Microelectronic Engineering 159 (2016) 80–83

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Dual photonic–phononic nanocavities for tailoring the acousto-optic interaction

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ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 11 February 2016
Accepted 25 February 2016
Available online 3 March 2016

Keywords:
Photonic phononic cavities acoustooptic

ABSTRACT

We report on the influence of elastic waves on the optical response and light emission in simultaneously photonic and phononic resonant cavities. Elastic waves couple with light through the acousto-optic interaction. Concurrent control of both light and sound through simultaneously photonic–phononic, often called phoxonic, band-gap structures is intended to advance both our understanding as well as our ability to manipulate light with sound and vise versa. In particular, co-localization of light and sound in phoxonic cavities could trigger nonlinear absorption and emission processes and lead to enhanced acousto-optic effects. We review our recent work on sound-controlled optical response and light emission in phoxonic cavities and investigate the limits of validity of the photoelastic model that describes light–sound interaction to first-order approximation. Moreover we present some preliminary results on silicon nitride nanobeam phoxonic devices.

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Introduction

Typical acousto-optic (AO) devices control light through a piezoelectric transducer that launches an elastic wave, which causes deflection and frequency shift of an incident light beam. This is due to the photoelastic effect [1], which originates from the strain field associated with the elastic wave that changes the refractive index as it propagates through the material and, at the same time, induces deformations of the boundaries, which can be very important in micro- and nano-structures [2]. The presence of an elastic wave can also be viewed as a time-varying photonic environment. It is to be noted though that the variation is slow, since sound is several orders of magnitude slower than light, and therefore the interaction can be treated in a quasistatic approximation. The interest in light–sound interaction in recent years was mainly driven by cavity optomechanics [3], where the radiation pressure of localized light in an optical cavity produces an elastic wave through mechanical deformation. In this context, some remarkable achievements, like cooling of classical mechanical oscillators in the ground state through light [4], enhancement of stimulated Brillouin light scattering at the nanoscale [5], and electromagnetically induced transparency in one-dimensional photonic crystal silicon nitride nanobeams [6] were demonstrated. One of the main ingredients for enhanced AO interaction is the co-localization of light and sound. One way to achieve this is to engineer structures which exhibit dual spectral gaps, for both photons and phonons, so-called phoxonic or optomechanical crystals. So far, a variety of different phoxonic band-gap designs have been proposed and analyzed, including one-dimensional multilayer structures [7,8,9,10], two-dimensional periodic arrays of air holes [11,12,13,14], and two-dimensional crystals with veins [15]. Moreover, many systems that confine simultaneously optical and acoustic waves in the same region of space for a long time period, thus enhancing their interaction, have been considered [2,16,17,18].

The main idea in this emerging and rapidly expanding field of research is to explore the physics and the potential applications of strongly interacting, resonant light with resonant elastic waves, in properly designed nanostructures. Submicron structures can be designed to simultaneously localize both, photons and phonons, and are often called phoxonic or optomechanical cavities. They operate for optical and elastic waves with similar wavelength but different frequencies. In this paper we review our recent work on phoxonic architectures and analyze silicon nitride nanobeams perforated with holes as potential candidates to achieve enhanced AO interaction. We discuss three different structures: A single, dielectric microparticle, periodic multilayers, and silicon nitride nanobeams.

Enhanced interaction of light and sound

The AO interaction can be rather complicated even in simple systems such as a spherical dielectric particle. Usually spheres with diameters of the order of 100 μm that support modes localized in the perimeter of the sphere (whispering gallery modes) are considered and enhanced AO interaction has been demonstrated for such high finesse modes [19]. However enhanced AO interaction is also possible in

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http://dx.doi.org/10.1016/j.mee.2016.02.067
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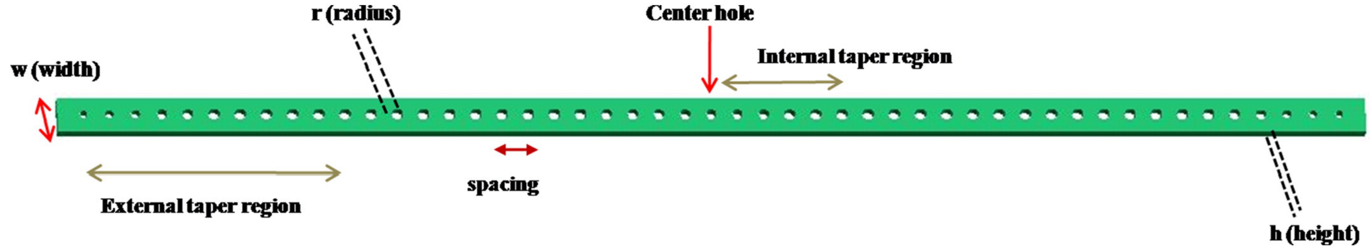

