Complete Control of Multichannel, Angle-Multiplexed, and Arbitrary Spatially Varying Polarization Fields

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In recent years, much effort is dedicated to the generation of vectorial optical fields with an arbitrary spatially varying polarization distribution by means of metasurfaces. However, simultaneous and independent control of the amplitude, phase, and polarization is still challenging, especially for the multichannel generation of a vectorial optical field with an angle-multiplexed functionality. Here, a facile route, called coherent pixel polarization metaholography, is proposed to realize multichannel, angle-multiplexed, and arbitrary spatially varying polarization fields and demonstrate how to enable a fully independent realization of full Poincaré beams (lemon, start, spider, and web beams), dual-way switching print images, vectorial print images, and optical polarization knot profiles. Importantly, the demonstrated angle-multiplexed metasurfaces have an independently controllable handedness and azimuth and can possess up to four channels. Such angle-multiplexed multichannel arbitrary spatial polarization fields may enable various applications, including optical dynamic displays, information communication, optical encryption, and quantum experiments.

1. Introduction

The utilization of a vectorial optical field with complete control over the phase, amplitude, and polarization has recently become a topic of extensive interest.[1–10] In particular, vectorial optical fields with an arbitrary spatially varying polarization distribution are playing an increasingly important role in the scientific discoveries of many physical systems and a variety of applications,[1–9] ranging from optical encryption[3,11] to communication.[5,9] For example, vector beams have been considered to be a promising candidate for an optical mode-division multiplexing system,[5] optical storage,[7,12] and quantum key distribution.[9,13] Full Poincaré beams have been used to investigate physical systems with exotic nonlinear dynamics.[2] The applications of optical images with spatially varying polarization manipulation include dynamic displays[4,14] and information encryption.[5,14] An attempt has also been made to reconstruct a Seifert surface structure by analyzing the polarization ellipse orientations of knotted polarization singularities.[1]

Motivated by such diverse applications, various structures, including a liquid crystal spatial light modulator,[1,14] diffractive optical elements,[2,10,16] and metasurfaces,[4,14,17,18] have been theoretically proposed and experimentally studied for the generation of light beams with arbitrary spatially varying polarization fields, including a full Poincaré beam,[2,19,20] a polarization knotted beam[14] and vectorial holographic images.[4,14] Metasurfaces have emerged as a practical paradigm for the generation of spatially varying polarization fields[3,4,8,14,21–39] and have been widely adopted to achieve different integrated multifunctional components, such as a lens,[27] spectrometer,[29] hologram,[4,14,21,22,30,31] and vector vortex beam,[28,29,35] Recently, angle-multiplexed metasurfaces[12] consisting of reflective dielectric U-shaped meta-atoms were introduced to encode independent wavefronts at different incident angles. Diatomic metasurfaces[14] consisting of two reflective orthogonal meta-atoms were proposed for the polarization switching of vectorial holographic images. Continuously polarization-controlled orbital angular momentum superpositions in multiple channels were reported using a single plasmonic metasurface.[29]

The coherent pixel method was proposed for the generation of optically switchable print images.[10] Although numerous publications have been dedicated to generating arbitrary vector fields, there are still fundamental and technical challenges that must be overcome for metasurfaces to simultaneously and independently control the phase, amplitude and polarization of light. Most previous work has focused on the capacity of high-grayscale images,[31,34,39] multi-image switching[4,30,37] and colorful outputs[33,38] based on the multiplex pixel method.

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or coherent pixel method. All of the existing techniques have limitations and cannot be used to generate multichannel angle-multiplexed vectorial optical fields with an arbitrary spatially varying polarization distribution.

To address the above-mentioned problem, we combine the coherent pixel feature with off-axis holography in order to locally, arbitrarily, independently, and dynamically tailor the amplitude, phase and polarization of a light beam. Based on this method, termed coherent pixel polarization metaholography, we report a straightforward method to generate multichannel angle-multiplexed vectorial optical fields with arbitrary spatially varying polarization distributions at high resolution, ranging from vectorial print image switching to optical polarization knot profiles. We demonstrate the angle-multiplexed generation of four-channel C-point beams, including lemon, start, spider or web beams, and also vectorial print images and optical polarization knot profiles based on a single transmission-type dielectric metasurface at different illumination angles. In addition, we theoretically and experimentally demonstrate multichannel angle-multiplexed metasurfaces with a controllable orientation and handedness in each channel.

