Dynamical generation of sound in photonic cavities and waveguides

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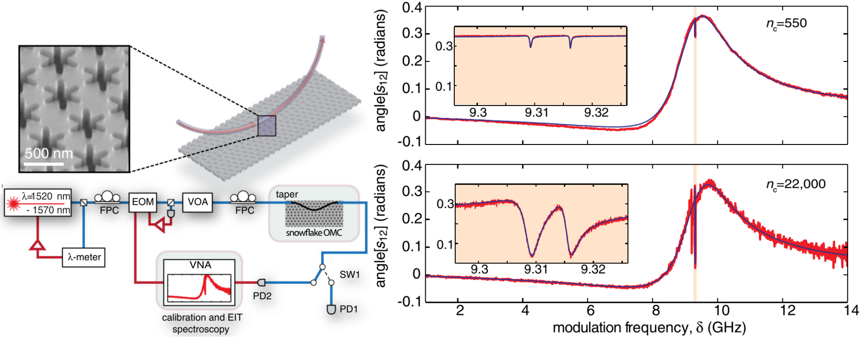
Outline

1. Introduction
2. Sound & light interaction
3. Phonon generation in photonic crystal cavity
4. Brillouin scattering and electrostriction in optical fibers and waveguides
5. Conclusion

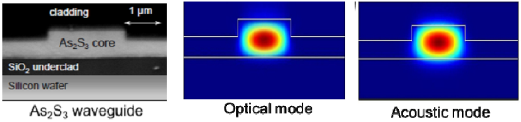
Optomechanics in photonic/phoXonic crystal slab cavity



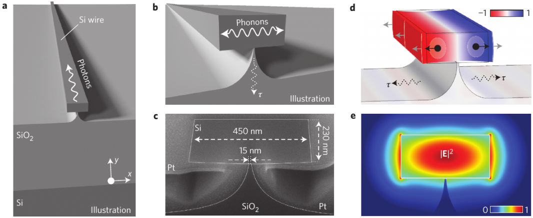
Safavi-Naieni *et al.*, PRL **112** 153603 (2014): phoXonic bandgap for photons (190 – 210 THz) and phonons (7 – 9.5 GHz).

Related structures: nanoscale waveguides

- Chalcogenide rib waveguide, Pant *et al.*, Opt. Express **9**, 8285 (2011); Merklein *et al.*, Nature Communications **6**, 6396 (2015)



- Silicon waveguide, Rakich *et al.*, Phys. Rev. X **2**, 011008 (2012); Van Laer *et al.*, Nature Photonics **9**, 199 (2015)



Problem considered: photon-phonon interaction

The consideration of nanoscale waveguides and cavities calls for a renewed view at acousto-optical and opto-acoustic interactions.

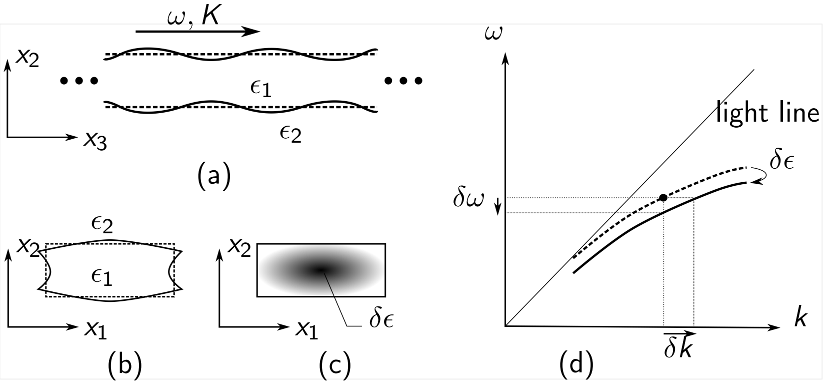
- Plane wave theories are not very useful anymore,
- The presence of surfaces and interfaces must be taken into account,
- All-optical generation of acoustic phonons can be observed at high power densities enabled by strong confinement.

Our approach: we formulate a **Lagrangian** (or energetic, or variational) picture of photon-phonon interaction under phase-matching.

