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Research progress on generating perfect vortex beams based on metasurfaces

Xiujuan Liu^{1,2}, Manna Gu^{3*}, Ying Tian¹, Mingfeng Zheng⁴, Bo Fang⁵, Zhi Hong^{2,3}, Chee Leong Tan⁶ and Xufeng Jing^{2,3*}

This article reviews the latest advances in the generation and control of perfect vector beams using metasurfaces. In recent years, metasurfaces have garnered increasing interest due to their simple fabrication and easy integration. Perfect vortex beams (PVBs), as a type of vector beams, exhibit complex polarization states that require the superposition of multiple phases for their generation. The use of metasurfaces provides a compact platform for the generation of perfect vortex beams and enables more complex vortex beam control tasks, which are quite challenging for traditional optics. This paper begins by introducing the principle of perfect vortex beam generation using metasurfaces, followed by a discussion on the generation of complex perfect vortex beams, including multi-channel and grafted perfect vortex beams. Subsequently, it explores the applications of perfect vortex beams in particle trapping and optical communication. Finally, the paper summarizes the key findings, highlights the limitations of metasurfaces in perfect vortex beam applications, and provides insights into potential future research directions and applications.

Keywords: metasurface; optics devices; vortex beams

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Introduction

Vortices are common physical phenomena in nature, such as those found in typhoons and ocean currents. Similarly, the concept of vortices also exists in the field of optics. Optical vortex (OV) beams are characterized by their helical wavefronts and carry a spatial phase factor of $\exp(il\varphi)$, where l is an integer representing the topological charge, and φ is the azimuthal angle^{1,2}. Consequently, optical vortex beams carry orbital angular momentum (OAM) and have a ring-shaped transverse intensity distribution. Although vortex beams have been widely applied in various optical applications, such as

quantum information processing^{3,4}, optical trapping⁵⁻⁷, and particle manipulation^{8,9}, the orbital angular momentum and the ring-shaped intensity characteristic of traditional vortex beams are influenced by their topological charge (TC), which limits applications that require the spatial superposition of vortex beams with different topological charges¹⁰.

In this paper, the concept of the perfect vortex beam (PVB) has been introduced, which features a constant ring-shaped intensity distribution and a spot diameter independent of the topological charge¹¹. To date, various strategies for generating PVBs have been demonstrated,

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such as using an axicon¹², a spatial light modulator (SLM)¹³, interferometers¹⁴, or digital micromirror devices (DMDs)¹⁵. However, all these traditional methods for generating PVBs require a series of bulky and space-consuming optical components that also need to be accurately aligned, and the physical free-space distances between them cannot be arbitrarily changed, which hinders the miniaturization and versatility of the devices. Moreover, any misalignment or incompatibility between the various optical elements can lead to unwanted aberrations, which degrade the quality of the generated PVB.

Metasurfaces, also known as two-dimensional metamaterials, are ultra-thin artificial engineered materials made of sub-wavelength building blocks^{16–21}. Compared to traditional three-dimensional structures, metasurfaces have the advantages of being more compact, easier to fabricate, and offering more precise control. Due to their ability to manipulate electromagnetic waves (EMWs) for various practical applications, they have attracted extensive research^{21–28}. Metasurfaces can tailor the wavefront of electromagnetic waves by introducing abrupt phase changes through ultra-thin sub-wavelength resonators. Metasurfaces were first proposed by Yu and Capasso²⁸, and subsequent researchers have proposed a multitude of innovative metasurfaces in the microwave²⁹, terahertz³⁰, near-infrared³¹, and visible light ranges³². These metasurfaces can be used to achieve many applications, such as focusing with sub-wavelength planar lenses³³, optical stealth^{34,35}, generating non-diffracting beams³⁶, manipulating phase distributions with orbital angular momentum³⁷, photonic spin Hall ef-

fects³⁸, and performing optical computing with encoded metasurfaces^{39,40}, which have propelled the rapid development of optical technology.

Metasurfaces can precisely control the target continuous phase through subwavelength-scale discrete units, based on the following principles: First, when the unit period (p) is less than half of the working wavelength, the Nyquist sampling theorem can be satisfied to avoid the loss of phase information caused by higher-order diffraction. Second, each subwavelength unit can independently control the amplitude or phase of the incident light through geometric phase design, achieving continuous phase coverage in the range of $0-2\pi$. Finally, by optimizing the unit arrangement (such as gradient metasurface design) or using algorithmic compensation (such as inverse Fourier transform), the discrete phase distribution can approximate the continuous target phase with high precision (error $< 5\%$), thereby reproducing complex wavefronts such as perfect vortex beams on a macroscopic scale^{41–45}.

As shown in Fig. 1, the purpose of writing this review is to introduce the application of metasurfaces in the generation of perfect vortex beams, in order to promote the development of vector beams control by metasurfaces and the application of perfect vortex beams. In the numerous discussions on the manipulation of vector beams by metasurfaces, there are few reviews that focus on perfect vortex beams. For discussions on other types of vector light, readers are referred to some previous reviews^{46–48}. In this review, first, we briefly discuss the principle of generating perfect vortex beams using the

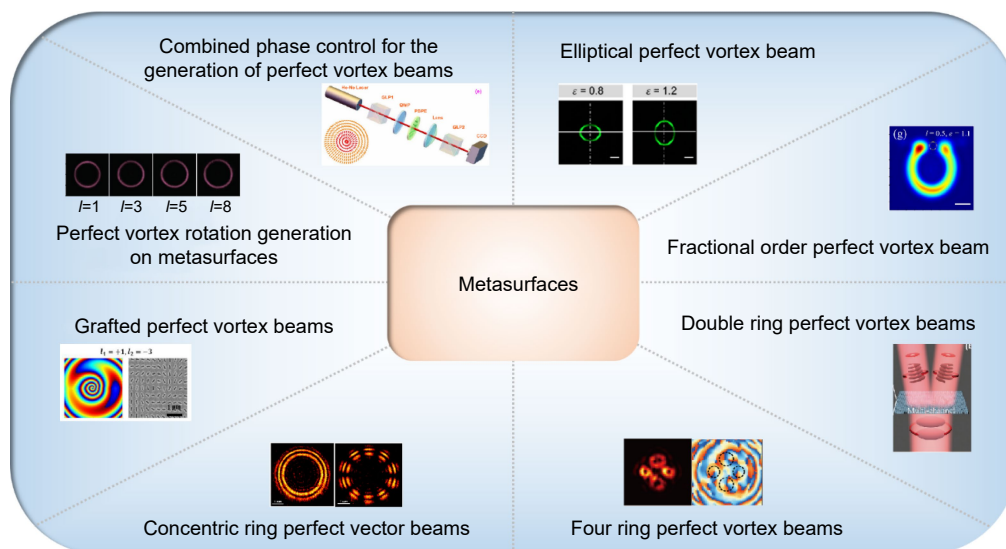


Fig. 1 | Metasurface generation of perfect vortex beams^{49–95}.

Pancharatnam-Berry (PB) phase of metasurfaces. Next, we discuss the research progress of metasurfaces in more complex perfect vortex beams control, such as multi-channel generation of perfect vortex beams and the grafting of perfect vortex beams, which are novel research directions. Then, we provide a brief overview of the applications of perfect vortex beams. Finally, the review summarizes the potential challenges and future research directions of applying metasurfaces to perfect vortex beams.

Generation of perfect vortex beams based on the PB phase

Theoretically, the radial intensity distribution of a PVB is independent of the topological charge and can be generated by Fourier transforming a Bessel beam⁴⁹:

$$E_B(r, z) = J_l(k_r \rho) \exp(im\theta + ik_z z), \quad (1)$$

here, J_l represents the first kind of l -th order Bessel function, $k = \sqrt{k_r^2 + k_z^2} = 2\pi/\lambda$ is the wave vector, λ is the incident wavelength, $r=(\rho, \theta)$ are the polar coordinates within the beam cross-section, and (k_r, k_z) are the radial and longitudinal wave vectors, respectively.

However, in practical applications, the Bessel-Gauss (BG) beam is often used as an alternative to the ideal Bessel beam due to the infinite energy of the ideal Bessel beam. The complete conversion of a Gaussian beam to a PVB involves three key stages of mathematical transformations^{50–52}:

1) The spiral phase plate is utilized to transform a Gaussian beam into a Laguerre-Gauss (LG) beam.

Phase modulation function of the spiral phase plate:

$$\phi_{\text{SPP}}(\theta) = l\theta. \quad (2)$$

Input Gaussian beam:

$$E_{\text{in}}(r) = E_0 \exp\left(-\frac{r^2}{w_0^2}\right), \quad (3)$$

where E_0 is the amplitude and w_0 is the waist radius.

Output LG beam after modulation:

$$E_{\text{LG}}(r, z) \propto \left(\frac{r\sqrt{2}}{w_0}\right)^{|l|} L_p^{|l|}\left(\frac{2r^2}{w_0^2}\right) e^{-r^2/w_0^2} e^{il\theta}, \quad (4)$$

where $L_p^{|l|}$ is the associated Laguerre polynomial, and w_0 is the girdle radius.

2) The axicon is used to transform a LG beam into a BG beam.

Transmission function of the axicon (with cone angle α):

$$t_{\text{axicon}}(r) = \exp(-ik_r r), k_r = k(n-1)\alpha. \quad (5)$$

Generation of an approximate Bessel beam:

$$E_{\text{Bessel}}(r) \propto J_l(k_r r) e^{-r^2/w_0^2}. \quad (6)$$

3) The Fourier lens is used to transform a BG beam into a Partially Vector Bessel-Gauss beam.

The Fourier transform action of the lens:

$$f\{E_{\text{Bessel}}\} \propto \delta(\rho - \rho_0) e^{il\phi}, \quad (7)$$

$$I(\rho, \phi) \propto \text{circ}(\rho/\rho_0) \delta(\phi - l\theta), \quad (8)$$

where the ring radius $\rho_0 = fk_r/k$, and f is the focal length of the lens.

Figure 2(a) illustrates a set of traditional refractive devices used for generating PV beams⁵¹. The vortex plate, which increases in thickness along the azimuthal direction, can induce a phase variation of the beam from 0 to 2π times, converting a regular Gaussian beam (Fig. 2(a-i)) into a high-order LG beam (Fig. 2(a-ii)). Subsequently, an axicon with a conical surface is applied to obtain the corresponding BG mode (Fig. 2(a-iii)). Finally, a plano-convex lens is used to perform the Fourier transformation and generate the PV beam, as shown in Fig. 2(a-iv). Therefore, to generate PV beams, the metasurface must possess the combined phase profiles of a spiral phase plate, an axicon, and a Fourier transformation lens.

In 2017, Liu et al.⁵¹ demonstrated a method for generating perfect vortex beams using the PB phase. By designing planar PB phase units, they replaced all the required phase devices, which is a simpler approach compared to traditional methods for generating perfect vortex beams. Furthermore, as compared to using an axicon to produce a BG beam, designing a planar device to introduce a phase derived from the Bessel function⁵³ is a more straightforward solution. Therefore, the phase distributions corresponding to the vortex plate Φ_V , Bessel transformer Φ_B , and lens Φ_L can be defined as:

$$\Phi_V(x, y) = m \cdot \arctan\left(\frac{y}{x}\right), \quad (9)$$

$$\Phi_B(x, y) = \arg[E_B(r, z)], \quad (10)$$

$$\Phi_L(x, y) = \frac{2\pi}{\lambda} [\sqrt{(x^2 + y^2) + f^2} - f], \quad (11)$$

here, (x, y) are the Cartesian coordinates within the beam's cross-section, m is the topological charge of the desired mode, and $E_B(r, z)$ is the function of the Bessel beam given in Eq. (1). When $l=0$, f is the focal length of the lens. An example of the phase distribution ($m=1$) is shown in the inset of Fig. 2(b).

