TUNABLE PHONONIC WAVEGUIDE: FINITE ELEMENT ANALYSIS

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In this study, the band structure of the phononic crystal with square lattice consisting of piezoelectric cylindrical rods and the transmission loss of finite structure was calculated by the finite element method. The band structure along the *Γ-X-M-Γ* path was obtained by applying Floquet periodicity conditions to the side walls and the free boundary conditions on the top and bottom surfaces of the three-dimensional unit cell, which is periodic in the *x* and *y* directions, infinitely in the *z* direction. A 17x17 array was created from $LiTaO_3$ rods to show transmission losses and adjustable waveguide formation. The perfectly matched layer boundary condition is applied to the beginning and end of the finite structure, and symmetry boundary conditions are applied to the side walls in the *x* direction. The bottom surfaces of all $LiTaO_3$ cylindrical rods are defined as ground potential. To demonstrate the usability of the finite structure as an adjustable waveguide, it has been shown that the wave applied from the input travels along this path by applying a 5V DC voltage to the upper surfaces of the rods in the desired path.

Keywords: Piezoelectric material, Phonoic crystal, Tunable waveguide, Finite element analysis

INTRODUCTION

Phononic crystals (PnC), which have interesting properties such as band gap [2], negative refraction [1], wave focus [3,4], are of great interest due to their potential application areas and new properties.

Many studies have been done on the band structures of PnCs [5-8] and PnC based high performance detection systems [9-11]. One of the important features of PnCs is that they have forbidden bands that do not allow waves of certain frequencies to advance.

In the literature, there are many studies using the waveguide obtained by removing some bars in PnCs with wide forbidden bands [12-15]. One of them is the active waveguide made using piezoelectric material [16].

In PnC, instead of the static waveguide made by removing some rods, an adjustable waveguide can be designed by using the coupling feature of piezoelectric materials. In the waveguide where piezoelectric material is used, each bar can be controlled separately and the desired path can be set as a waveguide. In recent years, micrometer scale PnC waveguides and radio frequency (RF) communication and micro electromechanical systems (MEMS) have emerged.

In this study, it has been shown that a wide band gap PnC is designed with finite element method and piezoelectric rods, independent circuits can be controlled and an adjustable waveguide that allows the wave to move along the desired path.

THEORY

Equations 1 and 2 describe the structural equations of piezoelectric materials.

$$T = cS - e^{T}.E \tag{1}$$

$$D = eS + \varepsilon.E \tag{2}$$

In these equations, *T, S, E, D* are stress, strain, electric field and electric density, *c, e* and *ε* are values of elastic stiffness, piezoelectric coupling and electrical permittivity respectively.

When voltage is applied to rods made of piezoelectric material, the coupling effect "e" in equations 1 and 2 disappears. The dispersion effect of PnC will be different depending on whether the voltage is applied (on) to the piezoelectric rods or not (off). If the piezoelectric rods are arranged periodically in the x-y plane and the polarization is in the z-axis direction, the out-of-plane (in the z-axis direction) displacement will be affected due to the piezoelectric coupling. When no voltage is applied to the circuits connected to the piezoelectric rods, waves with frequencies in forbidden bands cannot propagate in a periodic structure, while when voltage is applied to the circuits, the band will disappear and allow the wave to propagate.

MATERIAL AND METHOD

The lattice constant of the unit cell of the phononic crystal with a square lattice is a=30 mm, the cylinder radius is r=6 mm, and the height is $h=0.25\times a$ (Figure 1). In order to obtain the band structure of the PnC, the 3-dimensional (3D) unit cell in Figure 1 was used. By applying the Floquet Periodicity Boundary Conditions to the side walls of the unit cell in the *x* and *y* axis direction (surfaces no 1-2, 3-4), the band structure was obtained in the 1st Brillouin region along the Γ-X-M-Γ path. In order to compare the band structure and the transmission losses of PnC, a finite structure consisting of 17×17 $LiTaO_3$ rods placed in the epoxy matrix was used in Figure 2a. *Perfectly Matched Layer* (PML) was applied to the right and left edges, and *Symmetry Boundary Condition* was applied to the lower and upper edges (Figure 2.b and c). Transmission loss was calculated by applying a force of 1 N/mm^2 in the *x*, direction and -1 N/mm^2 in the *z* direction to the left edge of the building in the frequency domain in the

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frequency domain, in the frequency domain, in the range of 15kHz-55kHz. The bottom of the piezoelectric rods in Figure 2a were defined as ground potential. In Figure 2 b and c, 0V voltage was applied to the upper area of the green bars, 0V then 5V voltage was applied to the upper area of the red rods. It was observed that when a 0V voltage is applied, waves with frequencies in the forbidden bands in the band structure cannot propagate in the structure, while when a 5V voltage is applied to the same rods (red ones), it works as a waveguide where the waves can propagate.

