Progress and perspectives on phononic crystals

Cite as: J. Appl. Phys. 129, 160901 (2021); https://doi.org/10.1063/5.0042337
Submitted: 29 December 2020 • Accepted: 01 April 2021 • Published Online: 22 April 2021

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Submitted: 29 December 2020 · Accepted: 1 April 2021 · Published Online: 22 April 2021

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ABSTRACT
Phononic crystals (PnCs) control the transport of sound and heat similar to the control of electric currents by semiconductors and metals or light by photonic crystals. Basic and applied research on PnCs spans the entire phononic spectrum, from seismic waves and audible sound to gigahertz phononics for telecommunications and thermal transport in the terahertz range. Here, we review the progress and applications of PnCs across their spectrum, and we offer some perspectives in view of the growing demand for vibrational isolation, fast signal processing, and miniaturization of devices. Current research on macroscopic low-frequency PnCs offers complete solutions from design and optimization to construction and characterization, e.g., sound insulators, seismic shields, and ultrasonic imaging devices. Hypersonic PnCs made of novel low-dimensional nanomaterials can be used to develop smaller microelectromechanical systems and faster wireless networks. The operational frequency, compactness, and efficiency of wireless communications can also increase using principles of optomechanics. In the terahertz range, PnCs can be used for efficient heat removal from electronic devices and for novel thermoelectrics. Finally, the introduction of topology in condensed matter physics has provided revolutionary designs of macroscopic sub-gigahertz PnCs, which can now be transferred to the gigahertz range with advanced nanofabrication techniques and momentum-resolved spectroscopy of acoustic phonons.

I. INTRODUCTION
In 1932, Frenkel used the term phonon to describe a quantum of the acoustic field, a new hypothetical particle introduced 2 years earlier by Tamm. The word phonon originates from Greek ωνή (phone, meaning voice), and it is an analogy to a photon being the quantum of the electromagnetic field. Needless to say that the importance of phonons in fundamental and applied research goes far beyond the common understanding of sound. The full phononic spectrum spans a broad, mostly inaudible, range of frequencies from a few millihertz up to dozens of terahertz. In general, the phononic spectrum (Fig. 1) consists of infrasounds (< few Hz), audible sound (from few Hz to 20 kHz), ultrasounds (from 20 kHz to 1 GHz), hypersons (from 1 GHz to 1 THz), and heat (≥ 1 THz at room temperature). For all these bands, acoustic waves/phonons are information and energy carriers that play an inherent role in condensed matter physics. The properties of the hosting medium dictate two fundamental features of phonons, i.e., their dispersion relation (spectral and spatial) and mean free path (lifetime and attenuation). For bulk, homogeneous solids, one can distinguish three orthogonal modes (polarizations) of acoustic phonons: one (fast) longitudinal and two (slow) transverse phonons. At wavelengths much longer than the interatomic distances, all three modes are non-dispersive (phase and group velocities are independent of the momentum), typically up to hundreds of GHz. Hence, classical elastodynamics is sufficient to determine the phonon velocities.

To alter the phonon propagation, one can employ spatial confinement and modulation of the material. The former approach turns bulk acoustic waves (BAWs) into surface acoustic waves (SAWs) propagating in close vicinity of free surfaces (Rayleigh, Sezawa, and Love waves) or Lamb waves in free-standing slabs and membranes. The second strategy was successfully realized in Phononic Crystals (PnCs), i.e., synthetic materials with periodic modulation of elastic properties utilizing the wave-like nature of phonons. The structure of PnCs mimics the arrangement of atoms in natural crystals and results in phononic features typical for thereof. These are the appearance of the second-order Brillouin zones, modification of the phonon dispersion, zone folding, and...
Generally, the Notably, one has to give credit While In the last three decades, theoretical and experimental These experiments have to be realized in the geological in the configurations like inclusions and were further expanded in the point of view on the nature of phonons, their coupling with other elementary excitations, and their inseparable connection with the condensed matter. This paper presents an experimentalists’ point of view on the recent progress and prospects of PnCs. We present an overview of the advances in fabrication, experimental characterization, and new features for the broad spectrum of acoustic waves/phonons. The paper is organized as follows: first, we consider macroscopic PnCs aiming at the manipulation of sub-GHz waves (infrasound, sound, and ultrasound). Second, we focus on PnCs of a sub-micrometer feature size operating at GHz frequencies (hypersound). Third, we consider THz photon–GHz phonon coupling, both at sub-micrometer wavelengths, in periodic phononic–photonic crystals (phoxonic, optomechanical crystals). Fourth, we discuss the role of THz phonons as the heat carrier in periodically modulated structures. Finally, we cover recent advances and prospects of topological phononics in a broad spectrum of frequencies.

II. SUB-GIGAHERTZ PHONONIC CRYSTALS

Since the earlier works on sonic bandgap crystals, research on PnCs and acoustic metamaterials (AMMs) in the sub-GHz frequency spectrum is an active domain with promising applications. First, the technological advances in additive manufacturing (3D printing) offered a great solution to transfer many intricate theoretical designs into laboratory-scale structures. The challenges of practical applications can be resolved with auxetic metamaterials, acoustic metasurfaces, and tunable and multifunctional AMMs. In particular, widening the locally resonant bandgaps of periodic structures can improve the performance of seismic shields, ultrasonic waveguides, and other phononic devices. Sub-GHz phononics need a heterogeneous community to bring together the concepts of several scientific disciplines: device physics, geology, mathematics, civil engineering, electronics, and telecommunications, to name a few. Here, we address the possible directions of phononic materials research for manipulating seismic waves, sound, and ultrasonic waves with the feature size ranging from a few meters to micrometer scale, respectively. Theoretical PnC designs are out of the scope of this Perspective, and a detailed review on PnCs and AMMs can be found in other articles.

A. From infrasonic to ultrasonic designs

The practical size limitation of PnCs is enough to motivate locally resonant structures for ultra-low frequency applications. However, functional sub-wavelength scale PnCs need improvement regarding compactness, weight, and cost effectiveness. For example, a metamaterial consisting of few-meter-sized resonant structures (cylindrical mass in concrete slabs) can convert the seismic Rayleigh surface waves (RSWs) to shear BAWs that attenuate on the soil surface. Such locally resonant structures are widely used as seismic shields/insulators in the configurations like inclusions in the soil or buried mass resonators. Interestingly, AMMs are not strictly artificial. A forest of trees can act as a natural PnC [Fig. 2(a)] and offers large attenuation of seismic RSWs and shear waves (S-waves) in the broad frequency range below 150 Hz [Fig. 2(b)]. Graded vertical pillars arranged on an elastic substrate can block RSWs by reflecting them (classical wedge showing rainbow effect) or by converting them to BAWs (inverse wedge). These experiments have to be realized in the geological scale, and they involve designing tree wedges with height varying profiles and artificial vertical pillars for seismic protection. However, the potential of each design depends on the geometry of the structure and the viscoelastic properties of the soil. While numerous theoretical models of phononic structures in various geometries and dimensions are available, the experimental realization is still challenging. Fabrication methods experience several limitations in terms of low-cost raw material choice, minimum feature size, aspect ratios, or support requirements. Additive manufacturing technologies, including stereolithography, material jet printing, fused deposition modeling, and microlaser sintering/melting, make the design of 3D sonic PnCs much more feasible in the millimeter scale. Rainbow metamaterials are one of the best examples of structures with broad and robust sonic bandgaps. Such systems with lightweight structures were first observed in the context of optical waves and were further expanded to realize their acoustic analogs. Chen et al. have designed a gradient metamaterial beam for the enhancement of flexural waves. Disorder induced bandgap tuning has been studied using a 3D
FIG. 2. Sub-GHz phononic materials: (a) natural PnC made of trees and (b) filtering of seismic Rayleigh and S-waves. (c) 3D sonic rainbow metamaterial and (d) annular hole PnC. Waveguides made of (e) SiC–air PnC in a hexagonal lattice, (f) h-BN coupled resonator arrays, and (g) microlattice for ultrasonic transmission. (h) Pillar PnC arrays for (i) acoustofluidics and (j) acoustic diode. Tunable granular crystals: (j) macroscopic bead array of steel–aluminum spheres of millimeter size and (k) self-assembled 2D layer of polystyrene particles of 1 μm diameter and the schematic of the pump–probe experimental setup to probe the interactions between spherical particles contact resonances and propagating SAWs. (a)–(k) Reproduced with permissions from Colombi et al., Sci. Rep. 6, 19238 (2016). Copyright 2016 Springer Nature; Huang et al., Int. Soil Water Conserv. Res. 7, 196 (2019). Copyright 2019 Elsevier Ltd./iswcr; Meng et al., Sci. Rep. 10, 18989 (2020). Copyright 2020 Springer Nature; Ash et al., Nat. Commun. 8, 174 (2017). Copyright 2017 Springer Nature; Ghasemi Baboly et al., Appl. Phys. Lett. 112, 103504 (2018). Copyright 2018 AIP Publishing LLC; Wang et al., ACS Photonics 6, 3225–3232 (2019). Copyright 2019 American Chemical Society; Krödel and Daraio, Phys. Rev. Appl. 6, 064005 (2016). Copyright 2016 American Physical Society; Hsu and Lin, Sens. Actuators A 300, 111651 (2019). Copyright 2019 Elsevier Ltd.; Li et al., Phys. Rev. Lett. 106, 084301 (2011). Copyright 2011 American Physical Society; Kim and Yang, Funct. Compos. Struct. 1, 012002 (2019). Copyright 2019 IOP Publishing; and Vega-Flick et al., Phys. Rev. B 96, 024303 (2017). Copyright 2017 American Physical Society.
printed cantilever-in-mass design showing the wave trapping effect. This study revealed that mistuning in the design of the metamaterial can destroy its bandgaps. In some cases, irregularities in the design of PnCs can lead to wider bandgaps. For sonic rainbow PnCs [Fig. 2(c)], a nearly periodic system of cuboids connected by curved beams shows an attenuation bandwidth twice that of the periodic design of equal mass. Although 3D printing methods have revolutionized microscale structures with complex geometries, a large scale production strategy at low cost is still under development. 4D printing methods are the next game-changer, which may accelerate the scaling-up procedure from laboratory prototypes to large-scale devices. In addition, artificial intelligence (AI) based techniques, like topological optimization and machine learning, may lead to improved design methodologies.

