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Flat Bands in One-dimensional Solid-Fluid Phononic Crystals

1 次元固体液体フォノニック結晶におけるフラットバンド

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1. Introduction

In phononic crystals (PhCs), there exist the phononic band-gaps (i.e., frequency gaps or phononic stop bands) due to the Bragg reflections of the phonons [1]. Recently, PhCs consisting of solid and fluid layers have been studied [2-4].

Ultrasonic band-gaps were clearly observed for sound propagating through a one-dimensional periodic array of water and perspex plates [2,3]. These studies demonstrated that the frequencies and widths of the ultrasonic band-gaps can be engineered. In these studies, the direction of the propagation is limited to normal to the interface. In this case, mode conversion does not occur at the interfaces between solid and fluid layers. Thus, only the longitudinal vibrational modes were considered.

On the other hand, Hassouani *et al.* studied the sagittal acoustic waves in finite solid-fluid SL theoretically, using the Green's function method [4]. In this paper, they suggested the existence of flat bands in these structures.

In the present paper, we theoretically study the peculiar properties of phonons in PhCs consisting of solid and fluid layers and examine the flat bands.

2. Method of Calculation

We assume that the solid layers are isotropic continuum. In this approximation, the phonon modes polarized in the sagittal plane and the horizontally polarized shear mode are decoupled. Then, sagittal modes are considered.

Next, liquid is assumed to be ideal. In this approximation, viscous shear stresses vanish in the fluid layers and at the interfaces between solid and fluid layers.

The boundary condition we should use is that the stress normal to the interface and the normal component of the velocity of phonon are continuous at the interfaces between solid and fluid layers.

The above boundary conditions are expressed in terms of the transfer matrix. Using the transfer matrix method, we calculate numerically the dispersion relations of the solid-fluid PhCs. Moreover, transmittance of phonons propagating through the finite solid-liquid PhCs are also calculated.

3. Numerical results and discussions

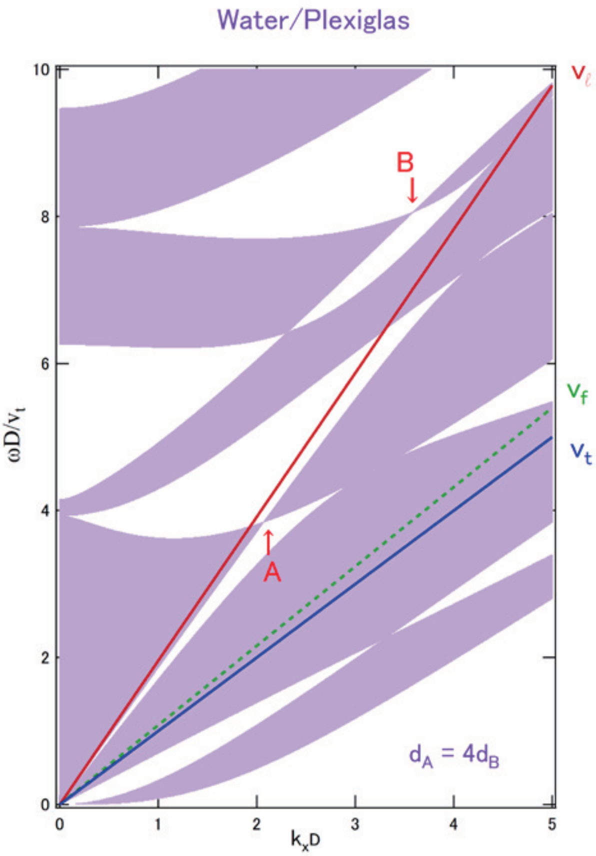

Fig. 1 The phonon dispersion relations calculated for a Plexiglas/water phononic crystal. The thickness d_f of a fluid layer is assumed to be $4d_s$, where d_s is the thickness of a solid layer. The red and blue lines illustrate the longitudinal and transverse velocities in Plexiglas, and the green line is the longitudinal velocity in water.

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As a numerical example, we illustrate in Fig. 1 the phononic band structure of a PhC consisting of water and Plexiglas.