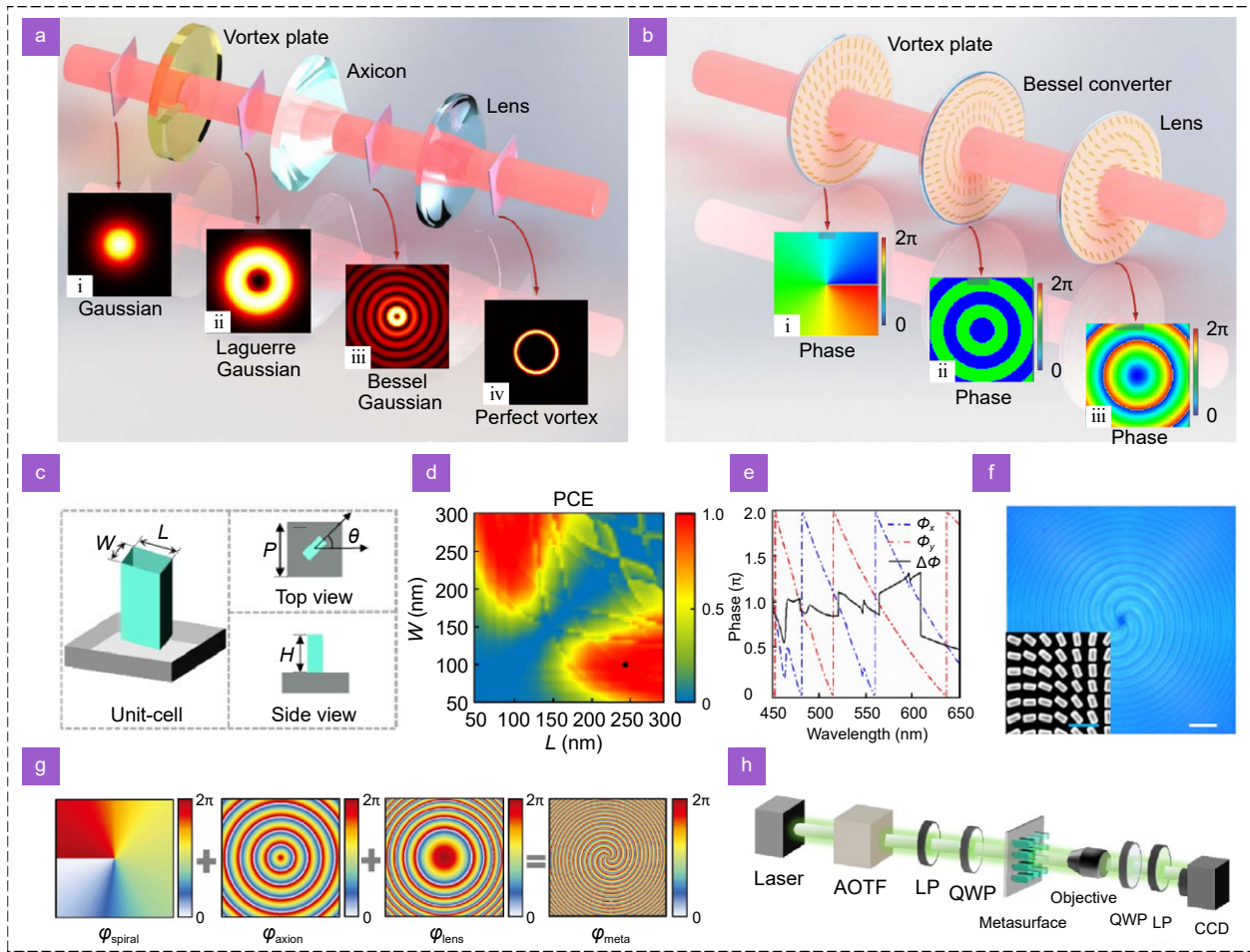


Fig. 2 | (a) A traditional optical system for generating vortex beams based on bulky refractive devices. The combination of a vortex plate and a Bessel light converter transforms a general Gaussian beam into a Bessel-Gaussian light mode. Subsequently, a lens performs a Fourier transformation on the BG beam, yielding a perfect vortex beam. The illustration shows the intensity patterns at each step of this system. (b) A PB phase element system for generating PV beams. The planar vortex plate and Bessel converter work together to produce a higher-order BG mode. This mode is then transformed into the corresponding perfect vortex beam by a Fourier transformation lens. The insets show the phase distribution at each step. (c) Left: A schematic diagram of the rectangular nano-pillar unit structure. Right: A top view and side view of the unit structure. (d) The calculated polarization conversion efficiency as a function of the nano-pillar length and width at a wavelength of 530 nm. The black dots represent the selected structural parameters of the nano-pillar. (e) The calculated phase Φ_x , Φ_y for x and y polarized light and their difference $\Delta\Phi$. (f) An optical microscope image of the metasurface fabricated using nano-pillars as unit structures. Scale bar: 10 μm . The inset at the lower left shows the scanning electron microscope (SEM) image of the metasurface. Scale bar: 500 nm. (g) The principle of superimposing phase contours for the designed metasurface, which includes the three phase contours of the vortex phase plate, axicon, and Fourier transform lens. (h) The optical setup for the generation and analysis of PV beams based on metasurfaces. Figure reproduced with permission from: (a, b) ref.⁵¹, (c–h) ref.⁵⁵, under a Creative Commons Attribution 4.0 International License.

Due to the local adjustability of the response of the PB phase elements by adjusting the orientation of the units, they have been extensively studied in recent years. PB phase units are obtained by rotating anisotropic unit structures. Under circularly polarized incidence, a geometric phase can be acquired, and $\Phi = \pm 2\varphi$ ⁵⁴, where the sign depends on the helicity of the circular polarization, and φ refers to unit rotation angle. The phases for the vortex plate, Bessel transformer, and lens can be derived as⁵³:

$$\varphi_v(x, y) = \frac{m}{2} \cdot \arctan\left(\frac{y}{x}\right), \quad (12)$$

$$\varphi_B(x, y) = \frac{1}{2} \arg[E_B(r, z)], \quad (13)$$

$$\varphi_L(x, y) = \frac{\pi}{\lambda} [\sqrt{(x^2 + y^2) + f^2} - f]. \quad (14)$$

Figure 2(b) illustrates the schematic of using these PB phase elements to generate PV beams. The short lines on each circular substrate indicate the direction of unit rotation angle. Compared to traditional methods, the PB

phase devices reduce the thickness of multiple modules to the thickness of a single metasurface, significantly reducing the total thickness of the device.

Due to the phase superposition capability of metasurfaces, it is possible to utilize the PB phase principle to stack the total phase profiles of a spiral phase plate, an axicon, and a Fourier transform lens within a single metasurface. The use of PB phase elements simplifies the experimental device and significantly reduces the volume of the optical system. Recently, Zhou et al.⁵⁵ utilized the proposed metasurface to achieve the generation of perfect vortex beams. Compared with traditional optical devices, the metasurface PVB generator can greatly simplify optical equipment. Figure 2(c) shows the basic unit that makes up the metasurface, which is rectangular TiO₂ nano-pillars with a height of $H=600$ nm, arranged spatially on a fused silica substrate with a lattice constant $P=350$ nm. This metasurface has a broadband response to visible light. The choice of material, TiO₂, is based on its high refractive index and low loss at visible light frequencies. For incident circularly polarized light, the PB phase is obtained by rotating the anisotropic rectangular nano-pillars acting as half-wave plates to produce a local phase shift, which is derived by the following formula⁵⁴:

$$\varphi_{\text{PB}}(x, y) = 2\theta(x, y). \quad (15)$$

In which, θ is the in-plane orientation angle of the nano-pillar relative to the fast axis. For the generation of PVBs, the required PB phase $\varphi_{\text{PB}}(x, y)$ must be equal to $\varphi_{\text{PV}}(x, y)$, hence the rotation angle $\theta(x, y)$ of each nano-pillar in space can be simply determined as:

$$\theta(x, y) = \varphi_{\text{PV}}(x, y)/2. \quad (16)$$

The polarization conversion efficiency is defined as:

$$\text{PCE} = \frac{|t_{\text{cross}}|^2}{|t_{\text{co}}|^2 + |t_{\text{cross}}|^2} = \frac{T_{\text{cross}}}{T_{\text{co}} + T_{\text{cross}}}. \quad (17)$$

In which⁵⁵,

$$|t_{\text{cross}}|^2 = \frac{1}{4} \left(\sqrt{|t_x|^2} e^{i\varphi_x} - \sqrt{|t_y|^2} e^{i\varphi_y} \right)^2, \quad (18)$$

$$|t_{\text{co}}|^2 = \frac{1}{4} \left(\sqrt{|t_x|^2} e^{i\varphi_x} + \sqrt{|t_y|^2} e^{i\varphi_y} \right)^2, \quad (19)$$

in which t_x 、 t_y 、 φ_x 、 φ_y are the transmission coefficients and phase shifts for linearly polarized light along the x -axis and y -axis, respectively.

To achieve a higher polarization conversion efficiency (PCE), nano-pillars with $W=100$ nm and $L=250$ nm (indicated by the black dot in Fig. 2(d)) were selected. For

these nano-pillar dimensions, it can be observed from Fig. 2(d) that the average PCE is also relatively high across the entire visible light spectrum. Moreover, the nano-pillars can induce a phase delay close to π between the x -polarized and y -polarized components (as shown in Fig. 2(e)), which is a prerequisite for having good half-wave plate functionality over a broad wavelength range. These two characteristics ensure the metasurface's effective broadband response to visible light. Figure 2(f) displays the optical microscope image of the fabricated metasurface PVB generator, with the inset showing the SEM image of the nano-pillars that make up the metasurface. The total size of the metasurface is $90 \mu\text{m} \times 90 \mu\text{m}$, and the focal length of the lens designed for the 530 nm wavelength is $f=150 \mu\text{m}$. The principle of phase superposition can be clearly demonstrated in Fig. 2(g). Figure 2(h) shows a schematic diagram of the experimental setup for the metasurface PVB generator. A supercontinuum laser connected to an acousto-optic tunable filter (AOTF) was used to produce a collimated linearly polarized laser beam. Subsequently, a combination of a linear polarizer and an achromatic quarter-wave plate (QWP) was used to convert the incident light into a circularly polarized beam. A microscope objective with $20\times$ magnification was used to collect the transmitted light containing cross-polarized and co-polarized components through the metasurface. Then, another pair of QWP and a linear polarizer are used to block any undesired zero-order co-polarized background that directly transmits through the metasurface. Finally, a charge-coupled device (CCD) camera was used to capture the entire light field distribution.

The experiment was conducted with visible light of different wavelengths⁵⁵. As shown in Fig. 3(a), the experimentally measured intensity distributions of vortex beams generated by metasurfaces with topological charges ranging from $l=1$ to $l=4$ at free-space wavelengths of 450 nm, 530 nm, and 630 nm are presented. The most fundamental characteristic of perfect vortex beams is that the radius R of the intensity maximum ring is independent of the topological charge number l , and is determined solely by the wave vector k and the beam parameters. In contrast, for conventional vortex beams (such as LG beams), the ring radius increases with increasing l experimentally, the stability of the ring radius (with a variation rate of less than 5%) needs to be verified by measuring the intensity distribution for different values of l . At the same longitudinal propagation

distance, the aperture sizes for different topological charges are essentially the same. By examining the spiral branches on the aperture interference patterns, one can clearly distinguish the light with different topological charges. Figure 3(b) shows the normalized intensity distribution cross-section extracted along the y -direction at

a wavelength of 530 nm, whose consistent cross-sectional intensity distribution has confirmed that the size of the generated vortex beams is insensitive to the topological charge. Moreover, the measured aperture radius was quite close to the theoretically calculated value of 24 μm .

