

RESEARCH ARTICLE

Three-Dimensional Vectorial Holography With Full Polarization Control via End-to-End On-Chip Metasurface

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ABSTRACT

The generation and manipulation of 3D and vectorial optical fields are essential for advanced applications such as optical tweezers, information encryption, and volumetric display. Conventional metasurfaces offer powerful solutions for complex optical field modulation while typically suffer from underexplored polarization multiplexing capability and low design efficiency. Here, we propose an end-to-end on-chip metasurface design strategy based on gradient optimization to realize full-parameter control of 3D vectorial optical fields. By jointly encoding Pancharatnam–Berry (PB) phase and detour phase within a single-atom on-chip metasurface, the intrinsic constraints of the Jones matrix are effectively overcome. Through continuously adjusting the input and output polarization states, it enables flexible generation of vectorial optical fields. Experimentally, polarization-multiplexed holography with up to 36 independent channels is demonstrated, along with 3D spatial tunability. This work significantly expands the polarization-multiplexed capacity of meta-holography while improves the design efficiency of on-chip metasurface, providing a scalable pathway toward advanced photonic information processing and secure optical systems.

1 | Introduction

The generation and manipulation of complex 3D optical fields using holographic projection has shown significant potential in applications such as optical storage, information encryption, augmented/virtual reality, and biomedical imaging [1–6]. However, traditional holography techniques, which rely on spatial light modulators, digital micromirror devices, or volumetric media, suffer from drawbacks such as zero-order diffraction, low integration, and limited modulation dimensionality. Metasurfaces, as artificial flat optical devices with periodically arranged nanoscale unit cells, offer rich degrees of freedom (DoF) to manipulate the amplitude, phase, and polarization of optical fields [7–13]. Due to such multi-dimensional modulation capabilities, metasurfaces

have revolutionized traditional optical elements across a wide range of fields including achromatic lenses, holography display, imaging, and complex beam generation [14–20].

In particular, meta-holography demonstrates distinctive merits in terms of ultrathin profile, high efficiency, and multi-dimensional manipulation capability [21]. Accordingly, holographic multiplexing techniques have been developed in metasurfaces to leverage polarization multiplexing, wavelength multiplexing, spatial multiplexing, and orbital angular momentum (OAM) multiplexing [22–29], which allows for a high-dimensional multiplexing capacity. As an intrinsic degree of freedom of light, polarization provides a natural basis for orthogonal channels enabling enhanced robustness and minimal inter-channel crosstalk for

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information multiplexing [30, 31]. Consequently, polarization-multiplexed metasurface has emerged as a powerful approach for multi-channel holography while maintaining fidelity and efficiency. In essence, the polarization response of metasurfaces can be characterized by an equivalent Jones matrix. For single-layer metasurfaces under free-space illumination, the number of independent polarization-multiplexed channels is fundamentally limited to three due to the symmetry of Jones matrix. Although this limitation can be broken under specific polarization states, such schemes are incompatible with arbitrary polarization multiplexing [32, 33]. Extensive efforts have been devoted to decoupling the Jones matrix elements to improve polarization multiplexing capability, including cascading two single-layer metasurfaces and employing a noise engineering strategy [34, 35]. However, such approaches either rely on complex fabrication processes with stringent alignment requirements or exclude polarization conversion functionality, posing challenges in metasurface design and polarization multiplexing capacity [36, 37].

Recently, an on-chip metasurface strategy was proposed to circumvent the aforementioned challenges, which integrates detour phase with PB phase and propagation phase, enabling full-parameter decoupling of the Jones matrix [38]. Compared with free-space metasurfaces, on-chip metasurfaces with guided-wave illumination exhibit distinct advantages, including additional DoF of in-plane illumination and the suppression of zeroth-order diffraction [39–41]. It is especially promising for generation of 3D vectorial holography with expanded multiplexed channels and high quality. To this end, on-chip metasurfaces have been explored to achieve meta-holography for augmented reality, 3D light field manipulation, and optical encryption [42–44]. Current on-chip metasurface research has achieved notable progress, yet several limitations remain. Huang et al. demonstrated high-capacity 3D optical information storage by optimizing only the target phase, but the absence of multiplexing across additional light-field dimensions constrains the achievable capacity [1]. Jin et al. realized vectorial beams with longitudinally varying polarization in the microwave regime via interference between two sets of PB phase meta-atoms; however, this approach sacrifices spatial resolution [45]. Li et al. further exploited both in-plane and out-of-plane DoFs to enable six-channel independent holography and amplitude imaging, yet the forward-design paradigm inherently limits multiplexing scalability to the available meta-atom DoF [46]. Therefore, to take full advantage of on-chip metasurface platform, a metasurface design strategy, that features reduced design complexity and enhanced polarization-multiplexed capability, remains highly desirable for high-capacity 3D meta-holography [47].

In this study, we propose an end-to-end on-chip metasurface design method based on gradient descent algorithms, achieving 3D vector control of optical fields that break the limitations of the Jones matrix, within a single-atom scheme. By introducing joint modulation of PB phase and detour phase, the mathematical constraints of the Jones matrix are broken to realize complete decoupling of polarization responses. In previous studies, a forward design approach required metasurface units to provide enough DoF to control all Jones matrix parameters. Utilizing the end-to-end design approach, full coverage of the polarization dimension was realized. Furthermore, with the optimized efficiency and the balanced crosstalk of multi-

plexing channels, 36 polarization-multiplexed channels for 3D vectorial holography has been demonstrated. Our work further increases information capacity of metasurfaces, and advances the expansion of meta-holography applications, holding promises for advanced holographic displays and information transmission in photonics.

