

Topological valley quasi-bound states in the continuum for radiatively accessible robust transport

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Topological valley photonics enables on-chip light transport robust against backscattering, but valley edge states typically lie outside the light cone and cannot be directly excited from free space. Existing devices with radiative functionality mainly exploit on-chip-to-free-space emission through strongly leaky modes, where enhanced radiative coupling compromises transport performance. Achieving free-space-to-on-chip excitation while preserving low-loss topological transport therefore remains a challenge. Here, we experimentally demonstrate topological valley quasi-bound states in the continuum (QBICs) in terahertz valley photonic crystals. By introducing geometric modulation and Brillouin-zone folding, valley edge states are folded into the light cone and transformed into topological valley QBICs with controllable radiative coupling while preserving robust valley transport. Using time-domain terahertz near-field imaging, we directly visualize their transport and demonstrate tunable propagation lengths together with robust transport through sharp bends. We further realize on-chip routing functionalities based on junction and splitter architectures, illustrating free-space-to-on-chip excitation and subsequent signal processing. Our work establishes topological valley QBICs as a platform for interfacing free-space radiation with low-loss topological transport, opening new opportunities for integrated terahertz devices.

The terahertz (THz) band (0.1–10 THz) is a promising platform for enabling terabit-per-second wireless links in future sixth generation (6 G) and beyond (XG) communication systems, owing to its ultrahigh carrier frequencies, broad bandwidths, and low latency^{1–5}. Valley photonic crystals (VPCs), in which inversion symmetry breaking gives rise to topological valley edge states, provide a powerful route toward robust on-chip light transport with suppressed backscattering^{6–14}, enabling low-loss and compact integrated terahertz devices^{15–17}. However, topological valley edge states typically lie outside the light cone

and are therefore intrinsically decoupled from free-space radiation. Existing devices with radiative functionality have consequently exploited strongly leaky edge states for on-chip-to-free-space emission¹⁸. While such approaches enable efficient radiation, the associated low *Q* factors and short propagation lengths limit their suitability for low-loss topological transport. Achieving free-space-to-on-chip excitation while preserving robust transport therefore remains a challenge.

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Quasi-bound states in the continuum (QBICs) provide a promising route to address this trade-off. Unlike ideal bound states in the continuum, which exhibit infinitely large Q factors but remain decoupled from radiative channels^{19–21}, QBICs acquire finite radiative coupling through controlled symmetry breaking while retaining strong field confinement^{22–27}. Their radiative leakage rates and Q factors can therefore be engineered by design. QBICs have enabled diverse functionalities, including unidirectional guided resonance²⁸, intrinsic chirality^{29,30}, complete polarization conversion^{31,32}, abrupt beam shifts^{33,34}, among others^{35–38}. Integrating QBIC physics with valley topology offers a route toward modes that are simultaneously radiatively accessible and robustly guided on-chip, establishing a controllable interface between free-space radiation and topological transport. However, topological valley QBICs have not yet been experimentally demonstrated.

Here, we experimentally demonstrate topological valley QBICs that enable radiative coupling from free space to robust on-chip topological transport in terahertz compound VPCs. By introducing geometric modulation, we fold topological valley edge states into the light cone through Brillouin-zone folding and transform them into QBIC modes with controllable radiative coupling. Using time-domain terahertz near-field imaging (Fig. 1a, b), we directly visualize their real-space propagation, demonstrate geometry-tunable propagation lengths, and observe robust propagation through sharp bends. Splitter and junction architectures further show that the free-space-excited QBICs can be routed on-chip for subsequent processing. Our work establishes topological valley QBICs as a platform for interfacing free-space radiation with low-loss topological transport.

Results

Design principle

A schematic configuration of a compound VPC formed by onsite-potential modulation is illustrated in Fig. 1c. The Hamiltonian for a VPC is

$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + \sum_i U_i c_i^\dagger c_i, \quad (1)$$

where $\sum_{\langle ij \rangle}$ denotes the summation over nearest-neighbor pairs, t is the nearest-neighbor hopping, and $c_i^\dagger$ (c_i) denotes the creation (annihilation) operator at site i . The onsite potential U_i is given by

$$U_i = \begin{cases} U_1, & i = 2n, \\ -U_1, & i = 2n + 1, \end{cases} \quad (2)$$

where n is an integer. After introducing onsite-potential modulation, the Hamiltonian for the compound VPC can be described as

$$H_{3P} = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + \sum_i U_i c_i^\dagger c_i + \sum_i \delta U_i c_i^\dagger c_i, \quad (3)$$

The onsite-potential modulation δU_i is given by

$$\delta U_i = \begin{cases} \delta U, & i = 3n, \\ 0, & i = 3n + 1, \\ -\delta U, & i = 3n + 2, \end{cases} \quad (4)$$

where $\delta U = U_2 - U_1$ is the amplitude of the period-tripling onsite-potential modulation. Here, U_1 and U_2 denote the onsite potentials associated with the two different unit cells in the compound VPC.

