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Thermal tuning of the interfacial adhesive layer on the band gaps in a one-dimensional phononic crystal

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ABSTRACT

Phononic crystals possess unique acoustic properties due to their artificial periodic structure. They have been used in a wide range of applications such as wave guides, filters, noise suppression, vibration control, etc. In this paper, an analytic model based on the transfer matrix method is established to study the band gaps of P- and SH-waves in a one-dimensional phononic crystal consisting of alternating strips of two different materials bonded by an interfacial adhesive layer. The analysis accounting for the temperature dependent elastic property of the interfacial adhesive layer indicates a different but an effective approach for thermal tuning of the acoustic band structures. It is shown that the first band gap width may decrease over 50% as the temperature increases from 20 °C to 80 °C. These results provide design guidelines for thermal tuning of wave propagation in phononic crystals.

1. Introduction

Phononic crystals made by different materials periodically in one-dimension [1–4], two-dimension [5–12] or three-dimension [13–18] possess superior acoustic properties. For example, it could realize the complete acoustic band gaps, in which the acoustic wave is forbidden for transmission. This feature enables many applications such as vibration control, noise suppression, acoustic transducers, filters, and so on.

Despite the fixed band gaps by designing the geometry and constituents in the phononic crystals, tunable phononic crystals are very attractive for actively changing their band gaps within the same fabricated sample. There are two main approaches to realize tunable phononic crystals. One is to apply external strain [19–21] or initial stress [22,23] to phononic crystals consisting of common materials. For example, Bertoldi et al. [19,20] investigated the deformation-triggered transformations of phononic band gaps in periodic elastomeric structures. Feng and Liu [23] studied the dependence of band gaps on the initial stresses in phononic crystals. The other is to apply external electric or magnetic fields to phononic crystals consisting of smart materials [24–27]. For example, dielectric and electrorheological materials have been proposed to tune the band gaps of phononic crystals since their periodic structure or elastic properties can be changed by an electric field [27].

Recently, temperature has been shown to be an effective routine to tune and control the band gaps due to the temperature sensitive constituents in phononic crystals [28–32]. For example, Jim et al. [28] studied the thermal tuning of a phononic crystal composed of a ferroelectric ceramic and epoxy. Chen [29] investigated the temperature-tuned omnidirectional reflection bands in a one-dimensional finite phononic crystal. The temperature effects on the band gaps of lamb, SH-, P-, and SV- waves were also studied in one- or two-dimensional periodic structure composed of constituents whose elastic properties strongly depend on the temperature. Most of existing studies on thermal tuning of band gaps only account for the temperature sensitive properties of constituents of phononic crystals and ignore the effect of the interfacial adhesive layer. However, the modulus of the interfacial adhesive layer may change one to two orders of magnitude with the increasing temperature, which will induce non-negligible effect on the band gaps.

This paper aims to investigate the thermal effects of the interfacial adhesive layer on the band gaps of P- and SH- waves in a one-dimensional phononic crystal consisting of alternating strips of two different common materials, whose elastic properties are independent of the temperature, bonded by an interfacial adhesive layer, whose elastic properties are sensitive to the temperature.

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The dispersion equations determining the band gaps of phononic crystals are derived in Section 2. The transmission spectra of phononic crystals are presented in Section 3. Section 4 illustrates the results and discussion. The main conclusion is summarized in Section 5.

2. Band gaps of phononic crystals

Fig. 1 schematically shows a one-dimensional phononic crystal with one unit cell composed of alternating strips of two different materials denoting by A and B with the width of a_1 and a_2, respectively. These two materials are bonded by an interfacial adhesive layer with the width of d. The material A (and B) is modeled as a linearly elastic medium in which the equation of motion satisfies

$$\mu\nabla^2\mathbf{u} + (\lambda+\mu)\nabla(\nabla\cdot\mathbf{u}) = \rho\frac{\partial^2\mathbf{u}}{\partial t^2}, \quad (1)$$

where λ and μ are Lamé constants, ρ is the mass density, $\mathbf{u}$ is displacement vector. The interfacial adhesive layer is thin and can be modeled as a spring as shown in Fig. 2 with the normal and shear coefficients given by [33],

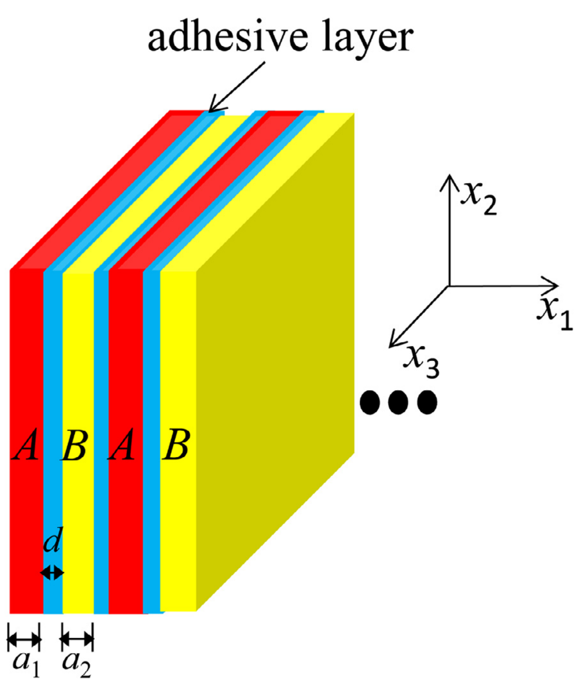

Fig. 1. Schematic diagram of an infinite one-dimensional phononic crystal.

