

Article

Robust Terahertz Refractive-Index Sensor Based on Cavity-Edge-State Coupling in a Topological Photonic Crystal

Rongbing Yang ^{1,†}, Shirui Liu ^{1,†}, Zhang Zhang ^{1,*}, Wei Xu ¹, Kaishuai Yang ¹, Yawei Kuang ¹, Zhida Han ¹, Zijie Dai ², Kejiang Yan ¹, Yi Liu ¹, Shuai Yin ¹, Tianyue Yao ¹, Jun Yang ¹, Feiyang Zhang ¹, Ziyang Zhou ¹, Chenchen Zhao ¹, Wenjuan Han ¹, Guohui Tu ¹, Longhai Liu ³, Lanju Liang ⁴ and Jianquan Yao ³

¹ School of Electronic and Information Engineering, Suzhou University of Technology, Suzhou 215500, China

² School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China

³ The Key Laboratory of Opto-Electronics Information and Technology, Institute of Laser and Opto-Electronics, College of Precision Instruments and Opto-Electronics Engineering, Tianjin University, Tianjin 300072, China

⁴ School of Opto-Electronic Engineering, Zaozhuang University, Zaozhuang 277160, China

* Correspondence: zhangzhang@csjg.edu.cn

† Contributed equally to this work

Abstract

Topological photonics provides a robust framework for controlling light, with edge states offering immunity to disorder. However, utilizing this stability for practical sensing remains a challenge, as conventional high-sensitivity photonic crystal sensors suffer common imperfections. Here, we numerically design a topological photonic crystal sensor for THz refractive-index detection. The silicon-based structural slab is engineered, showing a wide photonic bandgap (PBG). By breaking the inversion symmetry, two structures with trivial and nontrivial topological phases are constructed. Due to their opposite valley Chern numbers, the topologically protected edge states can be formed at the interface. Such edge states were further integrated with the resonant cavities, so that the resonant frequencies were observed in transmittance property, forming a stable cavity–edge states coupling channel for refractive-index sensing. Numerical results demonstrate strong suppression of transmission distortion induced by boundary defects, verifying favorable topological robustness of the proposed architecture. The structure exhibits linear refractive-index response with a simulated sensitivity of 1.9 THz/RIU, outperforming conventional photonic crystal sensors in numerical comparison. This work merges topological stability of edge states with high sensitivity response of resonant frequency, offering a theoretical candidate for robust biosensing and chemical detection.

Keywords: topological photonic crystal; terahertz; cavity-edge-state coupling; refractive-index sensing

Received: 1 June 2026

Revised: 19 July 2026

Accepted: 21 July 2026

Published: 23 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

Topological photonics has emerged as a revolutionary paradigm for controlling the flow of light, offering excellent robustness against structural imperfections and backscattering due to the topological protection of its edge states [1–5]. Originating from the discovery of topological insulators in condensed matter physics, this concept was rapidly translated into photonic systems by engineering artificial gauge fields and symmetry-protected band structures, leading to the numerical realization of photonic analogs of the quantum Hall effect, quantum spin Hall effect, and valley Hall effect [6–10]. The inherent stability of topological edge states stems from global topological invariants, such as the Chern number or valley Chern number that characterize the photonic band structure. This stability is fundamentally different from conventional waveguiding mechanisms, as it does not rely on fine-tuned local parameters but rather on the global geometry of the bandgap. Consequently, topological edge states exhibit remarkable properties, including unidirectional propagation, immunity to backscattering from defects or sharp bends, and resilience against disorder-induced localization [11–14]. These features are particularly advantageous for developing integrated photonic devices such as waveguides, splitters, resonators, and lasers that require reliable operation under non-ideal fabrication and operating conditions [15–20]. Indeed, the topological lasers with single-mode operation and high-power efficiency, as well as topological delay lines with low dispersion, are demonstrated in recent years [21–25]. By enabling robust light transport even in the presence of significant structural imperfections, topological photonics has opened new avenues for designing next-generation photonic circuits with enhanced performance, functionality, and scalability [26–28]. The unique combination of robustness and light field properties naturally raises the question: can these topological principles be exploited to overcome longstanding challenges in photonic sensing, where stability against environmental fluctuations and fabrication errors is crucial?

Despite these remarkable advances, a significant challenge remains in effectively utilizing topological properties for practical sensing applications. Conventional photonic crystal sensors, which typically rely on defect modes induced by point or line defects within a perfect periodic lattice, have achieved high sensitivity by strongly confining light in a small modal volume. However, these defect-mode-based sensors are fundamentally limited by their extreme demands for fabrication imperfections and environmental disturbances. Even nanometer-scale deviations in hole radius or lattice constants can detune the resonance condition, leading to degraded quality factors and reduced signal-to-noise ratios [29,30]. In addition, conventional sensors are susceptible to fabrication defects, whose transmission spectra are significantly perturbed by such structural disorders. This critical shortcoming highlights the urgent need to develop novel sensing architectures that not only retain high sensitivity but also inherit the intrinsic robustness of topological photonic systems. A promising strategy is to integrate topological edge states with resonant cavities, where the topological protection ensures stable operation while the cavity enhances light-matter interaction for high sensitivity at resonant frequency. However, achieving the cooperation between the extended nature of edge states and the localized nature of cavity modes requires careful design of their coupling strength and spectral response. Additionally, the terahertz (THz) regime, which lies between microwave and infrared frequencies, offers unique opportunities for sensing due to the strong characteristic absorption fingerprints of many biomolecules, explosives, and pharmaceuticals, yet it also poses severe challenges for device stability because of the long wavelengths and large feature sizes involved [31]. As a result, there is an urgent demand to explore the integration of topological edge states with resonant cavities to create a new class of sensors that combine superior stability with enhanced sensing capabilities, especially in the technologically important THz band.

To address the above sensing demands, researchers have developed diverse topological photonic sensing platforms, covering quantum-Hall/spin-Hall photonic systems, one-dimensional topological interface-state sensors, high-order topological corner-state cavities, topological nanocavities and cavity-waveguide coupled resonators [32–38]. Nevertheless, most existing schemes still suffer from single-mode detection limits or weak anti-disorder capacity. Distinct from the reported architectures, this work proposes a simulated THz silicon valley-Hall photonic crystal with triangular air holes, where cavity-edge-state coupling is adopted to realize multi-mode refractive-index sensing in numerical simulation. Compared with previously reported 1D topological sensors, hyperbolic graded topological resonators and topological-assisted metasurface liquid biopsy detectors [32–38], our device integrates four exclusive merits: terahertz operating band, orientation-selective cavity-edge coupling, multi-mode resonant response, and inherent immunity to boundary defects, which collectively constitute the core novelty of this research.

Here, we report the theoretical design and numerical investigation of a topological photonic crystal sensor for high-performance refractive-index sensing in the THz regime. We first engineer a single-hole silicon photonic crystal exhibiting a wide complete photonic bandgap and confirmed non-trivial topology, which serves as the optimal platform. Subsequently, by combining two photonic structures with different symmetry features, we construct a topological interface supporting robust edge states with high transmission efficiency. After introducing and coupling defect-like resonant cavities to this topological channel, we establish a sensing mechanism based on cavity-edge-state interaction. Numerical simulations reveal that this integrated system exhibits strong tolerance to intentionally introduced boundary defects, verifying its inherent robustness resulting from topological protection. Furthermore, we achieve highly sensitive refractive-index detection with linear response and a sensitivity up to 1.9 THz/RIU, outperforming conventional defect-based photonic crystal sensors in simulated comparison. All analyses presented in this manuscript are purely numerical simulations without experimental fabrication and measurements. This work supplies a new route for addressing the critical challenge of stability in photonic sensors by exploiting topological principles. Also, it establishes a theoretical framework for designing robust, high-sensitivity devices for prospective label-free biosensing and precise chemical detection in future experimental research.

