Localizing a Topological Mode Using a Near-Conservation of the Valley Degree of Freedom

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Abstract: We demonstrate the energy localization at the end of an abruptly terminated topologically nontrivial waveguide. This localization relies on a near-conservation of the valley degree of freedom and does not require time-reversal symmetry breaking.

Recent researches reveal that optical energy can be localized at the end of a terminated or closed waveguide, without specifically building any resonator [1, 2]. Such energy localization is because the backward propagation after the reflection is largely prohibited by the robustness of the mode, granted by its nontrivial topology. However, in those cases, robust propagation is achieved through breaking the time-reversal symmetry, by applying an external magnetic field. Conversely, in a T-invariant system, discrete degrees of freedom (DOF), such as spin and valley, which have been widely used in condensed matter physics, can also ensure the robust propagation for photonic states [3]. How to localized a T-invariant topological state has not yet been studied. We propose a novel mechanism of localizing a topological state in a reciprocal scenario, based on a near-conservation of the valley DOF.

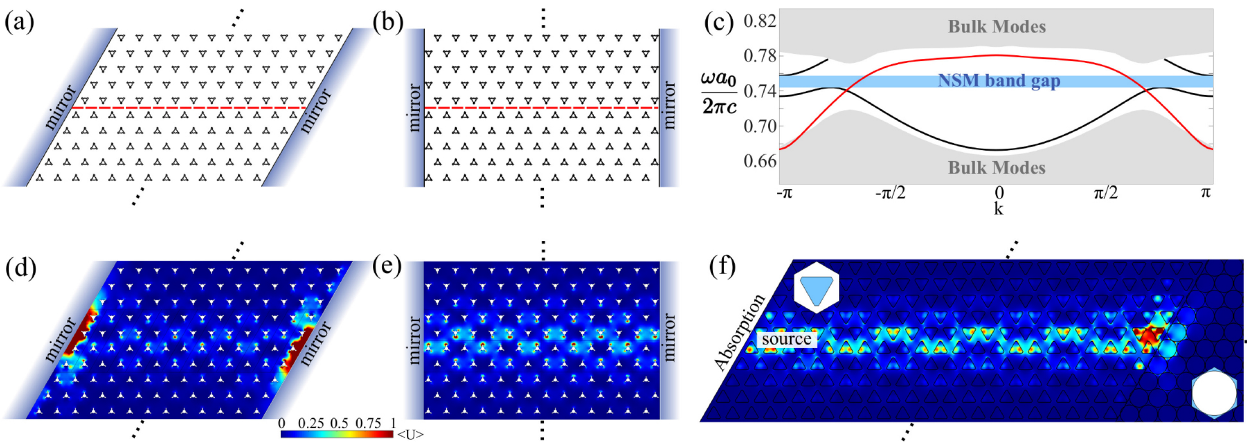

Fig. 1: (a,b) The CKS waveguide with two ends terminated by perfect mirrors. (a) The zigzag termination; (b) The armchair termination. The red lines represent waveguide at the domain wall between two topologically different VPCs. (c) the band diagram of the TE-polarized CKS (red line) and the TE-polarized surface modes (black lines) along the VPC/mirror interface. The blue region spans the no-surface-mode (NSM) band gap where the energy localization phenomenon emerges. (d,e) The time-averaged energy distributions of the eigenmodes with (d) zigzag terminations. The field is localized at mirror surfaces; (e) armchair terminations. The field distribution resembles a Fabry-Pérot resonance. (f) A 2D all-dielectric nano-fabricable design. Energy from a excited CKS is localized at the cavity. On the unit cell diagrams, the blue region is Si ($\varepsilon_{\mathrm{Si}} = 13$); the white region is air ($\varepsilon_0 = 1$). Color: time-averaged energy density.

Our platform is based on a valley photonic crystal (VPC). The interface between the two VPCs associated with opposite valley-Chern numbers is a topologically nontrivial waveguide that carries the chiral kink state (CKS).

The waveguide is abruptly terminated by a perfect electric conductor (PEC) that functions as a perfect mirror [4]. Because the entire structure is symmetric about the mid plane, the electric field distribution is either even or odd with respect to reflections about that mirror symmetric plane. We refer to the even and odd modes as TE- and TM-polarized, respectively. We focus on the TE-polarization infra.

