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Phononic crystals at various frequencies

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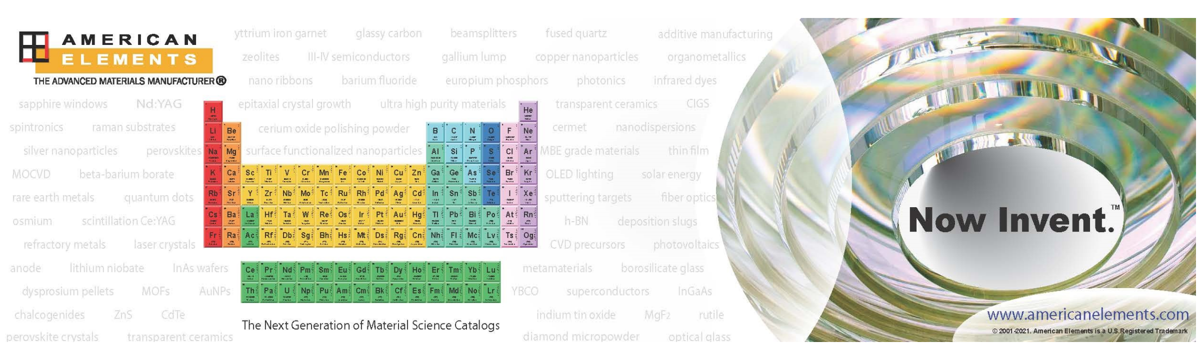

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Over the past three decades, phononic crystals (PnCs) have attracted scientific interest by demonstrating a variety of unique manipulations of sound and elastic wave propagation through control of wave dispersion by Bragg scattering. The high freedom in the choice of materials and designs of PnC systems and the wide available frequency range provide researchers with a vast playground in physics and applications. The field started with studies in the sonic and the ultrasonic frequency range, with applications in acoustic metamaterials, sound shielding, sound absorption, medical imaging, microelectromechanical systems, surface acoustic waves, acousto-optics, and optomechanics. Concepts have then been extended to nonlinear physics and non-reciprocal acoustics. Recently, downsizing of PnCs has broadened the research area toward higher frequencies and has enabled manipulation of heat conduction in solids. The new concept of thermocrystal opens a new possibility of the PnC assisted by material science and nanofabrication technology.[1] Following fundamental advances in topological insulators made in solid state physics, topological phononics now promotes protection against radiation loss and spurious scattering. This special topic aims at providing a comprehensive overview of the most recent advances in research and applications of PnCs at various frequencies, from sound to heat.

Laude reviews the principles and properties of PnC waveguides. Waveguides are indeed among the main applications of PnCs and can be achieved at any frequency and scale. In defect PnC waveguides, the cladding of classical homogeneous waveguides is replaced by a crystal possessing a complete phononic bandgap. Coupled-resonator waveguides rely on coupled discrete cavities instead of linear defects. The different material systems used to implement PnC waveguides are reviewed. Finally, the principles of topological waveguides leading to backscattering free propagation are presented.[2]

Wang *et al.* explore the propagation of guided Lamb waves in reconfigurable PnC waveguides and phononic circuits created by defects composed of threaded rods held with nuts in a perforated solid PnC slab. Adjusting the free length of the rod, the resonant frequency of the defect can be tuned, without any change in the supporting PnC slab. Both straight and bent waveguides are fabricated and measured in an aluminum sample with a lattice constant of 20 mm and a complete bandgap extending from 50 to 70 kHz.[3]

Kumar *et al.* argue that nonlinear ultrasonic guided waves are among the most promising new tools for early stage damage detection owing to their high sensitivity and long-range propagation features. However, they observe that signatures from instrumentation, transducers, and couplant effects can create false positives and lead to inaccurate measurements. They propose using a waveguide metamaterial rod acting as a mechanical acoustic filter for suppressing higher harmonic components in the measured signal. The method is demonstrated by detecting a discontinuity in a workpiece through its nonlinear response enhanced using the metamaterial.[4]

Wang *et al.* report on the experimental realization of a pillared metasurface for flexural wave focusing. A metasurface is an array of subwavelength units allowing modulated refractive/reflective properties in compact functional devices. The authors propose an elastic metasurface consisting of a line of pillars with gradient heights, erected on a homogeneous plate. They design a focusing metasurface and compare the properties of the focal spots through simulation and experiment. They notably show the robustness of the focusing pillared metasurfaces with respect to fabrication imperfections.[5]

Wang *et al.* discuss tunable guided waves in a soft PnC containing a line defect. They investigate numerically and experimentally

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the propagation of waves inside a PnC containing defects, consisting of a soft porous matrix hosting hard inclusions placed along a line. They observe that static and dynamic localized states appear due to the presence of the line defect and that those can be harnessed by a uniaxial compression, resulting in tunable elastic waveguiding.[6]

Martí-Sabaté and Torrent look into a quasi-periodic line of scatterers in a two-dimensional elastic plate and study the development of edge modes for flexural waves. By multiple scattering numerical simulations, the authors show that the spectrum of the edge modes has the shape of a Hofstadter butterfly. The advantage of the proposed structure is that bound edge flexural modes are not surrounded by gaped bulk materials. In addition, when mirroring the structure, the quality factor of these modes is increased. The analysis introduced is general and can be applied to acoustic and electromagnetic waves as well.[7]

