2P1-2

Interfacial elastic waves in the interface between tunable two-dimensional phononic crystals composed of magneto-elastic materials

磁気弾性体を用いた 2 次元フォノニック結晶界面における界面弾性波の磁場制御

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1. Introduction

Surface acoustic wave (SAW) devices have been developed and exploited for a long time, while devices using interfacial elastic waves (IEWs) propagating along an interfacial boundary between different substances have not attracted much attention. However, the IEW is expected to have the potential of further integration of the device, because it is less influenced by the environment and easy to have multichannel by fabricating the multilayer structure. Nevertheless, the reasons why the IEWs have not been developed until now are the following:
(1) The combination of substances capable of containing IEWs is specified.
(2) Since IEWs propagate inside the substance, we have the difficulty to control them compared with SAWs.

Recently, we have proposed a device combining two different phononic crystals, called a *dual phononic crystal*, as shown in Fig. 1. [1] We found that the band structure and group velocity of the IEWs could be controlled with varying the composition and filling fractions of the constituent materials.

However, the composition and filling fractions of the constituent phononic crystals (PCs) are determined at the time of device fabrication, and we have difficulty to change these quantities after the fabrication. Therefore, to vary the elastic properties after fabrication, we need to use materials with the elastic properties depending on an external field (electric, magnetic, pressure fields) as a constituent material. PCs composed of piezoelectric or magnetoelastic materials have been proposed in previous researches. [2, 3] In particular, Terfenol-D, a magnetoelastic material, has its elastic constants and magnetoelastic coefficients varying approximately three times by the external magnetic field. It has been reported that the phononic bandgap (PBG) is modulated as a function of the external magnetic field in the two-dimensional (2D) PC composed of Terfenol-D. [3]

In the present work, we show the existence in IEWs in a dual 2D PC containing Terfenol-D and investigate the possibility to manipulate the IEWs by an external magnetic field.

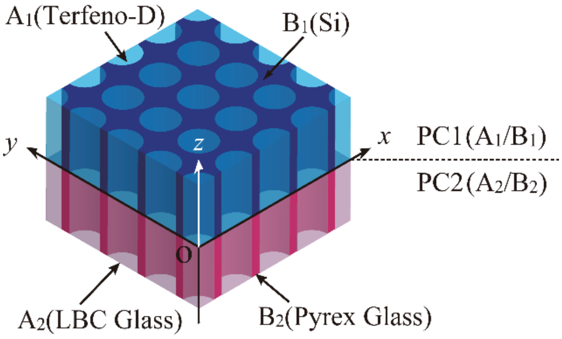

FIG. 1 Schematic diagram of a dual phononic crystal system (PC1+PC2) considered here. The *z*-direction is along the cylindrical axes of 2D PCs. The interface between PC1 and PC2 sets z=0.

2. Model and methodology

Consider a system in which two 2D PCs, PC1 (z>0) and PC2 (z<0), are connected at the z=0 plane, as shown in FIG. 1. PC1 (PC2) is assumed to be a square-lattice PC composed of periodic arrays of Terfenol-D (LBC glass) cylinders embedded into Si (Pyrex glass) substrate. The period of each PC is the same: $a=a_1=a_2$. The radii of the cylinders in PC1 and PC2 are assumed to be r_1 and r_2, respectively. Therefore, the filling fractions of the PC1 and PC2 are expressed as $f_1=\pi r_1^2/a^2$ and $f_2=\pi r_2^2/a^2$, respectively.

The equations of motion governing the displacement **u** and the magnetic flux density **b** in the PC composed of a magneto-elastic material are given by

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j} \quad (i = 1, 2, 3),$$

$$\frac{\partial b_i}{\partial x_i} = 0,$$

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where ρ is the mass density, and σ is the stress tensor. The constitutive equations for the stress and magnetic flux density are

$$\sigma_{ij} = C^H_{ijkl}(H)\frac{\partial u_k}{\partial x_l} + q_{lij}(H)\frac{\partial \phi_m}{\partial x_l} \quad (i,j=1,2,3),$$

$$b_i = q_{ikl}(H)\frac{\partial u_k}{\partial x_l} - \mu_{il}(H)\frac{\partial \phi_m}{\partial x_l} \quad (i=1,2,3),$$

where C^H is magneto-elastically modified elastic constant, q is piezo-magnetic constant, and μ is magnetic permeability. These coefficients are functions of the external magnetic field H. And, ϕ_m is the magnetic potential defined by

$$\mathbf{h} = -\nabla \phi_m ,$$

where $\mathbf{h}$ is the magnetic field in the system.