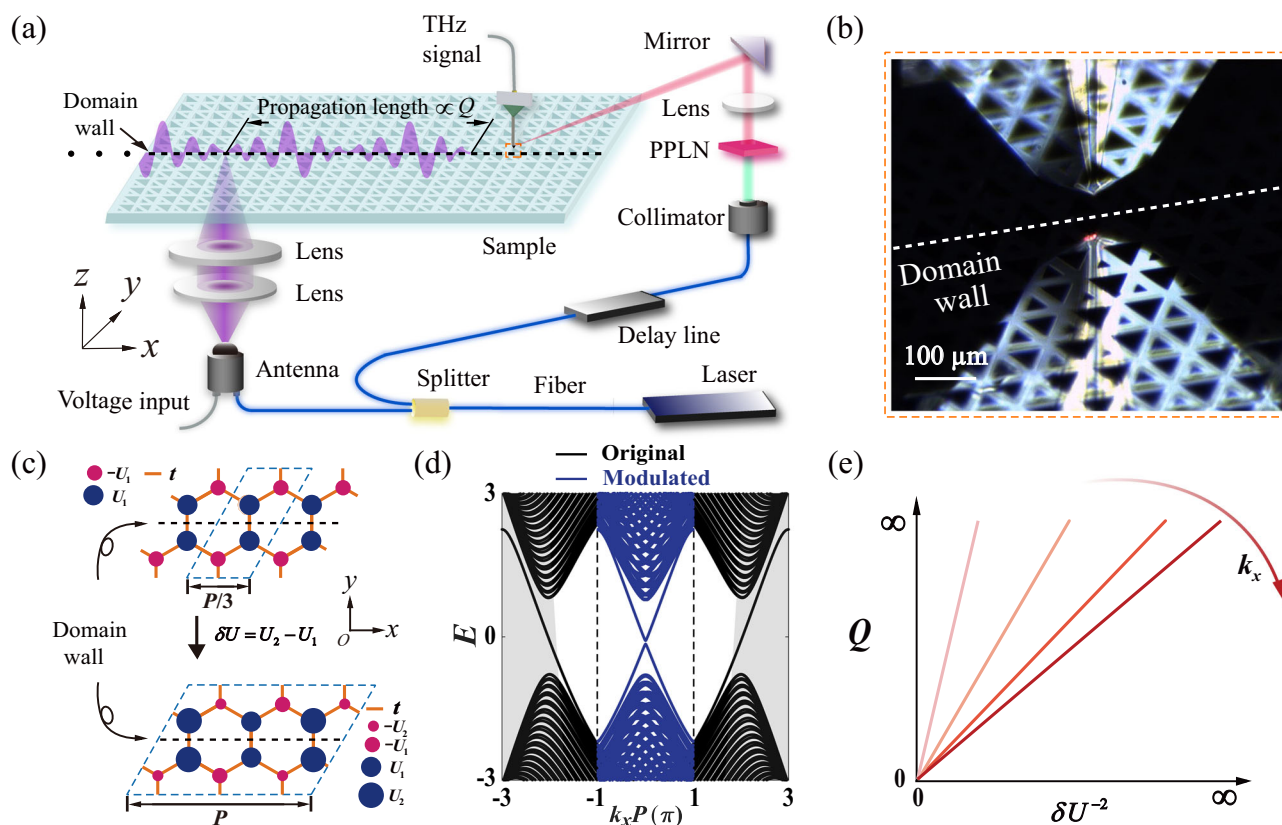


Fig. 1 | Schematic of topological valley QBIC bands in compound VPCs.

a Schematic of the time-domain terahertz near-field scanning system used to record the electric-field distributions of a compound VPC. **b** The optical image of the terahertz probe above a compound VPC in the experiment. **c** Schematic of a

VPC with an onsite-potential modulation introduced along the domain wall. **d** The corresponding dispersions before and after the onsite-potential modulation. **e** Dependences of the Q factors of the topological valley QBICs on the inverse square of the onsite-potential modulation δU at different momenta.

The domain wall constructed by the compound VPCs without onsite-potential modulation supports the topological valley edge states, as shown in Fig. 1d. The topological valley edge states lie below the light cone, indicated by the gray region in Fig. 1d, and therefore are non-radiative bound states with infinite radiative Q factors. In contrast, introducing the onsite-potential modulation changes the effective lattice period of the compound VPC and induces Brillouin-zone folding. This folding brings the valley edge states toward the Γ point and opens a small bandgap through Bloch-state coupling³⁶. Consequently, the originally non-radiative topological valley edge states are folded into the light cone and acquire finite radiative Q factors. The effective tight-binding Hamiltonian captures the band-folding mechanism, whereas the radiative Q factor is determined by the radiation-coupling strength. As the modulation strength δU decreases, the radiative coupling becomes weaker, and the Q factors are expected to increase following the inverse-square scaling $Q \propto \delta U^{-2}$, as schematically shown in Fig. 1e. This behavior is confirmed by the simulations below. In the limit $\delta U \rightarrow 0$, the radiative coupling vanishes and the Q factors diverge, corresponding to the topological valley BIC limit. We note that $\delta U = 0$ leads to a discrete change in the lattice constant compared with the cases of finite δU , resulting in a discontinuous change of the first Brillouin-zone boundary³⁴. Therefore, the Q factor near this discontinuity is evaluated through the limiting behavior $\lim_{\delta U \rightarrow 0} Q = \infty$, indicating that the folded topological valley edge states can continuously approach the topological valley BIC limit. For finite $\delta U \neq 0$, the folded topological valley edge-state bands in the compound VPC form topological valley quasi-BIC bands, and the corresponding edge states are identified as topological valley QBICs.

When a focused terahertz beam is incident on the domain wall formed by a compound VPC, the topological valley QBICs with a non-zero group velocity ($v_g \neq 0$) are excited and propagate along the domain wall. The propagation distance can be estimated as $L = v_g \tau$, where τ denotes the lifetime. Generally, the Q factor is defined as $Q = 2\pi f_0 \tau$, where f_0 is the resonance frequency³⁴. Thus, the propagation length of the topological valley QBICs satisfies $L = v_g Q / (2\pi f_0)$, where v_g and f_0 are the group velocity and frequency of the topological valley QBICs, respectively. For a fixed frequency and comparable group velocity, the propagation lengths of the topological valley QBICs are proportional to their corresponding Q factors, as illustrated in Fig. 1. Thus, measuring the propagation lengths provides an alternative way to reveal the Q factors of topological valley QBICs. Since the excited topological valley QBICs are well confined at the domain wall, we use a time-domain terahertz near-field scanning imaging system to observe the corresponding electric-field distribution, as schematically illustrated in Fig. 1a. Figure 1b illustrates the experimental configuration of the sample and the terahertz near-field probe, captured by a charge-coupled device (CCD) camera. The black regions correspond to areas where the incident light from the light-emitting diode (LED) is reflected outside the collection angle of the CCD, causing these regions to appear dark in the optical image (Supplementary Note 1 for details). The coherent detection method enables simultaneous phase and electric-field detection with a high signal-to-noise ratio. The excited topological valley QBICs exhibit finite radiative leakage, resulting in different propagation lengths determined by their Q factors. A near-field terahertz probe is raster-scanned above the top surface of the compound VPCs, recording both the phase and amplitude of the electric field with a spatial resolution of approximately 80 μm . The terahertz probe is located approximately 66 μm above the top surface of the sample, as depicted in Fig. 1b. The measurement height is 0.11 times the operating wavelength (e.g., 601.20 μm), indicating that the measured electric field is in the near-field region.

