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Enhancement of acousto-optical coupling in two-dimensional air-slot phoxonic crystal cavities by utilizing surface acoustic waves

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ABSTRACT

A phoxonic crystal is a periodically patterned material that can simultaneously localize optical and acoustic modes. The acousto-optical coupling in two-dimensional air-slot phoxonic crystal cavities is investigated numerically. The photons can be well confined in the slot owing to the large electric field discontinuity at the air/dielectric interfaces. Besides, the surface acoustic modes lead to the localization of the phonons near the air-slot. The high overlap of the photonic and phononic cavity modes near the slot results in a significant enhancement of the moving interface effect, and thus strengthens the total acousto-optical interaction. The results of two cavities with different slot widths show that the coupling strength is dependent on the slot width. It is expected to achieve a strong acousto-optical/optomechanical coupling in air-slot phoxonic crystal structures by utilizing surface acoustic modes.

1. Introduction

In recent years phoxonic crystals (PXCs) are of particular interest owing to their possibility of simultaneously manipulating light and sound [1]. The PXCs behave like photonic crystals (PTCs) and phononic crystals (PNCs), and possess photonic bandgaps (PTBGs) and phononic bandgaps (PNBGs) simultaneously. The PXCs can be designed straightforwardly as dual-functional (optical and acoustic) devices, such as waveguides, sensors, superlenses, etc., which have been studied in the regimes of PTCs [2–4] and PNCs [5,6]. Moreover, since the PXCs can simultaneously confine photons and phonons in the same volume, they can be utilized as a promising platform to enhance acousto-optical (AO) or optomechanical (OM) coupling in micro- and nano-structures. At the early stage, many efforts have been devoted to the generation of dual bandgaps [7–15]. And nowadays various potential applications based on PXCs, including PXC cavities [16], waveguides [17–19], sensors [20–23] and mode converters [24], have been reported. Meanwhile a number of research groups focus on the photon–phonon coupling in cavities and waveguides [25–37]. Eichenfield et al. [25,26] designed and experimentally demonstrated a one-dimensional (1D) optomechanical crystal (OMC) nanobeam cavity with large OM coupling. Gomis-Bresco et al. [27] designed, fabricated and measured a 1D PXC nanobeam cavity capable of transducing confined phononic modes inside a complete PNBG. Alongside these works, other groups theoretically investigated OM interactions between photons and phonons in 1D nanobeam structures [28–30]. Psarobas et al. [31] reported strong nonlinear AO interactions in a 1D multilayer PXC cavity. Almpanis et al. [32] studied different aspects relating to the occurrence of nonlinear AO effects in a 1D multilayer PXC cavity. The OM interactions inside two-dimensional (2D) silicon and gallium arsenide PXC cavities were theoretically studied by El-Jallal et al. [33]. Experimental works on OM couplings between photons and phonons in 2D OMC or PXC slabs have also been reported [34,35]. Chang et al. [36] proposed a novel approach to light storage involving an optical waveguide coupled to an OMC array. Very recently dual complete bandgaps and defect-free localization for photons and phonons in the phoxonic quasicrystal structures have been demonstrated [37].

Among various types of PTC cavities and waveguides, air-slot structures can provide high optical quality factors and small mode volumes [38–41]. The light enhancement and confinement are caused by the large discontinuity of the electric field at the high index-contrast (air/dielectric) interfaces [38]. The OM coupling phenomena in several kinds of air-slot PTC or PXC cavities have been reported [42–46]. In such systems the strong photon–phonon coupling stems from the high spatial confinement of the electric field near the air/dielectric interfaces. Very recently, based on the bandgaps of both the surface optical wave (SOW) and the surface acoustic wave (SAW), Ma et al. [47] investigated a 2D PXC cavity which can confine simultaneously optical and acoustic waves near

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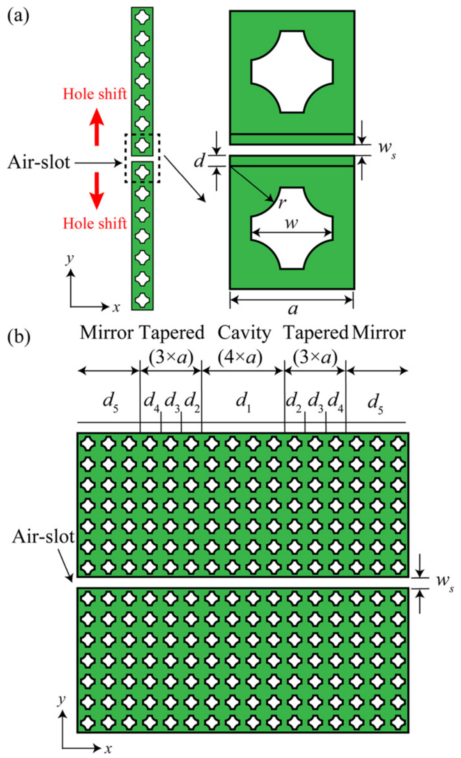

Fig. 1. (a) Schematic diagram of the 2D PXC waveguide and the enlargement of the air-slot region. The geometrical parameters a, r, w, d and w_s represent the lattice constant, circle radius, hole width, distance shift parameter and slot width, respectively; (b) Schematic diagram of the 2D air-slot PXC cavity. The geometrical parameters of the unitcell are $r = 0.35a$ and $w = 0.9a$. The shift parameters d_1, d_2, d_3, d_4 and d_5 are $0.12a$, $0.13a$, $0.14a$, $0.15a$ and $0.16a$, respectively.

the structural surface. It is noteworthy that the free surface is also the air/dielectric interface, which means that SAW can be highly localized near the interface within a small volume. Inspired by the concepts of the air-slot cavities and surface mode cavities, we will study the AO coupling in 2D air-slot PXC cavities in this paper. Due to the existence of the SAWs the phonons can be confined near the air/dielectric interfaces, which is distinguished from previous studies. The high overlap of the photonic and phononic cavity modes near the air/dielectric interfaces can enhance the AO interaction greatly.

