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Rectification of Lamb wave propagation in thin plates with piezo-dielectric periodic structures
圧電-誘電体周期構造による Lamb 波伝播の整流機構

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1. Introduction

Acoustic diode [1] has recentry attracted much attention as a means of achieving high efficiency for noise insulation and/or as an energy harvester which transforms vibrational energy in environment to electricity. Various types of rectification mechanisms have been proposed; a method for rectification by using phononic band gap and second harmonic wave generated by nonlinear medium [1], and a method for realizing an acoustic analogy of the topological insulator by involving circulating fluid in the structure [2]. Most of the models realize the rectification via asymmetry in time and space given by applying external fields such as fluid flow in the media and external biases in the system. In this study, we design a new acoustic diode model, based on a one-dimensional structure consisting of piezoelectric ceramic films placed periodically in an epoxy plate [3]. Specifically, the model is designed to exhibit an efficient rectification effect in the audible and ultrasonic range. Our model includes no artificial forces to generate the asymmetry in the system but utilizes a mode conversion of elastic-wave propagation at an interface. We demonstrate numerically the effect on the Lamb-wave propagation in a thin plates. In addition, optimum material parameters toward the fabrication of prototype model are discussed.

2. Analysis method and proposed model

Our model is based on a composite plate consisting of periodic arrays of piezoelectric and dielectric materials. Two different periodic structures are jointed at the sides of each plate, and the Lamb wave propagates across the interface. This structure is similar to the one originally proposed by Zou *et al.* [3]. In the previous model, the Lamb-wave mode (S/A mode) [4] of each natural frequency is controlled by changing the electrical boundary conditions at upper and lower surfaces of the PZT units using electrodes. On the other hand, we proposed new acoustic diode model with no electrode for S/A mode wave rectification. Here we assume that mode hybridization can occur at the entrance of the incident wave.

2.1. Band calculation by FEM

In order to achieve a rectifying property for wide frequency range, we calculate and optimize the phonon band structure. **Fig. 1** depicts the unit cell of the periodic structure with the piezoelectric and dielectric material. We adopt PZT-5H for the piezoelectric part and acrylic for dielectric part. In the phonon-band calculation, the periodic boundary conditions are imposed in the left and right sides of the unit cell and the displacement field with Floquet function (Bloch function) are obtained by solving the eigenvalue problem for each given wavevector (k_x). The COMSOL Multiphysics® software based on the finite element method (FEM) is used for the band calculations.

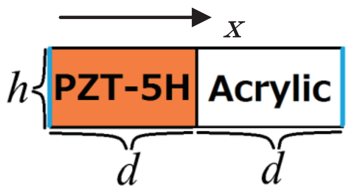

Fig.1 Unit cell model

2.2. S mode wave rectification model

We designed a new acoustic diode model with two parts, *i.e.* the mode conversion part and the mode selection part, and they are different in their periodicity. The band structure of the unit cell in each part is calculated seperately and adjusted to have proper alignment of the bands with each other, as shown in **Fig. 2**. First, the S mode wave at a frequency in the shaded area of Fig. 2 incident from the left side is converted to the hybridized S+A mode at the entrance of the part, and the hybridized wave passes through the conversion part. At the interface with the mode selection part, the S mode wave is blocked and only the A mode wave can pass, since the frequency of the S mode is in the forbidden band in the mode selection part. On the other hand, the incident S mode wave from the right side is blocked at the entrance of the mode selection part. The rectification effect is then achieved. Therefore, there must be the frequency ranges that are pass band for both A and S mode in the mode conversion part while they are forbidden band for S mode and pass band for A mode.

We confirm the S mode rectifying properties described above by numerical simulation for the system shown in **Fig. 3**. The results of the transmission loss for forward and backward incident waves are shown in **Fig. 4**. We obtain 30dB of the transmission loss difference between forward and backward direction at 15.8kHz.

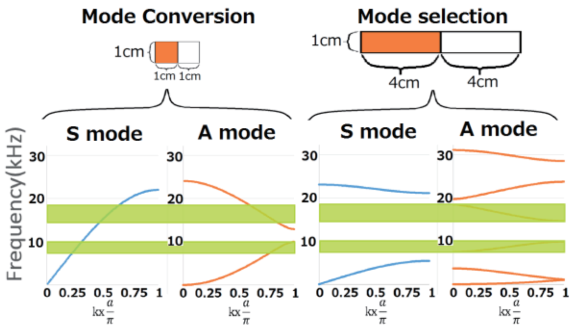

Fig.2 Band structure of two different units of piezo-dielectric composites.

