussion

We have demonstrated a reprogrammable mechanical PB metasurface platform and showcased its superior dynamic and efficient control of the impinging wavefront by reconfiguring in real-time its operation across a number of operations, including metalensing, focused vortex generation and holographic imaging. Notably, while in this work we demonstrate the quasi-continuous phase control of 28 levels, it is possible to achieve higher levels or even continuous phase control by adopting more advanced motors^{58,59}. From the information perspective⁵⁵, the quasi-continuous phase control feature empowers reprogrammable metasurfaces with much larger information capacity than that of 2 or 4 phase control levels, which could be further extended to build software-controlled or intelligent meta-devices with programmable functions for practical wireless systems^{52–54}. From the diffraction optics

metasurface gradually converges to the ideal response as the

phase control level increases. Supplementary Information 6 uses metalensing as an example and numerically compares the performance of 2 level, 4 level, quasi-continuous (28 levels), and ideal phase control schemes, showing that the focus intensity of our quasi-continuous scheme is nearly identical as the ideal one, about 2.61 and 1.25 larger than the case of 2 and 4 level phase control schemes, respectively.

It should be emphasized that, since our mechanically reprogrammable modules and meta-atoms are detachable, the proposed metasurface template can be updated on-demand by changing suitable meta-atoms with customized properties. Although only one circular polarization is manipulated in this work, this metasurface platform also holds promise for more complicated reprogrammable polarization operations, such as simultaneous control of the amplitude and polarization state of reflected beams, and of planar chiral responses. Moreover, the mechanical manipulation can be extended to the control over the propagation phase by dynamically altering the position of each supercell along the propagation axis, by mechanically shifting the meta-atoms along the z direction. The spin-dependent PB phase in conjunction with spin-independent propagation phase can therefore allow a decoupled manipulation of both circular polarizations¹⁷.

In summary, we have demonstrated a versatile approach to implement a mechanically reprogrammable PB metasurface with superior performance. In principle, this metasurface can be reconfigured with large speed and high repeatability to yield optical functionalities of choice. High-performance functionalities can be dynamically switched by this cost-effective metasurface, of great interest in various microwave applications, such as in the context of wireless networks and systems^{52–54}. Precise and reversible control of micro/nano elements in space and time has long been pursued in the context of micro/nanotechnologies^{58–61}. We envision that our work may further boost endeavors into the interdisciplinary fields between micro/nanotechnologies to push these concepts to higher frequencies, enabling precise rotation control of micro/nanoscale PB meta-atoms with full addressability and programmability to compress optical reprogrammable metasurfaces into a single chip.

Method

Measurements. In experiments, a VNA was used to acquire the response data by measuring the transmission coefficients (S_{21}). During measurements, the feed horn antenna and receive antenna/probe are respectively connected to the output and input ports of VNA through two 3-m-long 50 Ω coaxial cables. The excitation source is a linearly polarized wave emitted by the feeding antenna with working bandwidth from 2 to 18 GHz and. The experimental results shown in Fig. 2 are obtained by adopting a broadband antenna (the same as the feeding antenna) as the receiver. By respectively rotating the feed and receive antenna, the reflection coefficients for different linearly polarized waves, i.e., R_{xx} , R_{xy} , R_{yx} and R_{yy} , can be obtained, then the reflection coefficients for circularly polarized waves can be calculated using the transformation

$$\begin{pmatrix} R_{rr} & R_{rl} \\ R_{lr} & R_{ll} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} R_{xx} - R_{yy} + i(R_{xy} + R_{yx}) & R_{xx} + R_{yy} - i(R_{xy} - R_{yx}) \\ R_{xx} + R_{yy} + i(R_{xy} - R_{yx}) & R_{xx} - R_{yy} - i(R_{xy} + R_{yx}) \end{pmatrix}$$

1.

The experimental results shown in Figs.3-5 are obtained by adopting a waveguide probe as the receiver. Driven by an electric-controlled translation stage, the waveguide probe raster scans the linearly polarized waves over a large area, and the field distributions of $(|R_{rr}|^2)$ are also calculated by Eq. 1. For reference, Supplementary 7 presents the photos and schematics of the experimental setups.

Declarations

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Author contributions

Q. Xu, X. Su, and J. Han conceived the idea and designed the prototype. Q. Xu and X. Zhang conducted the numerical calculations. X. Su, L. Dong, L. Liu, J. He, L. Wen, Y. Liu, and Y. Huang assembled the reprogrammable metasurface and performed the measurements. L. Dong, Y. Shi, Q. Wang, M. Kang, and A. Alù contributed to the data analysis. Q. Xu and A. Alù wrote the manuscript. S. Zhang, J. Han, and W. Zhang supervised the project. All authors discussed the results and commented on the manuscript.

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Figures

Figure 1

Schematics of the metasurface and its supercell. (a) The metasurface is formed by an array of super-cells, arranged in a square lattice with period of 43.5 mm. The PB phase response of each super-cell is controlled by an addressable wireless signal and can be independently tuned over 28 phase levels. The

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the custom functionalities including metalensing, focused

vortex beam generation, and holographic imaging by proper design of the PB phase distribution. (b) The PB phase control in each super-cell is achieved by transmitting the torque from a stepping motor to the PB meta-atoms through a set of gears. Here the modules of all gears are 0.5. The yellow-green gear has 30 teeth, the light-blue gear has 30 and 16 teeth in bottom and top layer, and the pink gear has 14 teeth, respectively.

Figure 2

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PB phase response. (a) The top portion of the PB meta-atom is a pair of Archimedean spirals with same geometric parameters: inner radius (1.9 mm), outer radius (4.3 mm), height (0.035 mm), width (0.4 mm), and number of turns (2 turns). The pink and sky-blue dials schematically depict the PB phase control resolution and variation gradients for Rrr and Rll, respectively. (b-c) Measured amplitudes of Rrr and Rll, respectively. (d, e) Measured PB phase response of Rrr and Rll, respectively, versus different rotation angles.

Figure 3

Realization of metalensing. (a, d, g) Required rotation profiles to realize different metalens operations for RCP waves. (b, e, h) Measured electric field intensities ($|R_{rr}|^2$) at 7 GHz on the focal plane. (c, f, i) Horizontal cuts of the metalens focal spots, with FWHMs = 42, 44, and 44 mm, respectively.

Figure 4

Focused vortex beam generation. (a, e, i, m) Required rotation profiles to generate focused vortex beams with the topological charges of $l = 1, 2, 3, 4$, respectively. (b, f, j, n) Measured electric intensity ($|R_{rr}|^2$) distributions and (c, g, k, o) measured phase ($\angle$) distributions of different vortex beams, respectively, obtained at the focal plane. (d, h, l, p) OAM amplitude $|S_n|$ extracted from the measured complex amplitudes of different vortex beams, respectively.

Figure 5

Holographic imaging. (a-d, i-l) Required rotation profiles to generate holographic images of Chinese sentences “天津大学” (Tianjin University) and “大同云冈” (Datong Yungang), respectively. (e-h, m-p) Corresponding measured electric field intensities ($|R_{rr}|^2$) of holographic images obtained at $z = 600$ mm.

Supplementary Files

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