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Metamaterial and Topological Physics Approaches for Designing Efficient Acoustic/Elastic Devices

効率的な音響/弾性デバイス設計のためのメタマテリアルおよびトポロジカル物理的アプローチ

Kenji Tsuruta[1†] ([1]Faculty of Nat. Sci. & Technol., Okayama Univ.)
鶴田健二（岡山大院自然）

1. Introduction

Among metamaterials, which are artificial materials showing unique wave response characteristics, “Acoustic metamaterials" [1,2] have provided novel insights in the development of acoustic devices. Also, "topological phononics /mechanics" [3,4] based on the analogy of the classical vibration to the electron wave function in the topological insulator has initiated a new trend of the ultrasonic technology. These approaches have been examined and verified in the wide frequency band from audible range (kHz) to extreme ultrasonic wave (GHz) [5] until now. Especially, time inversion asymmetry (nonreciprocity) and propagation efficiency improvement in the extreme ultrasonic frequency regime are expected to contribute to the realization of the next generation (Beyond 5G/6G) information device through the combination with electronic and/or optical devices. In this presentation, I try to survey recent research trends on acoustic metamaterial design, specifically metasurfaces, and on topological physics approach for acoustic waveguide design utilizing the phase invariant of phonon band of PnC.

2. Acoustic Metasurfaces

Recent attention on the metasurface has begun in the context of the generalization of Snell’s law [6] applied to controlling light reflection/refraction on a surface by introducing phase discontinuities induced resonantly by plasmonic nanostructures fabricated artificially on the surface. As acoustic waves also follow the generalized Snell’s law, the concept can be allied to tailor wavefront on sound-wave refraction, as schematically illustrated in **Fig.1**. Modulation of the sound with longer wavelength than the thickness of the metamaterial is realized, for example, by tuning of the material’s impedance through resonators built in the structure and its nonuniform distribution [7]. Among the various attempts to realize such exotic acoustic properties, nearly perfect sound absorbers based on acoustic metasurfaces have been attracting much attention as a simple yet powerful concept to design new acoustic devices for practical applications such as noise shielding. Different from conventional sound absorbers, which rely on materials loss and/or the interference with transmitting and reflecting waves, the metasurface utilizes strong wave-matter interaction of resonators to produce perfect impedance matching at the interface as well as strong loss in the thin structure.

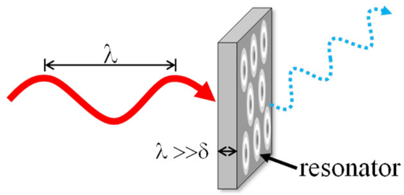

Fig. 1. Schematic of an acoustic metasurface with a wavefront controllability for an incident wave.

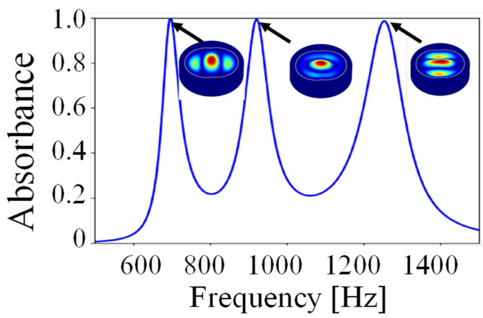

Fig. 2 Absorption spectrum of dual circular DMR model and their resonance mode at peaks 698Hz, 922Hz, and1254Hz.

As an example, the Decorated Membrane Resonators (DMR) have demonstrated such unique properties [8]. The high sound absorption occurs when the membrane and air layer vibrate to dissipate sound energy as heat. The high efficiency for sound absorption of the DMR is achieved by the hybridization of vibration modes in the membrane and the backing air layer in the DMR, whose effective impedance can be expressed as $Z_h = Z_M + Z'$, where Z_M and Z' are the impedance of the membrane and that of the air layer in the DMR, respectively.

In spite of the nearly 100% sound absorption at the resonance frequency of the DMR, the very narrow spectrum hampers to apply the design concept to practical sound insulations. We have recently proposed a novel metasurface structure which can exhibit broader absorption spectra [9]. Our approach is based on the multiplication of membrane modes by simply introducing an asymmetry in the membrane shape. **Figure 2** shows designed structures with dual circular shape of the membrane along with its absorption spectrum obtained by a numerical simulation. The results show multiplexing and broadening of the absorption peak with a single DMR structure.

3. Topological Phononics

The discoveries of the quantum Hall effect and topological insulators have stimulated the search for analogous topological states in classical systems such as light, sound, and mechanical waves. Topological invariance in dispersion curves drawn in the reciprocal space is hold also in the classical systems.

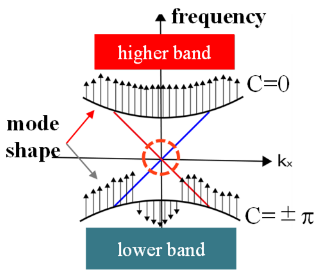

Fig. 3 Schematics of topological phase transition in phononic band and an edge mode generated at the interface between bands with different phases (C).

The acoustic topological insulator has two different topologies near the band gap in its dispersion characteristics, and there exists a band which shows the phase transition of the band topology via the continuous change of the structure. **Figure 3** illustrates a schematic of topological phase transition in phononic bands and localized propagation modes (edge modes) generated at the interface between bands with different phases. Transmission characteristic with very small loss is obtained due to the propagation through this topologically protected state. We have applied this concept to the topological acoustic waveguide design by the phononic structure in water and have demonstrated numerically and experimentally that robust wave transmission, *i.e.,* immune to backscattering by defects and/or corners in the waveguide, is possible even in the waveguides with complex propagation paths as long as the edge mode is properly excited in the paths [10].

Recently, further attempts have been made to control elastic waves at ultra-high frequency regime (GHz) in thin films with phononic crystals [5,11,12]. In the presentation, I will discuss an extension of the topological physics approach to elastic waves in thin films, such as those depicted in **Fig.4** [13].

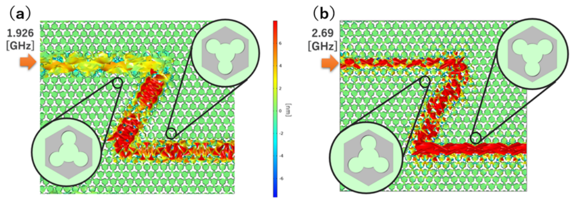

Fig. 4 Out-of-plane displacement in a membrane topological phononic waveguide for the elastic-wave propagation **(a)** at 1.926 GHz and **(b)** at 2.69 GHz via a finite-element simulation.

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