To implement the topological valley QBICs, we consider the TE modes (electric-field components in the xy plane) of a compound VPC. The compound VPC consists of three constituent VPC cells and has a period $P = 513 \mu\text{m}$ and thickness $h = 150 \mu\text{m}$, as depicted in Fig. 2a. The

periods of adjacent VPCs are identical, denoted as $P/3$. The side lengths of the triangular holes on the left and right are $w_{L1} = (0.65 + \delta w)P/3$ and $w_{R1} = (0.45 - \delta w)P/3$, respectively. In contrast, the side lengths of the triangular holes in the middle are $w_{L2} = 0.65 P/3$ and $w_{R2} = 0.45 P/3$, respectively. Here, δw is a tunable geometric parameter that represents the width difference between two adjacent VPCs. This geometric perturbation δw can be regarded as an effective onsite-potential modulation δU ³⁹ (Supplementary Note 2 for details).

Figure 2b illustrates the dispersion of a domain wall formed by the compound VPCs with $\delta w = 0$, where the compound VPC is a mono-periodic VPC with the first Brillouin-zone boundary at $k_x = 3\pi/P$. The black dashed lines indicate the light cone. Most topological valley edge states lie below the light cone and are therefore inaccessible to excitation by a free-space terahertz beam. In contrast, in the case of $\delta w \neq 0$, the compound VPC constitutes a tri-period VPC with a period of P . As the period of the compound VPC changes from $P/3$ to P , the first Brillouin-zone boundary changes from $k_x = 3\pi/P$ to $k_x = \pi/P$. Figure 2c depicts the dispersion of the domain wall consisting of the compound VPCs with $\delta w \neq 0$. The corresponding topological valley edge states are folded into the light cone and thus become accessible to excitation by a free-space terahertz beam. The small bandgap observed in Fig. 2c and Fig. 3d–f originates from the band-folding effect introduced when $\delta w \neq 0$. The geometric perturbation associated with a nonzero δw breaks the translational symmetry of the original structure and introduces Bloch-state coupling. As a result, folded Bloch states that become degenerate or nearly degenerate can couple to each other, leading to an avoided crossing and the opening of a small bandgap. Similar bandgap-opening phenomena induced by periodic perturbations have been reported in previous studies of folded BIC systems³⁶.

Consequently, as the geometric parameter δw is reduced to zero, the modulation-induced Brillouin-zone folding and radiative coupling vanish, and the topological valley edge states evolve from radiatively accessible QBICs to radiatively inaccessible topological valley BICs. Therefore, the topological valley edge states in the domain wall formed by the compound VPCs with $\delta w \neq 0$ are topological valley QBICs. The Q factors of the topological valley QBICs exhibit an approximately linear dependence on δw^{-2} at different momenta, as depicted in Fig. 2d. The red and blue lines in Fig. 2d represent the Q factors of the upper and lower topological valley QBIC bands in Fig. 2c, respectively. For clarity, we plot the Q factors of the topological valley QBICs as a function of δw^{-2} at three momenta: $k_x P = 0$ (circle), $k_x P = 0.01\pi$ (square), and $k_x P = 0.02\pi$ (triangle), as shown in Fig. 2e. The symbols (circle, square, and triangle) denote the simulated Q factors. The solid lines represent the corresponding linear fits. The fitted results indicate an approximately inverse-square dependence of the Q factor on the geometric perturbation δw , which is consistently observed for different momenta (incident angles)^{22,40}. We then simulate the z -component of the magnetic field (H_z) distributions of the topological valley QBICs in the compound VPCs with $\delta w = 0.18$, $\delta w = 0.12$, and $\delta w = 0$ at 0.500 THz, as shown in Fig. 2f. When $\delta w \neq 0$, the period-tripling perturbation breaks the original translational symmetry along the x -direction, causing the z -component of the magnetic field of the topological valley QBICs in the compound VPCs to become nonuniform along the domain wall, unlike the uniform distribution in the unmodulated VPC with $\delta w = 0$, shown in Fig. 2f. As the geometric parameter δw decreases, the magnetic field distributions of the topological valley QBICs in the compound VPCs with $\delta w \neq 0$ become more uniform along the domain wall, approaching those of the VPC with $\delta w = 0$.

Experimental results

We then fabricated compound VPCs with different δw values by etching a silicon wafer followed by grinding. Figure 3a–c show optical images of the compound VPCs with $\delta w = 0.18$, $\delta w = 0.15$, and $\delta w = 0.12$, respectively. The cyan lines indicate the domain walls. The lower