In addition to the standard perfect vortex beams, the

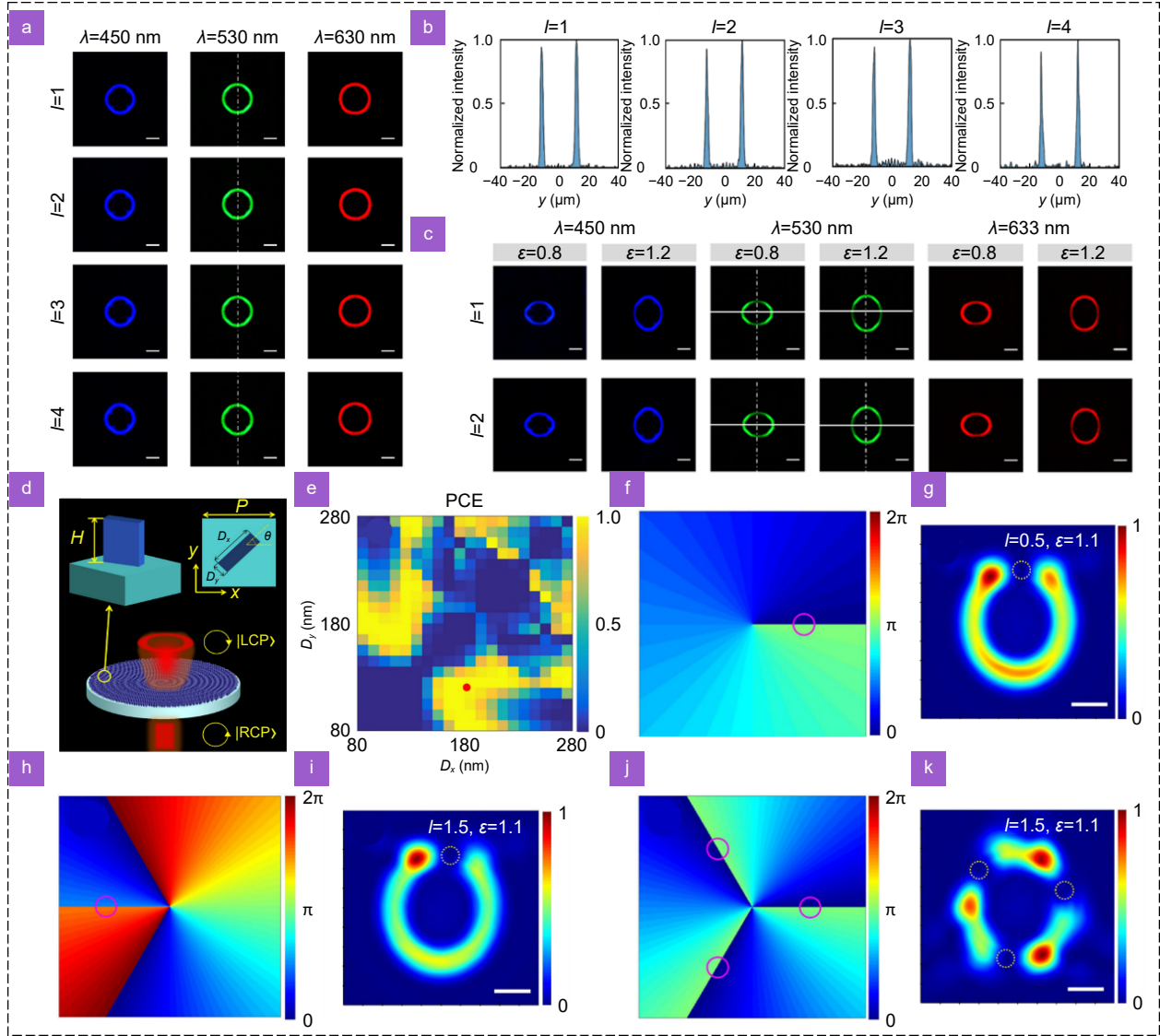


Fig. 3 | (a) The annular intensity distribution of the generated PVB ($\epsilon=1$) measured on the x - y plane with topological charges of $l=1, 2, 3$, and 4 (from top to bottom), wavelengths of 450 nm (blue), 530 nm (green), and 630 nm (red). The propagation distances are $z=180 \mu\text{m}$ (blue), $150 \mu\text{m}$ (green), and $128 \mu\text{m}$ (red), respectively. (b) The normalized cross-sectional intensity distribution of PVBs with topological charges of $1, 2, 3$, and 4 along the vertical direction at a wavelength of 530 nm. (c) Represents the measured ring-shaped intensity distributions on the x - y plane for the elliptical perfect vortex beams (EPVB) ($\epsilon = 0.8$ and $\epsilon = 1.2$) with topological charges of 1 and 2 (from top to bottom) at incident wavelengths of 450 nm, 530 nm, and 630 nm. The propagation distances are $z=180 \mu\text{m}$ (blue), $150 \mu\text{m}$ (green), and $128 \mu\text{m}$ (red). Solid lines indicate the horizontal direction, while dashed lines indicate the vertical direction. Scale bar: $10 \mu\text{m}$. (d) Schematic diagram of the designed metasurface and unit. (e) Simulated relationship between PCE and the nano-pillar geometric parameters D_x and D_y when illuminated with 780 nm near-infrared. The red dot represents the selected size of the unit cell. (f, h, j) The phase arrangement of the metasurface designed to generate elliptical light intensities with topological charges of $0.5, 1.5$, and 1.5 , respectively. (g, i, k) Simulated results of elliptical perfect vortex beams with different fractional topological charges produced by the metasurfaces corresponding to (f, h, j). Figure reproduced with permission from: (a–c) ref.⁵⁵, under a Creative Commons Attribution 4.0 International License; (d–k) ref.⁶⁸, AIP Publishing.

asymmetry and multi-mode of vortex beams are of significant importance in many advanced fields, including the formation of optical traps⁵⁶, optical microfluidic sorting⁵⁷, manipulation and acceleration of micro-particles^{58,59}, etc. The gradient force of the vortex beam can drive the movement of particles. For asymmetric vortex beams, such as EPVBs⁶¹, the direction of the gradient force is closely related to the eccentricity of the ellipse^{60,61}. Elliptical perfect vortex beams can also be generated by changing the metasurface parameters. Equation (9) and Eq. (12) can be rewritten as Eq. (20) and Eq. (21)⁶², respectively:

$$\phi_v(x, y) = m \cdot \arctan\left(\frac{\varepsilon y}{x}\right), \quad (20)$$

$$\phi_v(x, y) = \frac{m}{2} \cdot \arctan\left(\frac{\varepsilon y}{x}\right), \quad (21)$$

in which ε represents the ellipticity. When ε is equal to 1, the generated vortex beams are a standard circular ring. When ε is not equal to 1, elliptical vortex beams can be produced. Figure 3(c) displays images of elliptical perfect vortices with $\varepsilon = 0.8$ and $\varepsilon = 1.2$. When ε is less than 1, the horizontal radius of the ellipse is greater than the vertical radius, and when ε is greater than 1, the horizontal radius is less than the vertical radius. This indicates that metasurfaces can not only generate vortex beams with "perfect" characteristics, but also independently control their shape and size, which further enriches the design flexibility of vortex beams produced using metasurfaces.

Additionally, the generation of fractional-order perfect vortex beams is a current hot topic in research. Their unique characteristic of having a fractional topological charge rather than an integer topological charge results in distinctive low-intensity gaps in their intensity distributions^{63,64}, which has attracted increasing attention from researchers. In the field of optical manipulation, their unique properties can be used for novel applications such as cell sorting and precise control of cell orientation^{65,66}, and they can also expand the communication capacity in optical communication systems⁶⁷. In 2022, Chen et al.⁶⁸ generated fractional-order perfect vortex beams using a dielectric metasurface in the 730–880 nm wavelength range, marking a new breakthrough in the study of vector beams manipulation with metasurfaces. Researchers designed and simulated the performance of an all-dielectric silicon metasurface and its building blocks. A high-performance metasurface based on geometric phase can be obtained by using the half

wave plate nanopillar shown in Fig. 3(d), which exhibited broadband and high PCE characteristics in the near-infrared range. PVB with different fractional topological charges can be generated by designing different metasurfaces. Figure 3(e) shows the simulated relationship between PCE and the geometric parameters D_x and D_y of the nano-pillar at 780 nm near-infrared incidence, using a finite-difference time-domain method based on periodic boundary conditions. According to the simulation results, D_x and D_y could be set to 186 nm and 122 nm, respectively, to achieve the highest PCE (indicated by the red dot in Fig. 3(e)). Figure 3(f) and 3(h) illustrate the fractional vortex beams with topological charges of $l = 0.5$ and $l = 1.5$, respectively, with an ellipticity of $\varepsilon = 1.1$. The resulting ring patterns are shown in Fig. 3(g) and 3(i), where it can be seen that the rings form low-intensity gaps at the phase discontinuities. Therefore, by rearranging the phase distribution, more phase discontinuities could be produced, resulting in more low-intensity gaps on the light intensity ring. Figure 3(j) shows the fractional-order perfect vortex beams with a topological charge of $l = 1.5$ formed using a $0-\pi$ phase range, creating three phase discontinuities and ultimately forming three low-intensity gaps on the light intensity ring, with the generation results shown in Fig. 3(k). The application of metasurfaces in fractional order vortex beams has provided more flexibility in their manipulation, offering more directions for the generation of vortex beams.

Combined phase control for the generation of perfect vortex beams

Currently, the methods for generating ideal vortex beams can mainly be divided into two categories: one is the PB phase method mentioned earlier⁶⁹. The other is the dynamic phase method, which is typically produced through a lens-spatial light modulator (SLM) combination or a combination of a spiral phase plate, an axicon, and a lens^{70–72}. Pure dynamic phase devices or PB phase devices can effectively generate ideal vortex beams, but there are certain limitations in generating ideal vector beams. Generating ideal vector beams based on pure dynamic phase devices requires the modification of interferometers, which will greatly increase the complexity of the system and bring inconvenience to the construction of the optical system. Pure PB phase device is difficult to generate ideal vector beams, as the PB phase is related to spin, and the wavefronts of the two circular polarization components are conjugate, making it challenging to

produce ideal vector beams with pure PB phase devices. Therefore, some researchers have combined the two methods⁷² to effectively avoid these shortcomings.

In 2019, Ke et al.⁷⁴ successfully generated perfect vortex beams using a combined modulation method. They achieved the generation of perfect vortex beams by combining PB phase modulation with dynamic phase modulation. Specifically, when left-handed or right-handed circularly polarized Gaussian light was incident on a metasurface based on PB phase, the PB phase modulation not only maintained the handedness of the circularly polarized light but also transformed the beam into a higher-order Bessel–Gaussian beam. Subsequently, a lens was used to form the perfect vortex beams at the focal

point. The researchers illustrated the principle of this process with diagrams. Figure 4(a) and 4(b) clearly show the schematic diagrams of generating perfect vortex beams using combined modulation. Figure 4(c) and 4(d) present the phase carried by the PB phase element and the dynamic phase modulation element, as well as the combined phase image, with Fig. 4(c) corresponding to the incidence of left-handed circularly polarized light and Fig. 4(d) corresponding to the incidence of right-handed circularly polarized light.