2 | Theory and Design

As shown in Figure 1, the proposed on-chip metasurface consists of a silica waveguide layer and a silicon metasurface array. The silicon metasurface is periodically arranged on the waveguide layer, with the same period $P = 750$ nm in both the x - and y -directions. The dimensions of the silicon meta-atoms are $L = 270$ nm (length) and $W = 90$ nm (width), while the height of the nanocylinders is $H = 380$ nm. Each meta-atom forms a pixel unit and providing three DoFs, namely 2D displacement δ_x, δ_y , and the rotation angle θ .

For the birefringent meta-atoms that constitute the metasurface, when the rotation angle is 0, their Jones matrix can be expressed as

$$J = \begin{bmatrix} t_x & 0 \\ 0 & t_y \end{bmatrix} \quad (1)$$

where $t_x = a_{x0}e^{i\varphi_{x0}}$ and $t_y = a_{y0}e^{i\varphi_{y0}}$, a_x, a_y and, $\varphi_{x0}, \varphi_{y0}$ represent the amplitude and phase responses of the birefringent meta-atom under x - and y - linearly polarized incident light, respectively. When a rotation angle is applied to the meta-atom, its Jones matrix can be expressed as [48]:

$$J = R(\theta) \begin{bmatrix} t_x & 0 \\ 0 & t_y \end{bmatrix} R(-\theta) = \begin{bmatrix} t_x \cos^2 \theta + t_y \sin^2 \theta & t_y \sin \theta \cos \theta - t_x \sin \theta \cos \theta \\ t_y \sin \theta \cos \theta - t_x \sin \theta \cos \theta & t_x \sin^2 \theta + t_y \cos^2 \theta \end{bmatrix} \quad (2)$$

where $R(\theta) = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$ is the rotation matrix, and the rotation angle is θ . When the incident light is totally internally reflected and propagates within the silica waveguide, by displacing the meta-atoms within the unit, a detour phase is introduced to break the symmetry of Jones matrix and decoupling the non-diagonal terms. The Jones matrix after introducing the detour phase is expressed as:

$$J = \begin{bmatrix} t_x \cos^2 \theta + t_y \sin^2 \theta & t_y \sin \theta \cos \theta - t_x \sin \theta \cos \theta \\ t_y \sin \theta \cos \theta - t_x \sin \theta \cos \theta & t_x \sin^2 \theta + t_y \cos^2 \theta \end{bmatrix} \cdot e^{i\varphi_{\text{detour}}} \quad (3)$$

where, $\varphi_{\text{detour}} = \varphi_1 + \varphi_2$, the detour phase of each meta-atom can be calculated as the sum of two components: one is the detour phase φ_1 accumulated by the metasurface atom relative to the zero-phase reference plane, and the other is the detour phase φ_2 generated by the phase displacement of the metasurface atom within its unit cell [43, 49–51]. φ_1 and φ_2 can be expressed

