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Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)

16-18 November, 2016

Band Gap Control with Acoustic Diffraction Modes in Two-dimensional Phononic Crystals

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1. Introduction

Phononic crystals (PCs) are composite materials consisting of periodic scattering structures. PCs have some remarkable properties such as acoustic diffraction, negative refraction, and band gaps. Most previous studies have focused on a search for large band gaps, expecting applications such as acoustic filter, sound barrier, and acoustic imaging. In this paper, we report the control of the band gaps by acoustic diffraction modes in two-dimensional (2D) PCs immersed in water.

2. Theory

The acoustic band gaps are specific frequency ranges that wave cannot propagate through a PC. These are associated with Bragg scattering of acoustic waves with wavelength comparable to the lattice constant of the PC. When the wavelength of the incident beam is of the same order of magnitude as the lattice constant, the surface of the PC tends to behave as a diffraction grating1). At the band gap frequencies, waves are not allowed to propagate through the PC, and reflected backward with diffraction. According to the diffraction law, the zeroth order diffraction mode corresponds to a wave reflected normally upon the surface of the PC, and the non-zeroth order modes correspond to waves reflected obliquely. The acoustic band gaps can be classified into two types by the diffraction modes in a reflection region2). Type A is related to the zeroth order diffraction mode, and Type B is related to the non-zeroth order diffraction modes. From the diffraction law, the frequency of diffraction modes strongly depends on the vertical lattice constant perpendicular to the direction of wave propagation except the zeroth order diffraction mode. This means that the center frequency of the type B band gap can be controlled by adjusting the vertical lattice constant of PCs. In the present study, we theoretically and experimentally investigated the variation of the type B band gap with the vertical lattice constant of PCs.

3. Material and Setup configuration

We fabricated 2D PCs consisting of periodic square arrays of stainless-steel solid cylinders with diameters of 1.0 mm in water. The horizontal lattice constant parallel to the direction of wave propagation was fixed to be 1.5 mm, and the vertical lattice constants perpendicular to the direction of wave propagation were 1.5 and 3.0 mm. The densities of water and stainless steel are 998 and 7800 kg/m^3, respectively. The longitudinal speeds of sound in water and stainless steel are 1500 and 5980 m/s, respectively.

The acoustic wave propagation in the 2D PCs was simulated by using the finite element method (FEM) with help of acoustic module of COMSOL Multiphysics software. At the interfaces between the stainless-steel cylinders and water, the reflecting boundary conditions were imposed; hence, the normal component of the velocity of the water particles is zero in the walls of the cylinders. At the exterior edges of the rectangular computational domain, the absorbing boundary conditions were imposed to avoid any of the energy being reflected. We calculated and visualized the acoustic pressure fields at specific frequencies with COMSOL.

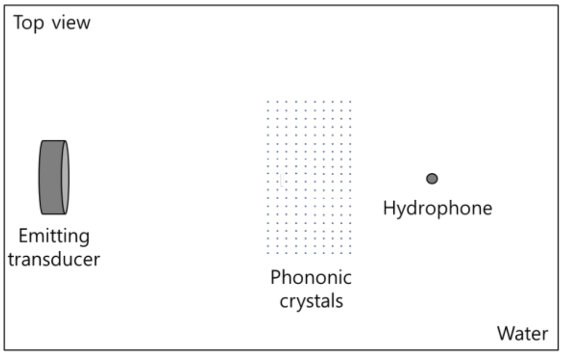

Fig. 1 Top view of the configuration of an emitting transducer, a hydrophone, and a 2D PC for FEM simulations and experimental measurements.

To experimentally measure the transmission coefficients of the PCs, we used a conventional through-transmission method in water. **Fig. 1** shows the top view of the configuration of an emitting transducer, a hydrophone, and a 2D PC for FEM simulations and experimental measurements. Two emitting transducers with center frequencies of 500 and 1000 kHz were used for broadband frequency measurements. The usable bandwidth of the 500 kHz transducer was taken to be from 300 to 700

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kHz, and that of the 1000 kHz transducer was taken to be from 700 to 1300 kHz. A hydrophone was used for receiving transmitted signals in water. The amplitude transmission coefficient as a function of the frequency was determined from the ratio of the magnitudes of the fast Fourier transforms of the transmitted and the reference pulses.

