Direct Observation of Topological Edge States in Silicon Photonic Crystals

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Abstract: We directly observe the states of topological photonic crystals at telecom wavelengths. Using the states' intrinsic radiation, we measure dispersion, loss, pseudospin, and spin-spin scattering. We image spin-selective unidirectional propagation around sharp corners and junctions.

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1. Main Text

The concept of topology has proven immensely powerful in physics, describing new phases of matter with unique properties. There has been a recent surge in attempts to implement topological protection in the photonic domain [1], owing to the application potential of robust transport immune to scattering at disorder. A famous class of electronic topological insulators relies on the quantum spin-Hall effect (QSHE) [2], which uses spin-orbit coupling to cause spin-up and -down electrons to propagate in opposite directions in states that are protected by time-reversal symmetry. Photonic analogues of QSHE were realized using arrayed ring resonators [3, 4], and recently predicted to occur in photonic crystals with special symmetries [5, 6]. Such states were observed in the microwave domain [7, 8], and coupled to spin-polarized quantum dots [9]. Interestingly, topological photonic crystals employing QSHE offer the possibility to access their properties via far-field radiation [10].

Here we directly observe topological photonic states at telecom wavelengths in photonic crystals in silicon-on-insulator (SOI) technology. Through angular spectroscopy and polarimetry, we retrieve the properties of the bulk states of crystals with different topological order, as well as the edge states that appear at their interfaces. We reveal that the radiation of the topological states carries a signature of their origin in photonic spin-orbit coupling, linking unidirectional propagation to circular polarization (see Fig. 1a). Through this connection, we selectively excite modes in opposite directions and map their propagation in real space.

Fig. 1. a. Schematic representation of spin-orbit coupling in topological photonic crystals: Chirality of the radiation field is connected to propagation direction of states at edges between photonic crystals with different topological bandstructure. b. A scanning electron micrograph of the fabricated sample, with unit cells indicated in blue and red and edge between two topologically different domains by the yellow line. c. Measured reflectometry, showing the edge state dispersion. d. Measured circular polarization intensity (normalized Stokes parameter $S_3$) when the edge is excited with light that is linearly polarized along $y$, showing that the pseudospin is encoded in $S_3$.

Figure 1b shows the employed photonic crystals, composed of hexagonal unit cells with six sites each, that are either ‘shrunken’ or ‘expanded’ to open bandgaps of different topological order at the Γ point [5, 6]. The edge
between two domains supports topological edge states of differing pseudospin, protected by the $C_6$ symmetry of the photonic crystal lattice. We analyze these states by dispersing normal-incidence reflected intensity in both frequency and angle, to map the edge state dispersion shown in Fig. 1c. It displays the characteristic linear dispersion of the edge states, with measured group velocity $c/8$ and quality factor $\sim 450$.

We demonstrate that the positive and negative group velocity modes can be selectively excited with opposite circular polarization. Conversely, the states’ pseudospin can be probed directly in the far field through the $S_3$ Stokes parameter obtained from polarimetry (Fig. 1d). Our Fourier spectroscopic measurements moreover reveal a small gap at the edge state crossing that is related to spin-spin scattering. This coupling is inherent to the symmetry breaking at the edge, and differentiates these bosonic topological states from their fermioning QSHE counterparts.

Through the far-field spin-orbit link, we selectively excite edge states in opposite directions, and image their propagation in real-space microscopy. Figure 2 shows examples of the spin-selective excitation with a focused laser beam of circular polarization, and the routing of the edge state at a sharp waveguide junction. Interestingly, we observe an absence of backscattering or forward scattering, demonstrating the topological protection of unidirectional propagation. In fact, the states closely follow the photonic crystal edge — defined by the junction’s chiral structure of sub-unit cell size — even though their transverse extent is significantly larger.

The employed imaging and Fourier spectroscopy techniques establish a straightforward yet versatile path for testing and optimizing novel topological systems for a wide variety of applications in optics, including components for integrated photonic chips, quantum optical interfaces, enantiomeric sensing, and lasing at the nanoscale.

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