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انتشار همزمان امواج نوری و صوتی در بلور فوکسونیکی

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چکیده - ما یک ساختار بلور فوکسونیکی طراحی کرده ایم که قابلیت هدایت امواج نوری با قطبش عرضی مغناطیسی و امواج صوتی را از طریق اثر باند ممنوع دارد. این ساختار از مواد تنگستن و پلی متیل متاکریلات تشکیل شده است که دارای اختلاف های خوبی در ضریب شکست و ثابت های الاستیکی می باشند. این امر سبب شده تا با درصد تخلخل پایین بتوان این ساختار را پیاده کرد. درصد تخلخل بالا یک مشکل در روش ساخت می باشد.این ساختار یک باند ممنوعه کامل فونونیکی و یک باند ممنوعه فوتونیکی برای امواج با قطبش مغناطیسی را نشان می دهد. یک موج بر با زاویه ۹۰ درجه تعریف شده است که نشان می دهد نور و صوت می توانند از این ساختار عبور کنند بدون اینکه هیچ اختلالی رخ بدهد. برای شبیه سازی از روشهای المان محدود، بسط امواج تخت و تفاضل محدود حوزه زمان استفاده شده است . کنترل همزمان نور و صوت در ساختارهای در ابعاد زیر-میکرون امکان بهبود برهمکنش نور و صوت را از طریق اثر های همچون اثر نور-الاستیک افزایش می دهد.

کلید واژه- باند ممنوع، بلورهای فوکسونیکی، ثابت های الاستیکی، درصد تخلخل.

Simultanoeus Guiding of Light and Acoustic Waves in the Phoxonic Crystal

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Abstract- In this paper, we characterize a phoxonic crystal for guiding the TM-polarized light and acoustic waves at the same time through the band gap effect. The structure is made of Tungsten and poly methyl methacrylate (PMMA) which show a good contrast in their refractive indices and elastic constants. That makes it possible to fabricate the structure with a low filling fraction. High filling fraction is a problem in the fabrication process. This structure shows a complete phononic band gap with a TM-polarized photonic band gap. A waveguide with an angle of 90 degree is defined that shows light and sound can propagate through the structure without any distribution. For the simulation, finite element (FE) method, plane wave expansion (PWE) and finite difference time domain (FDTD) are used. Localization of light and sound in sub-micron structures enhance the interaction of photon and phonon through effects like photo-elastic effect (PE).

Keywords: Band gap, Elastic constants, filling fraction, phoxonic crystals

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1 Introduction

A recently introduced phoxonic crystal has the feature of photonic and phononic crystals at the same time [1, 2]. Phoxonic crystals can control the propagation of light and sound because they have periodicity in refractive indices and elastic constants [3]. In these structures, the very strong spatial confinement of the wave energy and the reduction of group velocities by several orders of magnitude are made possible [4]. However the velocity of the acoustic waves are five orders of magnitude lower than the velocity of light in the vacuum but it should be noted that the wavelength governs the frequency ranges where waves strongly faces periodicity and Phononic crystals are operating in the GHz range and photonic crystals operating in the visible and near-IR spectrum, the common point is that the relevant wavelengths are in the sub-micron range [4]. The interesting point of these structures is the confining of the optical and acoustic energy simultaneously which leads to the enhancement of interactions between photons and phonon [5]. This results in effects like photo-elastic effect, moving interface effect and radiation pressure [6]. They are also useful for the development and improvement of devices of integrated acousto-optic, such as filters and sensors [7].

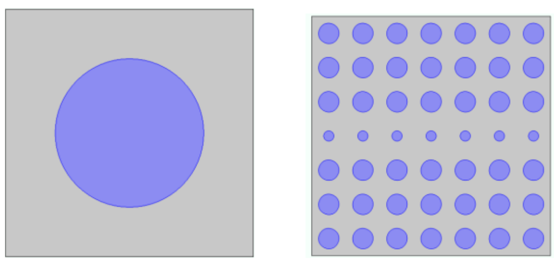
In this paper, we show theoretically that photons and acoustic phonons can be simultaneously guided in a 2D infinite square-lattice solid-solid phoxonic crystals via the phoxonic band gap effect. Geometrical parameters are first optimized to achieve a complete phononic band gap and a TM-polarized photonic band gap.

