

Article

Polarization-Encoded Switchable Structured Light Generator Based on All-Dielectric Holographic Metasurfaces

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Abstract

Metasurfaces, as emerging functional optical coatings, enable precise wavefront manipulation at the subwavelength scale. In this work, we propose a polarization-encoded switchable structured light generator based on a single-layer holographic metasurface composed of silicon nanopillars. By combining Fresnel holography technology and the Pancharatnam–Berry phase modulation principle, two sets of holographic phase distributions for perfect vortex beams corresponding to orthogonal circularly polarized states are superimposed onto a single metasurface. The optimized nanopillar achieves a transmittance of approximately 85% and a polarization conversion efficiency of around 98% at the wavelength of 632.8 nm. By simply adjusting the incident polarization state, the metasurface generates a perfect vortex beam under right-handed circularly polarized light illumination and a cylindrical vector beam under horizontal linearly polarized light illumination, enabling on-demand switching between the two structured light modes. Furthermore, we design and validate a spatially multiplexed perfect vortex beam generator, in which the radius, topological charge, and focal plane position of each channel can be independently controlled. This flexible thin-film metasurface platform offers a promising route toward compact, multifunctional photonic devices for advanced optical integration.

Keywords: metasurface; multidimensional photonic structures; perfect vortex beam; vector beam; wavefront control

1. Introduction

In recent years, structured light has attracted significant research interest due to its ability to flexibly control light fields in various dimensions, including phase, polarization, and amplitude [1–3]. Among the various types of structured light, vortex beams and vector beams are two typical categories, both characterized by an annular optical field distribution. Vortex beams, featuring helical phase fronts and carrying orbital angular momentum (OAM), have found broad applications in fields such as optical encryption [4,5], optical manipulation [6], super-resolution imaging [7–9], and quantum information processing [10,11]. For a traditional vortex beam, the beam radius scales with the topological charge, which may impose limitations in applications that demand a constant beam size. In contrast, the radius of a perfect vortex beam (PVB) is independent of the topological charge [12], effectively decoupling beam size from OAM state. This unique property eliminates beam size instability caused by topological charge variations, and provides an efficient way to construct highly efficient and



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scalable optical systems. In addition to vortex beams, vector beams are characterized by spatially non-uniform polarization distributions, among which the cylindrical vector beam (CVB) is the most representative [13]. CVBs, with their tightly focused and polarization-sensitive properties, have demonstrated significant practical value in numerous fields, particularly in high-resolution imaging [14], material processing [15], optical trapping [16], and optical information encoding and encryption [17]. Despite the flexibility offered by traditional structured light generation methods, such as spatial light modulator [18], spiral phase plates [19,20], and interferometers [21], their bulky size pose challenges for integration into compact and portable systems. To overcome this fundamental limitation, metasurfaces stand out as a particularly promising platform.

Metasurfaces are two-dimensional planar structures composed of subwavelength artificial microstructures. Compared with traditional electromagnetic devices, metasurfaces offer miniaturization, lightweight design, and functional integration, providing an ideal platform for compact, high-efficiency systems. By carefully designing the geometric parameters of the microstructures, metasurfaces can not only precisely control the amplitude, phase, and polarization of the transmitted or reflected electromagnetic waves in the far-field [3,22–25], but also actively manipulate near-field electromagnetic distributions [26]. These capabilities have enabled metasurface applications in diverse fields, including wireless communication, photonic computing, and high-quality-factor resonant sensing [27–29]. In the area of light-field manipulation, optical metasurfaces have achieved significant progress, especially in the generation and manipulation of structured light fields, including vortex beams carrying different topological charges and vector beams with distinct polarization distributions [3,23,30–37]. Holographic metasurfaces combine computational holography with metasurface design, using inverse diffraction calculations to determine the required phase distribution from the target light field and then encoded into the geometric parameters of individual meta-atoms for accurate wavefront reconstruction [32,33]. This approach enables metasurfaces to generate arbitrarily complex light fields, opening new avenues for the precise manipulation of multiple degrees of freedom in structured light [36,37]. Despite this significant progress, dynamic switching between perfect vortex beams and vector beams on a single metasurface remains worthy of exploration. As summarized in Table 1, previous works have mostly focused on generating vortex or vector beams individually, with polarization switching largely confined to parameter tuning within a single beam type. Polarization-encoded switching between these two distinct beam categories on one metasurface remains an underexplored direction.

Table 1. Performance comparison of metasurfaces for structured light generation.

Reference	Wavelength	Transmission Efficiency	Polarization Conversion Efficiency	Main Function	Dynamic Control	Multiplexing Capability
[33]	632.8 nm	Not reported	~45%	Perfect vortex beam (PVB)	Fixed	Transverse spatial
[34]	450–780 nm	21.6%	Not reported	Cylindrical vector beam (CVB)	Fixed	Transverse spatial
[35]	632.8 nm	16.4%	46.3%	Perfect vector vortex beam (PVVB)	Polarization-switched	Transverse spatial
[36]	632.8 nm	Not reported	Not reported	PVVB	Fixed	Transverse and longitudinal spatial
This work	632.8 nm	85%	98%	PVB/CVB	Polarization-switched	Longitudinal space

In this work, we introduce a polarization-encoded switchable structured light generator based on a holographic metasurface. The design synergistically combines Fresnel holography technology with Pancharatnam–Berry (P-B) phase modulation prin-

ciples. Nanopillars with high transmittance and high polarization conversion efficiency are utilized to encode the required spatial phase distributions for PVBs under orthogonal circularly polarized light illumination onto a single metasurface. Simulation results demonstrate that under right-handed circular polarized (RCP) light illumination, the metasurface generates a PVB of the corresponding topological order. When illuminated by horizontal linearly polarized (HLP) light, two PVBs with opposite topological charges are simultaneously excited. These two beams coherently interfere at the focal plane, producing a CVB with zero net topological charge and a spatially non-uniform polarization distribution. By adjusting the design parameters, the polarization order, topological charge, radius, and spatial position of the generated structured light can all be independently controlled, demonstrating the broad versatility of this approach. Furthermore, we extend this study to the simultaneous generation of two PVBs at distinct focal planes to enhance spatial multiplexing capability. The focal planes, radii, and topological charges of these two PVBs can be independently controlled with negligible crosstalk between them. Although our work is based on numerical simulations, the proposed all-dielectric metasurface can be fabricated by using nanofabrication processes such as electron-beam lithography (EBL) and reactive ion etching (RIE) [34,35], which indicates its potential for practical realization. The proposed method provides a viable approach for designing multifunctional structured light generators on demand, contributing to the development of advanced functional optical coatings and compact integrated photonic devices.