2. Materials and Methods

Numerical simulations are performed using the finite element method in COMSOL Multiphysics (COMSOL Multiphysics® 6.4 software, Sweden). All calculations adopt two-dimensional planar models without slab thickness. The entire computational domain is wrapped by perfectly matched layers (PML) for eigenfrequency and transmission simulations to eliminate spurious boundary reflections, and chiral excitation sources are applied to analyze TE polarization modes only. Silicon is assigned a constant refractive index of 3.42 in the studied THz band, and material dispersion and silicon absorption losses are fully neglected. This approximation is reasonable since this paper mainly proposes a structural design concept instead of precise quantitative performance assessment. Silicon loss only uniformly weakens transmittance amplitude and cannot alter resonant positions, mode splitting or topological anti-defect immunity, which are the core mechanisms focused on in this work. The lattice constant is set as 5 μm with penetrating triangular air holes. The band structure is calculated along the Γ -K-M- Γ high-symmetry path under Floquet periodic boundary conditions. In this work, two honeycomb unit cell layouts (dual-hole and single-hole) are first designed for photonic bandgap screening. Both configurations break the intrinsic central inversion symmetry of pristine honeycomb lattices via internal asymmetric triangular air-hole arrangement, rather than shifting or displacing air holes artificially. Band structure calculations verify that the single-hole lattice possesses a

wider complete photonic bandgap, which is therefore selected as the fundamental valley photonic crystal platform of this study. The single-hole lattice generates opposite magnetic vortex phases at K and K' valleys with non-zero Berry curvature, confirming that it belongs to a nontrivial topological system. The topological domain wall between Type-A and Type-B lattices adopts a zigzag geometry. To acquire two single-hole structures carrying opposite valley Chern numbers, we perform a global mirror reflection transformation on the optimized single-hole lattice, where the mirror operation only flips the sign of the valley Chern number without changing the intrinsic symmetry-breaking feature of the single-hole unit cell. We calculate Berry curvature and valley Chern numbers following standard valley-Hall THz photonic crystal schemes. Only the two bands directly bounding the complete photonic bandgap are calculated. Berry curvature $\Omega(\mathbf{k})$ at each discrete k-point is solved via discrete Kubo formula on dense uniform k-meshes covering the full Brillouin zone. The hexagonal Brillouin zone is split into two non-overlapping triangular integral domains separated by Γ -M high-symmetry boundaries to avoid inter-valley flux mixing. Integrating Berry curvature over each valley yields $C_K = -1/2$, $C_{K'} = +1/2$ for the primitive single-hole cell. The mirror-reflected Type-B lattice flips all k-space coordinates, reversing the sign of Berry curvature everywhere and producing opposite valley Chern values $C_K = +1/2$, $C_{K'} = -1/2$. The dual-hole lattice also breaks inversion symmetry but delivers narrower bandgap and weaker integrated Berry flux, so it is not adopted in our device design.

The defect cavity is introduced by uniformly scaling the triangular air hole with a factor of $\delta L = L_2/L_1$. Here, L_1 represents the side length of triangular air holes in the standard single-hole primitive unit cell, and L_2 is the side length of the shrunk triangular air hole used to construct resonant defect cavities, where δL quantifies the proportional scaling ratio between the defect hole and the original lattice air hole. To avoid confusion of symbolic representation, an independent parameter δB is defined to describe the scaling factor of artificial boundary defects on the topological waveguide channel, which is different from the cavity scaling parameter δL . In here, $\delta B = W_2/W_1$ (W_1 = standard boundary hole side length, W_2 = perturbed defect hole side length). Notably, the defect maintains local C_{3v} point-group symmetry after uniform scaling. Eigenfrequency and frequency-domain transmission simulations adopt scattering boundary conditions to eliminate boundary reflections. The structural robustness is evaluated by introducing artificial boundary defects and comparing the corresponding field distributions and transmission spectra. For refractive-index-sensing simulations, the air regions are filled with analytes with refractive indices ranging from 1 to 1.04, and the sensitivity is defined as $S = \Delta f/\Delta n$, FOM = S/FWHM . The tiny refractive perturbations within 0.04 represent the most challenging weak signal detection scenario for biosensing devices. By testing the device response under such slight refractive changes, we can fully verify its ultrahigh sensitivity performance for trace biological analytes. Additionally, the full-filling scheme is adopted in our model for the following reason: our micrometer-scale THz topological photonic crystal chip has no isolated sealed microchannels for separate liquid loading. Capillary action uniformly fills all air holes after analyte deposition, validating the full-filling simulation model.

3. Results and Discussion

Based upon the fundamental principle that the topological properties of a periodically driven system are dictated by the band structure of its effective Hamiltonian ($\mathbf{H}_{eff}$), which allows for the engineering of non-trivial topology even in initially trivial static systems, our analysis of the designed photonic crystals proceeds as follows. Specifically, Figure 1 presents two distinct silicon photonic crystal structures: a dual-hole configuration with reduced unit cell symmetry and a single-hole structure preserving uniform crystal-line symmetry. The corresponding calculated band structures, which are plotted along the

high-symmetry path in the first Brillouin zone, reveal critical differences. While both structures exhibit corresponding photonic bandgap (PBG), it is observed that the single-hole crystal significantly possesses a wider PBG. More importantly, as shown in the inset of Figure 1d, the single-hole photonic crystal breaks inversion symmetry. The phase rotation of the $\mathbf{H}_z$ field presents opposite characteristics (clockwise and counterclockwise) at the K and K' points, which verifies the existence of non-zero Berry curvature and nontrivial topological properties. Specifically, under broken inversion symmetry, the $\mathbf{H}_{eff}$ near the K and K' valleys acquire a Dirac form, leading to valley-contrasting orbital magnetic moments. This results in quantized Berry phases of π and $-\pi$ respectively, which integrate to a non-zero valley Chern number, a topological invariant characterizing the valley degree of freedom. Hence, the opposite phase rotation serves as a real-space signature of the underlying valley-dependent geometric phase, analogous to the circular dichroism used to probe valley polarizations in electronic transition. Such a topological signature ensures robust, valley-locked edge states at the domain wall between two regions with opposite valley Chern numbers, providing the foundation for topological transport even in the absence of an external magnetic field. Furthermore, the wider band gap in the single-hole structure implies a larger normalized frequency range, which are essential for practical device applications such as accommodating fabrication errors, environmental anti-perturbations and enabled broadband operation. Therefore, based on this combined evidence of confirmed non-trivial topology and superior band gap width, the single-hole silicon photonic crystal is conclusively selected as the optimal platform for subsequent investigations into topological photonic phenomena.