In terms of experimental design, as shown in Fig. 4(e), a laser was used as the light source. After passing through a laser polarizing prism and a quarter-wave plate, the light was converted into polarized light, and

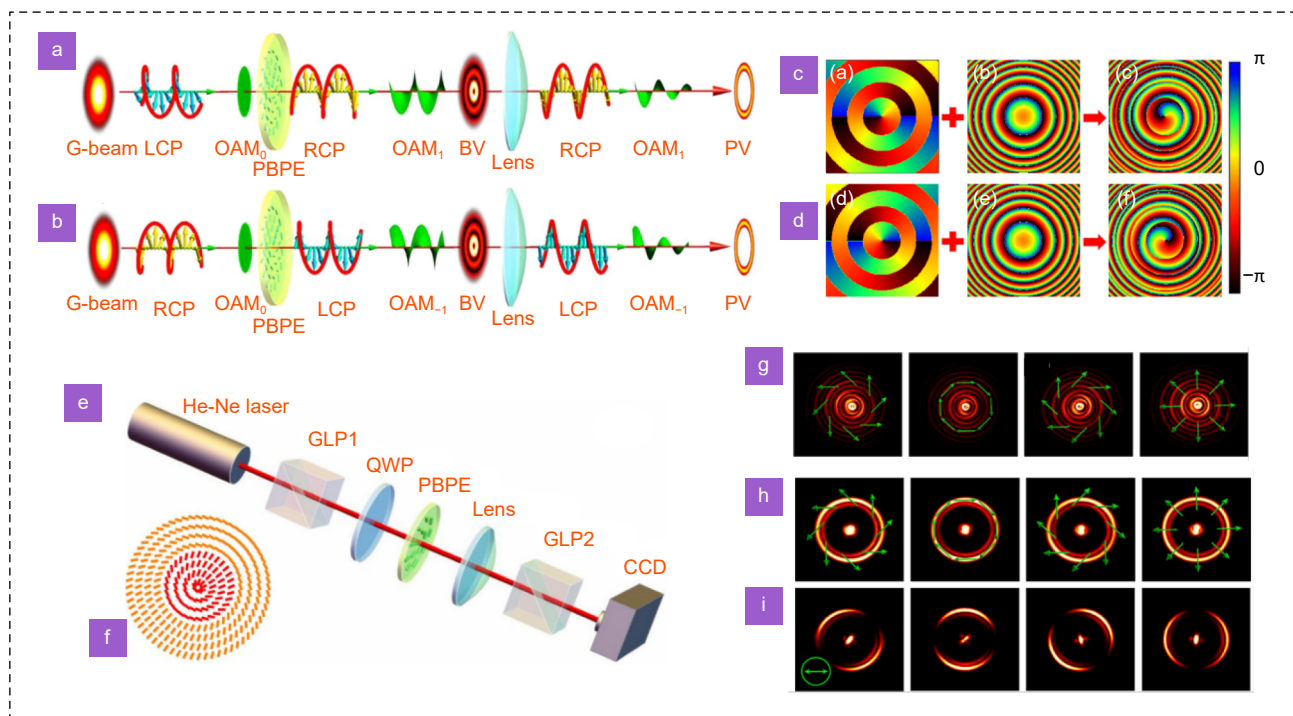


Fig. 4 | (a, b) Illustrate the schematic for generating perfect vortex beams through the combined modulation of dynamic and geometric phase. (a, b) refer to left-handed circular polarization (LCP) and right-handed circular polarization (RCP) incident light, respectively. The PB phase element flips the circular polarization and converts the incident Gaussian beam with a planar wavefront into a high-order BG mode. The following lens performs a Fourier transformation of the high-order BG beam, producing a perfect vortex beam at the focal plane. The sign of the topological charge of the generated perfect vortex beam is controlled by the chirality of the circularly polarized incident beam. G-beam, Gaussian beam; LCP, left-handed circular polarization; RCP, right-handed circular polarization; PBPE, PB phase metasurface; OAM, orbital angular momentum; BV, high-order Bessel-Gaussian beam; PV, perfect vortex beam. (c, d) Represent the phase distribution created by the sequence from left to right of the PBPE, lens, and the combination of PBPE (geometric phase) and lens (dynamic phase). (c, d) correspond to incident beams with left-handed and right-handed circular polarization, respectively. (e) The experimental setup for generating and demonstrating perfect vector beams. GLP, Glan laser polarizing prism; QWP, quarter-wave plate; PBPE, PB phase element; CCD, charge-coupled device. (f) The spatial distribution of the designed beam's axis, with short lines indicating the local direction of the beam's axis. (g) The intensity distribution of the generated Bessel vector beam recorded by the CCD under different polarizer orientations, with green arrows indicating the schematic of the polarization distribution. (h, i) The intensity distribution of the generated perfect vector beam under different polarizer orientations recorded by the CCD, with green arrows indicating the schematic of the polarization distribution. The double-headed arrows within the circles represent the orientation direction of the polarizer's axis. Figure reproduced with permission from ref.⁷⁴, Elsevier.

then perfect vortex beams were generated through geometric phase and dynamic phase modulation. A subsequent polarizing prism was used to analyze the generated perfect vortex beams, and the beam pattern was finally captured using a CCD camera. Figure 4(f) shows the pattern of the PB phase device, which was formed by continuously etching nano-grooves in a fused quartz substrate using femtosecond laser technology. Figure 4(g) presents the pattern of the vector Bessel beam obtained after geometric phase modulation, where the characteristics of the vector Bessel beam can be clearly observed. Figure 4(h) shows the intensity pattern of the perfect vortex beams formed by the vector Bessel beam after dynamic modulation, which also includes the additional phase of the Fourier transform lens.

However, some areas for improvement were identified during the experiment. The center of the ring did not exhibit a perfect singularity state. This may be due to the fact that the metasurface was not finely fabricated and did not meet the standard of a perfect half-wave plate. Therefore, when the beam passed through the PB phase element, a small number of photons did not receive additional PB phase modulation. These unmodulated photons were focused by the subsequent lens, forming a focal spot in the center of the perfect vortex beam. To distinguish the generated beam, a polarizing prism was placed in front of the receiver. The final beam pattern is shown in Fig. 4(i), where the intensity pattern shows two lobes and rotates with the rotation of the polarizer.

Simultaneous generation of multi-ring perfect vortex beams

Four ring perfect vortex beams

Previous studies have largely focused on the generation of single perfect vortices, which limits applications that require the simultaneous use of multiple vortex beams. The generation of multi-channel perfect vortex beams has become a main research direction, which is applicable to multi-path particle capture and optical multi-channel communication, among other studies^{75–78}. Generating multi-channel vortex beams using metasurfaces is more streamlined than traditional methods. More importantly, multifunctional metasurfaces can replace several bulky components with a thin planar layer, making them an ideal choice for miniaturization and integrated systems. Multi-channel vortex beam generators based on PB phase metasurfaces have been reported in the visible

light domain. As early as 2018, Zhang et al. proposed an array of gold nanholes that used only the PB phase principle to generate perfect vortex beams of different wavelengths and achieved multi-channel vortex beams generation⁷⁹. As shown in Fig. 5(a), the structure consists of rectangular holes on a square gold plate. Although the gold nanholes were simply constructed, they could enhance the spatial resolution of the metasurface and achieve finer phase modulation precision. The overall size of the metasurface was of $50\ \mu\text{m} \times 50\ \mu\text{m}$. For the PB phase, the rotation angle of the rectangular holes is closely related to the phase. Figure 5(b) shows the phase curves at different rotation angles, with the phase curves being uniformly and smoothly changing within the 600–1000 nm wavelength range, exhibiting a very high tolerance. As shown in Fig. 5(c), the array was arranged by rotating the rectangular holes, aligning the phase distribution of the entire array with the design requirements. Figure 5(d) shows the simulated and experimented the longitudinal intensity distribution of the perfect vortex beam at 633 nm. It could be seen that the beam diffuses outward and forms a perfect vortex ring at a location greater than $150\ \mu\text{m}$. For the ring greater than $150\ \mu\text{m}$, the ring thickness is the same, and the ring radius increased with increasing distance. Figure 5(e) shows the interference pattern at $z = 200\ \mu\text{m}$. Under the same conditions, the ring radius of the light intensity for beams with different topological charges was essentially consistent. The topological charge number could be identified by observing the interference fringes of the pattern. Finally, for the multi-channel generation of perfect vortex beams, the complex amplitudes of different single vortex beams were superimposed, and then the sum of the complex functions was calculated to determine the phase contour for generating the beam array. As shown in Fig. 5(f), different phase arrangements were designed for different focal lengths, and four rings with consistent size but different topological charges could be observed simultaneously on the same focal plane.

In the field of visible light, vortex beams play a crucial role in mode division multiplexing (MDM), quantum information processing, and the detection of spinning objects. For terahertz waves, vortex beams are essential for future research in magnetism, plasma physics, and quantum physics. In the early years, the development of multi-channel perfect vortex beams in the terahertz band was slow due to differences in material response and experimental characterization. With the rising interest in

