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Design on tubular topological phononic waveguides

Yuta Kono[1‡], Hiroaki Takeshita [1], Yusuke Hata [1], Yuri Fukaya [1], and Kenji Tsuruta[1*]
([1]Okayama Univ.)

1. Introduction

In recent years, phononic crystals have attracted attention as a means to control the propagation of sound waves and elastic waves by artificially arranging their periodic structure, and a wide range of applications are expected.[1)] In this study, inspired by the unique structure of carbon nanotubes, phononic structures were placed on the surface of a cylinder and their dispersion properties were analyzed using FEM. Carbon nanotubes (CNTs) are nanoscale cylindrical carbon materials made by rolling planar graphene, in which carbon atoms are arranged in a hexagonal lattice, into a cylindrical shape, and various studies have been conducted on their unique electronic and mechanical properties.[2)] Single-walled CNTs have a significant effect on their physical properties , such as electronically metallic or semiconducting, depending on how they are rolled (spiral, zigzag, armchair).[3)] Following the design strategies eraborated in CNTs, we attempted to control the transport properties of elastic waves on the tubler phononic system. Especially we designed efficient waveguides based on the topological band engineering, where robust propagations along the interface between non-trivial phononic crystals were expected. This opens new possibilities for the design of compact and/or integrated acoustic devices with multiple propagation channels and, furthermore, contributions toward nanoscale elastic wave engineering

2. Topological phononic crystal

Phononic crystal is an artificial structure in which materials with different acoustic properties are arranged periodically. In conventional phononic waveguides, the transmission loss increases due to scattering of sound waves at defects and bends. Here we adopted a topological phononic crystal, which introduces the concept of topology in designing the phononic bands.[4)] Topology is a geometric property that is maintained under continuous deformation, whereas it is changed for discontinuous deformation. It is known that edge states, which are localized states, appear at the interface when materials with different topologies are combined.[5)]

The unit cell used in this study is shown in **Figs 1(a)** and **(b)**. The values of each parameter are as follows: the lattice constant a = 6.98 mm, the radius of the central circle r_b= 1.52 mm, the radius of the three outer circles r_s = 1.14 mm, the distance between the centers of the two circles c_d = 2.09 mm, and the thickness of the cylinder t = 1.92 mm. Rotating this structure around the axis by $\theta = 5°$ and $\theta = -5°$ slightly changes the shape of the cell, eliminates the degeneracy and opens up the gap between two phononic bands that hold clockwise and counterclockwise energy vortices. It has been shown that by coupling these phononic crystals with different topologies, topologically protected edge states can be created in the band gap frequencies, enabling highly efficient propagation of elastic waves at the frequencies.[6,7)]

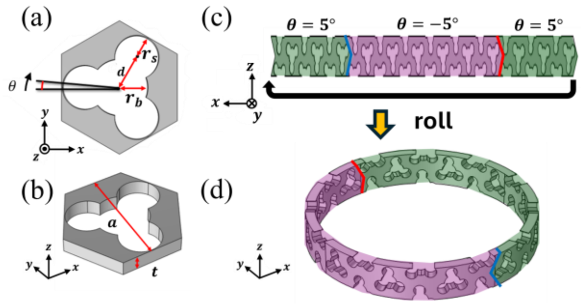

Fig. 1 Supercell with boundary along the cylinder axis

3. Topological waveguides parallel to cylindrical axis

As shown in **Fig. 1(c)**, a supercell with two types of boundary surfaces was designed by arranging unit cells with $\theta = 5°$ in the left layer, structures with $\theta = -5°$ in the middle layer, and $\theta = 5°$ in the right layer. Here we set a periodic boundary condition in the z direction. Hereinafter, the boundary between the left layer and the middle layer will be referred to as edge-A, and the boundary between the middle and right layer will be referred to as edge-B. A cylindrical supercell was designed by rolling up this supercell in the designated directions. By stacking the cylinders in **Fig. 1(d)** in the z direction, we can design a cylinder with two boundaries along the z axis.