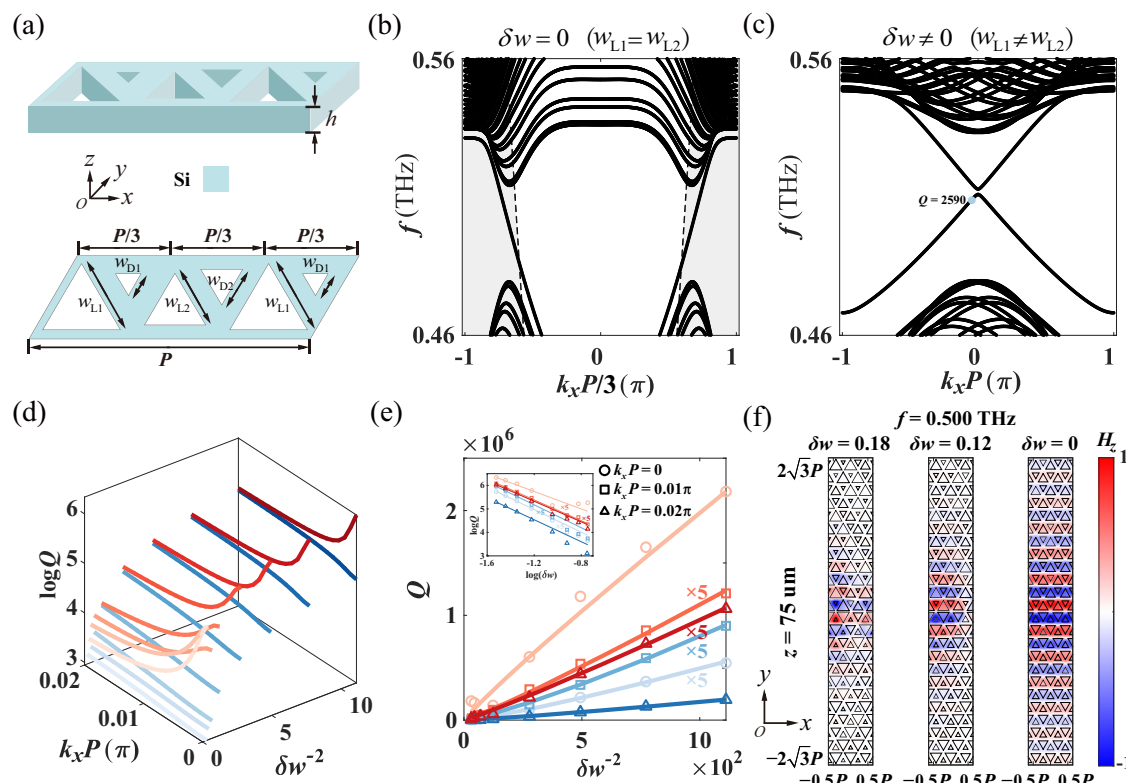


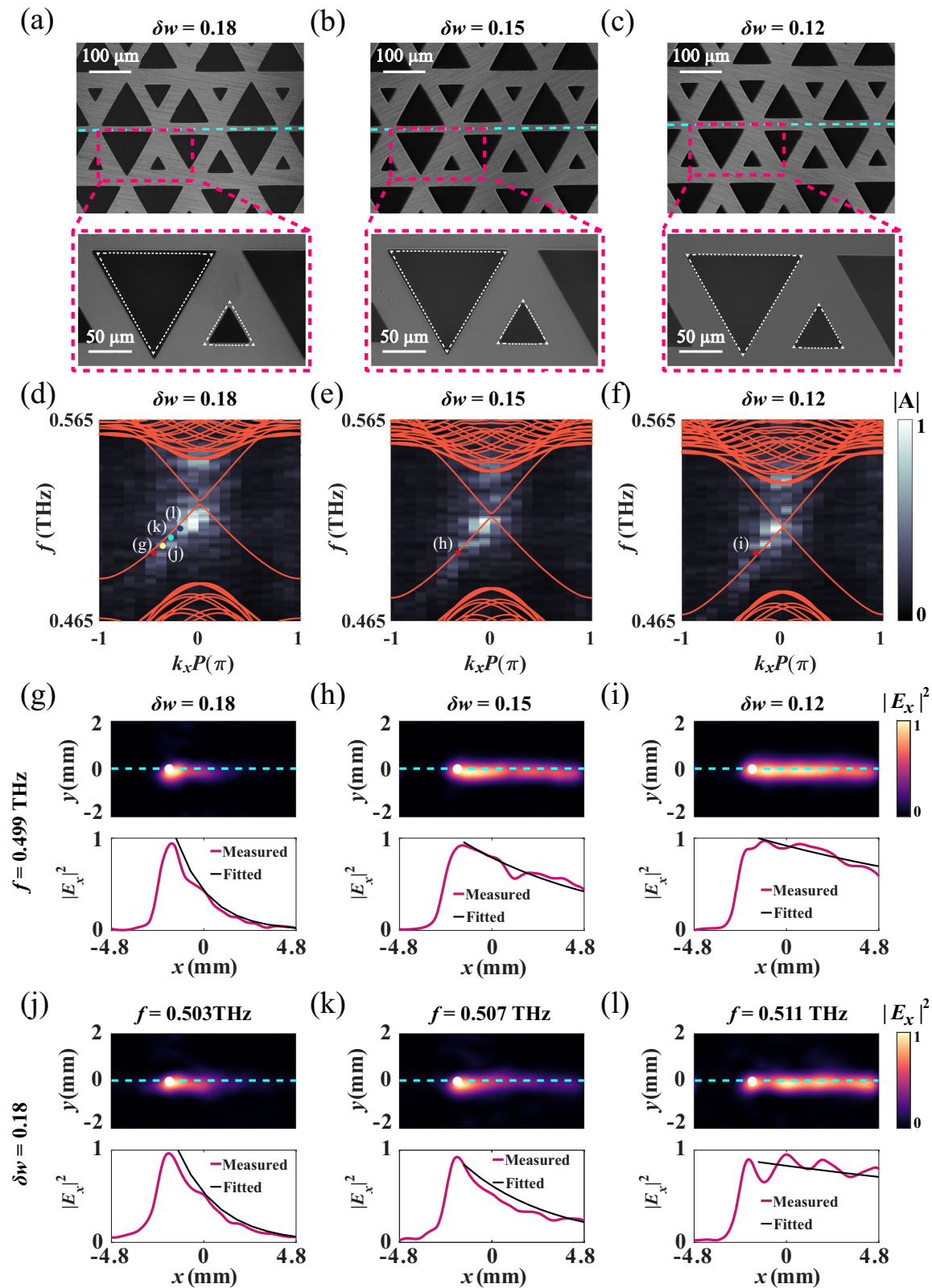
Fig. 2 | Topological valley BICs and QBICs in the compound VPCs. **a** The schematic of a unit cell of a compound VPC. **(b,c)** Dispersions of the domain walls constructed by the compound VPCs with $\delta w = 0$ (**b**) and with $\delta w \neq 0$ (**c**), respectively. In (**c**), the folded topological valley edge state forms a QBIC with a Q factor of approximately 2590 at $k_x P = 0.01\pi$. **d** Dependences of the Q factors of the topological valley QBIC bands on the inverse square of the geometric parameter δw for different momenta. The red and blue lines represent the Q factors of the upper and lower topological valley QBIC bands, respectively. **e** Dependences of the Q factors

of the topological valley QBICs on the inverse square of the geometric parameter δw for $k_x P = 0$ (circle), 0.01π (square), and 0.02π (triangle), respectively. The inset shows the same data on a log-log scale, demonstrating an approximately inverse-square dependence of the Q factor on the geometric parameter δw . **f** The z -component of the magnetic field of the topological valley QBICs at the middle plane ($z = 75 \mu\text{m}$) of the compound VPCs with $\delta w = 0.18$, $\delta w = 0.12$, and $\delta w = 0$ at 0.500 THz , respectively.

