Communicating Quantum Materials

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OBJECTIVE

We propose a framework that will allow visitors to explore the properties of quantum materials through two interactive exhibits that model quantum topological insulators with acoustic metamaterial analogs. The first exhibit features a set of vibrating strings that serve as analogs for electron waves states. Users will be able to add weights to these strings, to illustrate that waves can be physically manipulated to exhibit topological band inversion. The second exhibit is an interactive acoustic metamaterial system where visitors can expand or contract the metamaterial to switch on or off topologically protected transport of a classical acoustic wave. The proposed acoustic metamaterial design is based on our recent invention of "Topological phononic logic", featured on the cover of Physical Review Letters in Jan. 2022 (Ref. 1).

1 INTRODUCTION

Topological insulators – In 2016, the Nobel Prize in Physics was awarded to Thouless, Haldane, and Kosterlitz for their theoretical work on topology in condensed matter physics. Their work paved the way for the study of topological insulators, superconductors, and other quantum materials.

Electrons travel through quantum materials as waves. In a conventional ("trivial") material, the energy of the wave typically increases with the number of nodes (locations where the wave crosses zero). In a "topological" material, the electron bands are inverted, so an electron wave with fewer nodes may have higher energy. At the boundary between a conventional insulator and a topological insulator, the inverted bands must cross each other, giving rise to a robust edge state, i.e. an electron wave that can travel without resistance. Thus quantum materials of different topology can be joined together to form a dissipationless electronic waveguide, which could be switched ON or OFF by changing the topological phase of one of the constituent materials. Such topological transistors could form the basis of future high-efficiency electronics.

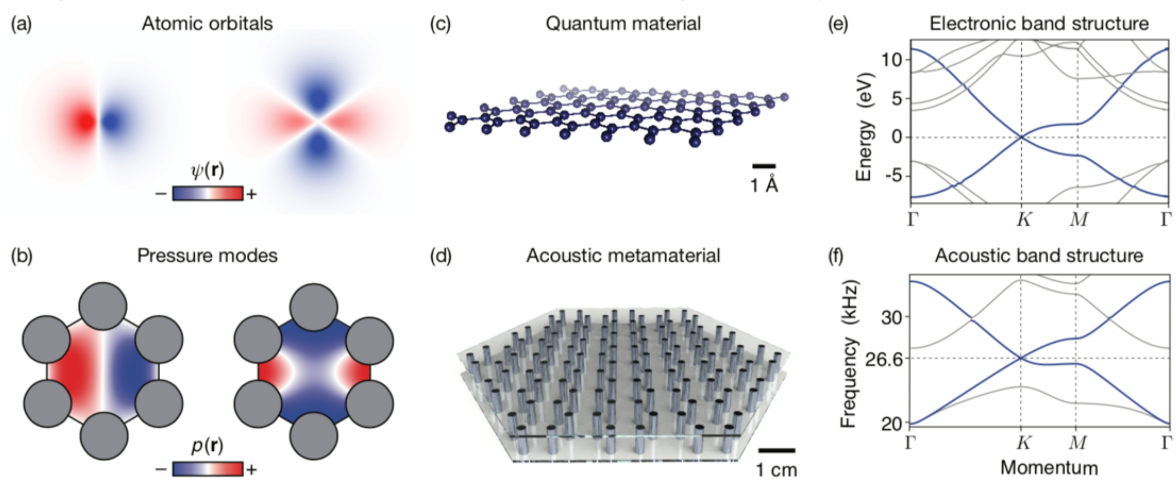

Fig. 1: Analogy between quantum materials and acoustic metamaterials. **(a)** Atomic p and d orbitals show the phase of the electron wavefunctions, in analogy to **(b)** positive and negative pressure regions in an acoustic air cavity between solid pillars. **(c)** Electron waves traveling through an atomic lattice such as graphene are analogous to **(d)** acoustic waves traveling through a honeycomb array of solid pillars. **(e)** The electronic band structure (energy vs. momentum of the electronic states) in a graphene lattice can be perfectly mimicked by **(f)** the acoustic band structure (frequency vs. inverse wavelength of sound) in a honeycomb lattice of pillars.

Although topological insulators were first conceived as quantum electronic materials, their topological property comes from geometric arrangement of the atoms that causes an inversion of energy bands. This band inversion is also present in many classical lattice systems, making it possible to illustrate similar topologically protected wave transport in macroscopic systems.

