

# Robust topological BIC nanocavities for upconversion directional emission

Yurui Fang

yrfang@dlut.edu.cn

Dalian University of Technology <https://orcid.org/0000-0002-3098-7681>

Yongqi Chen

Dalian University of Technology

Ming Zhu

Harbin Engineering University

Qingfeng Bian

Dalian University of Technology

Xiumei Yin

Dalian Nationalities University

Wen-Xin Wang

College of Physics and Optoelectronic Engineering, Harbin Engineering University

<https://orcid.org/0000-0001-8191-3976>

Bin Dong

Dalian Minzu University

---

## Article

**Keywords:** bound state in the continuum, oh symmetry broken, uniform direction, optical nanocavities, tunable photoluminescence

**Posted Date:** August 14th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10647363/v1>

**License:** © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**Additional Declarations:** There is no conflict of interest

---

# Robust topological BIC nanocavities for upconversion directional emission

Yongqi Chen<sup>1</sup>, Ming Zhu<sup>2</sup>, Qingfeng Bian<sup>1</sup>, Xiumei Yin<sup>3</sup>, Wenxin Wang<sup>2,\*</sup>, Bin Dong<sup>3,\*</sup>, and Yurui Fang<sup>1,\*</sup>

<sup>1</sup>. School of Physics, Dalian University of Technology, Dalian 116024, China.

<sup>2</sup>. Qingdao Innovation and Development Center, Harbin Engineering University, Qingdao, 266500, China

<sup>3</sup>. School of Physics and Materials Engineering, Dalian Nationalities University, Dalian 116600, China

\*Corresponding authors: wenxin.wang@hrbeu.edu.cn (W.W), dong@dlnu.edu.cn (B.D.), yrfang@dlut.edu.cn (Y.F.)

## Abstract:

Photonic bound states in the continuum (BICs) provide a revolutionary paradigm for boosting light-matter interactions in integrated nanocavity systems. Nevertheless, precise manipulation of open cavity-emitter architectures still faces critical challenges, especially in realizing deterministic directional radiation and suppressing the perturbation of intrinsic cavity modes induced by emitters as local impurities. Conventional investigations on cavity-emitter coupling are predominantly based on ensemble measurements, which inevitably mask the intrinsic physics underlying individual light-matter interactions. Here, we propose a robust strategy for controlling the directional upconversion and emission of an individual nanocrystal using a topological engineered plasmonic cavity with broken out of plane mirror symmetry  $\sigma_h$ . This symmetry engineering converts symmetry-protected BICs into finite-Q quasi BIC resonance, where nontrivial phase evolution and hybridization of transverse electric and magnetic modes open a well-defined far-field radiation channel for directional emission. Leveraging this scheme, we experimentally demonstrate strongly enhanced upconversion emission from an individual nanocrystal, together with uniform and deterministic directional emission, while achieving excellent structural robustness against local perturbations. This work establishes a general framework for engineering coherent directional light emission at the nanoscale, which lays a solid foundation for high-performance chip-scale integrated nanophotonic applications.

**Keywords:** bound state in the continuum,  $\sigma_h$  symmetry broken, uniform direction, optical nanocavities, tunable photoluminescence

## Introduction

Spatial manipulation and directional control of nanoscale light emission lie at the core of next-generation nanophotonic technologies, ranging from nonlinear bioimaging<sup>1–3</sup>, and single-photon sources to nanolasers<sup>4–6</sup>, dynamic metasurface modulators and on-chip photonic routing<sup>7–11</sup>. Over the past decades, extensive efforts have been devoted to enhancing spontaneous emission and radiation efficiency through plasmonic nanocavities<sup>12–17</sup>, whispering-gallery resonators<sup>18–20</sup> and surface lattice resonances<sup>21–24</sup>. While these platforms enable considerable light-matter interaction enhancement, they suffer from inherent limitations including fixed emission directionality governed by rigid mode dispersion, low quality factors, and severe mode distortion induced by local emitters acting as structural impurities<sup>25–28</sup>. These bottlenecks fundamentally restrict the realization of deterministic, robust, and high-efficiency directional emission required for high-precision imaging, holography, and multiplexed optical communication.

Topological photonics has emerged as a powerful framework to engineer robust light confinement and wave manipulation via nontrivial band topology<sup>29–34</sup>, offering unprecedented immunity to structural defects and local perturbations. Among diverse topological photonic states, bound states in the continuum (BICs) stand out as ideal candidates for extreme light localization, featuring theoretically infinite quality factors and deeply subwavelength field confinement. By breaking specific spatial symmetries, symmetry-protected BICs can be converted into quasi-BICs (q-BICs) with finite yet ultrahigh quality factors, enabling strong radiation enhancement and controllable far-field output<sup>35–40</sup>. Despite rapid progress in BIC-enabled light manipulation across various integrated platforms<sup>33,41–45</sup>, most existing studies focus on the collective response of emitter ensembles<sup>16,26,46</sup>, which inevitably blurs the intrinsic photophysical mechanisms of single-emitter radiation and directionality at the individual particle level<sup>47</sup>. Although topological cavity-emitter systems have recently emerged as a promising route to address this challenge<sup>48</sup>, to date, a universal, scalable, and low-cost platform that simultaneously achieves ultrahigh confinement, deterministic directional emission, and single-emitter compatibility in a robust topological cavity system remains largely unexplored.

Here, we theoretically design and experimentally realize a versatile platform for directional upconversion emission from a single nanocrystal (NC) by explicitly breaking the  $\sigma_h$  horizontal mirror symmetry in a topological plasmonic cavity (TPC, Fig. 1a). Leveraging mask-free guided anodization and wet chemical etching of long-range ordered porous alumina templates, we fabricate large-area plasmonic nanoantenna arrays that convert symmetry-protected BICs into finite-Q q-BICs resonance with controllable radiative leakage, opening well-defined far-field radiation channels (Fig. 1b). The engineered

TPC strongly confines optical fields at the antenna tips, yielding a deeply subwavelength mode volume ( $V_{\text{eff}}$ ). At the q-BIC resonance, we achieve more than 120-fold enhancement in the collected 550 nm upconversion PL intensity within the NA limited collection cone. This enhancement arises from the combined effects of surface lattice resonance, q-BICs outcoupling, and an increased effective radiative decay rate. The significantly boosted local density of optical states (LDOS), which spectrally overlaps with the 550 nm upconversion emission of single nanocrystals, leading to pronounced radiative enhancement. Through precise  $\sigma_h$  symmetry engineering (Fig. 1c), we achieve deterministic control over control over the emission direction of single NCs, efficiently funneling upconversion photons into well-defined directional radiation cones (Fig. 1d) with exceptional structural robustness against local perturbations. By directly integrating individual nanocrystals into the topological plasmonic lattice, our platform overcomes the limitations of conventional ensemble-based systems and establishes a general route toward nanoscale coherent directional nonlinear light sources. This work opens new opportunities for high-performance chip-scale nanophotonic applications including 3D projection imaging, directional optical antennas, and augmented reality photonic waveguides.

## Results

### TPC symmetry breaking band engineering

The boosting directional system schematic in Fig. 1a illustrates a cavity-emitter composed of our TPC and a single-NC. The periodic TPC is fabricated from an aluminum film pre-patterned with a high-density square lattice of nanopores (Fig. 1b, left). A two-step anodization process<sup>49</sup> followed by wet chemical etching is employed to convert this nanopore array into well-defined topological plasmonic cavity (Fig. 1b, right and Supplementary Fig. S3). This lithography-free method enables large-area fabrication of ordered nanostructures and is compatible with flexible electronics and nanophotonic applications. The resulting array, with a lattice constant of  $a = 400$  nm, is shown in the SEM image in Fig. 1b. At the intersection points of the grid, aluminum nanocones are located, while intercell ridges are shown along the grid lines. In large-area TPC, monodisperse upconversion NCs (Fig. 1a and Supplementary Fig. S5) were deposited onto the TPC, with single-NC lying horizontally filling the inter-cellular gaps, as shown in the inset of Fig. 1a.

