

Homotopic Vortex Lasing Mediated by a Resonant Geometric Phase in a Bound States in the Continuum Cavity

Ronghui Lin,[#] Thi Thu Ha Do,[#] Emek Goksu Durmusoglu,[#] Deepak K. Sharma, Syed Akhil, Vytautas Valuckas, Corentin Dabard, Arseniy I. Kuznetsov, Hilmi Volkan Demir,^{*} Jinghua Teng,^{*} and Son Tung Ha^{*}



Cite This: *Nano Lett.* 2026, 26, 13802–13809



Read Online

ACCESS |



Metrics & More



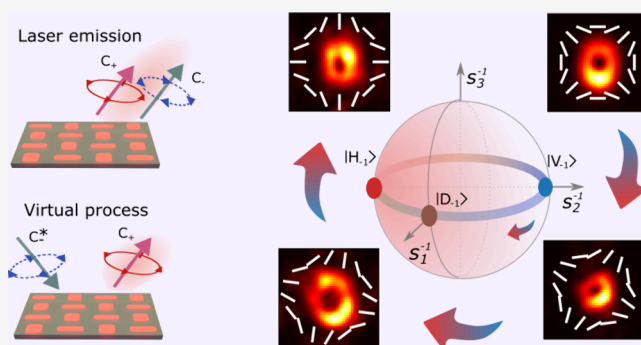
Article Recommendations



Supporting Information

ABSTRACT: Geometric phases are fundamental to wave physics and underpin a broad range of optical phenomena. The most prominent example, the Pancharatnam–Berry (PB) phase, originates from polarization evolution during wave propagation. In contrast, geometric phases associated with optical resonances and cavities remain largely unexplored. Here, we uncover the relation between the generalized PB phase and the far-field polarization evolution in bound states in the continuum (BIC) cavities. We demonstrate the continuous homotopic evolution of vortex lasing modes through geometric-phase engineering of BIC resonances. To experimentally validate this concept, we realize metasurface lasers composed of titanium dioxide hole arrays integrated with CdSe/Cd_xZn_{1-x}S core/shell colloidal quantum wells as the gain medium. Our results reveal a previously unexplored form of spin–orbit interaction in BIC cavities under oblique incidence and provide a versatile route for on-chip control of polarization and orbital angular momentum in nanolasers.

KEYWORDS: geometric phase, bound states in the continuum, polarization vortex laser, singular optics, photonic crystal



The geometric phase provides a powerful framework for the control of structured light, enabling robust manipulation of phase, polarization, and angular momentum in compact photonic systems.^{1,2} In contemporary geometric-phase optics, the Pancharatnam–Berry (PB) phase plays a central role. Arising from the evolution of polarization during wave propagation between circular polarization states of opposite handedness, the PB phase underlies a wide range of metasurface functionalities. However, this framework is intrinsically associated with the propagation of waves. In optical cavities, electromagnetic fields undergo multiple roundtrips and form standing-wave resonances prior to radiation leakage, such that the conventional propagation-based description of the geometric phase is no longer directly applicable. Establishing a geometric phase formalism for cavity-confined resonant states therefore remains an outstanding problem.

A particularly important class of related cavities is the BIC cavity.^{3–10} Owing to their intrinsic topological far-field properties, BIC cavities have emerged as a powerful platform for manipulating light polarization and generating vortex beams that exhibit both phase and polarization singularities.^{11–15} A central theme in the study of BIC-enabled vortex fields is understanding how modifications in the near field

influence the evolution of these singularities and, consequently, the resulting far-field polarization distribution.^{3,5,16–20}

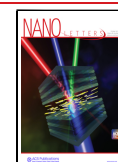
The dynamics of the topological singularities, including their interaction, generation, and annihilation, are governed by the conservation of total topological charge.^{21–23} Previous research has demonstrated that strategies such as symmetry breaking and the optimization of geometric parameters effectively govern the dynamic behavior of these singularities, including their translation, merging, and splitting.^{24–28} These methods have enabled the realization of topological singularities with different charges, giving rise to rich and diverse polarization textures. While topology governs the global characteristics of polarization fields, it does not uniquely determine the local polarization configuration. In particular, a given winding number corresponds to an infinite family of continuously deformable polarization textures belonging to the same homotopy class. Prior studies on bound states in the

