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Absolute band gaps and waveguiding in free standing and supported phononic crystal slabs

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Abstract

Using the finite element method (FEM), we investigate the existence of absolute band gaps and localized modes associated with a guide in thin films of phononic crystals. Two different structures based on two-dimensional (2D) phononic crystals are considered, namely a free standing plate and a plate deposited on a silicon substrate. The 2D phononic crystal is constituted by a square array of cylindrical holes drilled in an active piezoelectric PZT5A matrix. We demonstrate the existence of absolute band gap in the band structure of the phononic crystal plate and, then, the possibility of guided modes inside a linear defect created by removing one row of air holes. In the case of the supported plate, we show the existence of an absolute forbidden band in the plate modes when the thickness of the substrate significantly exceeds the plate thickness.

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Keywords: Phononic crystals; Plates; Absolute forbidden band; Waveguide

1. Introduction

Phononic crystals are heterogeneous materials constituted by a periodical repetition of inclusions in a matrix. Associated with the possibility of absolute band gaps in their band structures [1], these materials have found several potential applications, in particular in the field of waveguiding and filtering [2](like in their photonic counterpart), as well as in the field of sound isolation [3]. Recent works have dealt with the study of surface modes of semi-infinite two-dimensional (2D) phononic crystals [4–6] and, in particular, the existence of absolute band gaps in the dispersion curves of surface modes [6]. A few works also started to investigate the dispersion curves of free standing plates of 2D phononic crystals [7–9]. Indeed, the existence of band gaps in the latter cases may be quite useful for the purpose of introducing functionalities such as waveguiding and filtering in integrated structures. Such devices can operate at the common radiofrequency range for telecommunication applications (around a few GHz) if the thickness of the slab and the period of the phononic crystal are of micron size which is quite attainable by the current lithography techniques. In this paper, we use the finite element method [10] to calculate the dispersion curves of two different structures based

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on 2D phononic crystals, namely a free standing plate and a plate deposited on a silicon substrate. The 2D phononic crystal is constituted by a square array of cylindrical holes drilled in an active piezoelectric PZT5A matrix. We investigate the existence of absolute band gaps and then the possibility of localized modes associated with a linear guide created by removing one row of air holes in the phononic crystal.

2. Results and discussion

Let us first consider the case of a free standing plate of 2D phononic crystal. Of course, the existence of an absolute band gap in the band structure of the free standing plate is dependent upon all the physical parameters (elastic parameters of the constituents) as well as the geometrical parameters such as the thickness h of the plate, the period a, the filling fraction f or the shape of the inclusions (cylinders, square rods, etc.). However, one important result is that, even if the infinite 2D phononic crystal displays an absolute band gap for in-plane propagation, the existence of such a gap in the band structure of a finite plate requires the thickness h to be of the same order of magnitude as the period a of the crystal, typically h between $0.5a$ and $1.5a$ [7–9]. The absolute gaps disappear when h is much smaller or much larger than a. This behavior can be understood on the basis of the confinement of the modes in the thickness of the plate and the constraints imposed by the free surface boundary conditions on the wave vector perpendicular to the surfaces. An example of the dispersion curves for a free standing plate of air/PZT phononic crystal of square symmetry is given in Fig. 1. The following parameters have been used in the calculation: $a = 0.77$ μm, $h = 0.77$ μm, and $f = 0.7$. The absolute band gap extends from 1.1808 GHz to 1.3072 GHz. It is worthwhile to notice that, in general, in air hole/solid phononic crystals the band gap is obtained when the filling fraction is near to the close-packing. The band gap can be made larger for phononic crystals of graphite or BN structures [7]. In a next step, we were interested in the band structure of a phononic crystal plate containing a linear guide, obtained by removing one row of holes along the x direction. In practice, the FEM calculation is performed in a periodic structure with a supercell in such a way as to keep the neighboring guides far from each other. In this calculation (Fig. 2(b)), we used a (1×7) supercell, which means a cell with a width