To illustrate the above picture, we start from a standard photonic crystal template. When the incident light is reflected by the traditional flat periodic structure, its wavefront is partially shaped by the dispersion

relation of the optical resonance. Specifically, the interaction between the incident light and the periodic structure can be decomposed into two processes: part of the energy is directly reflected by the TPC without coupling to the resonant mode, while the other part excites the resonance and radiates<sup>40</sup>. At resonance, the enhancement factor of the single resonance intensity in the open cavity can be described by the temporal coupled-mode<sup>50</sup>:

$$G = \frac{|E_{\text{loc}}|^2}{|E_i|^2} \approx \kappa_i^2 \frac{Q_{\text{tot}}^2}{V_{\text{eff}}} = \frac{Q_{\text{tot}}^2}{Q_r V_{\text{eff}}} = \frac{Q_r^2 Q_a^2}{Q_r (Q_r + Q_a)^2 V_{\text{eff}}}, \quad (1)$$

where  $E_{\text{loc}}$  and  $E_i$  represent the localized field and the input field, respectively.  $\kappa_i$  is the coupling coefficient with the external input field, which depends on the radiation channel and is expressed as  $\kappa_i = \sqrt{2\gamma_r}$ , where  $\gamma_r = \omega / (2Q_r)$  denotes the radiative loss.  $\omega$  and  $Q_r$  represent the angular frequency and the radiative quality factor, respectively. In a lossy plasmonic structure, the total quality factor  $Q_{\text{tot}}^{-1}$  is defined as  $Q_{\text{tot}}^{-1} = Q_r^{-1} + Q_a^{-1}$ , which combines the radiative loss  $Q_r^{-1}$  and the non-radiative loss  $Q_a^{-1}$ .  $V_{\text{eff}}$  denotes the normalized effective mode volume. For an undeformed lattice array, when the incident light wavelength matches the resonance wavelength of the BIC mode, the symmetry-protected BIC mode at normal incidence ( $\Gamma$  point) is decoupled from the plane wave resonance mode. Consequently, the ideal BIC cannot be excited by the incident light or coupled to the far field, as shown in the left of Fig. 1b. While it possesses perfect spatial purity due to its symmetry, this also results in a vanishing field enhancement factor ( $G = 0$ ) and precludes any useful energy exchange or information flow. Trade-off Eq. (1), maximization of the field enhancement factor  $G$  which converges to the critical state can be achieved by the radiative losses balancing the non-radiative losses ( $Q_r = Q_a$ )<sup>51,52</sup>. Therefore, out of plane mirror symmetry breaking was intentionally introduced into the aluminum lattice to relax the far-field selection rules and convert the symmetry protected dark BIC into finite  $Q$  quasi BIC resonances. This transition introduces controlled radiative leakage channels, while the nanocone geometry provides localized localized plasmonic hotspots and reduced effective mode volume ( $V_{\text{eff}}$ ). Based on the undeformed flat crystal, we fabricated the TPC, as illustrated in the right panel of Fig. 1b. The three-dimensional morphology of the TPC was reconstructed as accurately as possible from AFM scanning images, with its thickness estimated to be approximately 220 nm based on the measured height difference (Supplementary Fig. S4).

As the wet-etching process gradually transforms the columnar lattice into a nanocone geometry (Fig. 1c), the out-of-plane mirror symmetry  $\sigma_h$  is broken while the in-plane square-lattice symmetry is largely

preserved. This symmetry breaking relaxes the parity selection rule of the vertically symmetric modes, allowing originally dark modes to couple to radiative channels<sup>53–55</sup>. Meanwhile, the transverse electric-like and magnetic-like modes become hybridized, further opening far-field radiation channels<sup>56</sup>. As the tip of the lattice became lower, the radiative angle was tuned (Fig. 1d). In addition, the fundamental  $m = 0$  mode characterized by a vertically oriented electric dipole, does not exist in symmetric lattices owing to the constraint of mirror symmetry. The field concentration near the tip produces an ultra-small optical mode volume and substantial field enhancement through geometric focusing. Consequently, the  $m = 0$  mode provides an efficient pathway for light–matter interaction enhancement and serves as a radiative channel complementary to the symmetry-protected q-BICs in the plasmonic cone array.

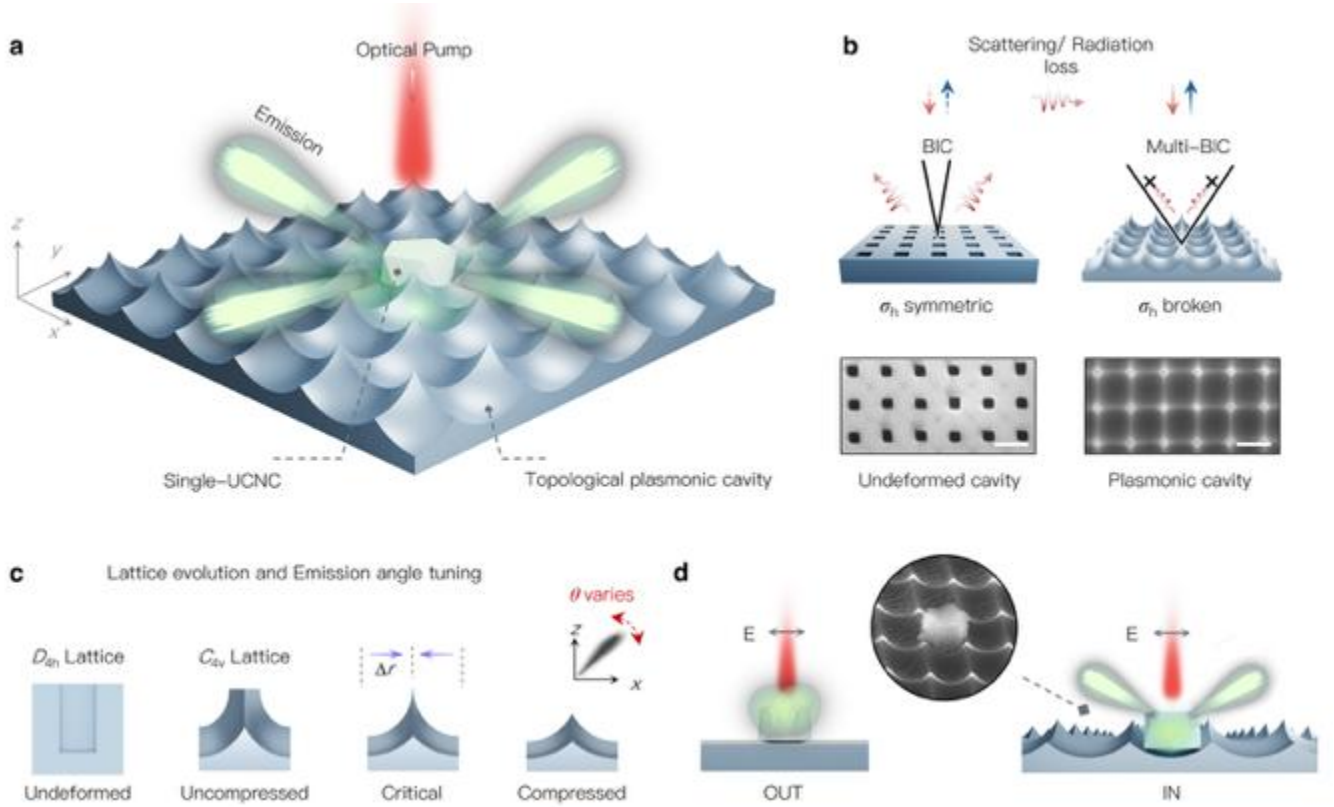


**Figure 1 Upconversion light field modulation of single-NC by  $\sigma_h$  Symmetry-broken TPC.** **a**, Schematic of the hybrid cavity-emitter system composed of a single-NC embedded in TPC. The periodic plasmonic nanostructures have a tetragonal lattice and form nanocones at the center of lattice. **b**, Left: In a  $\sigma_h$  symmetric (undeformed) lattice, the symmetry-protected quasi-boundary excited state at the  $\Gamma$  point has extremely low radiation loss but weak coupling with free-space excited states, while also exhibiting limited emission field confinement. Right: Breaking  $\sigma_h$  symmetry transforms the lattice into an out of plane asymmetric plasmonic cavity, which supports multiple q-BIC resonance with finite radiative leakage. The bottom panel shows scanning electron microscope (SEM) images of undeformed and

deformed plasmonic lattices, with a scale bar of 400 nm. **c**, the evolution of the lattice geometry from the undeformed state ( $D_{4h}$ ) to the compressed state ( $C_{4v}$ ) leads to a transition from q-BIC to multi-BIC. The tip of the compressed  $C_{4v}$  lattice is used to achieve a tunable emission angle. The emission direction  $\theta$  continuously evolves with structural deformation, accompanied by the underlying band topology. **d**, Schematic illustrating directional control of upconversion emission. Without cavity coupling (OUT), emission is isotropic. In contrast, when embedded in the TPC (IN), the NC emission is funneled into well-defined lattice plasmonic mode cones, resulting in sharply confined directional radiation under normal incidence.

We highlight the evolution from symmetry-protected states to radiative states and the control mechanism for directional emission by comparing the evolution of the energy band structure in the plasmonic lattice across the breaking  $\sigma_h$  symmetry. As shown in the top panel of Fig. 2a, the undeformed lattice of the two-dimensional square array belongs to the  $D_{4h}$  symmetry group, exhibiting reflection symmetry  $\sigma_h$  in the horizontal ( $x$ - $y$ ) plane. The corresponding TM-like polarized band structure is shown in Fig. 2a, where four bands are identified within the frequency range of interest. At the  $\Gamma$  point, the three-dimensional mode distribution of the low-frequency band ( $\Gamma_1$ , 616 nm) exhibits a quadrupole mode (Fig. 2d), while the high-frequency band exhibits a dipole mode (see Supplementary Fig. S1). Bands 2 and 3, under the  $D_{4h}$  symmetry, form a degenerate pair characterized by distinct symmetry-protected modal distributions.

