Defect-Engineered Topological Light Transport in 2D Photonic Crystals at Mid-IR Wavelengths

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ABSTRACT

Topological band structure engineering enables the development of robust light propagation states known as topological interface states, across a variety of media. These light states emerge at the interface between two topologically distinct lattices and are characterized by their remarkable robustness against structural imperfections. To highlight the distinctive properties of topological interface states in direct comparison with conventional light-guiding mechanisms, we present a systematic investigation of light transport in two-dimensional photonic crystal (PhC) waveguides. The study traces a clear progression from conventional defect-engineered designs to topologically robust architectures, enabling a direct and meaningful comparison between the two approaches. Initially, a topologically trivial 2D square unit cell with lattice constant **a** is designed and its photonic band structure is computed using COMSOL Multiphysics®. Based on this unit cell, a line-defect waveguide of width d=2**a** is introduced. Further, a tapered 2D waveguide is realized using point defects, with the defect width gradually reduced from d=4**a** at the input to d=2**a** at the output. Although both of these conventional PhC waveguides show efficient light transmission as obtained from comparable input and output field intensities, they lack robustness against structural perturbations and fail to support propagation of light through a bent path. Consequently, a topological defect-guided waveguide is demonstrated, utilizing a topologically non-trivial 2D unit cell design, verified via parity analysis of eigenmodes obtained from eigenfrequency simulations in COMSOL Multiphysics®. The conjoint array of trivial and non-trivial unit-cells, enables robust light transport through topological interface states along a 15-degree bend.

Keywords: Defect-guided light propagation, Mid-infrared, Photonic band structure, Topological waveguide.

I. INTRODUCTION

Photonic crystals (PhCs) are popular for their efficient low-loss waveguiding particularly due to the alternating dielectric periodic structures capable of light confinement and propagation. Such structures enable strong light confinement utilizing the photonic bandgap engineering [[1]-[4]]. In conventional PhC waveguide systems, light guidance occurs through line-defects introduced within the periodic geometry [1]. Furthermore, optimizing the defect width allows precise control over dispersion and enables functionalities such as broadband transmission, single-mode operation, and low-dispersion propagation [[5], [6]].

Though highly promising, such conventional defect-based PhC waveguides remain highly sensitive to structural imperfections and backscattering losses thereby leading to poor performance in bent geometries [7]. In order to address these limitations, concepts from condense matter physics, particularly exploitation of symmetry and photonic band topology have been adapted, giving rise to the novel domain of topological waveguides [8].

In two dimensional (2D) PhCs breaking a space inversion symmetry within the system induces a topological phase transition in the compact wave-vector space, the Brillouin zone, which is also identified as the parametric space. This results in a topologically non-trivial geometry characterized by the photonic bandgap structure (PBS). The trivial geometry corresponds to a zero Berry curvature, similarly the non-trivial geometry corresponds to a non-zero Berry curvature as obtained from the PBSs and there exists a localized backscattering-immune state of light at the junction between these two topologically distinct lattices [9] known as the topological interface state (TIS). Such interface states exhibit topologically robust propagation even at sharp bends (e.g., 60-degree and 120-degree) where the dispersion within the system can be modulated through the interface designs. Several works have been carried out exploiting the interface designs including mirror-symmetric (zigzag), glide-symmetric, bearded symmetric interfaces enabling

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slow-light propagation with enhanced dispersion control [10-12].

Owing to the existing symmetries in square-lattice PhCs, such unit-cell geometries are utilized for both conventional defect-guided waveguides as well as topological waveguides. Recent studies in non-topological systems mainly focus on high transmission leveraging mechanisms like polarization singularities and symmetry-protected mode coupling. However, topological guidance in waveguides have predominantly been explored in interfacial configurations. Latest advancements also show topological guidance with minimal bending-loss in triangular lattice PhCs utilizing chiral vortex- valley matching [13]. These developments indicate that topological guidance can be achieved even in non-topological PhC systems under appropriate symmetry optimization [14]. Despite these advancements, a clear and systematic comparison between conventional defect-guided PhC waveguides and topological waveguides has not yet been explored. Especially, keeping the PhC system same and studying the transition from non-topological to topological waveguide system highlighting the robust light transport behaviour under a unified frame-work has not been analysed before.