2. Design Principle of the Polarization-Encoded Metasurface

The schematic diagram of polarization-encoded structured light generation is illustrated in Figure 1a. When HLP or RCP light is incident on the structured light metasurface generator composed of the rectangular silicon nanopillars grown on a glass substrate, the transmitted optical field exhibits a ring-shaped distribution. Analysis of the y-component of the light field shows that the metasurface generates a PVB under RCP illumination, whereas under HLP illumination, it produces a CVB.

To realize this functionality, Fresnel holography technology and the P-B phase modulation principle are combined to superimpose two sets of orthogonal circularly polarized holographic phase distributions on the same metasurface. The metasurface design process is illustrated in Figure 1b. The first row represents the target PVB designed for RCP light with a topological charge of l_R , and the second row is a target PVB for left-handed circularly polarized (LCP) light with a topological charge of l_L . Both target light fields share the same radius r , and their complex amplitudes at the target plane (x_0, y_0) can be expressed as

$$E_0^s(x_0, y_0) = A \exp \left[-\frac{(\sqrt{x_0^2 + y_0^2} - r)^2}{w_0^2} \right] e^{jl_s \phi}, \quad s = R, L \quad (1)$$

where A and w_0 denote the amplitude and beam waist of the target PVB, respectively. And ϕ is the azimuth angle ranging from 0 to 2π . By performing an inverse Fresnel diffraction integral calculation on the target light field, the required complex amplitude distribution at the metasurface plane is obtained as

$$E^s(x, y) = \frac{\exp(jkd)}{jkd} \iint E_0^s(x_0, y_0) \exp \left\{ \frac{jk}{2d} [(x - x_0)^2 + (y - y_0)^2] \right\} dx_0 dy_0, \quad (2)$$

where d is the propagation distance. Since the metasurface is designed to generate and direct the PVB to the target plane, the propagation distance d is equal to the focal length f . And $k = 2\pi/\lambda$ is the wave vector of the incident light with wavelength λ . Figure 1b(iii,vi) display the phase holograms for generating PVBs with topological charges of l_R and l_L ,

respectively. Since the metasurface consists of discrete nanopillars units, the two sets of holographic phase distributions described above should be discretized. To integrate two phase distributions onto a single metasurface, one set of holographic phases is randomly sampled with a certain ratio of 50%, and the other set fills the remaining vacancies in a complementary manner, resulting in a superimposed discrete phase distribution, as shown in Figure 1b(vii). The 50% ratio ensures an equal distribution of energy between the two orthogonally polarized channels. Additionally, random sampling is adopted to effectively suppress the periodic grating effect. It is worth noting that this interleaving design intrinsically decouples the RCP and LCP channels, offering an additional degree of freedom that is inherently unavailable in a single-channel pure P-B metasurface.

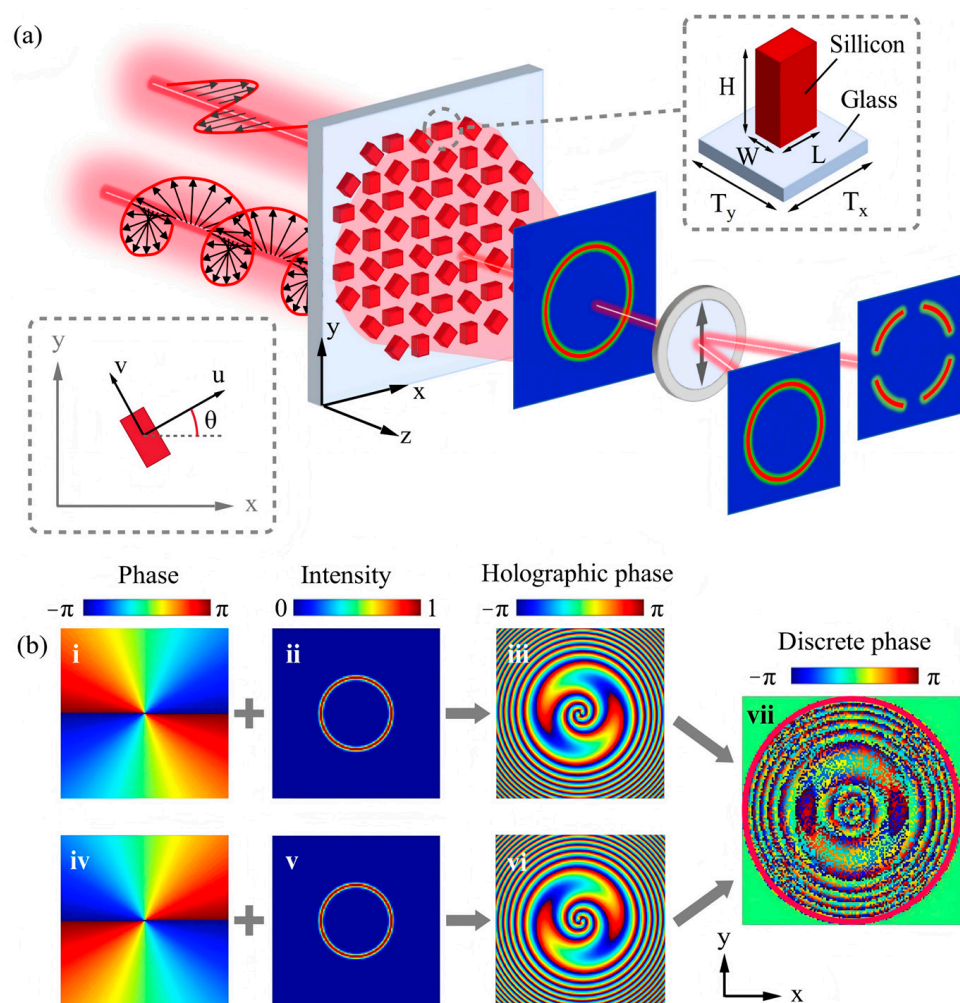


Figure 1. Design and generation of polarization-controlled structured light. (a) Schematic diagram of the structured light generation using a dielectric metasurface under horizontal linearly polarized (HLP) or right-handed circularly polarized (RCP) light illumination. (b) Holographic phase design for the metasurface. (i,iv) Phase distributions of the target PVBs with topological charges of +2 and −2, respectively. (ii,v) Corresponding intensity distributions. (iii,vi) Holographic phase distributions of the target PVBs. (vii) Discrete phase distribution superimposed with two PVBs.

