PhoXonic architectures for tailoring the acousto-optic interaction

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ABSTRACT

Periodic media offer impressive opportunities to manipulate the transport of classical waves namely light or sound. Elastic waves can scatter light through the so-called acousto-optic interaction which is widely used to control light in telecommunication systems and, additionally, the radiation pressure of light can generate elastic waves. Concurrent control of both light and sound through simultaneous 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. In the present communication, we present our efforts towards the design of different phoxonic crystal architectures such as three-dimensional metallodielectric structures, two-dimensional patterned silicon slabs and simple one-dimensional multilayers, and provide optimum parameters for operation at telecom light and GHz sound. These structures can be used to design phoxonic cavities and study the acousto-optic interaction of localized light and sound, or phoxonic waveguides for tailored slow light-slow sound transport. We also discuss the acousto-optic interaction in one-dimensional multilayer structures and study the enhanced modulation of light by acoustic waves in a phoxonic cavity, where a consistent interpretation of the physics of the interaction can be deduced from the time evolution of the scattered optical field, under the influence of an acoustic wave.

Keywords: photonic crystals, phononic crystals, phoxonic crystals, acousto-optic interaction

1. INTRODUCTION

Periodic structures are well known to interact with wave fields giving rise to intriguing phenomena like the creation of frequency regions where no wave propagation is allowed, termed band gaps, through the same mechanism (destructive wave interference) for electrons, photons and phonons. Artificial periodic media were used to achieve tailored propagation of microwaves or sound while modern submicron nanofabrication methods allow these so-called photonic or phononic structures to scale down to optical frequencies and GHz sound (hypersound). More recently, there has been increased interest in the study of optomechanical interaction in cavities.[1] Strong light localization in a photonic cavity can trigger mechanical motion and dynamic back action due to the radiation pressure, which offers new exciting possibilities for manipulation and control of light with sound and vise versa.[2] On the other hand, ultrafast acoustic methods exploit the acousto-optic (AO) interaction to study elastic wave propagation in nanostructures, which is monitored through changes in the optical transmission or reflection.[3–5] Alternative to pump-probe ultrafast acoustic methods, Brillouin or Raman inelastic light scattering are also used

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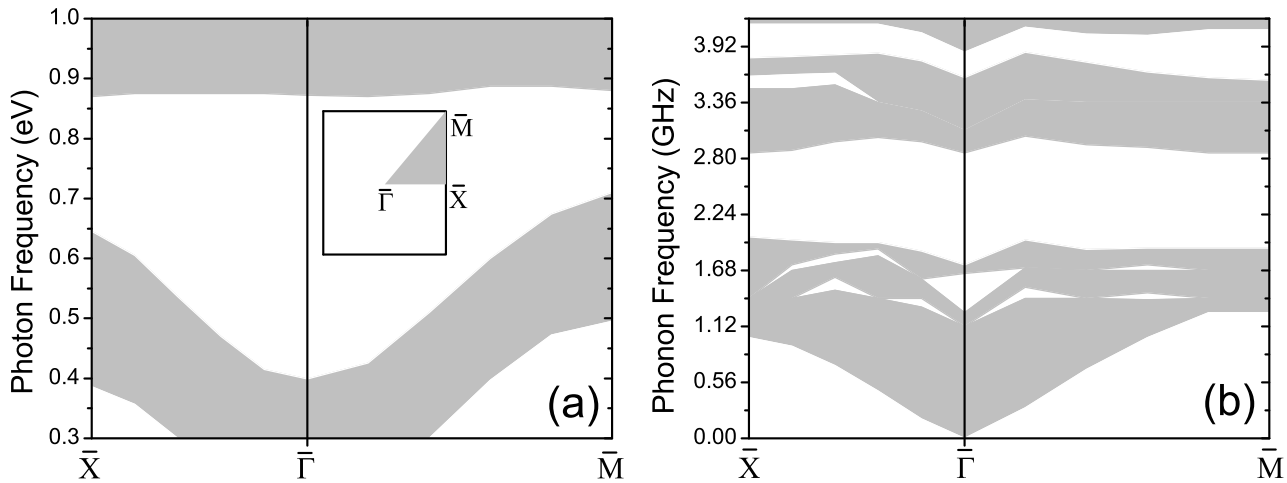