Received: June 12, 2026

Revised: September 18, 2026

Accepted: September 21, 2026

Published: September 29, 2026



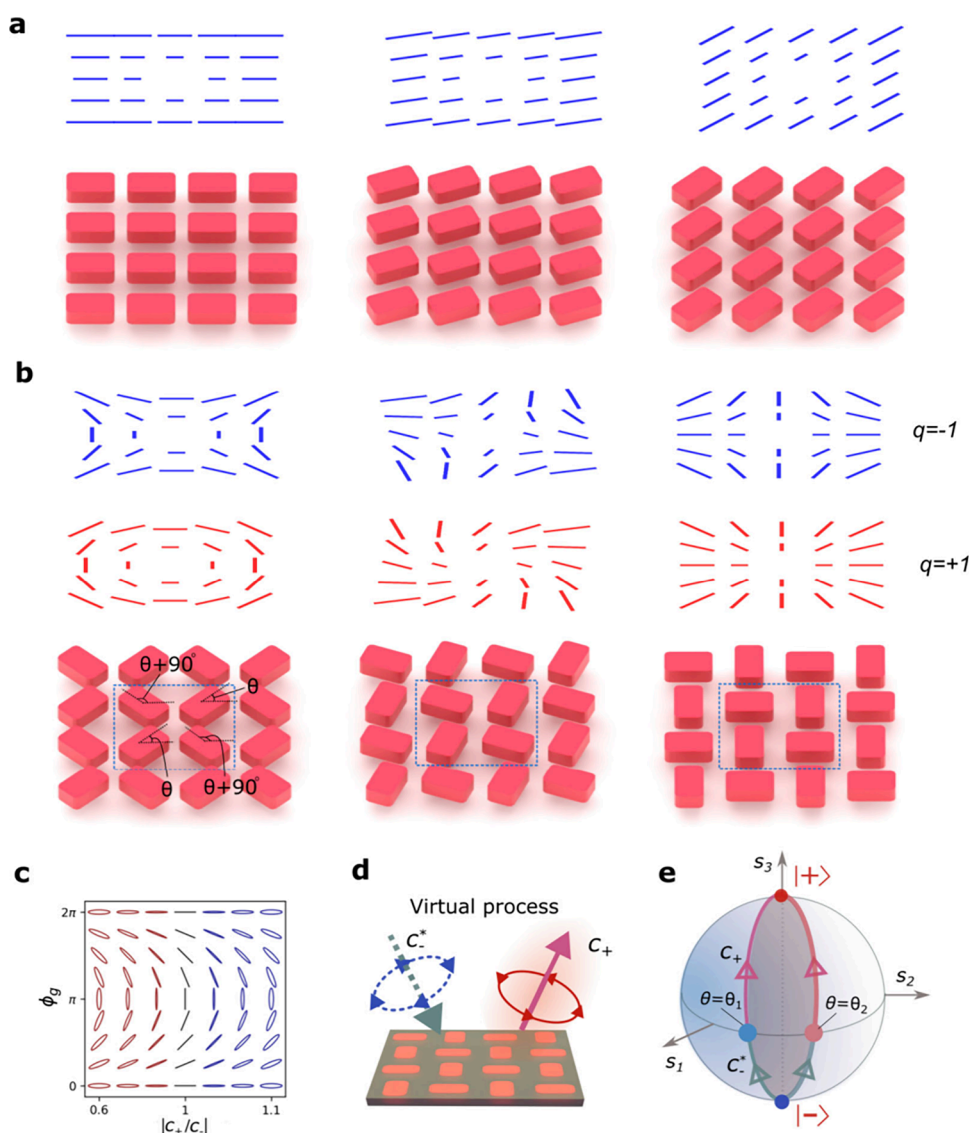


Figure 1. Homotopic evolution of polarization surrounding the BIC. (a) The permutation of a simple unit cell and the corresponding far-field polarization field. (b) Unit cell permutation and the rotation of the polarization field surrounding the BIC for topological charge -1 (top panel) and $+1$ (middle panel) and for complex cells with three representative values of $\theta = 45^\circ, 75^\circ$, and 90° . (c) Far-field polarization ϕ_g as a function of the amplitude and phase difference of c_{+-} , where c_- and c_+ denote out-coupling coefficients of the BIC mode to the far field with clockwise (+) and counterclockwise (-) electric field rotation, respectively. The blue and red colors indicate the handedness (left and right) of the elliptical polarization, respectively. (d) Schematic for an equivalent virtual process with the virtual in-coupling field c_-^* and the out-coupling field c_+ . (e) Evolution of the polarization states along the Poincaré sphere.

continuum (BICs) have firmly established the existence of continuous momentum-space polarization vortices,^{21–23} and the preservation of topological charge under structural variations remains an expected consequence of maintained C_4 symmetry. However, the quantitative physical mechanisms driving the continuous evolution of the polarization texture within a given topological class have remained largely unexplored.

In this work, we demonstrate that this continuous homotopic evolution is governed by a generalized resonant geometric phase tied directly to the cavity eigenmode. Using coupled-mode theory, we establish a direct mapping between this internal resonant phase and the far-field polarization states, providing a precise quantitative explanation for the observed nonlinear polarization rotation in the far-field emission. Crucially, whereas previous investigations of PB-phase effects

in BIC systems have been restricted to passive, scattering metasurfaces operating under external polarized illumination,^{11,29} our approach extends geometric-phase physics into the domain of active emitting systems. By decomposing the unpolarized cavity emission into circular components and their time-reversed counterparts, we construct a closed trajectory on the Poincaré sphere. This framework reveals that a generalized PB phase can emerge natively from the internal resonant and time-reversal symmetries of an active BIC cavity, expanding the scope of geometric-phase phenomena from passive wave manipulation to active laser and emission architectures.

To experimentally demonstrate this concept, we design and fabricate metasurfaces consisting of amorphous titanium dioxide hole structures filled with CdSe/Cd_xZn_{1-x}S core/shell colloidal quantum wells (CQWs) serving as the gain medium. By rotating the subunit-cell elements about their