To address the aforesaid limitations, here we present a systematic study of light transport in 2D PhC waveguides. By examining the transition from non-topological to topological waveguides, a comparative analysis is presented to reveal the distinct advantages and underlying physics of TISs in terms of light propagation. In this work, we demonstrate a systematic transition from defect-based to topology-driven light transport in 2D photonic crystal waveguide and reveal the enhanced robustness of topological waveguides under structural perturbations. Our work establishes a unified framework connecting conventional defect-guided and topologically protected light transport in 2D photonic crystal structures, enabling direct and demonstrating robustness arising parity-engineered band topology. We first design a topologically trivial 2D unit cell and compute its photonic band structure for a square lattice. An array waveguide is formed by introducing a line defect of width **d** = 2**a**, where **a** is the lattice constant. Using identical unit-cell parameters, a tapered waveguide is also realized with point defects varying from **d**= 4**a** at the input to **d** = 2**a** at the output, exhibiting comparable input and output field intensities and confirming efficient defect-guided transport. However, such conventional 2D photonic crystal waveguides remain sensitive to perturbations and cannot sustain robust propagation along bent paths. To overcome this limitation, we design a topologically non-trivial 2D unit cell and confirm the topological phase transition through parity analysis of eigenmodes obtained from eigenfrequency simulations in COMSOL Multiphysics®. By combining trivial and non-trivial unit cells, a topological defect-guided array waveguide is realized that supports propagation via a topological interface state along a 15-degree bend. Designed in the mid-infrared region, the proposed structure is relevant for sensing, imaging, and photonic integrated circuit applications, while highlighting the interplay among symmetry, defects, and topology for robust waveguiding.

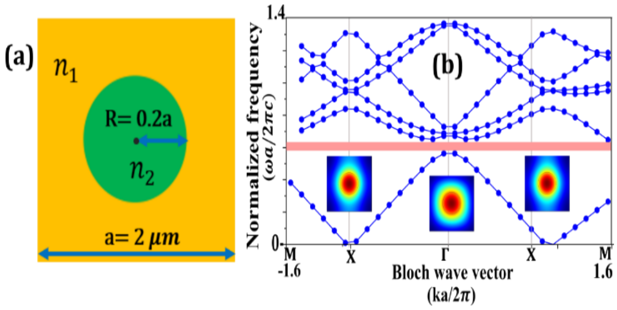

Fig. 1. (a) The schematic of the 2D square unit-cell geometry having a high-index dielectric rod surrounded by air (b) The transverse electric (TE) mode PBS of the unit-cell showing the three symmetry points e.g., **Γ**, **X** and **M** and the bandgap highlighted by an orange strip. The insets show the eigenmode solutions of the unit-cell at the symmetry points confirming it to be a trivial geometry.

II. 2D PHOTOTIC CRYSTAL STRUCTURE AND MODEL FORMULATION

The overall simulation workflow begins with a 2D photonic crystal (PhC) unit cell design, where geometric parameters and material properties are carefully selected to realize the desired refractive index contrast. The photonic band structure is then computed using an eigenmode solver to identify the presence of bandgaps and to distinguish between a topologically trivial and non-trivial unit-cell using parity analysis.

The 2D square unit-cell (Fig 1 (a)) is designed using a dielectric rod of refractive index $\boldsymbol{n_2} = 1.48$, surrounded by air of refractive index $\boldsymbol{n_1} = 1.00$. The lattice constant of the unit-cell is chosen as **a** = 2.0 μm and the radius of the dielectric rod is **R**= 0.2 **a**. The transverse electric (TE) mode, photonic band structure (PBS) of the unit-cell is computed using COMSOL Multiphysics® utilizing Finite Element Method (FEM). The eigenfrequency study in the Electromagnetic Waves, and Finite Element Domain (ewfd) interface are conducted where the Floquet periodic condition is applied and eigenmode solutions are calculated while sweeping the wave-vector $\boldsymbol{k}$ along the Brillouin zone (Fig 1 (b)). A 2D unit-cell structure has three symmetry points, namely, **Γ**, **X** and **M**. In order to check the topological characteristics of the designed unit-cell, we conduct a parity analysis of eigenmode solutions obtained from eigenfrequency simulations performed in COMSOL Multiphysics®

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utilizing Finite Element Method (FEM). As shown in Fig. 1 (b), the electric-field distribution of the eigenmode solutions at each symmetry