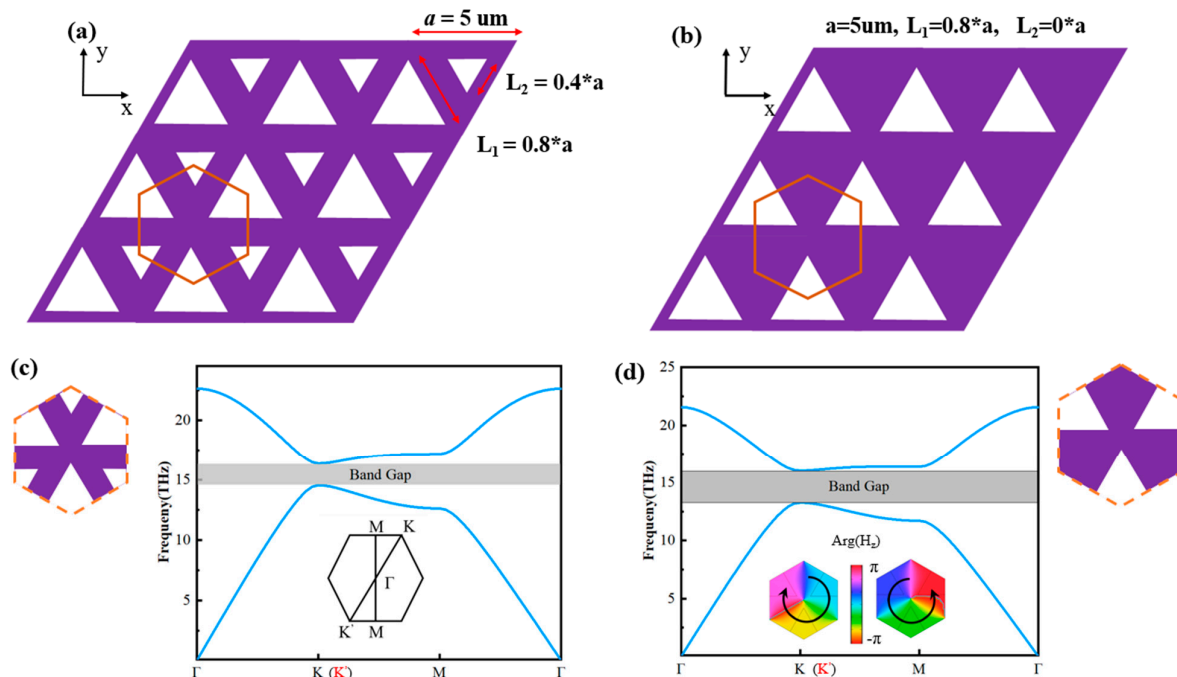


Figure 1. Structural schematics and photonic band structures of designed silicon photonic crystals. (a) Dual-hole structure with reduced unit cell symmetry. (b) Single-hole structure with higher crystalline symmetry. (c) Photonic band structure of the dual-hole crystal. (d) Photonic band structure of the single-hole crystal, with inset showing opposite H_z field phase at K and K' points indicating non-trivial topology. The single-hole structure exhibits a wider PBG.

Following the above property demonstration of designed structures, the topological edge states are expected to emerge at the domain wall between two photonic crystals with distinct topological properties based on the bulk-boundary correspondence. Conse-

quently, we construct a supercell by splicing two single-hole photonic crystals, Type-A and Type-B, which possess opposite topological invariants (Chern numbers) across a zig-zag domain wall, as schematically illustrated in Figure 2a. Figure 2b plots the calculated Berry curvature contour distributions at independent K and K' triangular integral zones. As quantified in Section 2, integrating Berry flux over each valley yields half-integer valley Chern numbers $C_K = -1/2$, $C_{K'} = +1/2$ for Type-A lattice, while mirror-transformed Type-B lattice holds reversed invariants $C_K = +1/2$, $C_{K'} = -1/2$, confirming their contrasting topological nature. The projected band structure of this supercell, presented in Figure 2c, reveals a distinct red band located within the complete photonic bandgap, which represents the topological edge band, while the gray bands correspond to bulk photonic bands. The horizontal axis is normalized wavevector $k/(2\pi/a)$, and the vertical axis covers the studied THz frequency range. This observation directly verifies the existence of non-trivial topological boundary modes at the interface, which is consistent with the theoretical prediction. Moreover, the inset in Figure 2c displays the z-component distribution of the magnetic field H_z at the eigenfrequency corresponding to $k = 0$, demonstrating that the electromagnetic energy is predominantly and tightly confined at the topological interface with negligible leakage into the bulk regions, confirming the excellent localization capability of the obtained edge state. To investigate its dynamic propagation characteristics, Figure 2d depicts the H_z field distribution of an excited topological edge state, which clearly shows that the electromagnetic wave propagates strictly along the channel defined by the topological boundary. This guided propagation is a typical feature of topological protection, enabling the photonic crystal with inherent robustness against structural imperfections and sharp bends, which is crucial for reliable THz signal transmittance. Finally, the performance of this topological waveguide is quantitatively assessed through the normalized transmittance spectrum shown in Figure 2e. The transmittance remains at a relatively high level (exceeding 0.9) within the frequency range from 13 THz to 16 THz, corresponding to the band covered by the edge state observed in Figure 2c. Outside this band, the transmittance drops quickly to near-zero. This result not only confirms the highly efficient THz wave guidance achievable within the topological bandgap but also exhibits excellent consistency with the band structure calculations, thereby providing comprehensive and conclusive evidence for the successful realization and functional performance of the proposed THz topological photonic crystal with edge-state mode.

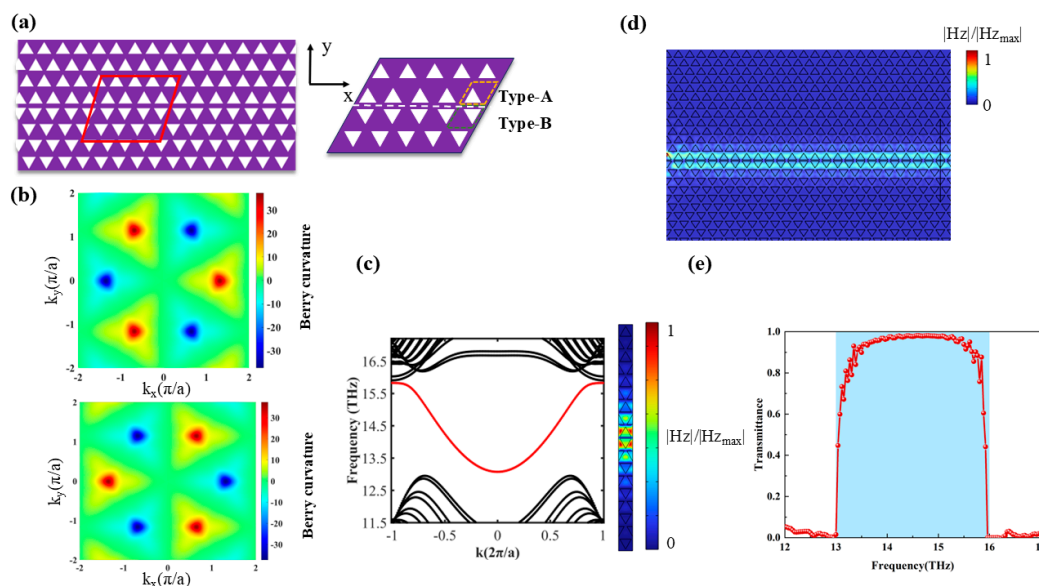


Figure 2. Structural and performance characterization of the THz topological photonic crystal edge-state system. (a) Schematic of the topological boundary formed by splicing two single-hole photonic crystals with opposite topological invariants, with the right panel showing a magnified view of the red-framed region. (b) Berry curvature contour plots over the K and K' triangular integral regions for Type-A and Type-B lattices. (c) Projected band structure of the supercell. Gray lines denote bulk bands, and the highlighted red line corresponds to the topological edge band. The horizontal wavevector axis is normalized as $k/(2\pi/a)$, and the vertical axis shows the full simulated terahertz frequency range, confirming the existence of non-trivial boundary modes at the interface; the inset shows the z-component magnetic field distribution at $k = 0$, indicating strong energy localization at the interface. (d) Magnetic field distribution of the propagating edge state, demonstrating guided wave propagation along the topological boundary channel with robust transmission against defects and bends. (e) Normalized transmittance for waves propagating along the boundary channel, showing high transmission (>0.9) within 13–16 THz and near-zero outside this range, consistent with the calculated projected band structure in (c).

