ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理
Chinese Physics B

Influence of temperature on the properties of one-dimensional piezoelectric phononic crystals

Ahmed Nagaty, Ahmed Mehaney, Arafa H Aly

Citation: Chin. Phys. B . 2018, 27(9): 094301. **doi:** 10.1088/1674-1056/27/9/094301

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Temperature rise induced by an annular focused transducer with a wide aperture angle in multi-layer tissue

Meng Qi(戚萌), Jiehui Liu(刘杰惠), Yiwei Mao(毛一葳), Xiaozhou Liu(刘晓宙)

Chin. Phys. B . 2018, 27(1): 014301. **doi:** 10.1088/1674-1056/27/1/014301

Acoustic-electromagnetic slow waves in a periodical defective piezoelectric slab

Xiao-juan Li(李小娟), Huan Ge(葛欢), Li Fan(范理), Shu-yi Zhang(张淑仪), Hui Zhang(张辉), Jin Ding(丁劲)

Chin. Phys. B . 2017, 26(7): 074302. **doi:** 10.1088/1674-1056/26/7/074302

Nonlinear response of ultrasound contrast agent microbubbles: From fundamentals to applications

Xu-Dong Teng(滕旭东), Xia-Sheng Guo(郭霞生), Juan Tu(屠娟), Dong Zhang(章东)

Chin. Phys. B . 2016, 25(12): 124308. **doi:** 10.1088/1674-1056/25/12/124308

Low band gap frequencies and multiplexing properties in 1D and 2D mass spring structures

Arafa H Aly, Ahmed Mehaney

Chin. Phys. B . 2016, 25(11): 114301. **doi:** 10.1088/1674-1056/25/11/114301

Interface-guided mode of Lamb waves in a two-dimensional phononic crystal plate

Huang Ping-Ping, Yao Yuan-Wei, Wu Fu-Gen, Zhang Xin, Li Jing, Hu Ai-Zhen

Chin. Phys. B . 2015, 24(5): 054301. **doi:** 10.1088/1674-1056/24/5/054301

Influence of temperature on the properties of one-dimensional piezoelectric phononic crystals

Ahmed Nagaty, Ahmed Mehaney, and Arafa H Aly[†]

Physics Department, Faculty of Sciences, Beni-Suef University, Egypt

(Received 4 May 2018; revised manuscript received 28 May 2018; published online 10 August 2018)

The current study investigates the influence of temperature on a one-dimensional piezoelectric phononic crystal using tunable resonant frequencies. Analytical and numerical examples are introduced to emphasize the influence of temperature on the piezoelectric phononic crystals. It was observed that the transmission spectrum of a one-dimensional phononic crystal containing a piezoelectric material (0.7 PMN-0.3PT) can be changed drastically by an increase in temperature. The resonant peak can be shifted toward high or low frequencies by an increase or decrease in temperature, respectively. Therefore, we deduced that temperature can exhibit a large tuning in the phononic band gaps and in the local resonant frequencies depending on the presence of a piezoelectric material. Such result can enhance the harvesting energy from piezoelectric materials, especially those that are confined in a phononic crystal.

Keywords: phononic crystals, resonant modes, piezoelectric material, thermal properties and temperature

PACS: 43.25.+y, 42.70.Qs, 91.60.Lj, 43.25.+y **DOI:** 10.1088/1674-1056/27/9/094301

1. Introduction

Over the past two decades, the propagation of acoustic/elastic waves using smart composite materials called phononic crystals (PnC) has received significant attention. The most important feature of PnC is the phononic band gap (PBG), which results from Bragg scattering or local resonance phenomena.[1–7] For Bragg scattering, the PBG is created at the boundary of the Brillion zone and its frequency is approximately equal to the lattice constant.[8–10] Liu *et al.* introduced the local resonance phenomena in a three-dimensional PnC, and the frequency of the PBG is two orders of magnitude smaller than its counterpart in Bragg scattering.[10] Owing to the presence of the PBG, PnCs have many significant applications, such as in acoustic filters, sensors, and waveguides.[11–15]

The resonance in PnCs is a very important phenomenon. The resonant mode (RM) can be generated inside the PBG by the introduction of defects in a regular PnC and it is defined as the maximum transmission peak inside the PBG.[16,17] These RMs are used widely in sensing applications owing to the link between the resonance frequency and the acoustic properties of the constituent materials.[18] RM can be altered and controlled using many parameters. Zubtsov *et al.* altered the position of the defect modes in PBGs by changing the concentration of the defect material.[16,18] In addition, Wang *et al.* could control the position of the RM by controlling the applied voltage based on the piezoelectric defect layer.[19]