Recently, soft AMMs were introduced to manipulate ultrasonic waves for applications like sub-wavelength imaging, acoustic lenses, and transformation acoustics. The design is based on sub-wavelength resonators suspended in an acoustic fluid. Such “soft-gel nature” offers a feasible step towards tunable and responsive AMMs that allows molding the metamaterial in the desired shape, size, and dimensions. 3D ultrasonic metalfluid with macroporous microbeads fabricated by soft matter techniques exhibited double negative acoustic impedances. The silicon rubber beads of mean radius 160 μm suspended in the water-based gel matrix act as Mie resonators showing strong monopolar and dipolar resonances. This approach can be exploited on large scale to produce zero or negative index materials for acoustic imaging applications.

Hierarchical architectures have been used to improve structural integrity and to minimize the amount of material. Several works have explored how the unit cell geometries, lattice material, and dimensions can tailor the phononic properties. A 3D microlattice [Fig. 2(g)] made by 2-photon lithography can exploit the ultrasonic wave propagation in water by elastoacoustic hybridization. The lattice design with truss-like elements (lattice constant about 70 μm) allows tailoring the HG that effectively attenuates the acoustic waves due to fluid interaction. A very high transmission (>80%) in the high frequency ultrasonic range (nearly 30 MHz) is observed outside this bandgap due to the impedance matching with that of water. This can be further used in biomedical imaging, where smaller penetration depth and higher resolution are important. These microlattices are scalable and can find use as resonators, acoustic insulators, and ultrasonic transducers.

Micro-electro-mechanical systems (MEMS) harnessing RF SAWs are important for signal processing and telecommunication. A standard design of SAW devices is a periodic array of etched holes. However, the bandgaps of such systems lie in the frequency range of leaky SAWs. In that sense, locally resonant (LR) structures in composite pillar arrays were used to open low-frequency LR bandgaps for SAW propagation. A finite depth annular hole PnC [Fig. 2(c)] analogous to the pillar architecture revealed potentially improved LR bandgaps. The uniform array of holes was fabricated in a lithium niobate (LiNbO₃) delay line using focused ion beam (FIB) etching. Moreover, the SAW attenuation has additional geometric freedom compared to the cylindrical pillar designs allowing tailorable SAW dispersions. This design can be exploited where strong acoustic confinement and miniaturization are indispensable. For example, a pillar PnC device [Fig. 2(h)] made of nickel pillars electroplated on the LiNbO₃ substrate achieved perfect scattering of standing SAWs (nearly 30 MHz). This generated strong acoustic radiation force and was exploited for concentrating and separating polystyrene microparticles. The annular hole PnC design can be exploited in SAW devices for microfluidics and further extended to different particle size combinations and biomolecules.

The introduction of defect modes in a periodic crystal can trap the acoustic energy. For example, inserting space gaps in a square array of cylindrical pillars improves the performance of demultiplexing and wave filtering. A 2D SiC–air PnC with circular inclusions produced waveguiding at 680 MHz allowing 39% transmission of the acoustic energy. Comparison of 90° bend and straight waveguides showed that curved paths produce additional losses. A coupled-resonator array [Fig. 2(f)] using hexagonal boron nitride PnC (fabricated by the integrative approach of dry exfoliation after FIB etching and patterning) supported the MHz wave propagation over an effective distance of 1.2 mm. The piezoelectric properties of this crystal, and van der Waals layered materials, can be explored further to generate tunable devices for RF applications. Recently, a virtual soft boundary based AMM design with resonant tube arrays allowed frequency separation keeping the flow of the medium unaffected. This method can be further explored to design complex functional waveguides and is also viable for microfluidic applications in the future. Waveguides suffer signal losses; future phononic devices have a significant role in achieving better confinement.

B. Tunable and active phononic structures

Granular crystals, ordered macroscopic beads [Fig. 2(j)] interacting via adhesion forces exhibited interesting wave propagation characteristics. From the experimental verification of “sonic vacuum,” these crystals demonstrated non-linear waves (solitons) with strong localization, discrete breathers, rotational elastic wave propagation, and several engineering applications as tunable wave filters, acoustic lenses, switches, and rectifiers. The flexibility in terms of size, shape, stiffness, and spatial orientation of solid particles in the lattice makes them easily tailorable for acoustic phenomena. In addition, tunability in terms of precompression transformed the wave propagation from a highly non-linear regime (with no compression) to a nearly linear regime (with precompression).

Self-assembling has enabled scaling down granular crystals to micrometer feature size large area/volume structures. In such systems [example in Fig. 2(k)], laser pump–probe experiments (transient grating technique) revealed a critical role of inter-particle and particle–substrate bonding due to adhesion in forming acoustic bandgaps for SAWs and Lamb waves. Notably, even disordered 2D granular crystals could effectively attenuate SAWs near their resonant frequency, serving as a perfect metamaterial for wave attenuation and filtering. Compared with commonly used pillar resonant structures, microgranular crystals are weakly adhered to the substrate. In this Perspective, the resonant frequency can be tailored by the inter-particle and particle–substrate contacts via temperature or hydrostatic pressure treatments below the glass transition temperature. A complex contact dynamics of SAW
attenuation was explained by Hiraiwa for tailored microspheres using scanned laser ultrasonics. The interparticle stiffness was modified via the deposition of a thin aluminum film over the monolayer, ultimately exhibiting horizontal-rotational contact resonances in addition to vertical resonances. This improved the attenuation regime opening additional bandgap at the lower resonances. Recently, splitting of the spheroidal contact resonance resulting from the symmetry breaking of the substrate was explained. These studies can lead to engineering of SAWs devices such as filters, sensors, and waveguides. In addition, advances in self-assembly enable scaling down to nanoscale dimensions, opening a broad horizon to manipulate wave propagation in the hypersonic regime (see Sec. III).