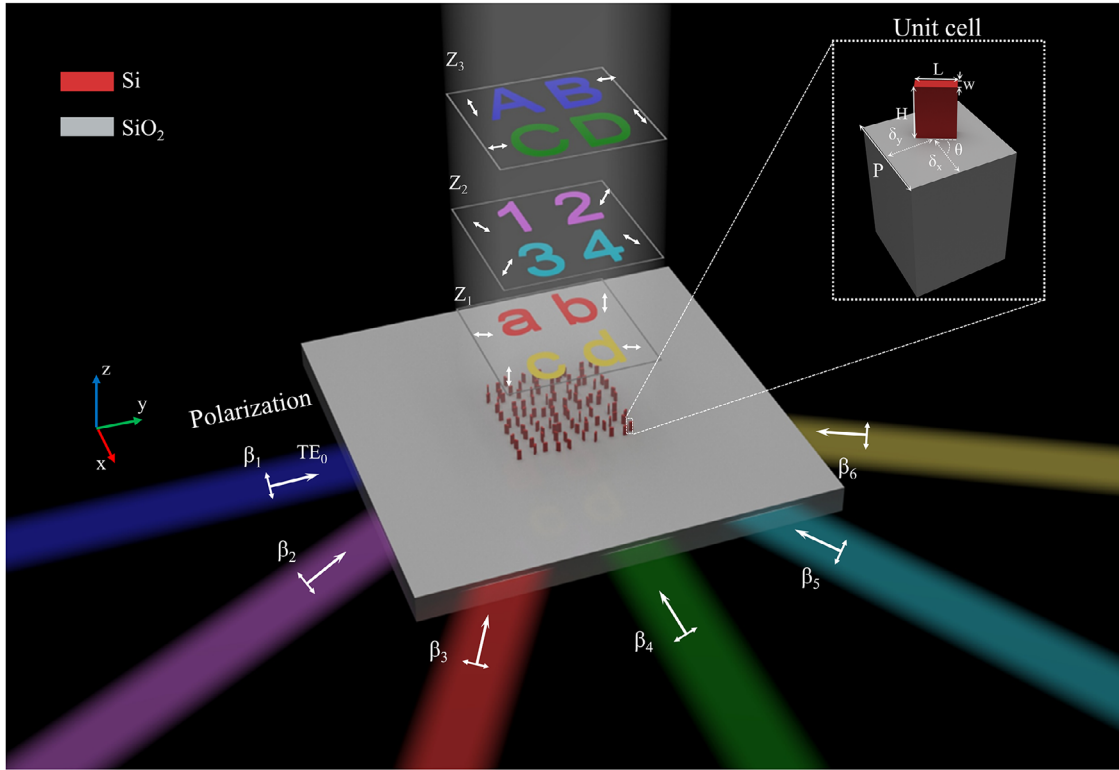


FIGURE 1 | The working principle of the on-chip metasurface for 3D vectorial holography. The schematic of the on-chip metasurface with a total of six different incident channels (corresponding to six incident linear-polarized states) and six output vectorial holography at three 2D planes Z_1 , Z_2 , and Z_3 . The inset shows an enlarged view of a single meta-atom. Single meta-atom with arm length $L = 270$ nm, arm width $W = 90$ nm, height $H = 380$ nm and period $P = 750$ nm. δ_x and δ_y are the relative displacement distances of the meta-atom in the x - and y -directions within a unit cell, and θ is the rotation angle of meta-atom.

respectively as:

$$\begin{aligned} \varphi_1 = & N \cdot 2\pi \cdot neff \cdot P \cdot \cos(\beta)/\lambda \\ & + M \cdot 2\pi \cdot neff \cdot P \cdot \sin(\beta)/\lambda + C \end{aligned} \quad (4)$$

$$\begin{aligned} \varphi_2 = & 2\pi \cdot neff \cdot \delta_y \cdot \cos(\beta)/\lambda \\ & + \cdot 2\pi \cdot neff \cdot \delta_x \cdot \sin(\beta)/\lambda + C \end{aligned} \quad (5)$$

where M and N represent the column and row indices of the metasurface atom, respectively, $neff$ is the effective refractive index under the condition of total internal reflection, and $neff \approx 1$. The calculation procedures of effective refractive index are presented in the Material and methods section. δ_x and δ_y represent the relative displacement distances of the metasurface atom in the x - and y -directions within a unit cell, C is a constant. The detailed calculation of the detour phase is presented in Note S1.

It is important to note that in the on-chip metasurface, the definition of the Jones matrix for the incident light differs from that in free space, as it depends on both polarization and the incident angle. The Jones matrix for the incident light is written as $[\cos(\beta) \sin(\beta)]^T$, where β is the angle between the incident light and the y -axis (Figure 1). The polarization of output light is defined in the same way as that of metasurfaces in free space.

For different incident linear polarized light and different output linear polarized light, the corresponding optical responses of the meta-atom can be expanded as [52]:

$$\begin{aligned} O(x, y) = & [P_{out}^1, P_{out}^2, \dots, P_{out}^n]^T \cdot J(x, y) \cdot [P_{in}^1, P_{in}^2, \dots, P_{in}^n] \\ = & \begin{bmatrix} O_{11}(x, y) & O_{12}(x, y) & \dots & O_{1n}(x, y) \\ O_{21}(x, y) & O_{22}(x, y) & \dots & O_{2n}(x, y) \\ \vdots & \vdots & \ddots & \vdots \\ O_{n1}(x, y) & O_{n2}(x, y) & \dots & O_{nn}(x, y) \end{bmatrix} \end{aligned} \quad (6)$$

where, $P_{in}^i = [\cos \beta_i, \sin \beta_i]^T$ and $P_{out}^j = [\cos \alpha_j, \sin \alpha_j]^T$. Each matrix element describes the response of a meta-atom to a given incident and output polarization state, x and y represent the indices of meta-atoms, respectively. The expanded form of Equation (6) is given in Note S2. Based on this, a method to break the symmetry limitation of the Jones matrix in mathematical form is derived, enabling more polarization dimension multiplexing. Compared to previous polarization-multiplexing metasurfaces, our multiplexing dimensions are not limited to the upper or lower triangular part of the response matrix, but instead fully utilize the dimensions of the response matrix, providing a theoretical foundation for the expansion of 3D vectorial holography. The multiplexing of more polarization dimensions also brings design challenges and sacrifices in spatial resolution.

