Tuneable phononic crystals and topological acoustics

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Sourav Banerjee, Professor from the University of South Carolina, navigates the field of tuneable phononic crystals and topological acoustics

Acoustics, an age-old field of study, has recently revealed new physics with new degrees of freedom of wave propagation. These new findings are invaluable for information processing using acoustic modality. Information processing using acoustics is called acoustic computing.

Computing Boolean algebra, which has already been demonstrated, could pave the pathways even for quantum computing using acoustics. Not in the very distant future, the recently discovered quantum and topological behavior of acoustics could be an integral part of computing modalities.

Acoustics and tunable phononic crystals

Acoustics are traditionally known as longitudinal pressure waves propagating like a spherical wavefront. However, when acoustic waves are exposed to specially designed engineered metamaterials made of tunable phononic crystals (TPCs), acoustics may manifest unseen unique behaviors that sometimes resemble quantum-like phenomena.

Under certain circumstances, how could a longitudinal wave interact with metamaterial to manifest spin-like properties and a new degree of freedom? The researcher found it to be surprising, intriguing, and simultaneously inspiring. The novel phenomena with TPCs and their manifestation in acoustic spin properties opened a new field of study, like topological acoustics (TA). Further, TPCs and TA could open new doors for multiple new applications where acoustic waves in fluid require tuning and designed manipulation for communication.

Among the latest advancements in the field of acoustics, TPCs and TA have emerged as frontrunners, showcasing the transformative power of sound waves in various applications like acoustic computing. This article delves into the intricate world of TPCs, explores the fascinating realm of topological behavior associated with acoustic spin, and contemplates the tantalizing prospect of acoustic Boolean algebra and even possible acoustic quantum computing.

Defining tunable phononic crystals

Phononic crystals are structured materials engineered to control the propagation of sound waves. Periodic repetition of a specific geometric pattern of hard solid material in a soft media-like fluid is called phononic crystal. Phononic crystals control the flow of sound and acoustic waves, which resembles the similar concept of how photonic crystals control the flow of light and electromagnetic waves.

What sets TPCs apart is their tunability, which allows researchers to dynamically modify their acoustic properties. This tunability is achieved through various mechanisms, such as applying specific electric or magnetic fields, changing the temperature gradient, and applying mechanical rotation and/or deformation by integrating electronic control.

In acoustic computing, TPCs can be integrated into devices to control the flow and processing of information encoded in acoustic signals. By dynamically adjusting the phononic crystal’s properties, one can tailor acoustic pathways, manipulate wave propagation, and even create acoustic analogs of electronic components crucial for computing tasks.

Acoustic computing

Acoustic computing concerns the execution of basic Boolean algebra computations using acoustic waves. Logic gates are the basic building blocks of any digital system: four basic gates are the AND gate, the OR gate, the NAND (not and) gate, and the NOR (not or) gate. It has been shown that producing basic acoustic logic gates makes computation possible, as it does with transistor circuits in electronic devices.

TPCs create the ability by design to send acoustic waves to a certain direction, trapping or localizing the waves at a certain location, focusing, and defocusing through positive and negative refraction of acoustic waves, creating the opportunity to design the acoustic logic gates. TPCs create these opportunities because certain physics plays a crucial role in metamaterial when the phononic crystals are tuned to explore certain behavior. Out of many such behaviors, our team explores the physics of Dirac-like cone and topological acoustics for acoustic computing.

Dirac-like cone behavior

In metamaterial composed of TPCs, the wave dispersion (where wave velocity changes with frequency) forms a Dirac-like cone at a point known as Gamma point at the center of the Brillouin zone (polyhedra that contains a single point in reciprocal space).

This formation is not always absolute but rather accidental. Certain geometrical and material parameters of the TPCs could create, alter, or destroy the band structure needed for acoustic computing. A band is a mode with a specific mode shape in wave dispersion plots that appear with certain geometrical and material parameters of TPCs. Some bands could be flat.

A flat band can have multiple frequencies at any certain wave number, resulting in zero group velocity, which is synonymous with energy being independent of momentum in quantum mechanics.

If such a flat band is trapped between two linearly intersecting bands, namely the top and bottom bands, owing to zero group velocity, no sound could pass through the metamaterial at that frequency in the forward direction. It is as if the band is deaf to the propagating frequency.

However, due to the antisymmetric mode shape of the deaf band and the mode shapes of the top and the bottom bands being opposite to each other (resulting in superposition and canceling each other), the wave propagates in the orthogonal direction. This is a particularly crucial behavior for acoustic computing. However, by tuning the TPCs this band structure could also be altered. The top and bottom bands could be separated, keeping the deaf band with one of the bands attached. This is further crucial for exposing the spin properties and manifestation of TA.

The research team has found two ways of forming a Dirac-like cone. A) The first is to keep a flat band trapped between two linearly intersecting bands, creating a deaf band. B) The second is where four bands intersect at the Gamma point. By virtue of TPCs, metamaterial could be transformed to allow a modal flip, so if two materials have opposite spin states, when they are brought together, an acoustic topological insulator is created, and a wave propagates along the boundary. The latter is called the quantum spin Hall effect.

Building an acoustic computer

Harnessing the quantum behavior of acoustics, together with exploiting and understanding the physics of Dirac cones and Dirac-like cones, has allowed our research team to design a metamaterial that permits the control of the acoustic waves in innovative ways that previously would have been thought impossible. The creation of all possible acoustic logic gates using a single structure was thought to be impossible. Still, with the help of TPCs, our team (1-5) has created a new direction for acoustic computing research.

Topological acoustics and spin properties

It was recently discovered that an extremely rare topologically protected acoustic behavior could be achieved near the Dirac-like cone when the top band and the deaf band together create a certain band gap from the bottom band. Acoustic topological phenomena are generally described using quantum anomalous hall effects (QAHE), quantum valley hall effects (QVHE), and quantum spin hall effects (QSHE), where spin-orbit coupling is predominant. Topological edge states are demonstrated by bulk-boundary distinction when the bulk is insulated.

However, exactly opposite to the behavior of a topological acoustic insulator wave could be trapped inside the metamaterial if the TPCs are tuned to certain geometrical configuration, where spin properties were found to be dominant. Acoustic waves are trapped under certain configuration of TPCs when the spin angular momentum is nonzero giving unnatural spin degrees of freedom to acoustics.

An ongoing area of research

As shown in the article (6), the wave continuously flips between up spin and down spin while trapped inside the metamaterial. Exploiting tuned localization of acoustic energy with the help of TPCs, memory storage could be exploited for acoustic computing. This application could open new horizons, beyond performing Boolean algebra through binary bites but exploiting qubits with the help of spin degrees of freedom. Exploiting quantum computing with TPCs, TA, and acoustic spin is still an ongoing area of research.

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