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Engineering of band gap and cavity mode in phononic crystal strip waveguides

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ABSTRACT

The optimal parameters for the largest band gap were investigated in three typical phononic crystal strip waveguides. Single cavity mode was created inside the band gap region by proper design of a defect. The band structures and the displacement distributions were discussed with the variation of the defect. Results show possibilities to guide extremely slow phonon cavity mode in strip waveguide with chosen displacement components, frequencies and symmetries.

1. Introduction

Phononic crystal(PC) materials are periodic elastic structures that exhibit a band gap with a certain range of acoustic waves inhibited to propagate [1–3]. The study of acoustic wave in PC structures has attracted attentions since decades ago [4–6]. Phononic band gaps were found in bulk PC materials, multilayer PC materials as well as PC plates, stubbed plates [7–9], and recently PC strips [10–12]. PC structures that exhibit phononic band gap also allow us to localize phonon cavity mode inside the band gap region by introducing a defect [13,14]. With proper design of the defect, the phonon cavity mode can guide a certain range of acoustic waves that we want. It can have many technological applications, such as reduction of noises of a certain range, acoustic filtering and many frequency control devices [15–17].

As the propagation of guided elastic waves along the PC structures can be greatly influenced by the structure, the defect size, and the boundary shapes. The engineering of PC structures and defects becomes increasingly important. Up to now the dominant engineering platform is usually the silicon slab with periodic arrays of sub-micrometer holes or periodic arrays of pillars. Such structures can be fabricated by the widely used silicon-on-insulator technologies. However, for wave guiding or filtering, it is more convenient to have linear structures such as strips. Periodic crystal silicon strips were found to have photonic band gap since decades ago and were widely used for confinement of optical waves [18], especially at wavelength 1550 nm in the telecom range. Recent studies found such strip structures can also have phononic band gap and the elastic properties of the strip can greatly influence the optical behavior. Efficient modulation of light pulses through Brillouin scattering by acoustic phonons has been observed at optical frequencies [19]. There has been an emerging research field of the so-called optomechanical or nanomechanical materials [20,21]. As optical strip waveguide were more widely used than its phononic counterpart, right now the focus was mainly on the optical properties of strip and the behavior of optical cavity mode. To enhance the photon–phonon interaction and design new nanomechanical devices, we need to have very high quality phonon cavity mode and study in detail the phononic properties of the cavity. Such as the slowness of the phonon cavity mode, the displacement distributions, and their symmetries.

In this Letter we study three strips that can be cut from the typical PC slabs and allow massive production by the widely used silicon-on-insulator technologies. We investigate the band structures of those strips to obtain the largest band gap and search the ideal phonon cavity mode by tuning the defect size. We further design defect that could have phonon cavity mode with extremely slow group velocity compared to the bulk counterpart. The displacement distributions and their symmetries of the cavity mode are also discussed.

The rest of the Letter is organized as follows. In Section 2 we describe the simulation model and computing details. Results and discussions of the band structure and cavity mode are presented in Section 3. A short summary is given in Section 4.

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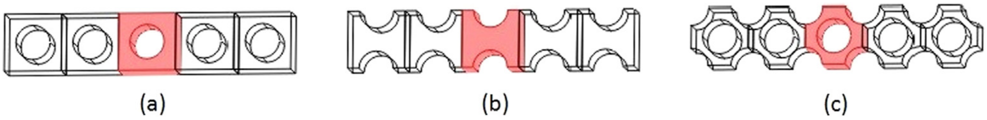

Fig. 1. Schematics of silicon strip waveguides with (a) type *i* unit cell in shadow, (b) type *ii* unit cell in shadow, and (c) type *iii* unit cell in shadow.