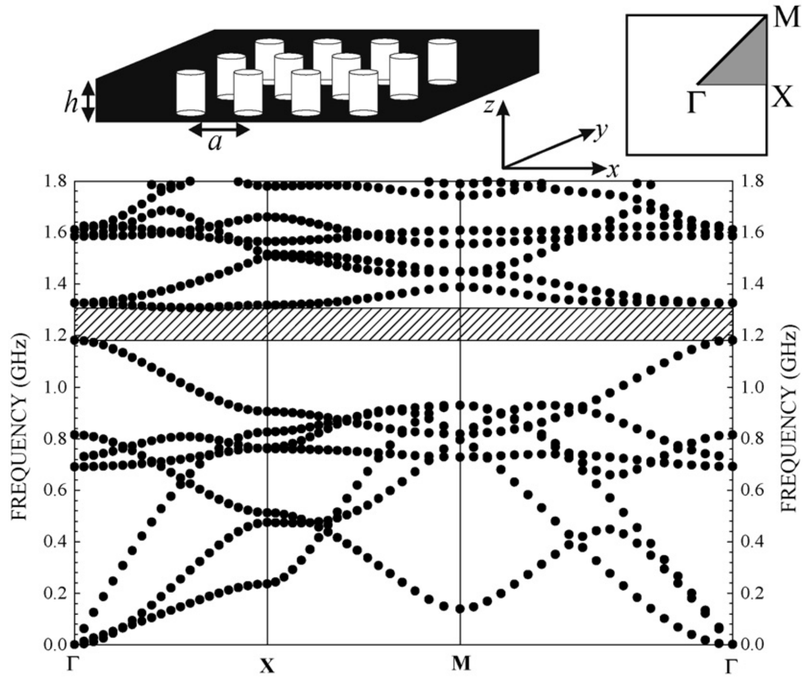

Fig. 1. Top panel: Free-standing phononic crystal plate of thickness h (the basic phononic crystal is composed of a square array of parallel cylindrical air inclusions (holes) of radius R drilled in a PZT5A piezoelectric matrix) and the first Brillouin zone (ΓXM) of the square array. Bottom panel: Elastic band structure calculated with the finite element method for the free-standing phononic crystal plate of thickness $h = a = 0.77$ μm with a filling fraction $f = 0.7$. The components of the wave vector at the Γ, X and M points are $(0, 0)$, $(\pi/a, 0)$ and $(\pi/a, \pi/a)$, respectively with $\pi/a = 4.08$ μm^{-1}.

along the x direction equal to a, a length along the y direction equal to $7a$, and the same thickness h as before along the z direction. For the sake of comparison we give also in Fig. 2(a) the band structure of the perfect phononic crystal plate (without the linear guide). Actually, the band structures in both Figs. 1 and 2(a) have the same physical meaning, the increase in the number of dispersion curves in Fig. 2(a) is the result of the folding of the dispersion curves in Fig. 1 in the reduced Brillouin zone associated with the supercell. One can also notice that the band gap is the same in both Figs. 1 and 2(a). In contrast, the band structure of Fig. 2(b), related to the phononic crystal plate containing a guide, displays additional modes in the band gap that correspond to localized modes associated with the guide. This means that these modes propagate along the guide while they cannot escape into the surrounding phononic crystal. As a matter of illustration, Fig. 3 gives a map of the mode indicated by the intersection of two straight lines in Fig. 2(b). It shows that the eigenfunction remains confined within the guide and penetrates only slightly into the neighboring rows of cylinders. Similar calculations can be performed for other defects such as cavities or coupled guide-cavities. Therefore, it becomes possible to realize integrated devices, based on phononic structures, for guiding and filtering applications in telecommunications. For the purpose of practical