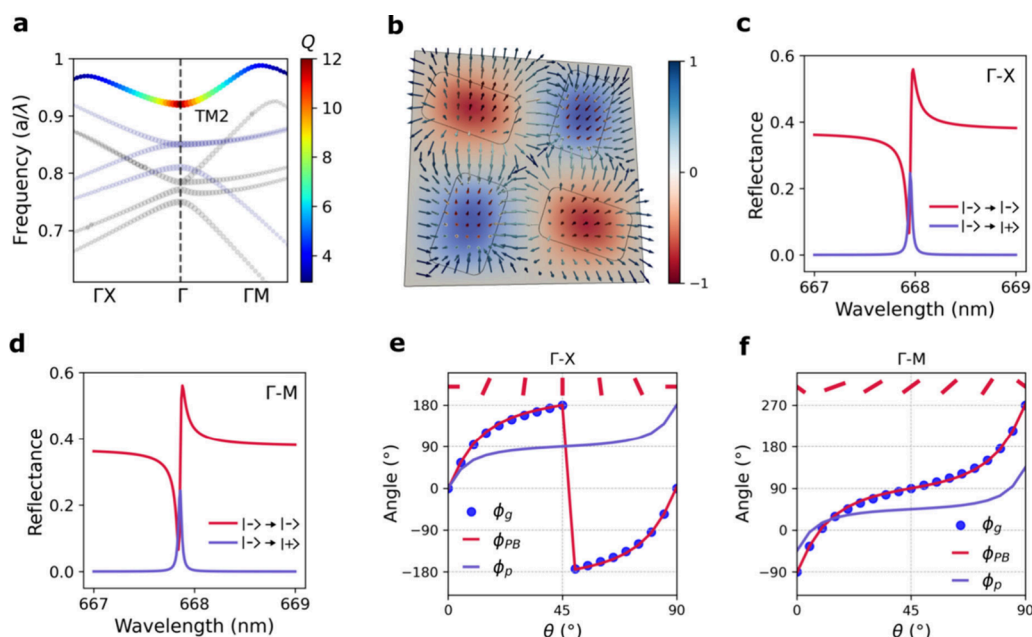


Figure 2. Geometric phase and the rotation of the polarization fields. (a) The simulated band diagram for the photonic crystal slab with $\theta = 75^\circ$. The color map indicates the quality factors in a logarithmic scale. (b) The mode profile for the TM2 mode for the case $\theta = 75^\circ$. The arrows indicate the electric field direction, and the color map shows the amplitude of the E_z component. (c, d) The simulated reflectance spectra with an oblique incident angle corresponding to $|k| = 0.02 \times \frac{2\pi}{a}$ in the ΓX and ΓM direction. (e, f) The simulated geometric phase and the far-field polarization angle as a function of the rotational angle θ for the mode corresponding to $|k| = 0.02 \times \frac{2\pi}{a}$ in the ΓX and ΓM direction, where ϕ_g , ϕ_{PB} , and ϕ_p are the geometric phase, PB phase, and the polarization angle, respectively. The red lines at the top show the evolution of the polarization angle at various θ .

center of mass, the geometric phase evolves analogously to a generalized Pancharatnam–Berry (PB) phase. Consequently, the emitted laser polarization undergoes a continuous rotation, tracing the equator of the higher-order Poincaré sphere.

For a simple metasurface consisting of nanofins. The rotation of these nanofins and the rotation of the far-field polarization have a one-to-one correspondence. This is schematically illustrated in Figure 1a. However, in a complex unit cell with C_4 symmetry, the evolution of polarization follows more complicated structures governed by the maintenance of topological charge; this is illustrated in Figure 1b. The complex unit cell is composed of four rectangular nanofins of identical dimensions but distinct orientations. Specifically, the rotation angles of the nanofins with respect to the x -axis are $\theta, \theta + 90^\circ, \theta, \theta + 90^\circ$. When the θ value is varied, the topological charge around the BIC point at the Γ -point can be expressed as³⁰

$$q = \frac{1}{2\pi} \oint_C d\mathbf{k} \cdot \nabla_{\mathbf{k}} \Phi(\mathbf{k})$$

where C is a closed loop around the BIC singularity, $\Phi(\mathbf{k}) = \arg(c_x(\mathbf{k}) + ic_y(\mathbf{k}))$ is the polarization angle, and $c_x(\mathbf{k}), c_y(\mathbf{k})$ represent the coupling coefficients of the Bloch mode to the far field along the x - and y -direction in the momentum $\mathbf{k}$ -plane.

To elucidate the correlation between θ and polarization rotation, we decompose the out-coupling fields of the BIC at off- Γ into circular bases: $c_{\pm} = c_x \mp ic_y$, where c_+ and c_- represent the out-coupling coefficients of the BIC mode to the far field with clockwise (+) and counterclockwise (−) electric field rotation, respectively. We find that rotating the nanofins does not significantly modify the mode profile; instead, it induces a local rotation of the coordinate frame, thereby generating a

geometric phase^{31,32} $\phi_{G,\pm} = -\int S_{\pm} \cdot \Omega_{\theta} d\theta$ where $S_{\pm}$ is the spin angular momentum of the optical field and Ω_{θ} is the rotating rate of the coordinate frame with respect to the parameter θ . We define a new geometric phase that governs the polarization direction as $\phi_g = \phi_{G,+} - \phi_{G,-}$, which can be calculated as $\phi_g = \text{Arg}(c_+) - \text{Arg}(c_-) = \text{Arg}(c_+) + \text{Arg}(c_-^*)$.³³ Here, the principal polarization direction is solely governed by ϕ_g , as illustrated in Figure 1c. We also observe that c_-^* is proportional to the in-coupling coefficient at the opposite $\mathbf{k}$ due to the time reversal and reciprocity symmetry (see details in SI, Section 1). With this equivalence, $c_-^* c_+$ represents a virtual process, where the in- and out-couplings are $|-\rangle$ and $|+\rangle$ states, as shown in Figure 1d. This process creates a pathway on the Poincaré sphere of polarization that connects the poles as shown in Figure 1e. The virtual processes mediated by BIC cavities with different θ form a closed loop on the Poincaré sphere, whose enclosed surface area corresponds to the geometric phase ϕ_g . This geometric phase also manifests as the generalized PB phase²⁹ when a circularly polarized incident wave is converted into its opposite polarization by the metasurface. A detailed derivation based on the coupled-mode theory is provided in Supporting Information (SI, Section 1).

Our theory depends only on the symmetry and is applicable for any medium. In our design, to enhance mode overlap and facilitate subsequent lasing, we employ TiO_2 metasurfaces composed of hole structures filled with $\text{CdSe/Cd}_{1-x}\text{Zn}_x\text{S}$ core/alloyed-shell CQWs as the gain medium. Each unit cell has a lattice constant of $a = 596$ nm, and each nanofin has the length of $L = 275$ nm and the width of $W = 175$ nm (SI, Figure S2). The total thickness of the metasurface is 120 nm. The simulated photonic band structure is shown in Figure 2a for a representative case $\theta = 75^\circ$, where the color bar indicates the

