Acousto-optic couplings in two-dimensional Lithium Niobate phoXonic crystal

Quentin ROLLAND1, Samuel DUPONT1, Joseph GAZALET1, Jean-Claude KASTELIK1

1Institut d’Electronique, de Micro-électronique et de Nanotechnologie, UMR CNRS 8520, Université de Valenciennes-Hainault-Cambrésis, Valenciennes, France

*Corresponding author: quentin.rolland@univ-valenciennes.fr

Abstract. We investigate the acousto-optic couplings in two-dimensional infinite piezoelectric phoXonic crystal cavities. The periodic structure considered consists in a square array of air inclusions drilled in Lithium Niobate matrix. This structure allows the simultaneous confinement of acoustic and optic waves in a point defect obtained by removing one hole from the structure. Our theoretical analysis takes into account three different coupling mechanisms. In addition to the traditional effects: photo-elastic effect and opto-mechanic effect existing in non-piezoelectric materials, we consider the electro-optic effect introduced by the electric field accompanying the phonon. Using the finite element method, we analyze the perturbation of the photonic cavity modes under the action of phononic cavity modes. We first discuss some aspects of the additional electro-optic effect. For illustration purposes, we compare the coupling strength of two analogous breathing modes, one as found in the LiNbO3 structure and another mode qualitatively comparable but evidenced in a similar silicon structure. Then, we end the discussion by an analysis of the coupling strength dependence on typical crystallographic cuts of Lithium Niobate.

1. INTRODUCTION

PhoXonic crystal designates a nanostructure that exhibits simultaneously photonic [1,2] and phononic [3-5] crystals behaviors. The capital letter X stands for both the characters t and n which refer to photonic and phononic. The strong interest for phoXonic devices is mainly triggered by the fact that these structures lead to acousto-optic devices with very promising efficiencies [6]. Indeed, these manmade crystals provide a tool for confining simultaneously photonic and phononic energy, in relation with slow-waves and/or forbidden frequency bandgaps phenomena that affect both light and sound waves. Beside the expected high efficient acousto-optic interaction, devices based on phoXonic crystals reduce the energy consummation owing to their miniaturization as compared to conventional acousto-optic devices [7]. Furthermore, phoXonic crystals offer the possibility to control simultaneously light and sound in frequency domains of interest for optical communication systems. For instance, the technology advances allow the design of PhoXonic crystals with periods extending a few hundreds of nanometers. At these dimensions, the optical operating wavelengths fall in the telecommunication ranges while the acoustic frequencies are in the GHz range.

Maldovan and Thomas [8] have demonstrated the existence of simultaneous photonic and phononic forbidden bandgaps in 2D square lattice realized by air holes drilled in bulk silicon. Other authors have extended the study to other materials and patterns. For example, simultaneous bandgaps have
been studied in sapphire [9], in lithium niobate [10] for different lattices like honeycomb or triangular lattices. More recently, researches on simultaneous bandgaps have been focused on 3D calculation including slabs [11, 12], pillars [13] or strip waveguides [14]. Also, acousto-optic modulators based on isolated cavities [6-15] and waveguides [16] have been investigated in silicon phoXonic crystal. Recently [17] we have demonstrated that square and honeycomb lattices, correctly designed on silicon and lithium niobate, may develop sufficiently wide optical and acoustic forbidden bands to provide simultaneous confinement of optical and acoustic modes. However, triangular lattice presents too thin acoustic bandgaps to ensure this simultaneous confinement.

In the present letter we study the acousto-optic modulation through the photoelastic, the optomechanic and the electro-optic effects in silicon and lithium niobate in different situations. This enables to get insights on the influence of the media on the acousto-optic couplings: by a judicious choice of some couples of mode (photonic-Phononic) we analyze the various interaction mechanisms and give an interpretation of their relative importance.