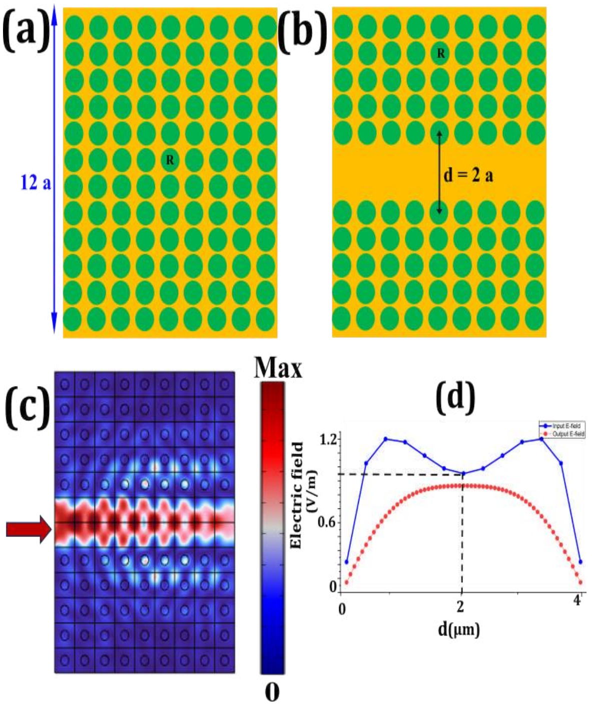

Fig. 2 (a) The schematic of the 2D array comprising 12 rows and 9 columns constructed from unit cell of lattice constant **a** = 2.0 μm and dielectric rod radius **R** = 0.2 **a**, surrounded by air. (b) The schematic of the line-defect guided 2D array waveguide, where the defect width is equal to **d** = 2**a.** (c) The Electric field distribution obtained from the wavelength domain study of the constructed line-defect guided waveguide from COMSOL Multiphysics® using the Electromagnetic Waves, Finite Element Domain (ewfd) interface. The location of input wave is marked by red arrow on the left. (d) The input (blue plot) and output (red plot) Electric field intensities plotted along the defect width, showing the efficiency of the line-defect guided 2D array waveguide.

Point shows no change as the wave-vector ***k*** sweeps along the Brillouin zone, showcasing a zero Chern number of the required band of interest. Such an observation confirms the trivial nature of the 2D unit-cell geometry. It is observed that this unit-cell can be used to develop both line-defect waveguide and point-defect waveguide and also to calculate their efficiency in light transport.

III. RESULTS AND DISCUSSION

A. Waveguide design with defects

A plane array waveguide comprising 12 rows and 9 columns is designed (Fig. 2 (a)) using the trivial unit cell as mentioned earlier having a lattice constant **a** and dielectric rod of radius **R** (Fig. 1 (a))**.** Into this waveguide a line defect in introduced having a width of **d** = 2**a,** as shown in Fig.2 (b). The defect width in the defect

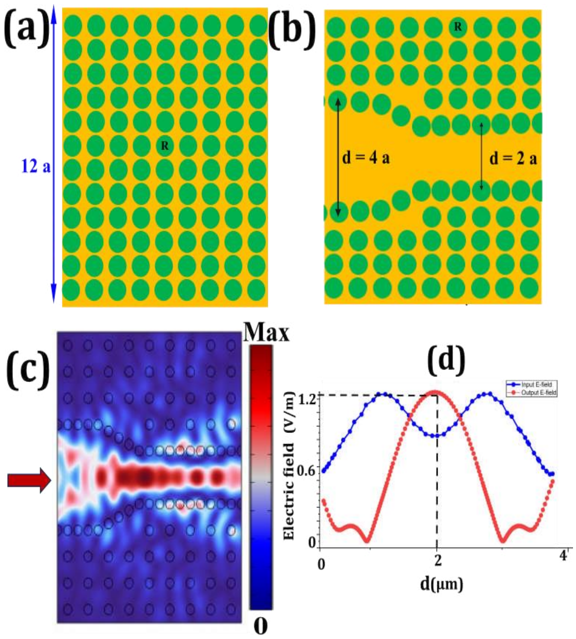

Fig.3. (a) The schematic of the 2D array comprising 12 rows and 9 columns constructed from unit cell of lattice constant **a** = 2.0 μm and dielectric rod radius **R** = 0.2 **a**, surrounded by air. (b) The schematic of the point-defect guided tapered 2D array waveguide, where the defect width gradually decreases from **d** = 4**a** to **d** = 2**a.** (c) The Electric field distribution obtained from the wavelength domain study of the constructed point-defect guided waveguide from COMSOL Multiphysics® using the Electromagnetic Waves, Finite Element Domain (ewfd) interface. The location of input wave is marked by red arrow on the left. (d) The input (blue plot) and output (red plot) Electric field intensities plotted along the defect width, showing the efficiency of the point-defect guided tapered 2D array waveguide.