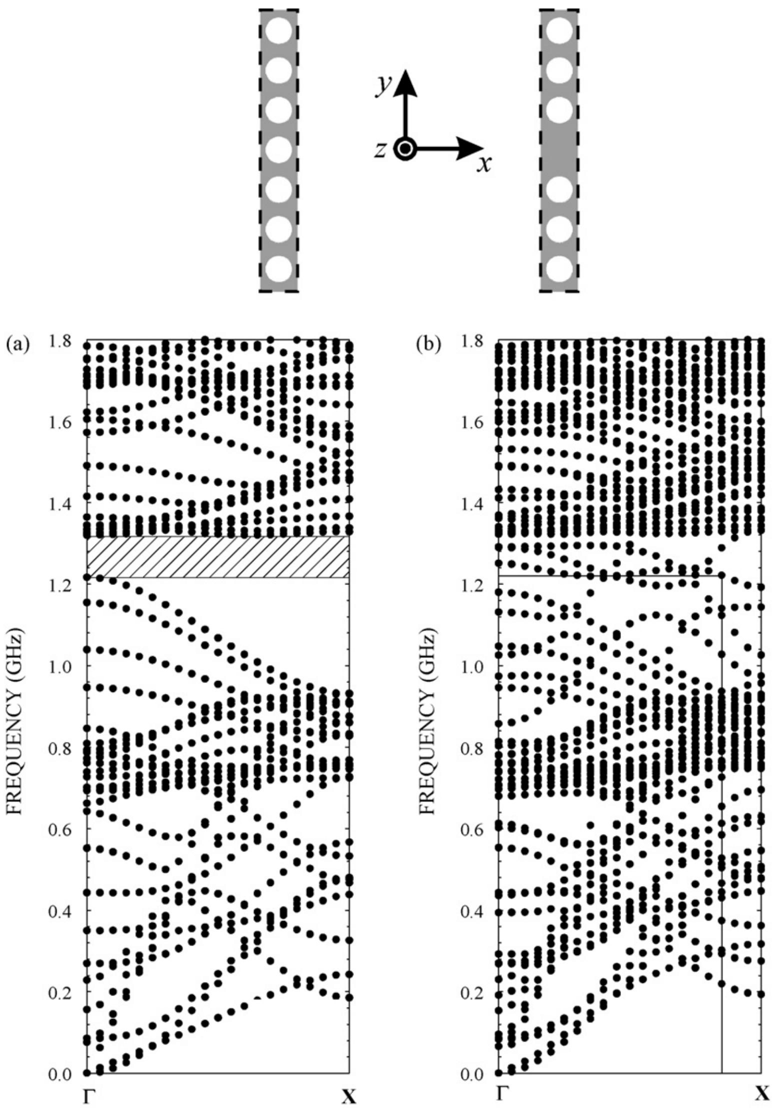

Fig. 2. Band structure along the ΓX direction calculated with a supercell containing 1×7 unit cell, for (a) the perfect phononic crystal plate, and (b) the phononic crystal plate containing a waveguide formed by filling the hole in the fourth unit cell. The inset depicts the 1×7 supercell considered in each case. The intersection of the horizontal and vertical straight lines indicates the location of the guided mode analyzed in Fig. 3.