Each rectangular nanopillar has two orthogonal principal axes supporting distinct phase retardation along each axis. In the local principal coordinate system (u, v) of the nanopillar, as shown in the lower-left inset in Figure 1a, the intrinsic Jones matrix of the nanopillar can be written as

$$J_0 = \begin{pmatrix} A_u & 0 \\ 0 & A_v \end{pmatrix}, \quad (3)$$

where $A_u = |A_u| \exp(i\varphi_u)$, $A_v = |A_v| \exp(i\varphi_v)$ are the complex transmission coefficients along the two principal axes, and φ_u , φ_v are the propagation phase delays. When the nanopillar is rotated counterclockwise by an azimuth angle θ relative to the Cartesian coordinate (x, y) , the Jones matrix in this basis is obtained by the rotation matrix

$$\mathbf{R} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \quad (4)$$

The Jones matrix in the Cartesian coordinate is written as

$$\mathbf{J} = \mathbf{R}^{-1} \mathbf{J}_0 \mathbf{R} = \begin{pmatrix} t_u \cos^2 \theta + t_v \sin^2 \theta & (t_u - t_v) \sin \theta \cos \theta \\ (t_u - t_v) \sin \theta \cos \theta & t_u \sin^2 \theta + t_v \cos^2 \theta \end{pmatrix}. \quad (5)$$

Then, in the (x, y) basis, the circularly polarized light can be expressed as

$$\mathbf{e}_\sigma = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i\sigma \end{pmatrix}, \quad (6)$$

where $\sigma = +1$ is for RCP and $\sigma = -1$ is for LCP. The transmitted optical field is decomposed into co-polarized and cross-polarized components

$$\mathbf{E}_{\text{out}} = \mathbf{J} \mathbf{e}_\sigma = \frac{t_u + t_v}{2} \mathbf{e}_\sigma + \frac{t_u - t_v}{2} e^{i2\sigma\theta} \mathbf{e}_{-\sigma}. \quad (7)$$

Obviously, the second term indicates that the cross-polarized component acquires a phase factor $\exp(i2\sigma\theta)$, which represents the P-B phase. In our design, each nanopillar is designed as a half-wave plate, the long axis serves as the slow axis owing to its higher effective refractive index, while the short axis serves as the fast axis. The phase retardation between the two axes is denoted as $\Delta\varphi = \varphi_u - \varphi_v = \pi$, so the cross-polarized term dominates. According to this property, a metasurface capable of simultaneously encoding two independent phase distributions can be realized by mapping the superimposed discrete phase distribution onto the angular distribution of the nanopillars. When RCP light illuminates the metasurface, the effective phase modulation experienced by the transmitted light is primarily determined by the holographic phase in the first row, thereby generating a PVB carrying a topological charge of l_R at the target plane. Since linearly polarized light can be regarded as a coherent superposition of two orthogonal circularly polarized components with equal amplitudes, HLP light illumination simultaneously excites both the RCP and LCP channels. The two PVBs carrying topological charges l_L and l_R then coherently superpose in space, resulting in a perfect vector vortex beam (PVVB), with the topological charge of $L = (l_L + l_R)/2$ and the polarization order of $P = (l_L - l_R)/2$. The light field of the generated PVVB can be expressed as

$$E(x, y) = A \exp \left[-\frac{(\sqrt{x^2 + y^2} - r)^2}{w_0^2} \right] (e^{il_L\phi} \mathbf{e}_L + e^{il_R\phi} \mathbf{e}_R) \quad (8)$$

where $\mathbf{e}_L$ and $\mathbf{e}_R$ represent the unit vectors of LCP and RCP light, respectively. In our design, we set $l_L = -l_R$. When HLP light is incident on the metasurface, the total topological charge reduces $L = 0$, indicating that no net orbital angular momentum is carried. Consequently, the resulting light field is a pure CVB without a helical phase front, possessing a polarization order of $P = l_R$.

3. Results and Discussion

3.1. Unit Structure Optimization

The proposed device employs a single-layer high-index dielectric thin-film metasurface composed of amorphous silicon rectangular nanopillars on a glass substrate. To ensure the designed metasurface achieves high transmittance and high polarization conversion efficiency, an optimization of a single rectangular silicon nanopillar is performed. Numerical simulations are performed using the finite-difference time-domain (FDTD) method via the commercial software Lumerical 2020 R2. The auto non-uniform meshing is chosen to balance accuracy and computational efficiency by dynamically refining the mesh at structural interfaces while coarsening it in homogeneous regions. The unit cell, shown in the inset of Figure 1a, consists of a rectangular silicon nanopillar on a SiO₂ glass substrate. In the simulations, the optical constants of the glass substrate are adopted from the “SiO₂ (Glass)—Palik” material model in the default material database provided by the software. This sampled data model provides wavelength-dependent complex refractive indices over a broad spectral range. At the operating wavelength $\lambda_0 = 632.8$ nm, the interpolation of the tabulated data gives the refractive index $n \approx 1.457$ and the extinction coefficient $k \approx 0$ for the glass substrate. The periodic boundary conditions are applied in the x - and y -directions with a period of $T_x = T_y = 0.27$ μm , and the perfectly matched layers are used in the z -direction. In our simulations, the optical constants of amorphous silicon are obtained from Karaman [38], with $n \approx 4.576$ and $k \approx 0.232$ at 632.8 nm, ensuring that material absorption is realistically accounted. We evaluate the nanopillar performance using two parameters: one is the transmission efficiency defined as the ratio of the total transmitted intensity to the incident intensity, and the other is the polarization conversion efficiency defined as the fraction of transmitted LCP light intensity within the total transmitted light intensity. With the nanopillar height fixed at $H = 0.31$ μm , the width (W) and length (L) are swept under RCP plane wave illumination at the wavelength of $\lambda = 632.8$ nm. Figure 2a,b present the transmission and polarization conversion efficiencies as functions of W and L . The optimal geometry $L = 0.17$ μm and $W = 0.09$ μm achieves a transmission efficiency of approximately 85% and polarization conversion efficiency of approximately 98%. It should be noted that the periodic boundary conditions used in the unit-cell optimization assume identical neighboring structures. In the actual metasurface, adjacent nanopillars can possess different orientations, and the resulting near-field coupling reduces the efficiency of the device. Nevertheless, since the geometric P-B phase depends only on the rotation angle of each individual nanopillar, the target wavefront is preserved. According to the P-B phase principle [30], the azimuth angle θ of a rotating rectangular silicon nanopillar introduces a geometric phase $\phi = 2\theta$ to the cross-polarized transmitted component. Figure 2c shows the longitudinal phase distribution in the x - z plane for an array of identically sized nanopillars with rotation angles varying from 0 to π along the x -axis. The corresponding rotation angle of each nanopillar is marked beneath the structure in the figure. A full 2π phase coverage is achieved as the nanopillar rotates by π , confirming the complete phase control required for the holographic design described in Section 2.