panels of Fig. 3a–c show the corresponding enlarged views of the triangular hole pairs. The white dashed triangles outline the triangular hole pairs in the compound VPC samples with $\delta w = 0.12$. The difference $\delta w = 0.03$ corresponds to a $5.13 \mu\text{m}$ size difference in the triangular hole pairs. The time-domain terahertz field-scanning imaging system records both the amplitude and phase distributions of the electric field above the sample. Based on the measured electric-field data, we perform a two-dimensional Fourier transform of the spatial electric-field distributions to obtain the experimentally measured projected dispersions of the domain walls formed by the compound VPCs with $\delta w = 0.18$, 0.15 , and 0.12 in momentum space, as shown in Fig. 3d–f. In Fig. 3d–f, the color maps represent the relative spectral intensity of the excited states at different frequencies and momenta. Therefore, the background features correspond to the experimentally measured projected dispersions of the domain wall formed by the compound VPC. The overlaid dispersion curves obtained from numerical simulations serve as a guide to identify the valley QBIC bands in the measured projected dispersions. For example, the red dots in Fig. 3d–f indicate the valley QBIC at 0.499 THz for the corresponding samples. The corresponding measured electric-field distributions, shown in Fig. 3g–i, are localized along the domain wall, indicating that the highlighted dispersion branch originates from the valley QBICs. In contrast, other bright features outside the highlighted dispersion branch, particularly those appearing near $k_x P = 0$ at higher frequencies, are bulk modes. The retrieved projected dispersions of the topological valley QBICs are consistent with the simulated results (as indicated by the orange lines), as illustrated in Fig. 3d–f, respectively. The lower

panels of Fig. 3g–i show the corresponding electric-field intensity distributions of the topological valley QBICs in the compound VPC along the x -axis at $y = 0 \text{ mm}$, respectively.

We extract the propagation lengths from the measured near-field distributions by fitting the electric-field intensity profile along the propagation direction. We fit the propagation length using $|E(x)|^2 \propto \exp(-x/L)$, where x is the coordinate and L is the propagation length. The fitted propagation lengths are 1.73 mm , 7.64 mm , and 17.22 mm for $\delta w = 0.18$, 0.15 , and 0.12 at 0.499 THz , respectively. The propagation lengths of the topological valley QBICs in the compound VPCs increase gradually as the geometric parameter δw decreases from 0.18 to 0.12 , consistent with the corresponding increase in Q factors at the same frequency. The corresponding Q factors are then obtained as $Q = 2\pi f_0 L / v_g$, where f_0 is the operating frequency and v_g is the group velocity. The group velocity is extracted from the simulated dispersion because the measured projected dispersions are consistent with the simulated ones. The retrieved Q factors for the compound VPCs with $\delta w = 0.18$, 0.15 , and 0.12 at 0.499 THz are 119.43 , 456.86 , and 958.89 , respectively. The corresponding simulated Q factors are 126.95 , 753.77 , and 3208.60 , respectively. These results show that the propagation lengths and retrieved Q factors increase as the perturbation strength δw decreases, consistent with the QBIC behavior. For the compound VPC with $\delta w = 0.18$, the propagation length and retrieved Q factor also increase with increasing operating frequency within the measured frequency range. The differences between the experimentally retrieved and simulated Q factors may be caused by fabrication-induced additional radiative loss and variations in the fitted



propagation length (Supplementary Note 3 for details). Figure 3j–l illustrate the electric-field intensity distributions of the topological valley QBCs in the compound VPC with $\delta w = 0.18$ at 0.503 THz, 0.507 THz, and 0.511 THz, respectively. The corresponding fitted propagation lengths are 2.20 mm, 4.64 mm, and 30.53 mm, respectively. The propagation lengths of the topological valley QBCs in the compound VPC with $\delta w = 0.18$ also gradually increase at these frequencies.

This trend is consistent with the simulations shown in Fig. 2d. The retrieved Q factors are 143.48, 291.45, and 1864.30 for the valley QBCs in the compound VPCs with $\delta w = 0.18$ at 0.503 THz, 0.507 THz, and 0.511 THz, respectively. Meanwhile, the corresponding simulated Q factors are 156.32, 467.34, and 864.74, respectively. We also retrieve Q factors for more frequencies of the compound VPCs with $\delta w = 0.18$, 0.15, and 0.12, respectively (Supplementary Note 3 for details). Overall,

Fig. 3 | Measured dispersions and electric-field intensity distributions of the topological valley QBICs in the compound VPCs with different δw . **a–c** The optical images of the compound VPC samples with $\delta w = 0.18$ (**a**), 0.15 (**b**), and 0.12 (**c**), respectively. The lower panels show the corresponding enlarged views of the triangular hole pairs in the compound VPC samples with $\delta w = 0.12$. The white dashed triangles outline the triangular hole pairs in the compound VPC samples with $\delta w = 0.12$. **d–f** The measured projected dispersions of the domain walls formed by the compound VPCs with $\delta w = 0.18$ (**d**), 0.15 (**e**), and 0.12 (**f**), respectively. The orange lines depict the simulated projected dispersions of the corresponding domain walls formed by the compound VPCs. The red, yellow, cyan, and blue dots represent 0.499 THz, 0.503 THz, 0.507 THz, and 0.511 THz, respectively. **g–i** The electric-field intensity distributions of the topological valley QBICs in the compound VPCs at 0.499 THz with $\delta w = 0.18$ (**g**), 0.15 (**h**), and 0.12 (**i**), respectively. The lower panels show the corresponding

electric-field intensity distributions of the topological valley QBICs in the corresponding compound VPCs along the x -axis at $y = 0$ mm, respectively. The black lines show the corresponding exponential fits used to extract the propagation lengths. **j–l** The measured electric-field intensity distributions of the topological valley QBICs in the compound VPC with $\delta w = 0.18$ at 0.503 THz (**j**), 0.507 THz (**k**), and 0.511 THz (**l**), respectively. The lower panels illustrate the corresponding electric-field intensity distributions of the topological valley QBICs in the compound VPC along the x -axis at $y = 0$ mm, respectively. The black lines show the corresponding exponential fits used to extract the propagation lengths. The cyan dashed lines indicate the positions of the domain wall in the compound VPCs. The white dots indicate the excitation positions. The electric-field intensity distributions are normalized by the maximum absolute value of the electric-field intensities in the corresponding figures.