Recently, new trends in PnCs have been studied and applied in society. Piezoelectric PnC is an important trend in the field of PnCs. Piezoelectric PnC is a PnC whose composite material contains a piezoelectric material. By using the plane wave expansion method, the 1-3 type piezoelectric composite has been studied by Wilm *et al.*[20] Li *et al.* analyzed the localization of the waves using disordered periodic layered piezoelectric composites.[21–23] Pang *et al.* studied the band structure of piezoelectric/piezomagnetic PnCs.[24] Aly *et al.* studied the effect of an external electric field on the position of the RM inside the band gap of a piezoelectric PnC.[25] The effects of initial stresses on the dispersion relations of elastic waves in a one-dimensional (1D) piezoelectric phononic crystal were studied by Guo and Wei.[26] The anisotropic nature of piezoelectric materials and the mechanic–electronic coupling nature are the most evident differences between the piezoelectric and isotropic materials.

In this paper, we present a 1D piezoelectric PnC analyzed using the transfer matrix method. In addition, we will introduce the influence of the relationship between the temperature and piezoelectric coefficient on the RM position inside the band gap. It is concluded that our structure can be used as a temperature sensor.

2. Theoretical analysis and modeling

The 1D PnC structure, which is composed of periodically alternating layers of aluminum and epoxy with thicknesses of a_1 and a_2, respectively, is presented in Fig. 1. The defect layer of a piezoelectric material (0.7 PMN-0.3PT) is positioned in the middle of the periodic structure. Thus, the 1D PnC has a mirror structure around the defect layer. We have studied the propagation of a longitudinal acoustic wave through a 1D PnC structure by using the transfer matrix method. The equation of

[†]Corresponding author. E-mail: arafa.hussien@science.bsu.edu

© 2018 Chinese Physical Society and IOP Publishing Ltd

the incident wave is given by

$$\frac{1}{c_j^2}\ddot{\gamma} = \nabla^2\gamma, \tag{1}$$

where c_j is the elastic wave phase velocity and j represents the layer type (Al, epoxy, or 0.69 PMN-0.31PT).

The solution of Eq. (1) is

$$\gamma = (A_1 \mathrm{e}^{\mathrm{i}k_j x} + A_2 \mathrm{e}^{-\mathrm{i}k_j x})\mathrm{e}^{-\mathrm{i}\omega t}, \tag{2}$$

where $k_j = 2\pi f/cj$ is the wave number and f is the frequency of the incident wave. By using the analysis of transfer matrix method obtained from Refs. [27]–[29] and applying the continuity conditions, we deduce the following two wave matrices:

$$K_{ij} = \frac{1}{2}\begin{bmatrix} \frac{Z_j + Z_i}{Z_j} & \frac{Z_j - Z_i}{Z_j} \\ \frac{Z_j - Z_i}{Z_j} & \frac{Z_j + Z_i}{Z_j} \end{bmatrix}, \tag{3}$$

$$K_j = \begin{bmatrix} \mathrm{e}^{-\mathrm{i}k_i d} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}k_i d} \end{bmatrix} \tag{4}$$

Equations (3) and (4) represent the wave matrix at the interface between the two layers and the wave matrix through each layer, respectively. $Z_j = \rho_j c_j$ is the acoustic impedance of each material (ρ_j is the material density and c_j is the longitudinal speed of sound). We investigate the relationship between the incident γ_o and transmitted γ_N wave state vectors as follows:

$$\gamma_o = K\gamma_N, \tag{5}$$

where K is the accumulative transfer matrix and we can calculate the transmission coefficient of the 1D PnC structure using the following relation:

$$T = \left|\frac{1}{K_{11}}\right|^2, \tag{6}$$

where K_{11} is the first element of the accumulative matrix K.

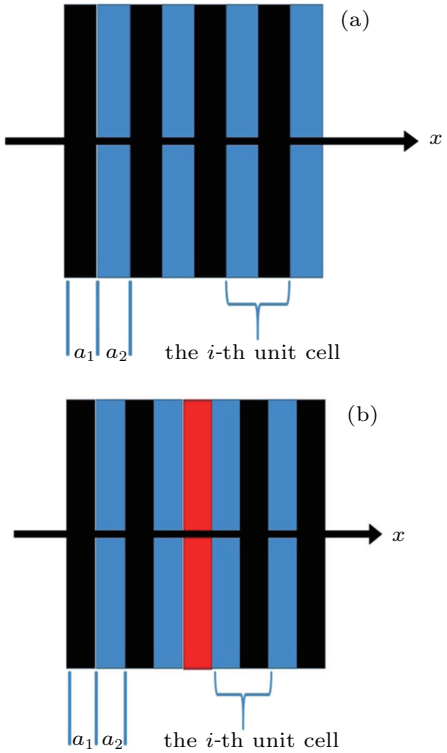


Fig. 1. (color online) (a) PnC structure composed of a periodic structure of Al and epoxy layers and (b) defected PnC structure with 0.7 PMN-0.30PT as a defect layer.