2. THEORETICAL MODEL AND MATHEMATICAL PROCEDURE

In a first step, the crystal phononic and photonic band structures are determined using the conventional unit-cell method combined with the Bloch-Floquet boundary conditions. Then, the localized cavity modes are established using a 7x7 supercell model. At last, the acousto-optic modulation is characterized in a quasi-static approach. This is fully justified considering the 5 orders of magnitude separating the phononic (Ω) and the photonic (ω) frequencies. In other words, the localized acoustic modes (instantaneous mechanical displacement vectors, deformation tensors and the companion piezoelectric fields in the case of LiNbO3 material) are determined at discrete time instants within an acoustic period 0≤Ω·t<2π. The resulting instantaneous maps of the acoustically disturbed permittivity are reintroduced within a multi-physics procedure, in order to determine the optical perturbed modes. The acousto-optic modulation results are presented as the photonic angular eigenfrequency (ω) excursions during a complete acoustic period 0≤Ω·t<2π.

From a phenomenological point of view, one can distinguish different effects contributing to the perturbation of the permittivity by the acoustic modes. Namely, the photo-elastic i.e. Pockel effect, and the opto-mechanical effect resulting from the moving hole boundaries. A third effect must also be taken into account in case of piezoelectric materials like LiNbO3. This is the electro-optic effect initiated by the piezoelectric field accompanying the deformation field.

The 2D model is developed using a commercial Finite Element Method (FEM) software. Concerning the photonic crystals modeling, all domains are meshed. Whereas, only solid materials domains are meshed for phononic crystal simulations, since elastic waves cannot propagate in air. For the computation, we use the values of the stiffness tensor, the mass density and the refractive index as published in [17] and [18] for silicon and lithium niobate respectively. Finally, the photo-elastic and electro-optic parameters are taken from [19] and [20] for silicon and lithium niobate respectively.

3. RESULTS AND DISCUSSION

All the presented results are given for square lattices with period a, of air holes included in bulk materials. The hole reduced radius r/a = 0.48 is chosen to provide bandgaps for both waves in silicon and lithium niobate simultaneously. The acoustical eigenmodes are labeled according to the ascending eigenfrequency order using capital letters in silicon and with primed capital letters in lithium niobate. Similarly, the optical eigenmodes are labeled with the same convention but with Greek letters. In both materials the eigenmodes are characterized by their eigenfrequencies and eigenvectors: the field distributions.

In order to compare the acousto-optic coupling mechanisms in the different materials, we have chosen acoustic modes with similar displacement spatial distributions: mode F in silicon and mode C’ in LiNbO3, as illustrated in fig.1 inset. Both modes are “breathing” modes: these particular modes induce a change of the cavity volume through a contraction and dilatation without too many distortions. The color scale depicts the total displacement amplitude whereas the arrows indicate the
displacement direction. Optical TE modes $\alpha$ and $\beta'$ have been chosen for the same reason: modal similarity among the two materials. They are both characterized by an $E_z$ field distribution with two principal lobes. For the TM polarization, no optical modes with such a degree of similarity have been found. So, we have made the choice of optical modes $\delta$ and $\varepsilon$ in silicon and modes $\alpha'$ and $\beta'$ for lithium niobate: both of these modes share the particularity of presenting four $H_z$ lobes. We present here the most representative results of an exhaustive numerical study to assess the effect of the different coupling mechanisms on the overall optical mode modulation.