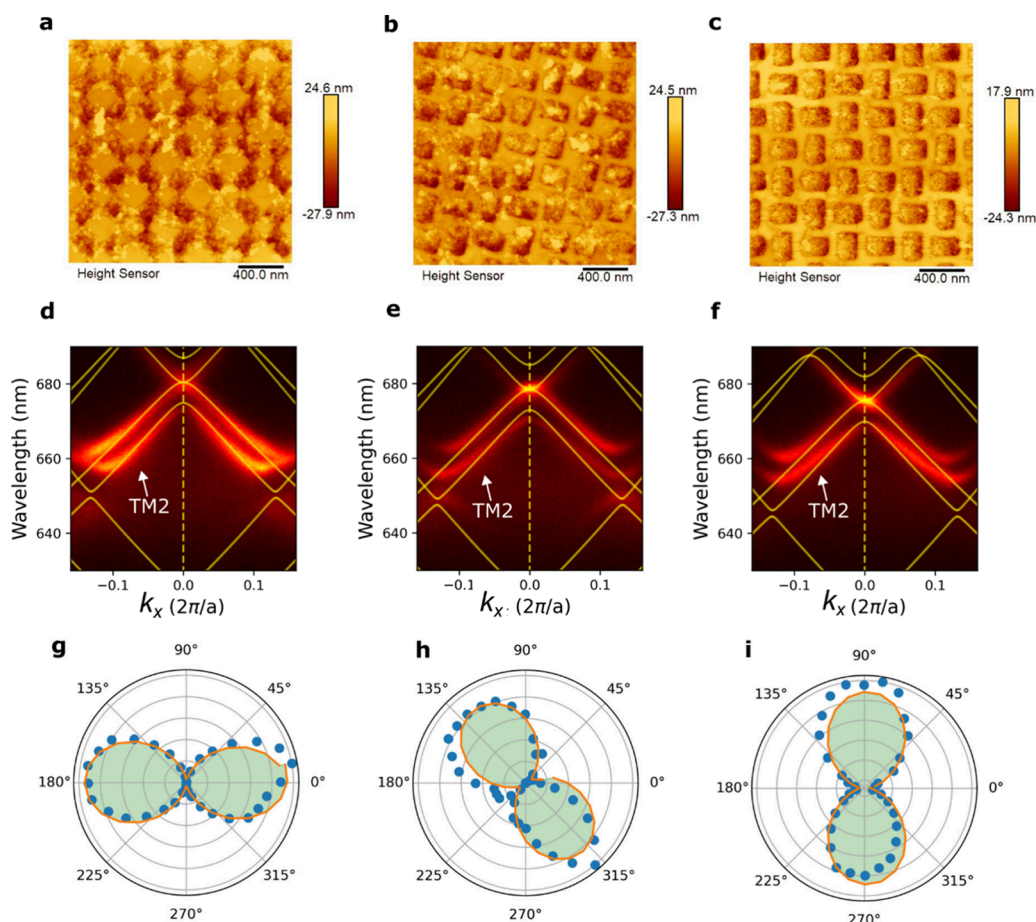


Figure 3. Characterization of the TiO_2 -CQWs metasurfaces. (a–c) Atomic force microscope (AFM) images of the TiO_2 metasurfaces coated with CdSe/CdZnS CQWs via spin-coating and subsequent planarization, presenting three representative rotation angles of the nanofins: $\theta = 45^\circ$, 75° , and 90° . (d–f) Unpolarized angle-resolved photoluminescence spectra measured for $\theta = 45^\circ$, 75° , and 90° showing the robustness of the symmetry-protected BIC on the TM2 band against the variation of θ . The yellow lines indicate the simulated band structures. (g–i) Integrated intensity of the TM2 band extracted at $|k| = 0.02 \times \frac{2\pi}{a}$ as a function of the detected polarization α . Orange solid lines are sinusoidal fitting curves.

Q-factor in a log scale. We focus on the TM2 mode, which contains a symmetry-protected BIC with a diverging Q-factor at the Γ -point. Note that the energy of the BIC is robust against the changes of θ as long as the C_4 symmetry is preserved as the mode is highly localized within each nanofin. Figure 2b shows the electric field distribution of the TM2 mode taken at the mirror symmetry plane in the z -direction. To verify the relationship between the ϕ_g and the generalized PB phase, we calculated the reflection spectra under oblique illumination of a circularly polarized plane-wave using the rigorous coupled-wave analysis (RCWA) method. The PB phase is defined as the phase difference between the reflected waves of the opposite electric field rotations when the polarization is converted from $|-\rangle$ to $|+\rangle$. Figures 2c,d present the reflectance spectra at an oblique incident angle corresponding to $|k| = 0.02 \times \frac{2\pi}{a}$ in the ΓX and ΓM directions, respectively. In both cases, when the polarization conversion is absent (i.e., $|-\rangle \rightarrow |-\rangle$), we observe a Fano-shaped reflection profile resulting from the interference between the resonant mode and the nonresonant background reflection. In contrast, the reflectance associated with polarization conversion (i.e., $|-\rangle \rightarrow |+\rangle$) exhibits a Lorentzian profile, as the nonresonant background contains no cross-polarized contribution. The phase difference associated with this cross-polarized reflection corresponds to the generalized PB phase, which originates

from the complex eigenmodes of the photonic supercell.²⁹ To investigate the dependence of PB phase ϕ_{PB} on the rotation angle θ of the nanofins, we extract ϕ_{PB} from the reflectance in both ΓX and ΓM directions as a function of θ . The results show excellent agreement with the ϕ_g calculated directly from the complex eigenmode of the cavity mode (Figure 2e,f), thereby confirming their common physical origin. Notably, the geometric phase exhibits a nonlinear dependence on the nanofin rotation angle θ , which arises from two distinct effects: (i) the rotation of the coordinate frame follows the principal axis,²⁹ which is typically different from the rotation angle of a single nanofin θ ; (ii) inter-unit-cell mode coupling within the supercell further perturbs the eigenmodes, leading to additional deviation from single-resonator geometric phase.

It is conventionally assumed that PB phases vanish in C_4 -symmetric lattices due to their isotropic nature.^{29,33} However, our results reveal that a PB phase can exist in C_4 lattices when the excitation occurs at oblique incidence. To further confirm the geometric nature of the observed effect, we demonstrate that BIC modes with different topological charges all acquire an identical phase as a function of θ (SI, Section 2).

As a result of the evolution of geometric phases, the far-field polarization (ϕ_p) rotates synchronously (red arrows in Figure 2e,f) and evolves homotopically while preserving the topological charge. An intriguing observation is the doubling

