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Robust chirality via merging accidental BICs with net zero topological charge

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Abstract

Chiral metasurfaces leveraging bound states in the continuum (BICs) offer a powerful route for enhancing light–matter interactions. However, existing quasi-BIC architectures typically face a fundamental trade-off between high quality (Q) factors and wide-angle chiral operation. Most designs confine strong circular dichroism (CD) to isolated points in momentum space (k-space) and often rely on intricate three-dimensional (3D) meta-atoms, rendering them highly sensitive to fabrication imperfections and angular misalignment. Here, we experimentally realize a planar dielectric metasurface that supports a wide k-domain chirality arising from accidental BICs with a net zero-topological-charge (ZTC). By lifting a Dirac-type degeneracy through controlled in-plane and out-of-plane symmetry breaking, we induce a deterministic topological evolution in which the same-handed circularly polarized (C) points migrate toward and accumulate near the Γ point, while the opposite-handed singularities annihilate or shift to higher k-space. This mechanism delivers record-level performance—an ultrahigh Q-factor ($\sim 10^4$), near-unity linear and nonlinear CD (0.99/0.999), and robust angular coverage ($|k_x P/2\pi, k_y P/2\pi| < 0.06$)—all within a fabrication-friendly, single-layer dielectric platform. These results establish a new regime for chiral photonics, unifying high chiral purity, angular robustness, and topological stability in a scalable planar architecture.

Keywords Chiral metasurface, Bound states in the continuum, Nonlinearity, Topological robustness, High-quality factor

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1 Introduction

Discrimination of chirality is of fundamental importance across chemistry, pharmacy, life sciences, and physics, particularly where opposite enantiomers can exhibit contrasting biological functions, serving as either an antidote or a toxin. Conventional characterization relies on the distinct interactions of enantiomers with left- and right-handed circularly polarized (LCP and RCP) light, making circular dichroism (CD) spectroscopy a widely used tool [1–3]. However, natural chiral materials generally exhibit inherently weak optical responses, limiting detection sensitivity and necessitating artificial structures for chiroptical enhancement.

Metasurfaces have emerged as an attractive platform for enhancing chiral light-matter interactions, offering precise resonant control through on-demand symmetry breaking in their meta-atom level. Although both two-dimensional (2D) and three-dimensional (3D) chiral metasurfaces have demonstrated strong chiroptical responses—manifested as large CD or optical activity (OA)—early works often relied on plasmonic resonances or low-order Mie resonances, which inherently yield moderate Q-factors and limited CD enhancement [4–8]. To overcome these limitations, bound states in the continuum (BICs) [9–12]—radiation-immune modes with theoretically infinite Q-factor—have recently emerged as a promising mechanism for achieving ultrahigh-Q chiral optical resonances with significantly amplified CD [13–15].

To harness these ideal BIC modes, structural perturbations are typically introduced to transform perfect BICs into quasi-BICs possessing finite yet ultrahigh Q-factor [16–28]. In particular, symmetry-protected (SP) BICs have been utilized to achieve these resonances by strategically breaking symmetries [29–36]. However, realizing such chiral SP-BIC designs often requires intricate 3D meta-atoms that impose significant fabrication challenges, limiting their scalability [33–38]. While planar (2D) alternatives have been proposed [39–42], they frequently suffer from experimental instability or theoretical

constraints. As a result, minor geometric deviations—inevitable during fabrication—can lead to drastic performance deterioration or even an inversion of the chiroptical response.

The transition of chiral metasurfaces from laboratory demonstrations to practical devices hinges on their robustness against geometric perturbations and the capability for wide-angle operational stability. Given that chip-scale photonic manufacturing inevitably introduces fabrication non-uniformity and angle misalignments, strategies that ensure chiral quasi-BICs (q-BICs) maintain large fabrication tolerances are urgently needed. While magnetic-optical BICs have been explored to circumvent certain symmetry-breaking requirements [43–45], they necessitate external magnetic field and specific material systems, presenting significant integration challenges in optical regime. Likewise, approaches based on merging BICs, despite enhancing chiroptical responses [46, 47], often remain constrained by extrinsic or 2D chirality mechanisms tied to SP-BICs at the Γ -point. Although approaches like flat-band engineering have demonstrated wide-angle chirality, their performance remains limited (e.g., $CD \sim 0.6$, $Q \sim 140$) due to insufficient robustness [38, 48]. These limitations highlight the critical need for a purely dielectric, fabrication-friendly approach capable of delivering ultrahigh Q-factor and near-perfect CD while remaining resilient to both angular dispersion and geometric deviations.

Here, we theoretically propose and experimentally realize robust high-Q wide k-domain chiral responses enabled by merging of multiple accidental BICs (Fig. 1). In contrast to conventional chiral q-BICs that rely on delicate symmetry perturbation and suffer from rapid Q-factor decay (Fig. 1b), our approach exploits zero-topological-charge (ZTC) merging BICs modes within a fully planarized, standard silicon-on-insulator (SOI) platform (Fig. 1c–g). This mechanism produces a cluster of chiroptical extrema, delivering simultaneous a record-high CD (0.99) and Q-factor ($\sim 10^4$) (Table 1, this work is in bold), that persist under continuous geometric tuning and

(See figure on next page.)