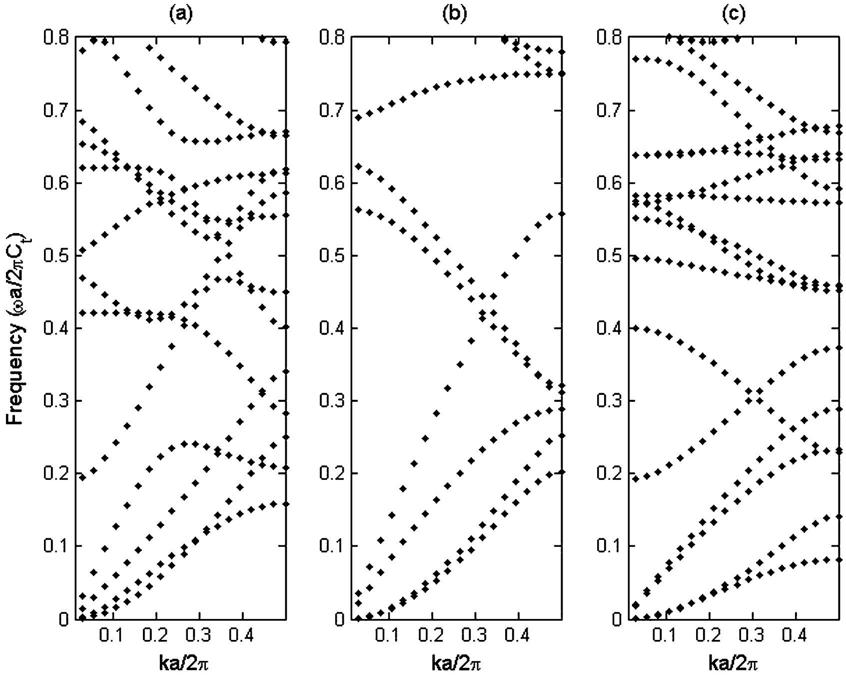

Fig. 2. Band structures for silicon strip waveguides type *i*, type *ii*, and type *iii*. Here we choose $r/a = 0.3$ and $h/a = 0.6$.

2. Computational details

The model is shown in Fig. 1. The so-called strip waveguide is cut from the usual silicon PC plates with vacuum holes. Strip type *i* and type *ii* are cut differently from the PC plates with square lattice, while strip type *iii* is cut from PC plate with triangle lattice. The thickness of the plate is h. The lattice constant is a and the radius is r.

The dispersion curve of PC materials can be calculated by various methods, such as plane wave extended method (PWE), finite-difference time-domain (FDTD) method, and finite-element (FE) method. The PWE method is very efficient in simulating band structures of some highly periodic bulk PC materials or PC plates [22]. While FDTD methods are commonly used in simulating dispersion curves and transmission spectrum of some structures with open boundaries. The FE method can be used in most structures and very good at displacement analysis. Results calculated from PWE, FDTD and FE are compared and coincided with each other in previous work [22]. In this work, we employed FE method in band structure calculation. Free stress boundary conditions are applied on all surfaces that contact with vacuum, as elastic waves cannot propagate in vacuum. Periodic conditions were applied on both terminals of the unit cell along the transport direction. Very fine meshes were chosen to converge the results. In calculating the band structure of perfect periodic PC strips, one unit cell is needed in simulation (as shown in the shadow part of Fig. 1). In calculating the band structure of PC strip with defect, super cell calculations were performed (with 6 unit cells on each side the defect) to converge the results. The frequencies are given in the dimensionless unit $\omega a/2\pi C_t$, where ω is frequency, a the length of unit cell in the transport direction, and C_t is transverse velocity of elastic waves in silicon ($C_t = 5844$ m/s). In our simulations, the elastic constants $C_{11} = 165.7$ GPa, $C_{12} = 63.9$ GPa and $C_{44} = 79.62$ GPa and mass density $\rho = 2331$ kg/m^3.

3. Results and discussion

Typical band structures are shown in Fig. 2 for three strip waveguides depicted in Fig. 1. It is impossible to find a phononic band gap for strip type *i*, even at very big filling factor of vacuum. However, with proper ratios, we can easily observe band gaps in Fig. 2(b) and (c) for strip type *ii* and type *iii*. Rough boundaries are necessary for strips to open a phonon gap, which is consistent with previous reports [10]. Besides, high filling factor of vacuum, and a reasonable thickness are essential to open a phonon band gap. The variation of band gap as a function of r/a and h/a is shown in Fig. 3. The grey region is the frequency region of the band gap. From the band map, we observe the optimal ratios for strip type *ii* ($r/a = 0.3$ and $h/a = 0.8$), and type *iii* ($r/a = 0.3$ and $h/a = 0.6$).

Now we introduce a defect in PC strip with the aim to localize phonon cavity modes. The defect is created by varying the radius of a single cylinder in the middle of a PC strip waveguide with perfect lattice. The radius of the defect cylinder is defined as r_0. Fig. 4(a) corresponds to the case of type *ii* perfect strip waveguide where we can define the band gap region when r_0 equals to r. Gradually varying the radius of central defect cylinder, the corresponding band structures are shown in Fig. 4(b) to (f). We only observe cavity mode appears in the middle of the gap region at $r_0/a = 0.15$. Similarly, Fig. 5(a) corresponds to the case of type *iii* perfect strip waveguide where we define the band gap region as a reference. The band structures of defected PC strips are shown in Fig. 5(b) to (f). Cavity modes are relatively easier to be created in this type. The frequency of cavity modes inside the gap region shifts slowly with the variation of the cavity cylinder. The