Fig. 1. Top view of the nanobeam cavity structure.

smaller spheres, with diameters close to one micron. We have studied the influence of elastic vibrations on the optical properties of such particles, taking also into account the excitation of elastic waves in our modeling. Generally, the spherical symmetry is lost for a general elastic eigenmode of the particle. However elastic vibrations in submicron particles can be generated through absorption and subsequent thermal expansion of a femtosecond laser pulse. These particles can be assumed to be isotropic, and the problem is simplified by considering only radially symmetric elastic vibrations, so called breathing modes, which are predominantly excited. Moreover, by including elastic losses, our simulations show that after few tens of nanoseconds upon excitation, the particle essentially vibrates in the fundamental breathing mode [20]. The vibration causes a temporal variation in the optical scattering cross section spectrum that is dominated by the Mie resonances. The strength of the AO interaction depends on the overlap between optical and elastic modes. For strongly localized optical modes with high quality factors, if the symmetry of the mode matches the symmetry of the elastic mode, strong photon–phonon interaction involving many phonons is anticipated [7].

A periodic multilayer is another model system that can be used to achieve simultaneous localization of light and sound. For example Si/SiO_2 multilayers with thickness of few hundred nanometers can form band gaps and cavities at the telecommunication frequency (200 THz) and ~10 GHz elastic waves (hypersound). Generally, any two materials with sufficient optical and elastic contrast can be used to fabricate structures with dual (light–sound) band gaps and eventually design cavities with simultaneous localization of light and sound in the same volume. Strong AO interaction occurs if the associated electric and strain fields have the same symmetry and strong overlap. The reflection of light with frequency $\mathit{\Omega}$, due to an elastic vibration with frequency Ω, is described by a time-varying periodic complex reflection coefficient: $r(t) = \sum_{n=0,\pm 1,\dots} r_n \exp(-in\Omega t)$, which leads to reflectivity, averaged over a time period of the acoustic wave: $<\Re(t)> = \sum_n |r_n|^2$, where the sum is often truncated only to the first order ($n = 1$) term [21]. For multilayers, in the first order Born approximation, denoted by a superscript (1), the reflection amplitude associated with one-phonon absorption (anti-Stokes process) is given by [22]

$$r_1^{(1)} = \frac{i\omega}{4cn_h E_{in}^2}\left[\int dz p_{12}\varepsilon^2(z)S(z)E^2(z) + \sum_j (\varepsilon_{j+1} - \varepsilon_j)u(z_j)E^2(z_j)\right],$$

where $E(z)$ is the electric field. The input electric field is E_{in} while $u(z)$ and $S(z)$ are, respectively, the elastic displacement and strain fields in the multilayer, extending in the z direction; p_{12} is the relevant AO coefficient and $\varepsilon(z)$ the dielectric function. The refractive index of the environment outside the multilayer is denoted by n_h. The first term in the above equation is the bulk contribution due to the refractive index change induced by the elastic strain field, while the second term is the interface contribution that involves a discrete sum over the interfaces. The linear-response regime breaks down when either the acoustic excitation increases, or the first-order AO interaction coupling element vanishes by symmetry, giving rise to the manifestation of multiphonon absorption and emission processes by a photon.

The influence of elastic vibrations on the optical response can be better studied by focusing on the temporal variation of the optical spectrum close to a resonance mode. The problem can be dealt in a quasistatic approximation by solving the electromagnetic problem at snapshots as the structure vibrates at the elastic frequency. In the general case, the maximum frequency shift of the optical resonance is a linear function of the input acoustic displacement. However, when the strain field is antisymmetric with respect to a plane of mirror symmetry passing through the middle of the cavity, the first-order Born approximation gives a vanishing contribution and, in this particular case, the maximum frequency shift of the optical resonance is a quadratic function of the input acoustic displacement [21].