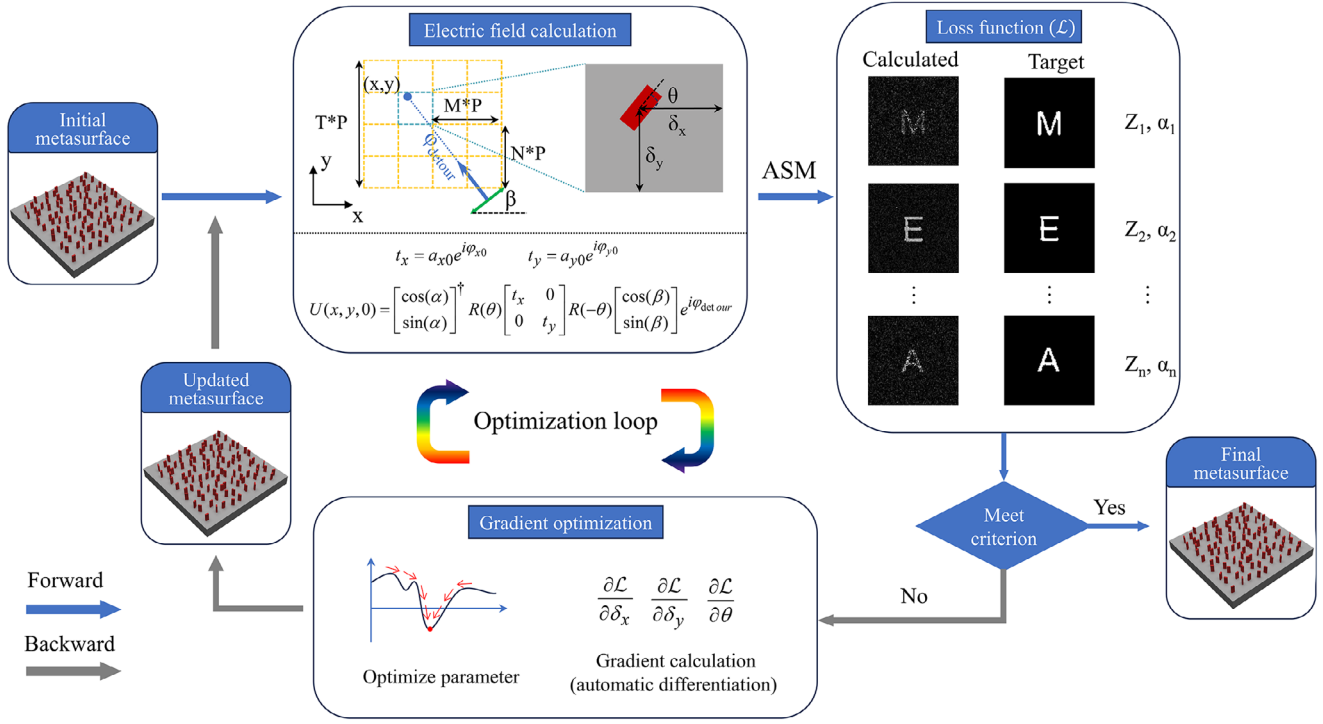


FIGURE 2 | Schematic of the end-to-end metasurface optimization framework. The metasurface parameters (e.g., position offsets δ_x , δ_y and orientation angle θ of meta-atoms) are first initialized. A forward propagation based on the physical model, including the Jones matrix and angular spectrum diffraction, is performed to generate the far-field hologram. The generated result is then compared with the target image to compute the loss function, consisting of MSE and NPCC. Gradients are obtained via automatic differentiation and backpropagated through the computational graph, and the parameters are updated using an optimizer. This process is iteratively executed within an optimization loop until convergence is achieved, yielding the optimized metasurface design.

To solve the Equation (6), an end-to-end inverse design approach has been adopted to determine the parameters of meta-atoms [53–55]. The end-to-end process can be formulated as a multi-objective optimization problem, optimizing the entire metasurface layout to control the entire 3D light field under simplified layout conditions [56]. The detailed optimization process is shown in Figure 2. First, we generate a metasurface array with a single meta-atom that has random displacements in the x and y directions and rotation angles. Through simulation, we can obtain the amplitude and phase responses of the meta-atom with arbitrary dimensions under x - and y -polarized incident light. The simulation method is described in the Materials and methods section. By substituting the known amplitude, phase, δ_x , δ_y , and rotation angle θ into the Jones matrix, the near-field response of any meta-atom can be calculated. We use the angular spectrum method (ASM) to propagate the near-field to an image plane at any distance, the calculation formulas are provided in Note S3. Assuming that E_{near} denotes the near-field distribution, the electric field distribution on the image plane is denoted as E_h . By comparing the far-field hologram generated using the ASM with the target image, the design process can be formulated as an optimization problem:

$$\arg \min_{p, q, z} \sum \mathcal{L}oss \{E_h(p, q, z), E_{\text{target}}(p, q, z)\} \quad (7)$$

$\mathcal{L}oss$ is the loss function, the loss function quantifies the discrepancy between the reconstructed and target holograms and

provides the optimization direction, guiding the metasurface parameters to converge toward the desired optical field distribution. The composition of the loss function is provided in Note S4. PyTorch's automatic differentiation engine performs backpropagation along the computational graph constructed from the physical model (e.g., Jones matrices and angular spectrum diffraction), and computes the partial derivatives (i.e., gradients) of the loss function with respect to the underlying physical parameters (δ_x , δ_y , θ) using the chain rule. It is worth noting that, for automatic differentiation to function properly, all operations involved in the computation must be continuous and differentiable. In this study, the entire computational pipeline, starting from the trainable parameters (δ_x , δ_y , θ), through the intermediate calculations of the Jones matrix, electric field, and diffraction intensity, to the final loss function, is composed of continuous and differentiable operations with well-defined derivatives provided by PyTorch [57]. Finally, the Adam optimizer utilizes this gradient information to iteratively update the parameters in each iteration, thereby driving the physical model to generate diffraction patterns that increasingly approach the target.

3 | Results

To verify the feasibility of the proposed method, multiple samples were designed, including three groups of 3D vectorial holographic metasurfaces with different polarization multiplexing schemes. For the first metasurface, four mutually orthogonal polariza-

