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A bright future for topological acoustics

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Topological physics has been driving exciting progress in the area of condensed matter physics, with findings that have recently spilled over into the field of metamaterials research inspiring the design of structured materials that can govern in new ways the flow of light and sound. While so far these advances have been driven by fundamental curiosity-driven explorations, without a focused interest on their technological implications, opportunities to translate these findings into applied research have started to emerge, in particular in the context of sound control. Our team has been leading a highly collaborative research effort on advancing the field of topological acoustics, dubbed 'New Frontiers of Sound' and connecting it to technological opportunities for computing, communications, energy and sensing. In this comment, we outline our vision towards the future of topological sound, and its translation towards industry-relevant functionalities and operations based on extreme control of acoustic and phononic waves.

The field of topology studies the geometrical properties of an object that are preserved under continuous transformations. While this area of mathematics can be traced back to centuries ago, its broad impact on physical sciences has been profound, in particular in the last few decades. As a testament of this broad impact, the 2016 Nobel Prize in Physics was awarded "for theoretical discoveries of topological phase transitions and topological phases of matter", driven by the discovery of *topological insulators*, whose unusual conduction properties are governed by the topological features of their electronic band structures[1,2]. The last few years have seen an explosion of interest in expanding these concepts beyond material science and electronic material responses, finding a rich and fertile ground in wave engineering. Optical[3,4] and acoustic[5–8] metamaterials have offered a powerful platform to enable topological phenomena for light and sound, and even to observe topological phases of matter that were only predicted but not experimentally discovered in electronic materials. In particular, the acoustic playground offers an exciting platform for these explorations, given the accessibility to fabrication techniques for acoustic metamaterials using, such as additive manufacturing techniques, the maturity of acoustical sciences and engineering, and the range of applications enabled by new modalities of sound control.

The electron spin governs topological phenomena in electronic systems, while phonons do not possess an intrinsic spin. Hence, in order to enable topological phases, topological acoustic metamaterials have relied on a range of *pseudospins*, based on angular momentum[9], tailored geometrical asymmetries[10,11], Floquet time-dependent material properties[12,13], and nonlinearities combined with spatial asymmetries[14,15]. These findings have uncovered new forms of control over sound transport, inherently endowed with robustness associated with their topological nature, which include for instance unidirectional acoustic waveguiding along the boundaries of structured media[5–13].

These emerging forms of sound transport, driven by the nontrivial topological properties of the band structure of acoustic metamaterials, are not the only way in which topological concepts have been advancing acoustic technologies in the past years. Topological acoustics has expanded also in the space of design parameters, enabling resonant systems that support *exceptional points* (EPs), at which the resonance eigenvalues and the corresponding eigenmodes coalesce and become degenerate, forcing the system to lose one or more dimensions. EPs possess highly nontrivial topological features, which offer exciting opportunities for wave manipulation and control[16,17], in particular in the context of sensing.

Topological features for wave control can emerge also in real space. As the spatial structure of acoustic fields becomes more complex in engineered metamaterials, they acquire a multi-dimensional vectorial nature, to which it is possible to associate a geometric phase. Rotations and other spatial transformations can then control such phase over the topological manifold of the acoustic field structure, enabling superior control and robustness of sound transport. As an example, spatially structured acoustic fields can be characterized by an orbital angular momentum, whose vortices formed by the acoustic phase fronts are characterized by a nontrivial topology and can be leveraged to enhance the channel capacity and multiplexing in communication applications and to enhance the robustness of sound propagation in multi-path environments[18].

While the progress in topological acoustics has been thriving, many of the initial discoveries have been focusing on the basic science aspects, e.g., on mapping topological concepts to acoustic wave propagation, without specific attention on the application space. For instance, while robust sound waveguiding is certainly interesting, and the analogies with the electronic response of topological insulators that guide currents on their boundaries is very elegant, from the practical standpoint acoustic topological insulators for waveguiding should be compared in terms of quantitative performance metrics with other solutions for sound transport. The last few years have indeed seen a renewed interest in exploring how topological acoustics can impact from a practical standpoint real-world applications and acoustic technologies.

Harnessing topological acoustics for applied solutions

Indeed, sound enables communication and perception and benefits society with numerous impactful and widespread technologies, spanning from seismic sensors to high-quality filters for wireless communications. Garnering enhanced control over sound propagation hence holds the prospect of advancing in disruptive ways many of these technological platforms. In the past year, we have launched a new Science and Technology Center (STC), funded by the U.S. National Science Foundation—New Frontiers of Sound (NewFoS)—with the bold goals of leveraging these basic science advances in topological acoustics and apply them in a transdisciplinary research effort across several universities to develop the transformative breakthroughs in acoustics for maximum technological and societal impact and to educate, mentor and train researchers, technologists, and leaders in a new science of sound.