Acoustic Metamaterials – A metamaterial is a composite structure whose behavior is determined primarily by its macroscopic geometry, rather than the microscopic properties of its constituent materials. At first glance, the Newtonian behavior of sound in a macroscopic structure seems completely detached from the quantum motion of electrons in solids. Yet at their heart, both systems follow straightforward wave equations: the acoustic wave equation for sound and the the Schrödinger equation for electrons. The similarity between these wave equations allows some ideas to be translated between quantum mechanics and acoustics. For example, the hydrogen-like solutions of the Schrödinger equation can be directly compared to the series of standing pressure modes in an air cavity (Fig. 1). Coupling two of these modes gives the same bonding and antibonding eigenmodes in acoustics as it does in quantum mechanics. We can push the analogy between acoustics and electronics even further: our exhibit will show that a sufficiently complex acoustic system of ~ 1000 rubber pillars in a honeycomb lattice can mimic the emergent, collective behavior of thousands of electrons in a solid!

2 PROPOSED EXHIBIT

2.1 Exhibit I: Waves on Strings

First, we will model electron waves using a set of vibrating strings to illustrate the underlying physics of topology. We want to convey that the atomic lattice of a material impacts the structure and energy of the electron waves. We use a string to show that it is possible to excite a wave at a higher frequency mode (more nodes) without changing the initial driving frequency, but by

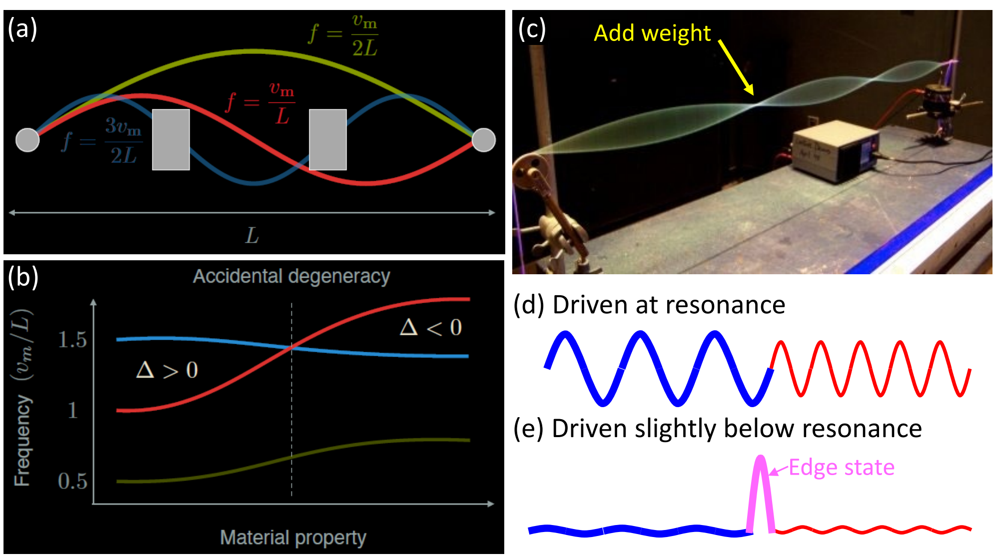

Fig. 2: Demonstration of electron waves using a vibrating string. **(a)** The placement of impediments (such as weights on a string, or pillars in a metamaterial) at strategic locations can "penalize" some standing modes but not others. For example, the gray impediments shown here penalize the red mode more than the blue mode. **(b)** As the impediments become more severe (weights become heavier, or pillars become thicker), the energy of the red mode increases and eventually crosses above the blue mode. **(c)** A string driven at its fundamental frequency can be coerced into a higher frequency oscillation by clipping on a weight[2]. **(d)** By driving two differently-weighted strings at resonance, two different vibration modes can be observed. **(e)** By driving slightly off-resonance, only an edge mode will survive.

physically manipulating the string as in Fig. 2(a-b), a concept that would be familiar to a violinist who lightly places a finger mid-string to emphasize a harmonic. Our proposed setup features a string fixed at one end and driven at the other end at a fundamental frequency of ~ 15 Hz, as in Fig. 2(c). By clipping a tiny weight onto the vibrating string, we can force it to vibrate at a higher harmonic, an integer multiple of the fundamental, without changing the driving frequency. The vibration of the string is influenced both by the location and mass of the clip, just as the motion of electrons inside an atomic lattice is influenced by the physical configuration of the atoms as well as the mass of the atoms themselves.

The required precision in placement of the weights presents a challenge in making this setup interactive. One possible solution is to clearly mark the location (the antinodes) where the weights need to be placed, but to provide a set of weights with varying masses that the visitor can choose from. This set of weights can have masses differing in proportion to elements with different masses in the periodic table, and can be labeled as the elements that they represent. That way, the visitor can still have some degree of freedom to explore the system while ensuring that the physics we would like to demonstrate will be present.