2. Result and Discussion

Let us begin with coherent Pancharatnam–Berry (PB) phase (also known as geometric phase) for a complex amplitude modulation.[17,18] The PB phase is related to the rotation (θ) of the nanorob of the geometric metasurface, where each nanorob behaves as a half-wave plate upon transmission. When a left circularly polarized (LCP) light beam is incident on the metasurface, the transmitted right circularly polarized beam (cross-polarized component) experiences an abrupt phase change of ±2θ. While the transmitted LCP beam (copolarized component), exhibits no phase change, or vice versa. As shown in the inset of Figure 1a, a pixel has two types of elements (A and B) with identical feature sizes and different orientations. The rotations of cells A and B are written as θ_A = (θ + ξ)/2 and θ_B = (θ - ξ)/2, respectively. These two types of elements (A and B) are encoded with pure PB phase modulations, expressed as u_A = exp (iθ + iξ) and u_B = exp (iθ - iξ), respectively. As a result, we can obtain the desired complex field u = cos ξ exp (iθ). Due to the photonic spin Hall effect, for incident beams of |L⟩ or |R⟩, the reconstructed fields u(r(x,y)) are cos ξ · exp (iθ|R⟩ or cos ξ · exp (-iθ|L⟩) for the conjugated complex amplitude and orthogonal circular polarization, respectively (a graphical interpretation of this process is shown in Figure S2a-c, Supporting Information).

Figure 1 shows a schematic illustration of the coherent pixel polarization metaholography approach for generating multichannel, angle-multiplexed, and arbitrary spatially varying polarization fields. The building blocks are amorphous TiO2 nanorobs with different orientations on a quartz substrate. The use of a TiO2 layer deposited by atomic layer deposition allows the metasurfaces to operate in transmission mode with negligible optical loss over the entire visible spectrum.[22,27,28] To provide full control of the phase, amplitude, and polarization, we simultaneously exploit the coherent pixel feature and off-axis holography. The desired light beams with spatially inhomogeneous polarization states can be described by a superposition of arbitrary orthogonal polarization states, |Ψ⟩ = u(α, β) p(x, y) = u |e⊥⟩ + u |e∥⟩ = |∑ α_e|L⟩ + |∑ β_e|R⟩ |L⟩ + |R⟩ |e∥⟩

![Figure 1](image-url)

**Figure 1.** Schematic illustration of the proposed coherent pixel polarization metaholography scheme. a) Schematic diagram of the angle-multiplexed metasurface. The inset shows the unit cell. (Photographs of James Clerk Maxwell, Marie Curie and Albert Einstein used with permission, see details in the captions to Figure 4 and 5, respectively.) b) For linearly polarized incident beams with the same angle but opposite directions, the polarization state |Ψ⟩ switches to |Ψ^α⟩, which has opposite handedness and a conjugated complex amplitude. c) The corresponding polarization pairs |(e⊥)|_α⟩ and |(e∥)|_α⟩ of the output polarization states.
where the polarization state $|e\rangle$ can be represented as $|e\rangle=(\alpha,\beta)^T$ for the circular polarization basis ($|R\rangle$, $|L\rangle$). It should be noted that $u(x, y)$ ($u_x$ and $u_y$) encodes arbitrary complex field, providing amplitude and phase modulation information. The off-axis geometric hologram for the multichannel angle-multiplexed function is $H(x, y)=\sum_{n=1}^{N} H_{k}^{\omega_{2},\omega_{1}}(x, y)$, where $N$ is the total number of channels. To obtain an arbitrary polarization state $|\Psi\rangle$ for a given channel $n$, $H_{k}(x, y)$ distribution of the desired complex hologram should be implemented

$$H_{k}^{\omega_{1},\omega_{2}}(x, y)=e^{i\omega_{2}x+i\omega_{1}y}\sum_{i} \alpha_{i} u_{i} + e^{i\omega_{2}x+i\omega_{1}y}\sum_{i} \beta_{i} u_{i}^*$$

