

Acoustic Metamaterials And Phononic Crystals Preamble

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Acoustic Metamaterials and Phononic Crystals A Comprehensive Overview

Acoustic metamaterials and phononic crystals represent a fascinating frontier in materials science offering unprecedented control over sound waves. While often used interchangeably, they possess subtle differences that impact their design and applications. This article provides a comprehensive overview, bridging the theoretical understanding with practical implications and future prospects.

I. Fundamental Concepts

What are Acoustic Metamaterials and Phononic Crystals?

Both acoustic metamaterials and phononic crystals manipulate sound waves through their carefully engineered microstructure, creating effective material properties not found in nature. Think of it like this: a single brick is just a brick, but arranging bricks in a specific pattern can create an archway, a structure with entirely new properties. Similarly, these materials leverage microstructure to achieve desired acoustic behavior.

Phononic Crystals (PnCs)

These are periodic structures, meaning their internal structure repeats itself regularly in space. Imagine a perfectly ordered array of air pockets within a solid material. The periodicity leads to the formation of band gaps, frequency ranges where sound waves are prohibited from propagating through the material. This is analogous to the forbidden energy levels in electronic band theory. The size and arrangement of the repeating units determine the position and width of these band gaps. They are inherently passive devices, manipulating wave propagation through their structure alone.

Acoustic Metamaterials (AMs)

AMs are more broadly defined. They can be periodic like PnCs, but they also encompass aperiodic structures and those with resonating elements. Instead of relying solely on periodicity, they may incorporate local resonators—small structures designed to interact strongly with sound waves at specific frequencies. Think of tiny springs and masses embedded within the material. These resonators can effectively absorb, deflect, or focus sound waves even at wavelengths much larger than the resonators' size. This is akin to using a small object to absorb a much larger wave.

AMs can be passive, like PnCs, or active, incorporating external energy sources to dynamically control their acoustic properties.

II. Theoretical Underpinnings

The behavior of both PnCs and AMs is governed by wave equations, often simplified using effective medium theory (EMT) for homogenization and analysis. EMT allows

treating the complex microstructure as a homogeneous material with effective material properties eg effective density and bulk modulus However EMT breaks down near band edges and resonances requiring more sophisticated numerical methods like finite element analysis FEA or finite difference time domain FDTD for precise modelling These methods directly solve the wave equation within the complex geometry of the material Band Gaps in PnCs The formation of band gaps in PnCs is attributed to Bragg scattering When the wavelength of the sound wave is comparable to the lattice constant of the structure waves scattering from different unit cells interfere destructively leading to wave suppression within the band gap This is analogous to Xray diffraction in crystals Resonant Effects in AMs The unique acoustic properties of AMs are often achieved through localized resonance effects Resonators within the AM interact strongly with incident sound waves at their resonant frequencies leading to significant absorption or scattering The design of these resonators is crucial for achieving specific acoustic functionalities III Practical Applications The ability to manipulate sound waves has opened doors to numerous applications Noise Control AMs and PnCs are being developed for noise barriers sound absorbers and vibration dampeners in various settings from construction to automotive industries Their ability to control sound propagation in specific frequency bands makes them highly effective Acoustic Imaging and Sensing PnCs can be designed to focus sound waves enhancing the resolution of acoustic imaging systems AMs can act as sensitive sensors detecting minute changes in acoustic environments Acoustic Cloaking By carefully designing AMs its possible to create devices that deflect sound waves around an object making it invisible to sound This has implications for stealth technologies and underwater acoustics Energy Harvesting AMs can be designed to efficiently harvest acoustic energy from the environment converting it into electrical energy This holds potential for selfpowered sensors and other applications Medical Ultrasound PnCs and AMs can improve the focusing and delivery of ultrasound waves enhancing medical imaging and therapeutic applications 3 IV Challenges and Future Directions While the field shows immense promise several challenges remain Fabrication Creating complex microstructures with high precision and reproducibility can be challenging and expensive Advances in 3D printing and microfabrication techniques are crucial for overcoming this hurdle Scalability Many AM and PnC designs are currently limited in size and scalability Developing costeffective methods for producing larger structures is essential for widespread adoption Modeling and Design Predicting and optimizing the acoustic properties of complex AM and PnC structures requires sophisticated numerical simulations Further developments in computational methods are needed The future of acoustic

metamaterials and phononic crystals lies in pushing the boundaries of material design fabrication and theoretical understanding. Research into novel materials, innovative fabrication techniques and advanced computational methods will unlock a wider range of applications and lead to even more impactful technological advancements. We can expect to see more sophisticated designs capable of manipulating not just the amplitude but also the polarization and phase of sound waves potentially leading to unprecedented control over acoustic fields.