An important aspect of phononic materials, which broadens their potential applications, is tunability. Some examples are self-modulated metamaterials, Helmholz resonators, membranes, fluid-filled hollow pillars (whispering gallery modes), split ring resonators, piezoelectric materials, decorated membrane resonators (DMRs), and electromagnetic field controls. Some studies have also focused on flexible origami and kirigami-inspired cut and folded metamaterials. A waveguide designed for audible frequency proposed a broad working band and switchable sound propagation. Pentamode metamaterials having their rigidity maintained at the point contacts of elongated unit cells show that their bulk and shear nature is essentially decoupled. Several of such designs can be proposed by virtue of their richness in deformation modes. We also envision that bioinspired and natural PnCs and AMMs will become a more intensive field of study. Overall, the future of sub-GHz phononics is vested in active and reconfigurable structures.

III. HYPERSONIC PHONONIC CRYSTALS

The frequency of 1 GHz is the conventional boundary between ultrasound and hypersonics that can also be assumed in the description of PnCs. Due to their small feature size, which is typically less than 1 μm, the fabrication, experimental characterization, and applications of hypersonic PnCs differ significantly from those of sub-GHz PnCs. Hypersonic PnCs can be potentially useful for the development of high-frequency signal processing devices for wireless communications. Nowadays, the operational frequency of wireless communications is in the order of 1 GHz. The future front-end modules have to manage signals from a few to hundreds of GHz to reach the requirements of the next-generation wireless networks. For this purpose, hypersonic PnCs can be implemented as BAW, SAW, and Lamb waves filters, according to their architecture.

A. Hypersonic phononic crystals in various dimensions

Three-dimensional (3D) hypersonic PnCs allow tailoring of BAWs dispersion employing Bragg reflections and local resonances similarly to sub-GHz PnCs. To date, a vast variety of 3D PnCs were fabricated employing self-assembling of monodispersed submicrometer particles into colloidal crystals (CCs). As in the case of sub-GHz PnCs, the key advantages of CCs are their large volume, low cost, and low-effort fabrication, maintaining a high-quality translational order. Also, the forbidden range of frequencies can be adjusted by the NPs size and material and the material of the matrix.

The first experimental observation of GHz bandgaps was reported by Cheng et al. in solid/liquid PnCs. The structures were made of polystyrene (PS) nanoparticles (NPs) self-assembled into face-centered-cubic (fcc) CCs and infiltrated with various fluids. Notably, the observed BG (at about 5 GHz) offered some degree of tunability by the NPs size and the infiltrated fluid type. Figure 4(a) displays an example of a solid/liquid PnC that was fabricated from self-assembled PS NPs embedded in the polydimethylsiloxane (PDMS) matrix. The band diagram and transmission spectrum calculated for this material revealed both BG and HG. However, the experimental data confirmed only the former type centered at about 4 GHz. In addition to the geometry and material parameters, the phononic dispersion of CC PnCs can be tailored by bondings between the NPs. This effect and filtering due to the local resonances were reported for CCs made of silica NPs. For this material, femtosecond pump–probe technique revealed a long-living mode at 7.5 GHz matching the center of the calculated bandgap. It was demonstrated that the sintering of silica NPs could modify this stop band.

The reduction of CCs symmetry results in higher acoustic anisotropy of PnCs. This effect was observed for CCs fabricated from non-spherical NPs, i.e., nanoeellipsoids depicted in Fig. 4(b). In such PnCs, the phononic dispersion can be tuned by changing the NPs’ aspect ratio, which leads to unidirectional HG. The symmetry reduction of PnCs was also achieved by directional deformation of flexible solid/solid CCs. This was demonstrated for PS–PDMS CCs stretched along the [111] direction. In this case, the unidirectional expansion of about 17% resulted in the redshift of the BG. Notably, HGs were found as practically resilient to structural changes. Two-dimensional devices that require the performance of PnCs robust to large deformations. In a more general context, HGs are independent of the PnCs’ structural imperfections. A recent study has demonstrated a new approach for tunability of HGs in hybrid organic/inorganic PnCs through a complex structure of spherical NPs. The PnCs were composed of self-assembled PS brush-grafted silica NPs with elastic anisotropy across the silica core–polymer shell interface. The spectral position of HGs was adjusted within 5.5–10 GHz range by the degree of polymerization, grafting density, and NP core size.

Two-dimensional (2D) hypersonic PnCs have been utilized for altering the propagation of different types of SAWs or Lamb waves. Such systems were designed as 2D periodic patterns on the free surface of bulk or membrane and fabricated employing the bottom-up or top-down approach. The former method is based on large-area 2D CC, i.e., self-assembling of NPs into close-packed monolayers. Figure 4(d) displays 2D PnCs composed of a PS NPs monolayer deposited on a 50 nm thick Si3N4 membrane. For these systems, the measured and calculated phononic dispersion pointed to three distinct types of bandgaps for Lamb waves. Namely, they were related to the lattice period (BG), NP–membrane contact resonance (HG), and local resonances of NPs (HG). Notably, the latter type was found to appear in the sub-wavelength (below BG) and super-wavelength (above BG) regimes. The central
frequencies of all three types of bandgaps can be tuned by the particle size, membrane thickness, and adhesion at the NP–NP and NP–membrane interfaces.

The top-down fabrication requires more effort as typically it is based on electron beam lithography (EBL) and reactive ion etching (RIE). Here, one can distinguish two types of PnCs: solid/air and solid/solid differing in the periodic motifs. The former is realized by the substrate perforation (holes), while the latter by the periodic mass loading (pillars). Both of these schemes were exploited in the PnCs dedicated to the SAWs management. In this case,
FIG. 4. (a) 3D PnC made of PS spheres embedded in solid PDMS matrix and corresponding band structure. (b) 3D PnC realized of carboxylate modified PS nanoellipsoids. Phononic band diagrams for the propagation directions when $\alpha/b = 2.12$ (blue squares), $\alpha/b = 3.99$ (green diamonds), and for $\alpha/b = 1$ (black circles). (c) PS brush-grafted silica NPs assembly; dispersion calculated along (i) [111] shows non-degenerate longitudinal (dark solid lines), double degenerate transverse (light solid lines), and dead bands (dotted lines); (ii) [112] shows non-degenerate of mixed character and the flatband. Hybridization gaps LHG (for longitudinal modes) and HG (for all modes) are indicated with shaded areas. (d) 2D PnC composed of single layer PS nanoparticles self-assembled on a thin Si$_3$N$_4$ membrane and related dispersion relation.

(e) Solid–air and solid–solid 2D PnC fabricated by making a pattern of holes and pillars in/on a thin Si membrane, respectively. (f) Optical image of the device showing a ribbon of the SAW PnC between emitter and receiver (top). SEM image of the cross section of 2D pillar-based SAW-PnC structure (bottom). (g) SEM images of 2D PnC with ordered (top) and disordered pattern of holes (bottom) in Si membrane. (h) Bragg structure made of periodically altering layers of Si with different porosity (left) and quasi-periodic Fibonacci structure (right) formed by stacking layers according to Fibonacci sequence. (i) 1D SAW PnC realized by rectangular-like periodic grooves on the (001) surface of crystalline silicon. In (a)–(d), the experimental dispersion relations (full/open points) were measured by Brillouin light scattering and calculated by finite element method (FEM). Panel (a) shows a calculated transmission spectrum. (a)–(i) Reproduced with permissions from Zhu et al., Phys. Rev. B 88, 144307 (2013). Copyright 2014 American Physical Society; Beltramo et al., Phys. Rev. Lett. 113, 205503 (2014). Copyright 2014 American Physical Society; Alonso-Redondo et al., Nat. Commun. 6, 8309 (2015). Copyright 2015 Springer Nature; Graczykowski et al., Nano Lett. 20, 1883–1889 (2020). Copyright 2020 American Chemical Society; Graczykowski et al., Phys. Rev. B 91, 075414 (2015). Copyright 2015 American Physical Society; Dehghanniaei et al., Phys. Rev. Appl. 10, 064019 (2018). Copyright 2018 American Physical Society; Wagner et al., Nano Lett. 16, 5661–5668 (2016). Copyright 2016 American Chemical Society; Aliev et al., J. Appl. Phys. 116, 094903 (2014). Copyright 2014 AIP Publishing LLC; and Graczykowski et al., Appl. Phys. Lett. 104, 123108 (2014). Copyright 2014 AIP Publishing LLC.
the frequency stop bands were detuned, in addition to the lattice spacing, by the geometric parameters, i.e., size and shape of holes and pillars and by solid or liquid inclusions. Figure 4(e) illustrates two examples of PnCs, i.e., solid/air and solid/solid fabricated from 250 nm thick Si membrane. The solid–air PnC revealed BG for all types of Lamb waves and BG for symmetric modes, both about 13 GHz. The band diagrams of solid–solid PnC showed apparent hybridization of local resonances of pillars with propagating waves in the membrane, albeit HG was not detected. Overall, 2D PnCs offer a versatile platform for manipulation of confined (SAW and Lamb) acoustic signals in the GHz regime, which can be utilized in wireless communication devices. For example, PnC made from the periodically etched silica film on a quartz substrate was demonstrated at a 1.25 GHz one-port Love waves resonator. In addition, recent work reported piezoelectric and CMOS-compatible pillar-based PnCs [Fig. 4(f)]. The experimentally measured transmission spectra revealed a 150 MHz wide SAW bandgap with the central frequency at about 1.65 GHz.