To evaluate the robustness of our metasurface against oblique illumination in practical optical systems, we investigated the incident angle response of the optimized nanopillar. Figure 2d shows the transmission and polarization conversion efficiencies as functions of the incident angle α . Under small-angle oblique incidence within $\alpha \leq 20^\circ$, the transmittance of the nanopillar remains above 70%, while the polarization conversion efficiency stays higher than 85%. These numerical results demonstrate that the local performance of each nanopillar is sufficiently robust against typical beam misalignment.

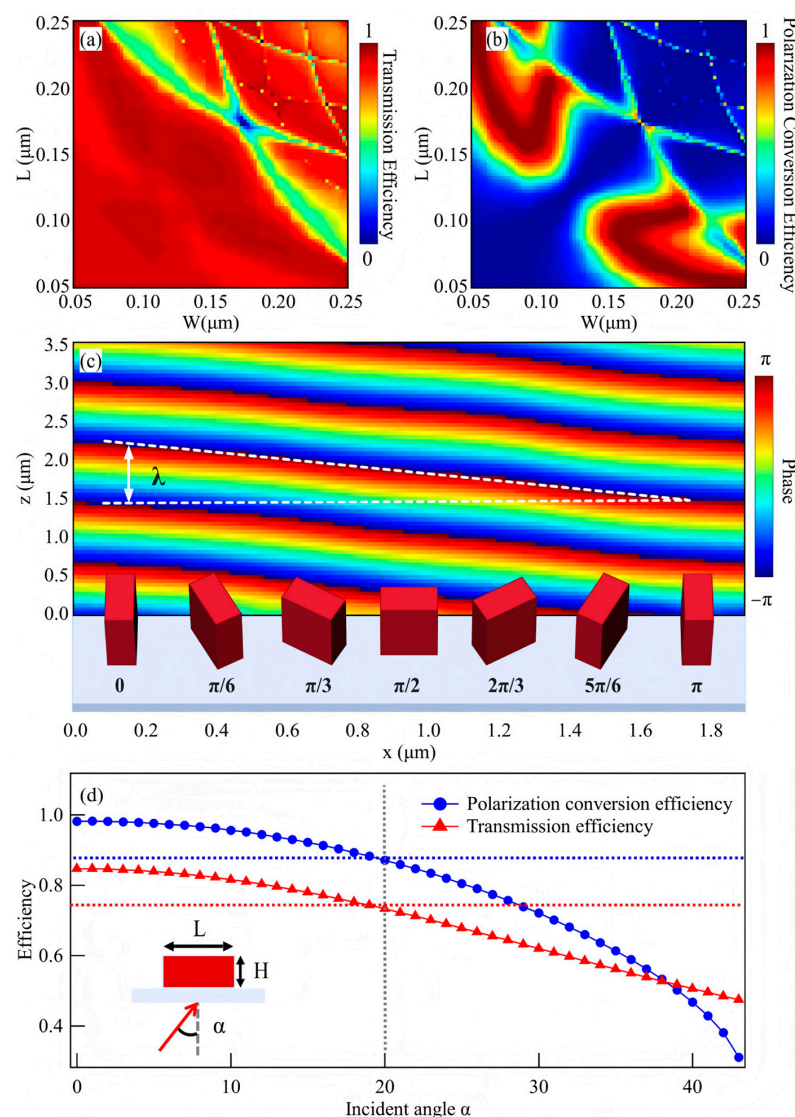


Figure 2. Optimization of the unit rectangular silicon nanopillar under RCP illumination at 632.8 nm. (a) Transmission efficiency and (b) polarization conversion efficiency as functions of nanopillar width and length. (c) Longitudinal phase distribution of the transmitted field in the x - z plane for rectangular silicon nanopillars arranged along the x -axis with rotation angles varying from 0 to π . (d) Transmission and polarization conversion efficiencies as functions of the incident angle α .

3.2. Polarization-Encoded Structured Light Generation

Following the design principle described in Section 2, we construct a holographic metasurface by superimposing phase profiles with topological charges of $l_R = +2$ and $l_L = -2$. The target vortices are designed with a common radius of $r = 8 \mu\text{m}$ and a focal plane at $f = 15 \mu\text{m}$ from the metasurface. The dimensions of the simulation region are set as $40 \mu\text{m} \times 40 \mu\text{m} \times 25 \mu\text{m}$. In order to avoid unexpected scattering, the perfect matching layer is chosen as the boundary condition. Figure 3a presents the physical layout of the designed metasurface. The main panel shows the full-aperture top-view layout of the entire metasurface. The inset provides a magnified view of a representative 5×5 subarray, displaying the actual shape and orientation of individual nanopillars. These spatially varying nanopillar orientations intuitively visualize how the discrete phase distribution shown in Figure 1b(vii) is physically encoded into the metasurface geometry. Figure 3b–g present the calculated transmitted optical field distributions under different polarization states. The simulated focal plane is located at $f = 13.8 \mu\text{m}$, which deviates from the designed value. To quantitatively understand this longitudinal focal shift, we extracted the cross-polarized transmission

phase of the nanopillar that rotates from 0 to π ; the actual phase changing reaches 2.145π , which is 7.25% larger than the ideal P-B phase modulation depth of 2π . The excess phase arises from anisotropic near-field coupling between adjacent nanopillars. Consequently, the effective refractive index for each pillar becomes angle-dependent, shifting the wavelength from its free-space value of $\lambda_0 = 632.8$ nm to an effective value of $\lambda_{\text{eff}} = 678.7$ nm. According to the Fresnel diffraction theory, $f_{\text{real}} = f_{\text{design}} (\lambda_0 / \lambda_{\text{eff}}) \approx 13.99$ μm , which deviates from the simulated value of 13.8 μm by only 0.19 μm . Considering secondary factors such as mesh discretization errors in the simulation and the finite size effect of the metasurface aperture, the focal shift can be understood. To correct the observed focal shift, all contributing factors can be calibrated into an overall compensation coefficient $\eta = f_{\text{target}} / f_{\text{real}}$, and set the designed focal length to $f_{\text{design}} = \eta f_{\text{target}}$ during the initial phase calculation. The second approach corrects only to correct the dominant factor by finding the actual phase-angle response and identifying the maximum rotation angle $\theta_{\text{max}} = 0.93\pi$ at which the phase exactly reaches 2π . The target phase $[0, 2\pi]$ is then linearly mapped onto $[0, \theta_{\text{max}}]$.

