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Cavity modes and optomechanic interactions in strip waveguide

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Abstract: Phoxonic crystals can exhibit dual phononic/photonic band gaps. Therefore, the confinement of both acoustic and optical waves in a phoxonic cavity can allow the enhancement of their interaction. In this paper, we discuss our recent theoretical works on the strength of the optomechanic coupling, based on both photoelastic and moving interfaces mechanisms, in nanobeam phoxonic crystals cavities.

1. Introduction

There has been a great deal of recent interest about optomechanical interaction in different structures based on slabs[1-3] and nanobeams[4-5] using well-defined cavities. However, most of these works considered localized phonons and photons that are not necessarily trapped inside a photonic and/or a phononic band gap. In this paper, we study optomechanic interactions in phoxonic crystals which are defined as dual phononic/photonic crystals that can exhibit simultaneously phononic and photonic band gaps. The existence of absolute band gaps allows the simultaneous confinement of both waves that, in turn, can produce the enhancement of their interaction for the purpose of novel and high-performance optomechanical and acousto-optic devices and applications. A main objective is the modulation of light by acoustic waves when both excitations are confined inside the same cavity or propagate with a slow velocity inside a waveguide. We have studied theoretically this optomechanic interaction in different (2D[6,7], slabs[8], and strip[11,12]) phoxonic crystals cavities. This paper will focus on the results of the strip waveguide structures.

2. Mechanisms and Methods

Two mechanisms contribute to the acousto-optic interaction, namely the photoelastic (PE) and moving interface (MI) effects[6,7]. The former is due to a local variation of the dielectric permittivity induced by the acoustic strain inside the materials (Pockels effect[9]), whereas the second mechanism comes from the variation of the dielectric permittivity in the vicinity of the interfaces due to the motions of the boundaries during the vibrations of the cavity. To evaluate the strength of the phonon-photon coupling, we calculate the modulation of the cavity photon frequency by the cavity phonon, namely the photonic mode frequency is calculated at several selected instants of an acoustic period under the assumption that the acoustic mode strain profile is being frozen at these instants[6,8]. This is justified by the fact that the photon frequency is higher by several orders of magnitude than the acoustic frequency. The acousto-optic strength is proportional to the amplitude of this photonic frequency modulation. The calculation should be done for each pair of phononic and photonic modes in order to compare the strength of the coupling between different pairs. The coupling may vanish to the first order for some combinations of phononic and photonic modes due to symmetry reason. From our calculation, we can evaluate the relative contributions of the PE and MI effects and, in particular, see whether both effects are in phase and add to each other or they are out of phase and partly cancel each other. Finally, the above analysis can be compared to the optomechanical coupling coefficient[5] that expresses the photonic frequency shift induced by the zero-point motion of the mechanical field of the phonon and which can be calculated from the knowledge of the acoustic and optical field distributions inside the cavity.

3. Strip waveguide

We have investigated phoxonic crystals constituted by 1D strip (or nanobeam) waveguides. The corrugated nanobeam is constituted by a backbone periodically drilled with holes and along which lateral stubs are periodically attached[10]. We have shown that the holes and the stubs are favorable for the opening of the photonic and phononic gaps, respectively, so this structure is suitable to provide simultaneous phononic and photonic gaps. Then, we have studied the possibility of cavity modes as well as slow guided modes in these structures[10].
In our previous work[10], we studied a simple cavity by introducing a silicon space defect between two holes. This cavity displayed both confined acoustic and optical modes. However, the quality factor of the photonic mode inside the gap was very low (less than 1000) which makes this cavity not attractive for the experimental observation of the optomechanic coupling. To overcome this disadvantage, we investigate here the design of new cavities providing both high photonic quality factors and strong optomechanic coupling coefficients.

The realization of a high quality factor can be achieved by tailoring a tapered cavity in which the geometrical parameters of the unit cells change progressively from the cavity center towards both sides to reach their values in the perfect crystal. For instance, by using a parabolic variation of the parameters when the parameters at the cavity center are about 70% of those in the perfect crystal, we are able to achieve quality factors as high as 2 to 3 10^5 at wavelengths of about 1500nm.