Beyond our basic science discovery and education goals, our STC has identified three application areas in which topological acoustics has gained sufficient maturity to make direct technological impact: (i) leveraging the vectorial nature of acoustic waves and their geometric phase to enable new forms of phase-based massively parallel storing, processing and retrieving of information; (ii) leveraging the robust and unidirectional features of topological sound transport to develop low-cost, miniaturized, low-power and functional topological acoustic devices for advanced telecommunication systems; (iii) leveraging the geometric phase for enhanced remote-sensing technologies, enabling new sensing modalities for direct and continuous monitoring of the natural environment, e.g., permafrost thawing in the boreal forest, or structural health monitoring of the built environment, e.g., detection of flaws in additively manufactured engineered structures.

Sound is already regularly used to transport information, e.g., in human speech. Topological acoustics has been enabling new forms of information processing that leverage pseudospins that go beyond the conventional properties of sound used for information encoding—frequency, wave vector and dynamical phase[19]. For example, pseudospins as new degrees of freedom for information transport can be utilized for robust acoustic Boolean logic elements, enable ultralow-energy computing. We have also been investigating the possibility to go beyond Boolean logic, at the basis of digital computing, and pursue geometric phase-based massively parallel information processing. Nonlinear topological sound waves can support coherent acoustic superposition of states spanning a Hilbert space that scales exponentially with the number of coupled states. This enables the realization of classical yet non-linearly correlated acoustic states analogous to quantum entangled states, whose number of degrees of freedom grows exponentially with the number of waves[20].

By leveraging quantum-like computing algorithms it is possible to enable a large degree of parallelism for information processing, which holds the promise for a classical platform based on sound for computation. While parallel efforts have been exploring photonic platforms for these goals, the strong nonlinearities of acoustic waves and the well-established acoustic technology platform offer unique opportunities to realize exponentially complex states, with a path towards platforms harnessing nonlinear correlations to speed up computational tasks beyond what can be achieved with digital computers.

Acoustic waves are at the basis of many wireless communication devices, in particular in the realization of compact filtering functionalities, thanks to their small wavelength and high-quality factor features. Within our STC, we are exploring the integration of topological acoustic devices in portable radio-frequency wireless systems, leveraging the robustness to defects associated with topological propagation features to enhance performance, decrease manufacturing costs, and reduce the requirements for high tolerance in fabrication. Topological wave propagation also allows breaking reciprocity over broad bandwidths and achieving superior phase and latency control, offering unique opportunities for the realization of reconfigurable radio-frequency devices supporting frequency diversity and signal-to-noise ratio enhancement. In parallel to macroscopic demonstrations of topological acoustic insulators based on tailored temporal modulations in piezo-electric lattices[13], also nanoelectromechanical and nanooptomechanical lattices of resonators have been demonstrated to support topological sound[21,22]. These acoustic device concepts can be applied not only to filtering and signal delay, but also to enable robust networking and information carrier. Integration of these components into radio-frequency systems compatible with portable headset requires not only system engineering, but also new communication protocols that exploit the new forms of signal transport enabled by topological acoustics, e.g., in the context of full-duplex communications.

A third pillar of our effort consists in the unparalleled sensitivity and resolution of acoustic-based systems for sensing and imaging. For instance, the sensitivity of the geometric phase of seismic waves to environmental conditions such as temperature, but also to physical parameters such as density or stiffness, has been explored in the areas of ecological and environmental sciences, in order to make precise measurements of changes in the natural environment[23]. In our effort, we have been exploring the use of geometric phase sensing techniques to provide reliable ways to monitor and characterize the changes in the properties of the subsurface in the arctic, e.g., of the permafrost. Topological acoustic attributes may be also leveraged for non-destructive testing of materials and structures, by operating around EPs in parameter space[16] but also by exploiting the sensitivity of the geometric phase around topological features of the acoustic field manifold. These concepts find applications in temperature, flow and pressure sensing[24,25]. The ultrasonic detection of a crack or flaws developing in a metallic structural component has been observed based on these principles[26–28].

Conclusions

Overall, the field of topological acoustics has been maturing in the past few years, going well beyond basic proof-of-concept demonstration of novel sound control methodologies, and it is making its way towards practical technologies of relevance to sensing, imaging, computing, transport, data storage and communications. Through our STC, we have been working with our partner companies to transition these functionalities into practical devices and system-level demonstrations, with the goal of pushing these *new frontiers of sound* towards practical impact, and inspire the next generation of engineers, scientists and acousticians to engage in this exciting interdisciplinary field of science and technology.

In order to achieve this feat, proof-of-concept demonstrations of topological acoustic responses are not sufficient, and an important effort must be spent on developing topological acoustic technologies that on one hand demonstrate significant enhancements of performance metrics relevant to the target applications—e.g., in terms of efficiency and footprint—and at the same time enable a scalable platform in terms of fabrication and integration with existing setups and systems. These are crucial requirements for topological acoustic technology to become mainstream. Given the inherent cross-disciplinarity of this emerging field of science, multi-institution efforts engaging different expertise and connected to the relevant industries like our STC are crucial, as they aim at forming the next-generation of scientists and engineers that can speak a common language addressing fundamental concepts and application-relevant metrics of performance. As more of such efforts emerge, we expect that in the coming years the field of topological acoustics will blossom and open disruptive directions in several applied technologies.

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Competing interests

The authors declare no competing interests.

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