Figure 1. (a) Photonic band structure of the sc lattice of silica core-Au shell spheres described in the text projected in the sc (100) surface Brillouin zone, shown in the inset. The gray areas extend over the frequency bands and the white regions correspond to band gaps. (b) Corresponding phononic band structure.

to study micro and nano systems.[6,7] Due to the difference in the velocities of light and sound, the variation of the elastic displacements is much slower compared with that of the electromagnetic (EM) field, so the acoustic excitation can be accurately described in the quasistatic approximation.

Simultaneous photonic and phononic, so-called phoxonic, band-gap structures have recently gained much attention and were predicted theoretically in a variety of materials and structures.[8–16] In particular simultaneous light and sound localization was first proposed in infinite two-dimensional (2D) systems[9,10] and later in 2D lithium niobate crystals.[11] Three-dimensional (3D) crystals of metallic spheres in a dielectric matrix were also investigated for this purpose.[16] In addition, several studies focused on silicon slabs, for which the optical properties are well understood,[17] and different phoxonic geometries were proposed.

Light and sound co-localization aims in enhancing the AO interaction. Slow-light effects on the AO interaction, and related applications, have been investigated both theoretically and experimentally. For example it was shown by means of numerical calculations that modulating a 1D optical cavity by a surface acoustic wave leads to enhanced AO diffraction.[18] Moreover, it has been experimentally demonstrated that modulating a 2D photonic crystal by a surface acoustic wave leads also to enhanced AO diffraction thanks to slow-light propagation.[19]

Here, we report a survey of our recent theoretical calculations of different phoxonic architectures using mostly the layer-multiple-scattering (LMS) method, which is well documented for both elastodynamics[20] and electrodynamics.[21,22] The method allows an accurate description of the acoustic and the optical response of layered structures which have the same 2D periodicity. The system under study is decomposed in a number of layers and the scattering properties of each layer is evaluated using multiple-scattering theory. Once the scattering properties of each layer are known, these are combined to obtain a solution for the whole structure. The method can provide the transmittance and reflectance of slabs as well as the band structure of corresponding infinite crystals, including possible material losses.

2. THREE-DIMENSIONAL STRUCTURES

Recently, hypersonic modulation of light was achieved in 3D photonic-phononic silica opals that exhibit partial band gaps.[5] Moreover, optical modulation through acoustic signals was demonstrated in 2D arrays of Au-capped polystyrene spheres.[23] In both studies, femtosecond laser pulses were used to excite elastic waves. On the other hand, some of the authors of the present paper have examined cubic structures of Au spheres in an epoxy matrix as potential candidates for phoxonic applications.[16] Almost touching Au spheres in a simple cubic lattice were

found to produce full, simultaneous band gaps for both photons and phonons. For sphere diameters close to half a micron, the photonic band gap is located around the telecom wavelength 1.55 μm while absorptive losses are low. Here we extend our previous study to silica spheres covered with a Au shell. We consider silica spheres with radius 175 nm covered with a 50 nm thick Au shell, so that the spheres have a total radius of 225 nm. The spheres are arranged on a sc lattice with lattice constant a=480 nm in an epoxy matrix. The dielectric function of Au was taken from tabulated experimental data[24] while a constant refractive index $n = 1.6$ (1.46) was used for the epoxy (silica). Generally, the experimental dielectric function of Au is complex and includes absorption losses which are significant in the optical region; however these losses are proven to be less important below 1 eV. In fact the photonic band structure of this crystal can be reproduced if we set the imaginary part of the dielectric function of Au equal to zero.[16] We use this approximation, which works well for Au around telecom frequencies and allows to define the band gaps unambiguously. The photonic band structure, calculated by the LMS method,[21] projected along two directions in the surface Brillouin zone of the (100) sc surface is shown in Fig. 1a. We observe an omnidirectional gap from 0.70 to 0.86 eV. These results are similar to those for the corresponding crystal of Au spheres.[16]