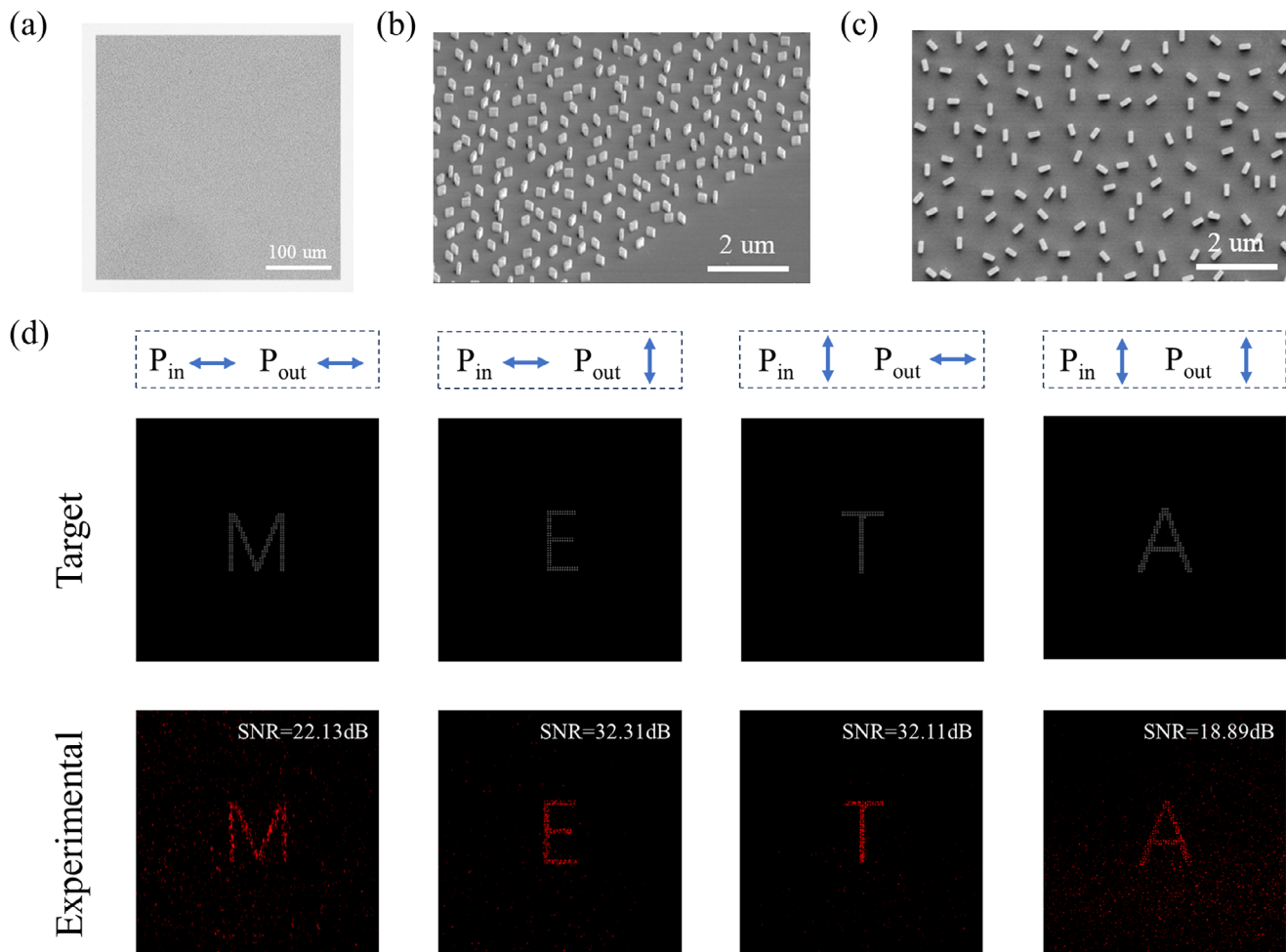


FIGURE 3 | Experimental demonstration of the 4-channel on-chip metasurface. (a) Optical micrographs of the fabricated sample, the scale bar is 100 μm . (b) Side-view and (c) top-view SEM micrographs of the fabricated sample, the scale bars are 2 μm . (d) Measured results for x - and y -linearly polarized incidence with x - and y -polarization analysis, respectively.

tion multiplexing channels were implemented, which serve as the basis for higher-dimensional polarization multiplexing. The metasurface consists of 500×500 silicon meta-atoms fabricated on a silica substrate, and is designed for an incident wavelength of 635 nm. In previous studies, even after introducing two orthogonal detour phases, supercell structures were still required to provide sufficient DoF, which inevitably leads to a loss of spatial resolution in 3D holography. In contrast, by employing an end-to-end design strategy and leveraging the global response of the metasurface, four holographic images are generated simultaneously without sacrificing performance. The end-to-end algorithm outputs not only the phase distributions corresponding to the four target images, but also the spatial positions and orientation angles of the meta-atoms.

Figure 3a–c shows the optical and scanning electron microscopy (SEM) images of the fabricated sample using standard electron beam lithography. The metasurface array exhibits steep sidewalls and well-defined profiles. The optical characterization setup is illustrated in Note S5. The target phase and meta-atom distributions are provided in Note S6. Figure 3d presents the results of the first sample. The holographic image plane of the metasurface is set at $Z = 200 \mu\text{m}$. Different from free-space illumination, the on-chip input polarization is dependent on the incident angle:

$\beta = 0^\circ$ corresponds to x -linear polarized incidence, while $\beta = 90^\circ$ corresponds to y -linear polarized incidence. For x -linear polarized incidence, polarization analysis of the hologram shows that the letter “M” is reconstructed under co-polarization, while the letter “E” is obtained under cross-polarization. For y -linear polarized incidence, the letter “A” appears under co-polarization, whereas the letter “T” is reconstructed under cross-polarization. These results demonstrate that the four polarization-multiplexed channels exhibit negligible crosstalk. It is observed that the images under co-polarization contain a certain level of background noise, whereas such noise is absent in the cross-polarization channels. The background noise observed in the co-polarized holographic channels mainly originates from fabrication imperfections and near-field coupling between adjacent meta-atoms, which introduce residual amplitude and phase errors into the reconstructed optical fields. In comparison, the cross-polarized channels exhibit lower background noise due to the polarization-selective nature of PB phase modulation. The signal-to-noise ratios (SNR) of the reconstructed holographic images are calculated under identical acquisition conditions and labeled in Figure 3d, quantitatively confirming the improved background suppression in the cross-polarized channels. This scheme is applicable not only to the design of 3D optical fields but also to far-field design, as shown in Note S7.