Second, we want to illustrate topology in the string system. By strategically placing weights along a vibrating string, not only can we force the string to vibrate at higher modes, we can also invert the energies of two modes, effectively creating a topological inversion within the string.

By coupling a topologically inverted string with a non topologically inverted string in Fig. 2(d), we aim to observe an edge state at the transition between these two topologically distinct string systems. When the driving frequency of the coupled string system is slightly below the resonant frequency, we expect a peak at the topological edge. To make this exhibit interactive, the system can allow the user to turn a knob which sets the driving frequency of the strings. We mark the resonant frequency at which the two strings vibrate at different modes. The visitor can turn the knob just below this resonant frequency to observe the standing modes of both strings disintegrate into disorder while a peak emerges at the interface of the two strings as in Fig. 2(e).

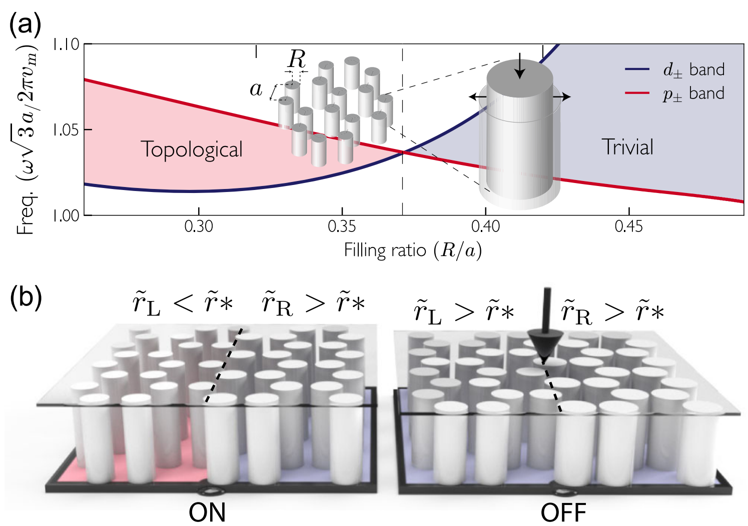

Fig. 3: A topological acoustic switch, composed of solid pillars of radius R arranged in a honeycomb lattice of spacing a. **(a)** At high filling fraction $r \equiv R/a$, the d (2-node) band is at higher frequency than the p (1-node) band, so the acoustic band structure is conventional, but as r is lowered through a critical value r^*, the p and d bands cross and then invert to form a topological state. **(b)** Left: a topological waveguide is formed at the interface between topological and trivial lattices. Right: by squishing the pillars from above, their radii expand, the topological side becomes trivial, and the waveguide turns off. Adapted from Ref. 1.

2.2 Exhibit II: Topological Acoustic Transistor

The next exhibit will be an interactive topological acoustic switch based on the concepts in Fig. 3 from Ref. 1. A metamaterial is created from three adjacent arrays of rubber pillars of radius R arranged in a honeycomb lattice of spacing a, as shown in Fig. 4(a). The visitor can turn three knobs to independently control the height of three blocks resting on each of the three lattice sections. Because rubber expands laterally as it is squished vertically, and vice versa, the knobs can be used to tune the lattice filling fraction $r \equiv R/a$.

If all three blocks are at the same position, the waveguide is OFF: sound cannot transmit through the system. The visitor can twist the knobs such that two sections with $r < r^*$ (topological) and $r > r^*$ (trivial) are next to each other, thus turning ON the topological phase and enabling the waveguide at the interface of these two pillar sections. Depending on which pillar section the visitor decides to tune, they choose one of two different waveguide paths, as shown in Fig. 4(b).

