



## Band gap in tubular pillar phononic crystal plate

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### ABSTRACT

In this paper, a phononic crystal (PC) plate with tubular pillars is presented and investigated. The band structures and mode displacement profiles are calculated by using finite element method. The result shows that a complete band gap opens when the ratio of the pillar height to the plate thickness is about 1.6. However, for classic cylinder pillar structures, a band gap opens when the ratio is equal or greater than 3. A tubular pillar design with a void room in it enhances acoustic multiple scattering and gives rise to the opening of the band gap. In order to verify it, a PC structure with double tubular pillars different in size (one within the other) is introduced and a more than 2 times band gap enlargement is observed. Furthermore, the coupling between the resonant mode and the plate mode around the band gap is characterized, as well as the effect of the geometrical parameters on the band gap. The behavior of such structure could be utilized to design a pillar PC with stronger structural stability and to enlarge band gaps.

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### 1. Introduction

Phononic crystals (PCs) [1,2] have drawn great attention during past two decades. The most notable property of the PCs is the existence of phononic band gaps (PBGs), making them excellent choices for applications such as noise control [3,4], acoustic filtering and confinement [5–8]. Because of the simple structure and being easy to fabricate, two kinds of the PC plates, i.e. the holed PC plate [5,9] and the pillared PC plate [10–13], have recently received increasing attention. However, the pillared PC plates possess more advantages. A high filling factor is usually required to obtain a wide band gap in holed PC plate, which results in fabrication challenges [14]. In contrast, pillar-based structures provide PBGs without stringent etching requirements [10]. Since they possess another degree of freedom in designing the PC, i.e. the height of the pillars. Furthermore, such kind of structure provides one side of perfect surface, a desirable platform for dealing with liquids or functioning process for immunological detection, showing great potential in bio-sensing applications [9].

The pillar PC plate is proposed and investigated independently by Wu et al. [10,13] and Pennec et al. [11,12]. After then, much effort has devoted to it. The researchers reported that the PC plates with soft pillars [4,11,15,16] or composite pillars [17–19] support ultra-low frequency band gaps, while plates with double-side pillar [17], “necked” pillar [20,21] and hole-pillar structures [22]

contribute to band gap enlargement. These works focused on gaps induced by locally resonance indicate great potential in sound insulation or acoustic control. Although pillar PC plates support Bragg band gaps as well [15,16], relative little attention has been paid to them [23]. Bragg gaps are of relative high frequency range and more suitable for sensing applications. Generally, hard pillars are required to obtain such gaps and tall pillars contribute to wide band gaps, indicating well acoustic energy confinement and high quality factors. As previous study reported, a band gap opens when the pillar height is triple the plate thickness and reaches maximal width when that ratio is ten [10,13]. However, tall pillars simultaneously increase the fabrication process cost and decrease the structural stability.

In this paper, we present an original structure composed of tubular pillars on a plate, by which we partially overcome the limitation for PBG generation condition, known as the ratio of pillar height to plate thickness. For classic cylindrical pillared PC, the ratio is about three. However, for tubular pillar PC, a complete PBG is observed with the ratio about 1.6. A tubular pillar design with a void room in it enhances acoustic multiple scattering and gives rise to the opening of the band gap. Based on such mechanism, a PC structure with double tubular pillars different in size (one within the other) is introduced and a more than 2 times band gap enlargement is observed. The coupling between the resonant mode and the plate modes on the PBG is characterized, as well as the effect of the geometrical parameters on the band gap. Such PC structures show great interest in complement of PC plate with stronger structural stability. Besides, they provide a new method of band gap enlargement.

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## 2. Model and simulation

The structure of the planer tubular pillared PCs realized in square lattices and irreducible Brillouin zones are shown in Fig. 1 (a) and 1(b), respectively. The lattice constant is denoted as  $a$  and the plate thickness is  $e$ . The height, outer radius and inner radius of the tubular pillar are  $h$ ,  $R$  and  $r$ , respectively. Both the substrate and the pillars are chose to be isotropic silicon (Si). The material properties are as follows, the mass density is  $2329 \text{ kg/m}^3$ , Young's modulus is  $1.7 \times 10^{11} \text{ Pa}$ , and the Poisson's ratio is 0.28.

The numerical calculation of the PC is based on an efficient finite element method (FEM) [15] implemented using the COMSOL Multiphysics software. The band structures are calculated by applying the Floquet periodic boundary conditions to the interfaces between the nearest unit cells, and then solving eigenvalues with discrete wave vectors along the edge of the first irreducible Brillouin zone based on the physical model described as the following equation,

$$\nabla \cdot C : \left[ \nabla^s u + \frac{i}{2} (k^T \otimes u + k \otimes u^T) \right] = -\rho \omega^2 u, \quad (1)$$

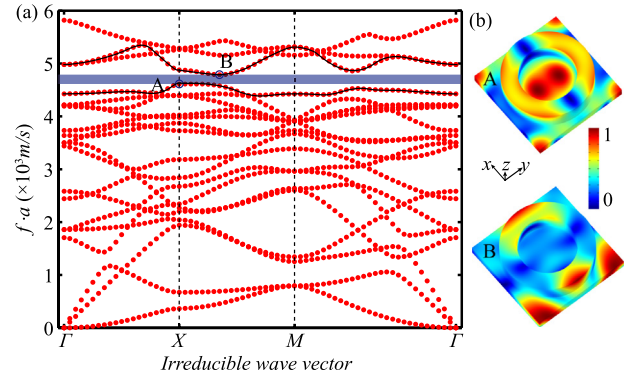
where  $C$  is the elasticity tensor,  $k$  is the wavevector,  $\rho$  is mass density,  $\omega$  is the frequency,  $u$  is the Bloch displacement vector and the symbol  $\otimes$  denotes the outer product.