The undeformed lattice, after wet chemical etching, exposes the underlying barrier layer, breaking the  $\sigma_h$  mirror reflection symmetry of the  $D_{4h}$  point group (top panel of Fig. 2b) and transforming the undeformed lattice into a plasmonic lattices ( $C_{4v}$ ) with a nanocone geometry (corresponding to the critical lattice in Fig. 1c). By tuning the compression parameter  $r$ , we force the bands to form accidental degeneracy near the  $\Gamma$  point, and the corresponding band structure of the plasmonic cone-shaped lattice is shown in Fig. 2b. Under these ideal conditions ( $r = a/2$ ), the perfect plasmonic lattice exhibits single-degenerate  $\Gamma_1$  and  $\Gamma_4$  modes at the  $\Gamma$  point, which overlap with the doubly degenerate  $\Gamma_{2/3}$  mode. This results in a fourfold degeneracy and a band gap closure, rendering the Zak phase ill-defined. As shown in Fig. 2c, to isolate the BIC mode, we further compressed the plasmonic nanocones, resulting in a topological plasmonic lattice configuration with  $\Delta r > a/2$  (corresponding to the compressed lattice in Fig. 1c). The corresponding band structure reveals a lifted degeneracy of the  $\Gamma_4$  mode, where the frequency shift of these bulk guided modes effectively prepares the system for the deterministic control of radiation directionality. At the upper band  $\Gamma$  point ( $\Gamma_4$ ), the three-dimensional mode profile retains the characteristic

quadrupolar field distribution of the undeformed unit cell (Fig. 2f). Although the  $E_z$  component of the lower band mode is also a quadrupole BIC mode, it is submerged in band 2, 3. In contrast, when the nanocones compression parameter crosses the critical value with  $\Delta r = a/2$  (Fig.1c), the band structure undergoes gap closing and reopening, accompanied by a Zak phase transition and modal inversion (see Supplementary Fig. S17).

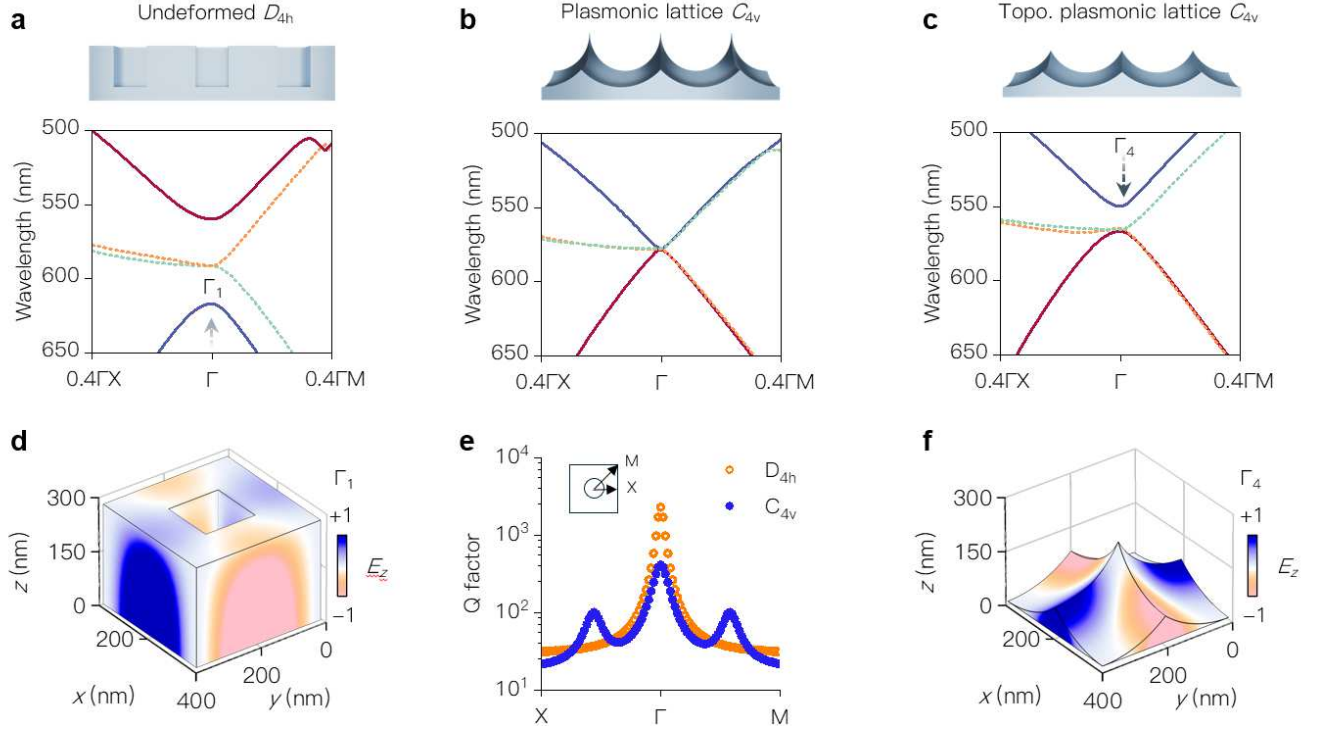


**Figure 2 Out of plane symmetry breaking and topological band reconstruction in the plasmonic quasi BIC cavity.**

**a**, Schematic and TM-polarized band structure of an undeformed square lattice with  $D_{4h}$  symmetry, which preserves horizontal mirror symmetry ( $\sigma_h$ ). Four photonic bands are observed near the frequency range of interest. At the  $\Gamma$  point, the lowest-frequency mode ( $\Gamma_1$ , 616 nm) exhibits a quadrupolar field distribution (shown in **d**). Bands 2 and 3 form a degenerate pair ( $\Gamma_{23}$ ) protected by symmetry. **b**, In plasmonic lattice with cone-shaped geometry ( $C_{4v}$  symmetry),  $\sigma_h$  symmetry is broken via guided anodization and wet etching to reach a critical state ( $\Delta r = a/2$ , corresponding to the critical lattice in Fig. 1c). The resulting band structure features accidental degeneracy at the  $\Gamma$  point between  $\Gamma_1$ ,  $\Gamma_4$ , and  $\Gamma_{23}$  modes. **c**, Further compression of the plasmonic nanocones to  $\Delta r > a/2$  (corresponding to the compressed lattice in Figure 1c), lifts the degeneracy of  $\Gamma_4$ , resulting in a topological plasmonic cavity with finite mode volume and well-separated bands. The upper  $\Gamma_4$  mode preserves quadrupole symmetry, as visualized in **f**. **d**, Three-dimensional field distribution ( $E_z$  component) of the  $\Gamma_1$  mode in the undeformed lattice. **e**, Q-factor evolution of BIC modes for both undeformed ( $D_{4h}$ ) and  $\sigma_h$  symmetry-broken ( $C_{4v}$ ) plasmonic lattices. The BIC in the  $D_{4h}$  lattice exhibits a high Q-factor, while symmetry breaking produces multiple q-BICs with finite simulated Q factors ( $\sim 10^3$ ). **f**, Three-dimensional  $E_z$  field profile of the  $\Gamma_4$

mode in the compressed topological plasmonic cavity, retaining a quadrupolar character but now with controlled radiative leakage.

This behavior indicates that, in addition to the conventional dynamical phase, the crystal band also acquires a topologically nontrivial geometric phase during the optimization of the sharp cone. For the quadrupole bands in both lattices, the band at the Brillouin zone center of the undeformed lattice exhibits a theoretical BIC with an infinite Q-factor, as indicated by the dashed line in Fig. 2e. In the topological plasmonic lattice ( $\Delta r > a/2$ ), breaking the  $\sigma_h$  mirror symmetry transforms the q-BIC into a multi-BIC (the three peaks in Fig. 2e and black arrows indicated in Fig. 3e) with a finite Q-factor ( $\sim 10^4$ ), thereby enabling controlled energy leakage to external plane waves, as shown by the solid line in Fig. 2e. Notably, the topological plasmonic lattice supports multi-BIC<sup>57</sup>, which compared to the q-BIC, exhibit a broader confinement angle in momentum space. This feature further enriches the system's directional emission characteristics.

To experimentally characterize the dispersion properties of the plasmonic lattices with broken  $\sigma_h$  mirror symmetry, we have established an angle-resolved scattering spectroscopy (ARSS) setup based on a  $4f$  optical system capable of rapidly switching between real and momentum space (Supplementary Materials Fig. S9). We measured the ARSS of the prepared undeformed lattice cavity, plasmonic cavity, and topological plasmonic cavity, and compared them with the angle-resolved reflection spectra (ARRS) from rigorous numerical simulations based on finite-element method.

As shown in Fig. 3, the experimental ARSS (a–c) and simulated ARRS (d–f) provide a comprehensive map of the lattice evolution and its impact on radiation. For the undeformed cavity (Figs. 3a, d), the spectra confirm the presence of a symmetry-protected BIC at the  $\Gamma$  point. Upon breaking the  $\sigma_h$  mirror symmetry (Figs. 3b, e,  $\Delta r = a/2$ ), the emergence of localized surface plasmon resonances (LSPR, red arrows) and multi-BIC modes (black arrows) serves as a clear signature of the deformed nanocone geometry. These characteristics contribute to local field enhancement, more importantly, the deterministic control of emission direction is mainly driven by multiple BIC modes generated through strong coupling between TE and TM modes. This coupling reshapes the entire radiative field in momentum space, directing the upconversion output into specific angular channels.

Crucially, the introduced  $\sigma_h$  symmetry breaking lifts the modal orthogonality, inducing a TE and TM modes hybridization that manifests as a distinct flat band intersecting the TM dispersion branches. This

hybridization is clearly observed in both experimental and simulated spectra (Figs. 3b, e), becoming more pronounced in the fully compressed topological cavity (Figs. 3c and f,  $\Delta r > a/2$ ). This mechanism effectively opens a specific radiation channel at 550 nm; because the hybridized band is remarkably flat, it possesses a near-zero group velocity, facilitating the efficient leakage of trapped light into a deterministic far-field direction. The high degree of consistency between the experimental ARSS and simulated ARRS confirms that this mode-coupling-induced leakage channel establishes the requisite physical foundation for the directional enhancement of upconversion emission from single quantum emitters.