In this calculation, parameters we used are as follows: ρ = 1.20 g/cm³, v_t = 1.38 km/s, and v_ℓ = 2.70 km/s for Plexiglas; ρ = 1.00 g/cm³, v_ℓ = 1.49 km/s for water. The thickness d_f of a fluid layer is assumed to be $4d_s$, where d_s is the thickness of a solid layer.

In Fig.1, the allowed frequencies are plotted for each k_x, which is the wave vector component parallel to the interfaces. That is, the white regions correspond to the phononic band-gaps, and the coloured regions are the allowed frequencies, i.e., the phononic bands. In this figure, the longitudinal and transverse velocities in Plexiglas are shown as the red and blue lines, respectively. In addition, the green line is the longitudinal velocity in water.

The width of a phononic band is a function of k_x. Figure 1 shows that the band widths become zero at several k_x, which are denoted by the points A and B. These correspond to the flat bands, that is, these bands have no dispersion as a function of k_z, the wave vector component perpendicular to the interfaces. This is a noticeable feature of the phononic bands of the solid-fluid PhCs. The point A exits below the red line, whereas the point B is located above this red line.

To demonstrate the flat band, we illustrate in Fig.2 the transmission rates and dispersion relations of the PhC for the incident angle $\theta = 29°$. This angle is slightly different from an angle at which the exact flat band exists. This difference leads to the finite width of the flat band. In the calculations of phonon transmission rates, the PhCs with the periods N=1, 2, 4, and 8 are assumed to be in water. At the frequencies and incident angles corresponding to to points A and B in Fig.1, the width of the phonon band becomes zero exactly.

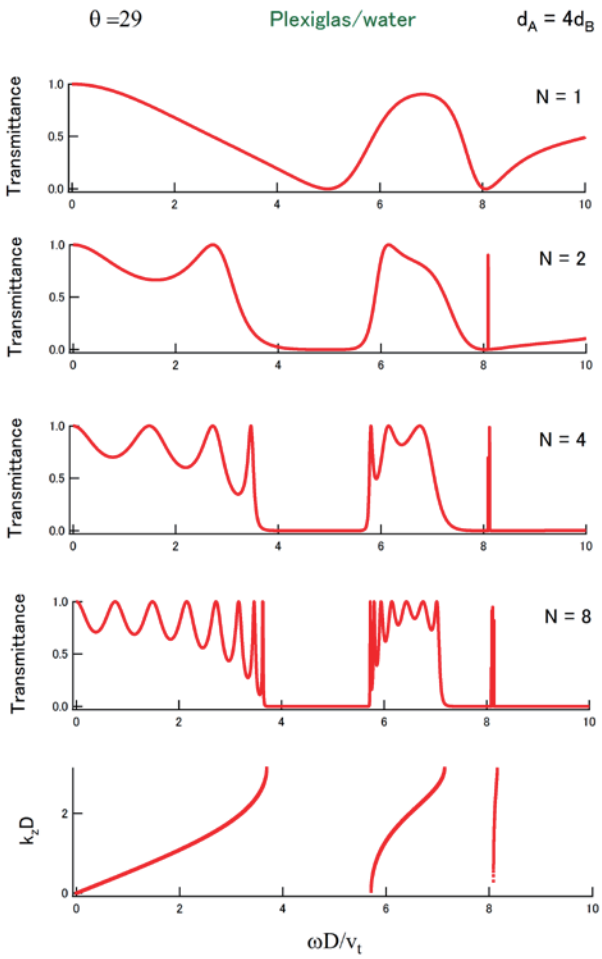

Fig. 2 Phonon transmission rates and dispersion relations of the Plexiglas/water phononic crystals. The propagation angle is assumed to be $\theta = 29°$ in water. In the calculations of phonon transmission rates, the periods of the phononic crystal are assumed to be N=1, 2, 4, and 8.

4. Conclusions

We have numerically calculated the dispersion relations and transmission rates for phonons in a phononic crystals consisting of Plexiglas and water. In these systems, the existence of the flat bands is clearly demonstrated. The velocity and stress fields corresponding to the flat band will be given elsewhere in the near future.

Acknowledgment

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