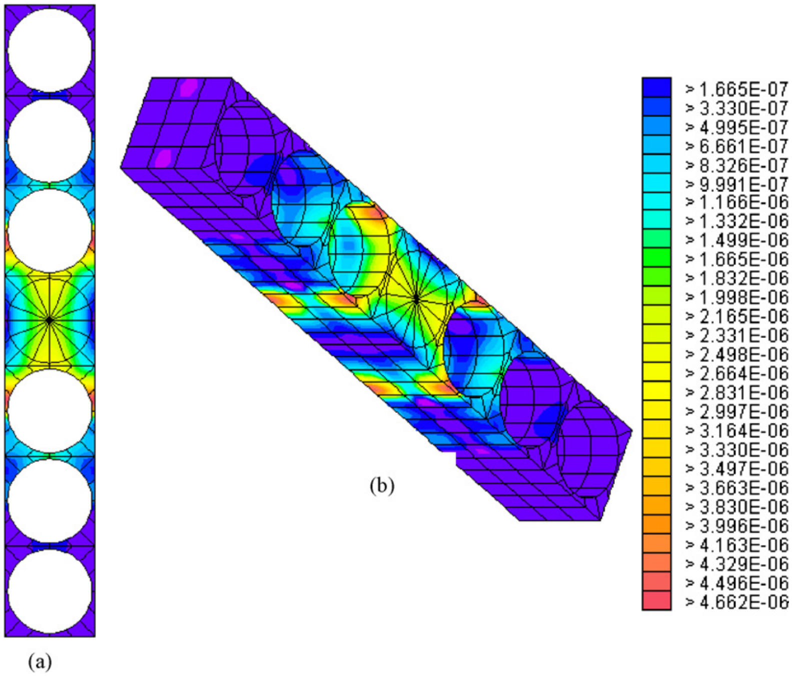

Fig. 3. Maps of the modulus (in arbitrary units) of the elastic displacement field for the waveguide mode with a frequency of 1.221 GHz and a wave vector of modulus 3.468 μm^{-1}(see Fig. 2(b); (a) top view; (b) three quarter view). The red color corresponds to the maximum displacement, whereas the blue color corresponds to the minimum.

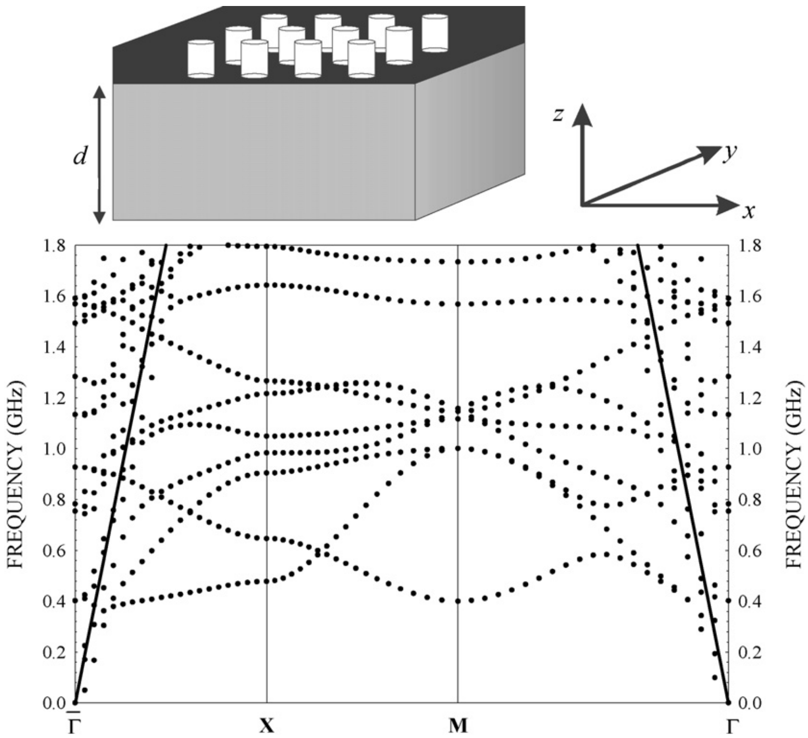

Fig. 4. Top panel: Phononic crystal plate deposited onto a homogeneous substrate of thickness d. Bottom panel: Elastic band structure for the air/PZT phononic crystal plate of thickness $h = a$ deposited onto a silicon substrate of thickness $d = 5h = 5a$. The thick solid lines represent the dispersion curves of the slower elastic waves propagating in an infinite, homogeneous medium composed of silicon, i.e. the waves of transverse polarization.