Fig. 1 Chiral metasurface enabled by zero-topological-charge (ZTC) merging BICs with wide k-domain chirality. **a** Schematic of a planar chiral metasurface composed of square island meta-atoms perforated by a pair of holes ($P=836$ nm, $L=746$ nm, $R=70$ nm, $t=220$ nm). The inset displays measured Q-factors and circular dichroism (CD) versus incidence angle. **b, c** Comparison between a conventional chiral symmetry-protected (SP) BICs (**b**) and the proposed ZTC BICs design (**c**). In contrast to SP-BICs, which exhibit rapid Q-factor decay away from the Γ point, the ZTC merging BICs concept supports high-Q chiral resonances across broader momentum and parameter ranges. **d** Schematic of the 2×2 unit cell of the initial degenerate parabolic bands at the Γ point prior to symmetry breaking. **e** Band structure illustrating that the reduction from C_4 to C_2 symmetry lifts the degeneracy, generating a pair of Dirac points along k_x . **f** Dissociation of the ZTC merging BICs into multiple accidental BICs distributed around the Γ point, achieved by tuning the in-plane parameter d_x . **g** Mechanism for establishing the chiral domain. Breaking out-of-plane symmetry (substrate $n_s > 1$) splits the integer-charge accidental BICs into pairs of half-integer C-points. A subsequent lateral perturbation d_x triggers topological charge inversion via interaction with the Dirac points, while simultaneously rotating the singularity distribution in k-space and segregating left-handed C-points, resulting in a robust, broad intrinsic chiral domain

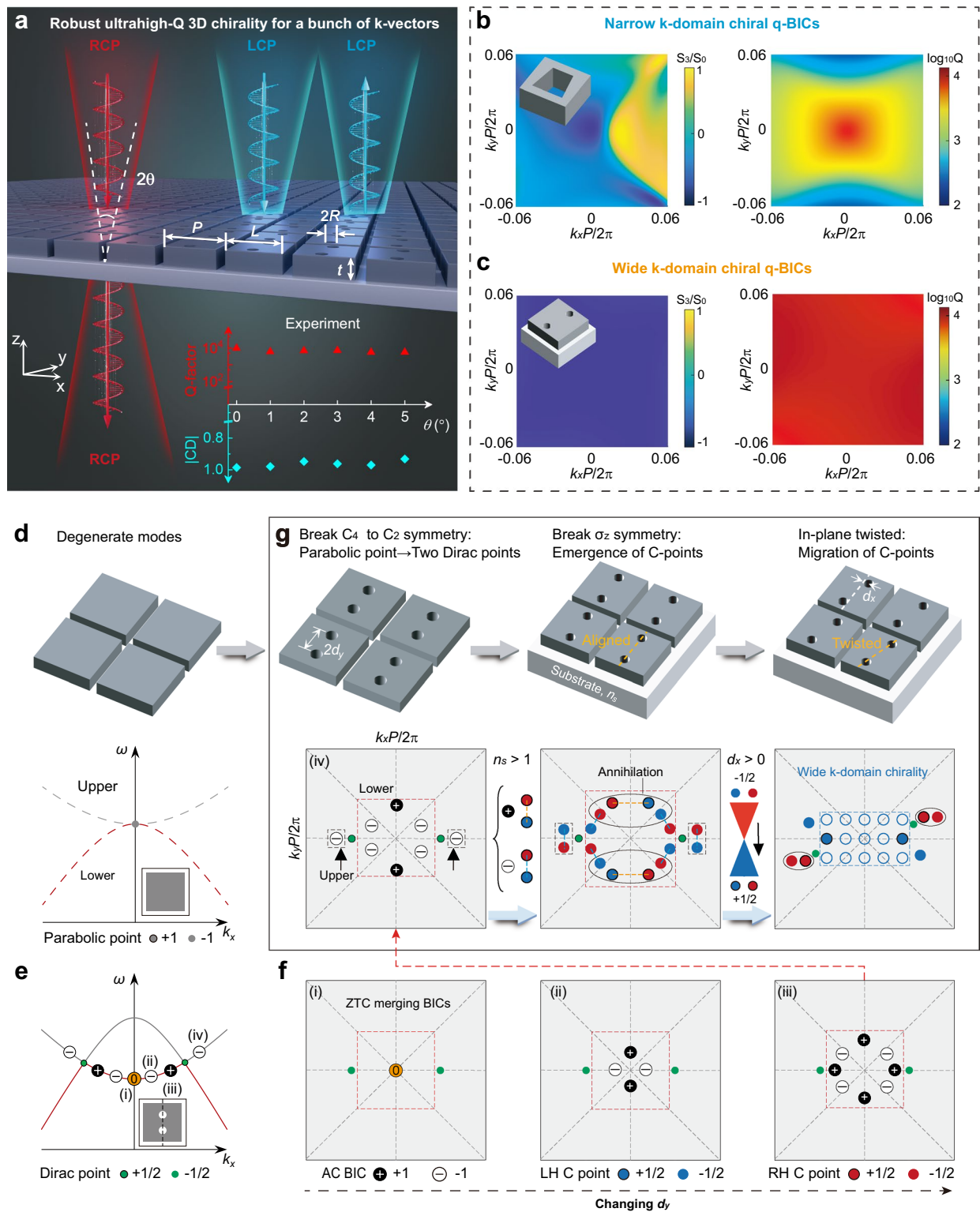
**Fig. 1** (See legend on previous page.)