Representation of the interaction problem

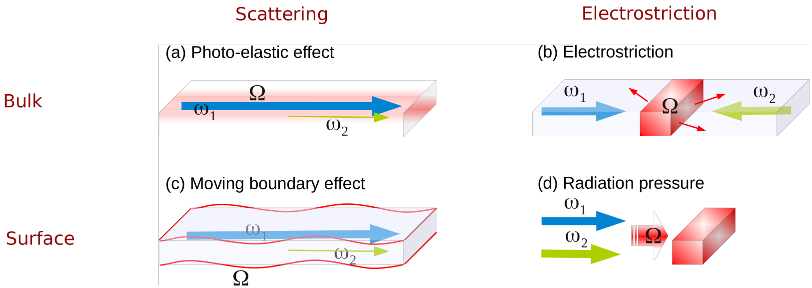
Basic idea

Perturbation of the optical polarization (dielectric tensor)



For a waveguide: $\delta k = -(v_g)^{-1}\delta\omega$

Bulk and surface effects [3-wave interaction picture]



Pennec *et al.*, Nanophotonics **3**, 413 (2014)

Lagrangian for Sound & light interactions

$$\mathcal{L} = \underbrace{\int_V \mathrm{d}V(\mathrm{EM})}_{} + \int_V \mathrm{d}V(\mathrm{mech.}) + \underbrace{\int_V \mathrm{d}V(\mathrm{inter.})}_{}$$

$\delta\mathbf{E}\downarrow$ $\downarrow\delta\mathbf{u}$ $\delta\mathbf{E}\downarrow$ $\downarrow\delta\mathbf{u}$

MI RP PE ES

$$(\mathrm{EM}) = \frac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{D} - \boldsymbol{B}\cdot\boldsymbol{H})$$

$$(\mathrm{mech.}) = \frac{1}{2}\rho\dot{u}_i\dot{u}_i - \frac{1}{2}u_{i,j}c_{ijkl}u_{k,l}$$

$$(\mathrm{inter.}) = -\epsilon_0 p_{ijkl}D_iD_ju_{k,l}$$

Acousto-optics	PE	photoelastic
	MI	moving interface
Opto-acoustics	ES	electrostriction
	RP	radiation pressure

Laude & Beugnot, New J. of Physics **17**, 125003 (2015)

Brillouin scattering: coupling coefficients

- Assume both the photonic mode and the phononic modes are known, then we can compute coupling coefficients
  - PE coupling

$$g_{PE} = -\frac{\omega}{2} \frac{\int_V \mathrm{d}V \ \epsilon_0 p_{ijkl} D_i D_j u_{k,l}}{\int_V \mathrm{d}V \ \mathbf{E} \cdot \mathbf{D}}$$

  - MI coupling

$$g_{MI} = -\frac{\omega}{2} \frac{\int_\Sigma \mathrm{d}S \ u_n \cdot (\Delta\epsilon |\mathbf{E}_{\|}|^2 - \Delta\epsilon^{-1} D_\perp^2)}{\int_V \mathrm{d}V \ \mathbf{E} \cdot \mathbf{D}}$$

- If there are well defined photonic and phononic modes, evaluation is straightforward.
- Criticism: if there are many phononic modes available (e.g., in extended membranes), how do we obtain them?

Electrostriction of acoustic phonons

- Since we can select a particular photonic mode of the cavity, can we know exactly which phonons are excited by light?
- Idea: we can obtain the elastodynamic equation (for elastic waves, or acoustic phonons) subject to an optical force.
- The bulk optical force is given by electrostriction

$$\rho \frac{\partial^2 u_i}{\partial t^2} - (c_{ijkl} u_{k,l})_{,j} = -T^{\mathrm{es}}_{ij,j}$$

with the ES stress tensor $T^{\mathrm{es}}_{ij} = -\frac{1}{2}\epsilon_0 p_{klij} D_k D_l$.
Beugnot *et al.*, PRB **86**, 224304 (2012)

- What about the surface optical force?

Surface contribution to electrostriction: radiation pressure

- The variation of the electromagnetic energy stored in the cavity is given by

$$\delta E \approx \int_{\Sigma} u_n dS \; F_s$$

with the surface force (pressure) $F_s = \frac{1}{2}(\Delta\epsilon E_{\parallel}^2 - \Delta\epsilon^{-1} D_{\perp}^2)$. The surface integral is added to the variational formulation of the elastodynamic equation:

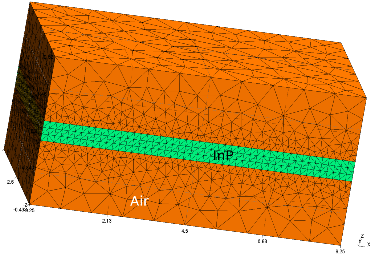
$$-\Omega^2 \int_V \rho u_i' u_i + \int_V u_{i,j}' c_{ijkl} u_{k,l} = \int_V u_{i,j}' T_{ij}^{\mathrm{es}} + \int_{\Sigma} u_n' dS \; F_s$$

where u' is the virtual displacement.

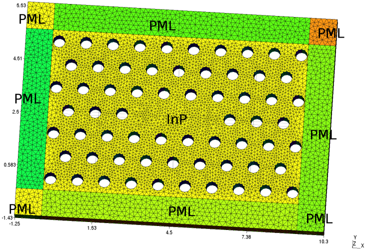
- These equations can be solved by a finite element method (FEM).

