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Extending and lowing band gaps in one-dimensional phononic crystal strip with pillars and holes

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ABSTRACT

Effectiveness of extending and lowing gaps in one-dimensional phononic crystal strips is conducted by periodically patterning pillar-type strip with holes. Finite element method is applied to the hybrid unit to calculate band structures and eigen modes. Transmission spectra and displacement fields are investigated to confirm the gap effect in the studied hybrid strips. Numerical results show that, the one-dimensional hybrid strip can open lower and wider gaps. Compared with two-dimensional phononic crystal plate, band structures of phononic crystal strip show different group velocities and frequencies in low-order bands, different eigen modes of gap edge because of boundary condition difference. The effectiveness of modulating gaps with strip width is investigated. Gap degeneration happens to adjust lower gap edge downward. Besides, hybrid structure with double-side pillar leads to more resonance bands than that with single-side pillar. Vibration mode of pure pillar type structure located in lower edge of the gap of hybrid single-side pillar-type structure, and some resonance modes in the hole-type strip are reserved in hybrid single-side pillar structure. Resonance in hybrid double-side pillar structure is introduced by vibration of the double-pillar character, to create more flat bands. Furthermore, gap sensitivity to geometrical parameters of pillars and holes is also investigated.

1. Introduction

Wave propagation in inhomogeneous material has attracted considerable attention in these two decades. Phononic crystals (PCs), which are composed of periodic structures, possess rich wave propagation physics. Theoretical calculations and experimental researches show the PCs' potential application in wave isolators, filters, resonators and waveguides [1–10]. The purpose of obtaining effective wave isolation, wave guiding in low and wide frequency domain as well as high Q factor resonator or integrated structures in micro-fabricated PCs, informing that PCs' band structures and band gap (BG) evolutions are of vital importance for the acoustic device design. In early studies, PCs have been researched by modulating filling ratio, lattice symmetry or constituent materials for wide frequency Bragg gaps [11–15]; soft material was introduced for low-frequency BGs and the corresponding PCs are called local resonance PCs [16–18].

Since the Bragg gap in bulk PCs is hard to tune low, and gaps in two- or three- dimensional local resonance bulk PCs are too narrow, gaps designed with two dimensional periodic PC plates are widely investigated as an effective way to gain wide and low frequency gaps [19,20]. For the PC plate, researchers have found many interesting results. Modulating parameters of PC plates with material component periodicity can influence conversion between Lamb mode and flexural or shear-horizontal mode, which cannot be excited in infinite periodic media [21]. Chen et al. investigated mode conversion in this kind of flat PC plates to distinguish band structures of PCs with infinite boundaries [22]. Besides the lattice symmetry, the filling ratio and the material contrast between different components [23–25], plate thickness [26] is a crucial factor that contributes more to the mode conversion and transformation. Another early studied hole-style PC plates were researched for the application of radio-frequency communication or filtering [27]. Gaps and reflections of Lamb waves in a two-port ZnO/silicon PC plate were analyzed and the resonance Q factor was examined [28]. Wang et al. proposed that etching cross-like holes in homogenous plate can open multiple wide band gaps [29]. Resonance in pillars can be formed to create flat mode and slower wave velocity near Brillion zone edge, and the generation of this low-frequency gap is due to local resonance in pillars. To enhance local resonance, stepped pillars with soft material [30], double-side pillars [31] and pillars with neck structures [32] were designed in succession. To widen the low-frequency BG, Bilal et al.

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and Assouar et al. induce holes to two-dimensional pillar-style PC plate, so as to wider low-frequency BG with holes [33,34].

Significantly, most researches on PC gaps are focused on two-dimensional periodicity, and ignore that a large amount of acoustic device should be highly integrated and designed as strips. PC strips can save more space and are good for integration. Band conversion and transformation in strips are quite different from those in two-dimensional PC plate due to the free boundaries in strips [35–37]. However, few researches are conducted to investigate lowering and widening gaps in PC strips. Actually, potential application with PC strips possessing the property of wide-low gap is significant, that overcomes manufacture difficulty of narrow-gap PCs, and save space by means of designing small periodicity as well as strip width. In this paper, we investigated the gap widening and lowering behavior in one-dimensional strips with both holes and pillars. Difference between hybrid PC plate and hybrid PC strip investigated in this paper are analyzed. Comparison between pillar-type strip, hole-type strip and strip with both the pillar and the hole shows that gaps can be tuned lower and wider simultaneously with hybrid unit. Using finite element method, dispersion relation as well as eigen modes are analyzed to explain the physical phenomenon. Gap evolution with the decisive geometrical parameters of the pillar and the hole is also investigated.

2. Modeling and calculation

Fig. 1 shows the hybrid PC plate and the PC strip etching from the plate. Each unit cell is composed of cylinders and holes. Geometrical parameters are as follows: lattice constant is marked with a, and d is the width of the strip; strip thickness is e. Stubs are designed with the same height h and radius r. Semi-circles are etched with centers placed on strip edge, and with radius r_h. The PC plate is periodic in both x and y directions, while the PC strip is periodic along x direction. Difference between the PC plate and PC strip is not only the periodicity, but also the boundary conditions. PC strip in y direction is finite that y direction boundary can reflect elastic waves, but for PC plate, only boundary along z direction can reflect waves. Furthermore, strip width d in y direction can be modulated without increasing lattice constant, while PC plate cannot. And, for the application condition, compared with two-dimensional PC plate, strips can save MEMS device die space and improve manufacturing precision. Thus, it is meaningful to calculate and analyze the physical character of the investigated PC strip in this paper.

