QUANTUM OPTICS

A topological quantum optics interface

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The application of topology in optics has led to a new paradigm in developing photonic devices with robust properties against disorder. Although considerable progress on topological phenomena has been achieved in the classical domain, the realization of strong light-matter coupling in the quantum domain remains unexplored. We demonstrate a strong interface between single quantum emitters and topological photonic states. Our approach creates robust counterpropagating edge states at the boundary of two distinct topological photonic crystals. We demonstrate the chiral emission of a quantum emitter into these modes and establish their robustness against sharp bends. This approach may enable the development of quantum optics devices with built-in protection, with potential applications in quantum simulation and sensing.

The discovery of the quantum Hall effects has inspired developments in similar topological phenomena in a range of platforms, including ultracold neutral atoms (*1*, *2*), photonics (*3*, *4*), and mechanical structures (*5*–*7*). Like their electronic analogs, topological photonic states are distinctive in their directional transport and reflectionless propagation along the interface of two topologically distinct regions. Such robustness has been demonstrated in various electromagnetic systems, ranging from the microwave (*8*, *9*) to the optical (*10*, *11*) domain, opening avenues for a plethora of applications—such as robust delay lines, slow-light optical buffers (*12*), and topological lasers (*13*–*15*)—to develop optical devices with built-in protection. Although the scope of previous work has remained in the classical electromagnetic regime, interesting physics could emerge by bringing topological photonics to the quantum domain. Specifically, integrating quantum emitters into topological photonic structures could lead to robust, strong light-matter interaction (*16*) and the generation of novel states of light and exotic many-body states (*17*–*19*).

We experimentally demonstrated light-matter coupling in a topological photonic crystal. We used an all-dielectric structure (*20*–*22*) to implement topologically robust edge states at the interface between two topologically distinct photonic materials, where the light is transversally trapped in a small area, up to half of the wavelength of light. We show that a quantum emitter efficiently couples to these edge modes and that the emitted single photons exhibit robust transport, even in the presence of a bend. Figure 1A shows the fabricated topological photonic crystal structure. The device is composed of a thin GaAs membrane with epitaxially grown InAs quantum dots at the center that act as quantum emitters (*22*).

The topological photonic structure comprises two deformed honeycomb photonic crystal lattices made of equilateral triangular air holes (fig. S2) on a GaAs membrane (*21*, *22*). Figure 1B shows a close-up image of the interface, where the black dashed lines identify a single unit cell of each photonic crystal. In each region, we perturb the unit cell by concentrically moving the triangular holes either inward (yellow region) or outward (blue region). The corresponding band structures of the two regions are shown in Fig. 1, C and D. The perturbations open two bandgaps exhibiting band inversion at the Γ point (*20*, *21*). Specifically, the region with a compressed unit cell, highlighted in yellow, acquires a topologically trivial bandgap, whereas the expanded region, highlighted in blue, takes on a nontrivial one. We designed both regions so that their bandgaps overlap. Photons within the common bandgap cannot propagate into either photonic crystal. However, because the crystals have different topological band properties, the interface between them supports two topological helical edge modes, traveling in opposite directions, with opposite circular polarizations at the center of the unit cell.

To show the presence of the guided edge mode, we measured the transmission spectrum. We illuminated the left grating ("L") with a 780-nm continuous-wave laser using a pump power of 1.3 μW and collected the emission from the right grating ("R"; Fig. 2A). At this power, the quantum dot ensemble emission became a broad continuum owing to power broadening, resulting in an internal white light source that spanned the wavelength range of 900 to 980 nm. Figure 2B shows the spectrum at the right grating, presented with the band structure simulation (*21*). Light emitted within the topological band efficiently transmitted through the edge mode and propagated to the other grating coupler, whereas photons outside of the bandgap dissipated into bulk modes.

To confirm that the emission originates from guided modes at the interface between the two topological materials, we excited the structure in the middle of the waveguide ("M") and collected the emission at the left and right grating coupler, which we independently calibrated (*22*). Figure 2C shows the transmission spectrum collected from the left coupler as a function of the laser spot position as we scanned the laser along the *y* axis (across the interface indicated by the blue arrow in Fig. 2A). The spectrum attained a maximum transmission within the topological band when the pump excited the center of the structure. When