Waveguide is parametrized using **d**, that signifies the separation between the center of dielectric rod in the top and bottom claddings. A wavelength domain study is done in COMSOL Multiphysics® using the Electromagnetic Waves, Finite Element Domain (ewfd) interface. The operating wavelength for this plane defect waveguide is **λ**= 3.2 μm and an input is applied from one side as shown in Fig.2 (c). A scattering boundary condition is applied and the Electric field distribution so obtained is corroborated in Fig. 2(c) where we see even distribution of Electric field with minimal scattering into the array structure. In order to quantify the field distribution, we plot the input wave and the output wave along the defect width (Fig. 2 (d)) and see about 70% light-transmission, calculated using peak input field strength and peak output field strength.

Next using the same 2D unit cell geometry (Fig. 1 (a)) we construct a tapered waveguide using point defects (Fig 3 (a)). We start from a plane array waveguide comprising 12 rows and 9 columns (Fig. 3 (a)) and introduce a tapered

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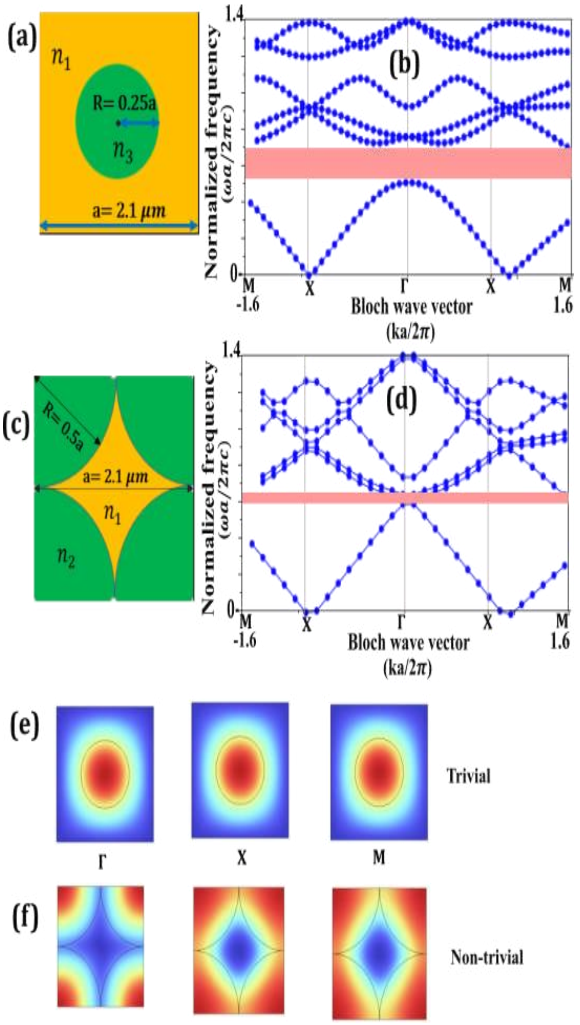

Fig. 4. (a) The schematic of the trivial 2D square unit-cell geometry having a high-index dielectric rod surrounded by air and (b) The transverse electric (TE) mode PBS of the unit-cell showing the three symmetry points **Γ, X** and **M** and the bandgap highlighted by an orange strip. (c) The schematic of the non-trivial 2D square unit-cell geometry having an air region surrounded by quarterly high-index dielectric rod domains and (d) The transverse electric (TE) mode PBS of the unit-cell showing the three symmetry points **Γ, X** and **M** and the bandgap highlighted by an orange strip. (e) The eigenmode solutions of the trivial unit-cell at the symmetry points. (f) The eigenmode solutions of the non-trivial unit-cell at the symmetry points.

