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Topological Protection in Radiative Photonic Crystal Cavities

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Abstract – **We study the signatures of topological light confinement in the leakage radiation of two-dimensional topological photonic crystal cavities that feature the quantum spin Hall effect at telecom wavelengths. The mode profiles in real and momentum space are retrieved using far field imaging and Fourier spectropolarimetry. We examine the scaling behavior of mode spectra, observe band-inversion-induced confinement, and demonstrate hallmarks of topological protection in the loss rates, which are largely unaffected by cavity shape and size.**

I. INTRODUCTION

Introducing topological concepts to the design of photonic crystal (PhC) cavities holds great promise for on-chip applications due to the prospect of topologically protected transport. Recently, a geometry-based approach toward photonic topological insulators (PTIs) that feature the quantum spin Hall effect (QSHE) was proposed in two-dimensional PhCs. [1] Building upon the light-guiding capabilities of PTIs, one can design ring-like topological PhC cavities. [2, 3] Interestingly, edge states in QSHE-type PTIs are intrinsically leaky, [4] providing a direct near-to-far field interface. At the same time, as the leakage is not contained in the topological description of the system, intriguing fundamental questions arise: how do the cavities' radiation losses affect topological robustness and, conversely, how does the PhC's band structure control the emitted radiation? Here, we experimentally study the leakage radiation of nanocavities in a topological PhC platform featuring the QSHE at telecom frequencies, showing that the cavity modes' origin in the topological bandstructure still manifests in its optical properties.

II. RESULTS AND DISCUSSION

We construct cavities in a silicon-on-insulator platform by enclosing a topologically non-trivial lattice in a trivial one and vice versa (Fig. 1a). The starting point is a honeycomb lattice of triangular air holes, featuring Dirac-cone dispersion akin to electrons in graphene. We vary the unit cell geometry by concentrically shifting holes in- or outwards to open a bandgap of either trivial (shrunken) or topological (expanded) nature. The topological nature of the system is associated with band inversion of the dipolar and quadrupolar bulk bands. To experimentally acquire full knowledge over the PTI cavities' spectral, angular, spatial, and polarimetric characteristics, we employ Fourier spectropolarimetry of the cavity far field radiation. We perform reflectometry measurements with a white light source to study the mode spectra for expanded (ER_n) and shrunken (SR_n) cavities of varying size. The recorded signal has a bright background of directly reflected light, with sharper resonant features on top that signify the photonic bands. Besides dispersive upper and lower bulk bands, we recognize flat states at discrete energies within the bandgap, which we identify as topological cavity modes (cf. e.g. ER_3 in Fig. 2b). The flat bands display a distribution of emission angles characteristic of their multipolar nature. We examine the latter more closely by addressing individual resonances with a monochromatic light source and recording the cross-polarized, angularly-resolved far field radiation, as shown in Fig. 1b (top panel) for a selected ER_2 cavity mode (H^*, cf. Fig. 1c). The mode displays considerable directional emission into a narrow spectrum of wavevectors around the normal axis, as a result of the topological edge state transport that involves Bloch components with well-defined, near-zero in-plane wavevectors, in contrast to trivial ring resonators based on total internal reflection. We also record polarization-resolved spatial cavity mode profiles (Fig. 1b, bottom panel) via raster-scanning the cavity through the excitation beam, such that each pixel in the reconstructed map corresponds to the collected radiated intensity

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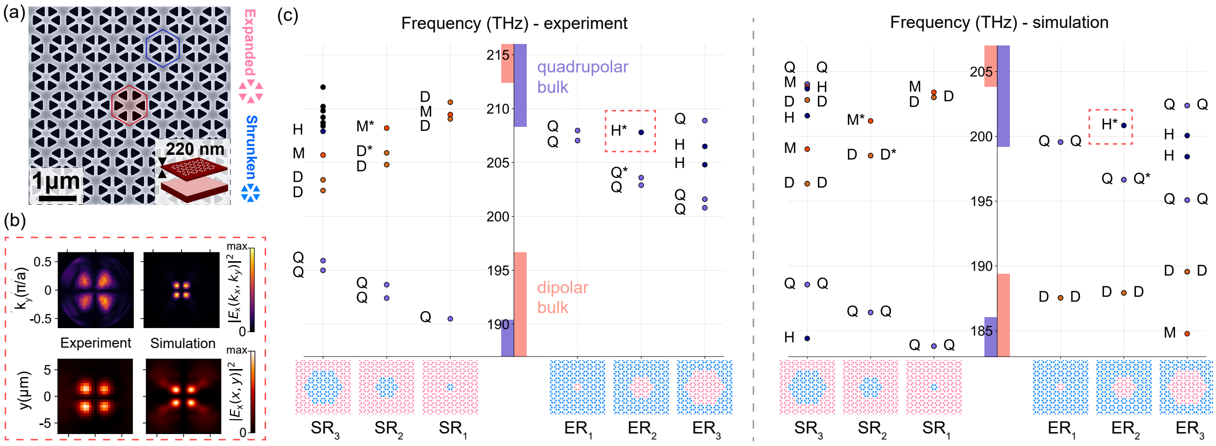

Fig. 1: a) Scanning-electron micrograph of a fabricated ER_1 cavity. b) Mode structure of H^* (cf. Fig. 1c) in momentum- and real-space. c) Mode spectrum and multipolar order for expanded/shrunken (ER_n/SR_n) cavities of various sizes.

at that position. Using near field phase information from simulations, we can directly infer the mode's multipolar order (here: hexapolar). The latter serves as an indicator for the topological charge of the emitted vector beam, implying the possibility to generate light with orbital angular momentum.