(1)

where the off-axis factors are $k_{x}^{*}=k_{0} \sin \theta_{x}^{*}$ and $k_{y}^{*}=k_{0} \sin \theta_{y}^{*}$, $(k_{0}=2\pi/\lambda)$. The designed complex hologram $H(x, y)$ can be given by the interference between the two type units with geometric phase $\theta_{x}(x, y)=(\phi+\xi)/2$ and $\theta_{y}=(\phi-\xi)/2$, respectively. The corresponding distributions of $\phi$ and $\xi$ are calculated as the normalized complex holograms $H(x, y)$/Max(|$H(x, y)$|) = $\cos \xi \exp(i\theta)$. The implementation details can be found in Note S6 of the Supporting Information. It should be noted that the produced spatial polarization fields are influenced by zero-order diffraction when the decomposition basis $|e\rangle$ is provided in Note S1 (Supporting Information). As shown in Figure 1c, in contrast to the decomposition polarization basis $|e\rangle$ and the desired beam $|\Psi\rangle$, the azimuth of the polarization basis $|e\rangle_{\omega_{2}}$ and the rotation of the azimuth of the generated states $|\Psi_{\phi_{a}}\rangle$ and $|\Psi_{\phi_{b}}\rangle$ can be controlled by varying the rotating angle of the linearly polarized incident light. Thus, for an arbitrary decomposition basis $|e\rangle$ of the Poincaré sphere, the orientation and handedness of the generated polarization states can be tuned in dual way, that is, by adjusting the azimuthal state $\theta$ and then varying the tilted angle $(\theta_{x}^{*}, \theta_{y}^{*})$ of the incident linearly polarized light. The details of the orthogonality of the polarization pairs of $|e\rangle_{\omega_{2}}$ or $|e\rangle_{\omega_{1}}$ are given in Note S2 (Supporting Information). Here, the multichannel functionality is readily realized by coherent pixel polarization metaholography based on two pixel types with a fixed resolution, rather than by increasing the number of interleaved meta-atoms or cells.[16,24]

To experimentally verify the proposed coherent pixel polarization metaholography scheme described above, we designed and fabricated an angle-multiplexed metasurface (META1) with $N=4$ for multimode full Poincaré beams, which can be expressed as $|\Psi_{\phi_{a}}\rangle=\phi_{a}^{LG} |R\rangle + \phi_{b}^{LG} |L\rangle$ ($l_{1} \cdot l_{2} = 0$, $l_{1} + l_{2} \neq 0$, $l_{1}, l_{2} \in \mathbb{N}$), where $\phi_{a}^{LG}$ represents the transverse distribution of a Laguerre–Gauss beam (Equation (S13), Supporting Information).[16,19] The fabrication details can be found in our previous work.[28] Microscopy and scanning electron microscopy (SEM) images of part of the fabricated sample are shown in Figure 2c. The radius of META1 is 150.5 µm. A pixel consists of four nanorods in the form of a checkerboard pattern, and the center-to-center distance between two pixels is $\Lambda=700$ nm. The checkerboard pattern has dimensions of 350 nm x 350 nm. Each nanorod is 250 nm in length, 95 nm in width, and 600 nm in height. All experiments were performed at the working wavelength of 532 nm. Figure 2a shows the incident conditions and polarization distributions for the desired lemon, star, spider, and web beams. The center red points with circular polarization are known as C-points possessing circular polarization where the orientation is undefined. The corresponding geometric phase profile of META1 is shown in Figure S2f (Supporting Information). The designed lemon, star, spider, and web beams have the same waist $\omega_{1}=\omega_{2}=20$ µm and $l_{1}=0$, with indices of $l_{1}=1, -1, 4, -4$, respectively. The lemon, star, spider, and web beams are generated with different incident angles of $(\theta_{1}=14^\circ$, $\theta_{2}=0^\circ$, $(\theta_{1}=0$, $\theta_{2}=14^\circ$, $(\theta_{1}=7^\circ$, $\theta_{2}=0^\circ$, and $(\theta_{1}=0$, $\theta_{2}=7^\circ$, respectively.