Figure 1.a presents the modulation of optical TE modes $\alpha$ and $\beta'$ eigenfrequencies under the perturbation of acoustic modes $F$ and $C'$ respectively as a function of the acoustic period $\Omega \cdot t$ varying between 0 and $2\pi$. As can be seen, in Silicon the modulation consecutive to the elasto-optic effect is not significant and the total modulation effect is due to the optomechanic effect. The results in Lithium Niobate are quite different: first one can observe that both optomechanic and elasto-optic effects produce significant modulations and are out of phase (consecutively their total contribution is less significant than one effect considered alone), whereas the electro-optic contribution is not significant. Such observations can be explained qualitatively by an inspection of the physical constant tensor elements at stake in the model. Strictly speaking, the electro-optic contribution would depend on $r_{33}$ electro-optic coefficient. But, in the case of a strictly 2D model considered here (i.e. the system is assumed to be invariant with respect to translation in the Z axis direction) this dependence no longer holds. On the other hand, the photoelastic constants at stake are: $p_{12} = 0.017$ in Silicon and $p_{31} = 0.17$ in Lithium Niobate. The factor ten between the constants is in correlation with the modulations observed.

Figure 1.b presents the modulation of the optical TM modes $\alpha$ and $\beta'$ eigenfrequencies consecutive to an acoustic perturbation respectively by modes $F$ and $C'$, as a function of the acoustic period: $0 \leq \Omega \cdot t < 2\pi$. As it can be seen in this case, the modulation induced by the elasto-optic effect is quite similar in both materials. The photoelastic tensor elements that are involved in the coupling now are a combination of: $p_{11} = 0.09$ and $p_{44} = 0.05$ in Silicon and $p_{12} = 0.09$ and $p_{11} = 0.026$ in Lithium Niobate.
The photoelastic constants at stake are quite similar in both materials, hence a modulation with the same order of magnitude is found.

Figure 2: Modulation of optical eigenmode frequencies as a function of one acoustic period, in LiNbO$_3$ Z-cut structure (left) and LiNbO$_3$ X-cut (right). The green, blue and black curves correspond to the modulation due to the photo-elastic, the optomechanic and the electro-optic effects respectively. The red curve presents the overall modulation when all acousto-optic mechanisms are taken into account.

Figure 2 now compares two situations for the same material LiNbO$_3$, but for different crystallographic cuts. The modulation of the optical TM modes $\alpha'$ eigenfrequencies consecutive to an acoustic perturbation by modes $A'$ in Z-cut and X-cut respectively is displayed as a function of the acoustic period $\Omega \cdot t$. At first sight, it is surprising that two acoustic modes sharing approximately the same displacement distribution and modulating two optical modes with very similar field distributions present quite significant different acousto-optic modulation profiles: those of the Z-cut are characteristic of a second order effect whereas the X-cut ones are typical of a first order effect. The second observation concerns the electro-optic effect. Practically unnoticeable in the case of a Z-cut material, it becomes the strongest effect in the case of an X-cut one. The latter observation is easily linked to the electro-optic coefficient at stake: for Z-cut, $r_{33} = 3.4 \times 10^{-12}$ V/m is at stake in the coupling whereas $r_{13} = 7.7 \times 10^{-12}$ V/m, $r_{22} = 3.4 \times 10^{-12}$ V/m, $r_{42} = 18 \times 10^{-12}$ V/m and $r_{33} = 28.8 \times 10^{-12}$ V/m are all together involved in the electro-optic coupling in X-cut. Concerning the second / first order behavior of the acousto-optic perturbation, we remind that the perturbation theory tells us that the first order correction vanishes whenever the perturbation owns an anti-symmetric plane and so, the usually weak second order effects are no more hidden and manifest themselves. This is exactly what happens in the case of the Z-cut LiNbO3. But, in the X-cut case, while at a first glance the acoustical displacement field seems to be very similar to that of the Z-cut, if the distribution of the perturbed permittivity tensor elements is carefully inspected, it reveals that the antisymmetric plane does not exist anymore. We attribute this observation to the strong acoustic anisotropy in the case of X-cut. [15,17]

