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Tunable passband in one-dimensional phononic crystal containing a piezoelectric $0.62Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.38PbTiO_3$ single crystal defect layer

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HIGHLIGHTS

- Investigation of band structure in 1D phononic crystal containing a PMN–0.38PT defect layer.
- Tunable frequency location of passband by external voltage on piezoelectric defect layer.
- Dependence of passband bandwidth on the acoustic impedance ratio of constitutive layer.

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ABSTRACT

Longitudinal acoustic wave propagation in one-dimensional phononic crystal containing a 0.2 mol% Fe-doped relaxor-based ferroelectric $0.62Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.38PbTiO_3$ (PMN–0.38PT) single crystal defect layer is theoretically studied using the transfer matrix method. A passband can be produced in the stopband when the inserted PMN–0.38PT layer with thickness around its half wavelength. The frequency of the passband is closely dependent on the PMN–PT strain coefficient, suggesting that the band structure of phononic crystal is tunable by applying external electric field onto the piezoelectric crystal. Also, we investigated the influence of acoustic impedance of periodic constitutive materials (layers A and B) on the passband, where the bandwidth of the new passband becomes narrower as the acoustic impedance ratio of layer A and B (Z_A/Z_B) increase. The simulated results provide valuable guidance for designing tunable acoustic filters and switches made of phononic crystal consisting of the piezoelectric defect layer.

1. Introduction

Phononic crystals are made of periodic arrays of elastic inclusions in an elastic matrix. Due to the geometry and composition characteristics, it exhibits forbidden gaps of elastic/acoustic wave propagation in the band structure, regardless of wave polarization and propagation directions [1,2]. Typical band gap features can be used to design acoustic devices, such as acoustic/elastic filters, acoustic waveguides, noise control, and improvements in transducer design [3–7]. In addition, acoustic wave dispersion is observed in the band structure of phononic crystals, and thus they are potentially useful in the development of high-resolution acoustic focusing and the acoustic beam autocollimation [8,9]. Moreover, some authors proposed that the passband can be induced inside the stopband by introducing a defect into perfect periodic phononic crystal, which can be used as selective filters or demultiplexing of acoustic waves [10,11].

For some acoustic devices, it is useful to realize tunable phononic crystals, so as to control the band structures, including the existence, location and bandwidth of the stopband and/or passband [12,13]. In order to achieve tunable passband and stopband in phononic crystals, some functional materials were introduced into the periodic structure such as thermally activated shape memory alloy, electrorheological material, dielectric elastomer layer, and magnetoelastic

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material [14–17]. By changing the geometry of the inclusions or by varying the elastic characteristics of the constitutive materials through external stimuli, the band structure of phononic crystal can be adjusted.

Recently, interests in the band structures of phononic crystals based on piezoelectric materials have grown because of their high electromechanical coupling factor and low acoustic impedance [18,19]. More importantly, piezoelectric materials have some advantages over other types of tunable materials, such as shape memory alloys, electro-rheological materials, etc., in terms of accurate control of displacement, quick response time, and small device size [20]. Relaxor-based ferroelectric single crystal, such as $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3–xPbTiO_3$ (PMN–xPT), is very attractive for this application because it demonstrates much better piezoelectric and electromechanical coupling properties than the piezoelectric ceramic [21,22]. Due to the high anisotropy, phononic crystal containing the PMN–0.28PT single crystal poled along different directions shows significant difference in acoustic wave propagation characteristics [23]. The aged 0.2 mol% Fe-doped PMN–0.38PT single crystal is capable of generating a giant recoverable strain due to its reversible domain-switching mechanism [24]. A 0.8% strain can be reached in the $[0\,0\,1]_c$-oriented tetragonal crystal at 1.2 kV/mm external electric field. Moreover, the piezoelectric single crystal has very good temperature stability in a wide temperature range, demonstrating a large electrostrain from room temperature up to 160 °C.

In this paper, we propose theoretically a novel tunable phononic crystal with a defect mode by inserting an aged 0.2 mol% Fe-doped PMN–0.38PT layer into a one-dimensional (1D) phononic crystal. The transfer matrix method was employed to obtain the band structure and to study the passband. We investigated the dependence of passband on the thickness/strain of the piezoelectric defect layer whose thickness can be nonlinearly adjusted by the external electric field. Also, the effect of acoustic impedance of constituent materials (layers A and B) on the band structure was calculated. The simulated results provide theoretical foundation for the design of acoustical filters and acoustic switches.

2. Model and methods

The 1D phononic crystal structure is shown in Fig. 1. The system is composed of periodically alternating layers A and B with thickness d_A and d_B, respectively. Layer C is positioned in the middle of the periodic structure as a defect layer. Thus, the 1D phononic crystal has mirror symmetry about the layer C, and there are two A/B unit cells on each side.