## 3. Results and analysis

### 3.1. Mechanism of PBG creation

We calculated the band structure of the model shown in Fig. 1(a) with geometrical parameters as the following:  $e = 0.1 a$ ,  $h = 0.2 a$ , and  $R = 0.45 a$ . The filling factor  $\beta$  is chosen to be fixed to 0.385, the same value as that in studies reported that a PBG in cylinder pillared PC is formed when the pillar height is triple of the plate thickness [10,13]. The inner radius of tubular pillar  $r = 0.283 a$ , which is determined by the relationship  $\pi (R^2 - r^2) a^2 = \beta$ . Because of the periodicity of the structure, only one unit cell is considered and the structure is assumed to be infinite and periodic in both  $x$  and  $y$  directions. Fig. 2 represents the band structure calculated by FEM. A complete PBG with normalized frequency extending from 4612 to 4786 m/s is observed.

The band gap in Fig. 2(a) shows some characteristics, indicating it is a Bragg band gap. First, the normalized center frequency of the PBG is about 4700 m/s, nearing the velocity of transverse waves in the Si membrane (about 5000 m/s). That is, at the frequency of the band gap, the wavelength is comparable to the period of the PC. Second, dispersion branches at the edges of the band gap show



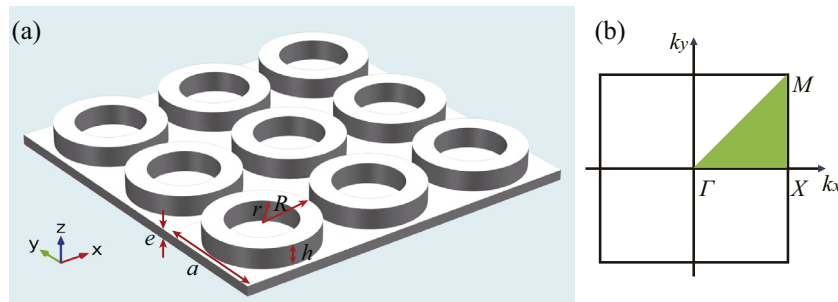
**Fig. 2.** (a) Band structure of the model in Fig. 1(a) with  $e = 0.1 a$ ,  $h = 0.2 a$ ,  $R = 0.45 a$ , and  $\beta = 0.385$ . The shaded rectangular region represents the complete band gap. A and B denote the modes on the lower and upper edge of the PBG. (b) The displacement profiles of modes A and B. The blue (red) color in the color legend corresponds to the lower (higher) value of the displacement field.

sharp curve shape. The displacement profiles of modes A and B, located respectively on the lower and upper edges of the band gap, are calculated and shown in Fig. 2(b). Both of them have displacement not only in the pillar but also in the membrane, indicating the group velocities are not zero.

The mechanism of the PBG opening in our model is similar to that in previous model, proposed by Wu et al. as mentioned in the introduction [13]. Oudich et al. have verified that the band gaps opening in their models are due to Bragg scattering. For structures constructed with a hard pillar on a plate, the coupling between the Lamb modes and the pillar modes is strong, a Bragg scattering procedure, which means that a periodic structure has to be used to obtain a PBG [16].

The key difference is that, compared to their model, a tubular pillar is used instead of the cylinder pillar. We argue that the designed structure consisting of a void room in pillar enhances the acoustic multiple scattering, and therefore, contributes to the band gap opening in structures with low height of pillars. To confirm that statement, a PC structure with double tubular pillars different in size stacked together (one within the other) is proposed. It is expected that a wider band gap will be observed since that the stacked tubular pillars provide even stronger multiple scattering of acoustic waves than a single tubular pillar.

The band structure of a double-pillar PC plate is calculated, with the geometrical parameters  $R_1 = 0.4 a$ ,  $r_1 = 0.29 a$ ,  $R_2 = 0.24 a$  and  $r_2 = 0.1 a$ , where  $R_1$  and  $r_1$  are the outer and inner radius of the tubular pillar of large size, respectively.  $R_2$  and  $r_2$  correspond these of the smaller one. The filling factor and the height of the pillars keep remain. The result is shown in Fig. 3(a), there exists an



**Fig. 1.** (a) Schematic of the PC constituted by a square lattice of tubular pillars arranged on a plate. The lattice constant is  $a$ , the thickness of the plate is  $e$ . The height, inner radius and outer radius of tubular pillar are  $h$ ,  $r$ , and  $R$ , respectively. (b) The corresponding first irreducible Brillouin zone (green region) and the high-symmetry points  $\Gamma$ ,  $X$ , and  $M$ .

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