To obtain the elastic response of the given crystal we assume all materials to be isotropic and lossless. The mass density of silica was taken $\rho = 2.2$ g/cm^3, with the respective compressional and shear speed of sound to be $c_l = 5970$ m/s and $c_t = 3760$ m/s. The corresponding values for Au are $\rho = 19.3$ g/cm^3, $c_l = 3376$ m/s and $c_t = 1482$ m/s and for the epoxy matrix $\rho = 1.19$ g/cm^3, $c_l = 2860$ m/s and $c_t = 1800$ m/s. The projected phononic band structure, calculated by the LMS method,[20] is shown in Fig. 1b. The calculations predict a large frequency gap from 1.95 to 2.8 GHz as well as additional gaps at higher frequencies. The origin of the gaps in such systems has been discussed previously.[25] The same band diagram is also valid at higher frequencies if the dimensions of the structure are scaled down accordingly, however we note that acoustic absorption increases quadratically with frequency and cannot be ignored at higher frequencies. Moreover, scaling to smaller dimensions is problematic for the optical response, since submicron metallic particles strongly absorb light about the particle-plasmon frequencies which, for spherical particles, are located in the visible and near-infrared part of the spectrum.

3. TWO-DIMENSIONAL PATTERNED SILICON SLABS

Patterned silicon slabs can be fabricated with silicon on insulator technology and offer an attractive platform for realizing phoxonic crystals. Periodic structuring of the slab is used to create destructive interference and band gaps for optical modes that are confined perpendicular to the slab by the contrast in the refractive index. Since the polarization of the injected light can be filtered, waveguiding and light localization can be achieved, even with partial gaps, only for modes of odd or even symmetry.[17] Acoustic phonons can be also generated and confined in free Si slabs, since the high impedance mismatch between Si and air traps acoustic waves generated in Si, which are essentially not allowed to couple to sound waves in air. Periodic patterning is expected to induce gaps, and thus phoxonic structures are anticipated. However all phononic modes are generated simultaneously and polarization filtering is not possible, so only full phononic gaps could be usefull. The conditions for the existence of a band gap in a slab are different from the conditions in an infinite 2D crystal. The hexagonal lattice of holes is one of the structures with sizable gap for photons, however this lattice shows no gap for phonons. An extensive study of possible phoxonic structures was recently reported.[13] Silicon slabs with different lattices of cylindrical holes were investigated: square, with one and two atoms per unit cell, honeycomp and more general boron nitride lattices. Complete phononic and photonic gaps where predicted for square and honeycomp lattices but also complete phononic and partial (odd or even) photonic gaps. Alternative structures without cylindrical holes were also proposed.[12] Despite the variety of designs, an experimental demonstration of a Si phoxonic crystal slab is still missing but should be probably expected soon.

4. ONE-DIMENSIONAL MULTILAYERS

The simplest phoxonic structure can be realized by 1D multilayers. The simplicity of the system allows a detailed analysis of the AO interaction. We consider a cavity in a 1D phoxonic crystal with lattice constant a, that consists of a Bragg mirror composed of eight periods of $[SiO_2(2a/3) - Si(a/3)]$ bilayers on the left, a cavity in the middle and eight mirror symmetrical $[Si(a/3) - SiO_2(2a/3)]$ bilayers on the right. The cavity consists of

