Topological Protection of Light Propagation in Photonic Crystals

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Abstract *Two-dimensional photonic crystals allow for various types of photonic topological insulators. In this paper, we present our efforts to directly image on-chip light propagation in topological edge states. We quantify the robustness of such states to scattering at sharp corners and defects.*

Introduction
Recent years have seen great interest in the possibility to realize topological insulators for light[1]. This is spurred by the unique features that are known for electronic topological insulators, in particular their ability to exhibit topological protection of electron transport along the edges of materials with a topologically nontrivial bandstructure[2]. The topological properties of such materials dictate that the conducting edge states *must* exist, regardless of defects, sharp corners, or other inhomogeneity in the edge of the material. The possibilities of such robust, protected propagation have strong appeal also outside the electronic realm, in particular for photonics. Light propagation is often hampered by the detrimental effects of scattering at defects. Moreover, routing of light at the nanoscale in small-footprint devices along sharp corners requires meticulous design and extreme fabrication quality to avoid suffering from scattering losses and device inhomogeneity. Topologically protected light propagation thus has strong appeal for on-chip applications. Furthermore, the idea of inherent robustness could be potentially extended beyond the passive guiding and routing of light to the protection of other functionality linked to light-matter interactions, such as light emission.

In the electronic domain, topological insulation can be reached either through the interaction of electrons with magnetic fields, giving rise to the integer quantum Hall effect, or spin-orbit interactions, which are at the root of the quantum spin Hall effect. At visible and telecom wavelengths, the inability of photons to interact with magnetic fields means that routes to mimic the quantum Hall effect rely on the generation of effective magnetic fields through temporal modulation, which is difficult to achieve in wavelength-scale components and scale to effective materials. Photonic spin-orbit coupling can however manifest itself in nanostructured materials, with a spin degree of freedom encoded in the electromagnetic vector field, e.g. its polarization helicity[3]. However, the situation is still markedly different than for electrons. Since for fermions Kramers degeneracy guarantees the existence of both spin states, topological states can be protected through time-reversal symmetry. For photons, another symmetry, such as a spatial crystal symmetry, must take that role. This brings along the interesting questions against which classes of defects photonic topological insulators can offer robustness, what are fundamental or practical limits to topological protection in passive systems, and how does this impact potential application performance.

Methods
The photonic topological insulators we realize are based on special symmetries and controlled breaking thereof in two-dimensional photonic crystals. In 2015, Wu and Hu layed out a route to nontrivial photonic topology through Dirac physics in honeycomb lattices[4]. These principles can be implemented in patterned semiconductor slabs[5],[6]. By suitable deformation of a unit cell in two different ways (either 'shrinking' or 'expanding' the hole pattern), the Dirac cone degeneracy is lifted and bandgaps of different topological order are opened. This means that light can be guided in topological edge states at the boundary of such effective materials (see Fig. 1). We fabricate these systems in a 220 nm thick silicon slab through e-beam lithography and reactive ion etching, for operation at standard telecom wavelengths (1550 nm).

To probe the edge states, we use the fact that they couple weakly to near-normal-incidence radiation[7]. This is the result of the fact that the Dirac cones appear at the Gamma point. We focus a broadband spectrum of light from a supercontinuum source to a diffraction-limited spot on the sample. This excites modes in the slab that have a (small) radiative component, with a broad range of wavevectors. We collect reflected and re-radiated light from a significant

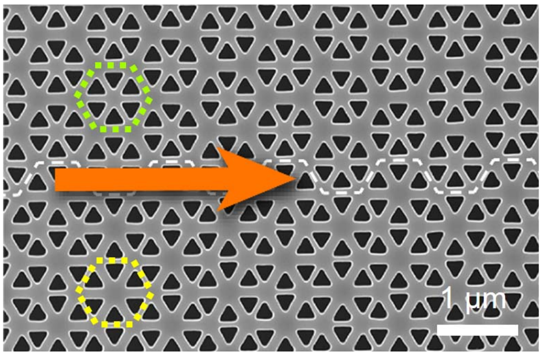

Fig. 1: Topological photonic crystal exhibiting the quantum spin Hall effect for light. The edge (white dashed line) separates two domains with differing bandstructure topology. The crystal structure is differentiated by the fact that the holes in the hexagonal unit cell are either closer together (green, 'shrunken lattice') or further apart (yellow, 'expanded lattice'). This deformation opens a bandgap on either side of the edge, which in turn supports a topological edge state.

area of the sample (≥ 100 μm), pass it through waveplates and an analyzer, and project a back focal plane on the entrance slit of a grating spectrometer. By reading off the output of the spectrometer on an InGaAs CCD array, we obtain a map of reflectance vs frequency and wavevector. The large area of collection means that delocalized modes, such as excited edge states propgating along the slab, can be resolved as narrow features in such diagrams. Alternatively, we excite the system with a narrow-band tunable laser, and image the spatial extent of the excited waves at the frequency of choice in real space by directly imaging the reflection from the sample.