Table 1. Material constants used in the calculations.[9,19,28,29]

Materials	Density/kg·m^3	C_L/m·s^{-1}	Thermal expansion coefficient β/°C
Al	2700	6400	23.9×10^{-6}
Epoxy	1180	2535	22.5×10^{-6}
Water	1000	1400	–
0.7 PMN-0.3PT	7901	4610	–

3. Results

3.1. 1D Piezoelectric PnC structure

In this section, we consider the propagation of normal incident acoustic waves in a 1D PnC composed of four unit cells with each unit cell composed of Al/epoxy. We assume that the entire structure is bounded by water as a semi-infinite material. The presence of water does not support the shear waves through the structure. The thicknesses of the first and second layers are $a_1 = \frac{C_{\mathrm{L}1}}{4\times10^6}$ m and $a_2 = \frac{C_{\mathrm{L}2}}{4\times10^6}$ m, respectively, where $C_{\mathrm{L}1}$ and $C_{\mathrm{L}2}$ are the longitudinal sound speeds of the first and second layers, respectively. We obtain the transmission spectra for perfect and defected PnCs as a function of the normalized frequency ($\omega a/2pi C_\mathrm{L}$), where ω is the angular frequency, $a = a_1 + a_2$ is the lattice constant, and C_L is the longitudinal speed of sound in the first layer.

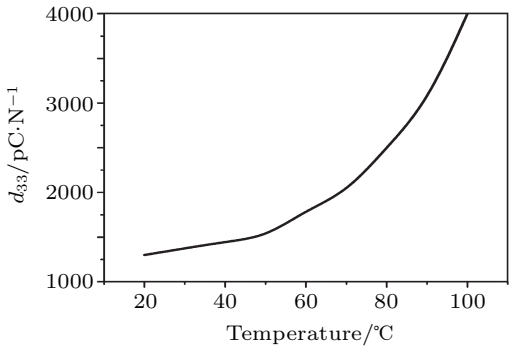


Fig. 2. Relationship between temperature and piezoelectric constant d_{33}.[16]

Figure 2 shows a correlation between the piezoelectric constant (d_{33}) and the increase in temperature.[30] As depicted in the figure, the piezoelectric constant increases with the increase in temperature owing to the increase in the movement of electric dipoles, phase transition, softening of Young's modulus, and increased mobility of the domain with temperature. We will perform our calculations based on this relationship.

From Fig. 3(a), we can observe that there is a large band gap from $\frac{\omega a}{2\pi i c_{\rm L}} = 0.17$ to $\frac{\omega a}{2\pi i c_{\rm L}} = 0.55$, resulting from the constructive interference of incident and reflected waves owing to Bragg scattering. Subsequently, we insert a layer of piezoelectric material (0.7 PMN-0.3PT) as a defect layer with the thickness of $\frac{C_{\rm L3}}{2\times 10^6}$ m, where $C_{\rm L3}$ is the longitudinal speed of sound in 0.7 PMN-0.30PT. It is known that piezoelectricity and piezomagnetism are phenomena where electrical and magnetic energy, respectively, are converted into mechanical energy and vice versa.[31–35] In the present calculations, we depend mainly on the well-known relation, $d = d_{33}E$, where d is the produced strain, d_{33} is the piezoelectric coefficient, and E is the electric field strength. Such piezoelectric materials are characterized by their high piezoelectric coefficient ($d_{33} = 2500$ PC/N), and they introduce extremely large piezoelectric strains (1.7%) as compared with ordinary ceramic piezoelectric materials.[27]