We characterized the fabricated META1 using an experimental setup with an off-axis illumination, as shown in
Experimental demonstration of the angle-multiplexed metasurface (META1) for multiple full Poincaré beams (including lemon, start, spider, and web beams). a) Polarization patterns of four C-point beams. The lemon, start, spider, and web beams are switched for a horizontally linearly polarized beam at different incident angles of $(\theta_x = 14^\circ, \theta_y = 0)$, $(\theta_x = 0, \theta_y = 14^\circ)$, $(\theta_x = 7^\circ, \theta_y = 0)$, and $(\theta_x = 0, \theta_y = 7^\circ)$, respectively. The red points at the origin indicate the components with circular polarization states, and the black dashed lines represent the L-line circles with linear polarization states. b) The experimental setup, where A is an attenuator; P1 and P2 are polarizers; M1 and M2 are mirrors; HWP represents a half-wave plate; QWP1 and QWP2 represent quarter-wave plates, and OBJ is an objective lens. c) Microscopic and SEM images of the fabricated META1. The inset shows a tilted-view SEM image with a tilt angle of 30°.

Figure 3. Note that a 4×/0.10 objective lens is used to eliminate the influences of the incident beams and high-order diffraction on the desired polarization field, and the frequency space concept is introduced to discuss the cross-talk between different channels (Figure S2g and Note S6, Supporting Information). As shown in Figure 3a–d, the lemon, spider, start, and web beams are generated with different incident angles for the horizontally polarized beams. The corresponding polarization states of the generated full Poincaré beams are characterized by their horizontal ($I_{H}$), vertical ($I_{V}$), antisymmetric ($I_{\overline{A}}$), diagonal ($I_{D}$), right-circular ($I_{R}$) and left-circular ($I_{L}$) polarized components, respectively. The experimental results agree well with the theoretical predictions (Figure S3, Supporting Information). According to Equations (2) and (3), the handedness of the generated full Poincaré beams can be switched by changing the incident angle in opposite directions. This theoretical prediction is demonstrated experimentally in Figure 3. At incident angles of $(14^\circ, 0)$ and $(-14^\circ, 0)$, the observed polarized components $I_{A}$, $I_{R}$, $I_{V}$, and $I_{D}$ of the generated lemon beams are the same, and the observed polarized components $I_{L}$ and $I_{R}$ are switched, indicating that the handedness is independently controllable. At a fixed incident angle of $(-14^\circ, 0)$, a rotation of the linear polarization leads to a rotation of the intensity profiles of the polarized components $I_{A}$, $I_{R}$, and $I_{D}$ with the same components of $I_{L}$ and $I_{V}$, as shown in Figure 3e–h. This indicates the controllable azimuth functionality of META1. The corresponding Stokes phases are also given (Figure S4a, Supporting Information). In contrast to previous $q$-plate experiments,[16] dynamic spider beams can be observed by changing the ellipticity of the polarization states of the incident light (Figure S4b, Supporting Information). This indicates the spin-controllable functionality and agrees well with the theoretical results (Equation (S28), Supporting Information).
Curie” after passing through the linear polarization component $I_H$ or $I_V$, respectively. When changing the polarization states of the incident beams from horizontal polarization to vertical polarization, the characters contained in the linear polarization components $I_H$ and $I_V$ change from “James Clerk Maxwell” to “Maria Curie” and “Maria Curie” to “James Clerk Maxwell,” respectively. The experimental results agree well with the theoretical results shown in Figure S5 (calculated by Equations (S16–S19) and (S22–S27), Supporting Information). In addition, for the QR superposition pattern with two orthogonal linear polarizations, the circular polarization acts as a filter characterized by a mathematical operation of $MJ + QQ$ or $MJ - QQ$.