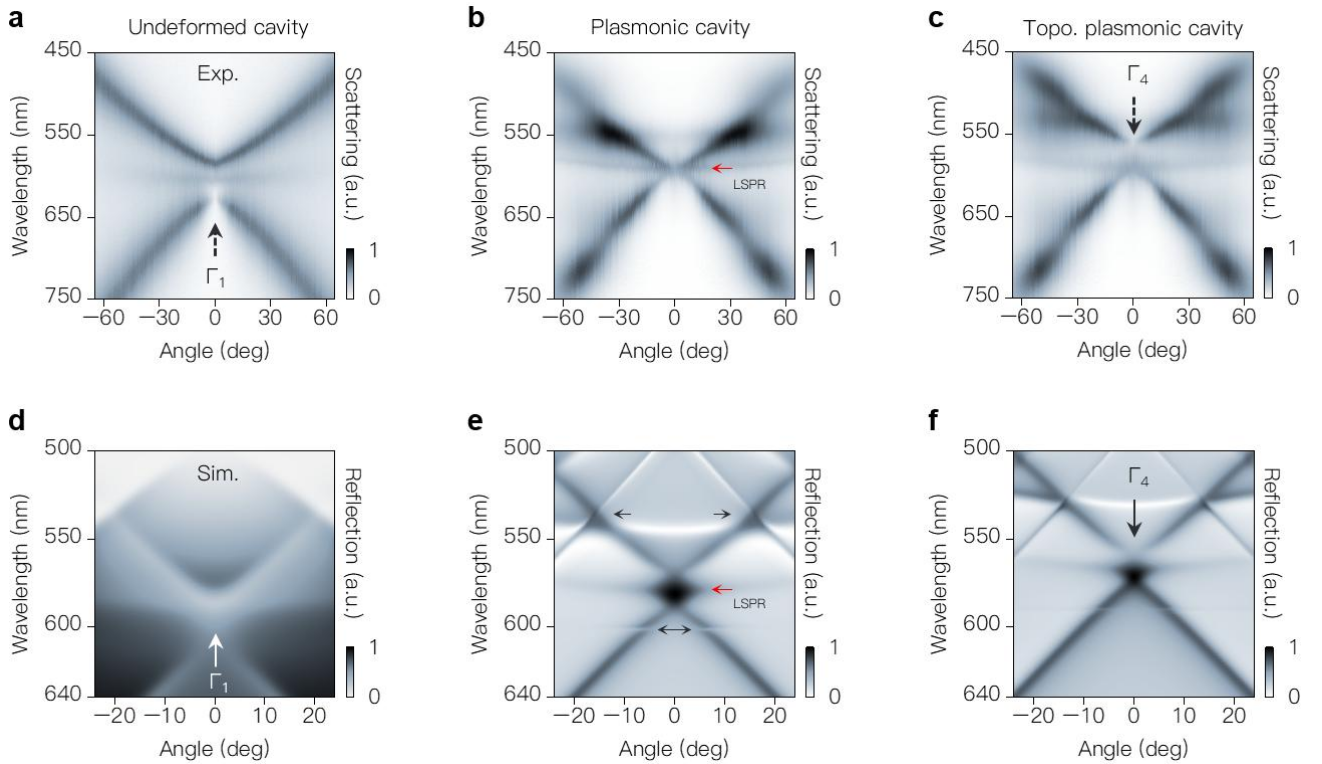


**Figure 3 Angle-resolved spectroscopy reveals topological phase transition and the emergence of LSPR after  $\sigma_h$  symmetry breaking.** **a–c**, Experimental ARSS of the (a) undeformed cavity, (b) plasmonic cavity, and (c) topological plasmonic cavity. The undeformed  $D_{4h}$ -symmetric cavity (a) supports a q-BIC at the  $\Gamma$  point in the lower-frequency  $\Gamma_1$  band, exhibiting vanishing reflectance due to its decoupling from the far field. Upon  $\sigma_h$  symmetry breaking (b), the lattice evolves into a  $C_{4v}$  symmetric plasmonic cavity, leading to an accidental fourfold degeneracy at the  $\Gamma$  point ( $\Delta r = a/2$ ), characterized by band touching and topological phase ill-definition. Further compression of the nanocones (c,  $\Delta r > a/2$ ) lifts this degeneracy, resulting in the emergence of a finite Q q-BIC associated with the  $\Gamma_4$  band in the upper band near 550 nm. Together with the calculated Zak-phase exchange and  $\Gamma$ -point modal inversion, the gap closing and reopening indicate a topological band inversion. **d–f**, Corresponding simulated ARRS of the three cavities, compared with simulated

angle-resolved resonance spectra. The  $\Gamma_1$  mode in the undeformed cavity (d) remains dark at the  $\Gamma$  point, while in the plasmonic cavity (e), a distinct localized surface plasmon resonance state emerges near the flat band (red arrow), arising from the extremely compressed cone tips. This LSPR persists in the topological plasmonic cavity (f), alongside the finite Q multi-BIC mode ( $\Gamma_4$  black arrow).

## Far- and near-field characterizations

To elucidate the near-field enhancement and directional emission characteristics of BIC modes, we conducted both near-field and far-field analyses for the undeformed and topological plasmonic cavities. Figs. 4a and 4b show the simulated  $xz$ -plane electric field profiles ( $E_z$ ) at the BIC resonance wavelengths for the conventional BIC ( $\Gamma_1$ ) and the finite Q q-BIC mode ( $\Gamma_4$ ), respectively. The undeformed cavity exhibits vertical symmetry and a flat-top surface, with its near-field enhancement effect confined within the cavity. In contrast, the topological plasmonic cavity exhibits significant electric field localization (highest LDOS) small mode volume at the nanocone tip (Supplementary Materials, Note 2 ), this is attributed to the extreme mode compression caused by the geometric conical structure, which enhances the surface electric field intensity through strong field hotspots. Additionally, the angular distribution of the induced scattered light under normal incidence conditions is redistributed, as indicated by the tilted field lobes in Fig. 4b.

To further investigate the spatial extent of field localization, we simulated the normalized electric field distributions in the  $xy$ -plane over a  $6 \times 6$  supercell (Figs. 4c and 4d). In the undeformed cavity ( $D_{4h}$  symmetry, Fig. 4c), the near field extends into the surrounding air, indicating weak lateral confinement. In contrast, the topological plasmonic lattice ( $C_{4v}$  symmetry, Fig. 4d) demonstrates strong in-plane field confinement, primarily due to the formation of multiple finite-Q BIC modes within the unit cell. This effective confinement forms the basis for enhanced light–matter interaction in the system.

We next evaluated how these two cavity types modulate the far-field radiation pattern of an embedded single-NC, modeled as a point electric dipole at the center of the supercell. As shown in Figs. 4e and 4f, the undeformed cavity directs the emission into three main beams, including a prominent vertical lobe, whereas the topological cavity suppresses vertical emission and promotes dual-beam radiation at oblique angles ( $\sim 56^\circ$ ). This directional pattern is a direct manifestation of the symmetry-broken q-BIC nature of the  $\Gamma_4$  mode, where vertical dipole components are suppressed and lateral radiation dominates.

The deterministic steering of upconversion emission through structural deformation is demonstrated in Figs. 4g and 4h. In the uncompressed nanocone lattice ( $\Delta r = 0.4a$ , Fig. 4g), a single-NC radiates two closely spaced emission beams under x-polarized excitation. However, as the lattice is further compressed to  $\Delta r = 0.55a$  (Fig. 4h), these beams undergo significant angular separation, resulting in highly directional emission. This evolution confirms that the  $\sigma_h$  symmetry breaking, combined with the deliberate lattice design, induces strong TE and TM mode coupling, providing a robust physical mechanism for tailoring far-field radiation. Fig. 4i quantitatively summarizes this angular tunability by superimposing emission curves across various nanocone radii, demonstrating that this mode-hybridization-driven approach enables precise control over the emission angle from a single point source.

