Topological phonon transport in an optomechanical system

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Abstract:

We report the observation of topological phonon transport within a multiscale optomechanical crystal structure consisting of an array of over 800 cavity-optomechanical elements. Using sensitive, spatially resolved optical read-out we detect thermal phonons in a 0.325 – 0.34 GHz band traveling along a topological edge channel, with substantial reduction in backscattering. This represents an important step from the pioneering macroscopic mechanical systems work towards topological phononic systems at the nanoscale. © 2021 The Author(s)

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Recent advances in cavity-optomechanics have now made it possible to use light to measure mechanical motion down to the individual phonons. At the same time, microfabrication techniques have enabled small-scale on-chip optomechanical circuits. Motivated by these developments, several theoretical works have envisioned larger scale optomechanical systems where light is used to steer and detect on-chip topological vibrations. We demonstrate the optomechanical detection of topological phonon transport in a multiscale OMC, which is fabricated on the surface silicon device layer of SOI microchip. Different from standard single-scale devices, the multiscale OMC consists of a superlattice structure which superimposing two patterns with very different lattice spacings. At the larger scale is a snowflake phononic crystal adopted from a well-known single-scale OMC design [1]. A smaller scale

Fig. 1. Design of the multiscale optomechanical crystal for topological phononics. **a**, Optical micrograph showing the snowflake triangular lattice. The axes are aligned with the silicon crystal. **b**, Focused Ion Beam (FIB) image of unit cell geometry with the simulated photonic-crystal cavity mode profile. **c**, Simulated phononic band structures with M_y mirror symmetry intact and broken. **d** and **e**, Optical microscope images and simulated mechanical mode profiles for two strip configurations, each comprising two topologically distinct domains. **f**, 1-D band structures calculated for the horizontal and slanted configurations. The red lines indicate the topological edge state dispersion.

Fig. 2. Characterization of topological edge states using optomechanical read-out. **a**, Optical microscope image of triangular topological mechanical cavity (Domain wall: dashed line. Read-out cavities for the measurements in **b**, and **c**: yellow dots). **b** and **c**, Measured (top) and numerically estimated (bottom) NPSD, respectively, on a slanted edge and on a horizontal edge.

photonic crystal, which hosts a high- Q optical nanocavity for optical read-out of phonons, is embedded within each unit cell of the phononic crystal. Local changes within the lattice of the phononic crystal unit cell are used to create topologically distinct mechanical domains, the boundary of these mechanical domains host phononic helical edge states based on the Valley Hall effect [2, 3].

Here, valley refers to the quasi-momentum region around a Dirac cone, which can be seen as a binary degree of freedom similar to the spin. Valley-polarized edge excitations propagate in opposite directions, akin to spin-polarized edge states in the Spin Hall effect. We open the bulk band gap by breaking M_y symmetry in the phononic unit cell (see Fig. 2c), this gap will host the helical edge states. The topological transport happens through these valley-polarized counter-propagating edge states which exist at the domain walls separating two topologically distinct mechanical domains. We construct from the deliberately mirror-symmetry-broken design described above a second domain by applying the mirror operation M_y (see Fig. 1d,e). The key feature leading to robust transport is that edge excitations can navigate a path with arbitrarily sharp angles while still remaining confined within the same valley region of quasi-momentum space. In such situation, backscattering would require large quasi-momentum transfer to reach a different valley, and is thus strongly suppressed.

In order to experimental test the above design, We have fabricated devices where an internal domain is surrounded by external domain, consisting of an equilateral triangle of 28 snowflake unit cells along each side (see Fig. 2a). The closed domain wall produces a topological mechanical cavity. In a topological cavity, counter-propagating running waves remain decoupled in spite of sharp turns and/or disorder. The mechanical noise power spectral density (NPSD) on slanted domain wall and horizontal domain wall are transduced by laser and measured on electronic spectrum analyzer (see Fig. 2b-c). Two dramatically different transport regimes can be seen in figures. At lower frequencies (321 MHz - 327 MHz), thermal phonon excitations are reflected and form standing waves. This is due to the absence of topological edge modes inside the horizontal domain wall at these frequencies, resulting in standing waves inside domain wall. In the higher-frequency regime (327 MHz - 337 MHz), there are backscattering-immune running waves, which is a direct visual signature of the formation of a topological mechanical cavity. There is also a crossover region (light grey in Figs. 2b-c, and in bandstructure plot in Fig. 1f) in between these regimes. In this region, the horizontal edge already supports edge states, but due to this is near the Brillouin zone boundary of the horizontal edge structure, backscattering is still possible because very small quasi-momentum transfers are sufficient to flip between horizontal edge states in different directions.

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