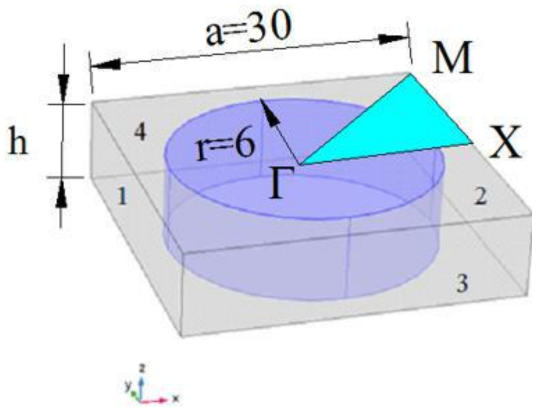
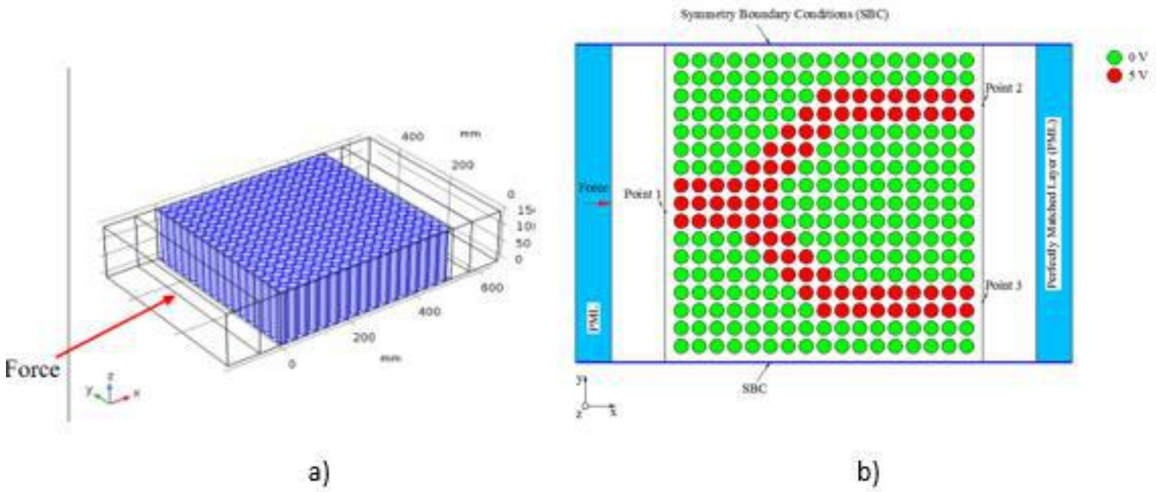


Fig. 1. Three-dimensional unit cell and 1st Brillouin zone



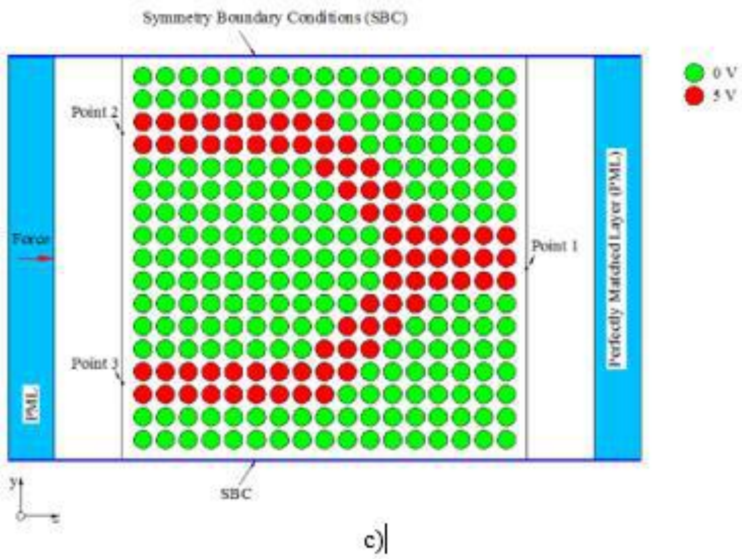


Fig. 2. a) Phononic crystal in finite structure b) appearance of the model 1 waveguide in the *xy* plane c) appearance of the model 2 waveguide in the *xy* plane.