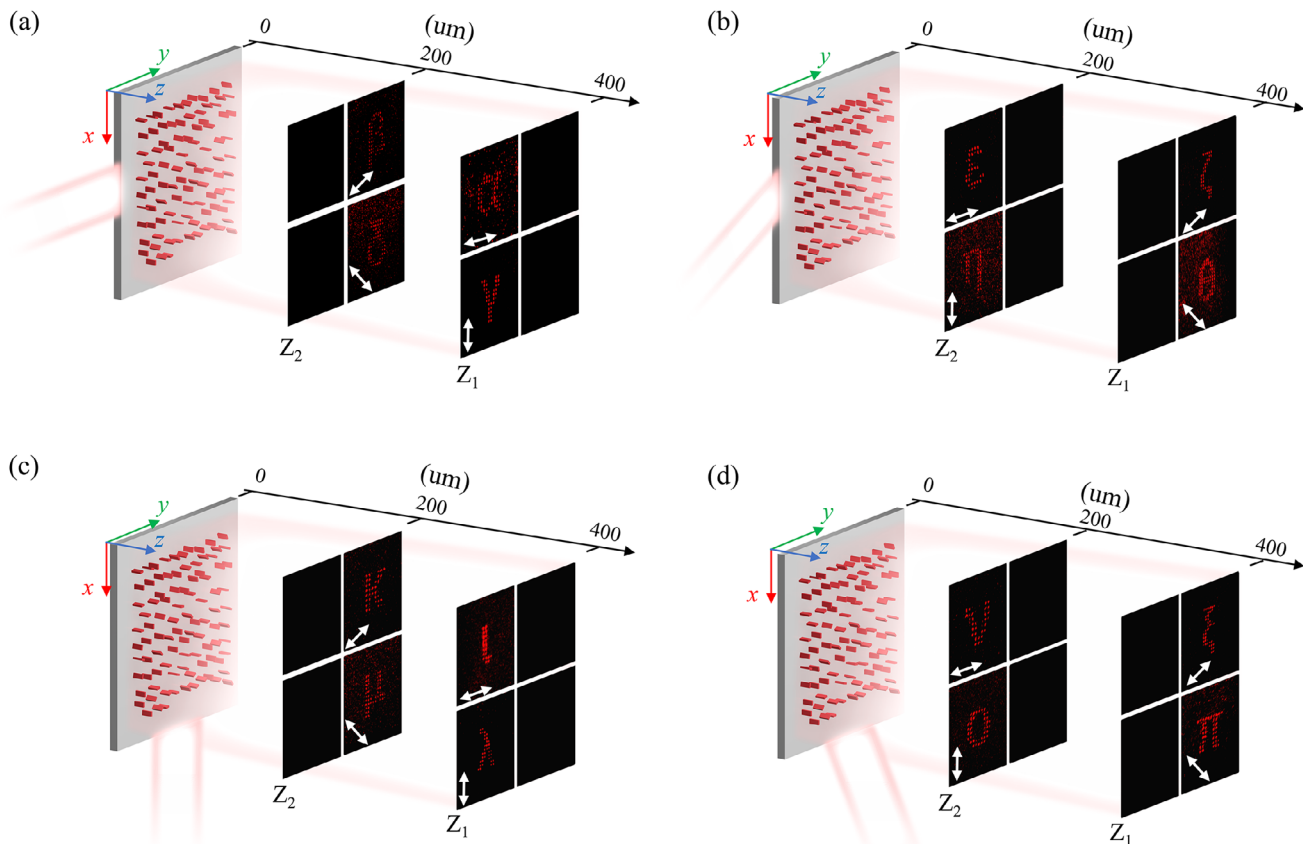


FIGURE 4 | Experimentally demonstrated 3D vectorial holographic metasurface with 16 channels. Four incident (a) 0°, (b) 30°, (c) 90°, and (d) 120° linearly polarization states and four corresponding analysis polarization states are selected, with the holographic images distributed across two planes at $Z_1 = 400 \mu\text{m}$ and $Z_2 = 200 \mu\text{m}$.

To demonstrate the capability of the proposed algorithm in manipulating 3D vectorial optical fields, a 3D vectorial hologram was designed based on the end-to-end framework. The hologram features two focal planes, four continuously varying incident polarization states, and four continuously varying output polarization states. The target patterns are illustrated in Note S8. For x -polarized incidence, at the focal plane $Z_1 = 400 \mu\text{m}$, the letter “ α ” with x -linear polarization is reconstructed in the upper-left region, while the letter “ γ ” with y -linear polarization appears in the lower-left region. At the focal plane $Z_2 = 200 \mu\text{m}$, the upper-right region shows the letter “ β ” with 30° linear polarization, and the lower-right region shows the letter “ δ ” with 120° linear polarization. For 30° linearly polarized incidence, at $Z_2 = 200 \mu\text{m}$, the upper-left and lower-left regions reconstruct the letters “ ϵ ” and “ η ” with x - and y -linear polarization, respectively. At $Z_1 = 400 \mu\text{m}$, the upper-right and lower-right regions display the letters “ ζ ” and “ θ ” with 30° and 120° linear polarization, respectively. For y -linear polarized incidence, at $Z_1 = 400 \mu\text{m}$, the letters “ ι ” and “ λ ” with x - and y -linear polarization are reconstructed in the upper-left and lower-left regions, respectively. At $Z_2 = 200 \mu\text{m}$, the letters “ κ ” and “ μ ” with 30° and 120° linear polarization appear in the upper-right and lower-right regions, respectively. For 120° linearly polarized incidence, at $Z_2 = 200 \mu\text{m}$, the letters “ ν ” and “ σ ” with x - and y -linear polarization are observed in the upper-left and lower-left regions, respectively. At $Z_1 = 400 \mu\text{m}$, the letters “ ξ ” and “ π ” with 30° and 120° linear polarization are reconstructed in the upper-right and lower-right regions,

