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Topologically robust sound wave transport using phonic crystal in water

フォノニック結晶を用いたトポロジカルなロバスト
水中超音波輸送

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1. Introduction

Phononic crystal has been investigated as one of the sound-wave transport devices whose acoustic characteristics can be tailored aritificially without much constraint by their materials in the structure. However, acoustic waveguides using conventional phononic crystals have a large transmission loss due to scattering of sound waves by defects and/or bending. Here, we focus on topological acoustics as an attempt to overcome this issue.

In recent years, topological insulators that maintain time-reversal symmetry in the principles of spintronics and valleytronics have attracted attention. Similarly to the topological insulators that exhibit topological transitions in the energy-band diagram of electrons, the phonon bands of sound waves can also be undertaken a topological phase transition. As a result, it is possible to make acoustic waveguides that have robustness against defects and bending in the edge state.

In this work, the finite element method was used to design the phononic structures with topologically protected edge states. By measuring the output pressure of spin-type and valley-type topological acoustic waveguides, we examine the edge characteristics and robustness of the designed waveguides.

2. Design of topological acoustic waveguide

The phononic structures in this study are composed of two-dimensional unit cells with equilateral triangles arranged in a hexagonal lattice. Both the spin-type and the valley-type band structures can be realized by different arrangements of the triangles, as depicted in **Fig. 1(a)** for spin type and **1(b)** for valley type. In both structures, the rotation angle α is defined for the equilateral triangle. We assume that the equilateral triangles are made of stainless steel and embedded in water.

Fig. 1(a) shows unit cells of the phononic structure and band diagrams of the spin-type unit cells. By rotating the equilateral triangles with angle α, the *p*-like and *d*-like mode of pressure fields appears at the Γ point in the band diagram at α = 0° and 30°. Mutual locations of these two modes in the band diagrams are inverted at α = 20.62°, indicating a topological phase transformation. Fig. 1(b) shows the structures and band diagrams of the valley-type unit cell. Similarly to the spin type, K+mode and K–mode appear at the K point in the band diagram for the structure of α = –30° and 30°, respectively. These two modes are inverted in their mutual location at α = 0°. From Fig. 1(a) and 1(b), we confirmed that topological phase transitions of phonon bands occur in the reciprocal space and can be controlled simply by α.

We construct topological acoustics waveguide with the supercell created by arranging unit cells composed of equilateral triangles with two different angles. The eigenmode analysis of this supercell reveals that the edge state appears at the Γ point for the spin-type band structure and the edge states appear at the K and K' points for the valley-type structure at around 400 kHz.

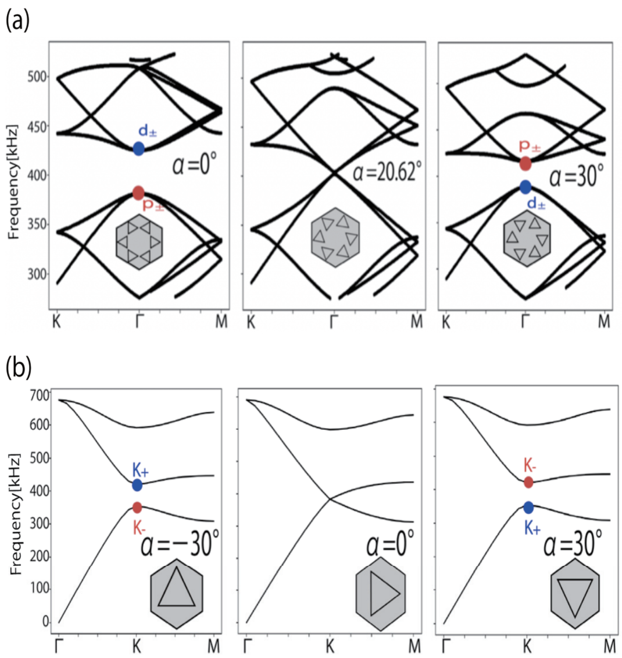

Fig 1. Unit-cell and phonon-band structures of (a) spin-type (b) valley-type phononic crystals.

Based on the above analyses, linear waveguides, defective linear waveguides, L-shaped waveguides, and Z-shaped waveguides were fabricated in the spin-type and the valley-type structures.

3. Sound pressure distribution and output pressure analysis

Fig. 2 shows sound pressure distribution (absolute value) in the Z-shaped topological acoustic waveguide for 400kHz incident wave; Fig. **2(a)** for spin-type, and **2(b)** for valley-type structures. We imposed perfect absorption boundary conditions (PML) on the top, bottom, left, and right boundaries of both structures to eliminate reflections at the boundaries. It is confirmed that the sound waves propagate on the interface of both the spin-type and the valley-type waveguide at 400kHz, indicating the edge states of topological acoustic bands can be realized at the interfaces.

For the incident pressure of 1Pa, we measured the output pressure of the spin-type and the valley-type waveguide. The output pressure is measured at the outlet of the structure. Comparison between the output pressure of the spin-type and that of the valley-type waveguide shows that the robustness in the spin-type waveguide holds only locally in the band gap, while the valley-type waveguide keeps high robustness in a wide band within the band gap.

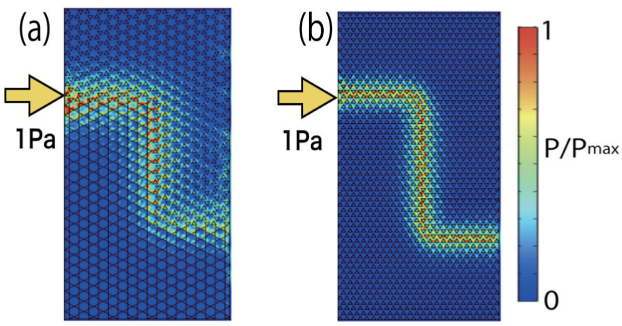

Fig2. Sound-pressure distribution (absolute value) in Z-shaped (a) spin-type and (b) valley-type topological acoustic waveguide for 400kHz incident wave.

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4. Conclusion

In this research, we confirmed that topological phase transitions of phonon bands occur in the spin-type and the valley-type unit cells. Furthermore, we demonstrated appearance of the edge states and the sound wave propagations on the interface at 400kHz. From the observations of pressure distributions on the interface and at the outlet of the waveguide, we conclude that the valley-type waveguide has higher robustness than the spin-type structure.

Acknowledgment

This work was supported in part by the JSPS KAKENHI Grant Number 17K19035.

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