Both for top-down and bottom-up approaches structural imperfection is an unavoidable issue. Nevertheless, the deviation from the ideal translational order of the lattice can lead to new phononic features. In particular, the disorder can destroy the coherent effects as it was experimentally proved for the example of holey Si membrane illustrated in Fig. 4(g). Also, theoretical studies revealed that the disorder could result in bandgap broadening and acoustic Anderson localization in PnCs. Undoubtedly, both works deserve experimental verification in the near future.

One-dimensional (1D) hypersonic PnCs are relatively less complex structures than previously discussed 2D and 3D PnCs. However, they can offer distinct phononic behavior for BAWs, SAWs, or Lamb waves propagating parallel or perpendicular to the periodicity. In practice, 1D bulk PnCs are superlattices (SLs), i.e., stacks of periodically alternating layers of different elastic impedances. 1D PnCs are straightforward systems, which can host both phononic and photonic bandgaps. The first direct measurement of the hypersonic phononic bandgap in SiO₂/PMMA SLs was reported by Gomopoulos et al. The Brillouin light scattering (BLS) results revealed that the BG in such PnCs could be altered through the porosity of SiO₂ layers. The lattice imperfections, defects, or aperiodicity were investigated experimentally in terms of new phononic effects. The defects were investigated by probing the acoustic transmission and dispersion relation (BLS). Going further, the aperiodic (quasiperiodic) 1D Fibonacci SLs were studied employing acoustic transmission and femtosecond pump–probe spectroscopies. In this case, the aperiodic structures were found as better acoustic filters than their ordered counterparts. In the case of the lattice disorder, acoustic Anderson localization was predicted theoretically for GaAs/AlAs SLs. The propagation of SAWs in surfaces periodically corrugated in one dimension was theoretically studied already in the 70s. The recent experimental realizations of hypersonic 1D SAW PnCs were examined by BLS and pump–probe experiments. This system revealed hypersonic filtering due to BG in the direction perpendicular to the grooves, while along the grooves, it worked as a waveguide for Lamb waves confined in the stripes. Recently, 1D gourd-shape PnC tethers showed reduced anchor losses and improved quality factor for Lamb wave resonators in the GHz range. This single-chip system can be potentially explored for applications for wireless communication devices.

B. Metamaterials made of low-dimensional nanostructures

The PnCs mentioned so far have their bandgaps centered around 1–20 GHz. To achieve higher frequencies (~100 GHz to 1 THz) the PnCs need to have smaller feature sizes, i.e., in the order of tens to few nanometers. This downscaling implies a major challenge for standard nanofabrication techniques. Potentially, smaller PnCs can be assembled by low-dimensional materials like nanoclusters or quantum dots (0D), nanotubes or nanorods (1D), and graphene-like materials (2D).

0D building blocks for nanodevices (e.g., quantum dots of chalcogenides and perovskites) have been widely studied due to their potential applications in optoelectronic devices, light-emitting diodes, photodetectors, and solar cells. Notably, 0D structures of chalcogenides like CdSe, CdS, and PbS can self-assemble and form CCBs. The available literature is comparably extensive for colloids based on perovskites such as mixed-halide nanocrystals and organometal halide perovskites. More information on semiconducting colloids can be found in previous reviews. Such systems have already been considered for the construction of photonic crystals. In comparison with photonics, the application of 0D semiconductors in phononic devices is limited. However, acoustic phonons and various other structural motions affect the electronic states and optical properties of chalcogenide and perovskite colloids and crystals. Regarding extrinsic interactions, scattering of SAWs on supported quantum dots can modify their energy levels. This interaction enables various interesting applications at the interface of phononics and optoelectronics, which involve control of semiconducting quantum dots with SAW devices. Based on all the above, CCs made of 0D semiconducting nanostructures represent a new type of phononic metamaterial that deserves additional experimental investigations—see the work of Yazdani et al.

While the formation of CCs relies on the spontaneous behavior of 0D nanostructures (self-assembly), the synthesis of metamaterials out of 2D nanostructures can be more controlled. For instance, 2D PnCs can be fabricated by pattering transition metal di-chalcogenides (TMDs) in the form of thin membranes. This means that their atoms are arranged in 2D layers held together by weak vdW bonds. Hence, various TMDs, like MoS₂, MoSe₂ and WS₂, can be prepared in the form of ultrathin membranes. The thickness of TMDs can be as small as one layer using liquid exfoliation or mechanical exfoliation from the bulk. In order to employ these materials as 2D PnCs, it is necessary to introduce periodic patterns. This can be achieved in various
ways. For instance, Yun et al. created nanopatterns on supported MoS$_2$ by block copolymer lithography. Munkhbat et al. created TMDC metamaterials with a three-step process: (i) transfer of mechanically exfoliated TMDCs on a desired substrate, (ii) use of nanopatterning techniques like EBL, RIE, or focused ion beam (FIB) and (iii) anisotropic wet etching [Fig. 5(b)]. This approach offers perforated TMDCs (like WS$_2$, MoS$_2$, and MoSe$_2$) with nearly atomically sharp zigzag edges. Moreover, FIB can be used to introduce single-atom defects/holes in free-standing monolayer TMDCs. Kozubek et al. used highly charged ions to drill well-defined pores in free-standing MoS$_2$ with sizes of several nanometers. Irradiation with He$^+$ has also been used to perforate free-standing TMDCs (MoS$_2$). Additionally, linear patterning of TMDCs can be used to prepare metamaterials with grooves. Zhang et al. moved a step further and demonstrated atomically thin photonic crystals made of square arrays of holes on free-standing WS$_2$. The system will act as a 1D superlattice normal to the layers and as a 2D metamaterial parallel to them.

The use of low-dimensional nanomaterials to construct novel PnCs will introduce new challenges for experimental and theoretical studies in photonics. Widely adopted experimental techniques like BLS, pump–probe measurements, Raman, x ray, and neutron scattering will have to deal with the poor signal-to-noise ratio due to the small dimensions of the samples. Spectroscopic techniques based on inelastic light scattering (for instance, spontaneous BLS) will be limited by the opaqueness of the samples and the high frequencies (small thermal occupations) of acoustic phonons. Moreover, the confined acoustic phonons are expected to be affected by various microscopic couplings that need to be measured. For instance, the use of metallic, semiconducting, or magnetic nanomaterials will enable couplings of acoustic phonons with plasmons, electron–hole pairs, and magnons. We believe that many of these challenges can be addressed with pumped-BLS, a recently developed hybrid technique that combines ultrafast photoexcitation of confined acoustic phonons with BLS detection in frequency-domain. This technique offers 100-fold amplification of BLS signal from semiconducting nanomembranes and reveals interactions of acoustic phonons with charge carriers—see Vasileiadis et al. for further details.

