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Topological phononic waveguide design on surface of 3D object and its application to ball SAW sensor

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1. Introduction

SAW (surface acoustic wave) filters are now widely used as frequency filters for mobile communications such as smartphones. SAW sensors have also been developed as a gas sensing device which measures wave attenuation changes due to gas adsorption by depositing a sensitive film on the SAW propagation path. However, the device performance is strongly degraded due to diffraction and attenuation when the waves propagate beyond a certain distance. Recently, it has been discovered that when SAW is generated under certain conditions on a spherical surface, the SAW propagates around the equator many times without attenuation and diffraction[1]-[3]. This phenomenon has been shown to dramatically improve the sensitivity of SAW sensors.

In the previous studies, the propagation of surface acoustic waves on a sphere was investigated by using a vibration source on a circular arc as shown in Fig. 1[1][2], where the aperture angle $2\theta_a$ defined as,

$$2\theta_a = \sqrt{\frac{\pi}{ka}} = \sqrt{\frac{\lambda}{2a}} \qquad (1)$$

where k and a are the wave number and the radius of the sphere, respectively. When equation (1) is satisfied, the SAW energy is confined to the equatorial part of the sphere.

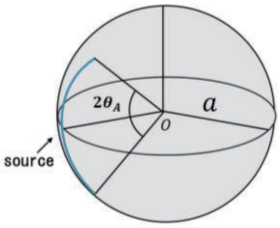

Fig. 1 Coordinate system of a sphere

The propagation of SAWs confined in a narrow orbit is not disturbed much even if the sphere is distorted or inhomogeneous, and thus the lowest attenuation and the highest number of circuits are expected. When attempting to achieve higher frequencies, the anisotropy and homogeneity of the sphere may affect diffraction, and high Q-value propagation may not be obtained even when equation (1) is satisfied. In this study, we examine the possibility of robust propagation of surface acoustic waves on a sphere using topological phononics, which has been the focus of much attention in recent years.

2. Topological phononic crystal

A phononic crystal is an artificial material consisting of periodic structures with different elastic properties. By periodically arranging materials with different elastic properties based on the order of the wavelength of phonons propagating in a solid, it is possible to realize phononic band gaps in which acoustic/elastic waves at a specific frequency are prohibited to propagate and phononic waveguides that guide the waves in a specific direction. Elastic waveguides based on phononic crystals are in the spotlight because of the possibility of controlling wave propagation along a desired path and frequency by using band engineering methods similar to those used in semiconductor electronic design. However, the practical application of elastic waveguides based on phononic crystals has been hampered by sound wave scattering at defects and transmission losses due to waveguide bending. By adding the concept of topology to the phononic band design, highly efficient elastic wave propagation can be achieved only at surfaces and interfaces where the propagating modes at the interfaces are protected by the topology of the band ("edge band") against the disturbance.

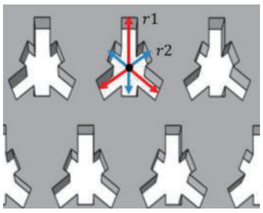

Fig. 2 Phononic crystal on a thin substrate.

Figure 2 shows the phononic structure used in this study. This phononic crystal consists of a hexagonal lattice of three-dimensional unit cells with snowflake-shaped holes. Snowflake-like unit cells have been used in various studies on phononic crystals as a very controllable structure for designing phonon band structures[5][6].

The hexagonal lattice has lattice constant $a = 6$ mm and thickness $t = 4$ mm. The snowflake-like crystalline scatterer has six legs of width $w = 1.1$ mm. The mirror symmetry of the unit cell can be broken by changing Δr, the difference between $r1$ and $r2$,

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while keeping the sum of $r1$ and $r2$ constant.

A further continuous decrease of Δr causes the gap to reopen. In addition, both K+ and K- pseudo-spin modes appear above and below the gap between the K and K' points in the Brillouin zone, respectively. The eigenmodes of the unit cell have opposite energy flows. This indicates a topological phase transition. Thus, the combination of the two structures results in the appearance of edge states in the phonon bands, allowing elastic wave propagation with robustness at the boundary.

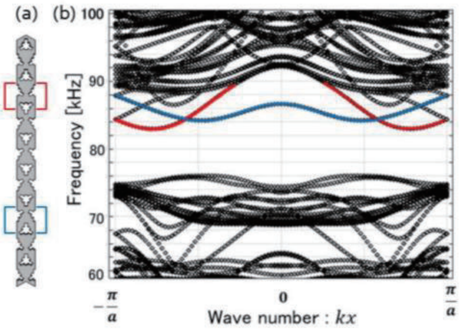

Fig. 3 (a) Structure of phononic waveguide, and (b) its phonon band diagram.

Figure 3(a) shows the supercell structure of the thin phononic crystal used in this study, and (b) shows the phonon band diagram of (a) obtained using eigen frequency analysis. The horizontal axis in Fig. 3 denotes the wave number and the vertical axis is the frequency. Figure 3(b) shows a band gap from 76 kHz to 83 kHz, where phonon propagation is prohibited. The red and blue lines in Fig. 3(b) from 83kHz to 88kHz indicate the edge states appear at the interface corresponding to the respective colors in Fig. 3(a). Here robust elastic wave propagation is possible at the boundary surface.

We also designed a Z-shaped waveguide with a snowflake-shaped topological phononic structure.

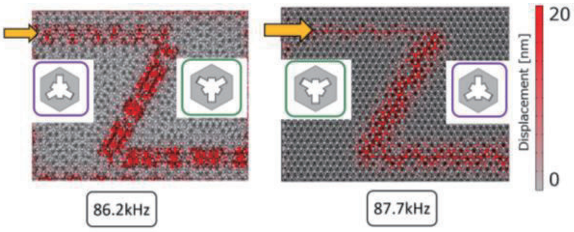

Fig. 4 Out-of-plane displacement in Z-shaped waveguide at two interfaces. (a) 86.2kHz and (b) 87.7kHz.

The finite element method was used to solve the differential equations and simulate elastic wave propagation. Figure 4 shows the out-of-plane displacement distribution of a wave incident on the Z-shaped waveguide. The Z-shaped waveguide has two obstructions, but the transmission loss at this interface is small due to the protected topological edge state. We confirmed that elastic waves propagate robustly on curved surfaces, such as the surface of a sphere, even in the edge state.

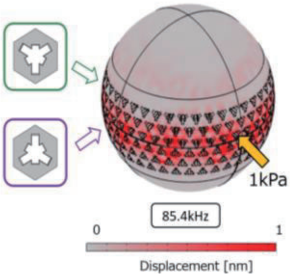

Fig. 5 Displacement field in a topological waveguide on the equator of the sphere for elastic wave propagations at 85.4kHz.

Applying the scheme of topological waveguide design described above. we develop a spherical elastic waveguide based on phononic crystals and a spherical elastic waveguide. Figure 5 shows a preliminary result of an edge-mode propagation along the spherical waveguide. It shows the SAW at the edge mode (85.4kHz) is confined effectively in the interface. Thus, the present scheme for topological phononic crystal is shown to be applicable to the surface of 3D-spherical object, which proves a promise for applying it effectively to ball SAW device. The details of the properties of this topological waveguide on a sphere will be discussed in the presentation.

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