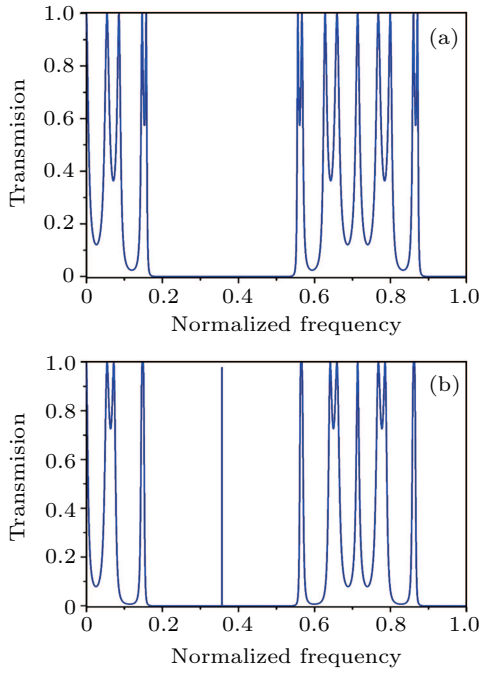


Fig. 3. (color online) Transmission spectra for (a) PnC composed of a periodic structure of Al and epoxy layers. (b) Defected PnC with 0.7 PMN-0.3PT with the thickness of $C_{\rm L3}/2\times 10^6$ m.

We can observe from Fig. 3 (b) that the band gap increased and an RM appeared in the middle of the band gap. The transmitted peak inside the band gap is formed owing to wave localization inside the defect layer. The defect layer acts as a trap for the incident mechanical energy and affects the periodicity of the perfect structure. Based on these assumptions, which are mentioned extensively in many literatures about the defected PnCs,[4,6] a sharp transmitted peak appeared inside the band gap of our PnC model. The resulting RM can be used as a sensor for specific frequencies. In addition, the position of the induced resonant peak resulting from the piezoelectric material inside the phononic structure can be controlled by applying an external electric field. Hence, the phononic structure can be considered as an acoustic switch.[19] In addition, the thickness of the piezoelectric material can be adjusted by applying an external electric field, which, in turn, changes the resultant strain induced inside the piezoelectric material.

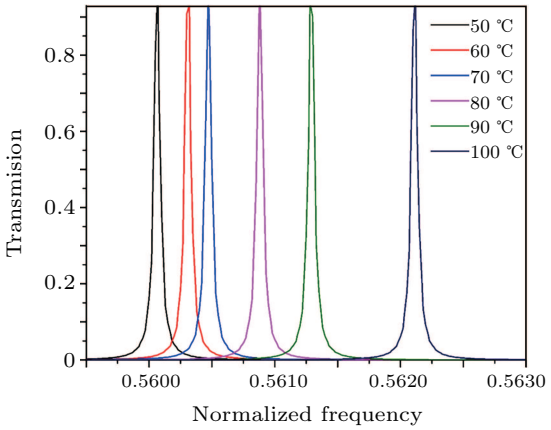


Fig. 4. (color online) Transmission spectra of defected PnC with 0.7 PMN-0.3PT at different temperatures.

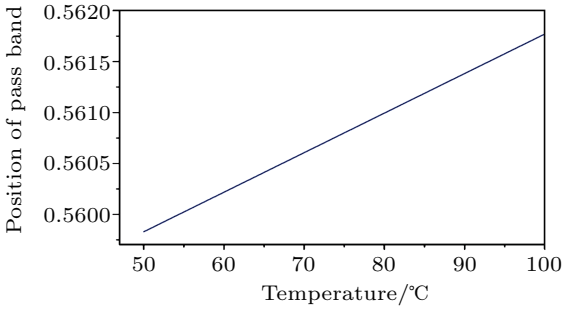


Fig. 5. (color online) Relationship between temperature and the position of passband inside the band gap.

Figure 4 shows the effects of temperature on the defected 1D PnC structure. We varied the temperature from 50 °C to 100 °C. The range of operating temperature results in a noticeable change only in the piezoelectric material because its effect on the other materials is negligible, as they require higher temperatures.[9] We can observe that the temperature has a significant effect on the position of RM owing to the softening of Young's modulus of 0.7 PMN-0.3PT, thus changing the longitudinal speed of sound in 0.7 PMN-0.3PT.[27] Thus, by increasing the temperature, the position of RM can be tuned and adjusted inside the band gap. Figure 5 shows the relationship

between the temperature and the position of RM inside the band gap. With the increase in temperatures, the RM moves toward higher frequencies.

4. Conclusion

In this study, we investigated the effects of temperature on the transmission properties of a 1D piezoelectric PnC structure. The results revealed that inserting a piezoelectric material (0.7 PMN-0.3PT) inside a perfect PnC could produce a sharp resonant peak inside the transmission spectrum of the PnC. Such a peak is significantly shifted toward higher frequencies with an increase in temperature. Moreover, it can be shifted toward lower frequencies with a decrease in temperature. Therefore, tuning the band gaps in PnCs can be easily achieved by changing the temperature. In summary, to the best of our knowledge, this is the first time that PBGs were tuned by controlling the temperature.