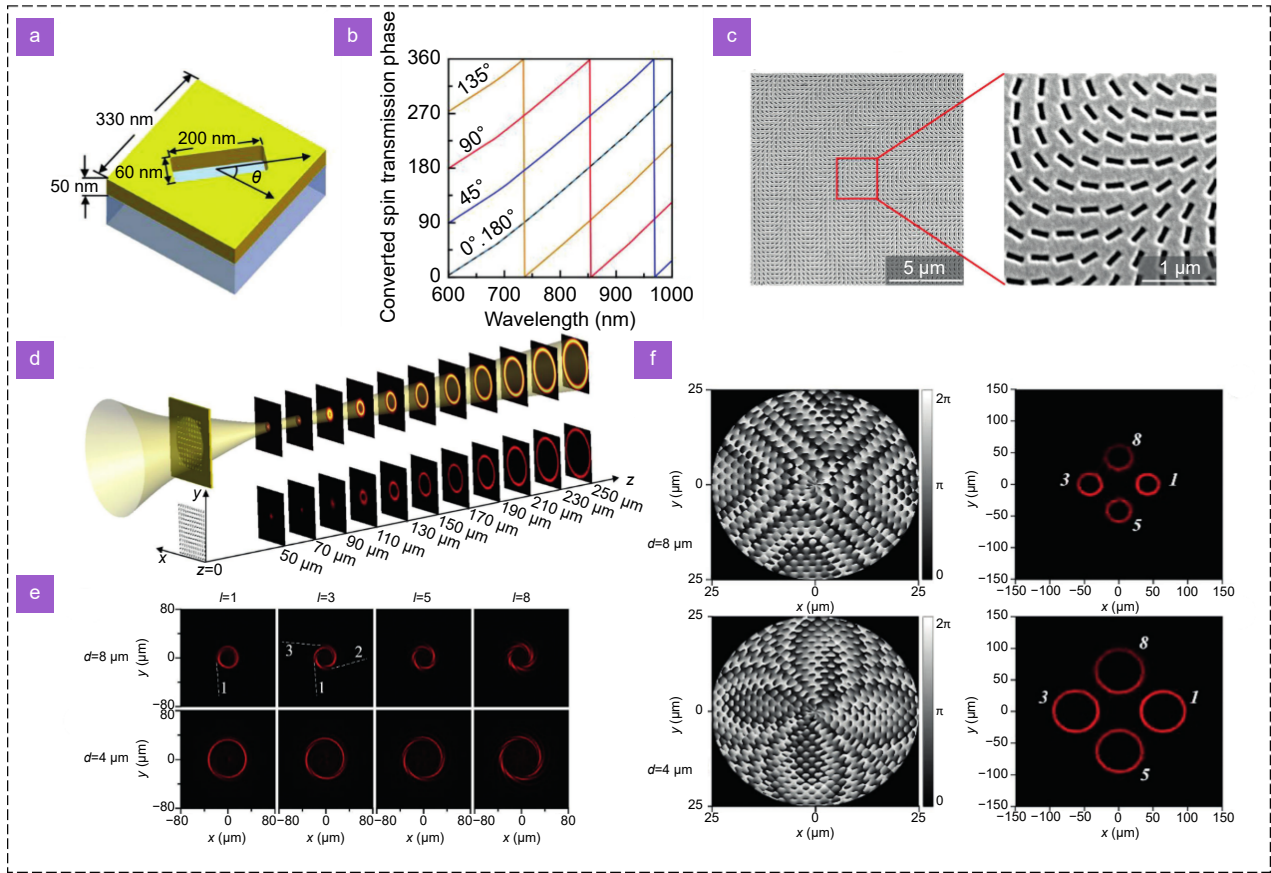


Fig. 5 | (a) Schematic diagram of the unit design of the rectangular hole antenna with a rotation angle of θ . (b) Transmission phase shift spectrum of the unit cell at rotation angles of 0° , 45° , 90° , 135° , and 180° . (c) SEM image of the fabricated metasurface sample. (d) Simulated and measured light intensity distribution of the focused 3D PV beam. (e) Interference measurement patterns captured at a distance of $z=200 \mu\text{m}$ from the transmission plane at a wavelength of 633 nm . From left to right, the topological charges are $l = 1, 3, 5$, and 8 , with axicon periods of $d=8 \mu\text{m}$ and $d=4 \mu\text{m}$. (f) Phase distribution for the generation of four PV beam arrays with $d=8 \mu\text{m}$ and $4 \mu\text{m}$ (top left and bottom left); Intensity distribution of the PV beam array generated at a propagation distance of $z=200 \mu\text{m}$ (top right and bottom right). Figure reproduced with permission from ref.⁷⁹, John Wiley and Sons.

the terahertz band, more researchers have begun to delve deeper into its exploration^{80–82}. The integration of multi-channel metasurfaces with dynamic systems can further enhance the flexibility of terahertz devices. In 2022, Liu et al.⁸³ proposed a metasurface capable of achieving multi-channel quasi-perfect vortex beams (Q-PVB) in the terahertz band. The introduced concept of Q-PVB has a smaller divergence angle and finer, more concentrated ring intensity compared to PVB, which can better serve OAM multiplexing in the terahertz band. The phase profile used to generate Q-PVB is based on the PB phase, defined by the following formula⁸³:

$$\phi_{\text{quasi-perfect}} = \phi_{\text{vortex}}(x, y) + \phi_{\text{negative axicon}}(x, y) + \phi_{\text{lens}}(x, y), \quad (22)$$

$$\phi_{\text{vortex}}(x, y) = l \arctan(y/x), \quad (23)$$

$$\phi_{\text{lens}} = 2\pi(\sqrt{f^2 + x^2 + y^2} - f)/\lambda, \quad (24)$$

$$\phi_{\text{negative axicon}} = -2\pi\sqrt{x^2 + y^2}/D. \quad (25)$$

In which, x and y are spatial coordinates, $\phi_{\text{vortex}}(x, y)$ is the phase distribution for the generation of the vortex beam by the spiral phase plate. ϕ_{lens} is the phase distribution of the focusing lens with focal length f , and λ denotes the wavelength. $\phi_{\text{negative axicon}}$ is the phase distribution of the negative axicon, where D represents its period.

To achieve the multi-channel generation of Q-PVBs, the metasurface was composed of multiple phase profiles with specific functions superimposed onto an array of staggered shared aperture units. The continuous phase distribution was transferred to a phase grid through phase discretization, with the interval between adjacent grids being a sub-wavelength period. Figure 6(a) illustrates the schematic for generating dual-channel PVBs,

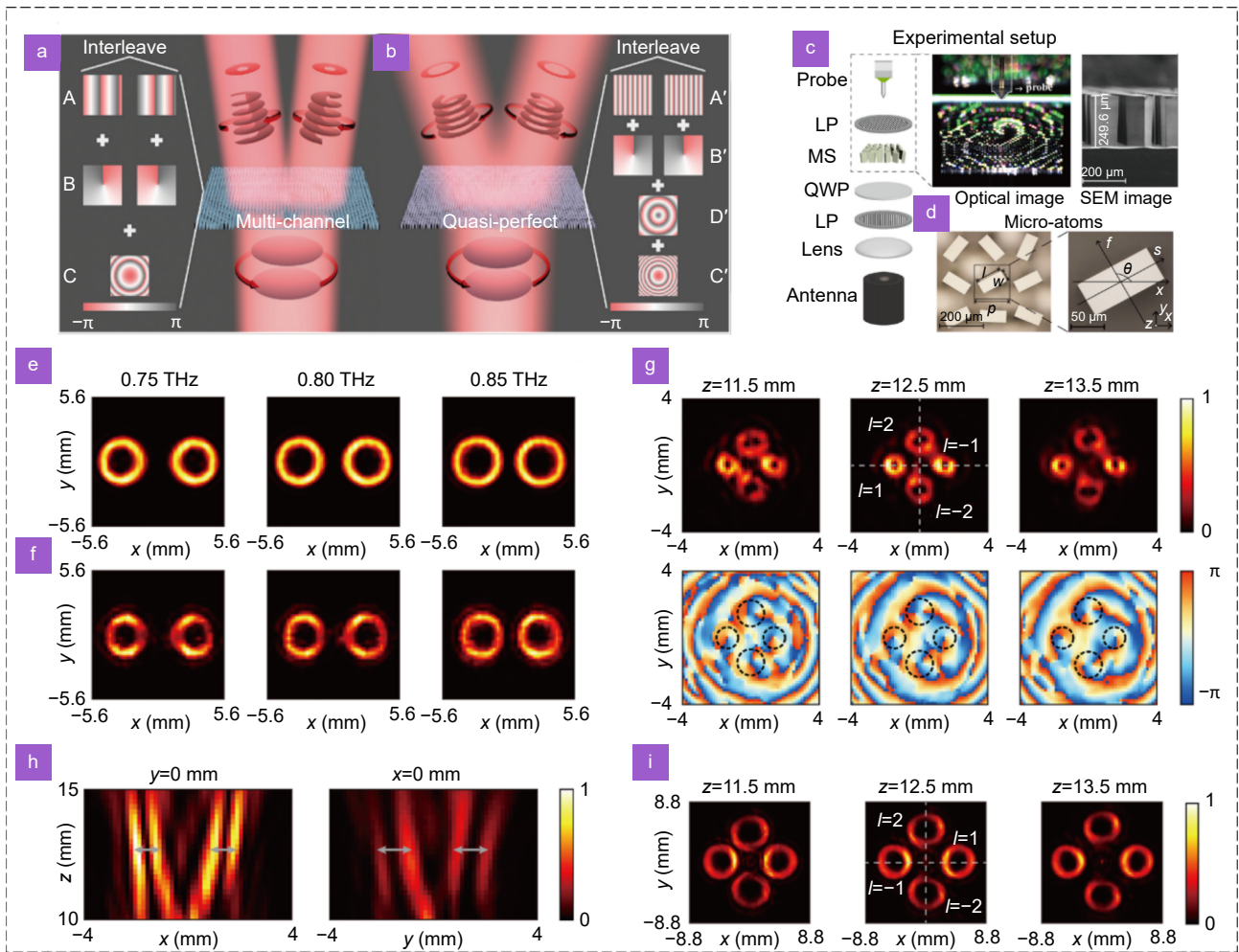


Fig. 6 | (a, b) Multi-channel and quasi-perfect vortex beams based on all-dielectric synthetic metasurfaces⁸³. The phase distributions of metasurfaces A (A'), B (B'), and C (C') correspond to beam deflection, OAM mode conversion, and beam focusing (from top to bottom). The inset in the figure shows metasurface D' designed to replace the negative axicon. Red arrows represent left-handed circular polarization (counterclockwise) and right-handed circular polarization (clockwise). Circles and helical planes represent the planar and helical phases of the terahertz wave. (c) Left: Schematic of the experimental setup. LP, linear polarizer; MS, metasurface; QWP, quarter-wave plate. Insets: The left inset shows the optical image of the fabricated metasurface sample and the terahertz probe, and the right inset shows the SEM image of the fabricated metasurface. (d) Partially enlarged optical image of the fabricated metasurface sample. p : unit cell period; l/w : length/width of the pillar; f/s : fast/slow axis; θ : rotation angle. (e) Calculated and (f) measured intensity distributions of focused Q-PVBs for topological charges $l=1$ and $l=-1$ at different frequencies. (g, h) Generation of four-channel focused vortex beams with different topological charges ($l=1, -1, 2$, and -2). Electric field intensity and phase distribution of the vortex beams generated in three different x - y planes. Electric field intensity at the $y=0$ mm and $x=0$ mm planes. (i) Electric field intensity distribution of four-channel Q-PVBs with topological charges $l=1, -1, 2$, and -2 at 0.75 THz. The x - y planes are at distances of $z=11.5$ mm, 12.5 mm, and 13.5 mm, respectively. Figure reproduced with permission from ref.⁸³, under a Creative Commons Attribution 4.0 International License.

while Fig. 6(b) shows the schematic for the dual-channel generation of Q-PVBs. Figure 6(c) presents the fabrication steps of the metasurface, where a metasurface sample with a unit period $p = 3.5$ mm was manufactured using lithography and deep reactive ion etching, as shown in Fig. 6(d). Figure 6(e, f) demonstrate the generation of dual-channel perfect vortex beams, with the generated ring's topological charges being $l = 1$ and $l = -1$. The po-

sition of the metasurface was set at $z = 0$, and incident waves of 0.75 THz and 0.80 THz were used. Figure 6(e) is the simulated electric field intensity distribution and phase distribution at the focal plane $z = 9$ mm. Figure 6(f) represents the experimentally measured electric field intensity distribution and phase distribution of the vortex beam at the focal plane $z = 9$ mm. It could be seen that the experimental results match the theoretical

results very well, indicating that the metasurface had a broadband characteristic. The authors further demonstrated the experimental results of multi-channel focused vortex beams and multi-channel quasi-perfect vortexes, as shown in Fig. 6(g), which from left to right represent the electric field intensity and phase distribution of the multi-channel vortex beams measured at propagation distances of $z = 11.5$ mm, 12.5 mm, and 13.5 mm, respectively. It could be seen that the multi-channel focused vortex beams at different distances can be well generated, and the conversion efficiency can reach up to 25%. Figure 6(h) shows the propagation paths of the focused vortex beams in the x - z plane and y - z plane. Similar to the principle shown in Fig. 6(a), each beam underwent a certain degree of deflection in its propagation, thus forming multiple vortex beams on the focal plane. Figure 6(i) is a schematic diagram of the generated multi-channel quasi-perfect vortex beams, where the four generated rings had almost the same size, providing ideas for the realization of multiplexing and multi-channel information transmission. Q-PVBs are of great significance for the study of vortex beams with high topological charges and controllable beam divergence, and the use of metasurface structures provides a highly integrated and compact platform, which will greatly promote the application of OAM in next-generation communications, surface plasmon excitation, and terahertz imaging.