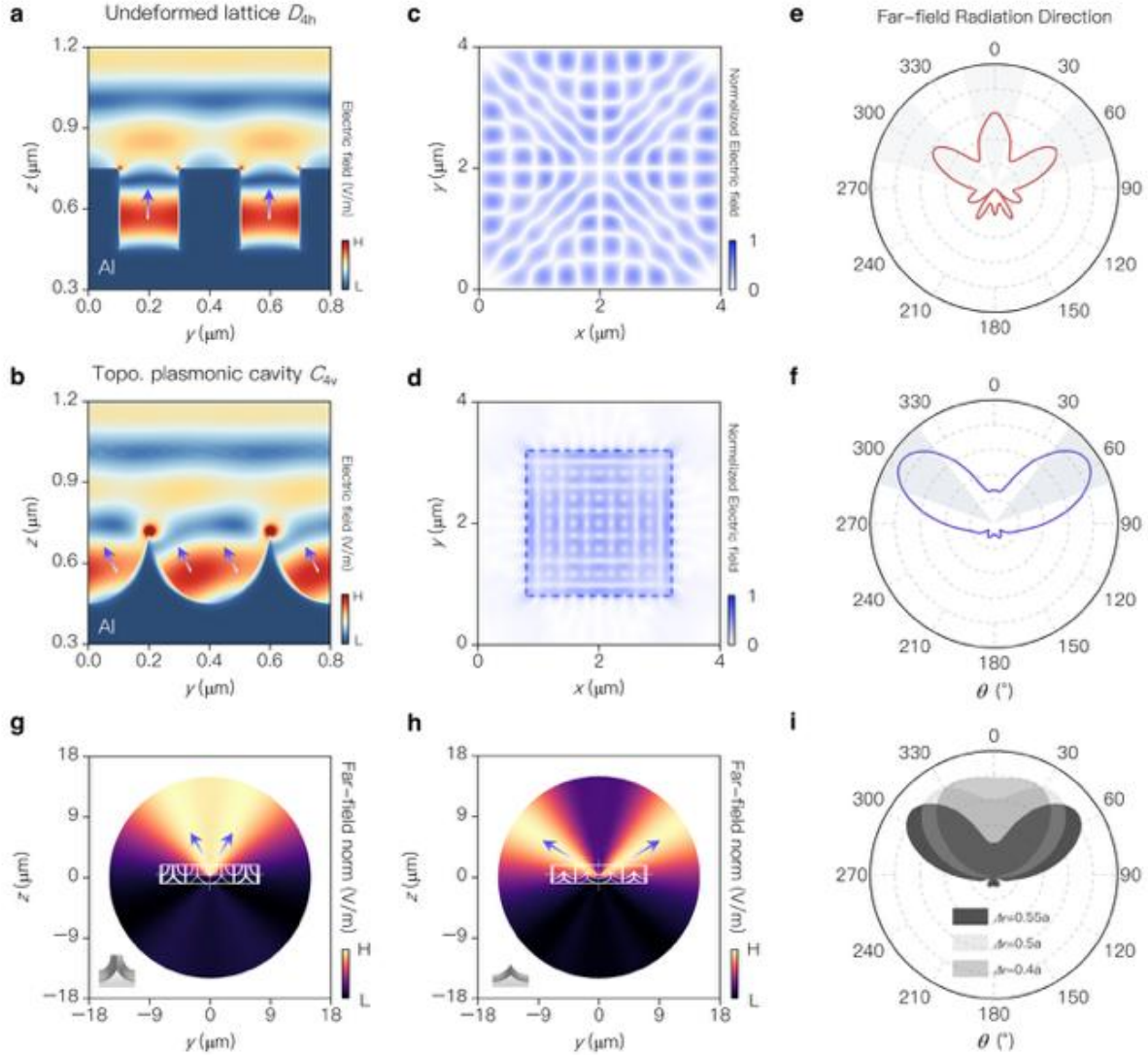


**Figure 4** Near-field enhancement and directional emission of undeformed and topological plasmonic cavities. **a,b,** Simulated  $xz$ -plane electric field profiles at the BIC resonances of the undeformed ( $\Gamma_1$ ) and topological plasmonic ( $\Gamma_4$ )

cavities. The blue arrow emphasizes the near-field Poynting vector. **c,d**,  $xy$ -plane near-field maps over a  $6\times 6$  supercell reveal improved in-plane confinement in the topological cavity due to multi-BIC formation. **e,f**, Far-field emission profiles for a single upconversion dipole placed at the supercell center: the topological cavity suppresses vertical emission and supports two symmetric large-angle beams. **g,h**, Far-field distributions under  $x$ -polarized excitation for cone base radii  $\Delta r = 0.4a$  and  $\Delta r = 0.55a$ ; increasing  $\Delta r$  leads to beam divergence. **i**, Polar plot of emission angle  $\theta$  for different cone radii, demonstrating emission angle control via nanocone tapering.

## Experimental demonstration

To verify the robustness of the topological plasmonic cavity against local perturbations, we characterized the system's response upon the introduction of a single upconversion nanoparticle (UCNP,  $\sim 400$  nm diameter) into the lattice. For comparison, the emission of an isolated UCNP on a flat aluminum film characterized by near-isotropic radiation and broad angular distribution is detailed in the Supplementary Note 11. Fig. 5a presents the simulated and measured mode distributions of the cavity before and after the placement of the nanoparticle. Despite the presence of the sub-wavelength scatter, the BIC mode remains spatially stable and structurally intact. This visual consistency confirms that the topological nature of the cavity suppresses scattering loss into the continuum, maintaining a high-quality factor even with local symmetry breaking.

This robustness is further quantitatively validated by the experimental angle-resolved scattering spectra shown in Fig. 5b. The angular dispersion remains remarkably clean and well-defined after the nanoparticle loading, with the characteristic resonance features showing negligible broadening or shift. The fact that the cavity's momentum-space signature is preserved against small-particle scattering highlights the practical advantage of using topologically protected states for stable, directional light-matter interactions.

However, in the absence of structural modulation or symmetry-defined mode selection, free-space NC emission remains omnidirectional, resulting in poor far-field coupling and limited suitability for directional beam shaping. To overcome this limitation and to explore cavity-enhanced emission dynamics, we deposited a dilute dispersion of NCs directly onto the topological plasmonic cavities. Due to the comparable size between the NC particles and the lattice pitch, isolated NC preferentially settle into the interstitial sites of the lattice, forming well-defined NC-cavity hybrid systems. One such NC particle was found to be precisely positioned at the center of a four-unit supercell gap (see Supplementary Fig. S7).

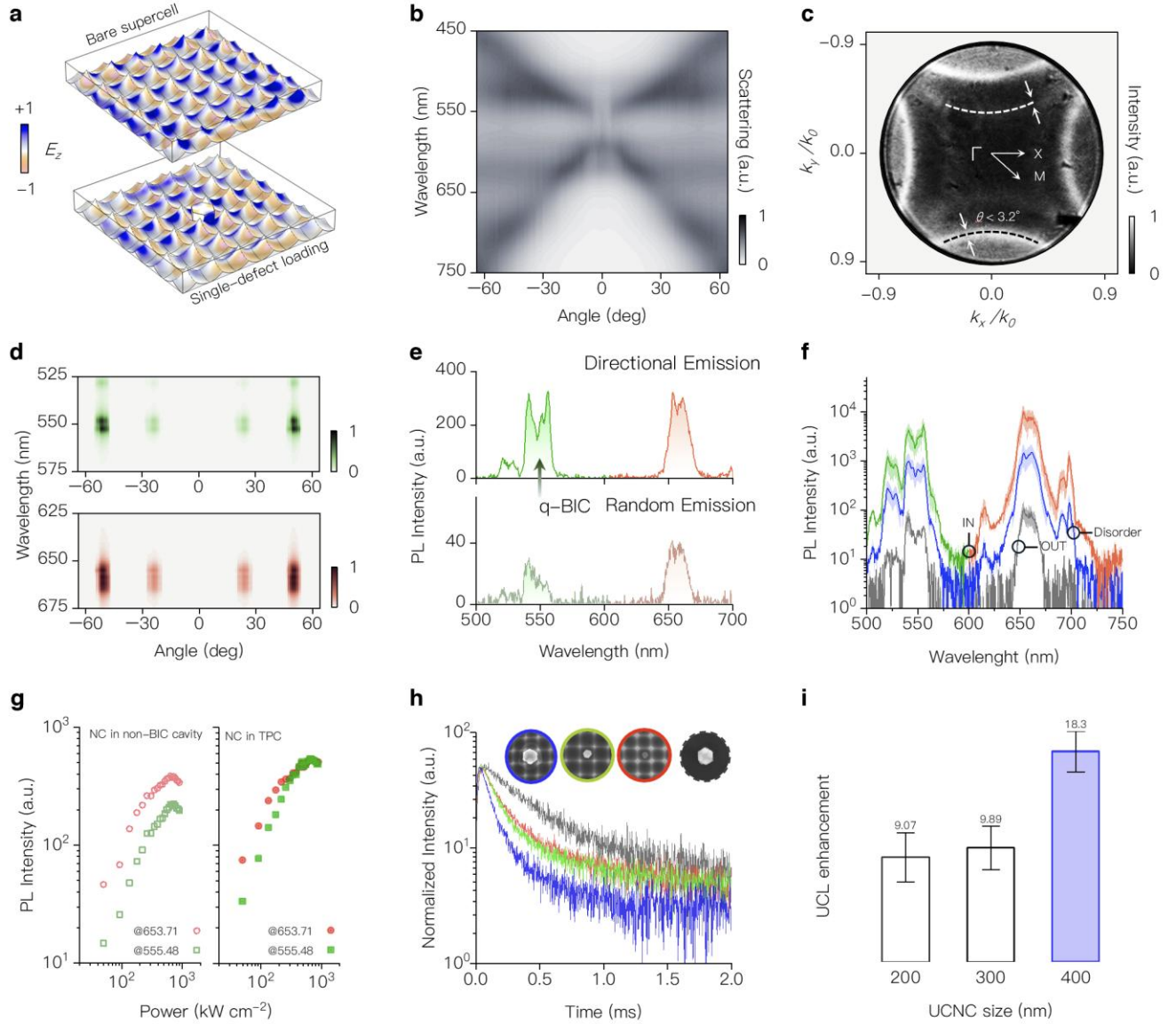


**Figure 5 Directional beam shaping and Purcell-enhanced upconversion emission from a single-NC coupled to TPC.**

**a.** Simulation of the real-space mode distribution of a topological plasmonic cavity before and after loading a single 400 nm upconversion nanoparticle (UCNP). **b.** Experimental ARSs of the cavity loaded with a single UCNP. **c.** Fourier-plane image of a single NC coupled to TPC, revealing a highly directional crescent-shaped emission cone confined within  $\pm 3.2^\circ$  (black dashed arc), indicating strong coupling between the NC and the multi-BIC of the TPC. A weaker secondary emission cone is also observed at  $\pm 26^\circ$  (white dashed arc). **d.** Angle-resolved photoluminescence spectrum of the single-NC-TPC hybrid along the X- $\Gamma$ -X direction. The outer ring ( $\pm 56^\circ$ ) and inner ring ( $\pm 26^\circ$ ) exhibit narrow-band strong emission aligned with the open radiation channel between multi-BICs. **e.** Comparison of emission spectra between a NC outside (bottom) and inside (top) the TPC. The 550 nm emission ( $^4S_{3/2} \rightarrow ^4I_{15/2}$ ) is significantly enhanced due to spectral