Defect into the array by rearranging dielectric rods as shown in Fig. 3 (b). The defect width **d** is gradually decreased from **d** = 4**a** to **d** = 2**a**. Following this, a wavelength domain study is done in COMSOL Multiphysics®. The operating wavelength for this tapered defect waveguide is **λ**= 3.2 μm and an input is fed from one side as shown in Fig.3 (c). A scattering boundary condition is applied and the Electric field distribution so obtained is shown in Fig.3(c) where we see even distribution of Electric field with minimal scattering into the array structure. In order to quantify the field distribution, we plot the input wave along with the output

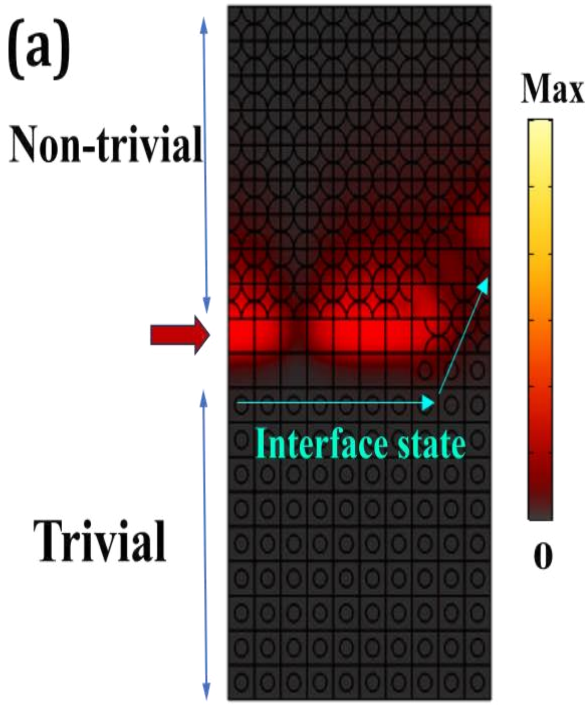

Fig. 5. (a) The Electric field distribution obtained from the Mode analysis study of the constructed topological defect guided waveguide constituting 10 trivial rows and 10 non-trivial rows where the interface has been created with a line-defect. The study is done in COMSOL Multiphysics® using the Electromagnetic Waves, Finite Element Domain (ewfd) interface, showing light transport through TIS.

Wave (Fig. 3 (d)) and see near 100% transmission, calculated using peak input field strength and peak output field strength.
Such a conventional defect guided light transport in 2D waveguide is applicable in high-sensitivity spectroscopic gas or liquid sensing, nonlinear optical processing, and on-chip infrared communication. However, it was observed that such 2D array waveguides are highly sensitive to perturbations, and are unable to support bent transport of light. Hence, we explore the enhanced performance of topological photonics when employed to defect-based systems by designing a topological line defect-based 2D array waveguide and observe 15-degree bent light transport.

B. Topological defect- engineered 2D array waveguide

To design the topological defect-engineered 2D array waveguide we begin with a new 2D square unit-cell of lattice constant **a** = 2.1 μm and dielectric rod of radius **R** = 0.25 **a** (Fig. 4 (a)**).** The dielectric rod has a refractive index $\boldsymbol{n_3} = 2.21$, surrounded by air of refractive index $\boldsymbol{n_1} = 1.00$. Following this, the photonic bandstructure for the transverse electric (TE) mode of the unit-cell is computed using COMSOL Multiphysics®. The eigenfrequency study in the Electromagnetic Waves, Finite Element Domain (ewfd) interface is done where the

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TABLE I
COMPARISON OF THE TOPOLOGICAL DEFECT WAVEGUIDE WITH OTHER PUBLISHED REPORTS ON DEFECT WAVEGUIDES

References	Efficiency (%)	Defect width in terms of *a*	Topological resilience
[10]	-	1.4	No
[7]	-	<1	Yes
[8]	70	1.66	Yes
Proposed line-defect waveguide	70	0.2	No
Proposed point-defect tapered waveguide	100	4-2	No
Proposed topological defect waveguide	40	4.2	Yes