respectively. The experimental results shown in Figure 4 agree well with the design, demonstrating accurate reconstruction of both spatial distribution and polarization states at different focal planes under varying incident polarization conditions.

The proposed 3D vectorial holography, enabled by the end-to-end design framework, allows arbitrary incident polarization states to generate holographic patterns with arbitrary output polarization at arbitrary 3D positions. This capability naturally lends itself to applications in augmented reality and optical information encryption. By encoding information simultaneously in spatial positions as well as in both incident and output polarization states, the security and information capacity of the encryption system can be significantly enhanced. To demonstrate its functionality in optical encryption, a metasurface generating 36-channel 3D holography was designed, corresponding to all alphanumeric characters on a keyboard. The 36-channel 3D vectorial holographic multiplexing results are presented in Figure 5a. Six incident linear polarization states ranging from 0° to 150° (with a 30° interval) are utilized as independent input polarization channels, while the same six polarization states are selected for polarization analysis. By jointly encoding polarization and spatial degrees of freedom, the 36 independent holographic channels are reconstructed at three distinct axial planes, namely $z_1 = 100 \mu\text{m}$, $z_2 = 200 \mu\text{m}$, and $z_3 = 300 \mu\text{m}$. Each letter and number is assigned an independent combination of polarization and spatial position. By allocating different encrypted channels to

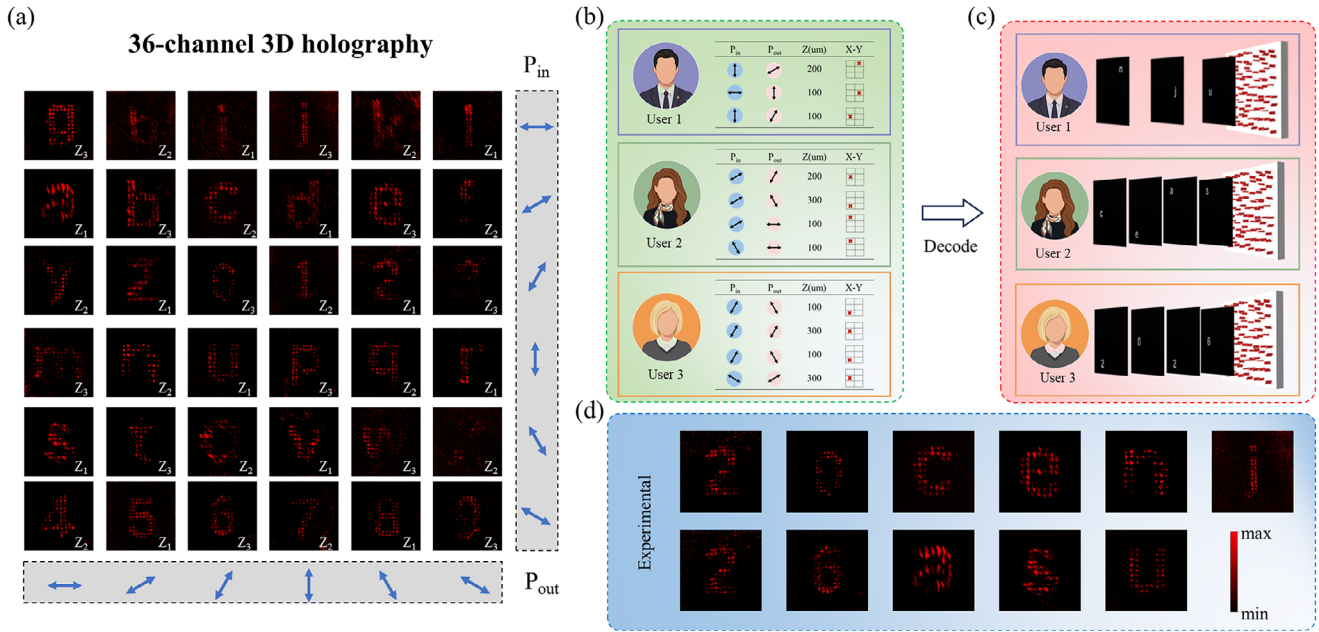


FIGURE 5 | Experimentally demonstrated information encryption using 36-channel 3D holography. (a) Experimental result of the 36-channel on-chip metasurface. (b) Schematic of optical information encryption. Each user can correctly decode the information only by accessing the appropriate polarization state and 3D spatial position. (c) Decoded results are “nju”, “ceas”, and “2026”, respectively. (d) Experimental decoding results.

multiple users, more users can be accommodated within a limited physical space. As shown in Figure 5b, six incident channels are grouped into three pairs of orthogonal polarization states, each assigned to a specific user, enabling access for three users in total. User 1 is assigned the 0° and 90° linearly polarized channels, and by analyzing the 3D spatial positions together with output polarization, the encrypted information “nju” can be retrieved. User 2 is assigned the 30° and 120° linear polarization channels, through which the decrypted information is “ceas”. User 3 is assigned the 60° and 150° linear polarization channels, and the corresponding decrypted information is “2026.” The experimentally decoded results are presented in Figure 5d. In summary, 3D vectorial holography, by leveraging the dual encoding of spatial position and polarization states, provides higher encryption strength and information storage capacity compared to conventional approaches. In the field of optical information encryption, this method not only enhances data security but also addresses the growing demand for privacy protection in future information storage and transmission, demonstrating significant application potential.