overlap with the high-Q cavity mode. **f**, Real-space overall upconversion emission spectra of a single-NC on a flat Al substrate (OUT, grey curve), inside a disordered nanocavity array (Disorder, blue curve), and inside the periodic TPC (IN, green/red curves). The solid lines and corresponding shaded error bands represent the mean intensities and standard deviations, respectively, derived from six independent single-particle measurements for each configuration. **g**, Power-dependent ARPL spectra showing emission enhancement dynamics. Single NC in disordered lattice (left) and TPC (right). With increasing 980 nm excitation power, the 550 nm emission overtakes the 650 nm transition, indicating cavity mode field enhancement induced by q-BIC. **h**, Time-resolved PL decay curves at the 550 nm emission of single-NCs with different diameters (200 nm red, 300 nm green, 400 nm blue) deposited on the TPC vs. a 400 nm NC on a flat substrate. The 400 nm NC shows the greatest lifetime reduction, indicating strong radiative rate enhancement via Purcell effect. **i**, Extracted Purcell factors for NCs of different sizes. A maximum Purcell factor of  $\sim 18.3$  is achieved for 400 nm NCs.

Under 980 nm excitation, the upconverted PL from the TPC and single-NC hybrid was projected to the Fourier back focal plane (Fig. 5c). The NC emission, which originally displayed near-isotropic radiation on a flat aluminum film (detailed in Supplementary Materials Note 8), is now reshaped into a sharp, crescent-shaped emission cone in momentum space (outlined by the black dashed arc). The measured angular divergence is below  $3.2^\circ$ , representing a dramatic enhancement in directionality. This behavior is fundamentally governed by the synergistic effect of the multi-BICs and the specifically tailored cavity fields induced by  $\sigma_h$  symmetry breaking. The engineered lattice periodicity effectively reconfigures the emission branches, constraining the radiation to the low Q region between the  $\Gamma$ -point BIC ( $0^\circ$ ) and the off- $\Gamma$  BIC ( $30^\circ$ ), see Supplementary Materials Note 5.

The periodic plasmonic potential reshapes the wavevector of the upconverted light, effectively folding it into Bloch modes governed by the cavity symmetry. Notably, the crescent deformation near M point reflects a gradual breakdown of the designed momentum constraint, where coupling to off-symmetry SPP modes becomes less efficient (56). Thus, the engineered lattice modulates both the spatial and angular distribution of a single emitter, enabling well-defined directional upconversion at the nanoscale. The appearance of this sharply confined momentum-space feature confirms the efficient coupling between the NC emission and the designed plasmonic multi-BIC states.

Angle-resolved photoluminescence measurements were performed on a single-NC coupled to a topological plasmonic cavity, and momentum space profiles were obtained by scanning along the highly symmetric X- $\Gamma$ -X direction (Fig. 5d). The outer emission ring corresponding to  $\pm 56^\circ$  appears particularly bright and spectrally narrow, marking the polarization exciton mode emission cone (black dashed arc in Fig. 5c). Its characteristics in momentum space are highly similar to those of finite-Q q-BIC in the cavity

band structure (see Supplementary Fig. S11), indicating that upconversion emission can be strongly influenced by the underlying plasmonic dispersion. Additionally, a weaker inner ring centered at  $\pm 26^\circ$  also appears (the white dashed arc in Fig. 5c), which is not clearly visible in the original Fourier plane image. Spectrally, the directional character of the cavity-enhanced emission is evident in Fig. 5e. The spectrum of the cavity-coupled NC was acquired at the  $56^\circ$  q-BIC radiation cone, where the emission is preferentially funneled by the cavity. In contrast, the reference NC outside the cavity emits nearly isotropically and shows no comparable enhancement at the same collection angle. The resulting increase of the 550 nm  $\text{Er}^{3+}$  emission demonstrates that the q-BIC cavity redirects spontaneous emission into a well-defined radiation channel.

To investigate the enhancement of upconversion emission in the  $\sigma_h$  symmetry-broken nanocavity, micro-area measurements of upconversion emission from single-NC was conducted. Fig. 5f compares the upconversion emission signals of a single-NC placed on a flat reference substrate (OUT, grey curve), inside a disordered nanocavity array (Disorder, blue curve, see Supplementary Note 12), and inside the TPC (IN, green/red curves). The discrepancy in enhancement factors occurs because Fig. 5e represents a localized measurement at a specific  $(k_x, k_y)$  point, whereas Fig. 5f accounts for the total real-space PL collected over the NA-limited collection cone of the objective. Thus, Fig. 5f accounts for all experimentally collected radiative channels integrated within the  $\text{NA} = 0.9$  collection range, rather than a single  $k$  spectrum. The directional nature of this enhancement is further illustrated by the angle-resolved photoluminescence measurements along the  $X-\Gamma-X$  trajectory (Supplementary Fig. S21). Statistical measurements reveal that the periodic TPC produces an average 120-fold enhancement, reaching a maximum of 147-fold, in the background-subtracted collected PL intensity at the 550 nm emission band. In comparison, the disordered nanocone array, which preserves the local nanocone geometry but suppresses long-range periodicity and q-BIC formation, yields a 23-fold enhancement. This comparison indicates an additional  $\sim 5.2$ -fold contribution from periodic-lattice-enabled q-BIC coupling and directional outcoupling (Supplementary Fig. S22). The two order of magnitude enhancement arises from the synergy between the small  $V_{\text{eff}}$  nanocone LSPR hotspots and the finite-Q q-BIC resonances that provide directional outcoupling. This enhancement becomes more apparent under power-dependent excitation. As shown in Fig. 5g, compares the power-dependent ARPL spectra of a single NC in a non-BIC disordered lattice (left) versus the TPC (right), with increasing pump intensity, the 550 nm emission gradually increases and eventually surpasses the 650 nm off-resonant transition, indicating q-BIC provides

cavity mode field enhancement. This crossover indicates cavity-selected directional upconversion through q-BIC assisted mode selection.

To quantify the Purcell enhancement within the nanocavity, we performed time-resolved PL measurements at the 550 nm emission band using pulsed 980 nm excitation for TSCPC analysis (Supplementary Materials Note 4). We recorded the decay curves at the 550 nm emission for single-NCs with varying diameters (200 nm, 300 nm, and 400 nm) on the TPC, using a 400 nm NC on a flat aluminum film as a reference (Fig. 5h). A distinct acceleration in the radiative transition rate is observed as the NC diameter increases, with the 400 nm NC showing the most significant lifetime shortening. The apparent Purcell factors, estimated from lifetime shortening relative to the flat-Al reference, are compared in Fig. 5i, with the 400 nm NCs showing the largest apparent Purcell enhancement of ~18.3-fold enhancement. The corresponding UCL decay kinetics and analysis details are provided in the Supplementary Materials Note 6. The stronger apparent Purcell enhancement observed for 400 nm NCs is attributed to their improved spatial overlap with the distributed q-BIC field and their closer coupling to nanocone-tip hotspots. (Supplementary Materials Note 3 and 4).

## Conclusion

In summary, we have experimentally demonstrated significantly enhanced directional upconversion emission from a single nanocrystal (NC) enabled by a  $\sigma_h$  symmetry-broken topological plasmonic cavity platform. We developed a mask-free, high-throughput, and low-cost fabrication strategy based on guided anodic oxidation and wet chemical etching to realize TPC architectures with explicitly broken  $\sigma_h$  mirror symmetry. By breaking the vertical mirror symmetry, we drive the transition of the lower-branch lattice plasmonic mode from symmetry-protected bound states in the continuum to high-quality-factor multi-BIC regimes at the  $\Gamma$  point, which generates intense localized surface plasmon resonance hotspots and simultaneously opens controllable far-field radiation channels. The plasmonic lattice is judiciously engineered in momentum space such that its q-BIC resonance spectrally overlaps with the characteristic 550 nm upconversion emission of dopant ions, thereby enabling bright, directional, and strongly amplified upconversion radiation from a single NC.

This work explicitly unveils the physical mechanism underlying q-BIC-enhanced upconversion luminescence and directional far-field emission of single nanocrystals in periodic plasmonic lattices, establishing a low-cost, high-efficiency nanoscale coherent light source with locked and controllable

wide-angle emission directionality. Benefiting from the strong coupling between q-BIC modes and single emitters in symmetry-broken TPCs, the proposed platform exhibits outstanding structural robustness against local perturbations and overcomes the inherent limitations of conventional ensemble-based emitter systems. Our strategy offers a universal and scalable route for engineering deterministic directional light emission at the single-particle level, paving the way for advanced applications including high-resolution 3D projection imaging, on-chip directional optical antennas, single-photon nonlinear devices, and coherent imaging systems integrated with augmented reality waveguides.