RESULTS AND DISCUSSION

In Figure 3, the band structure obtained by using the unit cell, and in Figures 4 and 5, the transmission losses obtained when I apply 0V (blue graphic) and 5V (green graphic) voltage to the finite PnCs of model 1 and model 2. As it is clearly seen from the figure, waves cannot propagate in the structure when applying 0V voltage, but when 5V voltage is applied to the same rods, the PnC allows the waves to pass by acting as a waveguide.

According to the transmission loss graphs of the finite model 1 and 2 in Figures 4 and 5, the propagation of the 27 and 49 kHz frequency waves in the forbidden band is seen according to the off and on position of the switches applying voltage to the piezoelectric rods (Figure 6-9). As it is clearly seen from the figures, waves cannot move when 0V voltage is applied to the piezoelectric rods in the waveguide, but waves can progress when 5V voltage is applied.

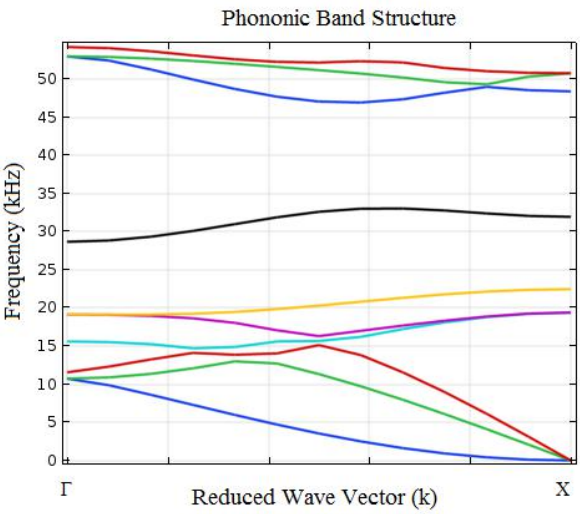


Fig. 3. Band structure of PnC.

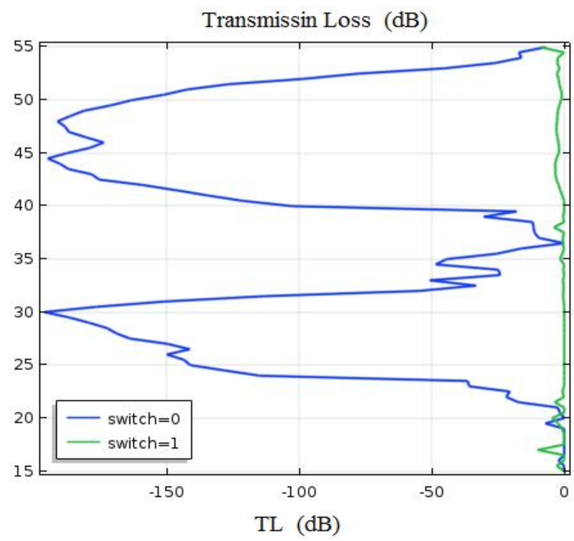


Fig. 4. Transmission loss of the model 1 waveguide.

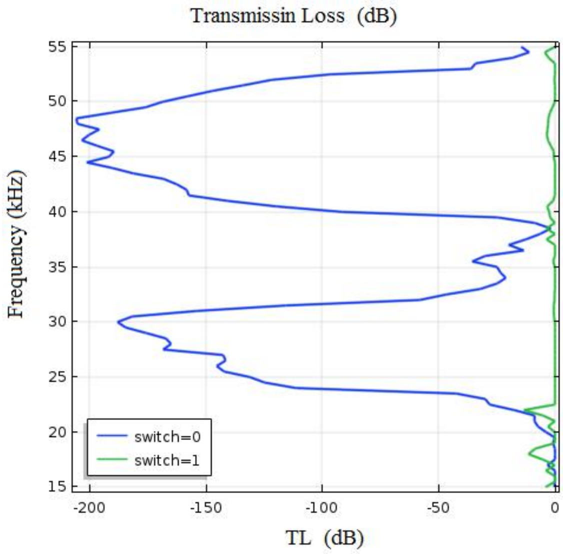


Fig. 5. Transmission loss of the model 2 waveguide.