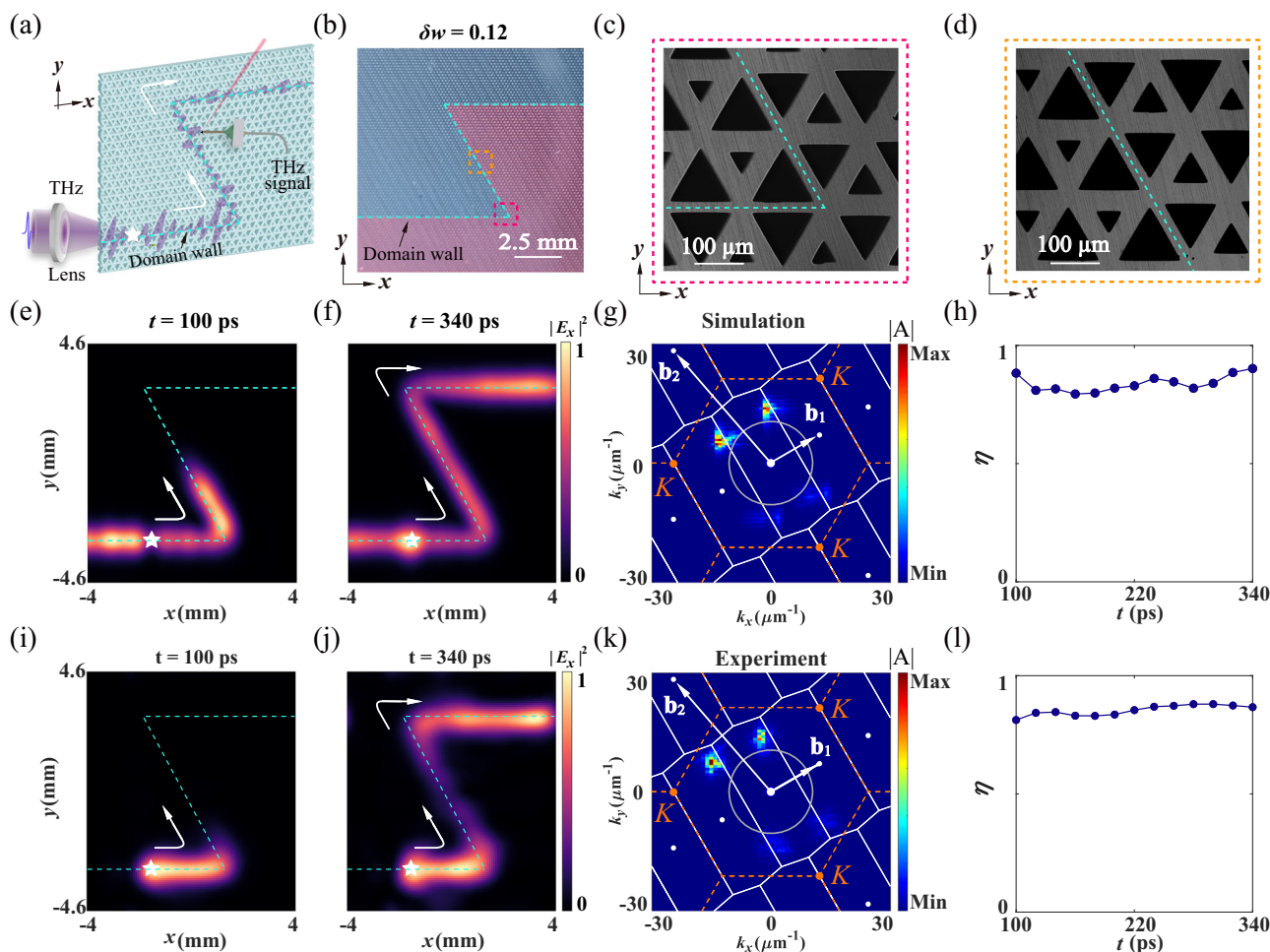


Fig. 4 | The simulated and measured electric-field intensity distributions of the topological valley QBICs in a Z-bend domain wall of the compound VPC with $\delta w = 0.12$. **a** Schematic of the time-domain terahertz near-field scanning system used to record the electric-field distributions of a Z-bend domain wall formed by the compound VPC with $\delta w = 0.12$. The cyan dashed line indicates the domain wall. The white star indicates the position of the incident focused terahertz beam. **b** The optical image of the Z-bend domain wall formed by the compound VPCs with $\delta w = 0.12$. The red and blue regions represent compound VPCs belonging to different valley Chern numbers, respectively. **c, d** The corresponding enlarged views of the compound VPCs at the bend and in the upper section of the domain wall, respectively. **e, f** The extracted simulated electric-field intensity distributions of topological valley QBICs in the Z-bend domain wall formed by the compound VPC

with $\delta w = 0.12$ at 0.495 THz at time delays of 100 ps and 340 ps, respectively. **g** The corresponding momentum-space distribution of (**f**). Orange dashed lines represent the Brillouin-zone boundary of the VPC with $\delta w = 0$. The white lines represent the Brillouin-zone boundaries of the VPC with $\delta w \neq 0$. **b₁** and **b₂** are the corresponding reciprocal lattice vectors. **h** The extracted simulated valley polarization contrast coefficient η at different time delays. **i, j** The extracted measured electric-field intensity distributions of the topological valley QBICs in the Z-bend domain wall formed by the compound VPC with $\delta w = 0.12$ at 0.495 THz at time delays of 100 ps and 340 ps, respectively. **k** The corresponding momentum-space distribution of (**j**). **l** The extracted measured valley polarization contrast coefficient η at different time delays. The electric-field intensity distributions are normalized by the maximum absolute value of the electric-field intensities in the corresponding figures.

the experimentally retrieved Q factors show the same increasing trend as the simulated values and are comparable in magnitude.