## Methods

**Characterization.** The surface characteristics of the samples were captured using a scanning electron microscope (SEM, MIRA3-LMH) operating in in-beam secondary electron mode at an accelerating voltage of 20 kV. For atomic force microscopy (AFM) imaging, a material-based AFM (BRUKER, Dimension FastScan) was used in contact mode, with a scan rate set for high-resolution imaging. The AFM images were processed and analyzed using NanoScope Analysis 3.00 software, which produced a detailed 3D topographical profile of  $2\ \mu\text{m} \times 2\ \mu\text{m}$ .

**Optical characterization (ARSS, ARPL and UCL lifetime).** Both ARSS and ARPL measurements were performed using a Fourier back-plane (FBP) imaging system (supporting). For ARSS experiments, a halogen lamp was used as the excitation source. The polarization direction of the incident light was controlled by a rotatable adjustable mount with a linear polarizer, which aligned the polarization along the  $y$ -direction before the light entered a beam-splitting prism. A dark-field module (model) was employed to direct the incident light onto a  $100\times$  Olympus objective lens, which had a high numerical aperture ( $\text{NA} = 0.9$ ) and an infinite conjugate design. The light was incident at a steep angle to the sample surface. The diffracted light was then collected by the same objective lens and sent into a  $4f$  optical system composed of three lenses and a pinhole. The Fourier plane of the diffracted light was projected onto a CCD camera (QImaging Retiga R1 from Cairn Research) and a fiber spectrometer (Exemplar®Plus, BTC655N) through beam splitter BS2. Spectral signals were gathered using a fiber with a core diameter of  $100\ \mu\text{m}$  (model), which was positioned to collect light spots on the Fourier plane. The fiber's collection end was mounted on a support rod connected to an electric displacement platform, allowing for precise point-by-point scanning with a  $0.1\ \text{mm}$  step. This setup enabled efficient dispersion imaging in momentum space and minimized stray light interference, ensuring sharp resonance peaks. The ARPL measurements were

performed using the same optical configuration, i.e. a single wavelength continuous laser ( $\lambda = 980$  nm) was used to vertically excite single-NC. The spotlight signal from the sample was passed through an 800 nm short-pass filter, capturing both the Fourier image and the ARPL spectrum using the FBP system (Supplementary Materials Note 3).

**Numerical Modeling.** The dispersion properties of the TPC structure and the emission enhancement of single-NCs in its lattice array were modeled using the commercially available software COMSOL Multiphysics. The optical constants of Al used in our simulation come from (Rakić 1995:  $n, k$  0.000124–200  $\mu\text{m}$ ). The three-dimensional model of the plasmonic lattices was obtained by Boolean operations on a tetragonal prism and an ellipsoid (long axis  $a$ , short axis  $b$ ), where the ellipsoid's center is highly aligned with the surface of the tetragonal prism. The three-dimensional energy band structure of the plasmonic lattices and the Q-factors of the corresponding bands were calculated using eigenfrequency studies with periodic boundary conditions, and redundant pseudo-modes were manually eliminated. Three-dimensional mode analysis and angle-resolved reflectance spectra of this periodic structure were calculated using frequency-domain studies.

### Supporting information

TPC fabrication, Synthesis of  $\text{NaYF}_4:10\% \text{Yb}^{3+}, 2\% \text{Er}^{3+}@\text{NaYF}_4$  core-shell nanocrystals, undeformed and plasmonic lattices  $\Gamma$ -point mode, Fourier back plane image of TPC, Comparison of  $D_{4h}$  and  $C_{4v}$  cavities for near-field enhancement are included in the supporting information at <https://xxx.xxx>.

### Acknowledgements

The authors thank the supporting of the National Key Research and Development Program of China (2024YFA1409900), National Natural Science Foundation of China (Grant No. 12274054, U24A2018, T2596034).

### Author contribution

Y.F. conceived the idea and directed the project. Y.C. performed the main experiment and the main FEM calculations. M.Z. performed the cavity substrate fabrication. Q.B. performed the time resolved florescence. X.Y. performed the upconversion nanoparticle synthesis. B.D. directed the upconversion nanoparticle synthesis. W.W. directed the cavity fabrication. Y.F. and Y.C. discussed and concluded the main results. Y.C. wrote the manuscript. All of the authors revised the paper.

## Conflicts of interest

The authors declare no competing financial interest.

## Data availability

The data that support the findings of this study are available on request from the corresponding author upon reasonable request.

## References

- 1 Yang Y, Cong Y, Lin X, Cao B, Dong D, Liu K *et al.* Dual LSPR of Au/W18O49 heterostructures for upconversion enhancement and application of molecular detection. *J Mater Chem A* 2020; **8**: 4040–4048.
- 2 Würth C, Manley P, Voigt R, Ahiboz D, Becker C, Resch-Genger U. Metasurface Enhanced Sensitized Photon Upconversion: Toward Highly Efficient Low Power Upconversion Applications and Nanoscale E-Field Sensors. *Nano Lett* 2020; **20**: 6682–6689.
- 3 Mattsson L, David Wegner K, Hildebrandt N, Soukka T. Upconverting nanoparticle to quantum dot FRET for homogeneous double-nano biosensors. *RSC Adv* 2015; **5**: 13270–13277.
- 4 Chen X, Jin L, Kong W, Sun T, Zhang W, Liu X *et al.* Confining energy migration in upconversion nanoparticles towards deep ultraviolet lasing. *Nat Commun* 2016; **7**: 10304.
- 5 Jin LM, Chen X, Siu CK, Wang F, Yu SF. Enhancing Multiphoton Upconversion from NaYF<sub>4</sub>:Yb/Tm@NaYF<sub>4</sub> Core–Shell Nanoparticles via the Use of Laser Cavity. *ACS Nano* 2017; **11**: 843–849.
- 6 Fernandez-Bravo A, Wang D, Barnard ES, Teitelboim A, Tajon C, Guan J *et al.* Ultralow-threshold, continuous-wave upconverting lasing from subwavelength plasmons. *Nat Mater* 2019; **18**: 1172–1176.
- 7 Mun KR, Kyhm J, Lee JY, Shin S, Zhu Y, Kang G *et al.* Elemental-Migration-Assisted Full-Color-Tunable Upconversion Nanoparticles for Video-Rate Three-Dimensional Volumetric Displays. *Nano Lett* 2023; **23**: 3014–3022.
- 8 Safiabadi Tali SA, Mudiyansele RRHH, Qian Y, Smith NWG, Zhao Y, Morral A *et al.* Dual-Modal Nanoplasmonic Light Upconversion through Anti-Stokes Photoluminescence and Second-Harmonic Generation from Broadband Multiresonant Metal Nanocavities. *ACS Nano* 2023; **17**: 11362–11373.
- 9 Feng Z, Shi T, Geng G, Li J, Deng Z-L, Kivshar Y *et al.* Dual-band polarized upconversion photoluminescence enhanced by resonant dielectric metasurfaces. *eLight* 2023; **3**: 21.
- 10 Tripathi A, Zalogina A, Liao J, Wurdack M, Estrecho E, Zhou J *et al.* Metasurface-Controlled Photonic Rashba Effect for Upconversion Photoluminescence. *Nano Lett* 2023; **23**: 2228–2232.

- 11 Mao C, Min K, Bae K, Cho S, Xu T, Jeon H *et al.* Enhanced Upconversion Luminescence by Two-Dimensional Photonic Crystal Structure. *ACS Photonics* 2019; **6**: 1882–1888.
- 12 Guan J, Sagar LK, Li R, Wang D, Bappi G, Watkins NE *et al.* Engineering Directionality in Quantum Dot Shell Lasing Using Plasmonic Lattices. *Nano Lett* 2020; **20**: 1468–1474.
- 13 Chen H, Jiang Z, Hu H, Kang B, Zhang B, Mi X *et al.* Sub-50-ns ultrafast upconversion luminescence of a rare-earth-doped nanoparticle. *Nat Photonics* 2022; **16**: 651–657.
- 14 Hsieh Y-H, Hsu B-W, Peng K-N, Lee K-W, Chu CW, Chang S-W *et al.* Perovskite Quantum Dot Lasing in a Gap-Plasmon Nanocavity with Ultralow Threshold. *ACS Nano* 2020; **14**: 11670–11676.
- 15 Xu Y, Hu H, Chen W, Suo P, Zhang Y, Zhang S *et al.* Phononic Cavity Optomechanics of Atomically Thin Crystal in Plasmonic Nanocavity. *ACS Nano* 2022; **16**: 12711–12719.
- 16 Li X, Wang Y, Shi J, Zhao Z, Wang D, Chen Z *et al.* Large-Area Near-Infrared Emission Enhancement on Single Upconversion Nanoparticles by Metal Nanohole Array. *Nano Lett* 2024; **24**: 5831–5837.
- 17 Yuan J, Hu J, Zheng Y, Wei H, Xiao J, Wang Y *et al.* Enhanced amplified spontaneous emission via splitted strong coupling mode in large-area plasmonic cone lattices. *Opto-Electron Sci* 2025; **0**: 240021–240021.
- 18 Gargas DJ, Moore MC, Ni A, Chang S-W, Zhang Z, Chuang S-L *et al.* Whispering Gallery Mode Lasing from Zinc Oxide Hexagonal Nanodisks. *ACS Nano* 2010; **4**: 3270–3276.
- 19 Kühner L, Sortino L, Berté R, Wang J, Ren H, Maier SA *et al.* Radial bound states in the continuum for polarization-invariant nanophotonics. *Nat Commun* 2022; **13**: 4992.
- 20 Shang Y, Zhou J, Cai Y, Wang F, Fernandez-Bravo A, Yang C *et al.* Low threshold lasing emissions from a single upconversion nanocrystal. *Nat Commun* 2020; **11**: 6156.
- 21 Freire-Fernández F, Park S-M, Tan MJH, Odom TW. Plasmonic lattice lasers. *Nat Rev Mater* 2025. doi:10.1038/s41578-025-00803-4.
- 22 Hoang TB, Akselrod GM, Yang A, Odom TW, Mikkelsen MH. Millimeter-Scale Spatial Coherence from a Plasmon Laser. *Nano Lett* 2017; **17**: 6690–6695.
- 23 Kravets VG, Kabashin AV, Barnes WL, Grigorenko AN. Plasmonic Surface Lattice Resonances: A Review of Properties and Applications. *Chem Rev* 2018; **118**: 5912–5951.
- 24 Hsu CW, Zhen B, Stone AD, Joannopoulos JD, Soljačić M. Bound states in the continuum. *Nat Rev Mater* 2016; **1**: 1–13.
- 25 Moilanen AJ, Cavigelli M, Taniguchi T, Watanabe K, Novotny L. Electrical Control of Photoluminescence in 2D Semiconductors Coupled to Plasmonic Lattices. *ACS Nano* 2025; **19**: 4731–4738.