To elucidate their origin and scaling behavior, we continue identifying all multipoles observed in cavities up to side length $n = 3$ (Fig. 1c, left panel). All resonators follow the expected trend of decreasing free spectral range with increasing size. Apart from ordinary photonic bandgap confinement, band-inversion-induced confinement in the topological PhC contributes to the localization of cavity modes in the bulk band region. Our cavities can be regarded as defects in an otherwise unperturbed TE-like PhC lattice. The entire system obeys C_6 rotational symmetry and as such supports M (monopolar), D (dipolar), Q (quadrupolar) and H (hexapolar) modes, named after the respective rotational symmetries of the H_z field. [5] It can be shown that D and Q modes are doubly degenerate, in contrast to the M and H singlet states. [6] The D and Q modes can be interpreted as traveling-wave modes, whereas the M and H modes have no traveling-wave analogue, and the system is better described as a PhC defect cavity. While conventional ring cavities may be designed perfectly circular to only feature traveling-wave and no standing-wave modes, cavities in the PTI platform support both types of modes due to their inevitably reduced spatial symmetry. Numerical simulations (Fig. 1c, right panel) corroborate the predictions of the supported multipoles and their degeneracies. Compared to simulations, we notice a constant offset on the order of $\sim 5 - 8$ THz that is attributed to deviation in the size parameters of the fabricated lattice. We also notice splitting of about 1 THz for D and Q modes in experiment. It is known that a small spin-spin-scattering gap in straight QSHE-based topological PhC edge state waveguides exists as a consequence of C_6 symmetry-breaking at the interface. [1] However, since a hexagonal cavity obeys C_6 symmetry, a strict degeneracy between modes of different polarization is expected in theory. [6] Notably, numerical simulations of larger hexagonal cavities have not always confirmed this degeneracy, [2] possibly due to simulation imperfections. Considering increasingly large expanded and shrunken resonators, it becomes evident that the modes originate and detach from the bulk bands and display an inverted scaling behavior of the multipoles. This observation becomes more clear if we, for instance, consider an infinite shrunken lattice into which we introduce increasingly larger defects in the shape of expanded unit cells. We effectively dope the lattice with patches of a material with inverted bandstructure, and the increasingly large defect "pulls" and "pushes" modes from the upper and lower bulk bands, respectively. This argument is supported by first-order calculations of the frequency shift upon infinitesimal variation of the unit cell geometry. [5] The inversion of mode scaling behavior results from the band inversion underlying the topological phase transition and represents a design advantage over trivial resonators, as it offers an additional degree of freedom to strongly tailor mode spectra by small geometrical variations of the unit cell whilst preserving the overall footprint.

Another key prospect of topological platforms is considered to be their enhanced robustness against defects, which we examine by comparing the radiative loss for cavities of increasing size. We investigate the higher energy quadrupolar mode (Q*) that all ER_n cavities have in common (Fig. 1c). The average extracted quality factors (Fig. 2a) show no significant variation with size, suggesting that scattering due to the curvature of the perimeters is not the dominant loss mechanism. The experimental linewidths are comparable to those of edge state dispersion curves along a straight zig-zag interface (Fig. 2a, red dotted line). [7] This is in stark contrast to trivial ring cavities, where for decreasing size light is forced onto an increasingly curved path dominated by bending losses. The enhanced robustness also becomes evident when comparing the dispersion of a hexagonal ER_3 cavity and another cavity EX_3, with same perimeter but drastically different shape (Fig. 2b). Apart from an overall increase in free spectral range, both spectra look fairly similar and the number of modes remains constant. Furthermore, the quality factors for ER_3 ($Q \gtrsim 210$) and EX_3 ($Q \gtrsim 260$) remain on the same order of magnitude. The number of modes as well as their lifetime is considerably well retained even for a significant perturbation of the resonator's shape, which can be regarded as a hallmark of topological protection. Moreover, the leakage radiation rate is a fundamental property that is not significantly affected by cavity size and shape.

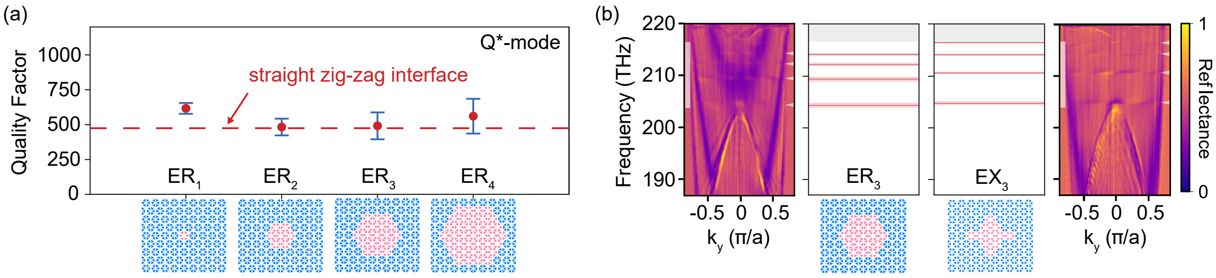

Fig. 2: Comparison of a) radiative quality factors and b) mode spectra for cavities of varying size and shape.

III. CONCLUSION

In conclusion, we experimentally investigate the optical confinement and radiation of telecom light in leaky topological PhC cavities mimicking the QSHE. We discuss the implications of the simultaneous presence of radiative loss and non-trivial topology onto the cavities' properties, elucidating the origin and scaling behavior of the multipolar modes and demonstrating the robustness of cavity spectra and quality factors with respect to alterations of shape and size. We envision the results of our study to advance the development of novel functional devices that aim to manipulate and control classical and quantum information.

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