2 Geometry and method of calculations

A square lattice of infinite long rods in a matrix is defined as the structure. The constitute materials are Tungsten and Poly methyl methacrylate (PMMA) because they have acceptable contrasts in their elastic constants (the key for opening phononic band gaps) and their refractive indices (the key for opening photonic band gaps). The parameters are given in Table 1 [8, 9]. The z axis is chosen to be perpendicular to the plate and parallel to the cylinder axis. The geometrical parameters are; lattice constant a=190nm and the radius of rods r=0.3a. One problem in the fabrication of these structures is high filling fraction but these parameters result in a filling factor of 28% which is so promising.

To calculate the phononic band structure, finite-element (FE) method has been used and periodic boundary conditions, using the Bloch-Floquet equations, are applied at each side of the unitcell, which means an infinite and periodic structure in the (x,y) plane [1].

For the photonic part, the calculations are done by Plane-wave expansion (PWE) method. In both phononic and photonic cases, the wave vector are swept along the high-symmetry points of irreducible Brillouin zone and the eigenfrequencies are obtained by solving the eigenvalue equation.



(a) (b)

Fig. 1. (a) The unit cell and (b) the supercell with defect.

Table. 1. The elastic and optical parameters of constituent materials.

Parameters	**Tungsten**	**PMMA**
Mass density	19350 [kg/m³]	1190 [kg/m³]
Young's module	411 [GPa]	3 [GPa]
Poisson ratio	0.28	0.4
Refractive index	3.6528	1.4848

3 Phoxonic band gaps

In this section the phononic and photonic band gaps will be calculated. In order to achieve the band gap of a perfect structure, a unitcell needs to be defined and periodic boundary condition (PBC) has to be applied on its sides as can be seen in Fig. 1(a). To obtain the phononic band structure, finite element (FE) method has been opted which was recently shown to be very efficient for obtaining phononic band structures. The governing equations of wave propagation in linear elastic materials are given by the equations of motions. These equations are: the generalized Hooke's law and the kinematic relations. By using the summation convention, they can be given as [١٢]:

$$\rho u_{p,tt} = \sigma_{pq,q}\,, \qquad (1)$$

$$\sigma_{pq} = C_{pqrs}\varepsilon_{rs}\,, \qquad (2)$$

$$\varepsilon_{rs} = \frac{1}{2}\left(u_{r,s} + u_{s,r}\right), \qquad (3)$$

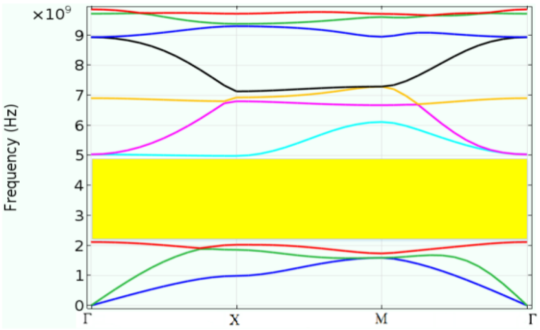
where u_p is the displacement, σ_{pq} is the stress, ε_{rs} is the strain components and c_{pqrs} is the stiffness tensor. The discretization of these equations leads to the following equation [١٢],

$$\left(K - \omega^2 M\right)V = 0 \qquad (4)$$

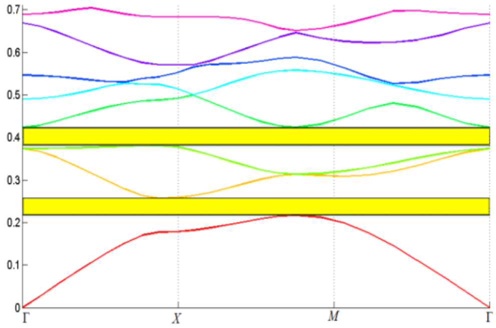
where K and M are the global stiffness and mass matrices of the unit cell respectively, and V is the vector of the nodal displacements. This equation can describe the vibrations and the eigenfrequencies of the unit cell. Here, we can have a wide band gap as can be seen in Fig. 2(a). To obtain the photonic band structure the plane wave expansion (PWE) are used. The fundamental equation [13] solved by this method is;