**IV. OPTOMECHANICAL CRYSTALS**

Optomechanical (OM) coupling is based on the commensurate wavelength of GHz phonons and electromagnetic radiation for telecommunications. The most important platforms for micro-electronics and photonics, such as silicon and silicon nitride, allowed the demonstration of OM coupling in micrometer size cavities. OM coupling exploits co-localization of phonons and photons to maximize the energetic exchange between them. This paves the way for manipulating the phonon population in various ways. For instance, using OM coupling it is possible to decrease the average population below 1 in selected modes (ground state cooling—red detuned light excitation) or to generate amplified...
coherent phonon emission\textsuperscript{183} (blue detuned light excitation and phonon lasing). In the same kind of cavities, other schemes exploit optical free carrier generation and thermal dynamics to generate self-sustained amplified phonons at lower frequencies.\textsuperscript{184}

Optomechanics is a huge research field with a plethora of promising applications in telecommunications and sensors (e.g., memories\textsuperscript{185} and accelerometers\textsuperscript{186}). It has a long term vision in quantum computation exploiting coherent phonon manipulation\textsuperscript{187} and in topological phonon propagation with OM as driving effect.\textsuperscript{188} In this direction, plenty of efforts have been devoted to increasing phonon lifetime by shielding the structures from the sources of dephasing. This can be achieved either by surrounding the OM cavities with a structure that has a phonon bandgap or with appropriately selected unit cells that provide their own bandgap in 1D\textsuperscript{190} [Fig. 6(a)] and 2D\textsuperscript{191}.

In particular, self-driven OM oscillators are ideal building blocks for exploring the collective dynamics of networks of coupled oscillators\textsuperscript{192,193}. The observation, control, and exploitation of collective phenomena such as synchronization can find various applications. Some examples are neuromorphic computational platforms, on-chip robust time keepers, and sensors of mass, gas, or force with extremely low phase noise. Experimental observation of synchronization phenomena in pairs of coupled OM oscillators\textsuperscript{193,194} has been already reported and scaling up the number of coupled oscillators will not increase substantially the technological requirements.

We center now our attention to the capability of OM systems for ultrasensitive sensing of mechanical wave propagation using light (transduction), which is essential to build circuit functionalities using phonons. This can be done by placing an optomechanical transfer gate, in the form of an integrated optomechanical cavity\textsuperscript{195} or by visualizing the movement of an antenna-like mechanical resonator coupled to propagating phonon modes.\textsuperscript{196} In the latter case, the phonon modes are visualized by analyzing the modulation of a reflected beam. This capability is particularly technologically relevant as it is currently being extended to bridge the transfer of information between microwaves, electrically and optically modulated signals in an energy efficient way. Hybrid systems, including piezoelectric and optomechanical systems, report the highest yields in the GHz regime at modest power dissipation. Using the standard LiNbO\textsubscript{3} platform\textsuperscript{197} [Fig. 6(b)], we can cover a crucial demand of our information society to build efficient transceivers for the huge data centers that operate nowadays. In such systems, a microwave signal incident on an Interdigital Transducer (IDT) is converted to a propagating phonon that is guided toward an OM cavity. In the OM cavity, the phonon modulates an optical signal. This process is bidirectional: a modulated optical signal injected in the circuit can excite mechanical motion in the OM cavity, which is then guided toward the IDT to generate a microwave signal.

To make these systems more compact, various works explored other mechanisms of efficient GHz phonon generation that can replace IDTs. The first proof-of-concept experiment\textsuperscript{189} where GHz phonons are generated in an OM cavity routed by phononic waveguides and transduced back to the RF signal by another OM cavity, have been followed by studies to increase phonon lifetime. Efforts to minimize phonon waveguide losses have exploited phononic bandgap acoustic shielding,\textsuperscript{198} engineering of elastic strain,\textsuperscript{199} and topologically protected edge states.\textsuperscript{200}

V. THERMAL TRANSPORT

Phonons are the primary heat carriers in solid dielectrics and semiconductors. According to Bose–Einstein statistics, at room temperature (RT), phonons of frequencies up to several THz are excited.\textsuperscript{201} Notably, this broad-spectrum contributes to the transport of the vibrational energy and can be effectively tailored by the spatial nanoconfinement.\textsuperscript{202–205} The recent remarkable progress in the field of the nanoscale thermal transport has proven the breakdown of Fourier’s law in spatially confined systems. Some examples of phenomena that go beyond the classical description of heat transport are strong suppression of the phononic thermal conductivity, wave-like propagation of heat, observation of the second sound in solids at moderate temperatures, thermal cloaking, and focusing and rectification.\textsuperscript{206} Nowadays, it is clear that confinement of thermal phonons in the micro- and nanoscale offers fascinating features and challenges in their transfer to the mainstream technology applications. In the following, we first distinguish between coherent and incoherent effects in thermal transport, and then we discuss the potential of thermal phonon management for applications like thermoelectrics and controlled heat transport in devices.

A. Coherent and incoherent effects

To explain the basic concepts of nanoscale thermal engineering, we recall the kinetic theory, which defines the phononic thermal conductivity as

\[ \kappa = C v g \Lambda \]

Here, \( \kappa \) is the heat capacity, \( v_g \) denotes the average group velocity, and \( \Lambda \) stands for the mean free path (MFP) of phonons. The latter parameter is an average distance traveled by a phonon between two scattering events, which can occur on impurities, imperfections, phonons (umklapp), electrons, and boundaries.\textsuperscript{3,21,207} Notably, this much-simplified
description allows for a good estimation of thermal conductivity for various materials. Furthermore, it points to phonon MFP and group velocity as being essential to alter the thermal conductivity. The research from the last decade has revealed that both of these quantities can be modified using PnCs with sub-micrometer feature size.\textsuperscript{21,206–222} Indeed, shortening of the phonon MFP can result from imperfections between periodic motives and the matrix constituting PnCs. In this case, the interface roughness is comparable with the wavelength of thermal phonons. Thus, thermal phonons behave like particles that are diffusively scattered on the interfaces. As the phase is not preserved, this phenomenon is referred to as the incoherent effect.\textsuperscript{21,211,212}

The second-order periodicity of PnCs alters the phonon dispersion relation, which implies reduced $v_g$, altered DOS, and under certain conditions, phononic bandgaps.\textsuperscript{21,206–222} This approach utilizes the wave nature of phonons, and it requires both specular reflections from interfaces and MFPs of phonons (more rigorously phonon coherence length) that are at least a few times longer than the PnC periodicity. This phenomenon is referred to as the coherent effect in the literature, while PnCs are termed thermocrystals.\textsuperscript{21,212} Unambiguous experimental evidence for the coherent heat conduction, thermal phonon localization, and crossover from coherent and incoherent regimes was demonstrated for 1D PnCs (superlattices). Notably, such phenomena to be observed at room temperature require structures of dense and atomically smooth interfaces.\textsuperscript{215–217}

The dual, wave-particle nature of thermal phonons in 2D PnCs is a topic of ongoing widespread debate. Numerous works have reported reducing phononic heat conduction in membranes of periodic porosity with respect to the pristine membrane. The controversial issue that has arisen is the contribution of coherent effects near room temperature in PnCs with lattice parameter greater than 100 nm.\textsuperscript{214,206–208,211,212,213,214,217,227,228} In this case, the relevant PnCs were made using electron beam lithography (EBL) and reactive ion etching (RIE) or focused ion beam (FIB) milling (see examples in Fig. 7). Both approaches allow the fabrication of holes with roughness of few nanometers, in the best scenario, and amorphization.\textsuperscript{210,208,211} To date, a real demonstration of the coherent effects was only possible at few Kelvin and sub-Kelvin temperatures exceeding 500 K remain primarily unexplored area due to experimental challenges. Thus, novel tools based on, most likely, contactless approaches are needed (Fig. 7(b)).

As follows from theoretical works, local resonances can be an alternative approach for thermal phonon blocking in 2D PnCs. In this concept, PnCs consist of a 2D array of pillars deposited on the membrane. In this structure, the hybridization between localized modes in pillars and propagating modes in the membrane results in sub- and super-wavelength bandgaps that are immune to the PnC lattice’s imperfections.\textsuperscript{233,234} Besides that, typical phononic effects can appear due to the periodic arrangement of pillars. Consequently, phonon group velocity, DOS, and hence thermal conductivity can be tuned (in addition to lattice spacing) by the characteristic sizes and mass of the pillar. The modification of the dispersion in these structures was confirmed experimentally for GHz phonons employing BLS.\textsuperscript{235} However, the importance of coherent effects on the thermal conductivity has been recently questioned based on the experimental results obtained in the 4–300 K range.\textsuperscript{229,236}

B. Perspectives and applications

Further development of PnCs dedicated to the management of thermal phonons can result from application-oriented directions such as thermal energy harvesting, extreme temperatures and gradients, effective heat dissipation, geometry engineering toward ray-like heat transfer, the synergistic combination of conduction with convection or radiation, and thermal rectification, new materials as platforms for PnCs, and materials hosting other elementary excitations being, in addition to phonons, heat carriers.