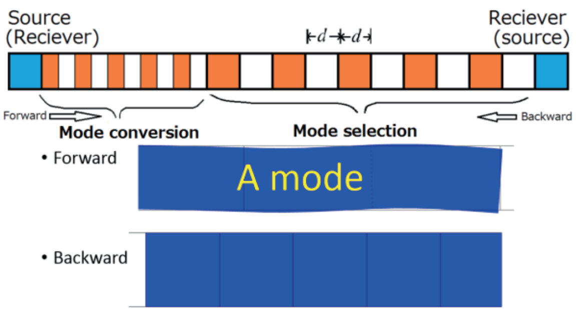

Fig.3 Proposed diode model (upper panel) and propagation analysis at 15.8kHz (middle panel for forward and lower panel for backward propagation).

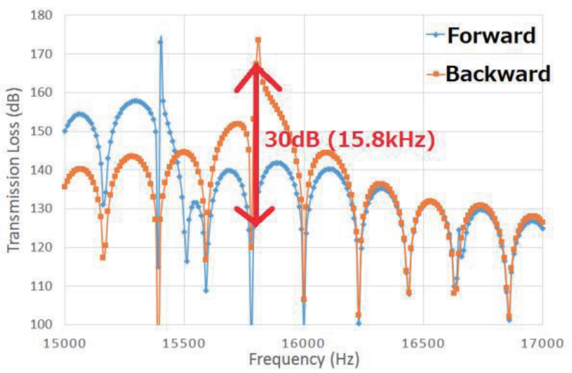

Fig. 4 Transmission loss analysis for S-mode

2.3. A mode rectification model

We also design the rectification of A mode wave generated by the oblique incidence of the wave into the upper and/or lower surfaces of the composite plate. If the frequency is in the A mode band gap and the S mode pass band, the A mode wave is converted into S mode wave at the interface between two structures. Similarly to the S-mode rectification model, an A mode wave incident from the left side is converted to the hybridized S+A mode and only S-mode component passes thourhg the mode selection part. On the other hand, the incident A mode wave from the right side is blocked by the bandgap, and the rectification effect is thus achieved. The transmission loss of this model is depicted in **Fig.5**. We obtain the maximum loss difference of 60dB between forward and backward direction at 17.32kHz.

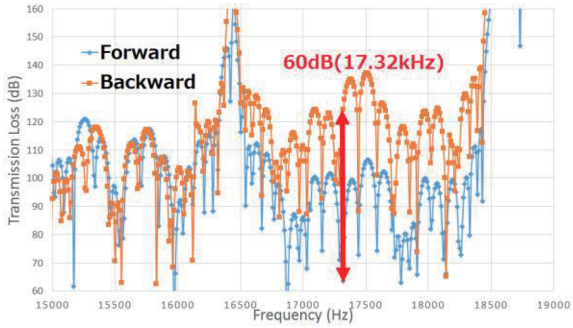

Fig.5 Transmission loss analysis for A-mode rectification model.

In summary, we numerically demonstrated the proposed acoustic-diode model achieved efficient rectification at a particular frequency range for both S-mode and A-mode incidence of the Lamb wave. Detailed analysis, such as the mode-conversion mechanisms and some prototype fabrication, will be reported in the presentation.

References

1. B. Liang, X. S. Guo, J. Tu, D. Zhang and J. C. Cheng, Nature Mater. **9**, 989 (2010)
2. Zhauju Yang, Fei Gao, Xihang Shi, Xiao Lin, Zhen Gao, Yidong Chong, and Baile Zhang, Phys. Rev. Lett. **144**. 114301 (2015)
3. Xin-Ye Zou, Bin Liang, Ying Yuan, Xue-Feng Zhu, and Jian-Chun Cheng, J. Appl. Phys.**114**, 164504 (2013)
4. Tetsuya Kimura, Katsuya Diimon, Takashi Ogami, and Michio Kadota, Jpn. J. Appl. Phys. **52**, 07HD03 (2013)