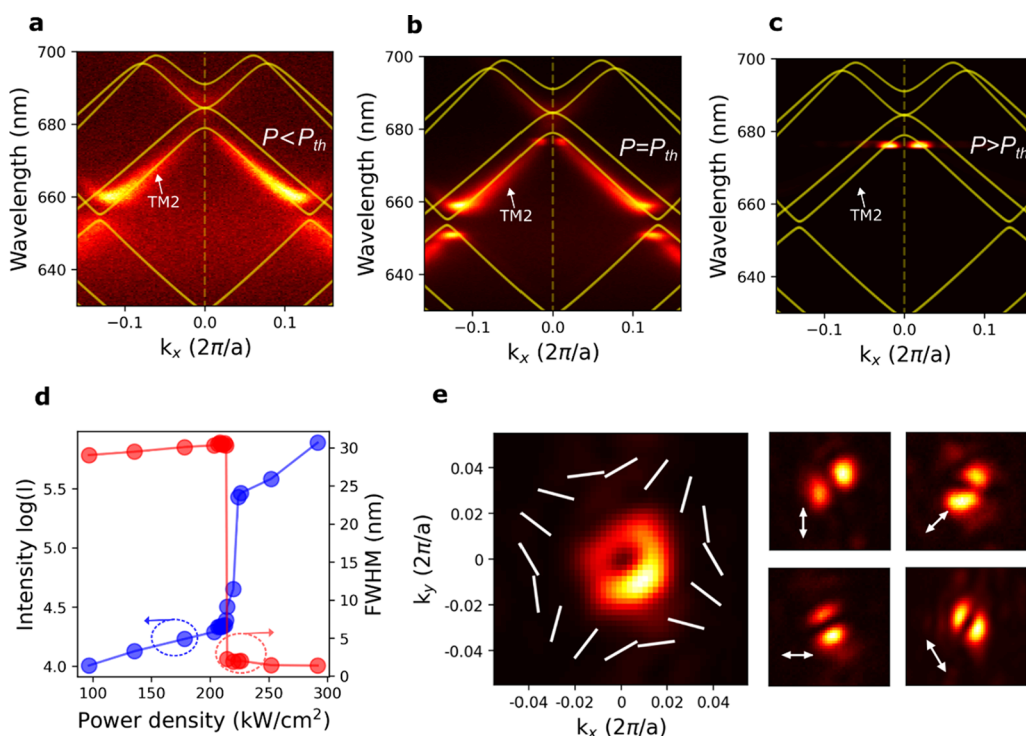


Figure 4. Characterization of the BIC lasing for a representative array with $\theta = 78^\circ$. (a–c) Polarization-resolved, angle-resolved PL spectra excited at below the threshold (a), near the threshold (b), and above the lasing threshold (c). White arrows: detection polarization. The yellow lines indicate the simulated band structures. (d) The emission intensity and fwhm as a function of the pump power density, showing the lasing threshold at $\sim 220 \text{ kW}/\text{cm}^2$. (e) Polarization patterns of the emission: left panel: unpolarized emission pattern, where the overlaid lines indicate the polarization state of the emitted beam; right panels: emission patterns detected at different polarization angles (white arrows).

relationship between the nanofin rotation angle and the resulting polarization: as the nanofin rotates from 0° to 45° or from 45° to 90° , the polarization direction rotates by 90° . This behavior arises because the lattice restores its original configuration after a 90° rotation, corresponding to a complete traversal of the Poincaré sphere surface and thus a 2π geometric phase. By symmetry, a 45° rotation introduces a π geometric phase, leading to a 90° rotation of the polarization angle. The orthogonal relationship between the $\theta = 45^\circ$ and $\theta = 0^\circ$ or $\theta = 90^\circ$ configurations further reflects the underlying lattice symmetry, as discussed in the SI, Section 3.

The TiO_2 metasurfaces were fabricated using electron beam lithography followed by a dry etching method (see Supporting Information, Section 4). The hole structures were then filled with synthesized CdSe/CdZnS CQWs as gain medium (see SI, Figures S8, S9 for CQW optical characterizations).^{34–36} To enhance the filling factor of the CQWs into the TiO_2 hole structures, we intentionally engineered the CQWs in a square shape, which promotes high emitter density, improves stacking of CQWs within the thin film, and ensures smooth surfaces and uniform optical gain across the cavity.

Importantly, to best resolve the pure polarization from the BIC mode and the evolution of its geometric phase, a planarized structure with minimal excessive CQWs on top is necessary, which requires precise control over the spatial distribution of CQWs within the TiO_2 template due to the strong localization of the electromagnetic field in the CQW-filled regions. Excess CQWs remaining on top of the TiO_2 slab can perturb the BIC resonance wavelength and alter its polarization characteristics. While spin-coating produces uniform coverage over both the cavities and the surrounding areas, we implemented a postdeposition planarization step to

selectively remove CQWs from the top surface while retaining them within the TiO_2 pockets. This was achieved by carefully sweeping the top surface under an optical microscope using ultrafine, fiberless swabs lightly moistened with ethanol, enabling targeted removal of CQWs without disturbing those embedded in the cavities. The atomic force microscope (AFM) measurements confirm the uniform thickness and excellent surface smoothness, both essential for minimizing scattering losses and preserving the high Q-factor of the BIC mode. This approach, combined with our pocket-based cavity design, ensures highly controlled CQW placement and minimizes scattering losses, thereby maintaining the high-Q characteristics necessary for further photonic applications such as lasing. Figure 3a–c show the AFM topology images of three typical metasurfaces with $\theta = 45^\circ$, 75° , and 90° (see SI, Figures S10, S11 for other arrays). As can be seen, the TiO_2 holes are completely filled with a minimal amount of excessive CQWs on top.

The photonic bands are investigated by a home-built angle-resolved microspectroscopy setup (see Supporting Information, Section 4). Figure 3d–f show the unpolarized angle-resolved photoluminescence (PL) spectra for three representative arrays with rotation angles of the nanofins of $\theta = 45^\circ$, $\theta = 75^\circ$, and $\theta = 90^\circ$. For all samples with different θ , the symmetry-protected BIC resonance is featured by the absence of signal at the Γ -point. The measured band also matched well with the simulated bands. It is noteworthy that some bands are missing in the measured spectrum because a polarizer is used during measurements; therefore, the bands with polarization perpendicular to the BIC bands will not show. We characterize the polarization of the TM2 band by varying the detection linear polarization angle α and extract the PL intensity at