The reduced thermal conductivity in 2D porous PnCs holds great potential for applications in thermal energy harvesting, sensing, and heat flow management.\textsuperscript{236} In particular, crystalline porous Si membranes can be used to realize Slack’s “phonon glass–electron crystal,” i.e., hypothetical material of maximized thermoelectric (TE) figure of merit $ZT$.\textsuperscript{230} Hence, the perfection leading to $\kappa$ as low as the amorphous limit has to maintain the electronic properties. The latter can be further engineered by doping toward an optimized electronic power factor. Yet, recent works have reported TE generators made of porous Si membranes with $ZT \ll 1$ around RT, which is significantly less than what is offered by conventional materials.\textsuperscript{210,213,214,229} However, Si PnCs are CMOS-compatible and therefore can be easily implemented in mainstream technology. For instance, the upcoming market of the Internet of Things can benefit from cheap and robust self-powered units or sensors based on such structures.

Furthermore, silicon and silicon on insulator (SOI) technologies are the most mature for producing micro- and nanoscale devices dedicated to high-temperature applications.\textsuperscript{231} The high temperature is a considerable value market for thermal sensing and energy harvesting in the automotive, airspace industry, space exploration, metallurgy, and conventional energy production.\textsuperscript{232} Besides a few recent works,\textsuperscript{206,217} thermal properties of PnCs at temperatures exceeding 500 K remain primarily unexplored area due to experimental challenges. Thus, novel tools based on, most likely, contactless approaches are needed (Fig. 7(b)).
Fig. 7. (a) SEM images of the Si PnCs fabricated in a suspended architecture for thermal reflectance measurement. (b) SEM image of a (left panel) periodic Si nanomesh with a period of 100 nm and (middle panel) an aperiodic Si nanomesh with the pitch varied from 80 to 120 nm. Scale bars are 200 nm (inset) and 600 nm (main). (right panel) Measured thermal conductivities of periodic and aperiodic nanomeshes as a function of temperature indicate the negligible role of the coherent effects. (c) One- and two-phonon Raman spectra of pristine 250 nm membrane without and with pores obtained at room temperature. The critical points of the first Brillouin zone are identical for both samples. (d) Thermal conductivity of porous membranes at 300 K as a function of the surface-to-volume ratio. (e) SEM images of (left upper panel) converging and (right upper) diverging thermal lens samples with slits for heat dissipation. The scale bar is 1 m. Monte Carlo simulations results of (bottom left) the formation of a hot spot in the focal point and (bottom right) dispersion of heat in the diverging lens. (f) TEM and SEM images of 20 nm-high nanopillars fabricated on 50 nm-thick silicon membranes. (g) A scheme and SEM image of a metalattice made of a closely spaced distribution of spherical voids in crystalline silicon. (h) From left to right: SEM images of the thermal rectifiers in the forward and reverse configurations, schematics of the two-laser Raman thermometry experiment, temperature profiles of the test devices in the forward (solid purple circles) and reverse (red-outlined circles) configurations, schematics of possible devices based on the thermal rectifier. Reproduced with permissions from Lee et al., Nat. Commun. 8, 14054 (2017). Copyright 2017 Springer Nature; Takahashi et al., Nano Energy 71, 104581 (2020). Copyright 2020 Elsevier Ltd.; Anufriev et al., Nat. Commun. 8, 15505 (2017). Copyright 2017 Springer Nature; Huang et al., ACS Appl. Mater. Interfaces 12, 25478–25483 (2020). Copyright 2020 American Chemical Society.
Recently, Anufriev and Nomura have proposed a concept of ray phononics utilizing ballistic heat transport in porous membranes. Such materials are envisioned for ray-like heat flow management in nanostructures regardless of their surface imperfections and foremost possible at room temperature. The proof-of-concept experiments have proved features like thermal phonon guiding, emission, and focusing [Fig. 7(e)].

Needless to say that wealth of new features resulting from the phonon confinement go hand in hand with technological challenges. Indeed, the progress of miniaturization and electronic devices’ performance in the last two decades has encountered a bottleneck related to the efficient removal of the produced heat. Thus, both size-reduced thermal conductivity and volume can lead to overheating and eventually damage of nanoscale devices. Porous membranes can be an effective and low-cost solution to this problem, which utilizes passive cooling units via air convection.

Simultaneously, the vast majority of previous thermal studies of porous membranes were performed in vacuum conditions. However, convection in porous membranes deserves more attention regarding the real conditions for their operation and possible application in passive cooling. As follows from recent experiments, the heat dissipation via combined convection and conduction can be optimized via the structure surface-to-volume [Fig. 7(d)] ratio.208,219

The enhancement of the heat dissipation in nanostructured membranes (depending on the material) can be seen in less obvious elementary excitations such as surface phonon-polaritons (SPhPs), magnons, or plasmons. Wu et al. have demonstrated that the thermal conductivity of sub-50 nm thick Si3N4 membranes doubles as the temperature increases from 300 to 800 K due to SPhPs.227 In this Perspective, new architectures of PnCs can primarily benefit from a synergetic combination of dielectric or semiconducting membranes with metallic and magnetic layers or nanostructured motives. In particular, the emerging fields of spin caloritronics234,240 and the intersection between plasmonics and phononics240 are attractive directions for further developing the nanoscale thermal transport in periodic structures. Another and quite natural step forward can be the fabrication of macroscopic 3D PnCs for thermal flow management using self-assembled colloidal crystals,241,242 metalattices,243 or atomic quality hybrid (organic-inorganic) Bragg stacks.244 Notably, the aim of the latter materials is, contrary to the majority of PnCs, to enhance the thermal conductivity to remove process heat in organic electronics preserving transparency and flexibility.

One of phononics’ main ambitions is to use heat as the information carrier and develop thermal analogs of diodes, transistors, and electronics switches.4,243–249 The fundamental requirements for a thermal diode (or rectifier) can be satisfied by porous membranes. Namely, they offer temperature dependence of the thermal conductivity (non-linearity) and space dependence (spatial asymmetry) of the thermal conductivity. Practical realization of thermal rectification was reported for perforated graphene (26% efficiency at RT)246 and recently for Si membrane. The latter structure (14% efficiency) is dedicated to operation at high temperatures up to 1000 K and can also be utilized as a thermal switch or optimized convective cooler [Fig. 7(b)].219

Overall, the future of PnCs requires new platforms that can host phononic effects and introduce new physical and chemical features. From this Perspective, an excellent opportunity is the wealth of van der Waals materials, and their heterostructures offer unique, highly anisotropic, and size-dependent electronic, optical, thermal, and mechanical properties.142,247–249 Nevertheless, this requires a significant advancement in the fabrication of robust large area samples and experimental tools development.

VI. TOPOLOGICAL PHONONICS

A. From symmetry to topology

Up to this point, we discussed phononic metamaterials whose properties depend solely on the crystal symmetry and are strongly affected by defects and disorder. The relevant transport phenomena are characterized by losses, left–right symmetry (parity, P), and time-reversal symmetry (T) and/or principles of thermodynamics. This section presents a novel type of metamaterials, termed topological phononics, which offers robustness to disorder, one-way propagation of phonons (broken P or T symmetry) and transport without losses. In most cases, the different phases of condensed matter are adequately characterized by distinct symmetries, and a symmetry-related order parameter describes the passage from one phase to another. However, it is possible to observe phases of matter that do not depend on the sample’s size, shape, composition, and impurities. The unique identification of such phases requires some topologically invariant property, meaning a property that remains constant under continuous transformations.