Figure 3 reveals the fundamental mechanism and tunable characteristics of the coupling between a localized photonic defect-cavity and propagating topological edge-states, which constitutes a crucial step towards functional topological photonic devices. Specifically, Figure 3a schematically shows the structural design. Near the topological interface exists a defect-cavity, in which a single air hole is shrunk by the scaling factor δL (L_2/L_1). The evidence for coherent coupling is established in Figure 3b, where the eigenfrequency analysis at $\delta L = 0.5$ confirms that the two cavity modes (red-marked balls) occur within the bulk photonic bandgap and spectrally overlap with the mode of the topological edge states (blue balls). By comparing the eigenfrequency spectra and Hz field distributions of the standalone isolated cavity and full cavity-edge coupled supercell, we find that the resonant frequencies and field profiles of the two cavity modes are exactly the same. This observation excludes the interference of finite-size effects, boundary proximity and residual symmetry breaking in the supercell, and directly verifies that the degeneracy lifting of cavity modes is solely induced by local asymmetric coupling between the defect cavity and topological edge states. This spectral overlap between cavity modes and topological edge bands, combined with the resonant transmission dips observed in Figure 3c,d, sufficiently demonstrates that energy exchange can occur between the resonant cavity and topological edge states. The insets in Figure 3b show that the two cavity eigenmodes feature mutually orthogonal field distributions. Different from mode splitting induced by broken C_4 rotational symmetry, the degeneracy lifting of cavity modes in this honeycomb lattice originates from the local asymmetric coupling between the defect cavity and topological edge states. Since the triangular air-hole defect is uniformly scaled only in size while keeping the local C_{3v} point-group symmetry at the defect center, the observed mode splitting does not arise from rotational symmetry breaking. It can thus be concluded that the spatial asymmetry between the resonant cavity and topological edge states reshapes electromagnetic field profiles and lifts energy degeneracy, producing two cavity modes with orthogonal field orientations. This difference in intrinsic field distribution leads to position-dependent coupling efficiency, a key property for designing functional topological photonic devices. The spectral transmittance, presented in Figure 3c,d, directly demonstrate this coupling. As shown in Figure 3c, the spectra for various δL values exhibit near-unity transmittance across the edge state bandwidth, but inserted by sharp, spectrally narrow dips at the cavity resonant frequencies. Notably, these resonant dips undergo a systematic blue-shift with increasing δL . This trend is attributed to the reduction in the effective mode volume and the increase in the local effective refractive-index contrast as the defect hole enlarges. Consequently, the defect hole size serves as a straightforward geometrical parameter for active frequency tuning. A detailed calculation at $\delta L = 0.5$

in Figure 3d reveals two distinct dips at frequencies f_1 and f_2 , which agree well with the eigenfrequencies identified in Figure 3b. The corresponding field distributions at these frequencies, shown in the insets, clearly provide evidence of strong coupling: the electromagnetic energy of the propagating edge state is locally captured by the cavity resonance, leading to the observed transmittance suppression. The field patterns at f_1 and f_2 preferentially couple to the horizontal and vertical field distributions of the cavity, respectively. This consistent result with the field profiles in the insets of Figure 3b verifies that the coupling strength varies with the intrinsic spatial field distribution of cavity eigenmodes, which allows selective excitation of specific resonant frequencies inside the topologically protected waveguide channel. Consequently, this cavity–edge coupled photonic crystal not only provides a reliable platform to study mode coupling in topological photonics, but also offers a flexible design guideline for on-chip topological functional devices including tunable filters and high-sensitivity sensors.

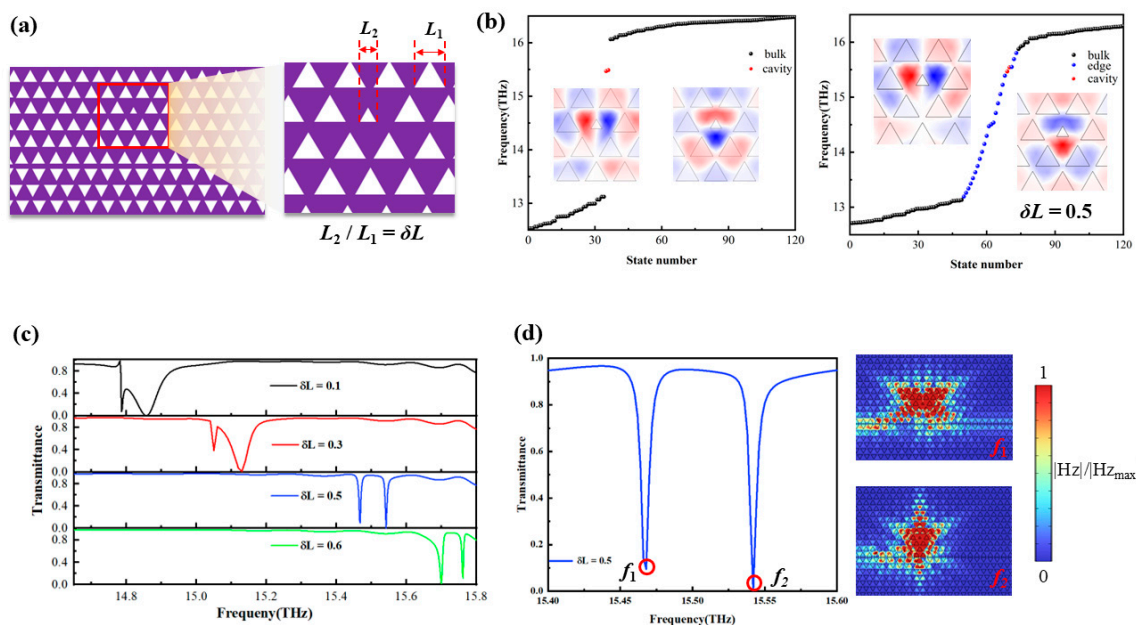


Figure 3. Design and optical response of the cavity-integrated topological boundary. (a) Schematic of the structure with a defect cavity formed by shrinking an air hole, where $\delta L = L_2/L_1$. (b) Eigenfrequency spectra of the standalone isolated cavity and full cavity–edge coupled supercell at $\delta L = 0.5$, where black lines represent bulk states, blue lines denote edge states, and red dots stand for cavity modes. The insets display the H_z field distributions of the two cavity eigenmodes. (c) Normalized transmittance of topological edge states for various δL , showing resonant dips that blue-shift with increasing δL . (d) Transmittance at $\delta L = 0.5$, with dips at f_1 and f_2 matching the cavity eigenfrequencies; insets show the H_z field distributions at f_1 and f_2 , indicating strong coupling and polarization-dependent field orientations.

