Phononic crystals and their applications

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Introduction

Phononic crystals are the analogue of *photonic* crystals for the acoustic waves. By adding scattering periodic inclusions forming a crystal inside an homogeneous host material, some ranges of acoustic frequencies are totally reflected and then forbidden in the resulting material. This creates acoustic band-gaps.

Initially, the constructed crystals were limited to frequencies below 1 MHz, but the micro-crystals made by micro-fabrication can reach very high and even ultra high frequencies, with an example above 1 GHz. [1]

Principle

Phononic crystals are periodic arrangements of inclusions inside a viscoelastic material or a fluid, for example metal in air, polymer in water, air in epoxy, etc. With such a structure, band-gaps may appear and are independent of the direction of propagation of the incident elastic wave. In this case, the phononic crystal behaves like a perfect non absorbing acoustic mirror for the rejected frequencies. [2]

The central frequency of the band-gap is determined by the size, periodicity, filling and arrangement of the inclusions. Physically, the phononic band-gap is due to the diffraction of phonons at the interface between the matrix and the inclusions. [1]

Creating defects by replacing or removing some of the inclusions in a phononic crystal, by making the arrangement irregular, allows certain frequencies to exist within the band-gap. Those defects behave like impurities in doped semiconductors. Thus, it is possible to tailor the acoustic properties of the crystal. [2]

The most typical crystals follow the Bragg and Mie resonance conditions. Fig. 1 represents a square lattice crystal. r is the inclusion radius; a is the distance between the inclusions. The irreducible Brillouin zone has three directions, ΓX, XM and $M\Gamma$. The fundamental Bragg resonance frequencies are $\frac{V}{2a}$ for the ΓX direction and $\frac{V}{2\sqrt{2}a}$ for the ΓM direction, where V is the average acoustic velocity in the crystal. This velocity depends on the filling ratio, $\frac{r}{a}$. [1]

Phononic crystals are elastic or acoustic depending on whether the host material can (solid) or cannot (gas or liquid) support transversely polarized waves. [3]

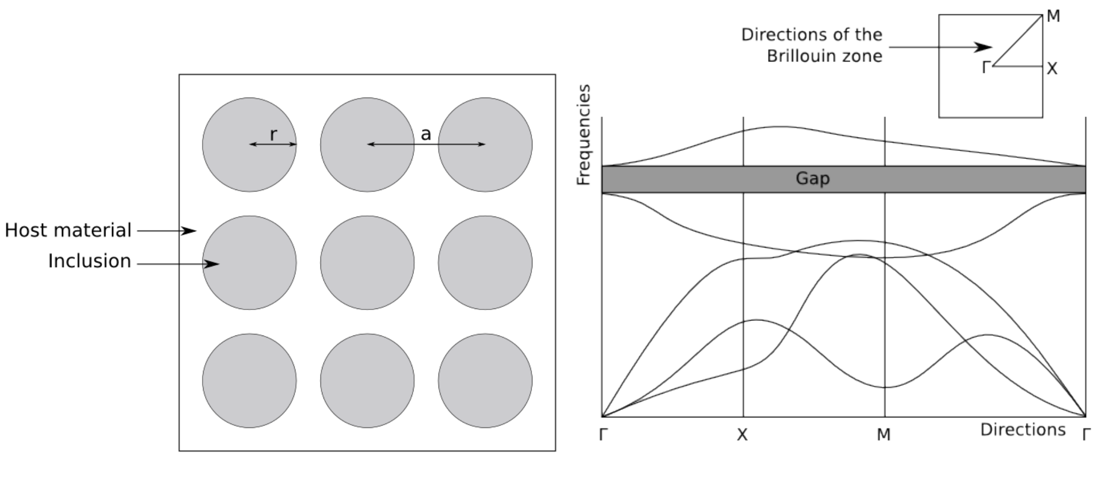

Fig. 1: Example of a phononic crystal showing the lattice parameters for the Bragg resonance on the left and the resulting band diagram on the right, as well as the directions of propagation in the Brillouin zone.

History

The very first known experimental observation of phononic crystals was when Narayanamurti *et al.* investigated the propagation of high-frequency phonons through a GaAs/AlGaAs superlattice, in 1979. Their superlattice can be considered as a 1D phononic crystal. [4] As for theoretical work, Kushwaha was the first to calculate full band-structure for periodic, elastic composites in 1993. [5]

However, the first complete phononic band-gap was only observed in 1998 by Montero de Espinosa, using an aluminum alloy plate with a square periodic arrangement of cylindrical holes filled with mercury. A band-gap appeared in the frequency range between 1000 and 1120 kHz. [6]

Recently, the variety of materials used in the fabrication of phononic devices allowed great improvements on the reachable frequencies for the band-gap, making it increase from about 1 MHz to very high frequencies (VHF: 30–300 MHz) and even ultra high frequencies (UHF: 300–3000 MHz). [1]
Gorishnyy demonstrated an hypersonic (above 1 GHz) phononic crystal using air scattering inclusions in epoxy in his thesis in 2007. The band-gap was measured by Brillouin light scattering. [7]

Tunable phononic crystals

As written above, tunability of phononic crystals can be achieved by changing the geometry of the inclusions.
Another way is to vary the elastic characteristics of the constitutive materials by applying external stimuli such as electric field, temperature or stress. However those techniques either require physical contact or the application of very large stimuli for a very small result. [8]

Robillard demonstrated the possibility of controlling the band-gaps using an external magnetic field, which allows contact-less tunability of phononic crystals, and Terfenol-D, a giant magnetostrictive material. [8]

Applications

The domains in which phononic crystals have potential applications are radio-frequency communications and ultrasound imaging for medicine and nondestructive testing. Focusing devices made with phononic crystals could miniaturize acoustic lenses, adapt impedance and decouple the transducer size from the aperture. [1]

Sub-diffraction-limited resolution and acoustic shielding could be reached by using them as wave-guides. [3]

Using the photon-phonon interaction would allow modulation and optical cooling. [1]
Such structure could also improve direct energy conversion by thermoelectric and thermophotovoltaic effects. [9]

At the micro-scale, they are used to isolate resonating structures, such as Coriolis force gyroscopes, mechanical resonators, filters and oscillators, from external vibrations and noise. [1]
Thus, they allow the rigid attachment of these devices to the substrate in an vibration-free environment, which allows to make high-precision mechanical systems. [2]

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