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Acoustic Metamaterials and Phononic Crystals

Bearbeitet von
Pierre A. Deymier

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Preface

Phononic crystals and acoustic metamaterials have generated rising scientific interests for very diverse technological applications ranging from sound abatement to ultrasonic imaging to telecommunications to thermal management and thermoelectricity. Phononic crystals and acoustic metamaterials are artificially structured composite materials that enable manipulation of the dispersive properties of vibrational waves. Phononic crystals are made of periodic distributions of inclusions (scatterers) embedded in a matrix. Phononic crystals are designed to control the dispersion of waves through Bragg scattering, the scattering of waves by a periodic arrangement of scatterers with dimensions and periods comparable to the wavelength. Acoustic metamaterials have the added feature of local resonance, and although often designed as periodic structures, their properties do not rely on periodicity. The structural features of acoustic metamaterials can be significantly smaller than the wavelength of the waves they are affecting. Local resonance may lead to negative effective dynamic mass density and bulk modulus and therefore to their unusual dispersion characteristics. Whether these materials impact wave dispersion (i.e., band structure) through Bragg's scattering or local resonances, they can achieve a wide range of unusual spectral (ω-space), wave vector (k-space), and phase (φ-space) properties. For instance, under certain conditions, absolute acoustic band gaps can form. These are spectral bands where propagation of waves is forbidden independently of the direction of propagation. Mode localization in phononic crystals or acoustic metamaterials containing defects (e.g., cavities, linear defects, stubs, etc.) can produce a hierarchy of spectral features inside the band gap that can lead to a wide range of functionalities such as frequency filtering, wave guiding, wavelength multiplexing, and demultiplexing. The wave vector properties result from passing bands with unique refractive characteristics, such as negative refraction, when the wave group velocity (i.e., the direction of propagation of the energy) is antiparallel to the wave vector. Negative refraction can be exploited to achieve wave focusing with flat lenses. Under specific conditions involving amplification of evanescent waves, super-resolution imaging can also be obtained, that is, forming images that beat the Rayleigh limit of resolution. Phononic crystals and acoustic metamaterials with anisotropic band structures may exhibit zero-angle refraction and can lead to wave guiding/collimation without the need for linear defects. The dominant mechanisms behind the control of phase of propagating acoustic waves at some specific frequency is associated with the noncollinearity of the wave vector and the group velocity leading to phase shift. More recent developments have considered phononic crystals and acoustic metamaterials composed of materials that go beyond the regime of linear continuum elasticity theory. These include strongly nonlinear phononic structures such as granular media, the effect of damping and viscoelasticity on band structure, phononic structures composed of at least one active medium, and phononic crystals made of discrete anharmonic lattices. Phononic structures composed of strongly nonlinear media can show phenomena with no linear analogue and can exhibit unique behaviors associated with solitary waves, bifurcation, and tunability. Tunability of the band structure can also be achieved with constitutive media with mixed properties such as acousto-optic or acousto-magnetic properties. Dissipation, often seen as having a negative effect on wave propagation, can be turned into a mean of controlling band structure.

Finally, the study of phononic crystals and acoustic metamaterials has also extensively relied on a combination of experiments and theory that have shown extraordinary complementarity.

In light of the strong interest in phononic crystals and acoustic metamaterials, we are trying in this book to respond to the need for a pedagogical treatment of the fundamental concepts necessary to understand the properties of these artificial materials. For this, we use simple models to ease the reader into understanding the fundamental concepts underlying the behavior of these materials. We also expose the reader to the current state of knowledge through results from established and cutting-edge research. We also present recent progresses in our understanding of these materials. The chapters in this book are written by some of the pioneers in the field as well as emerging young talents who are redirecting that field. These chapters try to strike a balance, when possible, between theory and experiments. We have made a coordinated effort to harmonize some of the contents of the chapters and we have tried to follow a common thread based on variations on a simple model, namely the one-dimensional (1-D) chain of spring and masses. In Chap. 1, we present a non-exhaustive state of the field with some attention paid to its chronological development. Chapter 2 serves as a pedagogical introduction to many of the fundamental concepts and tools that are needed to understand the properties of phononic crystals and acoustic metamaterials. Particular attention is focused on the contrast between scattering by periodic structures and local resonances. In that chapter, we use the 1-D harmonic chain as a simple metaphor for wave propagation in more complex structures. This simple model will recur in many of the other chapters of this book. Logically, Chap. 3 treats the vibrational properties of 1-D phononic crystals (superlattices) of both discrete and continuous media. A comparison of the theoretical results with experimental data available in the literature is also presented. Chapter 4 then considers two-dimensional (2-D) and three-dimensional (3-D) phononic crystals. A combination of experimental and theoretical methods are presented and used to shed light not only on the spectral properties of phononic crystals but also importantly on refractive properties. Particular attention is paid to the phenomenon of negative refraction. Chapter 5 considers acoustic metamaterials whose properties are determined by local resonators. These properties are related to the unusual behavior of the dynamic mass density and bulk modulus in materials composed of locally resonant structures. Chapters 6–9 introduce new directions for the field of phononic crystal and acoustic metamaterials. The more recent topics of phononic structures composed of dissipative media (Chap. 6), of strongly nonlinear media (Chap. 7), and media enabling tunability of the band structure (Chap. 8) are presented. Chapter 9 illustrates the richness of behavior of phononic structures that may be encountered at the nanoscale when accounting for the anharmonicity of interatomic forces. Finally, Chap. 10 serves again a pedagogical purpose and is a compilation of the different theoretical and computational methods that are used to study phononic crystals and acoustic metamaterials. It is intended to support the other chapters in providing additional details on the theoretical and numerical methods commonly employed in the field.

We hope that this book will stimulate future interest in the field of phononic crystals and acoustic metamaterials and will initiate new developments in their study and design.

Tucson, AZ Pierre A. Deymier