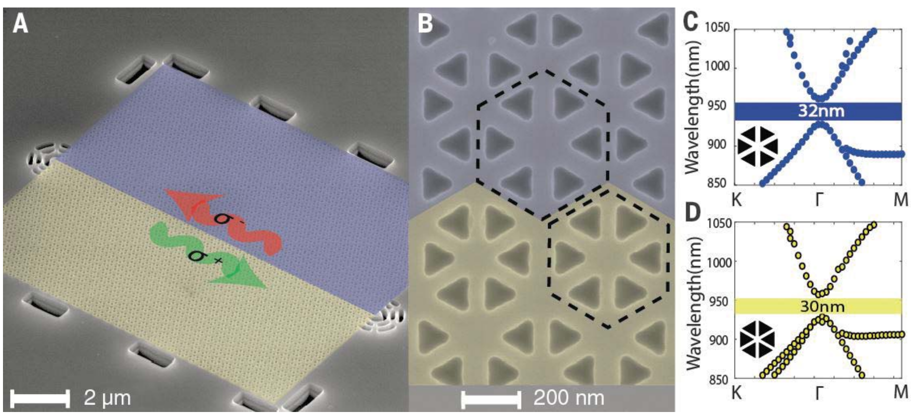

Fig. 1. Fabricated device and band structure. (**A**) Scanning electron microscope image of the device, which is composed of two regions identified by blue and yellow shading, corresponding to two photonic crystals with different topological properties. The interface between the two photonic crystals supports helical edge states with opposite circular polarization (σ^+ and σ^-). Grating couplers at each end of the device scatter light in the out-of-plane direction for collection. (**B**) Close-up image of the interface. Black dashed lines identify a single unit cell of each photonic crystal. (**C** and **D**) Band structures for the transverse electric modes of the two photonic crystals.

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we displaced the excitation beam by ~1.5 μm along the y direction, the transmission vanished, indicating that the photons were coming only from the waveguide.

A key feature of topological edge modes is the chiral nature of the coupling between the helical topological edge mode and the quantum emitter. Specifically, different dipole spins radiatively couple to opposite propagating helical edge states. To demonstrate this helical light-matter coupling, we applied a magnetic field in the out-of-plane (Faraday) direction on the entire sample. This field induced a Zeeman splitting in the quantum dot excited state, resulting in two nondegenerate states that emitted with opposite circular polarizations (fig. S5), denoted as $\sigma^{\pm}$ (Fig. 3A) (*22*, *23*). Although this magnetic field does not play a role in the topological nature of the waveguide, it enabled us to identify the polarization of the dipole by the frequency of emitted photons. By spectrally resolving the emissions, we were able to identify the dipole spin and correlate it with the propagation direction of the emitted photon.

To isolate a single quantum emitter within the topological edge mode, we reduced the power to 10 nW, which is well below the quantum dot saturation power. Using the intensities of the collected light at the two ends, we calculated a lower bound on the coupling efficiency of 68% (table S1), defined as the ratio of the photon emission rate into the waveguide to the total emission rate (*22*). This high efficiency is due to the tight electromagnetic confinement of the guided modes, which enhances light-matter interactions. Figure 3B shows the emission spectrum as a function of magnetic field, where we collected the emission directly from point M indicated in Fig. 2A. As the magnetic field increases, the quantum dot resonance splits into two branches corresponding to the two Zeeman split bright exciton states. We compared this spectrum with the one collected from the left and right gratings (Fig. 3, C and D). At the left grating, we observed only the emission from the σ^- branch, whereas at the right grating, we observed only the emission from the σ^+ branch. These results establish the chiral emission and spin-momentum locking of the emitted photons and provide strong evidence that the emitter is coupling to topological edge states that exhibit unidirectional transport. Such chiral coupling is in direct analogy to one-dimensional systems (*16*, *24*, *25*); however, the waveguided modes of our structure originate from two-dimensional topology. As a result, the topological edge mode should exhibit robustness to certain deformations, such as bends.

To establish this topological robustness, we analyzed the propagation of emitted photons in the presence of a bend. We introduced a 60° bend into the structure, as shown in Fig. 4A, and performed measurements similar to those in Fig. 3. Again, we observed that emitted photons propagate in opposite directions in a chiral fashion and arrive at the grating associated with their respective polarization (Fig. 4, B and C). The preservation of the chiral nature of the emission