4 | Conclusion

In summary, an end-to-end on-chip metasurface platform for 3D vectorial holography with high-dimensional polarization multiplexing have demonstrated. By overcoming the intrinsic limitations of the Jones matrix through joint PB phase and detour phase modulation and angle-dependent polarization encoding, our approach enables full decoupling of polarization channels and scalable extension to high-capacity multiplexing. The experimental realization of 36 polarization channels, 3D vectorial holography, and multi-user optical encryption highlights the versatility and robustness of the proposed framework. The ability to simultaneously encode information in spatial and polarization

domains offers substantial improvements in information capacity, security, and system integration compared to conventional holographic approaches. This work opens new opportunities for compact, high-performance photonic systems in applications such as augmented reality, high-density optical storage, and secure optical communication.

5 | Materials and Methods

5.1 | Metasurface Design and Simulation

In simulation, we calculate the response of the on-chip metasurface using the finite-difference time-domain (FDTD) method. Only one unit cell of the meta-atom is used in the simulation. Periodic boundary conditions are applied in the x- and y- directions, and perfectly matched layers (PML) are applied in the z- direction. The incident light is assumed to strike at a totally reflected angle. Since the silica substrate is sufficiently thick, the incident light source is placed within the substrate, while a point monitor and a field monitor are positioned in the air above the meta-atom to obtain the phase and amplitude responses, respectively.

For an integrated photonic waveguide with a thickness of only several hundred nanometers, its effective refractive index can be obtained through numerical simulations. For a bulk optical waveguide with a thickness much larger than the incident wavelength, the effective refractive index can also be calculated analytically. The propagation constant can be expressed as:

$$\beta = nef \frac{2\pi}{\lambda} = \frac{2\pi}{\lambda} n_{\text{tio2}} \sin \theta_{\text{tio2}}$$

where $neff$ is the effective refractive index, n_{tio2} is the refractive index of the waveguide material, and θ_{tio2} is the reflection angle

of the incident light at the waveguide-air interface. Under the condition of total internal reflection, we have: $\sin\theta_{\text{siO}_2} = 1/n_{\text{siO}_2}$, and substituting this relation into the propagation equation gives: $n_{\text{eff}} \approx 1$.

The holographic design was implemented using Python 3.9 and PyTorch 2.1. The models were trained with a fixed learning rate of 0.01. All computations were performed on a workstation equipped with two NVIDIA GeForce RTX 4060 GPUs, an Intel Core i9-12900K CPU, and 64 GB RAM, running the Windows 10 operating system. Within the end-to-end framework, the metasurface parameters, including in-plane displacements (δ_x , δ_y) and rotation angle (θ), were jointly optimized via gradient-based backpropagation. The forward model incorporates a Jones matrix formalism combined with PB phase and detour phase modulation, while diffraction propagation is computed using the angular spectrum method. A composite loss function based on mean squared error and negative Pearson correlation coefficient was adopted to ensure both pixel-level accuracy and structural similarity, with gradient clipping and adaptive learning rate scheduling applied to stabilize the optimization.

5.2 | Device Fabrication

The fabrication process started with a commercial silicon dioxide substrate. First, a 380 nm thick α -Si layer was deposited onto the silica substrate via plasma-enhanced chemical vapor deposition (PECVD). Subsequently, the α -Si layer was coated with a 200 nm film of PMMA A4 resist through spin-coating, followed by a five-minute bake at 170°C. To ensure effective charge dissipation during electron beam exposure, a 40–50 nm layer of water-soluble conductive polymer (AR-PC5092) was spin-coated on top of the resist. The metasurface patterns were then written onto the resist using an electron beam lithography system (e.g., Elionix ELS-F125). After exposure, the conductive polymer layer was removed by rinsing in deionized water, and the resist was developed in a standard developer solution. A chromium layer was subsequently deposited by electron beam evaporation and patterned via a lift-off process to form a hard mask. Using this chromium mask, the α -Si layer was etched through inductively coupled plasma (ICP) dry etching with a gas mixture of C4F8 and SF6, transferring the designed metasurface structures into the silicon layer with a target height of 380 nm. Finally, the remaining chromium mask was removed using a chromium etchant (e.g., ceric ammonium nitrate), resulting in the completed metasurface structure.

Author Contributions

Tao Li, Shu Zong and **Jitao Ji** conceived the concept; Shu Zong, Jitao Ji and **Xiaopeng Li** proposed the device design and performed the numerical simulations; **Xu Tu** fabricated the samples; Shu Zong, **Junyi Wang** and **Zihan Wang** performed the optical measurements; Shu Zong, Jitao Ji, and Tao Li wrote the manuscript, and all the authors discussed the results; Tao Li supervised the project.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The source data are available from the corresponding author upon reasonable request. All data needed to evaluate the conclusions are present in the manuscript and/or the Supplementary Material.

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Supporting Information

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Supporting File: lpor71812-sup-0001-SuppMat.docx.