Concentric ring perfect vector beams

While the study of perfect vortex beams with multiple non-circular rings is gaining popularity, research is also underway on perfect vortexes with multiple concentric rings. Although a single perfect vortex has played a role in advancing particle capture, there are still challenges in manipulating particles with low refractive indices. In 2023, the research by Andrea Vogliardi et al.⁸⁴ on double-ring perfect vortex beams offered a potential solution to the challenge of manipulating particles with different refractive indices. In their study, two bright rings were capable of capturing and rotating particles that have a high refractive index (RI), while particles with a low RI could be confined within the dark region situated between the two bright rings. Figure 7(a) shows the metasurface unit designed according to the PB phase requirements. Units A and B had common rectangular and elliptical columnar structures; Units C and D consisted of two rectangles, with the rectangular base be inscribed within a concentric circle with a radius of 250 nm, and

the center-to-center distance between the two rectangles was 300 nm. Figure 7(b) represents the available unit parameters, and the phase and transmission coefficients of these 13 units are given in Fig. 7(c), which were excellent half-wave plate structures both in terms of phase and transmission coefficients. The metasurface material used was silicon with a diameter of 600 μm , and Fig. 7(d) shows the SEM image of the manufactured silicon metasurface. Firstly, perfect vortex beams could be generated by controlling the Laguerre-Gaussian beams, which could produce a double-ring pattern with the same topological charge. Secondly, linearly polarized light could be considered as the vectorial sum of left-handed and right-handed circularly polarized lights. To achieve a vector beam when linearly polarized light was incident on a metasurface, topological charges with opposite values should be selected. Consequently, researchers chose perfect vortex beams with topological charges of $l = +5$ and $l = -5$. Figure 7(e) presents a simulated phase arrangement image for the PB phase control. Figure 7(f) displays the intensity pattern of the outgoing light obtained with vertically polarized light as the incident light. The image was a filtered light intensity image, and it was evident that the ring is evenly divided into 10 petals, consistent with the simulated results in Fig. 7(h). Figure 7(g) illustrates the radial distribution of the measured intensity pattern, confirming that the intensities of the two rings were nearly equal and that there was a dark region. This method can generate a double-ring pattern with a fixed dark area, and the generated double-ring structure has the same topological charge.

To more flexibly control the double-ring perfect vortex beams, the researchers proposed a new method that can independently adjust the size of the dark ring between the two rings and also control the mode of the two rings. Figures 7(i) and 6(j) show the metasurface phase distributions required for these two types of controls. Figure 7(k) displays the results of the experiment using the metasurface with linearly polarized light as the input. It was easy to observe that the light intensity distribution of the two rings was uniform and well separated, and they had different vector orders, meaning they had different topological charges. The study of double-ring perfect vortex beams can further expand the application of structured beams in OAM multiplexing for high-capacity and interference-resistant free-space communication^{85,86}, super-resolution imaging technology⁸⁷, and advanced coherent sources⁸⁸.

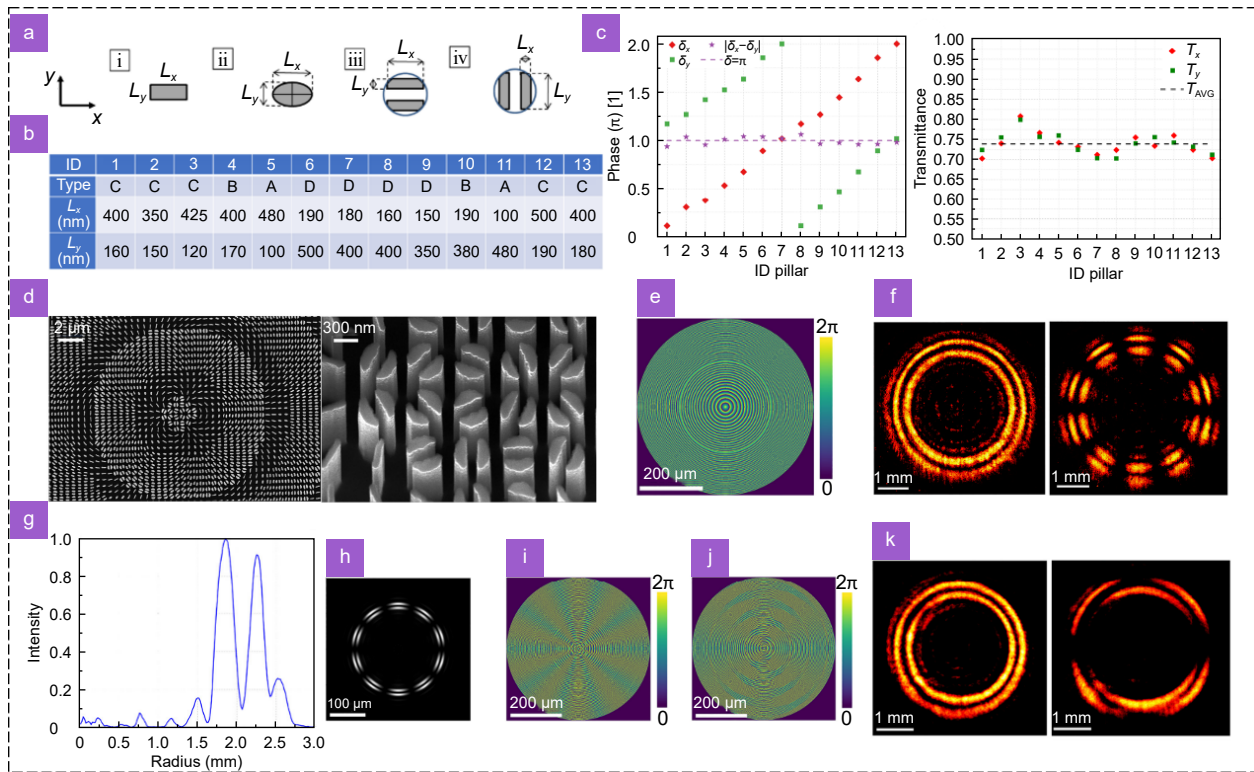


Fig. 7 | (a) Structural diagrams of different types of nano-pillars operating at 1310 nm. Independent rectangular and elliptical pillars (i, ii) are more common, while (iii, iv) shows double-pillar types, with a rectangular base inscribed within a concentric circle with a radius of 250 nm, and the center-to-center distance between the two pillars is 300 nm. (b) The nano-pillar library with all types and all parameters for different types. (c) The left graph shows the phase delay for y - and x - polarized light, and the right graph shows the transmittance for y - and x - polarized light. (d) The left image is a top-view SEM image of the fabricated sample, and the right image shows the unit structure of the sample's lens center area, where the different cross-sections and rotations of the nano-pillars are evident. (e) The dynamic phase diagram δx for simulating the generation of a double-ring perfect vector beam (DR-PVB) using high-order LG beam technology. (f) The optical properties of the designed sample in (e). The left image shows the DR-PVB generated by a metasurface designed using the high-order LG method and illuminated with vertically polarized light. The right image shows the corresponding petal-like structures measured using a linear polarizer as an analyzer, and (g) is the radial contour. (h) Simulation case, verifying the accuracy of the experiment. (i) The dynamic phase diagram δx for simulating the generation of a double-ring perfect vector beam with the same vector order, and (j) a double-ring perfect vector beam with different vector order rings using the balanced biaxial prism method. (k) The optical properties of the designed sample in (j). The left image shows the DR-PVB generated by metasurface designed using the biaxial prism method and illuminated with vertically polarized light. The right image shows the corresponding petal-like structures measured using a linear polarizer as an analyzer. Figure reproduced with permission from ref.⁸⁴, under a Creative Commons Attribution 4.0 International License.

Generation of perfectly grafted vortex beams

Ideal optical vortices exhibit a constant intensity distribution and ring radius, but this uniformity is not suitable for applications that require diverse OAM distributions, such as the capture and manipulation of multiple particles. Therefore, non-canonical optical vortices have been proposed to address these challenges. Examples include helical OAM distributions⁸⁹, non-uniform hollow circular OAM distributions⁹⁰, and structured OAM distributions⁹¹. However, these OAM distributions strongly depend on strength and cannot achieve individual OAM

modulation.

In 2019, researchers introduced the grafted optical vortex (GOV), which has an OAM distribution that is easy to modulate and maintains a constant intensity⁹². The grafted vortex beams are produced by grafting the helical phases of two or more optical vortex beams, and the grafting principle is shown in Fig. 8(a). In 2020, researchers achieved grafted vortices by performing a Fourier transformation on Bessel-Gaussian beams using an axicon mirror⁹³. To achieve flexible control, the transmission function of the axicon amplitude was applied to a spatial light modulator (SLM). However, the generation

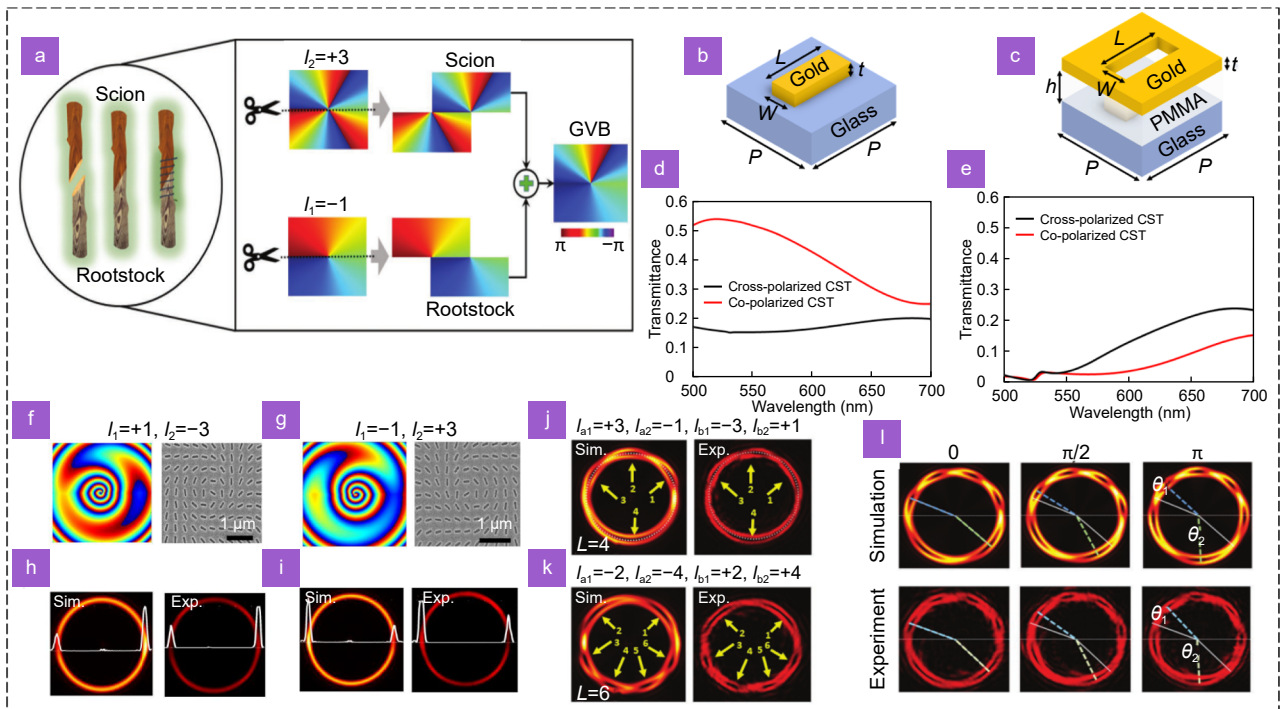


Fig. 8 | (a) A schematic diagram comparing the generation of GVB with plant grafting. (b) Single-layer unit structure, where $W=80$ nm, $L=200$ nm, $t=40$ nm, and $P=300$ nm represent the width, length, thickness, and periodicity of the gold unit cell, respectively. (c) Double-layer unit structure with a PMMA thickness of $h=100$ nm. (d, e) The transmission spectra for the single-layer and double-layer metasurfaces, respectively. The red solid line represents the co-polarized component, while the black curve represents the cross-polarized part. (f, g) Show the calculated phase cross-section of the grafted vortex (left) and the SEM image of the fabricated sample (right). (h, i) Simulated (left) and measured (right) intensity patterns. (j) Simulated and experimental intensity distributions for grafted vortex beams with $l_{a1}=+3$, $l_{a2}=-1$, and $l_{b1}=-3$, $l_{b2}=+1$. (k) Simulated and experimental intensity distributions for grafted vortex beams with $l_{a1}=-2$, $l_{a2}=-4$, and $l_{b1}=+2$, $l_{b2}=+4$. The number of singularities in the upper and lower halves of the superimposed beam can be designed with different combinations of topological charges. (l) Modulation of the singularity distribution in the superimposed GPVB. Simulated (top) and experimental (bottom) intensity distributions for metasurfaces with different initial phases (including 0, $\pi/2$, π). Each black hole in the ring corresponds to a singularity. When the initial phase is not zero, the positions of the two halves of the singularities can be rotated at different angles. θ_1 and θ_2 are the rotation angles of the upper and lower halves of the superimposed beam, respectively. The white solid lines indicate the central positions of the two original singularities, located in the two different halves of the superimposed beam. The blue and green dashed lines represent the new central positions of the two singularities in the upper and lower halves, respectively. Figure reproduced with permission from ref.⁹⁵, under a Creative Commons Attribution 4.0 International License.