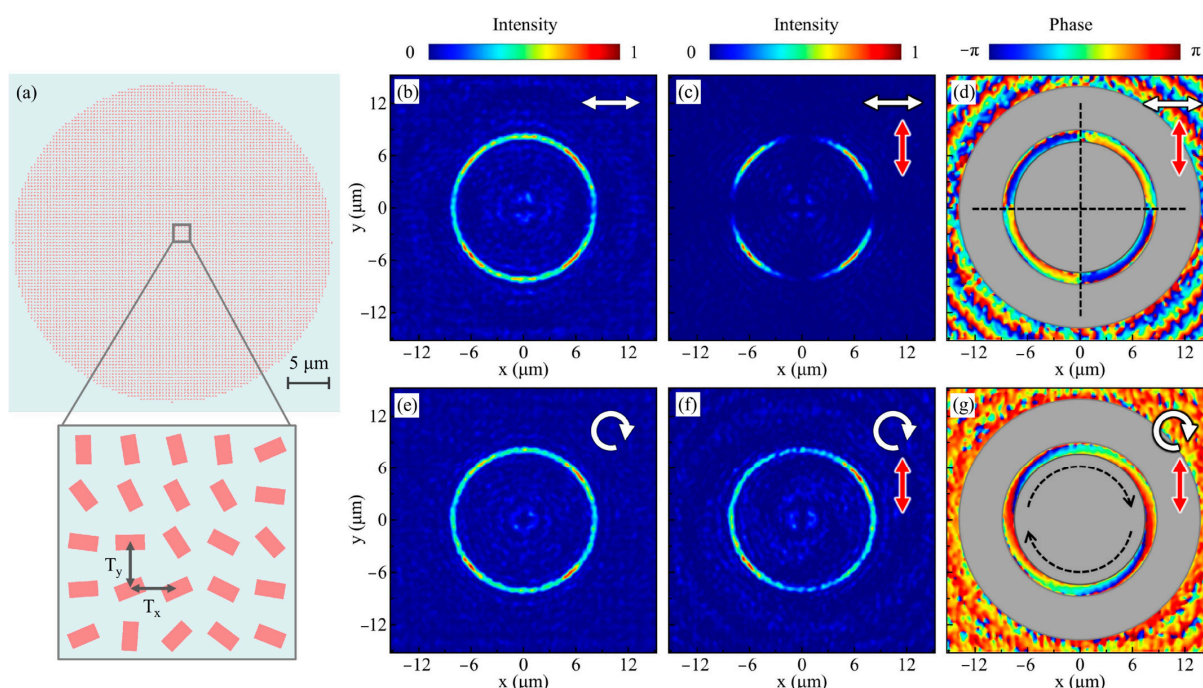


Figure 3. Physical layout of the designed metasurface and its transmitted optical field distributions. (a) Top-view layout of the entire metasurface, and the magnified view of a representative 5×5 subarray showing the actual shape and orientation of individual nanopillars. (b) Total intensity distribution under HLP light illumination at the focal plane 13.8 μm . (c) Intensity and (d) phase distributions of the transmitted y -component, indicating a CVB with polarization order 2. (e) Total intensity distribution under RCP light illumination. (f) Intensity and (g) phase distributions of the transmitted y -component, indicating a PVB with topological charge +2.

Figure 3b,e show the normalized intensity distributions under HLP and RCP light illuminations, respectively. Both conditions exhibit a ring-shaped optical field with a radius of approximately 8 μm , consistent with the design target. The polarization state of the incident light is denoted by the white arrow in the upper-right corner. Under HLP light illumination, the intensity and phase distributions of the y -component are shown in Figure 3c,d. The red arrow indicates the polarization selection direction. The intensity exhibits four-fold symmetry with a uniform phase distribution within each lobe, characteristic of a CVB with the polarization order $P_1 = 2$ and zero net topological charge $L_1 = 0$. Under RCP light illumination, the y -component intensity distribution in Figure 3f retains a uniform annular profile,

while the corresponding phase distribution in Figure 3g presents a clockwise double-helix structure. The accumulate phase around the singularity is 4π , confirming a topological charge of $L_2 = +2$. These results demonstrate that the designed metasurface enables on-demand switching between PVB and CVB simply by altering the incident polarization state.

To further validate the universality of this approach, we construct another metasurface by superimposing two sets of phase distributions with topological charges $l_R = -3$ and $l_L = +3$. The target structured light is designed with a radius of $r = 12\ \mu\text{m}$ and a focal plane at $f = 30\ \mu\text{m}$. Figure 4 displays the transmitted optical field distributions at the observed focal plane of $f = 27\ \mu\text{m}$. Under HLP light illumination, the total intensity exhibits a ring-shaped distribution, as shown in Figure 4a. The intensity distribution of the y -component in Figure 4b shows a six-fold symmetric lobe pattern, while the corresponding phase distribution in Figure 4c exhibits six uniform azimuth regions. These results confirm that the generated beam carries a polarization order of $P_1 = 3$ with zero net topological charge, which is in agreement with the theoretical design. When RCP light is incident on the metasurface, the total intensity also exhibits a uniform annular distribution with a radius of $12\ \mu\text{m}$. Figure 4e shows the intensity distribution of the y -component, which maintains a uniform annular pattern without petal-like modulation. The y -component phase distribution in Figure 4f displays an anticlockwise-rotating triple-helix structure, with a total phase accumulation of -6π , confirming that this beam carries a topological charge of $L_2 = -3$. These results verify that the generated structured light can be switched between PVB and CVB on demand by simply varying the polarization state. Furthermore, by adjusting the design parameters of the holographic phase distributions, the radius, topological charge, and focal plane position of the target structured light can be independently prescribed, demonstrating the flexible wavefront control capability of the proposed metasurface platform.