Results

Fourier spectroscopy of the reflected light from the two types of bulk photonic crystals reveals the expected bandgaps, as well as a band inversion associated with the topological phase transition: whereas in the shrunken lattice the bottom band edge is coupled to the light field, in the expanded lattice it is the top band that is 'bright'. This reflects the fact that the dipolar nature of the states on the band switch from the bottom to the top band across the transition from shrunken to expanded[7]. When placing the excitation focus now on the edge between two domains, sharp reflection bands appear in the bandgap that show the characteristic linear dispersion of topological edge states[8]. The linewidth of these states correspond to a quality factor of ~500, in agreement with finite-element simulations of the quasinormal modes of the system. We observe states with both positive and negative group velocity, which are selectively excited by right- or left-circularly polarized incident light. Conversely, when exciting both bands with linear polarization and analysing the degree of circular polarization of the reflected light, we see that the far fields of these states are associated with specific helicities, as depicted in Fig. 2. This helicity is directly associated with the edge states' pseudospin, with the measurement in Fig. 2 thus evidencing the photonic spin-orbit coupling that is at the root of the quantum spin Hall effect, also in this case. It can be understood when realizing that in a nearest-neighbour tight-binding model of the lattice edge, the Hamiltonian describing the edge is block-diagonal in a basis that adds the dipolar bulk bands with ±π/2 phase difference. Since the dipolar parts of the eigenstates are responsible for far field radiation, the pseudospin of the individual edge states is encoded in their circularly polarized far field.

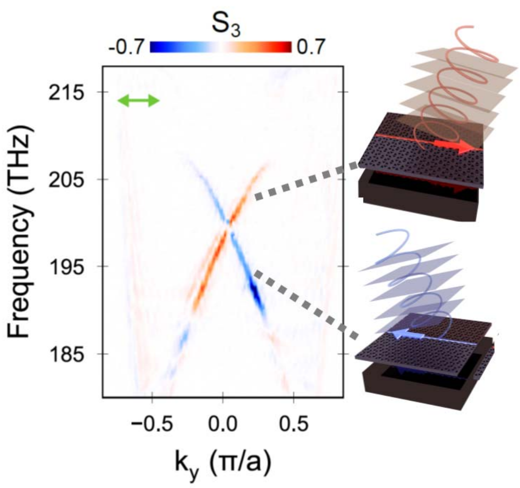

Fig. 2: Measured S3 Stokes component of the reflected light vs frequency and in-plane wavevector, quantifying the degree of circular polarization in the output field. One recognizes that only the edge states in the photonic bandgap (between 190 and 208 THz) display pronounced circular polarization, whose helicity is linked to propagation direction (i.e., the group velocity of the states' dispersion curves). This reflects the photonic spin-orbit coupling that is responsible for the emergence of these quantum spin Hall-like edge states. Figure adapted from [8].

Interestingly, the edge state dispersion in Fig. 2 shows a small mini-gap opening where the two edge state dispersions cross, at zero wavevector. This is impossible to happen for electronic edge states in the quantum spin Hall effect. However, a beyond-nearest-neighbour tight-binding model does predict this anticrossing to occur for the photonic edge states we study here. This is possible because in these systems, it is the spatial (C_6) symmetry of the lattice that offers the protection to the states. Since this symmetry is weakly but inherently broken precisely at the edge between the two domains, the topological protection is not complete. This highlights a potentially important limitation of this type of topological photonic states.

To study whether this apparently ‘limited’ form of topological protection can still offer robust routing of light at sharp corners and defects, we directly image the propagation of the states in real space, letting them impinge on sharp, 90 degree junctions between edge waveguides of different terminations. We observe that the states propagate along the bend seemingly unhindered, without a sign of backreflection, enhanced out-of-plane scattering, or transmission to other states of opposite pseudospin.

Discussion

This observation confirms that although topological protection in these systems is not as complete as for their electronic counterparts, they can still serve a role in routing light along sharp corners on chip. In contrast to conventional methods, designing such systems requires no other effort than adhering to the protecting lattice symmetry.

We note that the fact that the modes weakly couple to the far field causes loss, which is a trivial breakdown of topological protection. One can argue that this is not a fundamental limitation, as systems can be imagined in which such coupling is inherently avoided. Indeed, for this reason we also investigate related photonic crystals that exhibit the so-called quantum valley Hall effect analogue[6], which yield states without low-spatial frequency components that are responsible for radiation.

The breaking of the protecting symmetry, evidenced in our work, is however a potentially more fundamental limitation. It should be investigated if edges can be engineered such that the spin-spin scattering is reduced. This could be achieved through choosing local tuning of unit cell properties – a unique possibility in photonic crystals. Moreover, it raises the question if random defects that do not necessarily respect the protecting symmetry cause significant reflection in practice, and whether these kinds of topological states offer an overall advantage to scattering, averaged over any type of defect. It could be that their best application potential lies in local protection of a function in a compact device, that benefits from protection against specific classes of imperfections.

With that comes the interesting question if specific nanophotonic device functionality can be enhanced by employing topological states in light-matter interactions. The pronounced spin-orbit coupling raises the question if topological modes are available in which the chiral coupling of spin-polarized emitters to waveguides is robust against emitter positioning. This would be a great resource for creating quantum networks of interconnected spins[9],[10]. Moreover, topological modes have been proposed as useful for single-mode lasing[11]. At the same time, it has been argued that the linear dispersion of topological states leads to long-lived excitations that give rise to enhanced fluctuations in such systems[12]. The special properties of topological light at the nanoscale thus warrants further investigation.

Conclusion

In conclusion, we demonstrate topological states of light in a silicon photonic crystal platform at telecom wavelengths, and investigate their unique properties through direct in-situ observations of their fields. This allows us to study the limits of topological robustness in such nanophotonic passive systems, with the potential to explore the use of topological photonics towards potential applications in integrated photonics.

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