4. Results

The transmission coefficients obtained from the FEM simulations and the experiments are presented in **Fig. 2**. Figs. 2(a) and (b) are the COMSOL results for the two vertical lattice constants of 1.5 and 3.0 mm, respectively. Figs. 2(c) and (d) are the experimental results. As seen in Fig. 2, the experimental results were found to be in reasonable agreement with the FEM simulation results. Fig. 2 (a) and (b) show the change of the width and the center frequencies of band gap. The width of the shaded and the hatched areas decreased at the same time. On the contrary, the center frequency of the hatched area is shifted to lower frequency while the shaded areas are not. From these results, the hatched area is related to the vertical lattice constant. It indicates that the hatched area is the type B band gap.

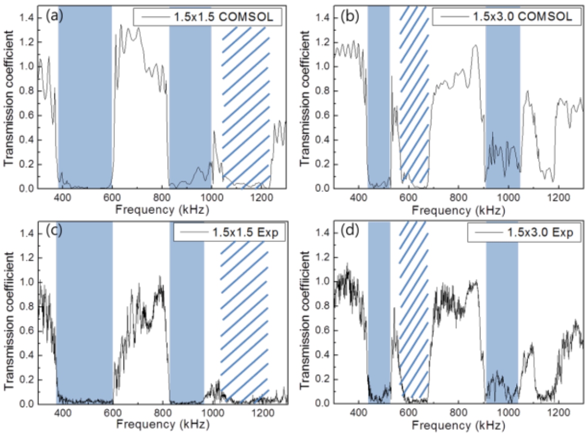

Fig. 2 Transmission coefficients for the two vertical lattice constants: (a) 1.5 mm COMSOL, (b) 3.0 mm COMSOL, (c) 1.5 mm Experiment, (d) 3.0 mm Experiment.

Fig. 3 shows the acoustic pressure fields at specific frequencies lying in the shaded and hatched areas in Fig. 2, as calculated with COMSOL. Figs. 3(a), (c), and (e) are the COMSOL results for the vertical lattice constant of 1.5 mm, and Figs. 3(b), (d), and (f) are 3.0 mm. Figs. 3(a) and (b) demonstrate the acoustic pressure fields at 470 kHz, and Figs. 3(c) and (d) is 960 kHz, respectively. In the figure, the zeroth order diffraction mode exists only. As shown in Figs. 3(e) and (f), lying in the hatched areas, the non-zeroth order diffraction modes exist. This indicates that the shaded areas are the type A band gaps, and the hatched areas are the type B band gaps.

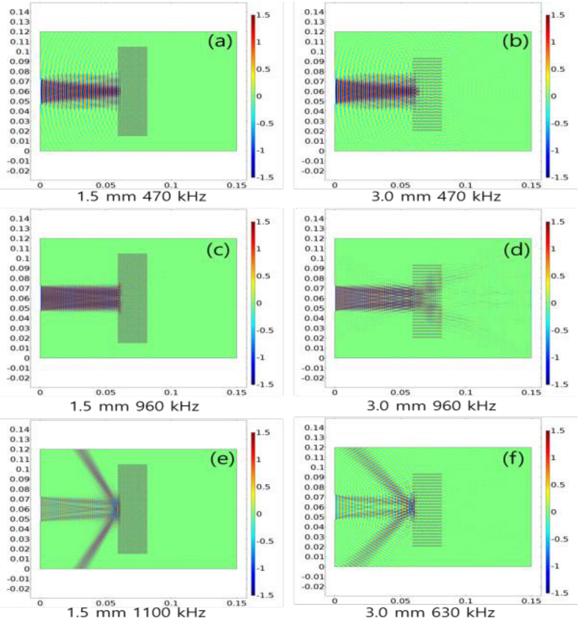

Fig. 3 Acoustic pressure fields: (a) 1.5 mm 470 kHz, (b) 3.0 mm 470 kHz, (c) 1.5 mm 960 kHz, (d) 3.0 mm 960 kHz, (e) 1.5 mm 1100 kHz, (f) 3.0 mm 630 kHz.

5. Conclusion

In this paper, we investigated the control of the band gap in the band structure by acoustic diffraction modes in 2D PCs immersed in water. From the diffraction law, the vertical lattice constants are related to the non-zeroth diffraction modes (type B band gaps). The theoretical and the experimental transmission coefficients were obtained for the two vertical lattice constants of 1.5 mm and 3.0 mm. The center of frequency of certain band gap was shifted and the width also decreased. To understand these phenomena, we considered the acoustic pressure fields at specific frequencies and confirmed that shifted band gap was type B. It is found that type B band gap could be controlled by adjusting the vertical lattice constants.

Acknowledgment

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2014R1A1A1A05002187).

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