- 26 Sergeeva KA, Pavlov DV, Seredin AA, Mitsai EV, Sergeev AA, Modin EB *et al.* Laser-Printed Plasmonic Metasurface Supporting Bound States in the Continuum Enhances and Shapes Infrared Spontaneous Emission of Coupled HgTe Quantum Dots. *Adv Funct Mater* 2023; **33**: 2307660.
- 27 Zhong H, Yu Y, Zheng Z, Ding Z, Zhao X, Yang J *et al.* Ultra-low threshold continuous-wave quantum dot mini-BIC lasers. *Light Sci Appl* 2023; **12**: 100.
- 28 Schiattarella C, Romano S, Sirleto L, Mocella V, Rendina I, Lanzio V *et al.* Directive giant upconversion by supercritical bound states in the continuum. *Nature* 2024; **626**: 765–771.
- 29 Jin J, Yin X, Ni L, Soljačić M, Zhen B, Peng C. Topologically enabled ultrahigh-Q guided resonances robust to out-of-plane scattering. *Nature* 2019; **574**: 501–504.
- 30 Qin H, Su Z, Zhang Z, Lv W, Yang Z, Chen W *et al.* Disorder-assisted real-momentum topological photonic crystal. *Nature* 2025. doi:10.1038/s41586-025-08632-9.
- 31 Deng H, Jiang X, Zhang Y, Zeng Y, Barkaoui H, Xiao S *et al.* Chiral lasing enabled by strong coupling. *Sci Adv* 2025; **11**: eads9562.
- 32 Wang H, Zuo Y, Yin X, Chen Z, Zhang Z, Wang F *et al.* Ultralow-loss optical interconnect enabled by topological unidirectional guided resonance. *Sci Adv* 2024; **10**: eadn4372.
- 33 Guo J, Jin R, Fu Z, Zhang Y, Yu F, Chen J *et al.* Topologically Engineered High-Q Quasi-BIC Metasurfaces for Enhanced Near-Infrared Emission in PbS Quantum Dots. *Nano Lett* 2025; **25**: 2357–2365.
- 34 Liu Y, Zhang J, Csányi E, Adanan NQ, Wang H, Zhang Z *et al.* Electrically Tunable and Modulated Perovskite Quantum Emitters via Surface-Enhanced Landau Damping. *Adv Mater*; **n/a**: 2419076.
- 35 Dang NHM, Zanotti S, Drouard E, Chevalier C, Trippé-Allard G, Amara M *et al.* Realization of Polaritonic Topological Charge at Room Temperature Using Polariton Bound States in the Continuum from Perovskite Metasurface. *Adv Opt Mater* 2022; **10**: 2102386.
- 36 Nan L, Mancini A, Weber T, Seah GL, Cortés E, Tittl A *et al.* Angular dispersion suppression in deeply subwavelength phonon polariton bound states in the continuum metasurfaces. *Nat Photonics* 2025; **19**: 615N
- 37 Kang M, Xiao M, Chan CT. Janus Bound States in the Continuum with Asymmetric Topological Charges. *Phys Rev Lett* 2025; **134**: 013805.
- 38 Liu W, Wang B, Zhang Y, Wang J, Zhao M, Guan F *et al.* Circularly Polarized States Spawning from Bound States in the Continuum. *Phys Rev Lett* 2019; **123**: 116104.
- 39 Chen Y, Deng H, Sha X, Chen W, Wang R, Chen Y-H *et al.* Observation of intrinsic chiral bound states in the continuum. *Nature* 2023; **613**: 474–478.
- 40 Huo P, Chen W, Zhang Z, Zhang Y, Liu M, Lin P *et al.* Observation of spatiotemporal optical vortices enabled by symmetry-breaking slanted nanograting. *Nat Commun* 2024; **15**: 3055.

- 41 Yang L, Li G, Gao X, Lu L. Topological-cavity surface-emitting laser. *Nat Photonics* 2022; **16**: 279–283.
- 42 Dikopoltsev A, Tristan H. Harder, Lustig E, Egorov OA, Beierlein J, Wolf A *et al.* Topological insulator vertical-cavity laser array. *Science* 2021; **373**: 1514–1517.
- 43 Parappurath N, Alpeggiani F, Kuipers L, Verhagen E. Direct observation of topological edge states in silicon photonic crystals: Spin, dispersion, and chiral routing. *Sci Adv* 2020; **6**: eaaw4137.
- 44 Han S, Cui J, Chua Y, Zeng Y, Hu L, Dai M *et al.* Electrically-pumped compact topological bulk lasers driven by band-inverted bound states in the continuum. *Light Sci Appl* 2023; **12**: 145.
- 45 Zhang Y, Chen A, Liu W, Hsu CW, Wang B, Guan F *et al.* Observation of Polarization Vortices in Momentum Space. *Phys Rev Lett* 2018; **120**: 186103.
- 46 Csányi E, Liu Y, Rezaei SD, Lee HYL, Tjiptoharsono F, Mahfoud Z *et al.* Engineering and Controlling Perovskite Emissions via Optical Quasi-Bound-States-in-the-Continuum. *Adv Funct Mater* 2024; **34**: 2309539.
- 47 Meng Y, Huang D, Li H, Feng X, Li F, Liang Q *et al.* Bright single-nanocrystal upconversion at sub 0.5 W cm<sup>−2</sup> irradiance via coupling to single nanocavity mode. *Nat Photonics* 2023; **17**: 73–81.
- 48 Chen Y, Liu J, Hu J, Wang Y, Yin X, Guo Y *et al.* Vertical Emission of Blue Light from a Symmetry Breaking Plasmonic Nanocavity-Emitter System Supporting Bound States in the Continuum. *Adv Funct Mater* 2025; **35**: 2500133
- 49 Lv F, La J, He S, Liu Y, Huang Y, Wang Y *et al.* Off-Angle Amplified Spontaneous Emission of Upconversion Nanoparticles by Propagating Lattice Plasmons. *ACS Appl Mater Interfaces* 2022; **14**: 54304–54312.
- 50 Schiattarella C, Romano S, Sirleto L, Mocella V, Rendina I, Lanzio V *et al.* Directive giant upconversion by supercritical bound states in the continuum. *Nature* 2024; **626**: 765–771.
- 51 Aigner A, Tittl A, Wang J, Weber T, Kivshar Y, Maier SA *et al.* Plasmonic bound states in the continuum to tailor light-matter coupling. *Sci Adv* 2022; **8**: eadd4816.
- 52 Liang Y, Koshelev K, Zhang F, Lin H, Lin S, Wu J *et al.* Bound States in the Continuum in Anisotropic Plasmonic Metasurfaces. *Nano Lett* 2020; **20**: 6351–6356.
- 53 Chen Y, Xie C, Zhu T, Ding W, Fang Y. Topological quasibound states in the continuum induced by  $\sigma h$  symmetry being broken beyond a threshold. *Phys. Rev. B* 2026; **113**: 245419.
- 54 Babadjanyan AJ, Margaryan NL, Nerkaryan KhV. Superfocusing of surface polaritons in the conical structure. *J Appl Phys* 2000; **87**: 3785–3788.
- 55 Stockman MI. Nanofocusing of Optical Energy in Tapered Plasmonic Waveguides. *Phys Rev Lett* 2004; **93**: 137404.

- 56 Overvig AC, Malek SC, Carter MJ, Shrestha S, Yu N. Selection rules for quasibound states in the continuum. *Phys Rev B* 2020; **102**: 035434.
- 57 Cui J, Han S, Zhu B, Wang C, Chua Y, Wang Q *et al*. Ultracompact multibound-state-assisted flat-band lasers. *Nat Photonics* 2025; **19**:643–649.
- 58 Regan EC, Igarashi Y, Zhen B, Kaminer I, Hsu CW, Shen Y *et al*. Direct imaging of isofrequency contours in photonic structures. *Sci Adv* 2016; **2**: e1601591.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [v3.21SupplementaryMaterials.pdf](#)