To demonstrate the robustness of the proposed topological photonic crystal structure, as illustrated in Figure 4a, the boundary defects (green triangles) were intentionally introduced on edge-state channel coupling with resonant cavities (yellow triangles) to mimic practical fabrication imperfection effects. Remarkably, the H_z field distribution in Figure 4b indicates that the topological edge mode remains well-confined and propagates without significant energy leakage even at the defect sites (Position 1 and Position 2), directly verifying the intrinsic robustness of the topological boundary state. This foundational property is critically examined through a systematic transmittance analysis. Specifically, for structures with a single resonant cavity ($\delta L = 0.5$), Figure 4c–e reveal that the

resonance dips, arising from the coupling between the cavity and the topological edge state, exhibit negligible changes in their spectral position, depth, and linewidth when subjected to boundary defects of varying sizes ($\delta B = 0.9, 1.1$) and quantities. This obviously differs from the performance of conventional, non-topological sensors, whose transmission spectra are significantly perturbed by such disorders. It also indicates that the operational performance of the topological sensor is inherently more stable under real conditions, where fabrication errors and randomly distributed impurity are inevitable. Notably, this robustness against structural disturbances is a distinct advantage resulted by the topological protection mechanism and should not be conflated with the device's sensitivity, which originates from refractive-index sensing near the resonant cavity. Furthermore, extending the design to a dual-resonant-cavity configuration ($\delta L = 0.5$ and 0.6), the results shown in Figure 4f–h imply that the number of supported resonance modes successfully doubles, confirming a certain correlation with the number of integrated cavities, while simultaneously maintaining the same good insensitivity to introduced boundary defects. These findings validate that the robust resonance characteristics are preserved in multi-cavity integrated systems, thereby providing a reliable technical pathway for designing high-performance, multi-mode topological photonic devices. The proposed structure, therefore, emerges as an ideal candidate for topological sensing chips, as it effectively avoids the performance degradation typically caused by fabrication imperfections, enabling stable and high-sensitivity analyte detection in prospective experimental testing.

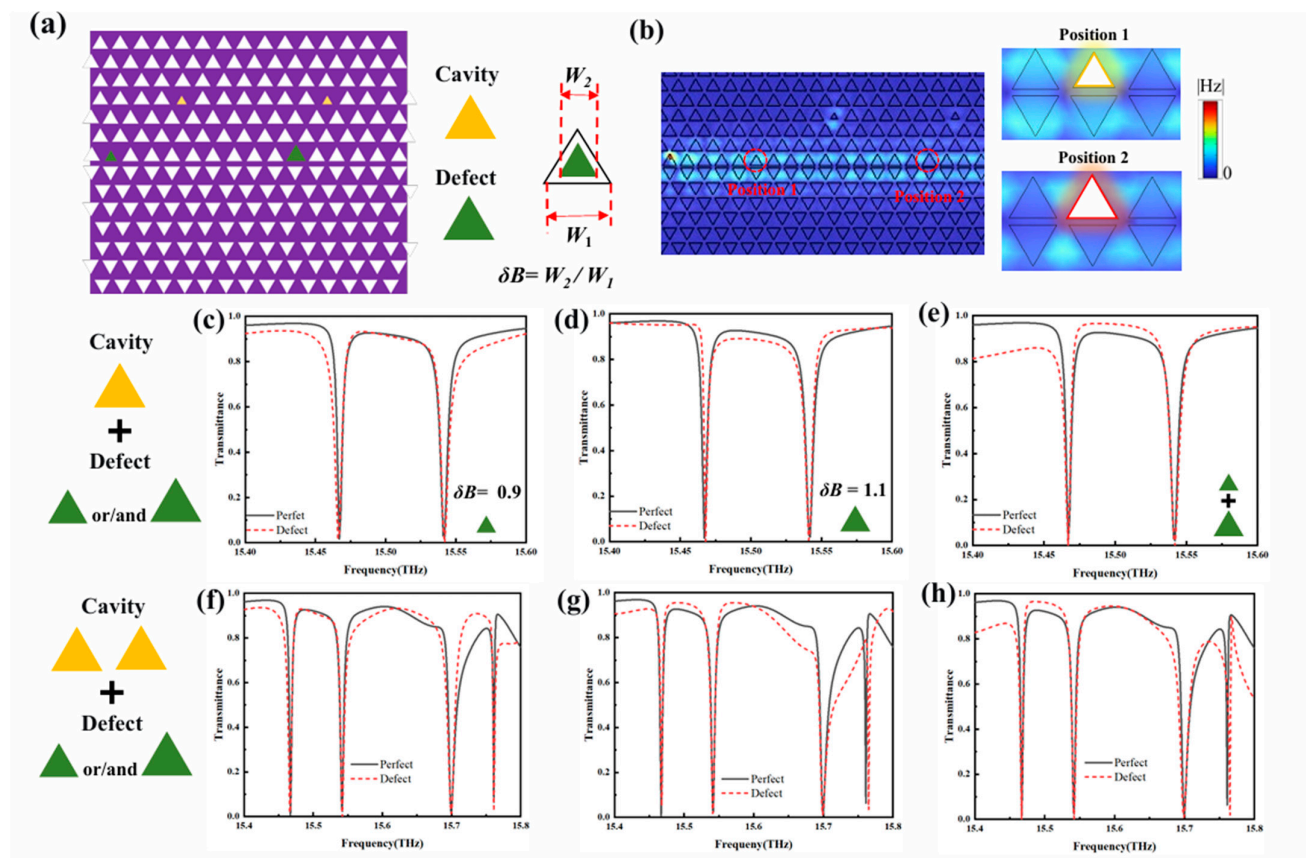


Figure 4. Structural design, field distribution, and transmission characteristics of the topological photonic crystal. (a) Schematic of the photonic crystal structure with integrated resonant cavities and boundary defects. (b) Hz field distribution of the topological boundary state, with insets showing magnified views at defect locations. (c–e) Normalized transmittance for a single cavity with

small ($\delta B = 0.9$), large ($\delta B = 1.1$), and both boundary defects. (f–h) Normalized transmittance for dual cavities with small, large, and both boundary defects.

Following the deterministic boundary defect analysis in Figure 4, we further explore the anti-disorder robustness of the valley topological photonic crystal sensor against random fabrication errors, as illustrated in Figure 5. Figure 5a–c schematically present three typical lithography-induced structural imperfections encountered in practical device preparation: triangular air hole size deviation ($\delta B = 0.8, 0.9, 1, 1.1, 1.2$), lattice position offset δD ranging from $-0.2a$ to $0.2a$, and continuous geometric transformation of air holes from circle, square, equilateral triangle, rectangle to ellipse. As presented in Figure 5d, the resonant frequencies of Mode 1 and Mode 2 maintain nearly identical values under size, position and shape disorder, with negligible vertical gaps between three groups of bars, indicating that the resonant frequency is barely affected by structural perturbation. As illustrated in Figure 5e, the FWHM values of both modes remain below 0.012 THz for size and position disorder; only shape disorder leads to a mild broadening of resonant linewidth, yet the overall FWHM is still limited within 0.015 THz. As displayed in Figure 5f, the transmission amplitudes of Mode 1 and Mode 2 are suppressed severely under size and position disorder. By contrast, shape disorder yields obviously higher transmission intensity, while clear resonant signals can still be distinguished under all three disorder conditions. Benefiting from valley topological edge-state protection, the proposed sensor exhibits superior tolerance to machining errors compared with conventional terahertz metasurface sensors.