4. CONCLUSION
Considering two materials, silicon and lithium niobate, we have established that the acousto-optic coupling between an optical and an acoustical cavity mode is strongly influenced by the choice of the couple of modes. The different interaction mechanisms can sustain or oppose each other. We give an interpretation of the modulation behavior based on an analysis of the materials intrinsic parameters. As it is established for propagating waves, different interaction configurations result in different interaction efficiencies, this is also the case here for cavity modes. On the other hand, the strong anisotropy of lithium niobate influences the acoustic field distribution: different cuts provide different modes. Moreover, when quasi-similar modes are found on different cuts, they may lose symmetry elements which drastically modify the optical modulation. The crystallographic cut is found to be a crucial factor in the design process of phoXonic crystals for acousto-optic interaction.
References
[1] E. Yablonovitch, *Phys. Rev. Lett.* **58**, 2059 (1987)
[2] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, Photonic Crystals: Molding the Flow of Light (*Princeton University Press*, 2008)
[3] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, *Phys. Rev. Lett.* **71**, 2022 (1993)
[4] M. M. Sigalas and E. N. Economou, *Solid State Commun.* **86**, 141 (1993)
[5] Y. Pennec, J. Vasseur, B. Djafari-Rouhani, L. Dobrzynski, and P. A. Deymier, *Surf. Sci. Rep.* **65**, 229 (2010)
[6] I. E. Psarobas, N. Papanikolaou, N. Stefanou, B. Djafari-Rouhani, B. Bonello, V. Laude, *Phys. Rev. B* **82**, 174303 (2010)
[7] N. Courjal, S. Benchabane, and J. Dahdah, G. Ulliac, Y. Gruson, V. Laude, *Appl. Phys. Lett.* **96**, 131103 (2010)
[8] M. Maldovan and E. L. Thomas, *Appl. Phys. Lett.* **88**, 251907 (2006)
[9] D. Bria, M. B. Assouar, M. Oudich, Y. Pennec, J. Vasseur, and B. Djafari-Rouhani, *J. Appl. Phys.* **109**, 014507 (2011)
[10] S. Sadat-Saleh, S. Benchabane, F. I. Baida, M. P. Bernal, and V. Laude, *J. Appl. Phys.* **106**, 074912 (2009).
[11] Y. Pennec, B. Djafari Rouhani, E. H. El Boudouti, C. Li, Y. El Hassouani, J. O. Vasseur, N. Papanikolaou, S. Benchabane, V. Laude, and A. Martinez *Optics Express* **18**, 1314301 (2010)
[12] Y. Pennec, B. Djafari Rouhani, E. H. El Boudouti, C. Li, Y. El Hassouani, J. O. Vasseur, N. Papanikolaou, S. Benchabane, V. Laude, and A. Martinez *Chinese Journal of Physics* **49**, 1 (2011)
[13] Y. El Hassouani, C. Li, Y. Pennec, E. H. El Boudouti, H. Larabi, A. Akjouj, O. Bou Matar, V. Laude, N. Papanikolaou, A. Martinez, and B. Djafari Rouhani, *Phys. Rev. B* **82**, 155405 (2010)
[14] Y. Pennec, B. Djafari Rouhani, C. Li, J. M. Escalante, A. Martinez, S.Benchabane, V. Laude, and N. Papanikolaou, *AIP Advances* **1**, 041901 (2011)
[15] Q. Rolland, M. Oudich, S. El-Jallal, S. Dupont, Y. Pennec, J. Gazalet, J. C. Kastelik, G. Lévêque, and B. Djafari-Rouhani, *Appl. Phys. Lett.* **101**, 061109 (2012)
[16] Tzy-Rong Lin, Chiang-Hsin Lin and Jin-Chen Hsu, *J. of Appli. Phys.* **113**, 053508 (2013)
[17] Q. Rolland, PhD thesis « Couplages acousto-optiques dans les cristaux photoniques et phononiques » (2013)
[18] D. K. Biegelsen, *Phys. Rev. B* **32**, 211196 (1974)
[19] R.S. Weis and T.K. Gaylord, *Appl. Phys. A* **37** (4), 191-203 (1985)
[20] M. Jazbinsek and M. Zgonik *Appl. Phys. B* **74**, 407–414 (2002)