E-mail: ‡ pxjz2v8r@s.okayama-u.ac.jp *tsuruta@okayama-u.ac.jp

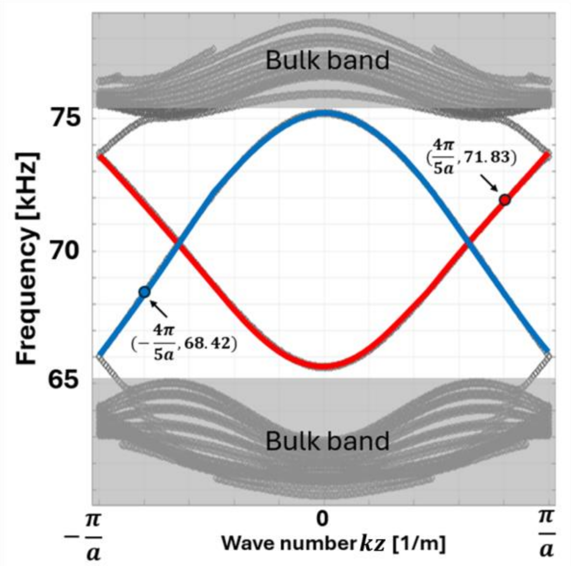

Fig.2 Band structure of the supercell shown in Fig.1(c)

Figure 2 shows phononic band diagram of the supercell depicted in Fig. 1(c). The red and blue bands in the figure represent two edge modes, with the blue line being the mode at edge-A and the red line being at edge-B. In this diagram, only the bands for out-of-plane vibrations are depicted. The figure implies that the frequency range between 65 and 75 kHz impedes propagations other than the edge modes of flexural wave incident to the structure, leading to an elastic waveguide along the edges. We thereby designed a waveguide by periodically arranging the supercells shown in Fig. 1(c) in the *z* direction. We then constructed a tubular phononic waveguide by stacking the supercell of Fig. 1(d) in the *z* direction. The transmission analyses on these waveguide structures were performed by exciting an elastic wave of 1 GPa in the edges.

4. Chiral type phononic crystal

We designed a chiral-type phononic crystal supercell inspired by the chiral-type CNT. This structure is a periodic arrangement of the unit cells rotated 90° counterclockwise, forming the oblique (spiral) boundaries by imposing the periodic boundary condition. A tubular supercell was designed by rolling up the planar supercell, as shown in **Fig. 3**, and we performed the eigenmode analysis.

When elastic waves are incident on boundary A and B from lower left as in Fig. 3, direction of the phase velocities of the waves propagating boundary A and B are opposite to each other. Such a selectiveness of propagation directions in these boundaries can be attributed to the positive/negative convex of the dispersion curves in Fig.2. In this way, this structure allows the design of two channels of

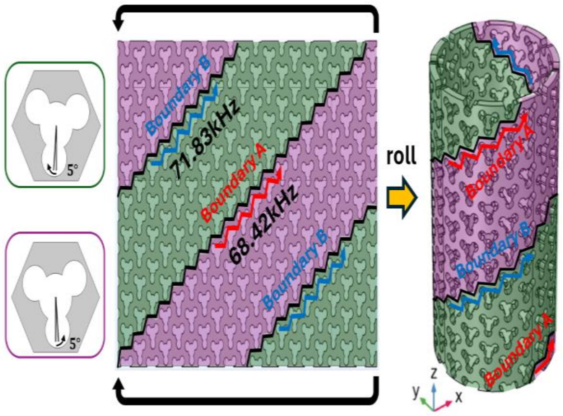

Fig.3 Chiral type photonic crystals.

waveguides in which elastic waves propagate efficiently at different frequencies. This is the same for both plate and tube shapes. In addition, we investigated how the eigenmodes and edge states are changed when a plate shaped supercell was rolled up into a tube. Details including transmission properties in these structures will be given at the presentation.

Acknowledgment

This work was supported in part by the JSPS KAKENHI Grant Numbers JP21H05020.

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