To demonstrate the versatility of the coherent pixel polarization metaholography method in the reconstruction of complex vectorial optical fields, as shown in Figure 5a, we designed and fabricated three angle-multiplexed metasurfaces (META3, META4, and META5) for multiplexing vectorial print images and optical polarization knot profiles with multiple polarization singularities at the C-point. META3 encodes a chiral grayscale portrait image of Albert Einstein with spatially varying polarization states and a Hopf link polarization knot profile. META4 encodes a vectorial image of Einstein with an inhomogeneous strip polarization distribution and a trefoil polarization knot profile. META5 encodes a print image with the characters of “RHLV” and a cinquefoil polarization knot profile. The characters of “RHLV” represent right-handed circular ($|L\rangle$), horizontally linear polarization ($|H\rangle$), vertically linear polarization ($|V\rangle$), and left-handed circular ($|L\rangle$) polarization, correspondingly. The above designs are calculated for horizontally polarized beams at two different incident angles of ($\theta_x = 0, \theta_y = 10°$) and ($\theta_x = 10°, \theta_y = 0$). Here, the optical polarization knot profiles with multiple C-points were obtained by a superposition of a conventional Gaussian beam and knot singularities with multiple phase singularities (Figure S1 and Note S5, Supporting Information). The corresponding holograms and spatial frequencies were calculated with the decomposition bases $|R\rangle$ and $|L\rangle$ (Figure S2f, Supporting Information). The experimental results are shown in Figure 5b. With regard to a horizontally polarized incident beam passing through the fabricated metasurfaces at an incident angle of ($\theta_x = 0, \theta_y = 10°$), for the fabricated META3, uniform intensity distributions are achieved, and positive and negative Einstein portraits are

Figure 3. Measured intensity distribution of the C-point beams and their corresponding polarization components, including the horizontal ($I_H$), vertical ($I_V$), antidiagonal ($I_A$), diagonal ($I_D$), right-circular ($I_L$), and left-circular ($I_R$) polarized components. a–d). The generated lemon, star, spider, and web beams for a horizontally linearly polarized beam at different incident angles of ($\theta_x = 14°, \theta_y = 0°$), ($\theta_x = 0°, \theta_y = 14°$), ($\theta_x = 7°, \theta_y = 0°$), and ($\theta_x = 0°, \theta_y = 7°$), respectively e–h) The generated azimuth-controllable lemon beams for different linearly polarized incident beams at a fixed incident angle of ($\theta_x = -14°, \theta_y = 0°$). The red double-end arrows denote the incident polarization states.
observed for the circular polarization components $I_R$ and $I_L$, respectively. For the fabricated META4, the Einstein portrait print image is also produced, and strip-like polarization distributions are demonstrated for the polarized components $I_H$, $I_V$, $I_R$, and $I_L$, respectively. For the fabricated META5, the letters “RHVL” can be clearly observed. As expected, the letters “H”/“V” or “R”/“L” disappear for the linear ($I_V/I_H$) or circular ($I_L/I_R$) polarized components, respectively. With regard to a horizontally polarized incident beam passing through the fabricated metasurfaces at an incident angle of $(\theta_x = 10^\circ, \theta_y = 0^\circ)$, the Hopf link, trefoil, and cinquefoil polarization knot profiles and their corresponding polarized components are observed for the fabricated META3, META4, and META5, respectively. The experimental intensity distributions of the optical polarization knot profiles and the vectorial print images are in good agreement with the theoretical results (Figure S6, Supporting Information). In contrast to Figure 5b, by changing the incident angle and rotating the polarization states of the incident light beam, one can control the handedness and the azimuthal angle of the vectorial print images for the dynamic display, as shown in Figure 6a. For multiple C-point profiles, as shown in Figure 6b, the measured and changeable Stokes phases $\phi_{12}$ of the Hopf link (META3), trefoil (META4), and cinquefoil (META5) polarization knot profiles have 4, 6, and 10 phase singularities with fixed positions, respectively, indicating azimuth-controllable polarization knots profiles where the C-points of the polarization singularities are unchanged (Figure S7, Supporting Information).