Topology has first entered the realm of experimental, condensed matter physics in 1980 with the discovery of the Quantum Hall Effect (QHE) by Von Klitzing et al.250 The QHE is the quantized Hall conductance of a two-dimensional (2D) electron gas in a strong magnetic field and at low temperature. Subsequent studies revealed several more types of topological phenomena for electrons and spins in crystals. For instance, in the Quantum Spin Hall Effect (QSHE) the spin Hall conductance of 2D crystals is quantized due to spin–orbit coupling without a magnetic field. Another relevant electronic degree of freedom is the valley, i.e., the bands extreme that the electrons occupy, which gives rise to the Quantum Valley Hall Effect (QVHE). The observation of topological phenomena in three-dimensional (3D) crystals gave rise to the so-called topological insulators.251–263 In these materials, the topology of the bulk states is distinct from that of the surrounding vacuum, leading to the creation of unique, conductive surface states. Dirac semimetals are insulating in the 3D bulk and have 2D surface states with Dirac cone dispersion.265 Weyl semimetals have topologically protected Dirac cones in the 3D bulk, and surface states with unique, arc-shaped dispersion.266–269 Additionally, Floquet topological insulators have conductive surface states due to external, periodic, temporal perturbations260,261. From the perspective of basic science, topological condensed matter systems can be used to perform tabletop experimental studies of exotic particles that remain unobserved in nature, like magnetic monopoles,262–264 as well as Dirac and Weyl fermions.255

The first experimental realization of topological phenomena for classical waves and metamaterials occurred in 2009 by Wang et al.265 who demonstrated a topological photonic metamaterial operating in GHz frequencies (microwave radiation). The readers can find more information about topological photonics in the
review articles of Lu et al. and Ozawa et al. The first topological acoustic metamaterial was realized by Fleury et al. in 2014. This acoustic crystal consisted of ring resonators, where left-handed and right-handed modes were initially degenerate. The degeneracy was then removed with a biasing airflow, leading to one-way transport of sound. Topological phononics have been discussed in a number of previous review articles. Here, after a short introduction, we emphasize the novel topics of 1D topological phononics, higher-order topological insulators, and programmable topological phononics. Next, we discuss how the various macroscopic designs can be re-adapted for topological nanophononics in the gigahertz (GHz) frequency range. We conclude this section with a proposal on studying low-dimensional, topological nanophononics in the GHz range, using a recently developed combination of Brillouin spectroscopy and ultrafast photoexcitation.

B. Topology for condensed matter physics

In the band structure theory of insulators, topology is used to examine if one insulator can be smoothly transformed into another. If this is not the case then a topological phase transition must occur at their interface leading to the creation of spatially non-zero Chern number. For plane waves or vacuum, the Berry curvature field through the Brillouin torus. To achieve interband transitions, we emphasize the novel topics of 1D topological phononics.

In one-dimensional (1D) phononic crystals, topological edge states are localized oscillations without transport. Topological properties in 1D can arise due to some spatial modulation, e.g., of losses. Fig. 8(b). The topological acoustic crystal of Gao et al. [8(c) left] has a bulk spectrum that is depleted at ~2150 Hz [Fig. 8(c) center], while the edges’ spectrum has a maximum at the same frequency [Fig. 8(c) right]. Additionally, 1D phononic crystals have been shown to possess interfacial states (states between topologically distinct insulators) and Weyl particle physics.

Since most of the relevant topological physics requires spin-dependent phenomena, several studies of acoustics explored acoustic pseudo-spin, acoustic QSHE, and acoustic analogs of spin-multipoles. Pseudo-spin-dependent transport was shown to be robust and to possess transmission without backscattering—see, for instance, Refs. 288 and 289. Pseudo-spin states can be formed in the presence of double Dirac cones. Double Dirac cones have been introduced in various ways, e.g., with zone-folding in a triangular lattice of rods, or with 2D arrays of Helmholtz resonators, or with local resonance states. Twofold Dirac point degeneracy appears for graphene-like phononic crystals and more complicated structures, like 2D kagome and Kekulé lattices. In the case of 2D square lattices, the Dirac cones can appear away from the high-symmetry points of the band-structure—a phenomenon described as accidental degeneracy. Moreover, 2D sonic crystals have been used to realize acoustic Floquet topological insulators. Notably, topological properties in 2D (or quasi-2D) systems can also arise from water surface waves.

Regarding 3D systems, He et al. showed that topological valley states can emerge at the interface of two crystals with opposite valley Chern numbers. Other studies using 3D metamaterials have demonstrated acoustic analogs of Weyl and Dirac semimetals, negative refraction, acoustic quadrupole and octupole topological insulators, and topological properties in granular metamaterials. Moreover, Peng et al. have demonstrated 3D Floquet insulators, using a periodic, spatiotemporal modulation in a sonic crystal. Very recently, Fu et al. have studied sound vortices in 3D cylindrical waveguides and demonstrated diffraction of sound that depends on the value of the topological charge. In relevance with sound vortices, helical-acoustic metamaterials can be used for dispersion-free deceleration of sound and can potentially be useful for topological acoustic metamaterials.

A special type of topological materials termed higher-order topological insulators support edge states that are two or more dimensions lower than the bulk states. For instance, in a third-order topological insulator, some of the states are confined
FIG. 8. Topological acoustics in 1D and 2D: (a) Rotatable three-legged-rods used to create spinning acoustic fields (up) and a topological phase transition of these acoustic pseudospin states (down) from Zhang et al.\textsuperscript{276} Copyrights obtained from 2018 American Physical Society. (b) Schematic of a 1D acoustic lattice with topological properties arising from spatial modulation of losses. Copyrights obtained from 2020 American Physical Society. (c) Image of the sample (left), acoustic resonances inside (center) and at the edges (right) of a structure studied by Gao et al.\textsuperscript{277} Copyrights obtained from 2020 American Physical Society. (d) Design of a second-order, 2D topological insulator,\textsuperscript{280} (e) its unit cell, (f) illustration of the boundaries between trivial and nontrivial topological regions, (g) diagram of the topological phase transition through band inversion, (h) VDOS for corner, edge and bulk states and (i) programmable patterns of acoustic fields. Tunable topological acoustics and applications: (j) Programmable 2D topological acoustic crystal controlled by pressurized air,\textsuperscript{281} (k) tunable 2D topological acoustic crystal using liquid infiltration,\textsuperscript{282} (l) acoustic delay line based on a tunable topological acoustic crystal,\textsuperscript{283} (m) directional emission of sound using topological acoustics.\textsuperscript{284} (a)–(m) Reproduced with permission from Zhang et al., Phys. Rev. Appl. 9, 034032 (2018). Copyright 2018 American Physical Society; Gao et al., Phys. Rev. B 101, 180303 (2020). Copyright 2020 American Physical Society; Zhang et al., Adv. Mater. 31, 1904682 (2019). Copyright 2019 John Wiley & Sons, Inc.; Xia et al., Adv. Mater. 32, 1805002 (2018). Copyright 2018 John Wiley & Sons, Inc.; Tian et al., Nat. Commun. 11, 762 (2020). Copyright 2020 Springer Nature; and Zhang et al., Adv. Mater. 30, 1803229 (2018). Copyright 2018 John Wiley & Sons, Inc.
on the corners (0D) of a 3D crystal.113 Zhang et al.280 have demonstrated a second-order, 2D topological insulator, whose structure and properties are illustrated in Figs. 8(d)–8(i). Its unit cell [8(e)] consists of four drilled holes; the yellow and the blue parts are the rigid materials and the air, respectively. This 2D crystal is split into two regions with trivial and nontrivial topological properties [Fig. 8(f)] by varying the ratio of the distance between holes R over the lattice constant a. Using finite element method (FEM), the authors have visualized the pressure distributions in the trivial and nontrivial regions and illustrated a band inversion from p- to s-like “conduction” states and from s- to p-like “valence” states [Fig. 8(g)]. The vibrational density of states [Fig. 8(h)], which was recorded using a loudspeaker and a microphone, shows 2D bulk states, 1D edge states, and 0D corner states, thus proving the second-order character of this topological acoustic crystal transport.