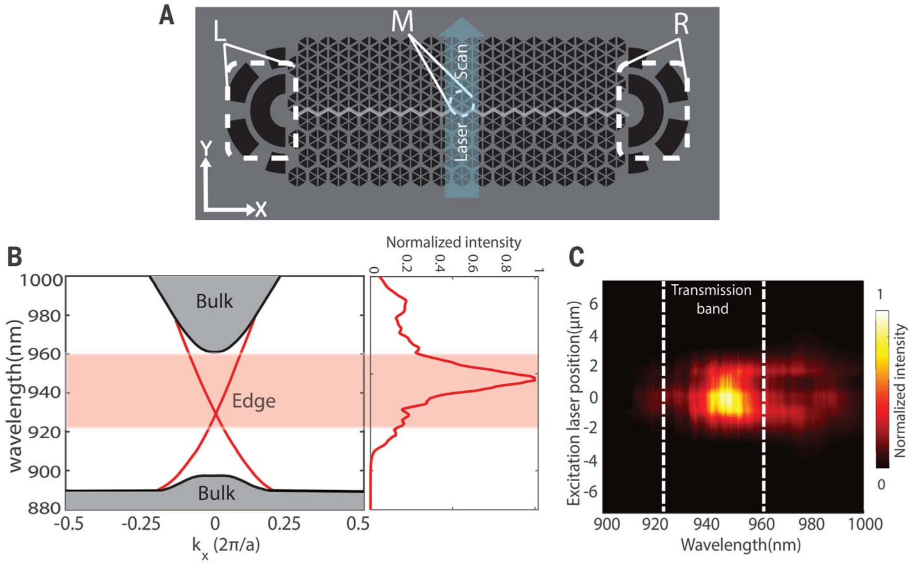

Fig. 2. Transmission characteristics of the topological waveguide. (**A**) A schematic of the excitation scheme identifying the three relevant regions (L, left grating; R, right grating; M, middle of the waveguide). (**B**) Simulated band structure of transverse electromagnetic modes of a straight topological waveguide. The gray region corresponds to bulk modes of the individual topological photonic crystals, and red lines represent modes within the bandgap corresponding to topological edge states. The adjacent panel shows the measured spectrum at the transmitted end of the waveguide. The red shaded region identifies the topological edge band. k_x, reciprocal wave vector; a, lattice constant. (**C**) Transmission spectrum at point L as a function of the excitation laser position.

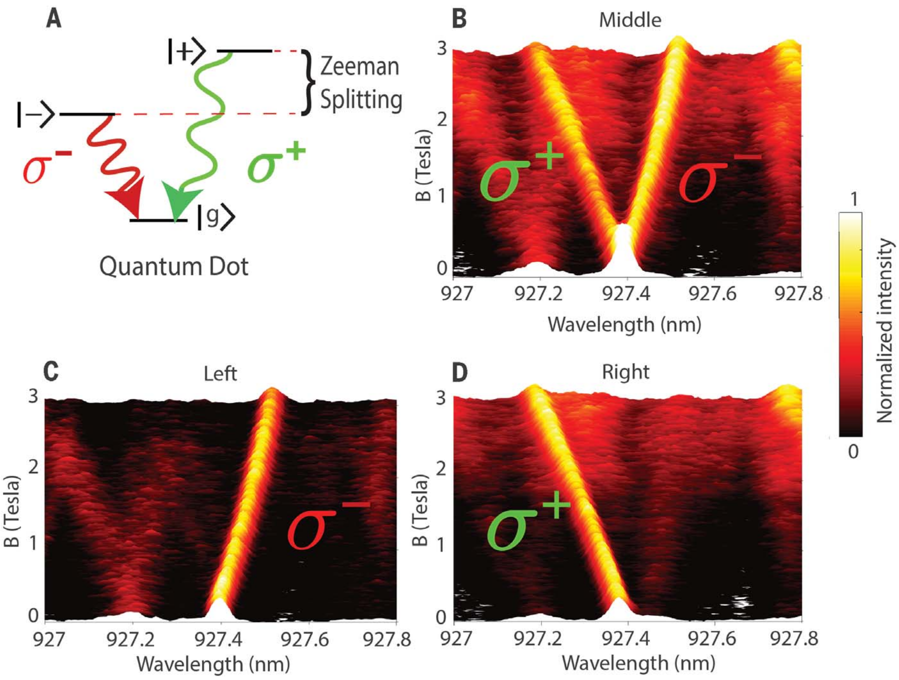

Fig. 3. Chirality in a straight topological waveguide. (**A**) Schematic of quantum dot–level structure in the presence of a magnetic field and radiative transitions with opposite circular polarizations. (**B**) Emission spectrum collected from the excitation region as a function of magnetic field (B). (**C** and **D**) Transmission spectra to left and right gratings, respectively.