$$\hat{L}u_k = iK + \nabla \times \left(\frac{1}{\varepsilon X} iK + \nabla\right) \times u_k = \omega'^2 u_k \qquad (5)$$

where we have defined the normalized frequency $\omega' = \omega/c$ and $\hat{L}$ is the operator . This equation has to be viewed as an eigenvalue equation for the unknown eigenvalue ω' and eigenvector u_k with wavevector K as a free parameter. The photonic band diagram for TE modes is shown in Fig. 2 (b).

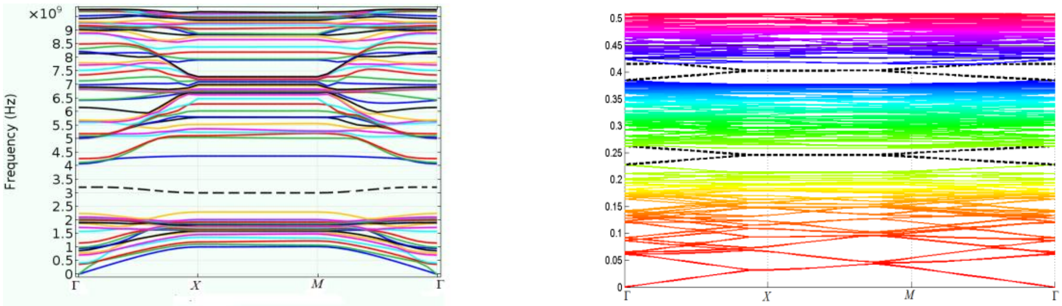


(a)



(b)

Fig. 2. The band diagram of the perfect structure; (a) phononic band diagram and (b) TM-modes photonic band diagram

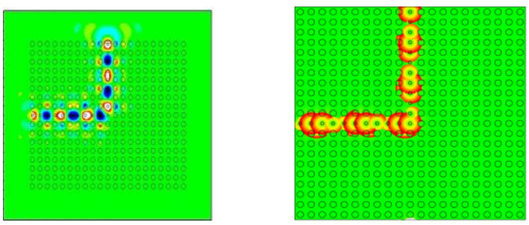


(a) (b)

Fig. 3. The band diagram of the supercell with line defect; (a) phononic part and (b) photonic part.

A wide phononic band gap extends from 2 GHz to 5 GHz between the 3-rd and 4-th bands and two TM-polarized gaps have been obtained. The first gap extends from a reduced frequency ($\omega a/2\pi c$, which ω is angular frequency and c is the speed of light) of 0.217 to 0.257 and for the second one from 0.38 to 0.423.
A line defect has to be defined to introduce some defect modes within the band gaps because these modes can propagate through the structure without being disturbed. For the line defect, the radii of one line of perfect rods reduced to 0.5r. To obtain the band structure, the supercell technique has been employed and a supercell is defined shown in Fig. 1(b).

By this line defect, guided defect modes introduced in the band gaps as can be seen in Fig. 3.
These black-dashed modes have the possibility of going through the structure without being spread. A waveguide is defined with a 90-degree angle to show the propagation of these modes in the structures. For the propagation of the modes, the finite difference time domain (FDTD) method and finite element (FE) method are used. Figure 4 shows the propagation of the phononic and photonic defect modes through the waveguide.



(a) (b)

Fig. 4. The propagation of the defect modes; (a) photonic mode with a wavelength of 840 nm and (b) the phononic mode with a frequency of 3 GHz.

4 Conclusion

A phoxonic crystal is designed that can show photonic and phononic band gaps simultaneously. The problem of high filling fraction is solved in our structure because it is only 28%. By introducing the line defect, slow light and elastic guided modes are added in the band gaps and it was shown that these modes can propagate through the structure without any distribution. It paves the way of making phoxonic components like filters and demultiplexers.

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