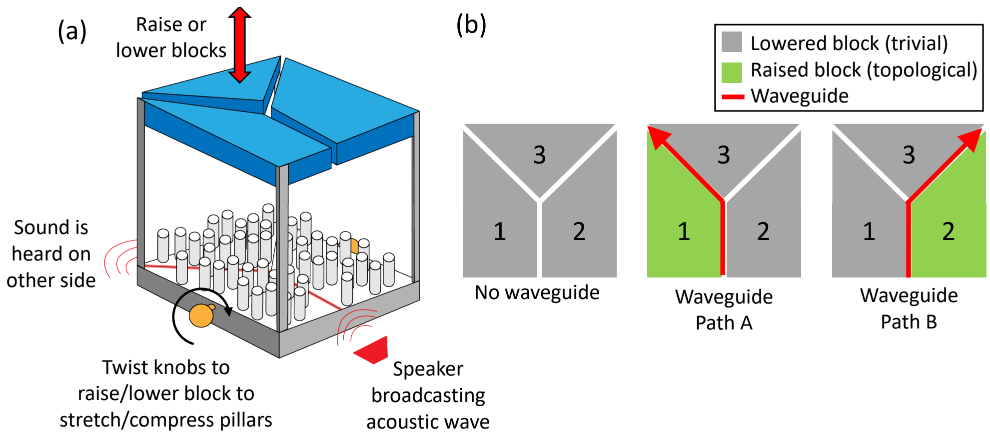

Fig. 4: Exhibit of topological acoustic switch. **(a)** Three-section acoustic metamaterial system with compressible rubber pillars in an air-tight box. **(b)** By stretching or compressing the pillars to change the topological phases of the lattice segments, the system can block sound, or transmit sound along Path A or Path B.

3 ACCESSIBILITY

We aim to make this exhibit accessible to visitors with either hearing or vision impairment. With cm-scale pillar spacing, the output of the topological switch can be heard at the end of either Path A or Path B in the audible range around 5-10 kHz. Sound waves can also be visualized using shlieren optics[3]. A shlieren optics setup takes advantage of the tiny changes in the index of refraction of air as a sound pressure wave passes through. Light passing through these pressure waves could be imaged as streaks (or "shlieren" in German) – but a real sound wave is far too fast for the human eye to perceive. Therefore, we use a strobe light slightly detuned from the frequency of the passing sound wave, which gives the visual appearance of sound waves propagating in real time, as can be seen in the movie in Ref. 4.

4 PROGRESS AND NEXT STEPS

We show a preliminary demonstration of the transmission of ultrasound through a topological waveguide in Fig. 5. Our initial attempt involved gluing 960 pillars into a honeycomb lattice with ∼mm precision. A key challenge remains to reduce the losses in the system, so that the sound wave can transmit fully through the waveguide. We are exploring professional machining solutions, as well as alternative materials, and we expect significant improvement.

We are also actively developing acoustic metamaterials of other quantum materials such as van der Waals heterostructures[5], twisted bilayer graphene[6], rippled graphene[7], flat bands in kagome

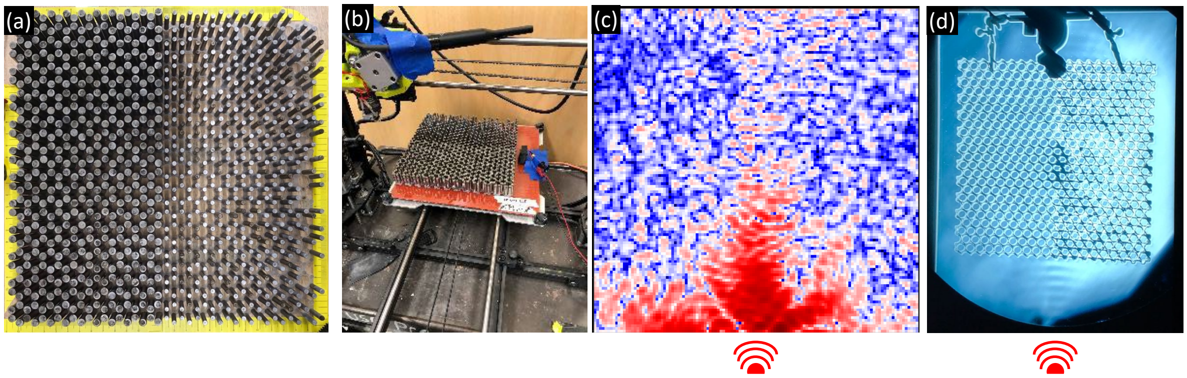

Fig. 5: Preliminary demonstration of a topological acoustic waveguide, using both acoustic and optical detection. **(a)** Metamaterial composed of 960 steel pillars in a honeycomb lattice with spacing $a = 0.697$ cm. The pillar radii are chosen to form a trivial insulator on the left, and topological insulator on the right, so the center should form a topological waveguide for 27 kHz ultrasound (the frequency of the strobe we happened to have access to). **(b)** Scanning microphone used to detect ultrasound amplitude, one pixel at a time. **(c)** Preliminary image of ultrasound amplitude traveling through the metamaterial waveguide. **(d)** Shlieren optic image of ultrasound, captured on a cell phone camera. The full movie is in Ref. 4.

materials[8], and twisted bilayer kagome structures[9]. We hope to soon extend our tangible, audible, and visible demonstrations of quantum materials to these forefront systems.

ACKNOWLEDGMENTS

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