Although the geometric perturbation along the x -direction folds the Brillouin zone, the local inversion-symmetry breaking of each constituent honeycomb lattice is retained in the compound VPC. The two compound VPCs forming the domain wall have opposite sublattice configurations and therefore carry opposite valley Chern numbers. Consequently, the domain wall supports valley-polarized topological edge states and enables robust edge-state transport. To investigate the robustness of the topological valley QBICs in the compound VPC, we employ a time-domain terahertz near-field scanning system to record the electric-field distributions of the Z-bend domain wall, as shown in Fig. 4a. The cyan dashed line indicates the domain wall, and the white star denotes the position of the focused incident terahertz beam. We fabricate a compound VPC with $\delta w = 0.12$ that forms a Z-bend domain wall, as shown in the optical image in Fig. 4b. The red and blue regions correspond to compound VPCs with opposite valley Chern numbers. Figure 4c, d show enlarged views of the bending region and the upper section of the domain wall, respectively. Figure 4e, f illustrate the extracted simulated electric-field intensity distributions of the topological valley QBICs at 0.495 THz after excitation for 100 ps and 340 ps, respectively, indicating robust propagation through the Z-bend domain wall. To demonstrate robust transport of the valley QBICs, we perform a two-dimensional Fourier transform of the complex near-field distributions. The orange dashed lines denote the Brillouin-zone boundary of the unmodulated VPC ($\delta w = 0$), whereas the white lines represent the Brillouin-zone boundaries of the compound VPC ($\delta w \neq 0$). The reciprocal lattice vectors of the compound VPC are indicated by $\mathbf{b}_1$ and $\mathbf{b}_2$. Two dominant momentum components are observed in the Brillouin zone of the compound VPC, corresponding to the folded K and K' valleys originating from the unmodulated VPC (Fig. 4g). We then define the valley-polarization contrast coefficient as $\eta = (I_K - I_{K'}) / (I_K + I_{K'})$, where I_K and $I_{K'}$ are the integrated spectral intensities around the folded K and K' valleys, respectively. The extracted simulated valley polarization contrast coefficient remains nearly unchanged during propagation (Fig. 4h), indicating suppressed intervalley scattering and robust transport through the Z-bend domain wall (Supplementary Note 4 for details). By analyzing the measured time-domain near-field signals, we directly visualize the propagation of the topological valley QBICs through the Z-bend domain wall (Fig. 4i, j). The measured valley QBICs propagate along the bent domain wall at 0.495 THz while maintaining strong confinement, with suppressed scattering into bulk modes. Consistently, two dominant momentum components are observed in the measured Brillouin-zone distribution of the compound VPC with $\delta w = 0.12$ (Fig. 4k), in agreement with the simulated results in Fig. 4g. The experimentally extracted valley-polarization contrast coefficient η remains stable during propagation through the Z-bend, as shown in Fig. 4l, indicating that the valley polarization is largely retained despite finite valley mixing. This result demonstrates robust valley-polarized transport in the Z-bend domain wall.

Moreover, we fabricated two additional designs to demonstrate the advantages of robust radiatively accessible transport enabled by valley QBICs. The first design is an on-chip beam splitter, as schematically shown in Fig. 5a. Figure 5b, c show the optical image and enlarged view of the splitter sample, respectively. The measured electric-field intensity distributions split into two branches at 0.495 THz, 0.500 THz, and 0.505 THz, as shown in Fig. 5d–f, respectively. The split ratio is defined as $\frac{\sum |E_U|^2}{\sum |E_L|^2}$, where $|E_U|^2$ and $|E_L|^2$ represent the electric-field intensities in the upper and lower domain walls at the operating frequency (f), respectively. The corresponding split ratios are 1.12, 1.18, and 1.07, respectively, indicating nearly balanced power splitting. The second design is a junction structure, in which the compound VPC with $\delta w = 0.12$ is directly connected to the

unmodulated VPC with $\delta w = 0$, as schematically shown in Fig. 5g. This design demonstrates the process of coupling a free-space terahertz signal into an on-chip VPC channel for further signal processing. Figure 5h, i show the optical image and enlarged view of the junction sample, respectively. Intensity peaks are observed around the intentionally introduced defect in the measured electric-field intensity distributions at 0.495 THz, 0.500 THz, and 0.505 THz, as shown in Fig. 5j–l, respectively. These peaks indicate that the free-space-excited valley QBICs are coupled from the compound VPC into the adjacent unmodulated VPC. These results indicate that free-space terahertz signals can be coupled into an on-chip VPC through our compound VPCs for subsequent signal processing.

Discussion

In conclusion, we experimentally demonstrate topological valley QBICs as a radiative platform for free-space-to-on-chip topological transport in terahertz compound VPCs. By introducing controlled geometric modulation, topological valley edge states are folded into the light cone through Brillouin-zone folding, enabling direct free-space excitation while largely preserving robust valley transport. The resulting valley QBIC modes exhibit geometry-tunable radiative coupling, allowing control of their Q factors and real-space propagation lengths. Using time-domain terahertz near-field imaging, we directly visualize their on-chip transport, demonstrate tunable propagation lengths through geometric engineering, and observe robust transmission through sharp bends. Furthermore, the splitter and junction architectures indicate that free-space-excited valley QBICs can be routed on-chip and connected to low-loss topological waveguides for subsequent photonic processing. Our work establishes topological valley QBICs as a platform for integrating free-space radiation with robust topological transport and provides new opportunities for compact terahertz photonic systems.

Methods

The time-domain terahertz near-field scanning system

The terahertz beam is collimated by a terahertz lens with a focal length of $F = 5$ cm. We then add two terahertz lenses ($F = 10$ cm and $F = 2.5$ cm) to focus the collimated beam. The polarization of the incident beam is adjusted to TE polarization, and the electric field is in the xy plane. The fitted beam waists along the x - and y -directions are approximately 0.5457 mm and 0.4262 mm, respectively (Supplementary Note 1 for details). A terahertz probe is utilized to record the electric field in the scanning area of the samples. The pitch of the sample holder is calibrated by adjusting the heights between the terahertz probe and the four corners of the scanning area of a sample. In calibration, the heights between the terahertz probe and the four corners of the scanning area of a sample are approximately 66 μm (see Fig. 1b) with a height error within 0.004 mm. The scan region is 4.00×9.60 mm with an increment of 0.08 mm for the compound VPCs with straight domain walls. The scan region is 9.20×8.00 mm with an increment of 0.08 mm for the compound VPCs with the Z-bend domain wall. The scan region is 8.00×8.40 mm with an increment of 0.08 mm for the compound VPC splitter. The terahertz signal is scanned up to 400 ps, which provides a frequency resolution of 0.0025 THz. We also perform zero-padding up to 3276.8 ps in the time-domain data to increase the number of frequency points, resulting in smaller intervals. Zero-padding does not change the intrinsic spectral resolution.