Table 1 Summary of high-Q chiral resonances

Mechanism	Measured Q-factor	Measured CD	Angle robustness	Intrinsic/Extrinsic	2D/3D chirality	Refs.
GMR	174	0.93	–	Intrinsic	2D	[6]
SLR	1,220	0.37	0°	Intrinsic	2D	[7]
SLR	872	0.7	0.9°	Extrinsic	2D	[7]
SP BIC	–	0.7	3°	Extrinsic	2D	[13]
SP BIC	390	0.88	0°	Intrinsic	2D	[29]
SP BIC	1,250	0.989	0°	Intrinsic	3D	[33]
SP BIC	2,663	0.93	0°	Intrinsic	3D	[34]
SP BIC	80	0.68	–	Intrinsic	3D	[35]
SP BIC	~600	0.979	–	Intrinsic	3D	[36]
SP BIC	~25	0.24	0°	Intrinsic	3D	[37]
SP BIC	~140	~0.6	$-5^\circ \sim 5^\circ \in (k_x, 0)$	Intrinsic	3D	[38]
GMR	~200	0.8	$-5^\circ \sim 5^\circ \in (k_x, k_y)$	Intrinsic	3D	[48]
Merging BIC	10,062	0.99	$-5^\circ \sim 5^\circ \in (k_x, k_y)$	Intrinsic	3D	This work

SP BIC symmetry-protected BIC; GMR guided-mode resonances; SLR surface lattice resonances; 2D two-dimensional; 3D three-dimensional

wide-angle operation (up to 5° polar and full 360° azimuthal coverage). We further demonstrate the power of this platform by achieving near-perfect nonlinear chirality (0.999) in third-harmonic generation (THG), thereby establishing a scalable route for next-generation active and nonlinear chiral photonic technologies.

2 Results

2.1 Design principle and topological evolution

Figure 1d–g illustrates the structural design and the associated topological evolution from ZTC merging BICs to wide k-domain chirality. To manipulate accidental BICs emerging from a degenerate band structure, we used a C_4 -symmetric silicon-island lattice ($P=836$ nm, $L=746$ nm) [49, 50]. As shown in Fig. 1d, the unperturbed system supports a pair of orthogonal upper and lower (TE_{23} and TE_{32}) modes that forms a parabolic degeneracy at the Γ point with a topological charge of $q = -1$. In addition, the lower band exhibits four accidental BICs with $q = +1$ along the diagonal directions (Supplementary Fig. S1) [51].

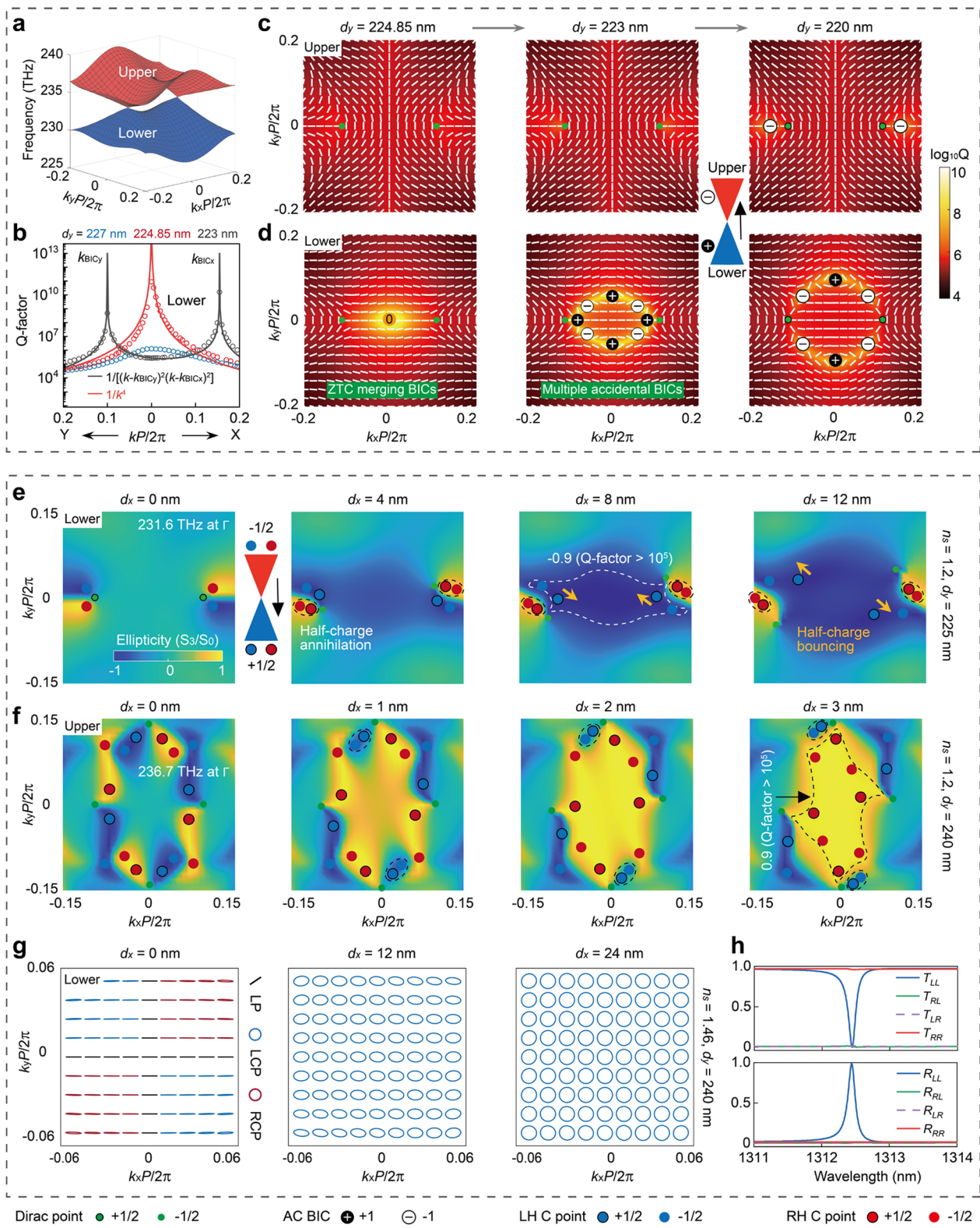
To break the lattice symmetry from C_4 to C_2 , we introduced a hole offset d_y (Fig. 1e). This perturbation lifts the parabolic degeneracy, resulting in a pair