Here we have proposed and experimentally demonstrated a scheme to generate multiple controllable reconstructions of complex vectorial optical fields at different illumination angles. The strategy relies on the proposed approach of coherent pixel polarization metaholography, which can locally, arbitrarily, independently, and dynamically tailor the amplitude, phase, and polarization. The proposed coherent pixel polarization
metaholography approach differs from conventional metaholographic field construction tools, where the Gerchberg–Saxton algorithm is often used to generate the phase profile.\textsuperscript{[4,30]} Rather, our approach can effectively combine the advantages of the coherent pixel method and off-axis holography into a single transmission-type dielectric metasurface, allowing one to directly tailor the amplitude, phase, and polarization of the local field with a higher spatial resolution. Near-unity conversion

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**Figure 5.** Angle-multiplexed vectorial print image and polarization knots profiles. a) Schematic illustrations of the angle-multiplexed generation of vectorial images and optical polarization knot profiles. META3, META4, and META5 encode a chiral grayscale image and a Hopf knot, a portrait of Albert Einstein (1879–1955), theoretical physicist (IanDagnall Computing/Alamy stock photo) with inhomogeneous strip polarization distribution and a trefoil knot, the letters “RHVL” and a cinquefoil knot, respectively. b) Measured optical images at different incident angles of $(\theta_x = 10^\circ, \theta_y = 0)$ and $(\theta_x = 0, \theta_y = 10^\circ)$. The incident polarization states are denoted with the bra-ket notation. The symbols $I_x, I_y, I_R,$ and $I_L$ denote the components passing through the polarization analysis system. The red scale bars are 50 µm.

| (a)       | META3 $(0, 10^\circ)$ | (10°, 0) | META4 $(0, 10^\circ)$ | (10°, 0) | META5 $(0, 10^\circ)$ | (10°, 0) |
|-----------|-----------------------|----------|-----------------------|----------|-----------------------|----------|
| (b)       | $I_O$                 | $I_H$    | $I_V$                 | $I_R$    | $I_L$                 | $I_R$    |
| META3     | $(10^\circ, 0)$       |          | $(0, 10^\circ)$       |          | $(10^\circ, 0)$       |          |
| META4     | $(0, 10^\circ)$       |          | $(10^\circ, 0)$       |          | $(0, 10^\circ)$       |          |
| META5     | $(10^\circ, 0)$       |          | $(0, 10^\circ)$       |          | $(10^\circ, 0)$       |          |
efficiency can be obtained at working wavelength of 532 nm (Figure S8, Supporting Information). The 1st order efficiencies for a normal CP light incident on three and four unit cells are about 41% and 79%, respectively (Figure S8, Supporting Information). Note that large phase gradients result in a decrease of the 1st order efficiency, and the 1st order efficiency is strongly dependent on the incident angle and the working wavelength. The efficiency can be further improved by using meta-atoms with high resolution and large tolerance of the incident condition. Such a method enhances the ability to explore direct multichannel, angle-multiplexed, and controllable superpositions of complex polarization fields with a fixed pixel size, ranging from vectorial print image switching to optical polarization knot profiles. Furthermore, it is implemented by choosing an uncorrelated polarization basis rather than the conventional circular polarization basis. Thus, one can generate multiple angle-multiplexed outputs for polarization-multiplexed print images with two superpositions of different polarization bases, which is desired for applications in optical encryption and dynamic displays, \cite{4, 14, 30} and higher-order Poincaré beams, \cite{5, 28, 35}.

An important aspect of this work is the generation optical polarization knot profiles with multiple polarization singularities and dual-way polarization-switchable vectorial images. To the best of our knowledge, this is the first realization of

![Figure 6](image-url)

**Figure 6.** Measured polarization switching vectorial print images and optical polarization knot profiles with an independently controllable azimuth and handedness. a) Measured polarized components with vertically polarized light illuminations at an incident angle of (θ_x = 0, θ_y = −10°). (Photograph of Albert Einstein used with permission, cf. Figure 5.) b) Experimental results of the Stokes phase φ_{12} of the Hopf link, trefoil and cinquefoil polarization knot profiles with different linearly polarized light illuminations. The rotational azimuth of the polarization knot profiles results in changeable Stokes phase profiles. The corresponding numbers of the phase singularities with fixed positions are 4, 6, and 10, indicating that the C-points of the polarization singularities are unchanged. The red and black scale bars are 50 µm.