In the present work, the plane-wave-expansion (PWE) method is used to obtain the displacement vector and magnetic potential of each PCs (PC1 and PC2). Then, obeying Bloch's theorem, the displacement vector and magnetic potential can be expressed as Fourier series:

$$\begin{bmatrix} \mathbf{u} \\ \phi_m \end{bmatrix} = \sum_{\mathbf{G}} \begin{bmatrix} \mathbf{U}_{\mathbf{G}} \\ F_G \end{bmatrix} \exp\left[i\left\{ (\mathbf{k}+\mathbf{G})\cdot\mathbf{x} + \lambda z - \omega t \right\} \right],$$

where $\mathbf{k}=(k_x,k_y)$ is the wave vector in the x–y plane, and $\mathbf{G}=(G_x,G_y)$ is the reciprocal lattice vector. λ is the element of the wave vector in the z-direction. The displacement vectors and the magnetic potential are specified by the following boundary conditions:

$$u_i^{(\mathrm{PC1})}\Big|_{z\to\infty} = u_i^{(\mathrm{PC2})}\Big|_{z\to-\infty} = 0 \quad (i=1,2,3)$$

$$\phi_m^{(\mathrm{PC1})}\Big|_{z\to\infty} = \phi_m^{(\mathrm{PC2})}\Big|_{z=-\infty} = 0 .$$

The conditions at the boundary plane $z = 0$ between the two PCs are as follows:

$$u_i^{(\mathrm{PC1})}\Big|_{z=0} = u_i^{(\mathrm{PC2})}\Big|_{z=0} \quad (i=1,2,3),$$

$$\sigma_{i3}^{(\mathrm{PC1})}\Big|_{z=0} = \sigma_{i3}^{(\mathrm{PC2})}\Big|_{z=0} \quad (i=1,2,3),$$

$$\phi_m^{(\mathrm{PC1})}\Big|_{z=0} = \phi_m^{(\mathrm{PC2})}\Big|_{z=0},$$

$$b_3^{(\mathrm{PC1})}\Big|_{z=0} = b_3^{(\mathrm{PC2})}\Big|_{z=0} .$$

By giving an in-plane wave vector $\mathbf{k}$ and searching ω that satisfies all of the above conditions, we can obtain the dispersion relation of the IEW: $\omega=\omega(\mathbf{k})$.

3. Numerical results

Figure 2 shows the dispersion relation of the IEWs with respect to the wave vector along the Γ–X–M–Γ direction in the x–y plane (the interface).

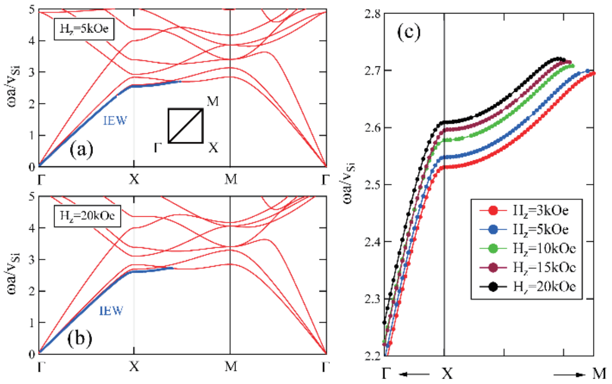

FIG. 2 Dispersion relations of the IEWs along the Γ-X-M-Γ direction in the x-y plane. The external magnetic fields applied along the z direction are (a) H=5 kOe and (b) H=20 kOe, respectively. (c) External magnetic field dependence of the IEW branches around the X point.

In our calculation, we put a=10 mm, f_1=0.45, and f_2=0.5. Figures 2(a) and 2(b) show the results when the external magnetic fields applied in the z-direction are 5 kOe and 20 kOe, respectively. In addition, Figure 2(c) shows the external magnetic field dependence of the IEW branches around the X point in the dispersion relations. Since the elastic constants and the piezo-magnetic constants of Terfenol-D greatly vary with the external magnetic field, we find that the dispersion relations of the IEWs are largely modulated by the external field.

4. Conclusions

Using the PWE method, we have investigated a new phononic-crystal device that can control the propagation of interfacial elastic waves by applying an external magnetic field. The device is composed of the combination of a magneto-elastic PC and a conventional PC. The interfacial elastic wave that exists can be further controlled by not only the combination and shape of the PC material but also the magnitude and direction of an applied magnetic field. Our findings here indicate a possibility of new acoustic/electronic devices utilizing the IEW.

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