

Phoxonic Crystals for Harnessing the Interaction of Light and Sound

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Abstract—Phoxonic crystals are periodic nanostructures that are simultaneously photonic and phononic crystals. Phoxonic cavities can trap visible or near infrared light and Gigahertz phonons in the same tiny volume, while phoxonic waveguides can confine their propagation to a tiny solid core, in both cases possibly promoting their interaction. This paper reviews various phoxonic nanostructures that have been proposed and discusses the interaction of light and sound within them.

Keywords—*photonic crystal; phononic crystal; phoxonic crystal; photoelastic effect; moving interface effect.*

I. INTRODUCTION

A phoxonic crystal designates a periodic structure that possesses simultaneously a photonic [1] and a phononic [2] band gap. The frequency band gap ranges for photons and phonons are usually vastly different. Given that the speed of elastic waves in solid materials is usually of the order of a few kilometers per second and that the speed of light in matter is of the order of a few 10^5 kilometers per second, the ratio of the involved photonic and phononic frequencies is of the order of 10^5 . Yet the very idea of the phoxonic crystal is that the photon and phonon wavenumbers have comparable orders of magnitude, because of their connection with the period (or lattice constant) of the crystal. A consequence is that both the electromagnetic wave (for classically described photons) and the elastic wave (the continuum mechanical description of low-frequency acoustic phonons) can be confined to the same tiny region of space of the order of the third power of the wavelength. This simultaneous confinement enables interactions between sound and light, or phonons and photons that renew the field of acousto-optics and opto-acoustics.

II. TYPES OF PHOXONIC CRYSTALS

A. Bulk Phoxonic Crystals

The concept of the phoxonic crystal was first introduced for the case of a nanostructure of silicon perforated with a periodical two-dimensional array of holes [3], following the discussion of the phononic properties of silica photonic crystal fibers [4]. These are both examples of bulk phoxonic crystals, meaning that waves propagate in an unbounded, though periodic, medium. Except for the case of the photonic crystal fiber, two-dimensional bulk phoxonic crystals are mostly a model for more complex structures. One important idea property is the existence of a complete phoxonic band gap,

valid for all angles of incidence, or equivalently all wavevectors of reciprocal space [5]. One-dimensional phoxonic crystals have also been investigated, based on periodic multilayer stacks [6,7], though admittedly waves are not confined in the plane and thus only plane-wave operation can be achieved. Three-dimensional phoxonic crystals composed of metal spheres in an elastic/dielectric medium have also been proposed theoretically [8].

B. Membrane Phoxonic Crystals

Membrane-type phoxonic crystals, similar to photonic crystal slab structures, offer a practical basis for fabrication using standard nanotechnologies, e.g. based on silicon-over-insulator (SOI) wafers. In order to obtain a photonic band gap for the near-infrared, it is known that membrane thicknesses of the order of 250 nm and lattice constants of the order of 500 nm are required. With these orders of magnitude, phononic band gaps around 5 to 10 GHz can be expected. The exploration of the optimal lattices and geometrical dimensions has been conducted in recent years for the case of circular holes [9,10], pillars [11], or mass-spring networks [12]. The first experimental demonstration of a phoxonic band gap was performed in the latter case [13].

III. DESIGN OF PHOXONIC CRYSTAL STRUCTURES

A. Holes, Pillars, or Stubs?

The type of inclusion that should be considered to obtain complete and large phoxonic band gaps is not an obvious choice. Circular holes are a natural choice that is well compatible with nanotechnological processes. They are well suited for large photonic band gaps, but they require very large filling fractions, i.e. almost touching holes, for large phononic band gaps. Alternatively, large phononic band gaps can be obtained by combining Bragg band gaps with local resonances in the case of periodic arrays of ‘masses’ connected by ‘springs’; masses are constituted from plain parts of the solid material while elastic springs are naturally formed by thin bridges etched in the same material. Pillars formed on top of the membrane also present natural local resonances that help form phononic band gaps. In addition, in the case of wire waveguides formed by structuration of the membrane, solid stubs can be added to the sides to act as local elastic resonators and combined with holes [14,15]. All in all, several types of working design solutions obtained by numerical optimization are now available [16].

B. Cavities and Waveguides

Various types of cavities and waveguides based on defects introduced in phoxonic crystals have been proposed. Those include Fabry-Perot interferometers in 1D phoxonic crystals [6,7], defect-based and tapered cavities in 2D phoxonic crystal slab structures [13,17,18,19]. Phoxonic crystal waveguides are also based on similar ideas and rely on a complete phoxonic band gap to ensure simultaneous light and sound confinement [20,21,22].

IV. INTERACTION OF LIGHT AND SOUND

The interaction of light and sound, or photons and phonons, in phoxonic crystals is governed by bulk and surface couplings. The coupling efficiency is usually rather small and interactions involve 2 photons (or 2 optical waves) and 1 phonon (or 1 elastic wave). The reason is that efficient interaction requires phase-matching conditions that can only be fulfilled by combining several frequencies in sums or differences. In the case of waveguides, in addition, wavevector matching must be achieved for efficient interaction, such as in the case of Brillouin light scattering by acoustic phonons.

A. Photoelastic and Moving interface effects

In acousto-optics, the dominant interaction occurs in the bulk of materials and is governed by an *ad hoc* photoelastic tensor. Multiplied by the strain tensor, which measures local deformations of the medium caused by the elastic wave, the photoelastic tensor gives the perturbative change in the electromagnetic permittivity. In phoxonic crystals, this photoelastic effect is obviously also present and is responsible for bulk inelastic light scattering.

Light confinement in phoxonic crystal relies on the strong contrast in dielectric constant between a material and air, or between different materials. As an elastic wave propagates, it causes a vibration of the interfaces and effectively modulates in time the resonance frequency of an optical cavity or the propagation constant (wavenumber) of an optical waveguide. This moving-interface effect can be significant in small core waveguides [23] and in silicon phoxonic crystal cavities [18,19], for instance.

B. Radiation Pressure and Electrostriction

As light can be strongly confined in tiny waveguides or cavities, in addition to sensing high-frequency acoustic phonons it can generate them. In optomechanics, the basic generation mechanism is often attributed to radiation pressure that light exerts on dielectric interfaces and can set it into motion [23]. This generation effect of sound by light is the reciprocal of the moving interface effect involved in surface inelastic light scattering. In a similar way, bulk generation of sound by light can be attributed to the reciprocal of the photoelastic effect, or electrostriction [24]. All effects can be gathered in a unique Lagrangian formulation from which efficient finite element computations can be performed.

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