Strong AO interaction can also be used to modulate light emission from active centers placed inside a phoxonic cavity. We have studied a cavity structure where optical and elastic energy is localized in a defect layer between two Bragg mirrors and allows for an enhanced AO modulation of light that escapes the cavity, as well as an appropriately engineered surface that sustains simultaneously surface-localized states for both optical and elastic waves and allows for strong modulation of light that couples to guided modes trapped in the multilayer. An elastic wave can strongly modulate light emission inside a cavity region formed between two multilayer Bragg mirrors. Even stronger modulation can be achieved if we design a $Si/SiO_2/Si$ slot waveguide on top of a Bragg mirror. The structure can be designed to sustain surface localized modes for both light and elastic waves and strong modulation for light guided at the surface is possible [9]. Such calculations provide evidence for strong dynamic modulation of spontaneous emission about the sharp edge of the optical resonant mode, under the influence of an external elastic wave that excites the elastic resonant mode and induces an enhanced AO interaction.

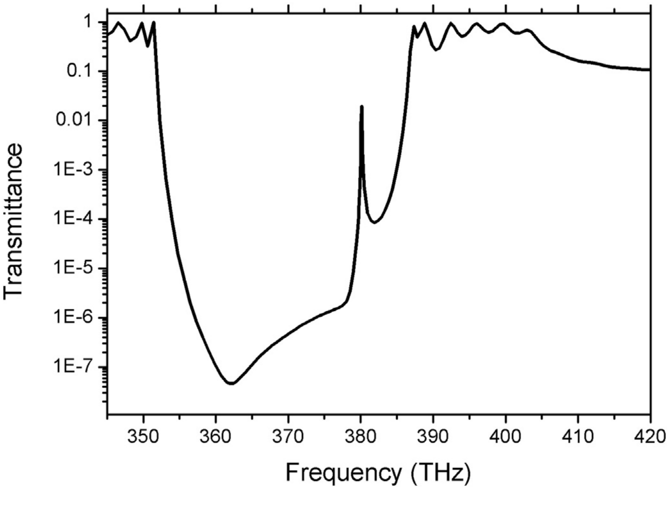

Fig. 2. Transmission spectrum through the nanobeam cavity for even–odd guided optical modes.