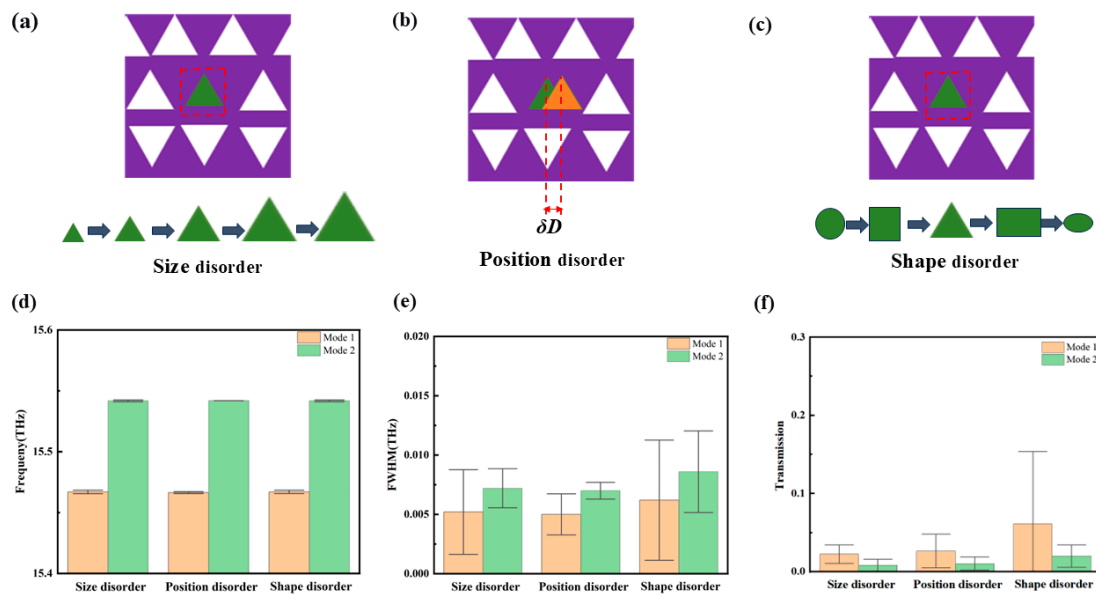


Figure 5. Robustness performance of the topological photonic crystal sensor against three types of structural disorder. (a–c) Schematic diagrams of size disorder, position disorder with offset δD , and shape disorder of triangular air holes. (d) Resonant frequency of Mode 1 and Mode 2 under three disorder cases. (e) Full width at half maximum (FWHM) of resonant peaks. (f) Peak transmission intensity of two working modes. Error bars represent data fluctuation from multiple random structural sampling simulations.

The proposed topological photonic crystal sensor is expected to be a theoretical candidate for refractive-index sensing with excellent performance, as evidenced by the results presented in Figure 6. The key mechanism originates from a perturbation on strong near-

field localization of defect-like cavity, which supports multiple resonant modes under the cavity–edge-state coupling. When the cavity is filled with an analyte, the resulting subtle change in the near-field dielectric environment induces a shift in the resonant frequency. This direct correspondence between the dielectric environment and the frequency shift provides the basis for refractive-index sensing of the analyte. To validate this property, all voids in the photonic crystal structure were uniformly filled with the analyte, of which the relative refractive index was varied over a range (seen in Figure 6a); the corresponding alterations in the resonance characteristics of the transmittance spectra were then observed. As shown in Figure 6b, when the analyte refractive index increases from 1 to 1.04, all four observed resonant modes exhibit a pronounced redshift in their transmittance spectra, confirming a strong interaction between the localized electromagnetic fields and the surrounding medium. This spectral frequency shift (Δf) is quantitatively analyzed by plotting the resonant frequency shift as a function of the refractive index, shown in Figure 6c. It reveals a good linear response for all modes across the tested range without observable nonlinear deviations, which is critical for reliable and predictable sensor calibration. In order to evaluate the performance of the four modes, the sensitivity defined as the slope of the linear Δf -refractive index correspondence was calculated. The results were compared in Figure 6d. It can be observed that among the four modes, Mode 4 achieves the highest value of 1.9 THz/RIU, while Mode 2 exhibits the lowest value of 1.66 THz/RIU. This performance diversity may be directly attributed to differences in electromagnetic field confinement within the analyte-filled cavity. Thus, the superior sensitivity of Mode 4 indicates its stronger field localization in the sensing region, thereby maximizing the light–matter interaction with the target analyte. In contrast, Mode 2 features relatively weaker field confinement, which would result in a weaker interaction and consequently lower sensitivity. Notably, the achieved sensitivities of our designed topological photonic crystal, particularly to Mode 4, surpass the values reported for conventional THz refractive sensors based on metasurfaces in numerical comparison [39–42]. For free-space incident measurement type of metasurfaces, the magnitude of the sensitivity is typically on the order of GHz/RIU. This great enhancement, together with the observed excellent linearity and mode stability, highlights the capability of the topological design in creating robust and highly sensitive resonant cavities. Furthermore, such a topological photonic sensor also presents great potential for prospective high-precision testing scenarios, such as label-free biosensing, trace chemical detection, and accurate refractive index measurements in the THz regime. This high-sensitivity refractive-index response enables the device to serve liquid biopsy for label-free cfDNA/ctDNA detection from peripheral blood, where ctDNA methylation induces subtle fluid refractive shifts. Our topological design has measurable merits over plasmonic, metasurface, microring and electrochemical sensors: Figure 4 confirms its strong immunity to fabrication defects; the 13–16 THz broadband high-transmission window supports multiplexed cavities; the 1.9 THz/RIU sensitivity outperforms conventional THz metasurface devices; and THz measurement avoids biomarker labeling.

After systematically analyzing the transmission characteristics, anti-disorder robustness and refractive-index sensing performance of the designed device, we summarize certain key sensing metrics and compare our sensor with previously reported terahertz devices, as illustrated in Table 1. It shows that conventional THz metasurface sensors work at 0.1–10 THz, but they suffer from low quality factor and limited FOM. Existing topological photonic crystal sensors can achieve ultra-high FOM, while their operating frequency is limited below 5.3 THz. Different from previous designs, our sensor operates in the high-frequency 13–16 THz band with a sensitivity of 1.9 THz/RIU. Its quality factor of 7849 greatly outperforms most terahertz metasurface sensors, and the FOM of 950 also exceeds the performance upper limit of traditional metasurface devices. Combined with the strong

fabrication tolerance verified in Figure 5, the high-frequency topological sensor simultaneously achieves competitive sensing performance and outstanding resistance to machining defects, exhibiting great application potential for high-precision terahertz biochemical detection.