and manipulation of grafted perfect vortex beams (GPVBs) are more challenging and complex due to the additional phase distributions involved with lenses and axicon mirrors. Current optical devices for generating GPVBs require a multitude of optical components, including spatial light modulators, lenses, pinhole filters, polarizers, and dichroic mirrors⁹⁴, leading to large spatial requirements and high costs. These optical systems are impractical for many applications, thus there is an urgent need for a compact, simple, and efficient method to generate and manipulate GPVBs.

To tackle the technical challenges in conventional optics, in 2022, Hammad Ahmed et al.⁹⁵ proposed and experimentally showcased a metasurface-based approach for the generation and control of GPVBs across various

channels. The distinctive feature of this method is that the superimposed GPVBs possess non-uniform OAM and asymmetric singularity distributions in different channels. These singularity distributions can be modulated by incorporating initial phase differences in the metasurface design. The metasurface method introduced has the potential to enhance system integration and device miniaturization and holds significant promise for new applications that may not be feasible with traditional optical systems.

Researchers utilized PMMA as the substrate material and designed both single-layer and double-layer metasurface unit structures with a unit period of $P = 300$ nm, then compared the two. For the single-layer structure, a rectangular gold nanostructure was attached on a glass

substrate, as shown in Fig. 8(b). This required an etching process to remove the PMMA around the gold nano-columns, leaving only the gold nano-columns. Figure 8(d) displays the simulated transmission spectrum of the single-layer metasurface, which shows a high co-polarized component, affecting the extraction of cross-polarized component information. Additionally, the fabrication of single-layer metasurface units necessitated an etching process to remove the PMMA around the gold nanostructures, complicating the manufacturing process. To address these issues, researchers designed a double-layer nanostructure, as depicted in Fig. 8(c), where PMMA and gold serve together as additional layers. The sample preparation process omitted the etching step, meaning that gold deposition was the final step in the nanofabrication process. Moreover, from the transmission spectrum in Fig. 8(e), it can be seen that the double-layer nanostructure can effectively suppress co-polarized polarization. It is worth noting that the conversion transmission efficiency is maintained above 10% within a visible light bandwidth of 125 nm.

Researchers had listed two grafting scenarios for perfect vortex beams. In the first scenario, they chose $l_1=+1$, $l_2=-3$, and in the second scenario, they chose $l_1=-1$, $l_2=+3$. For both scenarios, an axicon period $d=2.9 \mu\text{m}$ was selected. The left and right sides of Fig. 8(f) and 8(g) respectively show the phase patterns of the GPVB and the corresponding SEM images of the fabricated samples. Figure 8(h) and 8(i) depict the corresponding simulated and experimental intensity distributions. Due to the superposition of phases, the phase distribution of the grafted perfect vortex can be expressed as⁹⁵:

$$\varphi_{\text{GPVB}}(x, y) = \arg\{E \exp[i(\phi_{\text{lens}} + \phi_{\text{GOV1}, l_n} + \phi_{\text{axicon}})]\}, \quad (26)$$

$$\varphi_{\text{GPVB}}(x, y) = \arg \left\{ \exp \left[i \sum_{n=1}^N \text{rect} \left(\frac{N\psi}{2\pi} - \frac{N+1}{2} + n \right) l_n \psi \right] \right\}. \quad (27)$$

In which N and l_n , ψ respectively represent the number of grafted OVs, the topological charge, and the azimuthal angle, and $\text{rect}()$ is the rectangle function. For example, when grafting two OVs, $N = 2$, and l_1 and l_2 represent the topological charges of the rootstock and the scion, respectively.

The study of grafted vortex beams is aimed at generating optical vortices with controllable OAM distribution and constant intensity. Consequently, researchers conducted superposition experiments on GPVBs using dou-

ble-layer nanostructures. Figure 8(j) and 8(k) display the simulated and measured intensity distributions of GPVB superposition when the metasurface was illuminated by a vertically incident RCP beam. All simulated intensity distributions were obtained through the Fresnel-Kirchhoff diffraction integral⁹⁶. The measured patterns closely matched the simulated results, confirming the superposition of GPVBs. The number of singularities in the superimposed beam can be calculated using Equation $L = L_1 + L_2 = \frac{|l_{b1} - l_{a1}|}{2} + \frac{|l_{b2} - l_{a2}|}{2}$, where L_1 and L_2 represent the number of vortex singularities in the upper and lower halves, respectively. Unlike the superposition of POV beams, the superposition of GPVBs exhibits an asymmetric singularity distribution in the upper and lower parts. The uneven distribution of singularities provides greater freedom in designing the singularity distribution in GPVB superposition, which can be used for capturing and manipulating multiple particles.

To achieve more flexible control over the singularity positions, an initial phase is added to one of the grafted beams. The resulting superimposed complex amplitude can be expressed as⁹⁵:

$$E_T(r, \psi) = E_{\text{GPVB1}}(r, \psi)e^{i\phi} + E_{\text{GPVB2}}(r, \psi). \quad (28)$$

Figure 8(l) presents the simulated and experimental results of the superposition of GPVBs ($l_{a1}=+4$, $l_{a2}=+2$ and $l_{b1}=-4$, $l_{b2}=-2$), where the phase Φ ranges from 0 to 2π in increments of 2π . The white solid lines indicate the central positions of the two original singularities, located in two different parts of the superimposed beam, while the blue and green dashed lines represent the new singularities. The center positions of the two singularities in the upper and lower halves increase with the increase of Φ and phase difference. With the increase of the initial phase, a clear difference can be observed in one half of the superimposed beam. Figure 8(l) further illustrates the relationship between the rotation angles obtained from theoretical calculations, simulations, and experiments, and the initial phase. In this way, by controlling the initial phase, the position of each singularity can be precisely controlled. This unique feature of GPVBs helps to accelerate and accurately locate captured micro/nano particles.

Compared to traditional methods for generating and manipulating GPVBs, using metasurfaces to control grafted vortex beams simplifies the complex optical platform and procedures, and enables the modulation of

asymmetric singularities. This will provide new opportunities for exploring the interesting applications of GPVBs in a wide range of fields such as quantum science and singular optics.

Application of perfect vortex beams

Due to the unique properties of perfect vortex beams, they play a significant role in applications such as particle manipulation and optical communication. Here is a brief introduction to the application fields of perfect vortex beams.

Optical particle trapping

Since Ashkin⁹⁷ achieved the optical levitation and trapping of particles, optical tweezers and optical trapping have been widely applied in various fields such as physics, chemistry, biology, materials science, and atmospheric science^{97–101}. Over the past few decades, the majority of optical tweezers experiments have been conducted in liquid environments, primarily focusing on biological materials^{102–104}. In recent years, with the development of optical tweezers technology, optical capture has been able to capture various types of particles in gas environments^{105,106}, ranging from nanometers to micrometers in size, transparent and absorptive, spherical and irregular shapes. The principle of optical particle trapping is shown in Fig. 9(a), where two beams of light (white arrows a and b) passing through an off-axis dielectric spherical particle in the laser beam will change their propagation direction due to refraction, leading to a change in their momentum¹⁰⁷. As shown in the left image of Fig. 9(a), the gradient of the light field intensity will always lead to a gradient force (F_{grad}) on the particle towards the maximum intensity of the beam. For perfect vortex beams, the intensity is concentrated on the ring, so it is possible to concentrate the capture of particles on the ring-shaped light intensity. The motion of the captured particles is determined by the gradient and scattering forces generated by the perfect vortex beam. Due to the scattering force from the inclined wavefront, the particle moves continuously along the ring surface, as shown in Fig. 9(b) and 9(c). Since the OAM density is well defined in the perfect vortex beam, a linear relationship is guaranteed between the rotation rate and OAM for both negative and positive topological charges, as shown in Fig. 9(d). The experimental realization of perfect vortex beams is quite challenging because they often exhibit azimuthal intensity variations due to optical

aberrations. As a result, it is difficult for a single particle to maintain a constant rotation speed around the trap due to local intensity hotspots. Nevertheless, by using intensity distribution correction techniques, these hotspots can be eliminated, and the captured single particle can move continuously along the vortex ring, as shown in Fig. 9(e). However, due to the local variation of OAM density, the captured particle still exhibits uneven angular velocity, as shown in Fig. 9(f). Based on the linear dependence of particle rotation speed on OAM density, the angular velocity can be adjusted *in situ* by using a phase correction mask to correct the local OAM density. It is worth noting that experimentally, perfect vortex beams can induce captured particles to rotate at a constant speed with integer topological charges, while fundamentally, this cannot be achieved with fractional topological charges.

Optical tweezers technology is an important tool in biomedical and nanotechnology research. Pancharatnam-Berry Vortex Beam, with its unique annular intensity distribution, is particularly suitable for the trapping and manipulation of microparticles. Innovations in the application of metasurfaces in this field include: In terms of parallel manipulation of multiple microparticles, a multi-focus PVB array generated by metasurfaces can capture and manipulate a large number of microparticles simultaneously. Studies have shown that metasurface optical tweezers can achieve synchronous manipulation of more than 100 microparticles, with the intensity uniformity error at each trapping point being less than 5%¹¹². This performance is hard to achieve with the traditional scheme using acousto-optic deflectors (AOD). In terms of dynamic reconfiguration, by combining metasurfaces with tunable materials (such as liquid crystals), real-time control of PVB parameters can be realized. For example, by applying different voltages, the topological charge or ring radius of PVB can be dynamically changed, thereby achieving precise manipulation of trapped microparticles. This technology provides new tools for the study of living cells.