of Dirac points along k_x and a reconfigured set of topological charges [51, 52]. When d_y is varied, multiple accidental BICs emerge from the ZTC merging BICs (Fig. 1f). When an accidental BIC crosses a Dirac point, its charge undergoes a deterministic sign inversion due to the reorganization of the singularity structure in the band manifold [53, 54]. Figure 1g shows that breaking out-of-plane symmetry by adding a substrate result in the transformation of accidental BICs into pairs of C-points. The distribution of C-points can be controlled by d_y and the substrate refractive index. When an in-plane perturbation d_x is applied, the C-points are driven to twist in k-space and exchange half-charges with the Dirac point. As a result, the left-handed C-points converge toward the Γ point, whereas opposite-handed ones are expelled or annihilated. This process ultimately establishes a robust wide k-domain chiral response.

To visualize the topological evolution, we performed simulations starting from the ZTC merging BICs. Figure 2a–d show that when the lattice symmetry is reduced from C_4 to C_2 , the Γ point parabolic degeneracy evolves into two Dirac points, resulting in the splitting of the ZTC merging BICs (with total topological charge $q=0$)

(See figure on next page.)

Fig. 2 Evolution from ZTC merging BIC to robust chiral k-domain. **a** 3D band-structure of a C_2 -symmetric system showing two Dirac points k_x . **b** Evolution of Q-factors for the lower-band merging BIC as a function of hole offset d_y , with fixed parameters: lattice period $P=836$ nm, slab length $L=746$ nm, and hole radius $R=70$ nm. **c, d** Simulated Q-factors (color map) overlaid with eigen-polarization vectors in k-space for varying d_y , shown for **c** upper and **d** lower bands. Inset illustrate the topological transition: as an accidental BIC crosses the Dirac point, it jumps from the lower to upper band, with a sign reversal. **e, f** Evolution of C-points in upper (**e**) and lower (**f**) bands with increasing d_x . Dirac cone insets illustrate topological charge inversion. **g** Far-field eigen-polarization evolution for $d_x=0, 12, 24$ nm at $n_s=1.46$, $d_y=240$ nm (upward radiation). **h** Simulated transmission and reflection spectra under circular polarization at $d_x=24$ nm, confirming nearly perfect intrinsic 3D chirality

**Fig. 2** (See legend on previous page.)

splits into multiple accidental BICs. Figure 2a shows the 3D band structures of the upper and lower bands in k -space, where the two Dirac points exhibit half-integer charges. For clarity, we focus on the lower band. Figure 2b shows that the Γ point Q-factor diverges at $d_y = 224.85$ nm, marking the ZTC merging BICs condition (pre-merging), whereas deviations from this point yield finite-Q modes or separated accidental BICs. The Q-factor follows quadratic inverse scaling laws along the Y- Γ -X direction for multiple accidental BICs. Figure 2c, d show that when d_y is decreases from 223 to 220 nm, two +1 BICs in the lower band traverse the Dirac point and are transferred to the upper band as two -1 BICs. Consequently, the Dirac-point charge flips from $-1/2$ to $+1/2$ because of the conservation of total charge (Fig. S2–S4).

To enable wide k -domain chirality, we analyzed the transforms BICs into C-points, driven by controlled symmetry breaking based on the accidental-BIC framework. The introduction of a substrate breaks the up-down mirror symmetry, causing the accidental BIC to transform into a pair of C-points (Fig. 1g and Supplementary Fig. S6). Annihilation occurs when these C-points—sharing the same handedness yet carrying opposite topological charges—encounter each other [55, 56]. To visualize the evolution without interference from the light cone, we used a substrate with refractive index $n_s = 1.2$. Figure 2e shows the chirality distribution of the lower band near Γ point at $d_y = 225$ nm. At $d_x = 0$, opposite-charge pairs annihilate, leaving two C-points near each Dirac point across both bands.

When an in-plane perturbation d_x is introduced, both Dirac and C-points are rotated in k -space. A $-1/2$ C-point from the upper band transfers into the lower band and inverts its charge (Supplementary Fig. S9). When d_x increased, left-handed C-points shift are driven toward the k_x axis, resulting in wide k -domain chirality, whereas right-handed C-points annihilate. At $d_x = 8$ nm, chirality at Γ exhibits a maximum with ellipticity $S_3/S_0 \approx -0.9$ and Q-factor $> 10^5$. When d_x is further increased to 12 nm, half-charge “bouncing” results in reduced chirality at Γ point (Fig. 2e). Further details regarding the evolution, including band structures and Q-factors, are presented in Supplementary Figs. S8–S13. The upper band exhibits a similar mechanism, giving rise to wide k -domain chirality (Fig. 2f).

Figure 2g presents the chirality evolution of the lower band on SiO_2 , where intrinsic chirality increases toward unity as d_x increases. The angular range is restricted to $|k| < 0.06(2\pi/P)$ by substrate light-cone leakage rather than topological breakdown (Supplementary Fig. S15). To expand this range, strategies include lowering the substrate refractive index and increasing the near- Γ C-point

density (Fig. 2e, f). Figure 2h shows that the Jones matrix spectra exhibit a sharp peak in the polarization-preserving T_{LL} channel against a flat T_{RR} background, demonstrating near-perfect intrinsic 3D chirality. This response is maintained across wide incident angles.

2.2 Fabrication and experimental characterization

To verify the robust wide-range maximum chirality enabled by ZTC merging BICs, we fabricated the twisting-perforated square island metasurfaces using standard electron beam lithography (see the Sample fabrication). Figure 3a shows an SEM image of the fabricated sample and the incidence geometry, where the wavevector k is defined by incidence angle θ and azimuth angle ϕ . A home-built reflective optical system is used to characterize the circular polarization-based Jones matrix parameters of the fabricated samples, as shown in Fig. 3b.