V ExpertLevel FAQs

1. What is the key difference between a local resonance metamaterial and a Bragg scattering based phononic crystal? Local resonance metamaterials achieve their acoustic effects through the resonance of embedded subwavelength inclusions independent of the periodicity of the structure. Bragg scattering in phononic crystals relies on the periodic arrangement of the unit cells creating band gaps through destructive interference of waves scattered from different unit cells.
2. How can we overcome the limitations of effective medium theory in designing complex acoustic metamaterials? Effective medium theory often fails to accurately capture the behavior of complex structures with sharp resonances or near band edges. Fullwave numerical simulations such as finite element analysis or finite difference time domain are required for accurate modelling and design optimization.
3. What are the current limitations in manufacturing largescale acoustic metamaterials? Current manufacturing techniques often struggle with the high precision and complexity needed for largescale fabrication of acoustic metamaterials. Cost-effective scalable manufacturing methods such as advanced 3D printing and roll-to-roll processing are crucial for realizing largescale applications.
4. How can we design acoustic metamaterials for broadband sound absorption? Broadband sound absorption can be achieved through several strategies including combining multiple resonators with different resonant frequencies using graded structures with varying impedance or utilizing porous materials with inherent broadband absorption properties.
5. What are the potential applications of topological acoustic metamaterials? Topological acoustic metamaterials leverage topological protection to create robust waveguides and devices that are insensitive to structural imperfections. This is particularly relevant for creating robust acoustic circuits and waveguides for applications like energy harvesting and acoustic sensing in harsh environments.

Acoustic Metamaterials and Phononic Crystals

Phononic Crystals

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Acoustic Metamaterials and Phononic Crystals

Introduction to Photonic and Phononic Crystals and Metamaterials

Photonic and Phononic Crystals

Metasurfaces and Phononic Crystals for Manipulating Fluid Flow and Acoustics

Two-Dimensional Phononic Crystal Simulation and Analysis

Time-varying Phononic Crystals

Sonic and Photonic Crystals

Band

Gap Formation in Acoustically Resonant Phononic Crystals
Design Optimisation and Validation of Phononic Crystal Plates for Manipulation of Elastodynamic Guided Waves
Phononic Crystals to Control Surface Acoustic Waves in Piezoelectric Materials
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Phononic Crystals - Sonic Band-gap Materials
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Phononic Crystals to Control the Propagation of Elastic Waves
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this comprehensive book presents all aspects of acoustic metamaterials and phononic crystals the emphasis is on acoustic wave propagation phenomena at interfaces such as refraction especially unusual refractive properties and negative refraction a thorough discussion of the mechanisms leading to such refractive phenomena includes local resonances in metamaterials and scattering in phononic crystals

the book provides a comprehensive presentation of the topic of phononic and sonic crystals including acoustic and elastic wave propagation in homogeneous and periodic media bloch waves and band structures

surface phononic crystals and phononic crystal slabs evanescent bloch waves and complex band structures local resonance dispersion and negative refraction and phononic band gap guidance the book is accompanied with a comprehensive set of finite element model fem scripts for solving basic phononic crystal problems as supplementary material the scripts should allow the reader to generate band structures for 2d and 3d phononic crystals to compute bloch waves waveguide and cavity modes and more they can be accessed here members femto st fr vincent laude freefem scripts numerical simulation phononic crystals

this book provides an in depth analysis as well as an overview of phononic crystals this book discusses numerous techniques for the analysis of phononic crystals and covers among other material sonic and ultrasonic structures hypersonic planar structures and their characterization and novel applications of phononic crystals this is an ideal book for those working with micro and nanotechnology mems microelectromechanical systems and acoustic devices this book also presents an introduction to the fundamentals and properties of phononic crystals covers simulation techniques for the analysis of phononic crystals discusses sonic and ultrasonic hypersonic and planar and three dimensional phononic crystal structures illustrates how phononic crystal structures are being deployed in communication systems and sensing systems