References

[1] Cheng Y, Liu X J and Wu D J 2011 *J. Acoust. Soc. Am.* **129** 1157
[2] Aly A H and Mehaney A 2012 *Physica B* **407** 4262
[3] Maldovan M and Thomas E L 2008 *Periodic Mater. Interference Lithography: For Photon. Phononics Mech.* 1st edn. (Wiley-VCH)
[4] Aly A H, Mehaney and El Rahman E A 2013 *Int. J. Mod. Phys. B* **27** 1350047
[5] Khelif A and Adibi A 2016 *Phononic Cryst. Fundamentals Appl.* 1st edn. (New York: Springer Science and Business Media)
[6] Aly A H and Mehaney A 2017 *Ind. J. Phys.* **91** 1021
[7] Wang T, Sheng M P, Wang H and Qin Q H 2015 *Acoust. Aust.* **43** 275
[8] Aly A H, Nagaty A and Khalifa Z 2017 *Int. J. Mod. Phys. B* **31** 1750147
[9] Aly A H and Mehaney 2015 *Int. J. Thermophys.* **36** 2967
[10] Aly A H, Mehaney A and Eissa M F 2015 *J. Appl. Phys.* **118** 064502
[11] Zhang X, Liu Z Y, Liu Y Y and Wu F G 2003 *Phys. Lett. A* **313** 455
[12] Khelif, Choujaa A, Benchabane, Rouhani B D and Laude V 2005 *Europhys. Lett.* **71** 570
[13] Maznev A A, Lomonosov A M, Hess P and Kolomenskii Al A 2003 *Eur. Phys. J. B* **35** 429
[14] Aly A H, Mehaney A and Hanafey H S 2012 *Prog. Electromagnetics Res. Symp. Proceeding* March 27–30, 2012 Kuala Lumpu, Malaysi, p. 104
[15] Aly A H, Mehaney A and El-Nagga S A 2017 . *Supercond. Nov. Mag.* **30** 2711
[16] Arango S V, Sánchez D B, Torres R, Kyriacou P and Lucklum R 2017 *Sensors* **17** 1960
[17] Aly A H and Mehaney A 2016 *Chin. Phys. B* **25** 114301
[18] Zubtsov M, Lucklum R, Ke M, Oseev A, Grundmann R, Henning B and Hempel U 2012 *Sens. Actuat. A* **186** 118
[19] Wang Y, Song W, Sun E, Zhang R and Cao W 2014 *Physica E* **60** 37
[20] Wilm M, Ballandras S, Laude V and Pastureaud T 2002 *J. Acoust. Soc. Am.* **112** 943
[21] Li F M and Wang Y S 2005 *Int. J. Solids Struct.* **42** 6475
[22] Li F M and Wang Y S 2006 *J. Sound Vib.* **296** 554
[23] Li F M, Xu M Q and Wang Y S 2007 *Solid State Commun.* **141** 296
[24] Pang Y, Liu J X, Wang Y S and Fang D N 2008 *Acta Mech. Solida Sin.* **21** 483
[25] Aly A H, Nagaty A and Khalifa Z 2018 *Surf. Rev. Lett.* 1850144
[26] Guo X and Wei P 2016 *Int. J. Mech. Sci.* **106** 244
[27] Cao W and Qi W 1995 *J. Appl. Phys.* **78** 14627
[28] Long H, Cheng Y, Zhang T and Liu X 2017 *Acoust. So. Am.* **142** EL69
[29] Wang Y Z, Li, F M, Kishimoto K, Wang Y S and Huang W H 2010 *Arch. Appl. Mech.* **80** 629
[30] Uchino K 2010 *Advanced Piezoelectric Materials Science and Technology* (Wood head Publishing)
[31] Wang Y Z, Li F M, Kishimoto K, Wang Y S and Huang W H 2008 *Acta Mech. Solida Sin.* **21** 529
[32] Wang Y Z, Li F M and Wang Y S 2016 *Int. J. Mech. Sci.* **106** 357
[33] Wang Y Z and Wang Y S 2018 *Wave Motion* **78** 1
[34] Aly A H, Nagaty A, Khalifa Z and Mehaney A 2018 *J. Appl. Phys.* **123** 185102
[35] Nagaty A, Mehaney A and Aly A H 2018 *J. Supercond. Nov. Magn.*