Before evaluating the strength of the optomechanic coupling, it is worth noticing that, due to symmetry reasons, only acoustic modes having a symmetric-symmetric (SS) behavior with respect to the two symmetry planes of the nanobeam can couple to photonic modes. In addition, if the cavity itself has a symmetry plane at its middle, the considered phonon should also be symmetric with respect to this third plane and can be called SSS. Using the tapered cavity structure described above, we calculated the strength of the optomechanic coupling between all the photonic cavity modes and all the SSS acoustic modes up to 5 GHz (see Fig. 1). The phononic modes falling in the range of the absolute band gap (3.5 to 4 GHz) give relatively weak acousto-optic coupling, up to g~0.006 MHz. The strongest coupling of g~2.3 MHz (with PE and MI contributions of respectively 1.6 and 0.7 MHz) is obtained with an acoustic mode at 2.46 GHz which is not inside a gap and thus corresponds to a resonant, rather than to a localized, mode of the cavity. However, this mode is very close to a phononic gap of SS symmetry and below the full band gap, so we can expect that by changing slightly the shape of the tapered cavity, it can be pushed into the partial gap or above inside the full band gap without changing significantly the optical modes of the cavity. The modification of the cavity consists of increasing or decreasing the length of the stubs progressively from the perfect crystal towards the cavity center. The coupling factor is significantly increased when the acoustic mode is pushed inside the full band gap. This modification does not change significantly the coupling factor, but the mechanical quality factor of the acoustic mode pushed inside the partial band gap should be much improved. This can make the structure more attractive for the experimental observation of the optomechanical interaction. Figure 1 illustrates the results as concerns the geometry of the two kinds of strip and the corresponding coupling coefficients g between some photonic and phononic modes.

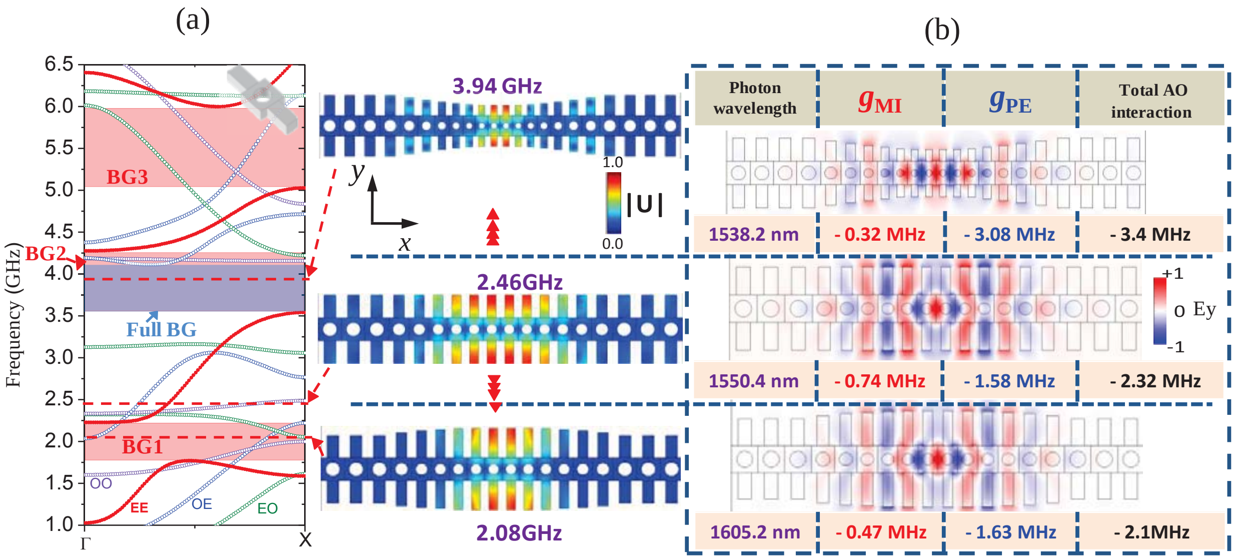
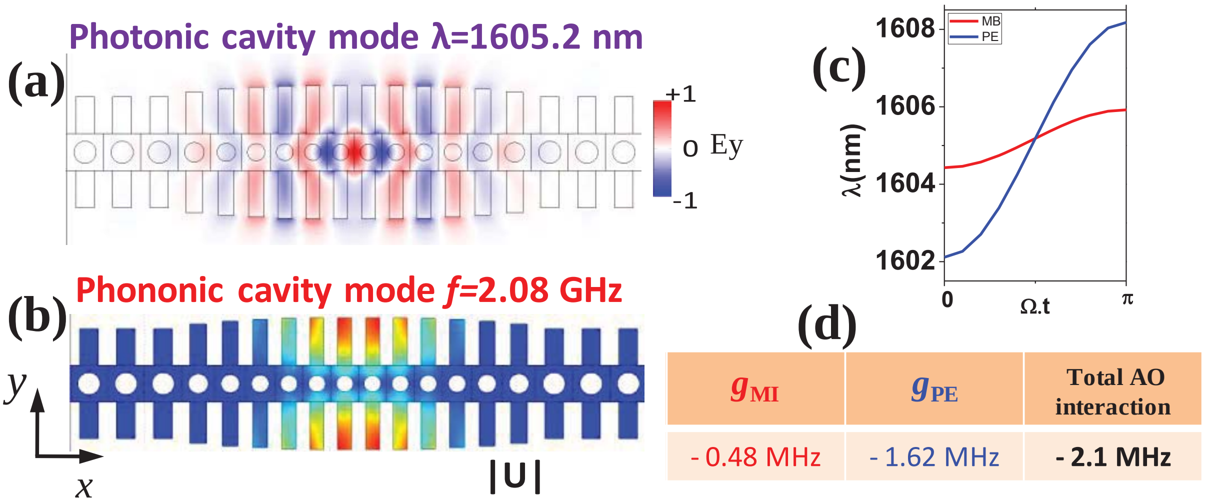