$$k_n = \frac{\lambda^* + 2\mu^*}{d}, \quad k_s = \frac{\mu^*}{d}, \quad (2)$$

where λ^* and μ^* are the Lamé constants of the interfacial adhesive layer, d is the width of adhesive layer. At the interface between A and B within the nth unit cell, the continuous condition is given by

$$\begin{cases} \sigma_{11}^{A_n r} = \sigma_{11}^{B_n l} = k_n(u_1^{B_n l} - u_1^{A_n r}) \\ \sigma_{12}^{A_n r} = \sigma_{12}^{B_n l} = k_s(u_2^{B_n l} - u_2^{A_n r}) \\ \sigma_{13}^{A_n r} = \sigma_{13}^{B_n l} = k_s(u_3^{B_n l} - u_3^{A_n r}) \end{cases}, \quad (3)$$

with the superscripts r, l denoting the right and left side of the interface, respectively. At the interface between the nth and $(n+1)$th unit cell, the continuous condition takes the form as

$$\begin{cases} \sigma_{11}^{A_{n+1} l} = \sigma_{11}^{B_n r} = k_n(u_1^{A_{n+1} l} - u_1^{B_n r}) \\ \sigma_{12}^{A_{n+1} l} = \sigma_{12}^{B_n r} = k_s(u_2^{A_{n+1} l} - u_2^{B_n r}) \\ \sigma_{13}^{A_{n+1} l} = \sigma_{13}^{B_n r} = k_s(u_3^{A_{n+1} l} - u_3^{B_n r}) \end{cases}. \quad (4)$$

2.1. Dispersion equation of p-wave

For an incident P-wave, the reflected and transmitted waves are the combinations of P-wave and SV-wave. The refraction angles of P-wave and SV-wave are defined as θ_1, θ_2 in material A and θ_3, θ_4 in material B. The stress and displacement in A and B in the nth unit cell can be expressed as

$$\begin{Bmatrix} u_1^A \\ u_2^A \\ \frac{\sigma_{12}^A}{i\mu_A k_{2A}} \\ \frac{\sigma_{11}^A}{i\mu_A k_{2A}} \end{Bmatrix}^n = [M_A]\begin{Bmatrix} A_{1,n}e^{ik_{1A}x_1\cos\theta_1} \\ A_{2,n}e^{ik_{2A}x_1\cos\theta_2} \\ A_{3,n}e^{-ik_{1A}x_1\cos\theta_1} \\ A_{4,n}e^{-ik_{2A}x_1\cos\theta_2} \end{Bmatrix} e^{i\kappa x_2 - i\omega t}, \quad (5)$$

and

$$\begin{Bmatrix} u_1^B \\ u_2^B \\ \frac{\sigma_{12}^B}{i\mu_A k_{2A}} \\ \frac{\sigma_{11}^B}{i\mu_A k_{2A}} \end{Bmatrix}^n = [M_B]\begin{Bmatrix} B_{1,n}e^{ik_{1B}x_1\cos\theta_3} \\ B_{2,n}e^{ik_{2B}x_1\cos\theta_4} \\ B_{3,n}e^{-ik_{1B}x_1\cos\theta_3} \\ B_{4,n}e^{-ik_{2B}x_1\cos\theta_4} \end{Bmatrix} e^{i\kappa x_2 - i\omega t}, \quad (6)$$

where

$$[M_A] = \begin{bmatrix} \cos\theta_1 & -\sin\theta_2 & -\cos\theta_1 & \sin\theta_2 \\ \sin\theta_1 & \cos\theta_2 & \sin\theta_1 & \cos\theta_2 \\ \frac{c_{TA}}{c_{LA}}\sin(2\theta_1) & \cos(2\theta_2) & -\frac{c_{TA}}{c_{LA}}\sin(2\theta_1) & -\cos(2\theta_2) \\ \left(2\cos^2\theta_1 + \frac{\lambda_A}{\mu_A}\right)\frac{c_{TA}}{c_{LA}} & -\sin(2\theta_2) & \left(2\cos^2\theta_1 + \frac{\lambda_A}{\mu_A}\right)\frac{c_{TA}}{c_{LA}} & -\sin(2\theta_2) \end{bmatrix}, \quad (7)$$

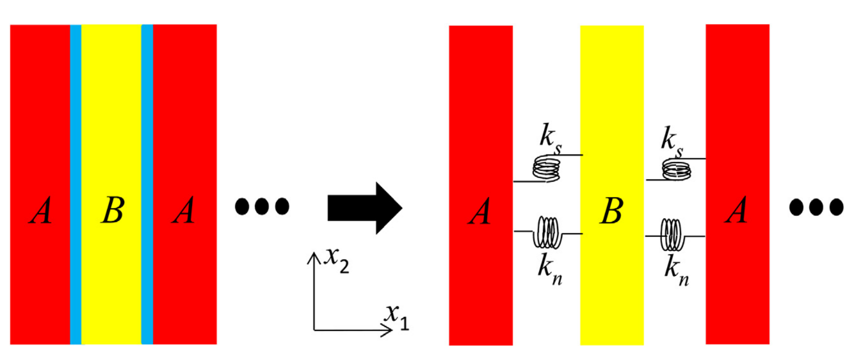

Fig. 2. Schematic diagram of the analytical model for one-dimensional phononic crystal with the interfacial adhesive layers.