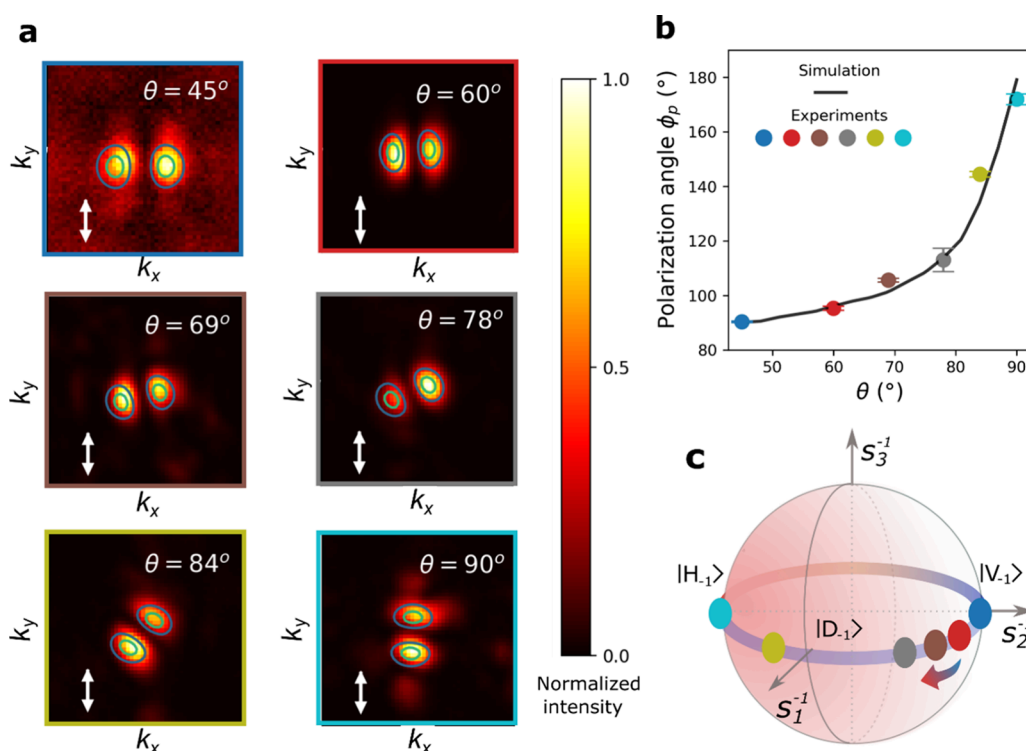


Figure 5. Homotopic vortex lasing control. (a) Polarization-resolved emission patterns for samples with different θ angles, where the white arrows indicate the detection angle of the linear polarizer. The contour in each panel indicates the best fit we obtained with the Hermite–Gaussian modes. (b) Measured polarization angle along the ΓX direction as a function of θ . (c) Mapping of the realized vortex beams onto the HOPS with a topological charge of -1 .

$|k| = 0.02 \times \frac{2\pi}{a}$. The polar plots (Figure 3g–i) unambiguously indicate the linear polarization of the BIC band with varying polarization angles. Notably, the polarization states corresponding to $\theta = 45^\circ$ and $\theta = 90^\circ$ arrays are orthogonal, following the doubling relationship between θ and far-field polarization rotation ϕ_p , as theoretically discussed in Section 2.1 and SI, Section 3. The intrinsic orthogonal polarization fields is guaranteed by symmetry, providing robustness to optical systems, which is critical in applications such as quantum information processing and data transmission.

To exclusively assess the symmetry-protected BIC mode TM2 and the evolution of its geometric phase, we studied the lasing emission pattern. The samples were optically excited using a nanosecond-pulsed laser with an emission wavelength of 532 nm, pulse width of 1.5 ns, and a repetition rate of 1 kHz. A pair of half-wave plates and an analyzer are placed along the detection path to analyze the linear polarization of the BIC mode.

Below the lasing threshold (Figure 4a), the emission is dominated by the broad spontaneous emission from the CQWs (Figure S9) that is coupled to photonic bands including the high-Q BIC mode at ~ 675 nm. As the pump power approaches the lasing threshold, enhanced emission emerges near the BIC mode (Figure 4b) and becomes dominant when the pump power exceeds the lasing threshold (Figure 4c). The measured lasing mode is found to coincide with the simulated TM2 branch, confirming that lasing originates from the intended symmetry-protected BIC mode. It is noteworthy that the band above the TM2 band is missing in these images because of the polarizer, which filters out the band above, which has an emission polarization perpendicular to the TM2 mode. The lasing action is revealed by analyzing

the integrated emission intensity over all angles and fwhm as functions of the pumping fluence, as shown in Figure 4d. As the excitation power increases, we observed typical S-curve behavior of the emission intensity and a reduction of the fwhm, unveiling a lasing threshold of ~ 220 kW/cm ^{2} .

The polarization vortex characteristics of the BIC lasers are investigated using back focal plane (BFP) imaging, which captures the angular distribution of the far-field radiation of the BIC mode. Figure 4e displays the BFP images of the lasing patterns for the case of $\theta = 78^\circ$. Without a linear polarizer, the BIC lasing emission exhibits the typical doughnut-shaped intensity profile with an emission angle of approximately 1 – 2° and a dark center due to the BIC singularity at the beam axis. When the linear polarizer is introduced, the lasing pattern transforms into a two-lobed structure that rotates as the half-waveplate is rotated. As a result, the full polarization state of the beams can be reconstructed as illustrated by the white lines. The symmetry in the polarization distribution confirms that the emitted beams are cylindrical vector beams ^{37} with a topological charge of -1 .

The rotation of the polarization for different θ can be confirmed by the lasing pattern when the polarizer direction is fixed, as shown in Figure 5a. As θ varies, we observe the continuous rotation of the emission pattern. To obtain the polarization angle ϕ_p , we fit the y -polarized emission pattern to the intensity profile of Hermite–Gaussian modes and convert the tilt angle of the Hermite–Gaussian modes to the polarization angle in the ΓX direction. To properly analyze the polarization angle, we normalized each intensity map to a range of $[0, 1]$. A detailed description of the fitting algorithm is provided in the Supporting Information (SI, Section 4.4). Because the intensity maps were acquired at different pump

powers and normalized individually, the absolute or relative intensities among different θ values cannot be directly compared. The relative rotation of the polarization angle ϕ_p along the ΓX direction with respect to the rotation angle of θ is plotted in Figure 5b. Due to fabrication imperfections and roughness, the modes are not entirely pure, causing some emission to scatter into different k-space regions and introduce noise. The fitting is repeated 40 times with different initial conditions. The error bar represents the standard deviation of the fitting. It can be observed that the trend of the measured ϕ_p agrees well with the simulation, which confirms the nonlinear geometric phase.