Floquet periodic condition is applied and eigenmode solutions are calculated while sweeping the wave-vector $\boldsymbol{k}$ along the Brillouin zone (Fig. 4 (b)). In order to determine the topological characteristics of the unit-cell a parity analysis of eigenmode solutions obtained from eigenfrequency simulations performed in COMSOL Multiphysics®. It is observed that the eigenmode solutions at the three symmetry points namely **Γ**, **X** and **M** remain unchanged as the wave-vector $\boldsymbol{k}$ sweeps along the Brillouin zone (Fig. 4 (e)), showcasing a zero Chern number of the required band of interest. Hence, the unit-cell geometry has a trivial nature. Now, in order to design the non-trivial unit-cell geometry, keeping the lattice constant **a** = 2.1 μm same as before, and a quarter of a dielectric rod of refractive index $\boldsymbol{n_2} = 1.48$ and radius **R** = 0.5 **a** is arranged around the unit-cell geometry as shown in Fig. 4 (c). The photonic band structure for the transverse electric (TE) mode of the unit-cell is computed using COMSOL Multiphysics®. The eigenfrequency study in the Electromagnetic Waves, Finite Element Domain (ewfd) interface is performed alongside the Floquet periodic condition and eigenmode solutions are calculated while sweeping the wave-vector $\boldsymbol{k}$ along the Brillouin zone (Fig. 4 (d)). In order to determine the topological characteristics of the unit-cell, a parity analysis of eigenmode solutions obtained from eigenfrequency simulations performed in COMSOL Multiphysics®. It is observed that the eigenmode solutions at the three symmetry points namely, **Γ**, **X** and **M** changes as the wave-vector $\boldsymbol{k}$ sweeps along the Brillouin zone, showcasing a non-zero Chern number of the required band of interest. Hence, the unit-cell geometry has a non-trivial nature (Fig. 4 (f)). This enables the formation of topologically protected light states, known as topological interface states (TIS), at the junction of two topologically different lattices and light transport will occur through this TIS.

Based on this classification as mentioned in Fig.4, a supercell is constructed by interfacing two PhCs with distinct topological characteristics, enabling the formation of localized interface states. Subsequently, finite element method (FEM) simulations are performed in COMSOL Multiphysics® to investigate light propagation along the interface and the transport properties are then analyzed. This systematic workflow shows a comparative study between conventional defect-guided waveguides and topologically protected defect light propagation within a unified simulation framework.

In order to confirm the presence of a TIS at the interface, we design a 2D array waveguide comprising 10 trivial rows and 10 non-trivial rows stacked with a line defect introduced at the junction in shape of a 15-degree bent as shown in Fig. (5 (a)). Following the geometry construction, a Mode analysis study is done in COMSOL Multiphysics® as before. The operating wavelength for this topological defect-guided waveguide is **λ**= 4.3 μm. The electric field distribution shows transport through the bent pathway utilizing a TIS (Fig. 5 (a)) and a 40% light-transmission is obtained. In order to validate the results so obtained we compare them to previously published articles on defect-guided waveguides in Table I.

IV. CONCLUSION

This work presents a systematic and unified framework that bridges conventional defect-engineered photonic crystal (PhC) waveguides with topologically robust light-guiding architectures in two dimensions, thereby addressing the lack of direct comparative studies in the literature. The overall simulation workflow begins with the design of a topologically trivial 2D square unit-cell and it is observed that the developed line-defect and tapered point-defect waveguides achieve high transmission efficiencies of 70% and 100% respectively. In the designed non-trivial 2D square unit-cell the resulting topological phase transition is rigorously verified through parity analysis of eigenmodes obtained from eigenfrequency simulations in COMSOL Multiphysics®. It is observed that the interface formed between the two topologically distinct arrays is capable of supporting a TIS, thereby, a topological waveguide is realized that supports robust TIS, enabling light propagation even in the presence of a 15-degree bend in the geometry. This study establishes a comparative and systematic transition from conventional to topological guiding mechanisms in 2D PhC waveguides, within a single design framework, thereby providing clear insight into the physics and advantages of TISs. The results demonstrate that topological designs offer superior robustness and flexibility compared to traditional approaches, highlighting their potential for stable light manipulation in complex photonic environments.

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The proposed design architectures open pathways for experimental realization and further investigation of different topological interface configurations, including higher dimensional structures. The integration of nonlinear materials with topological waveguiding can open several functionalities, while scaling these designs for large-scale photonic integration. Such topological waveguide systems lay a strong foundation for the development of next-generation photonic devices with enhanced performance and resilience.

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