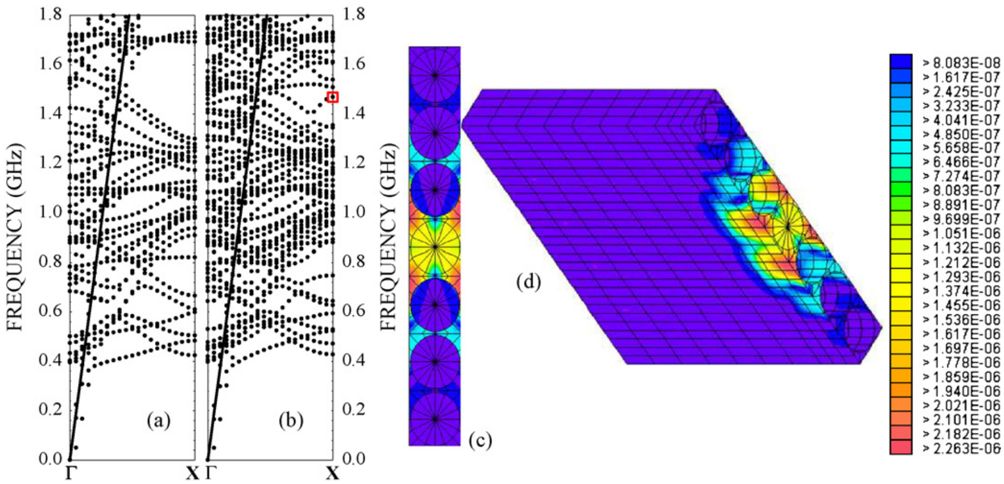

Fig. 5. Band structure along the ΓX direction calculated with a supercell containing 1 × 7 unit cells, for (a) the perfect air/PZT phononic crystal plate deposited on the silicon substrate, (b) the supported plate containing a waveguide formed by filling a hole in the fourth unit cell. The thickness of the substrate is the same as in Fig. 4, i.e. $d = 5h = 5a$. The red square indicates the location of the guided mode analyzed in (c) and (d). Maps of the modulus (in arbitrary units) of the elastic displacement field for the waveguide mode with a frequency of 1.469 GHz at the X point in (b), (c) top view, and (d) three quarter view. The red color corresponds to the maximum displacement, whereas the blue color corresponds to the minimum.

fabrication and utilization, it may be more appropriate to use a thin plate of phononic crystal deposited on a substrate rather than a free standing plate. However, the substrate should be chosen in such a way as to keep the waves confined in the phononic crystal at the surface. In this work, we have chosen silicon as the substrate since the high values of its velocities of sound can allow this confinement. For the purpose of numerical calculations, the substrate has a finite thickness which has been chosen to be $d = 5h$. However, we have checked that the results discussed below remain unaffected for a thicker substrate. Fig. 4 gives the dispersion curves of the air/PZT phononic crystal plate on silicon. The thick solid straight line represents the sound line of silicon for waves of transverse polarization. Only the modes below this line remain confined in the phononic crystal and are of interest for our purpose. These dispersion curves exhibit significant modifications with respect to the case of a free standing plate (Fig. 1), which can be understood on the basis of the boundary conditions imposed by the silicon substrate with respect to the case of a free surface. Nevertheless, below the silicon sound line, the band structure exhibits an absolute gap around 1.5 GHz. We consider now a supported air/PZT5A phononic crystal plate with a linear defect created by filling a row of holes with PZT5A. Fig. 5(a) and (b) illustrates the band structure along the ΓX direction of propagation, of a perfect supported phononic crystal plate and the defected one, respectively. As previously, the finite element calculations were done by considering a supercell containing 1 × 7 unit cells in the (xy) plane and of thickness $d + h$ along the z direction. Fig. 5(a) differs from Fig. 4 in that the bands are folded in a smaller Brillouin zone. In Fig. 5(b) we see additional modes in the frequency range of the band gap of Fig. 4. The displacement field in the supported plate corresponding to the mode localized within the band gap at the X point and a frequency of 1.469 GHz is illustrated in Fig. 5(c) and (d). It can clearly be seen that the eigenfunction is confined both laterally and vertically, which means it does not penetrate either the phononic crystal or the silicon substrate. One can also note that the maximum of the modulus of the elastic displacement field is of the same order of magnitude in Figs. 3 and 5.

3. Conclusion

We have shown the possibility of absolute band gaps in the band structure of a finite phononic crystal, either free or deposited on a substrate. For the purpose of practical applications in telecommunications, we have studied the case of an air hole/PZT phononic crystal and the substrate was chosen to be silicon in order to ensure the localization of the waves at the surface. We have also shown the possibility of waveguiding inside such a phononic crystal by removing one row of holes. The present work provides evidences that phononic crystal properties can be integrated with existing silicon-based microdevices technology. It also suggests that other structural defects such as point defects, cavities, various channels inserted inside the phononic crystal plate could also lead to the existence of vibrational modes inside the absolute stop bands. These defect modes could then be used to realize functional acoustic devices such as specific filters or demultiplexers.

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