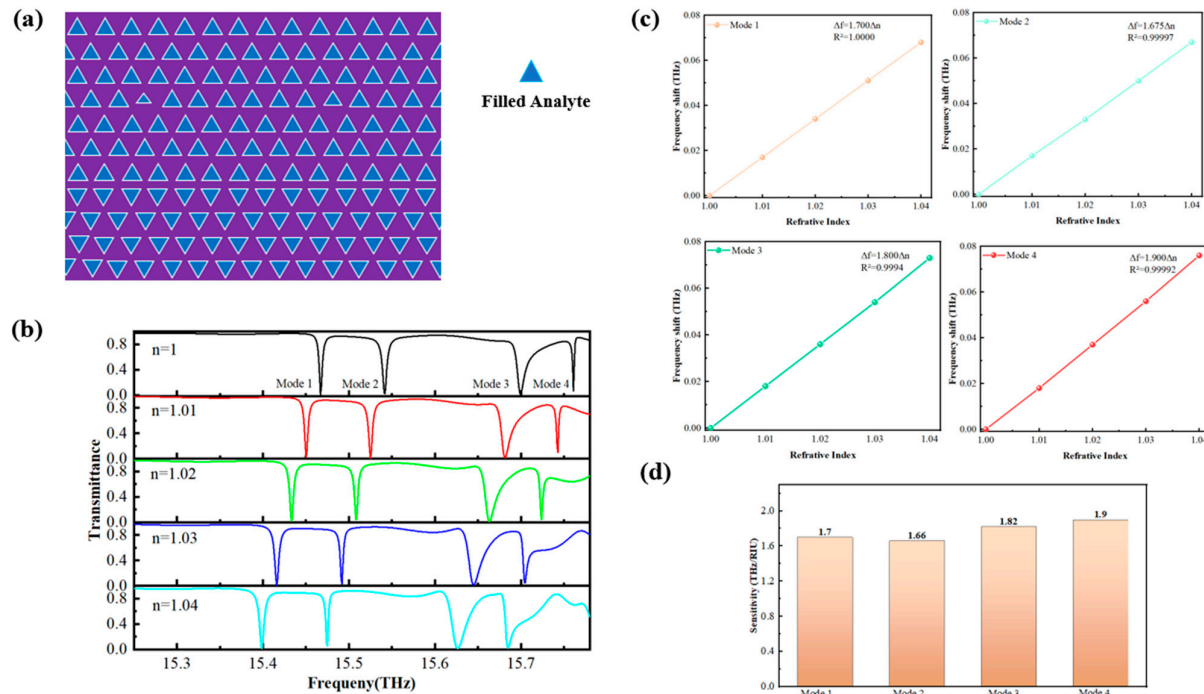


Figure 6. Structural design and sensing performance of the topological photonic crystal sensor. (a) Schematic diagram of the sensor structure with the analyte-filled resonant cavity highlighted. (b) Transmittance spectra under varying analyte refractive indices, showing a red shift in resonant modes. (c) Resonant frequency shift as a function of refractive index for four modes, demonstrating linear responses. (d) Calculated sensitivity for each resonant mode, with Mode 4 exhibiting the highest value.

Table 1. Sensing performance comparison among reported terahertz refractive-index sensors, the valley topological photonic crystal sensors and the sensor proposed in this work.

Device Category	Operating Band (THz)	Sensitivity (THz/RIU)	Quality Factor	FOM (RIU ⁻¹)
THz metasurface sensors [39–42]	0.1–10	0.1–3.5	20–500	5–120
Topological photonic crystal sensors [32–38]	0.2–5.3	0.056–2.06	1696–1.02 × 10 ⁵	4030–3.86 × 10 ⁴
This work	13–16	1.9	7849	950

4. Conclusions

We have numerically designed and theoretically investigated a topological photonic crystal in the THz regime for refractive-index sensing. Two photonic crystal structures with opposite topological properties are constructed based on a honeycomb lattice to form topologically protected edge states, supporting THz wave transmittance > 0.9 over 13–16 THz. By integrating a defect-like cavity with the topological channel, a certain number of transmission dips were produced and shown orientation-selective coupling, which is caused by mode degeneracy lifting due to local asymmetric coupling between the defect cavity and topological channel. Robustness tests verify that the proposed topological structure possesses strong immunity to boundary fabrication defects. For refractive-index

sensing, the cavity-edge-state coupling exhibits a linear response and a peak sensitivity of 1.9 THz/RIU, outperforming conventional metasurface-based THz sensors in simulated comparison. This study provides a feasible scheme for the design and performance optimization of robust THz topological refractive-index sensors. All results in this work are purely numerical, and several key tasks remain to be implemented in future research, including physical device fabrication, experimental optical characterization, microfluidic analyte delivery design, and experimental validation of the sensing performance. In addition, the influence of silicon material dispersion and absorption loss, which is neglected in this simulation, will be further analyzed in follow-up experimental research. We also note practical limitations for blood liquid biopsy: strong water THz absorption, complicated sample pretreatment, lack of specific biomarker capture on unfunctionalized cavities, and the need for microfluidic integration in future clinical testing.

Author Contributions: R.Y. and S.L. contributed equally to this work. Conceptualization, R.Y. and Z.Z. (Zhang Zhang); methodology, R.Y. and S.L.; software, W.X., K.Y. (Kaishuai Yang) and Y.K.; validation, Z.D., K.Y. (Kejiang Yan) and Y.L.; formal analysis, S.L., T.Y. and J.Y. (Jun Yang); investigation, S.L. and S.Y.; resources, F.Z., Z.Z. (Ziyan Zhou) and G.T.; data curation, S.L. and C.Z.; writing—original draft preparation, R.Y.; writing—review and editing, R.Y. and Z.Z. (Zhang Zhang); visualization, S.L. and W.H.; supervision, Z.Z. (Zhang Zhang), Z.H. and L.L. (Longhai Liu); project administration, L.L. (Lanju Liang) and J.Y. (Jianquan Yao); funding acquisition, Z.Z. (Zhang Zhang). All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Suzhou Science and Technology Development Plan (Grant No. ZXL2023174); the National Natural Science Foundation of China (Grant No. 62101078); the Project Special Funding of Taishan Scholar.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ozawa, T.; Price, H.M.; Amo, A.; Goldman, N.; Hafezi, M.; Lu, L.; Rechtsman, M.C.; Schuster, D.; Simon, J.; Zilberberg, O.; et al. Topological photonics. *Rev. Mod. Phys.* **2019**, *91*, 015006.
2. Ma, A.; Dai, T.; Li, G.; Yuan, L.; Capmany, J.; Chen, Z.; Gong, Q.; Wang, J. Reconfigurable and programmable integrated topological photonics. *Nat. Rev. Phys.* **2026**, *in press*.
3. Choi, Y.S.; Park, C.Y.; An, S.C.; Pyo, J.H.; Yoon, J.W. Topological guided-mode resonances: Basic theory, experiments, and applications. *Nanophotonics* **2025**, *14*, 1069–1082.
4. Ma, J.; Xi, X.; Sun, X. Topological photonic integrated circuits based on valley kink states. *Laser Photonics Rev.* **2019**, *13*, 1900087.
5. Jia, R.; Tan, T.C.; Mishra, S.S.; Wang, W.; Tan, Y.J.; Singh, R. On-Chip Active Non-Reciprocal Topological Photonics. *Adv. Mater.* **2025**, *37*, e2501711.
6. Abood, I.; El Soliman, S.; He, W.; Ouyang, Z. Topological photonic crystal sensors: Fundamental principles, recent advances, and emerging applications. *Sensors* **2025**, *25*, 1455.
7. Lindenthal, J.; Widulla, A.; Klemmt, S.; Benduhn, J.; Leo, K. 1D topological interface states for improving optical sensors. *Adv. Opt. Mater.* **2024**, *12*, 2401185.
8. Sheng, G.; She, K.; Shan, Z.; Xu, P.; Li, L.; Liu, E. Ultrahigh-quality-factor topological photonic crystal refractive index sensor based on second-order corner state. *IEEE Sens. J.* **2025**, *25*, 19876–19885.
9. Goyal, A.K.; Kumar, A.; Massoud, Y. Performance analysis of heterostructure-based topological nanophotonic sensor. *Sci. Rep.* **2023**, *13*, 19415.
10. Mulla, S.; Radhakrishna, A.P.; Sadhu, S.K.; Kumar, A. On-chip terahertz tunable topological valley photonic crystals. *J. Appl. Phys.* **2025**, *138*, 033107.
11. Xing, H.; Xu, G.; Lu, D.; Fan, J. Terahertz topological photonic crystals with dual edge states for efficient routing. *Opt. Lett.* **2023**, *48*, 2805–2808.