Figure 3c presents the measured reflection matrix of the metasurface sample under LCP and RCP excitations, here $R = 70$ nm, $d_x = 24$ nm, $d_y = 240$ nm. The absolute efficiency R_{LL} reaches 0.82 at $\lambda \approx 1312$ nm, while other components approaching zero. This high absolute efficiency surpasses that of most previously reported chiral resonant metasurfaces. The system exhibits a near-unity CD of -0.99 together with a record-high Q-factor of 10,062 under normal incidence (see Table 1 for comparison, this work is in bold). We extract the Q-factors by applying a Fano resonance fit to the measured spectra. Here, CD is defined by the difference in reflection coefficients between LCP and RCP illuminations, as detailed [1, 3]

$$\text{CD} = \frac{(R_{RR} + R_{LR}) - (R_{RL} + R_{LL})}{(R_{RR} + R_{LR}) + (R_{RL} + R_{LL})}, \quad (1)$$

where $R_{ij} = |r_{ij}|^2$ ($i = R, L; j = R, L$) denotes the reflection coefficients, with $i = j$ denoting co-polarization and $i \neq j$ cross-polarization.

Figures 3d–f shows the reflectance spectra of R_{LL} for θ from 0° to 5° (step 1°) at $\phi = 0^\circ, 60^\circ$, and 90° . The resonance peak and linewidth are maintained across this tilt range, demonstrating the robustness of the resonance. All reflectance spectral results for more incident angles are shown in Supplementary Figs. S19–S22. Quantitative extraction of the Q-factor and CD values (Fig. 3g, h) reveals that the Q-factor remains above 5000 and the CD near unity throughout the measured range. By contrast, the high-Q chiral mode in conventional SP-BIC devices is typically restricted to a very narrow angle near normal incidence.

