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Spatial confinement of acoustic and optical waves in stubbed slab structure as optomechanical resonator

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ABSTRACT

We theoretically demonstrate that acoustic waves and optical waves can be spatially confined in the same micro-cavity by specially designed stubbed slab structure. The proposed structure presents both phononic and photonic band gaps from finite element calculation. The creation of cavity mode inside the band gap region provides strong localization of phonon and photon in the defect region. The practical parameters to inject cavity and work experimentally at telecommunication range are discussed. This structure can be precisely fabricated, hold promises to enhance acousto-optical interactions and design new applications as optomechanical resonator.

1. Introduction

Phononic crystals or photonic crystals are periodic structures that exhibit band gaps with a certain range of acoustic or optical waves inhibited to propagate. They were proposed decades ago [1–4]. Since then various artificial periodic structures have been reported to have phononic or photonic band gaps. Although, most periodic structures usually have a photonic band gap but not a phononic band gap, or vice versa. Several specially designed structures have been proposed to have both phononic and photonic band gap. They are termed as phoxonic crystals [5] or optomechanical crystals [6]. The simultaneous existence of photonic and phononic band gaps is of great interest due to the potential to control light and sound in the same structure [7]. Although the velocity of acoustic waves is several order lower than the velocity of optical waves in those artificial structures, with proper geometry parameters in sub-micron range, we can tailor optical wave operates in the visible spectrum and acoustic wave operates in the GHz range for the same structure with relevant wavelengths in the same sub-micron range [8]. The control of phonons and photons in the same micro-cavity becomes possible. It has been found that the elastic properties of such micro-cavity can greatly influence the optical behavior because of the optomechanical interaction or acousto-optical interaction [9]. Efficient modulation of light pulses through Brillouin scattering by acoustic phonons or by picosecond acoustic pulses has been observed experimentally [10, 11]. There has been an emerging research field of the so-called optomechanical cavity or nanomechanical materials [12,13]. Among them, silicon slab structures with periodic arrays of air holes are very attractive, mainly because they are consistent with the usual silicon-on-insulator (SOI) technologies, and widely used in photonic community, recognized for its ability to manipulate light [14]. However, the proposed slab structures usually compose of arrays of sub-micrometer air holes, pillars, cross, or even snowflake structures [15–17]. In application, we are in favor of simple structures that can be precisely fabricated by the SOI technologies without drilling arrays of holes or other shapes. Besides, most experiments investigating optomechanical devices have been performed with optically passive systems only. Recent experiments find that a major step forward in implementing such optomechanical devices into integrated optoelectronic circuits would be the extension towards active structure that could generate light by active semiconducting layers like semiconductor quantum wells or quantum dots embedded in a micro-cavity [18]. If we want such applications as active optomechanical resonators, we need to design simple defected structure that could contain active semiconductor layers in the defect and have strong spatial localization of phonon and photon in the defect for strong resonances.

In this work we propose a simple stubbed slab that could strongly confine the acoustic wave and optical wave in the same defect region and could easily contain semiconductor layers in the cavity. We first study the band structures of the proposed stubbed

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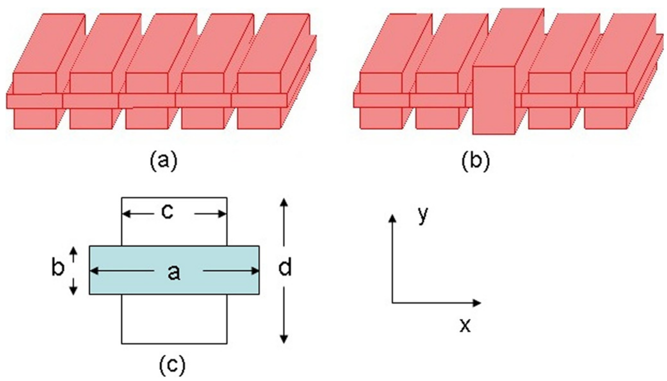

Fig. 1. Schematics of periodically stubbed slabs (a) with uniform unit cell; (b) with cavity cell in the middle; (c) and the geometry parameters for the primitive cell.

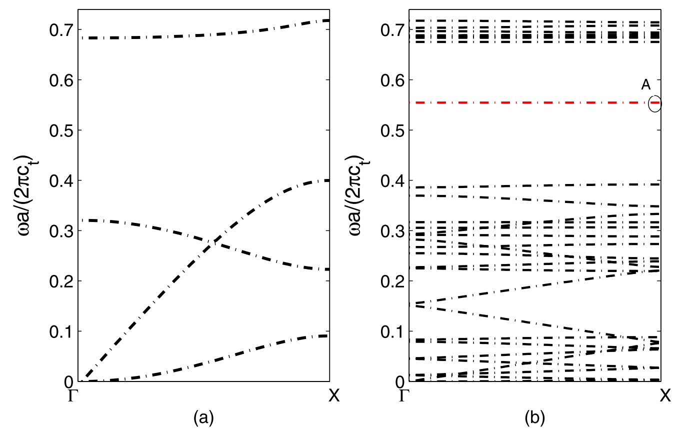

Fig. 2. Phononic band structures of phononic crystal (a) for perfect periodic structure with 1×1 unit cell at $b/a = 0.25$, $c/a = 0.75$, and $d/a = 1$; (b) for defected structure, the supercell (7×1 unit cell) with cavity cell $d/a = 1.2$ in the middle.