Data availability

The data supporting the findings of this study are available within the Article and its Supplementary Information. Source data underlying the figures are provided with this paper. Additional datasets, including the full electric-field distributions, are available from the corresponding authors upon request. Source data are provided with this paper.

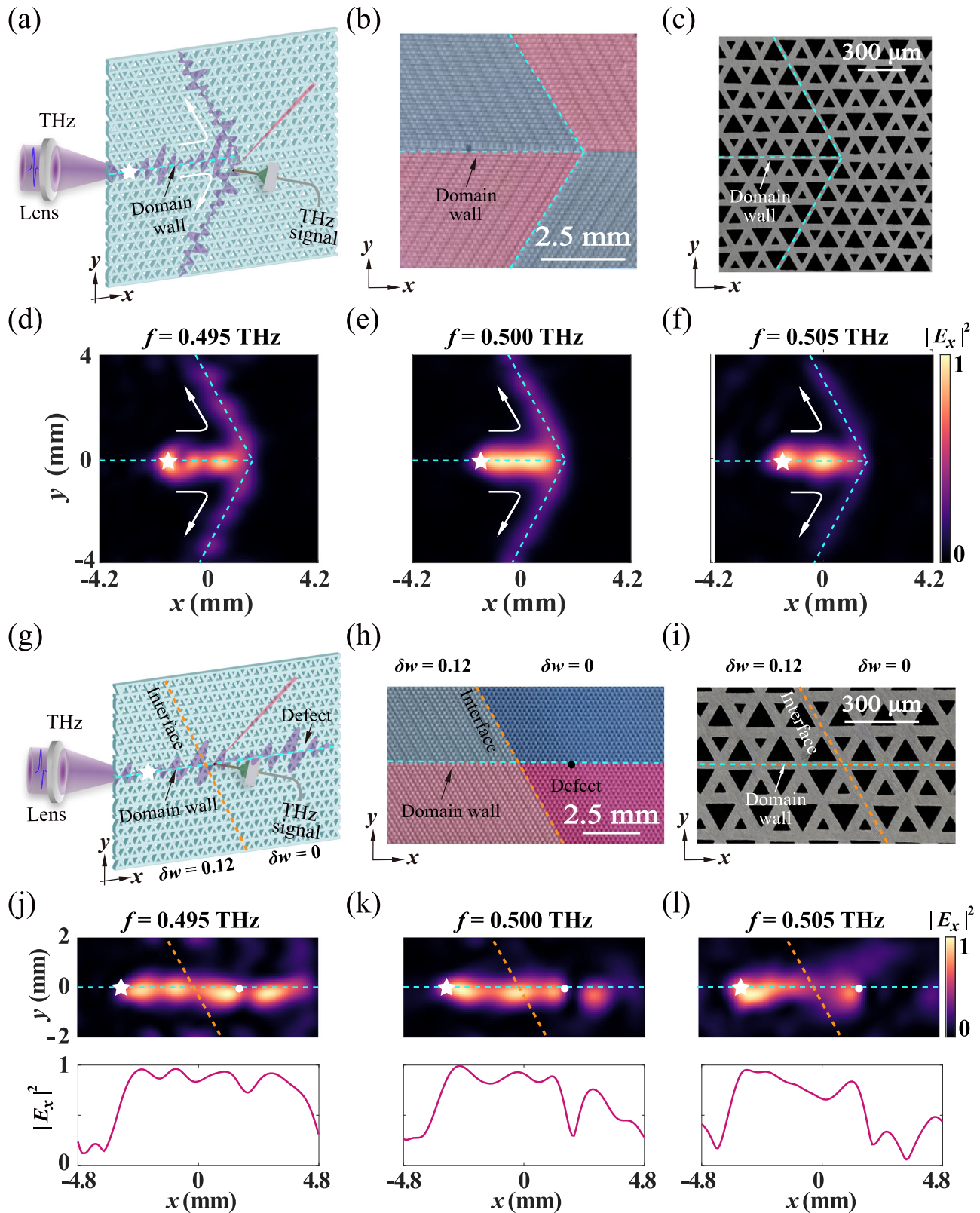


Fig. 5 | Measured electric-field intensity distributions of topological valley QBCs in the on-chip splitter and junction structures. **a** Schematic of the time-domain terahertz near-field scanning system used to record the electric-field distributions of the splitter design based on the compound VPC with $\delta w = 0.12$. **b** Optical image of the splitter sample. The red and blue regions represent compound VPCs with different valley Chern numbers. **c** Enlarged view of the splitter sample. **d-f** Measured electric-field intensity distributions of the splitter at 0.495 THz (d), 0.500 THz (e), and 0.505 THz (f). The cyan dashed lines indicate the positions of the domain walls in the compound VPCs. **g** Schematic of the time-

domain terahertz near-field scanning system used to record the electric-field distributions of the junction between a compound VPC with $\delta w = 0.12$ and an unmodulated VPC with $\delta w = 0$. **h** Optical image of the junction sample. The red and blue regions represent VPCs with different valley Chern numbers. **i** Enlarged view of the junction sample. **j-l** Measured electric-field intensity distributions of the junction design at 0.495 THz (j), 0.500 THz (k), and 0.505 THz (l). The lower panels show the corresponding electric-field intensity profiles along the x-axis at $y = 0$ mm. The white stars and dots denote the excitation and defect positions, respectively.

Code availability

Custom MATLAB scripts used for the Fourier-transform analysis and exponential fitting are available from the corresponding authors upon request.

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Author contributions

Y.L. and M.W. proposed the idea. M.W. and Y.L. designed the samples. M.W. and G.-G.L. performed the optical measurement and data analysis. M.W., Y.L., and G.-G.L. organized the manuscript. M.W., Y.L., G.-G.L., J.L., S.M., E.E.M.C., and B.Z. contributed to the writing and revision of the manuscript. G.-G.L., Y.L., and B.Z. supervised the work.

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Competing interests

The authors declare no competing interest.

Additional information

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