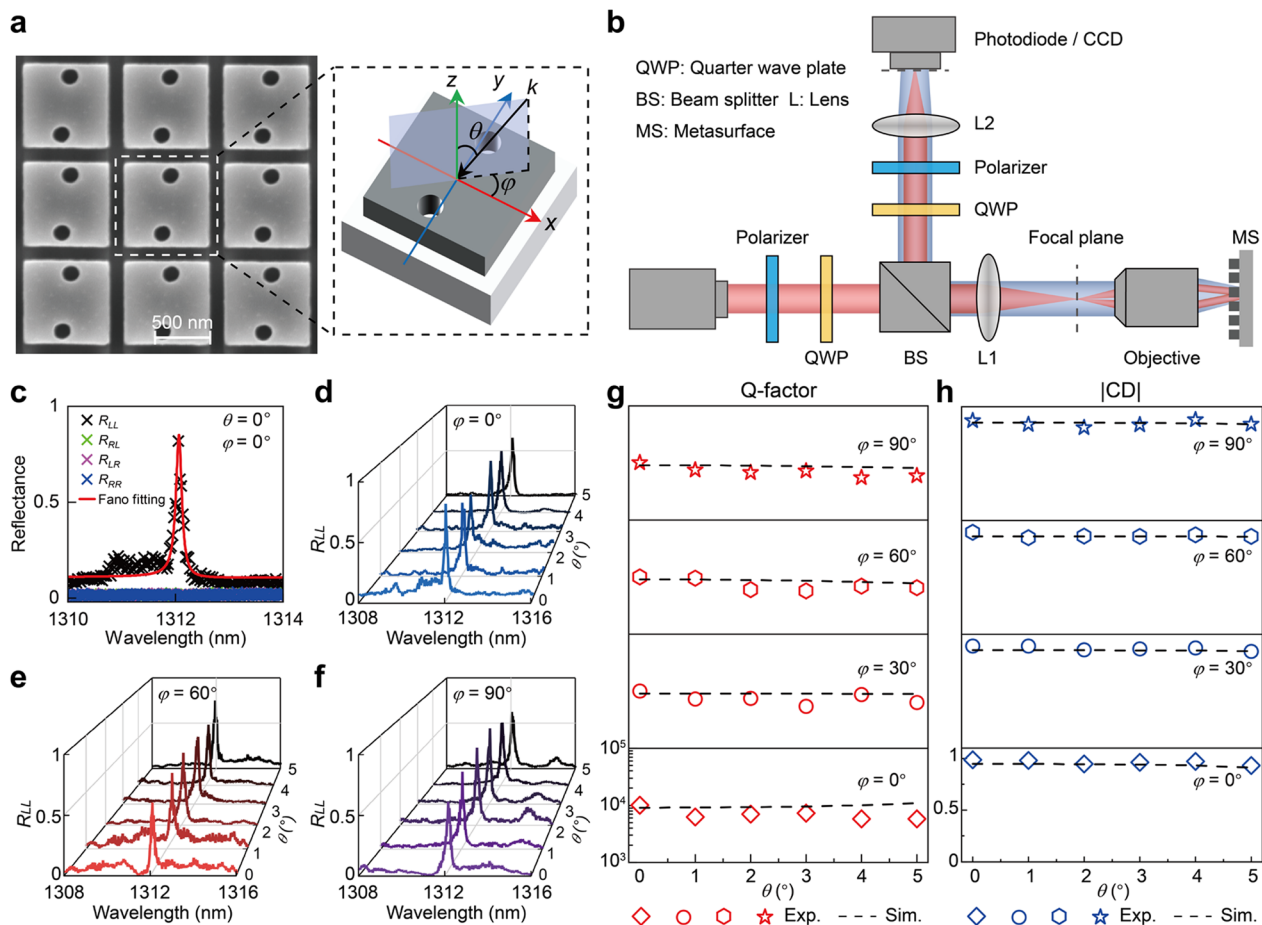


Fig. 3 Experimental validation of wide-range maximum chirality of the chiral k -domain metasurface. **a** Top-view scanning electron microscope (SEM) image of the fabricated planar chiral metasurface (left; scale bar: 500 nm) and a schematic illustrating the unit cell under a tilted wavevector k , dependent on incidence angle θ and azimuth angle φ (right). **b** Schematic of the home-built reflective spectroscopy setup that is used to measure the circular-polarization-based Jones matrix. **c** Measured reflection Jones matrix under LCP/RCP incidence for a sample with $R=70$ nm, $d_x=24$ nm, and $d_y=240$ nm. The solid red curve is the Fano fit of the R_{LL} component. **d–f** Measured reflectance spectra of R_{LL} with incidence angle $\theta=0^\circ$ to 5° in 1° increments for $\varphi=0^\circ$, 60° , and 90° , respectively. **g, h** Extracted Q-factor and CD values from the reflectance spectra as a function of θ at various φ

2.3 Tolerance to fabrication imperfections

To evaluate the robustness of the ZTC merging BICs mechanism against geometric variations, we performed extensive parameter space simulations as well as experimental measurements. The hole radius (R) and island width (L) were varied to mimic lithography errors. The merging topology exhibits a broad “stability plateau” in the R - L parameter space (Supplementary Fig. S27). Within this plateau, the chirality is maintained even though the topological charges shift in k -space.

Figure 4a–c show that reducing R from 70 to 50 nm results in a predictable redshift in resonance wavelength. Importantly, the CD remains high, and the Q-factor even increases due to reduced radiation leakage (Supplementary Fig. S28). Similarly, variations in island width L lead to spectral shifts while maintaining strong CD (Fig. 4d–f,

and Supplementary Fig. S29). These results confirm that the device exhibits substantial tolerance to typical in-plane fabrication deviations.

2.4 Third-harmonic generation measurement

To investigate THG enhancement enabled by the strong confinement of electromagnetic fields within the high-Q chiral mode, we measured the response from the metasurface under circularly polarized pumping (Fig. 5a). As shown in Fig. 5b, the THG signal follows a clear cubic dependence on the pump power, confirming its third-order nonlinear origin.

When pumped at the resonance wavelength ($\lambda \approx 1312$ nm), the metasurface exhibits a pronounced THG signal under LCP excitation, THG generated under RCP