2. Air-slot cavity design

The air-slot PXC waveguide shown in Fig. 1(a) is used to construct the air-slot cavity. The PXC is formed by drilling complex holes in a square lattice in the silicon matrix. This design of the PXC insures simultaneous large complete photonic and phononic bandgaps, which can provide the flexibility of designing the PXC structures [13]. For modifying the optical guided modes (or the surface acoustic modes), the holes in each column are shifted away from the slot by a distance of d, i.e., two identical silicon layers are added near the slot. Then by modifying the distance shift parameter d in different columns, one can create a hetero-structure cavity based on the mode-gap effect [48], as shown in Fig. 1(b). The geometrical parameters a, r, w, d and w_s represent the lattice constant, circle radius, hole width, distance shift parameter and slot width, respectively. In the present work the geometrical parameters of the cavity are similar to those in Ref. [47]. The geometrical parameters of the unitcell are $w = 0.9a$, $r = 0.35a$. The PXC cavity is composed of the cavity, mirror and tapered regions. We take the PXCs with $d = 0.12a$ and $d = 0.16a$ as the cavity and mirror regions, respectively. The tapered regions with d linearly varying are introduced between the cavity and mirror regions to reduce the effect of the interface mismatch. However, in this paper there is one more parameter, i.e., the slot width w_s, which needs to be determined. The corresponding material parameters (silicon) are the refractive index $n = 3.5$, mass density $\rho = 2331$ kg/m^3, elastic moduli $C_{11} = 16.57 \times 10^{10}$ N/m^2, $C_{12} = 6.39 \times 10^{10}$ N/m^2, $C_{44} = 7.962 \times 10^{10}$ N/m^2, photoelastic constants $p_{11} = -0.1$, $p_{12} = 0.01$ and $p_{44} = -0.051$, respectively [33].

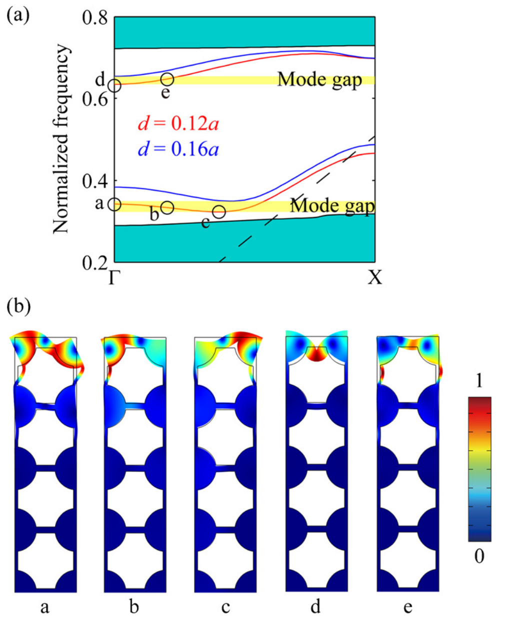

Fig. 2. (a) Dispersion curves of the acoustic surface modes. Red and blue bands are the results for $d = 0.12a$ and $d = 0.16a$, respectively. The yellow shadowed area represents the mode gap, and the black dashed line denotes the sound line. (b) Displace field distributions corresponding to different points in (a), where the wave vectors ($k_x a/2\pi$) for points a, b, c, d and e are 0, 0.1, 0.2, 0 and 0.1, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Throughout this paper, the analysis is performed by the finite element method (FEM) using COMSOL Multiphysics. For the acoustic cavity modes, the deformation (or vibration) is highly localized in the cavity region. And then the (left/right/upper/lower) boundaries of the structure are fixed for the PNC case. Besides in the calculation of the photonic cavity modes, perfect matched layers (PMLs) are applied as the boundary conditions for absorbing the radiating optical waves without reflection. The in-plane mode is considered for the PNC case and the transverse electric (TE) mode for the PTC one.

The dispersion curves of the SAWs for two different shift parameters, $d = 0.12a$ (for the cavity region) and $d = 0.16a$ (for the mirror regions), are shown in Fig. 2(a), where the SAWs propagating at the surface near to the air-slot is plotted. Two mode-gaps (the yellow shadows) can be observed in the band structure. The surface modes appear (disappear) when the shift parameter d is $0.12a$ ($0.16a$) in the frequency ranges of the mode-gaps. The modal distributions of different SAW modes are given in Fig. 2(b). For the lower SAW band, the modal distributions for points a, b and c correspond to the rotations of the semi-circles at the surface. But for the upper SAW band, the mode of the surface wave changes as the wave number varies. The mode of point d ($k_x a/2\pi = 0$) shows the vertical vibration of the surface while that of e ($k_x a/2\pi = 0.1$) corresponds to the horizontal vibration of the surface.

It is noteworthy that the SAW bands above the sound line (i.e. the black dashed line) can also exist. Here, we indicate that the structure is also periodic in the direction perpendicular to the