Fig. 2 is unit cell of pillar-type strip, hole-type strip and hybrid strip. Fig. 2(a) is the pillar-type strip with the cylinder stub distributed periodically on homogeneous strip on one side. Another stub with the same parameter is added on the other side of the strip in Fig. 2(b). The cylinder stubs are placed coaxial on both side of the strip. Different pillar-type strips are investigated to find out that how the stubs work to enhance local resonance in the strip. For the hole-type strip in Fig. 2(c), semi-circles are spatially etched along the strip with lattice constant. Fig. 2(d) and (e) are the hybrid strip that combine the unit components of pillar-type and hole-type in Fig. 2(a)–(c). In Fig. 2(d), unit cells can be viewed as combination of single-side pillar-type unit and hole-type unit. Similarly, Fig. 2(e) can be seen as combination of double-side pillar-type strip and hole-type strip. PC strips composed of these unit cells will be discussed to illustrate band evolution and gap formation.

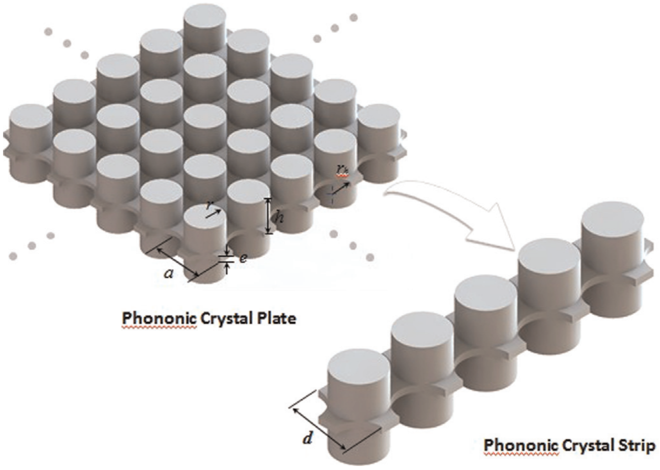

Fig. 1. Sketch of phononic crystal strip etching from the phononic crystal plate.

In order to investigate BGs and resonance in these strips, finite element method is selected to calculate the dispersion relations, eigen displacements of certain modes, transmission spectra and displacement fields of finite strips. To calculate dispersion relation, elastic wave propagation in solid strips can be described as

$$\sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left(\sum_{l=1}^{3} \sum_{k=1}^{3} c_{ijkl} \frac{\partial u_k}{\partial u_l} \right) = \rho \frac{\partial^2 u_i}{\partial t^2} \quad (i = 1, 2, 3), \tag{1}$$

where u_i, u_k, u_l are the displacements, c_{ijkl} are elastic constants, and t is the time. Displacement calculation is compressed to one unit cell due to the periodicity along strip. And the periodic condition is

$$u(x + a, y, z) = u(x, y, z)e^{ika} \tag{2}$$

k is the wave vector. Other strip surfaces are free. This finite element method calculation procedure is conducted in COMSOL MULTIPHYSICS [37]. Second-order Lagrange elements are used for accurate solution. Stress–strain boundary conditions are used for free strip surfaces. By sweeping wave vector k along the first irreducible Brillion Zone boundary of these proposed PCs, we can draw the dispersion relationship between wave vector and eigen frequencies. To calculate transmission spectra and displacement field distribution of the finite structure, 5 unit cells are considered. The finite strip is excited with time-harmonic elastic wave on one-side; energies are received on the other side. PMLs (Perfect Match Layers) are placed on both sides of the finite structure.

3. Results and discussion

3.1. Band structure and eigen modes

All the PC structures discussed in this paper are made of Al, with mass density $\rho=2730$ kg/m^3, Young's Modulus $E=77.6$ GPa, and Poisson's ratio $\nu=0.33$. Lattice constant $a=10$ mm; strip thickness $e=1$ mm; strip width $d=10$ mm; pillar radius $r=4$ mm; pillar height $h=3$ mm; hole radius $r_h=4.5$ mm. Band structures of hybrid PC plates and hybrid PC strips are demonstrated in Fig. 3. For the PC plate, first ten bands are calculated. The seven to ten bands are resonance flat bands that introduced by pillar's vibration. A wide-low gap occurs between the fifth and the sixth band, extending from 44.1 KHz to 121.8 KHz. For the PC strip, high order bands' frequencies are nearly the same as that of the PC plate. A wide-low gap also occurs between the fifth band and the sixth one, ranging from 41.2 KHz to 121.9 KHz, which is a little lower than that of the PC plate. High order bands of both hybrid PC plate and hybrid PC strip are nearly the same. This is because the high order resonance bands are formed by pillars' vibration, that interaction between Lamb wave and wave in pillars is not obvious. Differences between band structures of the PC plate and the PC