D. Programmable topological phononics and applications

Macroscopic metamaterials offer the possibility of real-time and on-demand structural changes. Thus, it is possible to control the topological properties in versatile, uncomplicated ways, and to construct smart devices for sound manipulation. For example, Zhang et al.280 generated programmable patterns of acoustic fields [Fig. 8(i)]. Xia et al.284 have developed honeycomb-lattice sonic crystals that can be reconfigured with air cylinders [Fig. 8(j)]. Using this design, the authors managed to control the path followed by the edge states between two topologically distinct phases [Fig. 8(j)] bottom]. Tian et al.285 have realized a tunable, sonic honeycomb lattice by infiltrating liquid in its holes [Fig. 8(k) top], which was again used to control the path of edge states [Fig. 8(k) bottom]. Zhang et al.276 constructed a hexagonal array of rotatable, three-legged elements [Fig. 8(l) top] that could be used as a phononic delay line [Fig. 8(l) bottom]. A prominent application of topological manipulation of sound is the construction of directional loudspeakers and microphones.285,314 [Fig. 8(m)]. Regarding prospects, another exciting class of devices (which have not been experimentally realized at the moment for phononics) are one-way, topological, beam splitters.315–318

Moreover, topological phononics support edge states with one-way transport284,285,319–321 and, thus, they can be used as phononic diodes219,322,323 or waveguides.322 It would then be interesting to use programmable topological phononics in order to construct switches and gates for phonons that mimic electronic circuits.320,323 Another interesting way for tuning the properties of topological phononic crystals is to take advantage of the physics of Floquet topological insulators, whose properties can be controlled by external fields, lasers, microwaves or other types of radiation.280 Finally, tunable topological acoustics can make use of soft, deformable materials.22

E. Topological gigahertz nanophononics

The topological phononic crystals mentioned so far have macroscopic dimensions, resulting in sound waves in the kHz to MHz frequency range. One of the most promising application of phononics is their use in wireless devices, where they mediate signal processing of microwaves. For such applications, the phononic structures need to operate in the GHz range. The growing demand for signal processing at higher operational frequencies (5G wireless networks and beyond), and the vast progress of THz light technologies, will likely require phononic devices with higher operational frequencies. Higher operational frequencies can be achieved by spatial confinement of the phononic structures in the sub-μm to nm lengthscales (nanophononics).

Topological GHz nanophononics can be 1D systems like coupled nanocavity arrays.326 These 1D systems are GaAs/AlAs superlattices with band-inversion at the interface, while the probing technique can be in frequency- (Raman129) or time-domain (ASOPS132). Regarding 2D systems, several interesting, macroscopic crystals (e.g., hosting topological acoustic polaritons131) can be scaled down to the sub-micrometer scale using lithographic techniques.323,340 Based on several theoretical proposals, experiments, and simulations, a good design for topological nanophononics is pillar phononic crystals.327–329

Classical, macroscopic metamaterials can be precisely engineered in terms of their size, shape, and dimensionality. Thus, they can be used to evaluate the various designs and decide which of these can be transferred to the sub-micrometer lengthscale and GHz frequency range. For macroscopic 2D topological acoustics (see the work of Zhang et al.280), the experiments require sample-preparation by 3D printing, a loudspeaker to emit sonic waves and a microphone to detect the edge- and corner-states. For nanophononics, the 3D printing technology can be replaced by lithographic techniques.129 Generation of coherent acoustic phonons can be carried out with ultrashort laser pulses—see, for instance, Arregui et al.330 The laser pulses generate coherent acoustic phonons through the thermoelastic effect and the displacement potential mechanism.331 The probing of topological phonons in 2D PnCs can be potentially performed by micro-BLS, which has the ability to map the vibrational density of states and the band structure,286 as well as the direction of phonons130 (asymmetric Stokes/anti-Stokes intensities) with micrometer spatial resolution. Finally, a practical way of tuning the crystal properties might come from heterostructures of hard semiconductors and soft, polymeric structures. In such heterostructures, it will be possible to deform the soft matter part with an externally applied strain, and therefore to tune topological phase transitions at the interface.286 In this case, the additional usefulness of BLS is that it can measure directly and accurately the local strain, which causes flexural Lamb waves of zero momentum to have non-zero frequencies.330,340

VII. SUMMARY

Research on PnCs is a relatively mature field that is more than 20 years old. The transition from research to the industry can be achieved for two types of PnCs: macroscopic sub-GHz PnCs for vibrational isolation and microscopic, hypersonic PnCs for MEMS and telecommunication. The design of PnCs can make use of various computational techniques like finite element methods,141,342 acoustic transfer matrix calculations,343 genetic algorithms,344,345 topological optimization,345,346 and machine learning.347 These computational methods provide efficient but complex architectures that can now be realized with 3D printing technologies, sophisticated machining, molding and casting for
macroscopic PnCs, and bottom-up or top-down synthesis for microscopic PnCs—see the review article of Choi et al.\textsuperscript{348}

Macroscopic PnCs with bandgaps at audible frequencies\textsuperscript{344,349,350} and various acoustic metamaterials\textsuperscript{357–359} can be used for sound insulation of buildings, vehicles, and machinery. Moreover, macroscopic PnCs with non-trivial topological properties can be used to construct loudspeakers and microphones that control the direction\textsuperscript{353,374} and timing\textsuperscript{276} of sonic signals. Additionally, PnCs have promising applications for ultrasonic imaging in biomedical applications (Sec. II). Research on PnCs can even be useful for civil engineering and urban design. For instance, strategic planting of trees is the ultimate green method for protection against sound pollution\textsuperscript{360,} and seismic waves.\textsuperscript{16–18} Protection from seismic waves can also be achieved with artificial, periodic structures called seismic metamaterials.\textsuperscript{19} Similar to seismic waves, PnCs and metamaterials that control water waves can be used for coastal engineering\textsuperscript{361} and to amplify energy harvesting from ocean waves.\textsuperscript{362}

Higher operational frequencies for phononic devices can be achieved through spatial confinement and nanostructuring. Thus, hypersonic PnCs have potential applications for signal processing applications at 5G frequencies and beyond. Apart from higher operational frequencies, PnCs for telecommunications need to maintain high-quality factors (minimize dissipation), which is one of the main advantages of phononic devices compared to electronic circuits.\textsuperscript{11} The most critical missing component is a reliable source of coherent phonons that can operate at high frequencies ($\gtrsim$10 GHz). Likely, the development of coherent phonon sources at high frequencies can be facilitated by research on optomechanics (Sec. IV). So far, PnCs were mostly based on semi-transparent, insulating materials (e.g., SiO$_2$ and polymers like PS) and well-known semiconductors with 3D crystal structures like Si. The need for further miniaturization of phononic devices might be covered by novel, low-dimensional, semiconducting nanomaterials (Fig. 5). For instance, ultra-small 0D nanoclusters can self-assemble into colloidal crystals, and vdW layered materials can be used to construct ultrathin, crystalline metamaterials (Sec. III). However, the use of such novel nanomaterials will likely require a deeper understanding of microscopic interactions and dissipation processes for acoustic phonons. For instance, the use of metallic, semiconducting, and magnetic nanomaterials will require studies on the coupling of acoustic phonons with plasmons, excitons, and magnons, respectively. Additionally, metamaterials made of low-dimensional semiconductors can also be interesting in view of thermoeléctrics (discussed in Sec. V). We expect that nanostructuring of 2D van der Waals materials\textsuperscript{341} or assembling carbon nanostructures with different dimensionalities\textsuperscript{363} will provide novel methods for thermal phonon management. The study and manipulation of thermal phonon transport can be useful for thermoelectrics or efficient cooling of electronic devices, but it is also fascinating from the perspective of basic research. Some examples are coherent effects in thermal transport, such as the second sound effect and various more deviations from Fourier’s law in nanoscale systems (Sec. V). In most cases, such novel properties of PnCs stem from static nanopatterns of holes, pillars, or self-assembled nanostructures. An interesting research direction is the synthesis of microscopic, hypersonic PnCs with tunable structures. Tunable hypersonic PnCs can result from liquid–solid or organic–inorganic heterostructures (Secs. III and VI), which will be controlled by infiltration or deformation, respectively. The waveguiding of phonons (for instance, in a delay line) can be achieved using PnCs with bandgaps and/or topological edge states (Sec. VI). Thus, we consider that research in topological phononics will gradually move to high-order 2D topological nanophononics at gigahertz frequencies.\textsuperscript{364}

ACKNOWLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme (No. 101003436), the Foundation for Polish Science (No. POIR.04.04.00-00-5D1B/18), and the Polish National Science Centre (No. UMO-2018/31/D/ST3/03882).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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