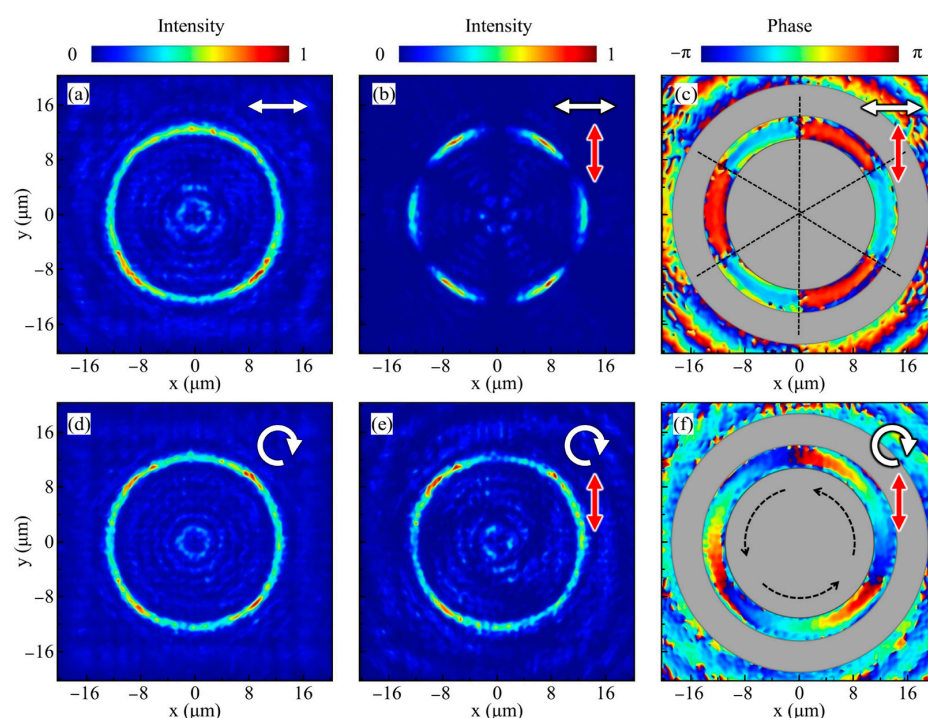


Figure 4. Transmitted optical field distributions of structured light with a radius of $12\ \mu\text{m}$ at the focal plane of $27\ \mu\text{m}$. (a) Total intensity distribution under HLP light illumination. (b) Intensity and (c) phase distributions of the transmitted y -component, indicating a CVB with polarization order 3. (d) Total intensity distribution under RCP light illumination. (e) Intensity and (f) phase distributions of the transmitted y -component, indicating a PVB with a topological charge of -3 .

It is worth noting that the metasurface maintains its functionality under oblique illumination. In the normally incident case, the phase distribution across the metasurface is uniform. However, under oblique illumination, the incident light introduces a linear phase gradient over the metasurface. This linear phase is completely decoupled from the locally encoded P-B phase, which depends only on the in-plane rotation angle of each nanopillar. Therefore, the linear gradient merely shifts the imaging position laterally, while the topological charge and polarization order of the generated structured light remain entirely unchanged.

4. Spatially Multiplexed Perfect Vortex Beams

To achieve parallel generation of multiple PVBs and expand the information capacity from a single channel to multiple channels, we extend the design to realize spatially multiplexed PVBs. Two holographic phase distributions for the target PVBs under RCP illumination are calculated and superimposed onto a single metasurface via random interleaving, which effectively suppresses mutual interference between the two channels during simultaneous beam formation. Figure 5a illustrates the operating principle. When the RCP light is incident on the metasurface, two spatially separated PVBs appear along the axial propagation direction. Each PVB possesses an independently topological charge l , ring radius r , and focal plane position f , and these parameters can be adjusted according to practical requirements. In this metasurface design, the first PVB is assigned $l_{R1} = +2$, $r_1 = 8 \mu\text{m}$ and $f_1 = 15 \mu\text{m}$, and the second PVB is assigned $l_{R2} = -3$, $r_2 = 12 \mu\text{m}$, and $f_2 = 30 \mu\text{m}$.

The total transmitted intensity distributions at the two focal planes $f_1 = 13.8 \mu\text{m}$ and $f_2 = 27 \mu\text{m}$ are shown in Figure 5b,e, with the corresponding y -component intensities presented in Figure 5c,f. At each focal plane, only the targeted PVB shows a distinct annular intensity distribution, while the other is substantially suppressed. Specifically, for the designed focal plane of the first PVB, the annular field with a radius of $r_1 = 8 \mu\text{m}$ is clearly visible, whereas the $r_2 = 12 \mu\text{m}$ annular field is barely discernible. At the second focal plane, $f_2 = 27 \mu\text{m}$, the opposite behavior is observed in Figure 5e,f: the $8 \mu\text{m}$ ring disappears and the $12 \mu\text{m}$ ring appears. Figure 5d,g show the corresponding phase distributions of the y -component at $f_1 = 13.8 \mu\text{m}$ and $f_2 = 27 \mu\text{m}$. The phase pattern in Figure 5d exhibits a clockwise phase accumulation of 4π around the annular region, confirming a topological charge of $+2$. As shown in Figure 5g, an anti-clockwise accumulation of -6π is observed, corresponding to three complete 2π phase cycles and indicating a topological charge of -3 . To quantitatively evaluate the generated PVBs, the mode purity and signal-to-noise ratio (SNR) were calculated at each focal plane. The mode purity is defined as the fraction of the total transmitted intensity within the target ring region, and the SNR is defined as the ratio of the average intensity within the ring to that outside the ring. At $f = 13.8 \mu\text{m}$, the target PVB achieves a mode purity of 18.41% and an SNR of 11.76 dB, with no visible parasitic feature. At $f = 27 \mu\text{m}$, the target PVB possesses a mode purity of 23.07% and an SNR of 10.3 dB. In this plane, a Laguerre–Gaussian-like (LGL) background mode appears at the center due to the helical phase distribution of the metasurface. To evaluate the influence of the background mode, the crosstalk is quantified as the ratio of the LGL mode intensity to the target PVB intensity. The LGL background mode accounts for only 2.59% of the total intensity, having a crosstalk ratio of approximately 11.2% relative to the target PVB. Although the LGL background mode is locally bright with a SNR of 24.11 dB, its total energy contribution is an order of magnitude lower than that of the target ring, confirming that the crosstalk does not degrade the target PVB. Furthermore, the ring radius and topological charge remain unaffected and in agreement with the design targets. These results confirm that the two PVBs are brought to image at their respective target planes with negligible crosstalk. Taking together, the intensity and phase distributions confirm the successful

generation of two spatially separated PVBs with an independently prescribed topological charge, ring radius, and focal position. This flexible design enables high-quality spatially multiplexed PVBs with potential applications in multi-channel optical communication and parallel optical manipulation.