As a CKS travelling along the topological waveguide hits the perfect mirror, it may leak out of the structure through one of the two types of surface modes, propagating either downwards or upwards. However, the dispersion relations of the surface states along the mirror do not span the entire spectrum of the valley CKS (Fig. 1 (c)) — there exists a no-surface-mode (NSM) band gap. Therefore, when a TE polarized CKS operated in this band gap hits the mirror boundary, it will be isolated at the spot which can be viewed as a zero-dimensional cavity (Fig. 1 (d)).

Because the structure is linear, lossless, and time- invariant, this system is reciprocal and time-reversal symmetric. The topologically nontrivial waveguide only supports two CKSs associated with two opposite valley-indices, which are time-reversal-conjugates of each other. Therefore, the only way that the energy can leave the cavity is through a time-reversal-conjugated process of the input CKS. This requires a flip of the mode's valley index. Once the mode's valley index is flipped, it couples to the time-reversal-conjugate of the input CKS and leaves the cavity immediately. So, the rate of valley-flipping is the decay rate from the cavity.

Previous studies on the CKSs revealed that the rate of valley-flipping depends on the types of terminations/domain walls. The zigzag termination significantly suppresses intervalley scatterings, minimizing the probability of such valley-flips; while the armchair termination suffers more back-scattering due to a larger amount of intervalley scattering. Consequently, when a CKS at a frequency inside the NSM band gap is excited towards a zigzag termination, energy is trapped in the cavity for a time delay. It is worthy to notice that the zigzag termination does not completely eliminate the intervalley scattering, because the 1D CKS is evanescent along a direction that is perpendicular to its propagation [4].

The energy stored in the zero-dimensional cavity follows a Lorentzian spectrum, $\frac{|A|^2}{|s^+|^2} = \frac{2\gamma}{(\omega-\omega_0)^2+\gamma^2}$, where A is the mode amplitude inside the cavity; s^+ is the wave amplitude coming into the cavity; ω_0 is the eigenfrequency; γ is the decay rate and $\gamma a_0/(2\pi c) = 4.90\times10^{-4}$. Then, we proceed to study a closed system that consists of two parallel mirrors, resembling the widely applied Fabry-Pérot resonator. We compare the two different types of terminations and reveal that, when the valley DOF is nearly conserved at the mirror surface, our platform supports a significantly different mode compared to that of the Fabry-Pérot resonator. We consider a topologically nontrivial CKS waveguide with both ends terminated by zigzag or armchair terminations. The mirrors on the right and left sides are mirror images of each other, forming two geometrically identical cavities. Such a structure is modeled as a one-port-two-cavity system [4]. With zigzag terminations, the energy is localized in the cavities at the mirror surface; while with armchair terminations, the energy distribution is similar to the Fabry-Pérot resonance between two mirrors (Fig. 1 (d,e)). This difference is because the reflection at zigzag terminations is significantly delayed, as a consequence of intervalley scattering suppression. Our model reveal that the decay rate of the cavity at the zigzag termination $\gamma_{\text{zig}}a_0/(2\pi c) = 1.01\times10^{-3}$, about $1/48$ of that at the armchair termination, $\gamma_{\text{arm}}a_0/(2\pi c) = 4.81\times10^{-2}$ [4].

Additionally, we demonstrate that the design can be delivered in optical frequency, on a 2D all-dielectric nanofabricable platform. We choose the all-dielectric VPC [3] and replace the mirror with a topologically trivial photonic band gap crystal that functions as a mirror. The dispersion of the surface mode along the VPC/PhC interface also opens a band gap. Therefore, when a topologically protected CKS encounters the interface, its reflection is delayed and energy concentrates at the cavity (Fig. 1 (f)).

Overall, we have demonstrated the localization of a topologically protected CKS based on the near-conservation of the valley DOF, without breaking the time-reversal symmetry. This discovery not only extends recent discussions on localized topological modes from nonreciprocal scenarios to reciprocal ones, but also may foster the development of new nanoplasmonic and quantum optical platforms.

References

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