Here, we used the transfer matrix method to study the acoustic wave propagation in 1D phononic crystal. For a normal incident

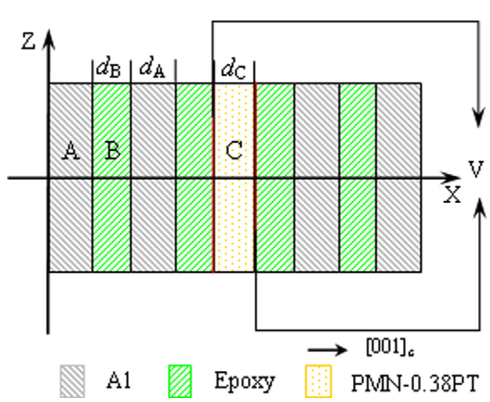

Fig. 1. Structure diagram of the one dimensional (1D) phononic crystal with a 0.2 mol% Fe-doped PMN–0.38PT defect layer.

longitudinal acoustic wave propagating through the phononic crystal from the left to the right, the pressure of the elastic wave in the medium is governed by the following wave equation,

$$\frac{1}{c_i^2}\frac{\partial^2 p}{\partial^2 t^2}-\nabla^2 p=0 \quad (1)$$

where c_i is the elastic wave phase velocity, and the subscript i represents the corresponding layer (A–C). The 1D plane wave solution of Eq. (1) is given by

$$p_i=P_i(x)e^{-i\omega t}=(A_i e^{ik_i x}+B_i e^{-ik_i x})e^{-i\omega t} \quad (2)$$

where the first and second terms on the right side of Eq. (2) represent the forward and reflected waves, respectively, $k_i=2\pi f/c_i$ is the wave number, and f is the wave frequency.

The continuity requirements for wave function and the normal stress at the interface between the sub-layers lead to the following relations [25],

$$M_{ij}=\frac{1}{2}\begin{bmatrix}\frac{Z_j+Z_i}{Z_j} & \frac{Z_j-Z_i}{Z_j}\\ \frac{Z_j-Z_i}{Z_j} & \frac{Z_j+Z_i}{Z_j}\end{bmatrix} \quad (3)$$

$$M_i=\begin{bmatrix}e^{-ik_i d} & 0\\ 0 & e^{-ik_i d}\end{bmatrix} \quad (4)$$

where M_{ij} is the wave matrix at the interface of sub-layers, M_i is the matrix of wave through the same layer, and $Z_i=\rho_i c_i$ is the acoustic impedance of the corresponding layer with the density ρ_i and thickness d_i.

According to the continuity conditions, the incident wave state vector P_0 and the transmitted wave state vector P_N has the following relationship,

$$\overrightarrow{P_0}=M\,\overrightarrow{P_N}=\begin{bmatrix}M_{11}M_{12}\\ M_{21}M_{22}\end{bmatrix}\overrightarrow{P_N} \quad (5)$$

$$\vec{P}_0=(A_0 e^{ik_0 x}, B_0 e^{-ik_0 x}) \quad (6)$$

$$\vec{P}_N=(A_N e^{ik_0 x}, 0) \quad (7)$$

where M is the relation matrix, and N is the number of cells. M can be expressed by

$$M=M_{01}M_1M_{12}M_2M_{21}\cdots M_{23}M_3M_{32}\cdots M_{12}M_2M_{21}M_1M_{10} \quad (8)$$

The transmission coefficient of 1D phononic crystal containing a piezoelectric layer can be represented by

$$T=|t|^2=\left|\frac{A_N}{A_0}\right|^2=\left|\frac{1}{M_{11}}\right|^2 \quad (9)$$

Based on Eqs. (3)–(9), the band structure of 1D phononic crystal can be simulated. In this work, we introduced an aged 0.2 mol% Fe-doped piezoelectric PMN–0.38PT single crystal as the defect layer C due to its giant recoverable field induced strain [24]. Its $[0\,0\,1]_c$ pseudo-cubic direction is parallel to the x-axis, and its thickness d_C can be adjusted by applying the external electric field [24]. In order to realize the expansion and compression of the single crystal, the compliant electrodes, such as carbon conductive grease, can be smeared onto the surface of the defect layer [16]. Because the applied compliant electrode is very thin, we can ignore its impact on wave propagation. The whole phononic crystal is merged into water, and the incident longitudinal acoustic wave has the center frequency f_0 at 1 MHz and frequency range investigated is from 0 to 2 MHz. We first investigated the band structure in the phononic crystal consisting of aluminum (Al, layer A) and epoxy (layer B) with their respective thickness to be $d_A=c_A/4f_0$ and $d_B=c_B/4f_0$. The defect layer C has an adjustable thickness of $d_C=xc_C/2f_0$, where the variable x is associated with the strain of