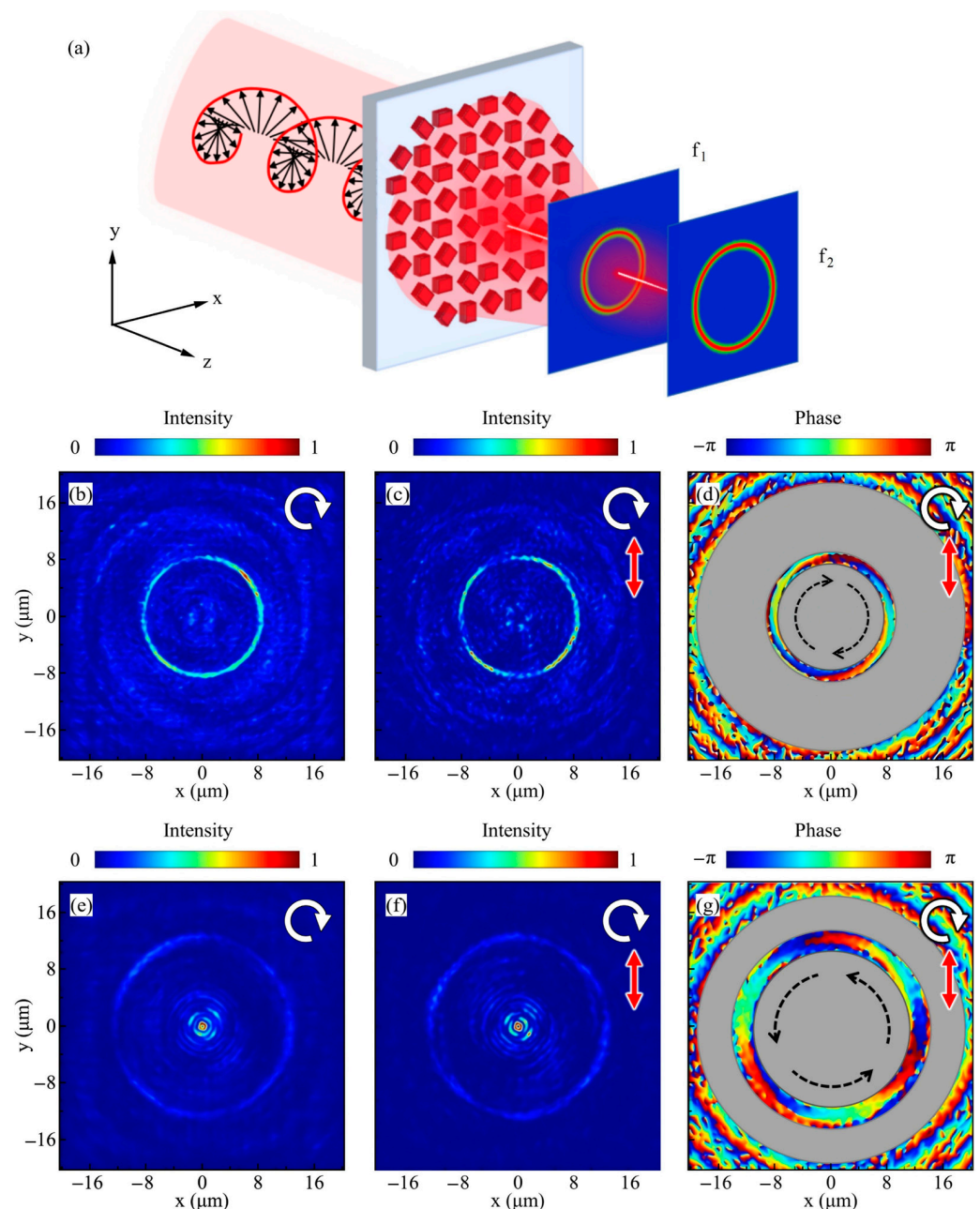


Figure 5. Generation of spatially multiplexed PVBs. (a) Schematic diagram of the dielectric metasurface generating two spatially separated PVBs under RCP light illumination. (b) Total transmitted intensity distribution at the focal plane $f_1 = 13.8 \mu\text{m}$. Corresponding (c) intensity and (d) phase distributions of the transmitted y -component. (e) Total intensity distribution at the focal plane $f_2 = 27 \mu\text{m}$. Corresponding (f) intensity and (g) phase distributions of the transmitted y -component.

5. Conclusions

In summary, we designed and numerically demonstrated a polarization-encoded structured light generator based on a single-layer metasurface consisting of thin silicon films. The optimized rectangular nanopillars achieve a transmittance of approximately 85% and a polarization conversion efficiency of approximately 98% at the operating wave-

length of 632.8 nm, enabling full 2π phase control via the P-B phase principle. By encoding two independent holographic phase distributions corresponding to two orthogonal circular polarization states, the metasurface generates a PVB under RCP light illumination and a CVB under HLP light illumination, achieving on-demand switching between the two structured light modes solely through polarization control. We further extended this design strategy to realize spatially multiplexed PVBs, where the ring radius, topological charge, and focal plane position of each channel can be independently prescribed with negligible crosstalk. Compared with plasmonic metasurfaces, our dielectric design not only eliminates ohmic losses for enhanced transmission efficiency, but also exhibits excellent environmental stability, making it highly compatible with diverse integrated photonic platforms. Since our metasurface is optimized for a single wavelength, its performance falls off considerably at other visible wavelengths, although it does not fail completely. Consequently, further structural optimization is needed to achieve stable broadband operation. In principle, the random interleaving multiplexing can be scaled to more channels. However, as the number of multiplexed channels increases, the effective sampling density per channel decreases and the risk of coherent crosstalk between neighboring channels grows, thereby limiting the per-channel performance. While experimental validation is not included in the present study, the fabrication feasibility is supported by a rigorous tolerance analysis presented in Appendix A, which demonstrates that the design maintains robust performance against typical nanofabrication errors, including dimensional deviations and sidewall tapering. These results indicate that the designed metasurface can be translated into physical devices using existing etching techniques. The demonstrated flexible wavefront control and the ultrathin profile of the thin-film metasurface platform offer a promising route toward compact structured light sources for multi-channel optical communication, highlighting the potential of metasurfaces as multifunctional optical coatings for integrated photonic systems.