The realized lasing emission can be mapped onto the equator of the HOPS with topological charge -1 ,^{38,39} as shown in Figure 5c. The concept of the HOPS extends the traditional Poincaré sphere representation, which maps uniform polarization states, to encompass beams with spatially inhomogeneous polarization. These HOPS beams are significant in various applications, including optical communications, microscopy, and quantum information processing, due to their unique properties and the ability to encode information in both their spatial and polarization structures. The controlled generation of high-purity HOPS beams at the source is nontrivial, which requires several cascaded waveplates inserted into the optical cavity. The present experiments demonstrate structural control of equatorial HOPS states corresponding to locally linearly polarized vortex beams. Extension to off-equator states with finite ellipticity remains an interesting direction for future work.

In conclusion, we demonstrate a method to control the homotopic rotation of the polarization fields by the geometric engineering of the supercell metastructure. We uncovered a new form of geometric phase in a BIC cavity with C_4 symmetry, arising from the spin–orbit coupling at an oblique angle. The geometric phase modulates the polarization of the states surrounding the BIC and effectively modulates the homotopic emission without the need for external phase plates. By integrating these nanostructures with high-quantum-efficiency core–shell colloidal quantum wells, we realize a polarization-vortex laser with tunable polarization characteristics. Our approach can be readily extended by tuning geometrical parameters or deliberately breaking symmetries to further manipulate the movement, splitting, or merging dynamics of topological charges. These results deepen the understanding of the spin–orbit interactions in BIC cavities and the topological nature of polarization fields and establish a versatile platform for structured polarization control in nanophotonic systems.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.6c02899>.

Coupled mode theory analysis and additional simulation and experimental details (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Hilmi Volkan Demir – Luminous! Center of Excellence for Semiconductor Lighting and Displays, School of Electrical and Electronic Engineering, School of Physical and Mathematical Sciences, School of Materials Science and

Engineering, Nanyang Technological University, Singapore 639798, Singapore; Department of Electrical and Electronics Engineering, Department of Physics, UNAM – Institute of Materials Science and Nanotechnology and National Nanotechnology Research Center, Bilkent University, Ankara 06800, Turkey; orcid.org/0000-0003-1793-112X; Email: hvdemir@ntu.edu.sg

Jinghua Teng – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore; orcid.org/0000-0001-5331-3092; Email: jh-teng@a-star.edu.sg

Son Tung Ha – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore; orcid.org/0000-0002-5475-8365; Email: ha_son_tung@a-star.edu.sg

Authors

Ronghui Lin – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore

Thi Thu Ha Do – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore

Emek Goksu Durmusoglu – Luminous! Center of Excellence for Semiconductor Lighting and Displays, School of Electrical and Electronic Engineering, School of Physical and Mathematical Sciences, School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore; orcid.org/0000-0001-6840-8342

Deepak K. Sharma – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore; orcid.org/0000-0002-5733-3952

Syed Akhil – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore

Vytautas Valuckas – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore

Corentin Dabard – Luminous! Center of Excellence for Semiconductor Lighting and Displays, School of Electrical and Electronic Engineering, School of Physical and Mathematical Sciences, School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore

Arseniy I. Kuznetsov – Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634, Republic of Singapore

Complete contact information is available at: <https://pubs.acs.org/doi/10.1021/acs.nanolett.6c02899>

Author Contributions

#R.-H. Lin, T. T. H. Do, and E. G. Durmusoglu contributed equally to this work. R. Lin led the numerical simulations. T. T. H. Do led the device fabrication and testing. E. G. Durmusoglu led CQW synthesis, deposition, and planarization. D. K. Sharma, S. Akhil, and V. Valuckas made contributions to

device fabrication. C. Dabard made contributions to CQW depositions. A. I. Kuznetsov, H. V. Demir, J. Teng, and S. T. Ha supervised the project and guided the manuscript preparation.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

S. T. Ha acknowledges the funding support from the Singapore National Research Funding (NRF) (NRF-F-CRP-2024-0009) & Singapore MTC Programmatic Fund, administered by A*STAR (H25-MPG3469). J. Teng gratefully acknowledges financial support from the National Research Foundation, Singapore, under NRF-CRP (NRF-CRP26-2021-0004), NRF Investigatorship Programme (NRF-NRFI10-2024-0003). H.V.D. also acknowledges support from TUBITAK 2247-A National Leader Researchers Program (121C266) and TUBA-Turkish Academy of Sciences.