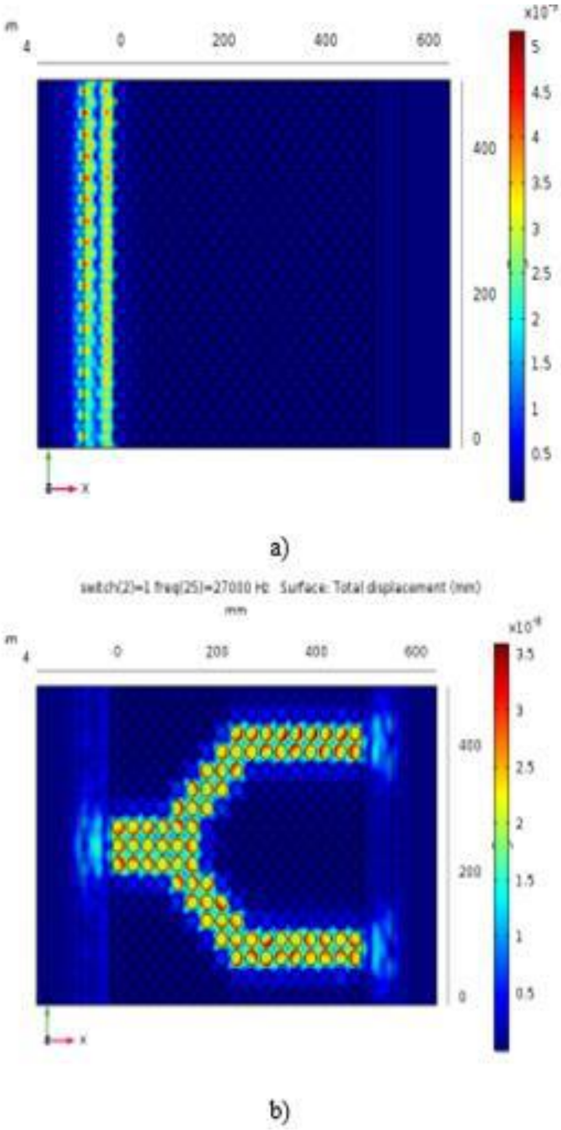


Fig. 6. Propagation of the wave with a frequency of 27 kHz in the model 1 waveguide when a) 0V and b) 5V is applied.

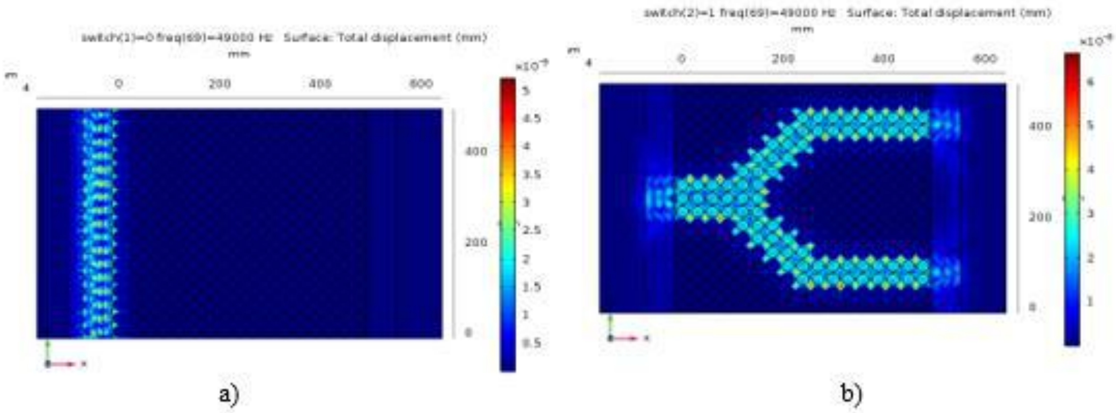


Fig. 7. Propagation of the wave with a frequency of 49 kHz in the model 1 waveguide when a) 0V and b) 5V is applied.