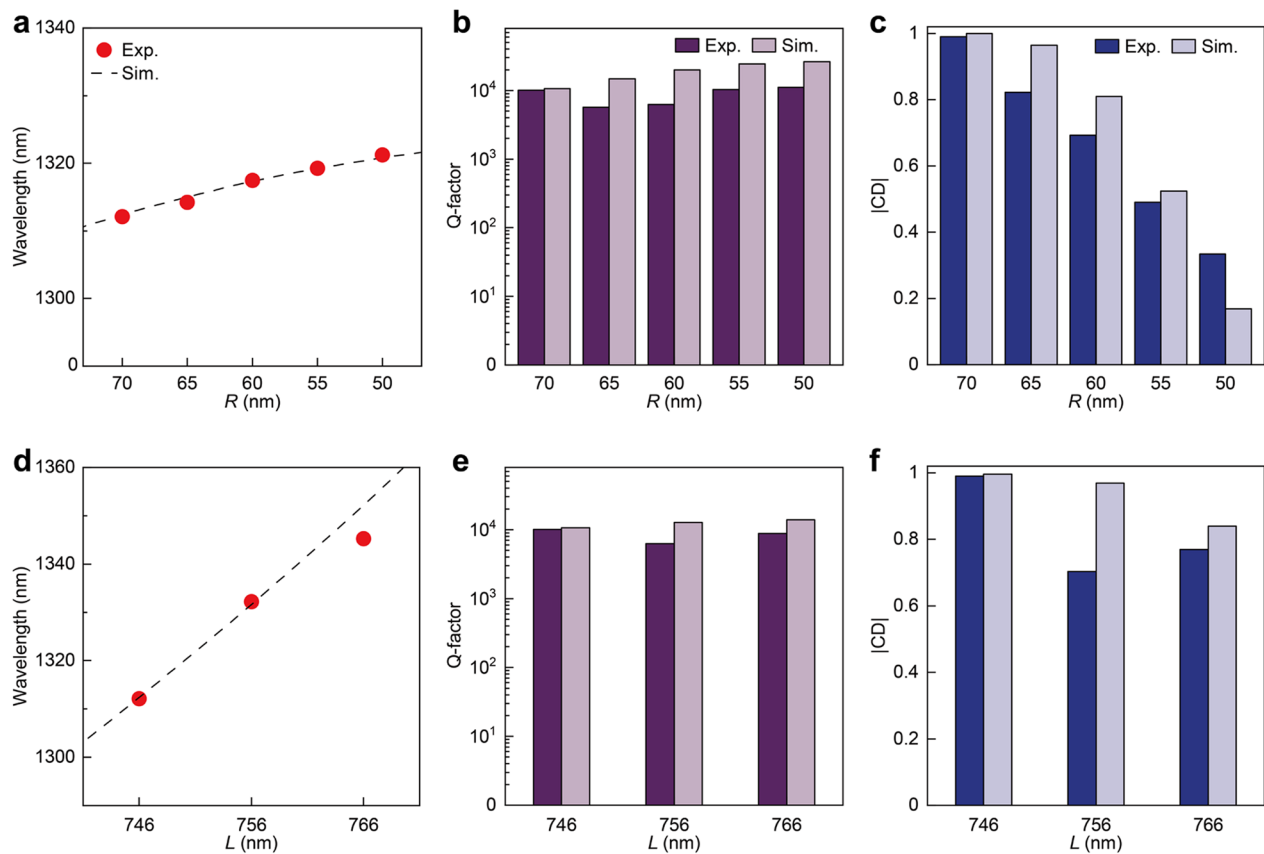


Fig. 4 Robustness of Q-factor and chirality against geometric parameter deviations. **a–c** Simulated and measured resonance wavelengths (**a**), Q-factor (**b**), and CD values (**c**) for hole radii of 70, 65, 60, 55, and 50 nm, respectively. **d–f** Simulated and measured resonance wavelengths (**d**), Q-factor (**e**), and CD values (**f**) for island widths of 746, 756, and 766 nm, respectively

excitation is suppressed to the noise floor (Fig. 5c, d). This demonstrates that the nonlinear process inherits—and even magnifies—the extreme chirality of the underlying linear mode, resulting in a measured nonlinear circular dichroism (CD_{THG}) of 0.999. This result demonstrates that the topological robustness of the linear mode translates directly into highly efficient and selective nonlinear chiral emission, paving the way for robust chiral quantum sources.

3 Discussions

In this work, we demonstrate a robust chiral k-domain by employing ZTC merging BICs, composed solely of accidental BICs. This approach overcomes the limitations of earlier chiral SP-BICs, offering significant enhancements in both topological robustness and practical feasibility. Experimentally, we observe a record-high intrinsic CD of 0.99 and Q-factor of 10,062 at optical frequency, using a perforated square silicon metasurface fabricated on an SOI wafer. Unlike chiral SP-BICs, the chiral resonance here arises from the merging of multiple accidental BICs,

leading to stable high-Q quasi-BIC states that span broad momentum space and geometry parameters spaces.

By introducing both in-plane twisting perturbations in the dimer holes and leveraging the natural out-of-plane asymmetry provided by the low-index substrate, we achieve universal maximum chirality on the quasi-BIC resonances. These resonances radiate uniform circular eigen-polarization in the far-field, covering a full azimuthal range (0° – 360°) and a broad polar span (0° – 5°). Notably, both the maximum chirality and high Q-factor resonances remain stable across momentum space and are robust against geometry variations induced by fabrication imperfections. This robust chirality response enhances nonlinear optical processes, enabling record high CD_{THG} of 0.999 from our silicon metasurface. The planar design, relying only on simple geometries, is readily extended to diverse material platforms—including light-emitting and 2D materials—and can be scaled across a broad electromagnetic spectrum, from the visible and ultraviolet to terahertz and microwave regimes. Our findings establish a practical and scalable pathway for chiral photonic devices, with promising applications