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introduction to photonic and phononic crystals and metamaterials by arthur r mcgurn presents a study of the fundamental properties of optical and acoustic materials which have been of recent interest in nanoscience and device technology the level of the presentations is appropriate for advanced undergraduates beginning graduate students and researchers not directly involved in the field references are given to guide the reader to more advanced study in these fields discussions of the physics of photonic and phononic crystals focus on the transmission properties of optical and acoustic radiation arising from their diffractive interaction in these engineered materials the frequency transmission and non transmission bands of radiation are explained in terms of the symmetry properties of the photonic and phononic artificial crystal structures basic applications of these properties to a variety of their technological applications are examined the physics of metamaterials is discussed along

with their relationships to the ideas of resonance properties of negative index of refraction perfect lens and unusual optical effects the new optics of metamaterial media makes available are examined related effects in acoustics are also covered basic principles of surface acoustic and electromagnetic waves are explained these form an introduction to the fundamental ideas of the recently developing fields of plasmonics and surface acoustics

the primary objective of this thesis was to gain a deeper understanding of acoustic wave propagation in phononic crystals particularly those that include materials whose properties can be varied periodically in time this research was accomplished in three ways first a 2d phononic crystal was designed created and characterized its properties closely matched those determined through simulation the crystal demonstrated band gaps dispersion and negative refraction it served as a means of elucidating the practicalities of phononic crystal design and construction and as a physical verification of their more interesting properties next the transmission matrix method for analyzing 1d phononic crystals was extended to include the effects of time varying material parameters the method was then used to provide a closed form solution for the case of periodically time varying material parameters some intriguing results from the use of the extended method include dramatically altered transmission properties and parametric amplification new insights can be gained from the governing equations and have helped to identify the conditions that lead to parametric amplification in these structures finally 2d multiple scattering theory was modified to analyze scatterers with time varying material parameters it is shown to be highly compatible with existing multiple scattering theories it allows the total scattered field from a 2d time varying phononic crystal to be determined it was shown that time varying material parameters significantly affect the phononic crystal transmission spectrum and this was used to switch an incident monochromatic wave parametric amplification can occur under certain circumstances and this effect was investigated using the closed form solutions provided by the new 1d method the complexity of the extended methods grows logarithmically as opposed linearly with existing methods resulting in superior computational complexity for large numbers of scatterers also since both extended methods provide analytic solutions they may give further insights into the factors that govern the behaviour of time varying phononic crystals these extended methods may now be used to design an active phononic crystal that could demonstrate new or enhanced properties

sonic phononic crystals termed acoustic sonic band gap media are elastic

analogues of photonic crystals and have also recently received renewed attention in many acoustic applications photonic crystals have a periodic dielectric modulation with a spatial scale on the order of the optical wavelength the design and optimization of photonic crystals can be utilized in many applications by combining factors related to the combinations of intermixing materials lattice symmetry lattice constant filling factor shape of the scattering object and thickness of a structural layer through the publications and discussions of the research on sonic phononic crystals researchers can obtain effective and valuable results and improve their future development in related fields devices based on these crystals can be utilized in mechanical and physical applications and can also be designed for novel applications as based on the investigations in this special issue

the work presented in this thesis is concerned with the propagation of acoustic waves through phononic crystal systems and their ability to attenuate sound in the low frequency regime the plane wave expansion method and finite element method are utilised to investigate the properties of conventional phononic crystal systems the acoustic band structure and transmission measurements of such systems are computed and verified experimentally good agreement between band gap locations for the investigative methods detailed is found the well known link between the frequency range a phononic crystal can attenuate sound over and its lattice parameter is confirmed this leads to a reduction in its usefulness as a viable noise barrier technology due to the necessary increase in overall crystal size to overcome this restriction the concept of an acoustically resonant phononic crystal system is proposed which utilises acoustic resonances similar to helmholtz resonance to form additional band gaps that are decoupled from the lattice periodicity of the phononic crystal system an acoustically resonant phononic crystal system is constructed and experimental transmission measurements carried out to verify the existence of separate attenuation mechanisms experimental attenuation levels achieved by bragg formation and resonance reach 25db the two separate attenuation mechanisms present in the acoustically resonant phononic crystal increase the efficiency of its performance in the low frequency regime whilst maintaining a reduced crystal size for viable noise barrier technology methods to optimise acoustically resonant phononic crystal systems and to increase their performance in the lower frequency regime are discussed namely by introducing the matryoshka acoustically resonant phononic crystal system where each scattering unit is composed of multiple concentric c shape inclusions

