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Design of topological phononic structure for multimode propagation
複数伝搬モードを有するトポロジカルフォノニック構造の設計

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1. Introduction

In recent years, as an analogy of topological insulators and superconductors, topological acoustics, which apply the concept of band topology to acoustic dispersion, have been attracting much attention. We have applied this concept to phononic crystals embedded in water[1]. So far, we have been focusing on two-dimensional phononic structure as the most fandamental model exhibiting desired band topology[2]. We have successfully demonstrated by numerical analysis and experiment that highly efficient sound wave propagation is possible in the designed structure. In the present study, we are aiming to develop highly efficient acoustic devices by extending design scheme to three-dimensional structures (membranes) and controlling elastic waves in the GHz band, which is useful for telecommunication applications[3]. In particular, by controlling elastic waves in multiple frequency bands, we are aiming to apply it to new functional devices such as multiplexers. In this study, we will search for topological phononic structures that enable frequency multiplexing for elastic wave control.

2. Design of 3D phononic crystal with 4 round holes

In phononic crystals, a bandgap appears in the dispersion relation, and sound waves in that frequency band are blocked against a wave incidence. Since the degeneracy of the phonon band occurs at the K point due to its structural symmetry, we searched for a simple phononic structure with C_{3v} symmetry that is easy to fabricate[4][5]. We adopt a phononic structure in which four round holes are formed in a hexagonal lattice with a period of 730 nm in a GaAs thin film with a thickness of 200 nm (**Fig. 1 (a)**). As a result of numerical simulation analysis based on the finite element method, a wide band gap was confirmed to emerge near 2 GHz and 2.5 GHz (**Fig. 1 (b)**).

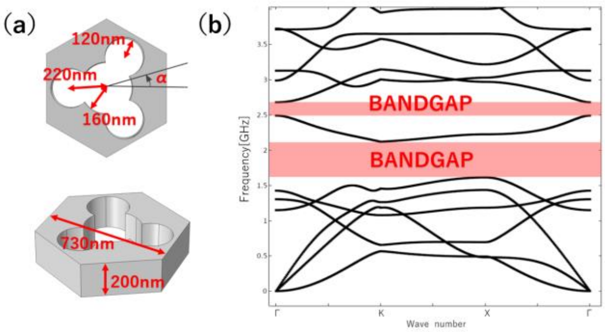

Fig. 1 (a) Unit cell structure of phononic crystal with 4 round holes and **(b)** its phonon band diagram.

Figure 2 shows the eigen mode and band diagram of the unit cell at the three angles of rotation α. K^+ and K^- are mode shapes at the K point of the structure of $\alpha = -30°$ and $\alpha = 30°$, respectively. In these two modes, rotational directions of the sound intensity are reversed at $\alpha = 0°$. From this analysis, it can be confirmed that a topological phase transition in the phonon band occurs between two symmetric structures.

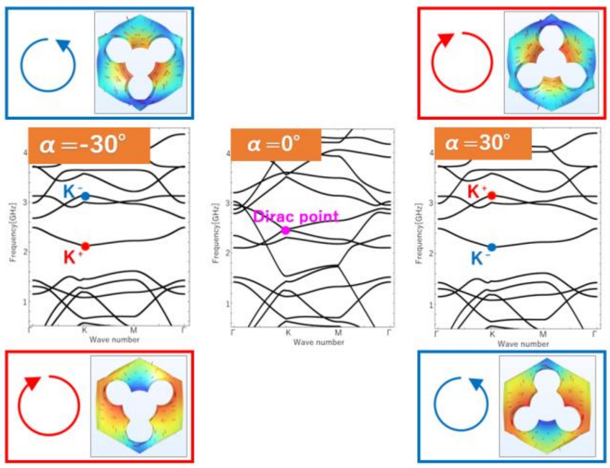

Fig. 2 Topological phase transition by changing the angle of rotation

Figure 3 shows the band structure of the supercell. The eigenmode analysis of this supercell shows that in the unit cell, the edge state band appears within the bulk band gap frequencies, as shown by the red line. An incident elastic wave at the gap frequencies propagates at the boundary between two frequency bands near 2 GHz and 2.5 GHz.

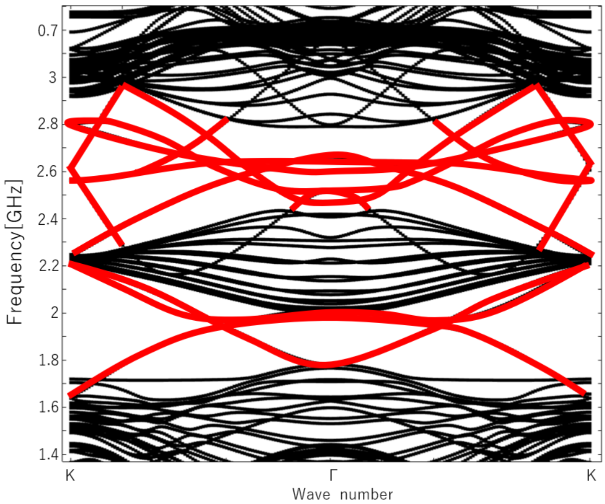

Fig. 3 Band structure of supercells in topological phononic crystals

3. Structural design of topological phononic elastic wave waveguide

Next, we designed a Z-type acoustic waveguide with a 4-hole structure. The boundary was created by placing a structure with α = -30° at the top and that with α = 30° at the bottom. Next, Fig. 4 (a) shows the out-of-plane displacement when 1.93 GHz is incident into the phononic structure, and Fig. 4 (b) shows the out-of-plane displacement when a 2.69 GHz wave has been emitted to the structure. The figure shows that it propagates along the boundary with high efficiency without much loss at both frequency and at corners. This indicates that topological waveguides may have high robustness in the multi-frequency band of elastic wave transport on thin plates.

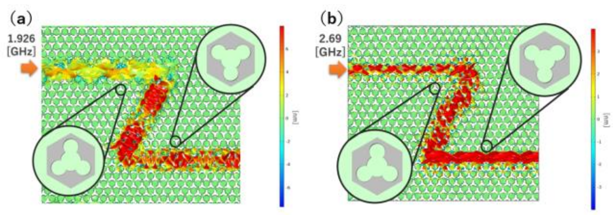

Fig. 4 Out-of-plane displacement in a membrane topological phononic waveguide for the elastic-wave propagation **(a)** at 1.926 GHz and **(b)** at 2.69 GHz via a finite-element simulation.

4. Conclusion

In conclusion, we extended topological phononic crystals into a three-dimensional system to control elastic waves. The topological phase transition was caused by changing the angle of rotation α using a four-circle structure, and the edge state of the two frequency bands was confirmed. We also designed an acoustic waveguide and confirmed that highly efficient elastic wave propagation is possible at both frequencies. We are confident that this technology will enable the development of applications for acoustic devices, especially new functional devices such as multiplexers.

Acknowledgment

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References

1. Z. Zhang, Y. Tian, Y. Cheng, Q. Wei, X. Liu and J. Christensen, Phys. Rev. Appl. **9**, 034032 (2018).
2. K. Okuno and K. Tsuruta, Jpn. J. Appl. Phys. 59 SKKA05 (2020).
3. D. Hatanaka and H. Yamaguchi Phys. Rev. Appl. **13**, 024005(2020).
4. J. Lu, C. Qiu, L. Ye, X. Fan, M. Ke, F. Zhang and Z. Liu, Nat. Phys. **13**, 369 (2017).
5. M. Yan, J. Lu, F. Li, W. Deng, X. Huang, J. Ma and Z. Liu, Nat. Mat. **17**, 993 (2018).