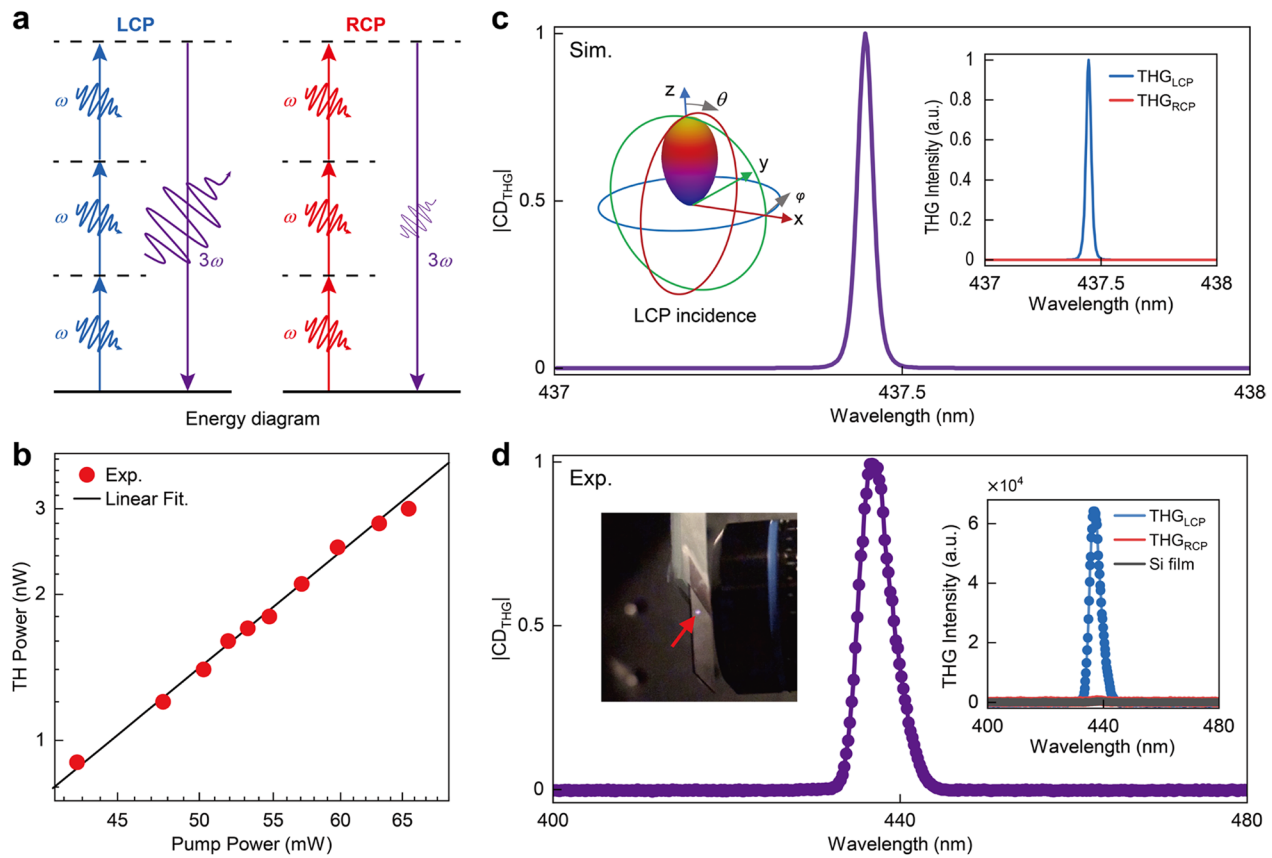


Fig. 5 Chiral nonlinear spectral response of the chiral k-domain metasurface. **a** Schematic of the third-harmonic generation (THG) energy levels in the chiral nonlinear optical process. **b** Measured THG power as a function of pump power, confirming a cubic dependence (slope ≈ 3.02). **c** Simulated CD_{THG} spectra at a fundamental wavelength of 1312.45 nm. CD_{THG} is defined as the normalized difference in THG intensities under LCP vs. RCP pumping. Insets: far-field intensity distribution under LCP (left) and the simulated THG intensity (right). **d** Measured CD_{THG} spectra from the planar chiral metasurface. Insets: optical image of violet THG emission near 437 nm (left) and the measured THG intensity (right)

in sensing, quantum optics, and optical communication systems, where strong chirality, high efficiency, and structural robustness are crucial.

4 Methods

4.1 Numerical simulations

Band structures, Q-factors, and far-field polarization distributions and nonlinear THG simulations were computed using a finite-element method (FEM) solver implemented in COMSOL Multiphysics. A single unit cell was modeled with periodic boundary conditions in the x - y plane and perfectly matched layers (PMLs) along the z direction. The refractive indices were set to $n_{Si} = 3.52$ and $n_{SiO_2} = 1.46$, consistent with experimental values.

To model third-harmonic generation, we employed the undepleted pump approximation in two steps: (1) The linear scattering fields at the pump frequency were computed; (2) The induced third-order nonlinear polarization $P^{(3)} = \epsilon_0 \chi^{(3)} E^3$, using $\chi^{(3)} = 2.45 \times 10^{-19} \text{ m}^2/\text{V}^2$ for Si, was

introduced as a source term to compute THG radiation. This widely adopted approach provides quantitative accuracy while remaining computationally tractable.

4.2 Sample fabrication

The metasurface was fabricated on a silicon-on-insulator (SOI) wafer with a 220 nm top silicon layer. First, electron-beam lithography (JEOL 6300FS) was used to pattern the resist, followed by deep reactive ion etching (Oxford 80) to transfer the pattern into the silicon layer. Post-etching, residual resist was removed using N-methyl-2-pyrrolidone.

4.3 Optical characterization

4.3.1 Linear spectral measurements

For linear spectral measurements, we employed a super-continuum laser (NKT SuperK) spanning 500–2200 nm. Polarizers and quarter-wave plates were used to prepare and analyze circularly polarized light in both left- and right-handed configurations. A set of lenses and an

objective lens (NA = 0.26, 10× magnification, 30.5 mm working distance) focused the collimated beam onto the sample, which was placed at the back focal plane of the objective. The reflected light from the metasurface was collected by the same objective and directed via a 50:50 beam splitter to a spectrometer (ANDOR SR750) and a camera. To achieve oblique incidence, we adjusted the vertical position of the objective, selecting an appropriate lens to collect the reflected light at different tilt angles. The beam then followed the same optical path to the spectrometer for detection.

4.3.2 Nonlinear optical measurements

For nonlinear experiments, we generated a femtosecond laser pulse using a Ti: sapphire oscillator (Chameleon, Coherent) with a 140-fs pulse width and a tunable wavelength range of 680–1080 nm. The beam was collimated, expanded through a telescope, and then sent into an optical parametric oscillator (OPO) to shift its wavelength to 1312 nm. Circular polarization was prepared by sequentially passing the OPO output through a broadband polarizer, a half-wave plate, and a quarter-wave plate, allowing precise control over the polarization state. The circularly polarized beam was split by a 50:50 beam splitter: one path went to a near-infrared CCD (Xenics Bobcat-640, 640 × 512 resolution, 8 μm pixel size) for alignment, while the other was focused onto the sample by a 50×, NA 0.65 objective lens. The reflected beam passed back through the same objective and a dichroic mirror, which transmitted near-infrared wavelengths and reflected visible light. A series of optical filters isolated the desired signal at the third-harmonic wavelength (~437 nm), which was recorded using an Ocean spectrometer (USB4000). This setup enabled direct spectral analysis of the third-harmonic generation from the metasurface under circularly polarized excitation.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43593-026-00126-z>.

Additional file 1.

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Author contributions

H.H. conceived the research and led the numerical calculations. G.H.L., Y.Z. and M.-X.H. prepared the samples and performed the experimental measurements. G.H.L., Z.-L.D., L.H., C.Z., J.L., and J.S. developed the theoretical models and analyzed the data. C.Z. provided guidance on visualization. M.-X.H., J.P., and H.T. assisted in numerical calculations. H.H. wrote the manuscript draft, which was revised and supervised by G.H.L., Z.-L.D., L.H., S.J. and C.-W.Q. All authors discussed the results and approved the final version of the manuscript.

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Data availability

All relevant data supporting the key findings of this study are available in the article and supplementary information file.

Code availability

The code that generates the data of this study are available from the corresponding authors upon request.

Declarations

Competing interests

Cheng-Wei Qiu serves as an Editor for the Journal, no other author has reported any competing interests.

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