this thesis proposes novel designs of phononic crystal plates phps allowing

ultra wide controllability frequency ranges of guided waves at low frequencies with promising structural and tunability characteristics it reports on topology optimization of bi material layered 1d phps allowing maximized relative bandgap width rbw at target filling fractions and demonstrates multiscale functionality of gradient phps it also introduces a multi objective topology optimization method for 2d porous phps allowing both maximized rbw and in plane stiffness and addresses the critical role of considering stiffness in designing porous phps the multi objective topology optimization method is then expanded for designing 2d porous phps with deformation induced tunability a variety of innovative designs are introduced which their maximized broadband rbw is enhanced by is degraded by or is insensitive to external finite deformation not only does this book address the challenges of new topology optimization methods for computational design of phononic crystals yet it demonstrated the suitability and applicability of the topological designs by experimental validation furthermore it offers a comprehensive review of the existing optimization based approaches for the design of finite non periodic acoustic metamaterial structures acoustic metamaterial lattice structures and acoustic metamaterials under perfect periodicity

sonic phononic crystals termed acoustic sonic band gap media are elastic analogues of photonic crystals and have also recently received renewed attention in many acoustic applications photonic crystals have a periodic dielectric modulation with a spatial scale on the order of the optical wavelength the design and optimization of photonic crystals can be utilized in many applications by combining factors related to the combinations of intermixing materials lattice symmetry lattice constant filling factor shape of the scattering object and thickness of a structural layer through the publications and discussions of the research on sonic phononic crystals researchers can obtain effective and valuable results and improve their future development in related fields devices based on these crystals can be utilized in mechanical and physical applications and can also be designed for novel applications as based on the investigations in this special issue

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phononic crystals and acoustic metamaterials are heterogeneous materials that enable manipulation of elastic waves an important characteristic of these heterogeneous systems is their ability to tailor the propagation of elastic waves due to the existence of band gaps frequency ranges of strong wave attenuation in this thesis i report discoveries of three new types of band gaps i band gaps induced by geometric frustration in periodic acoustic channel networks ii band gap induced by high connectivity in

periodic beam lattices and iii topological band gaps in gyroscopic phononic crystals that protects one way edge waves the investigations presented here shed new light on the rich dynamic properties of phononic crystals and acoustic metamaterials opening avenues for new strategies to control mechanical waves in elastic systems

this manuscript is about the focusing of elastic beams propagating in a plate or on the free surface of a semi infinite medium using flat acoustical lenses the devices we have studied are based onto 2d phononic crystals that are made of air inclusions in a solid matrix and featuring a gradient of their elastic properties along one direction of the lens the gradient index grin is obtained by modulating either the size of the air inclusions or the distance between two consecutive inclusions we primarily adopted a computational approach but a significant part of the work concerns the analytical calculation of the ray trajectories as well as the experimental check of the theoretical findings the analytical approach consists to calculate the ray trajectories of an elastic waves within the lens while accounting for the anisotropy along each lines of inclusions the analysis applied to the lowest order flexural lamb wave a_0 together with both the numerical results and the experimental data well explains the features of the displacements field in the focus area including the location shape and lateral width the formalism applies whatever the symmetry of the phononic crystal is and can be extended to other polarization of the elastic wave we show in this work that fwhm as small as 0.64 may be obtained when focusing inside the lens the formalism applies also to the focusing behind the lens in that case the resolution at the focus is determined by the maximum transverse wavenumber at the exit of lens in good agreement with the numerical and experimental results then we designed a grin phononic lens featuring resonant pillars in addition to the constitutive air inclusions the numerical analysis foresees the resolution at the focus beyond the diffraction limit while experimentally we measured the resolution to be just above the diffraction limit lastly we turned to the subwavelength focusing of rayleigh waves through grin lenses we found a good agreement between the ray trajectories calculation the numerical simulations and the experiments we further analysed the influence of energy transmission when the focus is located behind the lens

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