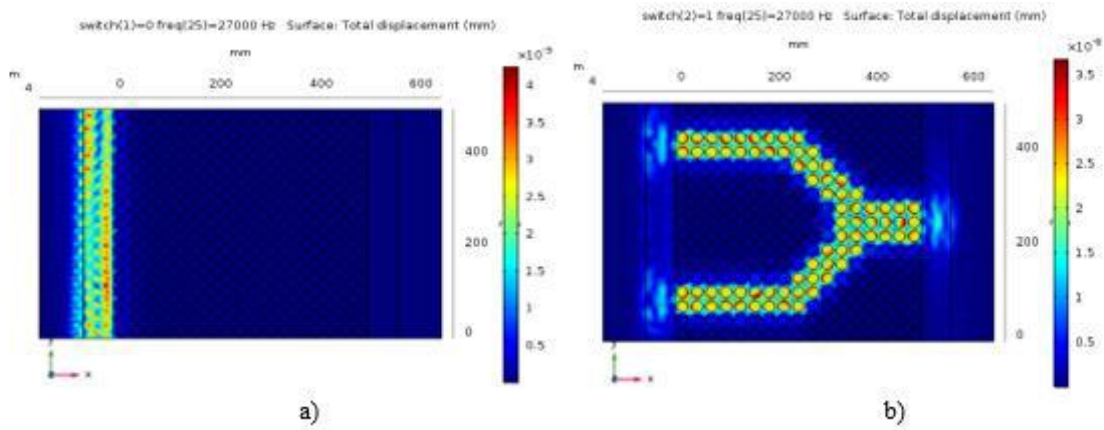


Fig. 8. Propagation of the wave with a frequency of 27 kHz in the model 2 waveguide when a) 0V and b) 5V is applied.

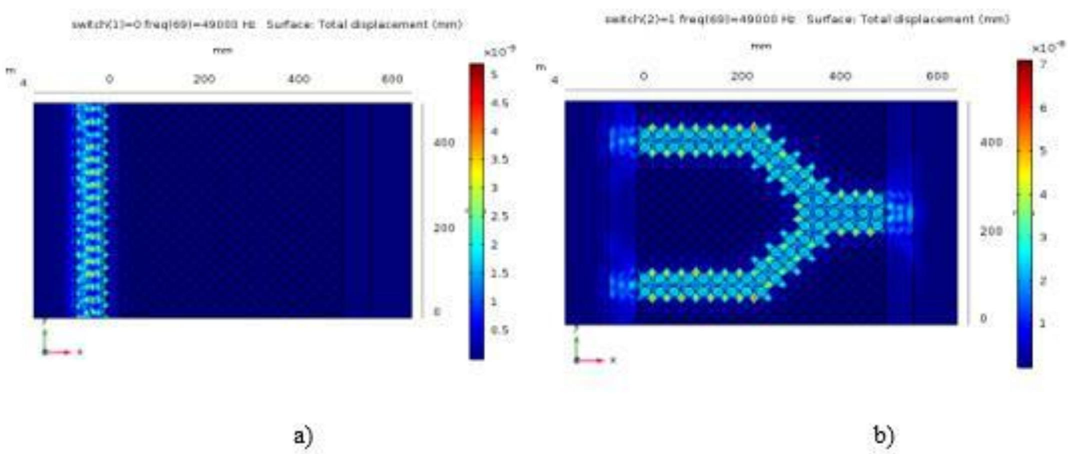


Fig. 9. Propagation of the wave with a frequency of 49 kHz in the model 2 waveguide when a) 0V and b) 5V is applied.

CONCLUSION

The result of this study shows that instead of the static waveguide created by removing the rods in classical PnCs, a PnC consisting of piezoelectric rods can form waveguides that can be dynamically shaped along the desired path. The circuits connected to the piezoelectric rods in the desired path of the wave can be switched and the PnC can be used as an tunable waveguide. PnC, consisting of piezoelectric rods contained in epoxy resin, can work as a waveguide since it has a forbidden band. The piezoelectric rods are connected in separate circuits, making it possible for each to be easily controlled independently, thus precisely guiding the wave. With the wave guiding method designed in this way, integrated elastic waveguiding devices can be developed.

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