Romero-García *et al.* investigate stealthy hyperuniform point patterns that are characterized by a vanishing spatial Fourier transform around the origin of reciprocal vector space. They point out that long-range point density fluctuations are, in principle, suppressed in materials consisting of such distribution of scatterers, opening up opportunities to control waves. They specifically analyze the transport properties of air-borne acoustic waves in one-dimensional phononic materials constituted of either non-resonant or resonant scatterers. The transport properties are found to be robust to both scatterer dimensions and inherent viscothermal losses, while strongly affected by the scatterer resonances, resulting in sharp dips in the transmission coefficient.[8]

Jiang *et al.* theoretically investigate the propagation of phonons through graphene superlattices and show, using wave-packet simulations, the existence of phonon wave interference effects in these two-dimensional materials. These effects arise in their simulations in the form of totally reflected and totally transmitted wave packets across the structure. The authors discuss the conditions for the appearance of wave effects in terms of the structural characterization of the graphene superlattice and provide a phonon level understanding of phonon propagation and wave interference effects.[9]

Luo *et al.* provide a theoretical analysis based on finite element simulations on the role of inclusion shape in periodic nanocomposites on the propagation and scattering of acoustic phonons. They analyze the transition from circular to fractal (dendrite) shaped inclusions periodically arranged in a matrix material. They report that the fractal shaped inclusions generate additional scattering mechanisms that lead to larger acoustic absorption which can be described by a compressed exponential function. The authors conclude that optimized acoustic absorption can be achieved by means of complex interface designs.[10]

Mori *et al.* calculate the thermal conductance of the one-dimensional mass-disordered atomic chains with the linear and quadratic dispersion relation using the R-matrix method, which enables a large-scale calculation. They compared the phonon transport properties between the linear and quadratic dispersion models. Thermal conductance shows the super-diffusive nature for the linear dispersion model, while it shows normal-diffusion for the quadratic dispersion model.[11]

Hatanaka and Yamaguchi study a PnC platform in the GHz regime for acoustically controlled spin-wave dynamics with small and inhomogeneous mode structures by simulation. Inhomogeneous strain distributions in the wavelength-scale resonant modes change the magnetostrictive coupling and the spin-wave excitation susceptible to an external field orientation. The simulated platform would be promising for enhancing the directionality and versatility of the magnetostrictive driving scheme to develop hybrid magnetomechanical circuitry.[12]

Zaremanesh *et al.* introduce a temperature biosensor by means of a PnC made of cylinders in a triangular lattice. The authors create a waveguide in the periodic lattice by introducing hollow cylinders. When the hollow cylinders are filled with the fluid Methyl Nonafluorobutyl Ether (MNE) at different temperatures, they observe changes in the frequencies of the guided modes as a function of temperature. The proposed PnC, thus, provides a material platform for sensing temperature changes in biofluids through acoustics.[13]

Fujikane *et al.* perform dynamic mechanical analysis and *in situ* electrical characterization by nanoindentation for a Si PnC. They found that, during the phase transition from the diamond to a metallic β-Sn structure, Young's modulus and critical phase-transformation pressure decreased as the neck size of a PnC. The change in mechanical property in nanostructures, where Young's modulus changes, should be taken into account to discuss phonon transport in nanostructures more precisely.[14]

Zhang *et al.* review theoretical and simulation works about the coherent thermal transport in PnCs at the nanoscale at low temperatures. They summarize theories to simulate minimum thermal conductivity and Anderson localization in various nanosystems. The thermal transport in the nanoscale can be described by wave-like/coherent and particle-like/incoherent manners. Phonon scattering mechanisms, such as impurity, mass disorder, structural randomness, and interface roughness, play important roles in thermal phonon transport.[15]

Heiskanen *et al.* study the thermal conductance of three-dimensional photonic crystals. The authors design and fabricate, using two-photon lithographic techniques, a 3D structure at the microscale that can manipulate phonon propagation in the GHz regime. GHz phonons have a significant contribution to thermal transport at sub-Kelvin temperatures, and the authors, thus, probe the thermal conductance of the proposed PnC at low temperatures. They find that the thermal conductance can be enhanced and such behavior requires additional studies on the role of coherent interference effects for thermal phonons.[16]

Anufriev *et al.* review the theoretical and experimental studies of coherent control of phonon and heat transport in one-dimensional PnCs. They summarize the coherent thermal phonon transport studies for superlattices with the periodicities of a few nanometers and carbon nanotubes with periodically encapsulated fullerene molecules at room temperatures. For the case of one-dimensional PnCs with the periodicities of hundreds of nanometers fabricated in semiconductor membranes, coherent thermal transport is reported at low temperatures. They point out that further miniaturization and improving fabrication quality are the main challenges faced by 1D phononic nanostructures.[17]

Guo *et al.* investigate the phonon localization in Si/Ge graded superlattices with short-range order and long-range disorder. They analyze the transmission, participation ratio, and phonon number density distribution based on their quantum transport simulation.

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There is a thermal conductivity minimum with a system length due to the exponential decay in the transmission to a non-zero constant. Their simulation is useful for heat conduction engineering using phonon localization.[18]

In conclusion, this special issue on PnCs at various frequencies illustrates how the field has matured during the last thirty years from fundamental considerations on the dispersion relation of acoustic phonons in solids and acoustic waves in diverse media toward applications making full use of the unique properties of PnCs. At the small scale, thermocrystals promise the control of thermal conductance via coherent phonon and heat transport engineering. PnC waveguides have evolved from crude lines of defects to intricate designs that benefit from both novel topology concepts and the precise control of local resonances. Wave control has advanced by leaps and bounds for optimal absorption, stealthiness, sensing, or the engineering of multiphysical couplings. There are remaining challenges ahead, for instance, with regard to nanofabrication of crystals. The advances in this collection of contributions, hopefully, will serve to address a wide array of fundamental materials and engineering challenges for the future development of phononic devices and systems.

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