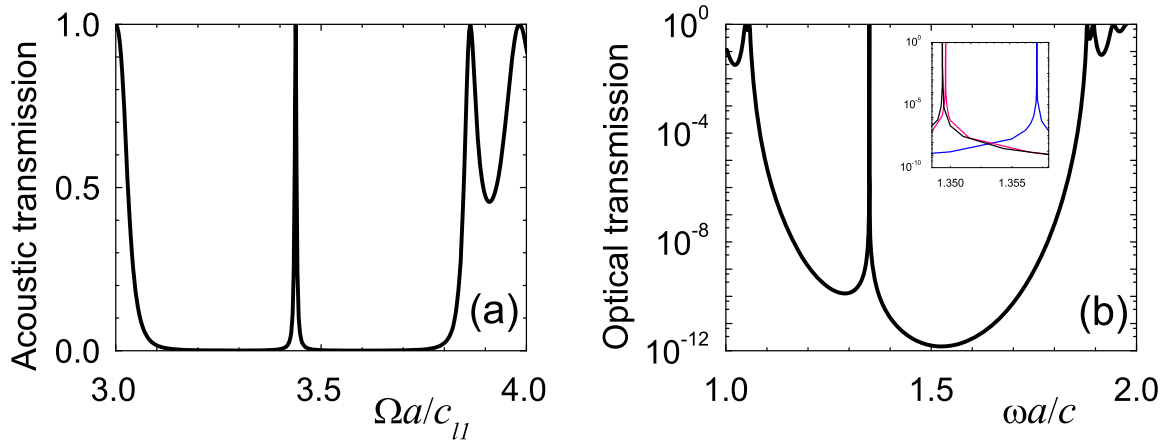

Figure 2. (a) Phononic transmission spectrum of a compressional acoustic wave normally incident on the multilayer structure described in text. (b) Optical transmission spectrum of the multilayer structure under study for normally incident light, without the AO interaction. The optical resonance appears close to $\omega a/c \simeq 1.349$. Inset: Maximum shift of the defect optical mode as elastic waves of different frequencies propagate through the multilayer. An acoustic off-resonance frequency $\Omega a/c_{l1} = 3$ causes only a small frequency shift. For a resonant acoustic wave with $\Omega a/c_{l1} \simeq 3.44$ the optical mode shows a large shift to $\omega a/c \simeq 1.357$.

a multilayer of $[SiO_2(5a/6) - Si(a/6) - SiO_2(2a) - Si(a/6) - SiO_2(5a/6)]$. The total length of the structure is $20a$. The relevant material properties for SiO_2 (Si) are characterized by the index of refraction $n = 1.46$ (3.46), photoelastic coefficient $p_{12} = 0.27$ (0.01), mass density $\rho = 2.20$ (2.33) g/cm^3 and longitudinal sound velocity $c_l = 5970$ (8430) m/s. The acoustic transmission was calculated by the full elastodynamic LMS method,[20] assuming that the structure is embedded in a SiO_2 matrix and shown in Fig. 2a. We consider a normally incident longitudinal elastic wave propagating through the structure. The lowest frequency gap, obtained from a band structure calculation of the periodic system without the cavity, extends from 3.14 to 3.90 in scaled units $\Omega a/c_{l1}$ where c_{l1} is the longitudinal sound velocity in SiO_2. Indeed, we observe almost vanishing transmission in the gap region while the presence of the defect leads to a resonance in the gap around 3.44 $\Omega a/c_{l1}$ as shown in the transmission spectrum in Fig. 2a.

Neglecting the AO interaction, the photonic transmission spectrum, calculated by the full electrodynamic LMS method [21] for the structure under consideration and normally incident light, shows a similar frequency gap, which extends from 1.06 to 1.86 $\omega a/c$, and a resonance inside the gap (Fig. 2b). For reasons explained above, the acoustic wave field will induce a quasi-stationary perturbation on the EM field. The compressional acoustic wave propagates along the z direction and corresponds to an elastic displacement field $u(z,t) = \Re\mathrm{e}\,[u(z)\,\exp(-i\Omega t)]$ which induces a strain field $S(z,t) = \partial_z\, u(z,t)$. These fields will actually determine the AO interaction with the EM wave. A longitudinal acoustic wave traveling through the structure will change the optical transmission through (i) local variation of the refractive index $n(z)$

$$\Delta n(z,t) = -\frac{1}{2} n^3(z) p(z) S(z,t), \tag{1}$$

where $p(z)$ is the appropriate photoelastic coefficient (p_{12}) of the material at point z and (ii) change in the material interfaces. To take into account the continuous variation of the refractive index implied by Eq. (1), we subdivide each layer in a large number of (homogeneous) elementary sublayers. Excellent convergence is obtained for about 100 sublayers in the whole structure, in all cases examined.