Optical communication

Vortex beams carrying OAM have garnered widespread interest in the field of optical communication because they can be used to expand the number of multiplexed channels and significantly increase transmission capacity^{108–110}. However, the ring of ordinary vortex beams is controlled by the topological charge, which limits their

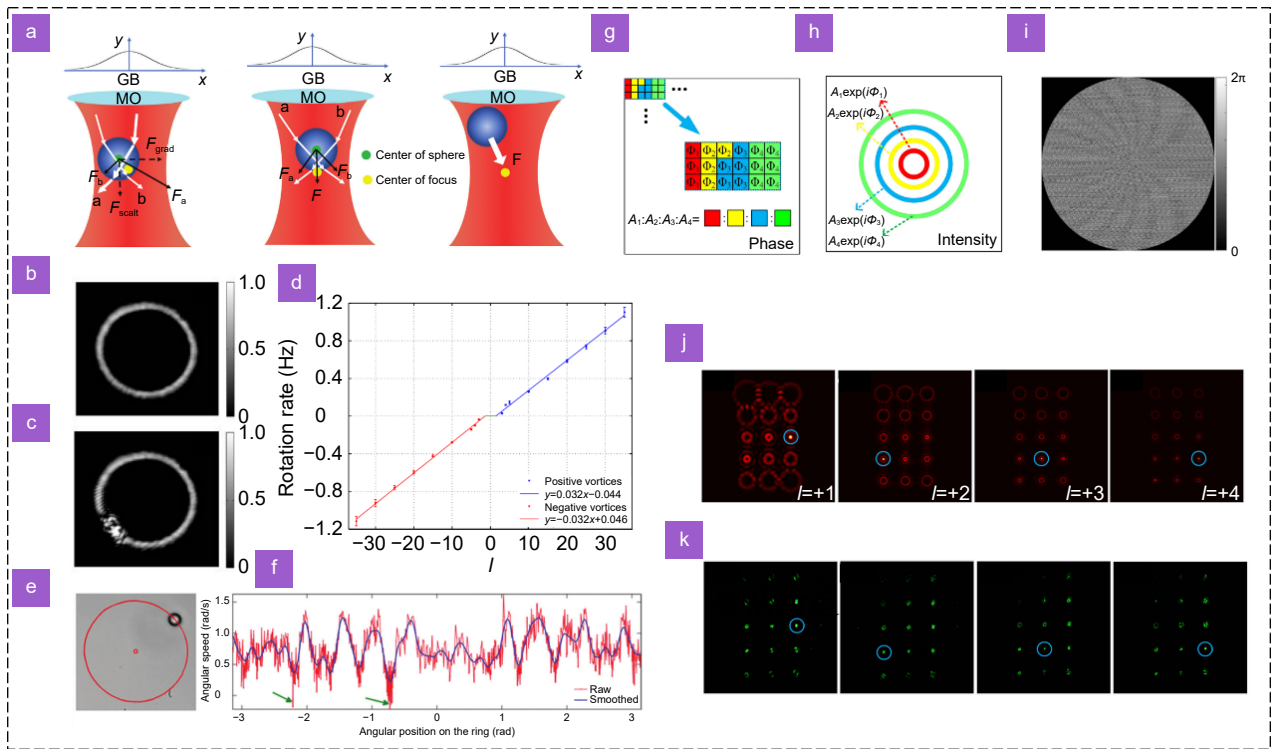


Fig. 9 | (a) Schematic of an optical tweezer (left) when the particle is off-center from the beam focus, (center) when the particle is slightly above the beam focus center, and (right) the net force acting on a dielectric sphere. F_a and F_b are the forces produced by the refracted beams a and b, respectively. F_{grad} and F_{scat} represent the gradient force and scattering force, respectively. GB: Gaussian beam; MO: Microscope objective. (b) A perfect vortex beam with a topological charge $l=25$. (c) The beam with scattered light from a single captured particle. (d) The linear relationship between the particle's rotation rate and its integer topological charge. (e) The captured particle rotating around the circumference of the perfect vortex beam indicated by the red circle. (f) The relationship between the particle's angular velocity and its angular position. (g) The pixelated checkerboard method for complex amplitude modulation and (h) a schematic of a light field with controllable amplitude and phase. (i) The phase of the demultiplexing array. Demultiplexing of multi-ring perfect vortex (MRPV) is performed through simulation and experiment. (j, k) Demultiplexing of MRPV through simulation and experiment, respectively. MRPVs with topological charges $l = 1, 2, 3$, and 4 , with OAM states marked by blue circles. Figure reproduced with permission from: (a–f) ref.¹⁰⁷, under a Creative Commons Attribution 4.0 International License; (g–k) ref.¹¹¹, under a Creative Commons Attribution 4.0 International License.

application in optical communication. Therefore, the emergence of perfect vortex beams has greatly promoted the development of optical communication.

In 2023, Zhou et al. proposed a dense space-division multiplexing (DSDM) scheme, using the small-range OAM modes of MRPV to further improve the transmission capacity and transmission capacity density of free-space optical communication¹¹³. The amplitude and phase of the light field were encoded onto a hologram, as shown in Fig. 9(g), where the pure phase hologram is divided into many chessboard patterns of single-pixel size. By using this hologram, four beams with additional phases Φ_1 , Φ_2 , Φ_3 , and Φ_4 could be generated. The final result is the MRPV shown in Fig. 9(h). MRPV allowed for the simultaneous transmission of perfect vortex beams in space, and demodulation on the four channels of MRPV was also important. Figure 9(i) shows the

phase of the vortex demultiplexing array, through which the OAM of a single ring was demultiplexed. There were 15 points in the array with inherent OAM states ranging from -7 to $+7$. When an OAM beam with a topological charge $l=1$ passed through the detection channel, the vortex beams spot with an inherent topological charge $l=-1$ would transform into a Gaussian-like spot. The simulated and experimental diagrams of demultiplexing are shown in Fig. 9(j) and 9(k). According to the position of the light spot transformed into a Gaussian-like spot in the demultiplexing array, the mode of the OAM beam transmitted in the four rings of MRPV could be directly derived as $l=1, 2, 3$, and 4 . The experimental results show that no other modes were detected in the demultiplexing array, indicating that the influence between the four rings of MRPV is minimal, which is a great advantage of PVB in the field of optical transmission.

In the field of optical communication, mode-division multiplexing (MDM) is considered an important means to break through the existing capacity limits of communication systems. Pancharatnam-Berry Vortex Beam, with its characteristic of carrying orbital angular momentum, can serve as an independent communication channel to significantly enhance system capacity. The application of metasurfaces in this field is mainly reflected in the following aspects:

At the transmitter end, metasurfaces can be directly integrated at the output end of a laser or the end of an optical fiber, directly converting a Gaussian beam into a PVB. Compared with the traditional scheme using a spatial light modulator, the metasurface approach is not only more compact in size but also extremely low in power consumption. By designing a specific phase distribution, metasurfaces can focus PVBs with different topological charges to different positions on a detector array, achieving rapid mode recognition. This approach avoids the complex optical systems required by traditional coherent detection methods and greatly simplifies the design of the receiver end.

Emerging applications

In addition to particle trapping and optical communication, PVBs hold significant potential in several other cutting-edge fields, each leveraging their unique properties^{114,115}. In quantum information processing, PVBs can be used to encode information in the OAM states of photons, enabling high-dimensional quantum states for quantum key distribution and quantum computing. The well-defined OAM modes of PVBs provide a robust platform for multiplexing and error-resistant quantum communication. However, challenges such as mode crosstalk and decoherence need to be addressed to fully exploit their potential in this domain.

In super-resolution imaging, PVBs can enhance resolution beyond the diffraction limit by exploiting their tightly focused intensity profiles and phase singularities. Techniques such as stimulated emission depletion (STED) microscopy could benefit from the precise control of PVBs' intensity nulls, enabling finer spatial resolution in biological and material imaging. The challenge here lies in optimizing the beam generation and alignment to achieve consistent performance across different imaging conditions.

For laser machining and material processing, PVBs offer the ability to create complex micro- and nanostruc-

tures with high precision. Their helical phase fronts and customizable intensity distributions allow for tailored energy deposition, enabling applications such as high-resolution lithography, laser ablation, and 3D printing. The main technical hurdle in this area is achieving high power efficiency and stability in PVB generation, which is critical for industrial-scale applications.

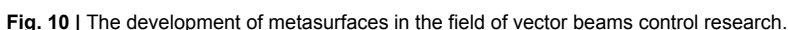
These emerging applications highlight the versatility of PVBs and underscore the need for continued advancements in metasurface design and fabrication. By addressing the technical challenges specific to each field, PVBs could unlock new possibilities in science and technology, further solidifying their role as a transformative tool in modern optics.

Summary and outlook

In this review paper, we have broadly surveyed the development of PVB in recent years. Since the proposal of perfect vortex beams, a multitude of studies and applications related to it have emerged. The characteristic that the intensity of PVBs do not change with the topological charge greatly enhances the application efficiency of vortex beams in particle manipulation and fiber optic communication. As research into perfect vortex beams deepens, there is an increasing demand for more complex forms of vortex beams, such as perfect vortex beams for multi-channel communication, OAM controllable grafting perfect vortex beams, and optical vortices with irregular OAM distributions.

This advancement has led to the optical experimental platforms becoming more complex, and the experimental operations more cumbersome. The complexity arises from the need to precisely control and manipulate the phase and amplitude of light to create these intricate vortex structures, which is essential for their potential applications.

In recent years, with the advent of metasurfaces, they have become a hot research topic over the past few years due to their efficient and unique functions in optical control, which are unattainable with traditional bulky optical components. Moreover, the manufacturing process of metasurfaces is simple and cost-effective, and they are compatible with existing systems, which has also spurred their importance in the optical control industry. Therefore, in this text, we mainly discuss the application of metasurfaces in the field of perfect vortex beams. As shown in Fig. 10, since 2014, metasurfaces have gradually been applied in the research on the control of



Metasurfaces can be categorized based on their material types into dielectric metasurfaces, metallic metasurfaces, and programmable metasurfaces^{124–139}. Different types of metasurfaces may have some differences in their applications across various scenarios^{140–151}. However, metasurfaces are not yet perfect in the control of perfect vortex beams and still face many technical challenges and limitations. First, since metasurfaces are designed based on subwavelength structures, their performance is closely related to the operating wavelength. For light in different bands (such as visible light, infrared light, or terahertz bands), different metasurface structures need to be designed, which limits their broadband applicability. In addition, when generating high-order vortex beams, diffraction effects can reduce the purity of the output beam. This issue is particularly prominent in the generation of perfect vortex beams, as they require higher precision in phase and polarization. These factors make it

At present, research on metasurfaces in the field of perfect vortex beams mainly focuses on the integration of optical platforms and functional expansion, with less attention paid to improving transmission efficiency. This is also one of the important reasons why metasurfaces have not yet completely replaced traditional optical components. For example, in practical applications such as optical communication or particle manipulation, low transmission efficiency can lead to signal attenuation or reduced manipulation accuracy, limiting the practicality

of metasurfaces.

To overcome these challenges, future research can be carried out in the following directions:

Developing new materials: Exploring low-loss, high-refractive-index materials (such as two-dimensional materials, transition metal sulfides, or metamaterials) to improve the transmission efficiency and working bandwidth of metasurfaces.

Optimizing fabrication processes: Investigating low-cost, high-precision nanofabrication techniques (such as self-assembly or nanoimprint lithography) to reduce the fabrication cost of metasurfaces and promote their large-scale production.

Dynamic tunability: Developing dynamic metasurfaces based on phase-change materials, liquid crystals, or mechanically tunable structures to achieve simultaneous control of wavelength, polarization, and phase, thereby enhancing their applicability and flexibility.

Metasurfaces, as an emerging and rapidly developing research field, offer new opportunities for cutting-edge areas such as optical communication, integrated optical computing, and quantum information processing when combined with perfect vortex beams. Although there are still many challenges at present, with the continuous progress of material science, nanofabrication technology, and optical design, it is believed that in the near future, the application of metasurfaces in perfect vortex beams will be more extensive and in-depth, paving new ways for the development of optical technologies.

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Competing interests

The authors declare no competing financial interests.



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