12. Mohamed, Z.A.; Elshahat, S.; Abd-Elnaiem, A.M.; Almokhtar, M. Sensing performance of Fano resonance induced by the coupling of two 1D topological photonic crystals. *Opt. Quantum Electron.* **2023**, *55*, 943.
13. Anjineya, K.; Mathew, D.; Meghna, C.H.; Mathew, V. Analysis of refractive index sensor using topological photonic protected edge state in one-dimensional photonic crystal. *Photonics Nanostructures-Fundam. Appl.* **2025**, *54*, 101388.
14. Entezar, S.R. One-dimensional topological photonic crystal-based thermal sensor. *Appl. Opt.* **2025**, *64*, 6672–6678.
15. Barvestani, J. Topological interface state-based photonic crystal sensor with porous cap layer for high-performance biosensing. *Sci. Rep.* **2025**, *15*, 43675.
16. Peng, Z.X.; Li, B.X.; Deng, C.S. Ultrahigh-Q Fano resonance in a cavity-waveguide coupled system based on second-order topological photonic crystals with elliptical holes. *Opt. Laser Technol.* **2025**, *181*, 111617.
17. Meghna, C.H.; Mathew, V. Self-referenced terahertz optical sensor with Dirac semi-metal and topological photonic crystal. In *IEEE Microwaves, Antennas, and Propagation Conference*; IEEE: Bangalore, India, 2022; pp. 165–170.
18. Entezar, S.R. Real-time dosimetry via porous silicon-based 1D topological photonic crystal sensor. *Waves Random Complex Media* **2025**, 1–12. doi: 10.1080/17455030.2025.2582549.
19. Pacholski, C. Photonic crystal sensors based on porous silicon. *Sensors* **2013**, *13*, 4694–4713.
20. Scullion, M.; Krauss, T.; Di Falco, A. Slotted photonic crystal sensors. *Sensors* **2013**, *13*, 3675–3710.
21. Zhan, Z.M.; Guo, P.Y.; Li, W.; Wang, H.-X.; Jiang, J.-H. Topological light guiding and trapping via shifted photonic crystal interfaces. *Appl. Phys. Lett.* **2023**, *123*, 251107.
22. Chen, X.-D.; Deng, W.-M.; Shi, F.-L.; Zhao, F.-L.; Chen, M.; Dong, J.-W. Direct observation of corner states in second-order topological photonic crystal slabs. *Phys. Rev. Lett.* **2019**, *122*, 233902.
23. Yang, Y.; Yamagami, Y.; Yu, X.; Pitchappa, P.; Webber, J.; Zhang, B.; Fujita, M.; Nagatsuma, T.; Singh, R. Terahertz topological photonics for on-chip communication. *Nat. Photonics* **2020**, *14*, 476–481.
24. Kong, Z.L.; Liu, Y.; Jiang, J.H. Topologically integrated photonic biosensor circuits. *Laser Photonics Rev.* **2025**, *19*, 2401209.
25. Ruan, W.S.; He, X.T.; Zhao, F.L.; Dong, J.-W. Analysis of unidirectional coupling in topological valley photonic crystal waveguides. *J. Light. Technol.* **2021**, *39*, 889–895.
26. Yan, B.; Liao, B.; Shi, F.L.; Xi, X.; Cao, Y.; Xiang, K.; Meng, Y.; Yang, L.; Zhu, Z.; Chen, J.; et al. Realization of topology-controlled photonic cavities in a valley photonic crystal. *Phys. Rev. Lett.* **2025**, *134*, 033803.
27. Dong, J.-W.; Chen, X.-D.; Zhu, H.; Wang, Y.; Zhang, X. Valley photonic crystals for control of spin and topology. *Nat. Mater.* **2017**, *16*, 298–302.
28. Zhou, X.; Xu, Z.; Fu, S.; Yang, Y. Two-dimensional valley photonic crystal resonant cavities. *J. Appl. Phys.* **2024**, *136*, 143106.
29. He, L.; Liu, D.N.; Zhang, H.Z.; Zhang, F.; Zhang, W.; Feng, X.; Huang, Y.; Cui, K.; Liu, F.; Zhang, W.; et al. Topologically protected quantum logic gates with valley-hall photonic crystals. *Adv. Mater.* **2024**, *36*, 2311611.
30. Wang, Z.; Chong, Y.D.; Joannopoulos, J.D.; Soljačić, M. Reflection-free one-way edge modes in a gyromagnetic photonic crystal. *Phys. Rev. Lett.* **2008**, *100*, 013905.
31. Tonouchi, M. Cutting-edge terahertz technology. *Nat. Photonics* **2007**, *1*, 97–105.
32. Colapietro, P.; Brunetti, G.; Panciera, C.; Elicio, A.; Ciminelli, C. Shining the path of precision diagnostic: Advancements in photonic sensors for liquid biopsy. *Biosensors* **2025**, *15*, 473.
33. Panciera, C.; Brunetti, G.; Ciminelli, C. Numerical investigation of IgG sensing through nanoscale topological-assisted metasurface for liquid biopsy. *Nanotechnol. Rev.* **2026**, *15*, 20250284.
34. R, L.T.; Priya, P.A. 1D topological photonic crystal based nanosensor for tuberculosis detection. *Nanotechnology* **2024**, *35*, 415204.
35. Dash, D.; Saini, J.; Goyal, A.K. Performance analysis of hyperbolic graded topological resonator for biosensing applications. *Sci. Rep.* **2025**, *15*, 4862.
36. Alsawafi, M.O.; Entezar, S.R.; Safari, E. 1D topological photonic crystals for reconfigurable terahertz sensing and filtering. *Solid State Commun.* **2025**, *406*, 116212.
37. Parandin, F.; Heidari, F.; Rahimi, Z.; Olyaei, S. Two-Dimensional photonic crystal Biosensors: A review. *Opt. Laser Technol.* **2021**, *144*, 107397.
38. Yu, Z.; Lin, H.; Zhou, R.; Wang, Y. A high-Q topological refractive index sensor based on high-order corner states. *Opt. Laser Technol.* **2025**, *181*, 111582.
39. Xu, W.D.; Xie, L.J.; Zhu, J.F.; Tang, L.; Singh, R.; Wang, C.; Ma, Y.; Chen, H.-T.; Ying, Y. Terahertz biosensing with a graphene-metamaterial heterostructure platform. *Carbon* **2019**, *141*, 247–252.
40. Hu, X.; Xu, G.Q.; Wen, L.; Wang, H.; Zhao, Y.; Zhang, Y.; Cumming, D.R.S.; Chen, Q. Metamaterial absorber integrated microfluidic terahertz sensors. *Laser Photonics Rev.* **2016**, *10*, 962–969.

41. Thévenot, D.R.; Toth, K.; Durst, R.A.; Wilson, G.S. Electrochemical biosensors: Recommended definitions and classification. *Biosens. Bioelectron.* **2001**, *16*, 121–131.
42. Shen, P.; Ji, Y.Y.; Yue, X.M.; Li, Y.; Han, M.; Ma, Y.; Meng, M.; Fan, F.; Chang, S. Ultrasensitive terahertz microfluidic biosensor integrated with tetrahedral DNA nanostructure for specific detection of live cancer cells. *Sens. Actuators B Chem.* **2025**, *428*, 137252.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.