Figure1: (a) Phononic band structure of the perfect nanobeam where the red shaded regions named BG1, BG2 and BG3 are the gaps for the modes which are symmetrical with respect to the symmetry planes of the nanobeam (red branches) and which are the only one that are able to couple with photonic modes and the gray shaded region for the full band gap. (b) AO coupling between the photonic cavity modes and the same phononic mode pushed up inside the full band gap or down inside the partial band gap by decreasing or increasing respectively the length of the stubs. In each figure we give the coupling coefficients g_{PE} and g_{MI}.

We present an example of strip waveguide where phononic and photonic cavity modes give strong AO coupling. The total coupling coefficient is evaluated at 2.1 MHz where the MI and PE effects contribute additively (see figure 2).

4. Conclusion

In conclusion, we have investigated the AO interaction in a corrugated phoxonic silicon nanobeam presenting band gaps both for photonic and phononic modes. By creating a well-designed tapered cavity, we were able to create highly confined phononic and photonic modes with high quality factor inside the gap which can then enhance their AO interaction. We have shown that this tapering can be adjusted to shift either the photon wavelength or the phonon frequency of interest in the suitable targeted wavelength or frequency range which can be useful for experimental AO phenomena observation and characterization. In particular, high mechanical quality factor can be achieved when the phonon mode that couples efficiently to photons is pushed inside a gap by choosing an appropriate tapering of the heights of the stubs.



g_{MI}	g_{PE}	Total AO interaction
- 0.48 MHz	- 1.62 MHz	**- 2.1 MHz**

Figure 2. (a) Electric field for the photonic mode, (b) norm of displacement field for the phononic mode, (c) modulation of the photonic mode by the acoustic cavity mode during half acoustic period, (d) the coupling coefficients g_{PE} and g_{MB} for photoelastic (blue solid line) and moving boundaries (red solid line) effects respectively.

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