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Appendix A Fabrication Tolerance Analysis

To evaluate the robustness of the proposed metasurface to typical nanofabrication errors, a systematic numerical tolerance analysis is performed using FDTD simulations. Since the metasurface performance depends on each nanopillar's local response, the unit-cell analysis offers a reasonable estimate of fabrication robustness. In our analysis, the transmission and polarization conversion efficiencies are monitored while independently sweeping the key structural parameters of the nanopillar around their optimized values. The length and width were each varied by ± 20 nm, which covers the typical patterning accuracy of standard electron-beam lithography. As shown in Figure A1a,b, the transmission efficiency remains above 80% across the full ± 20 nm range for both length and width variations, demonstrating excellent tolerance. The polarization conversion efficiency

shows a directional dependence on the length variation. It remains above 90% with a 20 nm increase, but drops to below 60% with a 20 nm decrease relative to the optimized value. For the width variation, the polarization conversion efficiency is above 70% over the 20 nm range. This asymmetric sensitivity to length variation suggests that a slight positive bias in length during fabrication can maintain high conversion efficiency. The nanopillar height is varied by ± 40 nm around the optimized value, as shown in Figure A1c; both the transmission and polarization conversion efficiencies improve as the height increases and degrade more rapidly as the height decreases. This indicates that fabricating taller nanopillars is preferable when the height deviations are unavoidable.

In order to emulate sidewall tapering, the top length and top width were independently swept to introduce sidewall angles of up to $\pm 8^\circ$, while the height is fixed at the optimized design. The results are presented in Figure A1d,e. In both cases, the transmission efficiency remains above 80% across the full tapering range. The polarization conversion efficiency exhibits a similar asymmetric trend. It decreases with an increasingly negative sidewall angle, dropping to 60% and 80% at -8° for the top length and top width variations, respectively. As the sidewall angle increases in the positive direction, the polarization conversion efficiency initially improves, and reaches a maximum at approximately $+5^\circ$ for the top length variation and $+2^\circ$ for the top width variation before gradually declining. Both cases demonstrate that the transmission efficiency is highly robust, while maintaining a positive or near-vertical sidewall angle is beneficial for achieving optimal polarization conversion performance.

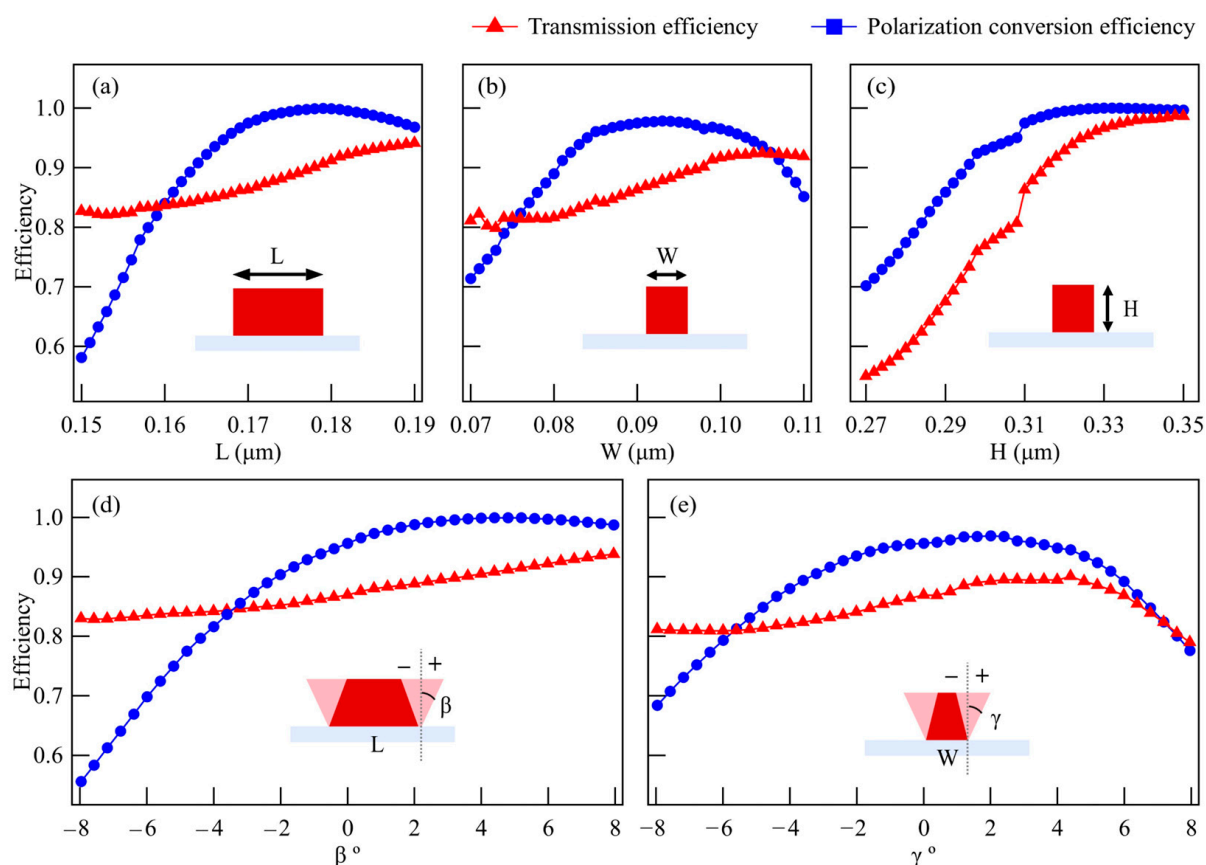


Figure A1. Numerical tolerance analysis. Transmission and polarization conversion efficiencies as functions of nanopillar (a) length, (b) width, and (c) height deviation from the optimized size. The transmission and polarization conversion efficiencies as functions of top (d) length and (e) width variation, emulating sidewall tapering angles up to $\pm 8^\circ$.

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