REFERENCES

- (1) Nolen, J. R.; Overvig, A. C.; Cotrufo, M.; Alù, A. Local control of polarization and geometric phase in thermal metasurfaces. *Nat. Nanotechnol.* **2024**, *19*, 1627–1634.
- (2) Wang, E. W.; Phan, T.; Yu, S.-J.; Dhuey, S.; Fan, J. A. Dynamic circular birefringence response with fractured geometric phase metasurface systems. *Proc. Natl. Acad. Sci. U. S. A.* **2022**, *119*, No. e2122085119.
- (3) Kodigala, A.; et al. Lasing action from photonic bound states in continuum. *Nature* **2017**, *541*, 196–199.
- (4) Ha, S. T.; et al. Directional lasing in resonant semiconductor nanoantenna arrays. *Nat. Nanotechnol.* **2018**, *13*, 1042–1047.
- (5) Huang, C.; et al. Ultrafast control of vortex microlasers. *Science* **2020**, *367*, 1018–1021.
- (6) Hwang, M.-S.; et al. Ultralow-threshold laser using super-bound states in the continuum. *Nat. Commun.* **2021**, *12*, 4135.
- (7) Zhong, H.; et al. Ultra-low threshold continuous-wave quantum dot mini-BIC lasers. *Light Sci. Appl.* **2023**, *12*, 100.
- (8) Yu, Y.; et al. Ultra-coherent Fano laser based on a bound state in the continuum. *Nat. Photonics* **2021**, *15*, 758–764.
- (9) Han, S.; et al. Electrically-pumped compact topological bulk lasers driven by band-inverted bound states in the continuum. *Light Sci. Appl.* **2023**, *12*, 145.
- (10) Do, T. T. H.; et al. Room-Temperature Lasing at Flatband Bound States in the Continuum. *ACS Nano* **2025**, *19*, 19287–19296.
- (11) Wang, B.; et al. Generating optical vortex beams by momentum-space polarization vortices centred at bound states in the continuum. *Nat. Photonics* **2020**, *14*, 623–628.
- (12) Kang, L.; Wu, Y.; Ma, X.; Lan, S.; Werner, D. H. High-Harmonic Optical Vortex Generation from Photonic Bound States in the Continuum. *Adv. Opt. Mater.* **2022**, *10*, 2101497.
- (13) Kang, M.; Liu, T.; Chan, C. T.; Xiao, M. Applications of bound states in the continuum in photonics. *Nat. Rev. Phys.* **2023**, *5*, 659–678.
- (14) Azzam, S. I.; Kildishev, A. V. Photonic Bound States in the Continuum: From Basics to Applications. *Adv. Opt. Mater.* **2021**, *9*, 2001469.
- (15) Xu, G. et al. Recent Advances and Perspective of Photonic Bound States in the Continuum. *Ultrafast Sci.* **2023**, *3*, 0033.
- (16) Wu, M.; et al. Bound State in the Continuum in Nanoantenna-Coupled Slab Waveguide Enables Low-Threshold Quantum-Dot Lasing. *Nano Lett.* **2021**, *21*, 9754–9760.
- (17) Wu, M.; et al. Room-Temperature Lasing in Colloidal Nanoplatelets via Mie-Resonant Bound States in the Continuum. *Nano Lett.* **2020**, *20*, 6005–6011.
- (18) Wang, J.; et al. Doubly resonant second-harmonic generation of a vortex beam from a bound state in the continuum. *Optica* **2020**, *7*, 1126–1132.
- (19) Kang, M.; et al. Coherent full polarization control based on bound states in the continuum. *Nat. Commun.* **2022**, *13*, 4536.
- (20) Fagiani, L.; et al. Dual-Mode Polarization Control with Quasi-Bound States in the Continuum. *Adv. Opt. Mater.* **2024**, *12*, 2301456.
- (21) Liu, W.; Liu, W.; Shi, L.; Kivshar, Y. Topological polarization singularities in metaphotonics. *Nanophotonics* **2021**, *10*, 1469–1486.
- (22) Wang, F.; et al. Fundamentals and Applications of Topological Polarization Singularities. *Front. Phys.* **2022**, *10*, (2022). DOI: 10.3389/fphy.2022.862962
- (23) Yoda, T.; Notomi, M. Generation and Annihilation of Topologically Protected Bound States in the Continuum and Circularly Polarized States by Symmetry Breaking. *Phys. Rev. Lett.* **2020**, *125*, No. 053902.
- (24) Qin, H.; et al. Arbitrarily polarized bound states in the continuum with twisted photonic crystal slabs. *Light Sci. Appl.* **2023**, *12*, 66.
- (25) Liu, W.; et al. Circularly Polarized States Spawning from Bound States in the Continuum. *Phys. Rev. Lett.* **2019**, *123*, 116104.
- (26) Zeng, Y.; Hu, G.; Liu, K.; Tang, Z.; Qiu, C.-W. Dynamics of Topological Polarization Singularity in Momentum Space. *Phys. Rev. Lett.* **2021**, *127*, 176101.
- (27) Chen, Y.; et al. Observation of intrinsic chiral bound states in the continuum. *Nature* **2023**, *613*, 474–478.
- (28) Zhang, X.; Liu, Y.; Han, J.; Kivshar, Y.; Song, Q. Chiral emission from resonant metasurfaces. *Science* **2022**, *377*, 1215–1218.
- (29) Xie, X.; et al. Generalized Pancharatnam-Berry Phase in Rotationally Symmetric Meta-Atoms. *Phys. Rev. Lett.* **2021**, *126*, 183902.
- (30) Zhen, B.; Hsu, C. W.; Lu, L.; Stone, A. D.; Soljačić, M. Topological Nature of Optical Bound States in the Continuum. *Phys. Rev. Lett.* **2014**, *113*, 257401.
- (31) Shao, Z.; Zhu, J.; Chen, Y.; Zhang, Y.; Yu, S. Spin-orbit interaction of light induced by transverse spin angular momentum engineering. *Nat. Commun.* **2018**, *9*, 926.
- (32) Bliokh, K. Y.; Rodríguez-Fortuño, F. J.; Nori, F.; Zayats, A. V. Spin-orbit interactions of light. *Nat. Photonics* **2015**, *9*, 796–808.
- (33) Jisha, C. P.; Nolte, S.; Alberucci, A. Geometric Phase in Optics: From Wavefront Manipulation to Waveguiding. *Laser Photonics Rev.* **2021**, *15*, 2100003.
- (34) Diroll, B. T.; Schaller, R. D. Reexamination of the Giant Oscillator Strength Effect in CdSe Nanoplatelets. *J. Phys. Chem. C* **2023**, *127*, 4601–4608.
- (35) Durmusoglu, E. G.; et al. High External Quantum Efficiency Light-Emitting Diodes Enabled by Advanced Heterostructures of Type-II Nanoplatelets. *ACS Nano* **2023**, *17*, 7636–7644.
- (36) Altintas, Y.; et al. Highly Stable, Near-Unity Efficiency Atomically Flat Semiconductor Nanocrystals of CdSe/ZnS Hetero-Nanoplatelets Enabled by ZnS-Shell Hot-Injection Growth. *Small* **2019**, *15*, 1804854.
- (37) Zhan, Q. Cylindrical vector beams: from mathematical concepts to applications. *Adv. Opt. Photonics* **2009**, *1*, 1–57.
- (38) Milione, G.; Sztul, H. I.; Nolan, D. A.; Alfano, R. R. Higher-Order Poincaré Sphere, Stokes Parameters, and the Angular Momentum of Light. *Phys. Rev. Lett.* **2011**, *107*, No. 053601.
- (39) Naidoo, D.; et al. Controlled generation of higher-order Poincaré sphere beams from a laser. *Nat. Photonics* **2016**, *10*, 327–332.