**Table:**

| META | (θ, φ) | \( I_0 \) | \( I_H \) | \( I_V \) | \( I_R \) | \( I_L \) |
|------|--------|--------|--------|--------|--------|--------|
| META3 | (0, −10°) | \( \uparrow \downarrow \) |        |        |        |        |
| META4 | (0, −10°) | \( \uparrow \downarrow \) |        |        |        |        |
| META5 | (0, −10°) | \( \uparrow \downarrow \) |        |        |        |        |
multichannel, angle-multiplexed, high-resolution, and switchable polarization fields with a tunable handedness and azimuthal angle (Table S2, Supporting Information). Interestingly, the spin-controllable character can be maintained when using the circular polarization basis. It should be noted that such an ultrathin multifunctional metasurface can be fabricated by standard complementary metal-oxide semiconductor processes, and will enable a broad range of applications, such as optical polarization Möbius strips,[40] polarization-encrypted data,[4,11] and quantum experiments,[6,8] a fiber mode-multiplexed communication system[5,13] and arbitrary polarization-multiplexed print images.[14,25]

3. Conclusion

In conclusion, many efforts have shown promise for generating and switching arbitrary spatially varying polarization fields with a single metasurface. We have realized multichannel, angle-multiplexed, and arbitrary spatially varying polarization fields with a single transmission-type dielectric metasurface, including full Poincaré beams (lemon, start, spider, and web beams), dual-way switching print images, vectorial print images and optical polarization knot profiles. Angle-multiplexed metasurfaces with up to four channels have been demonstrated as a spatial mode multiplexer for spin-controllable C-point beams. Our work has several advantages associated with polarization metaholography: dual-way controllable polarization state, high-resolution, arbitrary polarization-multiplexed, and angle-multiplexed generation of varying polarization fields. Our work may open new possibilities of the geometric metasurfaces for frontier research of dynamic polarization optics, information communication, optical dynamic displays, optical encryption/anticounterfeiting, and quantum experiments.

4. Experimental Section

Experimental Setup: The experimental arrangement is shown Figure 2b. The arbitrarily polarized light from the laser was generated by a half-wave plate (HWL), a quarter-wave plate (QWP), and a polarizer (P); and illuminated the back side of the substrate with an incident angle θ, which was adjusted by moving and rotating a mirror (M2). The horizontal or vertical incident conditions were adjusted by rotating the fabricated metasurfaces mounted on a rotational stage. The diffraction patterns from the metasurfaces were collected by a 4×/0.10 objective lens (NA = 0.1). The corresponding polarization states were analyzed by another QWP and P pair placed before the charge-coupled device camera.

Sample Fabrication: The nanofabrication of angle-multiplexed metasurfaces was realized by patterning, atomic layer deposition (ALD), and etching. First, a 600 nm thick poly(methyl-methacrylate) resist layer (MicroChem, 950PMMA, A5) was spin-coated onto a quartz substrate and then baked in an oven for 30 min at 170 °C to remove the solvent. Then, the desired structures were patterned using conventional electron beam lithography performed at 10 keV and subsequent development in a 3:1 IPA:MBIK solution. Next, an amorphous TiO2 thin film was deposited on the top and side of the poly(methyl-methacrylate) resist by ALD. TiCl4 and H2O were used as the precursors, and N2 was used as the carrier gas. The deposition temperature was 90 °C, and the corresponding deposition rate was 0.61 nm per cycle. Finally, the exposed tops of the amorphous TiO2 thin film were removed using reactive ion etching with an Ar/SF6 reactive gas mixture, and the residual electron beam resist was removed by oxygen plasma ashing.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

angle-multiplexed polarization metaholography, coherent pixel metasurfaces, dual-way polarization switching, optical polarization knot profiles, vectorial print images

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