When the acoustic excitation is switched on, the optical transmission spectrum varies periodically in time with the period of the acoustic wave. We assume an input strain level of 10^{-3}, which results to a maximum strain 1.5%, on acoustic resonance inside the cavity. In the inset of Fig. 2b we show the maximum frequency shift of the photonic resonance due to an elastic plane wave traveling through the structure at different frequencies. For an acoustic frequency $\Omega a/c_{l1} = 3$, away from the resonance, the calculation shows only a small shift of the

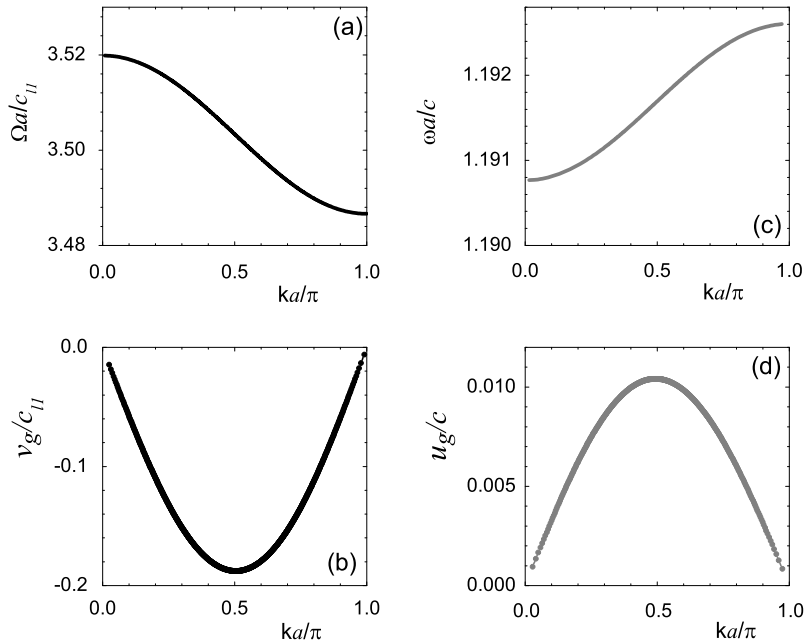

Figure 3. Dispersion of the acoustic and optical defect bands for the CCW described in the text (a, c) and corresponding group velocities (b, d).

optical resonance. On the other hand, when a resonant acoustic wave with $\Omega a/c_{l1} \simeq 3.44$ is launched through the structure, simultaneous localization of photons and phonons causes increased interaction and the maximum shift of the photonic resonance increases by a factor almost 30. The maximum variation in the frequency is proportional to the amplitude of the acoustic field or in other words the number of phonons in the cavity. The strength of the AO interaction is also related to the photonic quality factor. Analyzing the time variation of the electric field[26] we can conclude that simultaneous localization of light and sound can lead to multiphonon absorption-emission and high harmonic generation beyond the first Stokes and anti-Stokes harmonics. It is worth noting that, in the system studied, the dominant AO contribution comes from the interface effect.

Localization in phoxonic cavities can drive nonlinear effects but bound states could be problematic for some processes like stimulated Brillouin scattering (SBS).[27] Conservation of energy and momentum is required for the two optical (pump and Stokes) modes and the acoustic mode, together with a nonvanishing overlap integral of the three fields. This is hard to achieve in a cavity even if several discrete states are present. This could be improved if we consider slow light - slow sound waveguide modes that offer both localization and a continuum of available photonic and phononic states that could increase the efficiency of SBS processes. We have considered a coupled-cavity waveguide (CCW) structure using 1D multilayer $\mathrm{Si}-\mathrm{SiO_2}$ cavities. We use the same periodic multilayer structure considered above $[\mathrm{SiO_2}(2a/3)-\mathrm{Si}(a/3)]$ and introduce a $[\mathrm{SiO_2}(2a)-\mathrm{Si}(a/3)]$ cavity every 9 periods. In Fig. 3 we show the dispersion of the coupled cavity modes for phonons and photons in the corresponding band gaps, and the associated group velocities. The group velocities are small and could be further reduced by increasing the number of periods separating the cavities. However, absorption should be always considered, since slow velocity modes are connected with increased losses.

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