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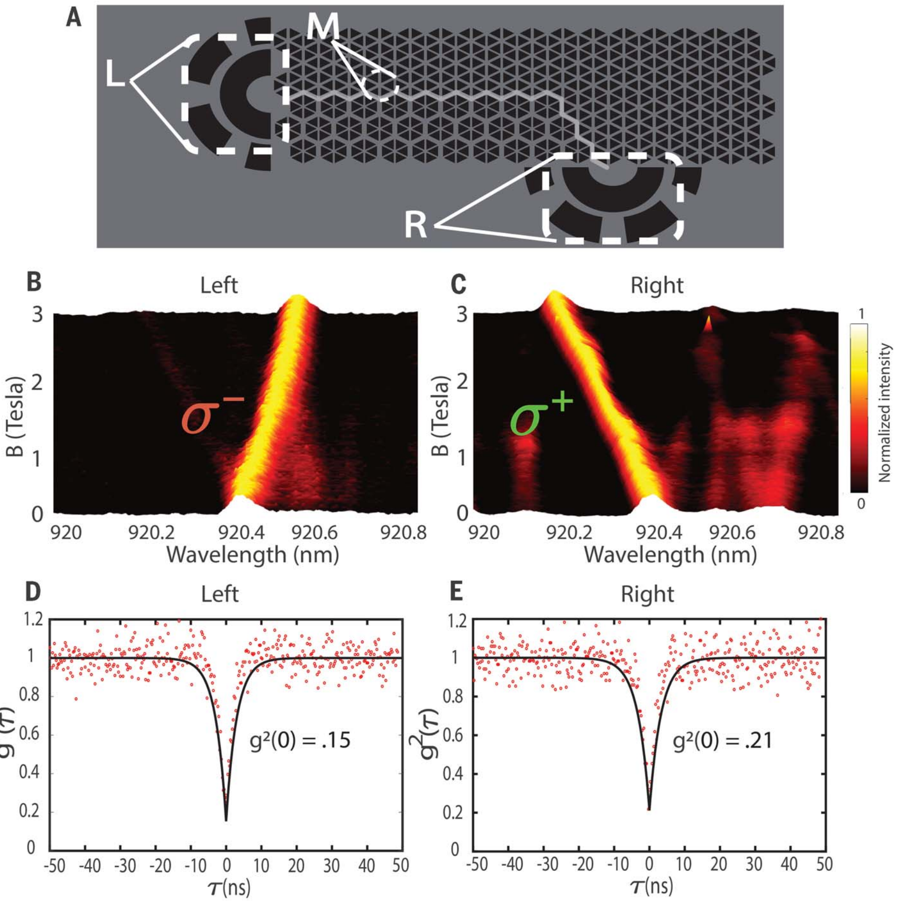

Fig. 4. Robust transport in two dimensions along a bend. (**A**) Schematic of a modified topological waveguide with a bend. (**B** and **C**) Photoluminescence collected from points L and R, respectively, showing only one branch of the quantum dot. (**D** and **E**) Second-order correlation measurement [$g^2(\tau)$, where τ is the time delay] data obtained from points L and R, respectively, showing antibunching. Red dots represent the experimental data, and the black line corresponds to fitting.

demonstrates an absence of back-reflection at the bend, which would result in a strong signal for both polarizations at the left grating. We also confirmed that these routed photons are single photons by performing a second-order correlation measurement for photons collected from both ends of the waveguide, which exhibits strong antibunching (Fig. 4, D and E). The robustness in this system is due to C_{6v} symmetry, and the boundary and disorder can break this symmetry and lead to backscattering of the edge modes. In the supplementary materials, we analyze the effect of certain types of disorder on the transmission properties of the edge modes and show that the unidirectional propagation is robust. The full characterization of robustness, beyond numerical simulations and the tight-binding model (*26*), requires further study.

In this work, we demonstrated coupling between single quantum emitters and topologically robust photonic edge states. Our approach opens new prospects at the interface of quantum optics and topological photonics. In the context of chiral quantum optics, one can explore new regimes of dipole emission in the vicinity of topological photonic structures and exploit the robustness of the electromagnetic modes (*16*). Furthermore, in a chiral waveguide, photon-mediated interactions between emitters are location-independent (*27*). This property could facilitate the coupling of multiple solid-state emitters via photons while overcoming scalability issues associated with random emitter position, enabling large-scale superradiant states and spin-squeezing. Ultimately, such an approach could constitute a versatile platform to explore many-body quantum physics at a topological edge (*28*), create chiral spin networks (*27*, *29*), and realize fractional quantum Hall states of light (*30*, *31*).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S5
Table S1

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Connecting quantum emitters

Exploiting topological properties of a system allows certain properties to be protected against the disorder and scattering caused by defects. Barik *et al.* demonstrate a strong light-matter interaction in a topological photonic structure (see the Perspective by Amo). They created topological edge states at the interface between two photonic, topologically distinct regions and coupled them to a single quantum emitter. The chiral nature of single-photon emission was used to inject single photons of opposite polarization into counterpropagating topological edge states. Such a topological quantum optics interface may provide a powerful platform for developing robust integrated quantum optical circuits.

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