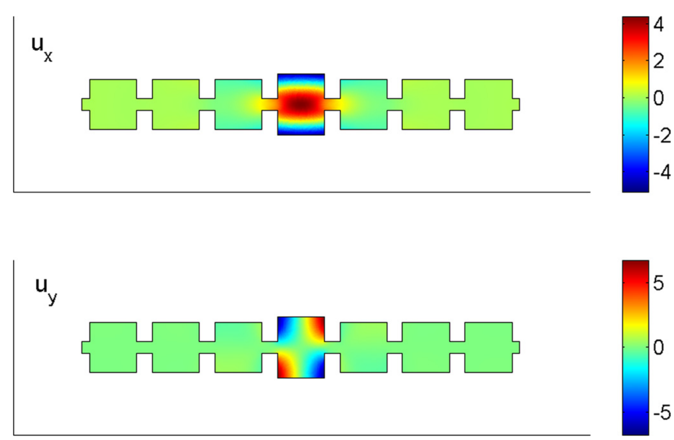

Fig. 3. Displacement distribution of u_x and u_y for cavity modes inside the phononic gap region. Here we choose point A in the cavity band shown in Fig. 2(b).

slabs and search the geometry parameters to achieve dual band gap. Then we introduce defects that could localize phonon and photon simultaneously. The spatial distribution, symmetries and the group velocity of the cavity mode are discussed in detail for strong spatial confinement of both acoustic and optical waves. Finally, the practical parameters to work experimentally for the localization of photon and phonon inside the band gap are discussed.

2. Computational details

The stubbed silicon slab structure is shown in Fig. 1(a). The periodic structure with defect stub is displayed in Fig. 1(b), where we have one stub in the middle enlarged in the y direction. The geometrical parameters of a periodic unit cell are the period a, the slab thickness b, the width of stub c, and the height of stub d as shown in Fig. 1(c). In our simulation we assume the slab along z direction is infinite.

The phononic or photonic band structure can be calculated by various methods, such as plane wave extended method (PWE), finite-difference time-domain (FDTD) method, and finite-element method (FEM). We are opted for FEM in this work as it is efficient in displacement analysis. For the phononic simulation, we assume the stubbed silicon slab is in vacuum. Only the solid part of the stubbed slab supports the elastic waves. So we can apply periodic condition in the x direction and Neumann boundary conditions on all the other faces of the structure. For the photonic case, vacuum surrounds the stubbed slab can also support the optical waves. In calculation we have to restrict the computation domain to a finite region and consider simple free boundary conditions a certain distance away from the slab surfaces [8]. For the analysis of the obtained dispersion diagrams, we need to take care to consider only the bands inside light cone [14].

For all the band structure calculation, we consider only the ΓX direction. The highest symmetry points Γ and X in perfect periodic stubbed slab refer to wave vector coordinates $(0, 0)$ and $(\pi/a, 0)$ respectively. In calculating the band structure of slab with defect stub, super cell calculations were performed. For phononic calculation, one super cell contains with 7 unit cells (with 3 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 ($C_t = 4683$ m/s). In our simulation, 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.

In calculating the photonic band structure, we assume vacuum has unit refractive index. The silicon slab has refractive index 3.48. Super cell calculation are performed for stubbed slab with defect. We separate the transverse-electric (TE) and transverse-magnetic (TM) modes. Here we focus on the TM polarization where we have transverse magnetic field in the x–y plane and electric field only component E_z [14].

3. Results and discussion

The phononic band structure of perfect stubbed slab is shown in Fig. 2(a) and displays a large elastic band gap along the ΓX direction. For the defected stubbed structure as depicted in Fig. 1(b), we observe in Fig. 2(b) that a cavity band appears in the middle of the band gap. The band in the middle of gap is very flat along the ΓX direction, which implies the group velocity of elastic wave along x direction is nearly zero. The elastic wave is localized in the defect stub. The displacement distribution of the cavity mode A in the cavity band is displayed in Fig. 3. The strong localization of displacement u_x and u_y polarization and their symmetries can be clearly seen.

The photonic band structure of TM waves along the ΓX direction for the same perfect stubbed slab is presented in Fig. 4(a). The dark gray region above the light line is the light cone for air. Bands below the light line are guided by the stubbed slab. The bands of TM waves guided by the slab show a band gap from reduced frequency value 0.25 to 0.3. Introducing the same defect as we did for the phononic counterpart, we observe a photonic cavity band appears inside the photonic band gap region at reduced frequency around 0.28. We further plot the field distribution of cavity mode B in this band in Fig. 5. It can be clearly seen that electric field is mainly localized in the defected stub.