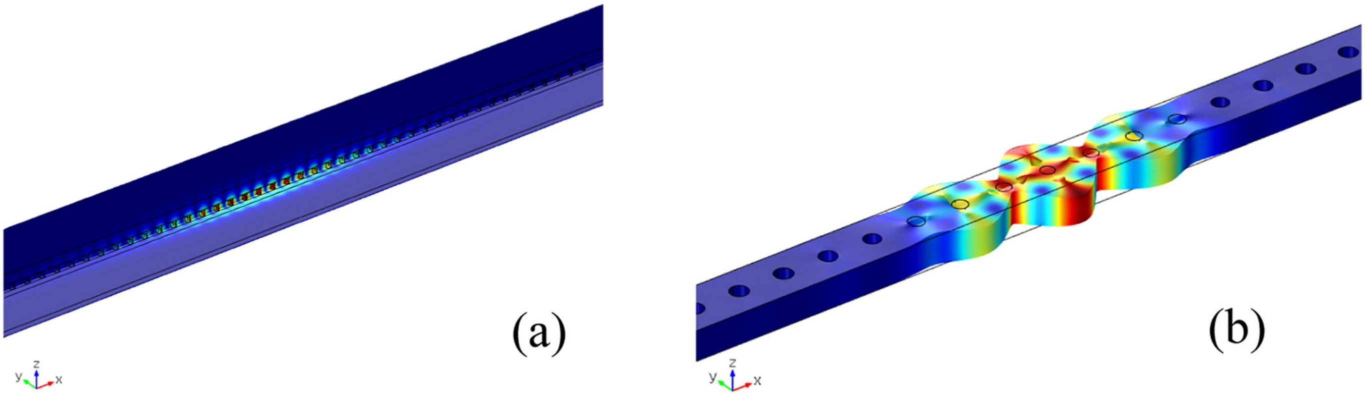

Fig. 3. (a) Electric field profile for the designed silicon nitride nanobeam cavity at the resonance frequency 380 THz, on the horizontal (x–y) and vertical (x–z) planes of mirror symmetry. (b) Elastic displacement profile on the surface of the nanobeam for an elastic eigenmode with frequency 8.3 GHz, in an enlarged view for the same structure. Note that the elastic displacement field is confined only inside the nanobeam and vanishes in air, contrary to the electromagnetic field. System parameters: $w = 400$ nm, $h = 200$ nm, $r = 60$ nm, $a = 315$ nm. The cavity consists of 11 holes between two Bragg mirrors with the radius of the central hole $r_0 = 45$ nm, and a linear taper on each side.

Silicon nitride nanobeams

We consider a silicon nitride nanobeam perforated with an array of holes designed to achieve simultaneous localization of light and sound. Both optical and elastic properties were studied by means of finite-elements simulations using the COMSOL Multiphysics package. There are several recent reports on nanobeam cavities in Si [2,23], diamond [24], as well as in silicon nitride [25]. By analyzing the optical and elastic eigenmodes of the structure we are able to design structures with high optical quality factors and simultaneously high elastic quality factors, which is necessary to achieve strong AO and optomechanical coupling. The designed structure is schematically presented in Fig. 1. The silicon nitride nanobeam has width $w = 400$ nm and height $h = 200$ nm and extends along the x direction. The refractive index was set to $n = 2.01$. A periodic array of holes with radius $r = 60$ nm and periodicity $a = 315$ nm exhibits no absolute band gap and only a partial gap for the lower frequency modes appears from 353 to 385 THz. The electric field associated with these modes is even upon reflection with respect to a horizontal (x-y) plane of mirror symmetry, which is parallel to the nanobeam and cuts the cylindrical holes in two cylinders of height $h/2$, and odd upon reflection with respect to a vertical (x-z) plane of mirror symmetry. We shall refer to these modes as even-odd modes. Here we should note that it is possible to experimentally control the symmetry of light propagating in the waveguide, so that partial photonic gaps can be used to produce strong light localization. A cavity can be formed between two Bragg mirrors created by the periodically spaced air holes shown in Fig. 1. As an example we consider here a cavity that consists of $2N_0 + 1 = 11$ holes with radii linearly decreasing from $r = 60$ nm towards the center ($r_0 = 45$ nm), with a step equal to $(r - r_0) / (N_0 + 1)$, symmetrically from both sides. An external taper can also be used (see Fig. 1) to facilitate coupling of light, with hole radii linearly decreasing from r to r_{out}. The radius of the central cavity and the positions of the holes can also be further optimized to obtain improved quality factors. The structure under consideration supports a strongly localized optical mode at frequency 380 THz, which is inside the partial band gap of the Bragg mirrors for the even–odd modes. In Fig. 2 we depict the transmission spectrum for these modes. It can be seen that the cavity mode is clearly manifested as a sharp peak in the transmittance inside the gap for the even-odd modes. The associated electric field profile is displayed in Fig. 3(a) on the horizontal (x–y) and vertical (x–z) planes of mirror symmetry.

Similarly, for elastic waves, the periodic arrangement of holes does not yield an absolute band gap but partial band gaps exist for certain symmetry, which allows the formation of strongly localized resonant elastic modes. There are several localized elastic modes. The one that is strongly localized in the cavity center occurs at 8.3 GHz and the associated displacement field on the surface of the nanobeam is displayed in Fig. 3(b). The quality factor of the cavity can be greatly enhanced if we increase the length of the linear tapering inside the cavity [25]. This is a simple and straightforward way to engineer highly localized modes, which have strong potential for enhanced AO coupling and a thorough investigation of the AO interaction of this system is under way.

Conclusions

In conclusion, phoxonic architectures, such as those studied in the present work, provide an efficient and versatile platform for tailoring the AO interaction and controlling photons with phonons. The strong optomechanical coupling that can be achieved in phoxonic cavities makes them suitable, also, for a variety of applications in cavity optomechanics.

Acknowledgement

This work was co-funded by the European Union (ESF) and the Greek state under the ARISTEIA II action (project 4709 THUNDER) of the operational program “Education and lifelong learning”.

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