Electrostriction in photonic crystal cavity

- Dimensions from Gavartin *et al.*, PRL **106** 203902 (2011): L3 cavity in an InP membrane ($h = 260$ nm, $a = 420$ nm, $r = 90$ nm). Optical index $n = 3.17$.



(a) Optical geometry

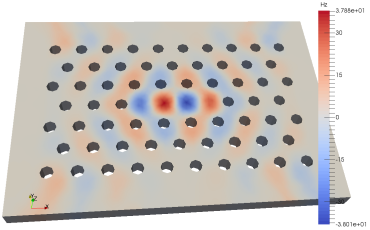


(b) Elastic geometry

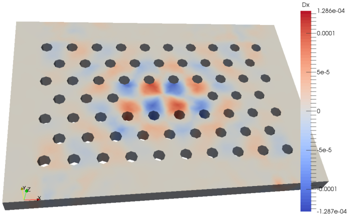
PML: perfectly matched layer

Photonic mode

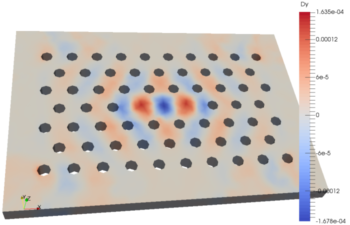
Fundamental TE mode at $\lambda = 1.55\ \mu\mathrm{m}$.



H_z

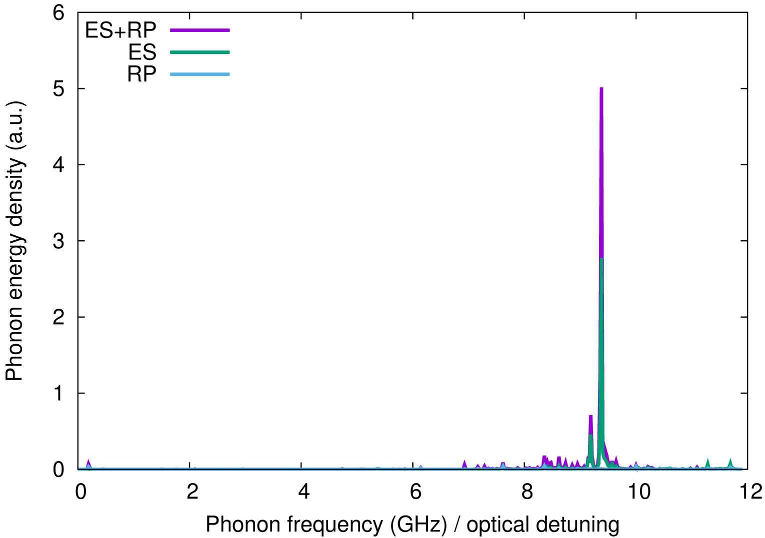


D_x

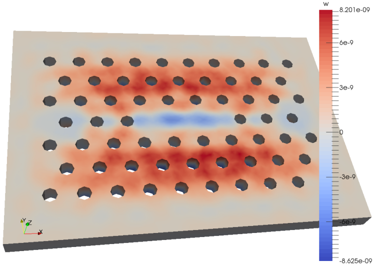


D_y

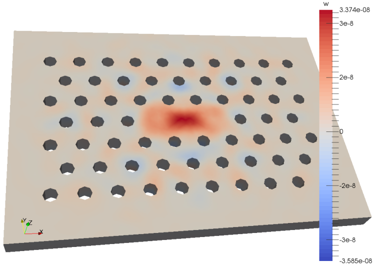
Phonon energy in the photonic crystal slab cavity



Phonon displacement distribution at the main resonances



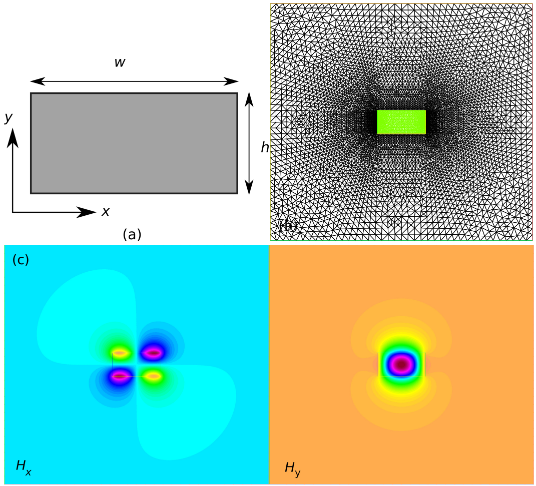
8.45 GHz



9.4 GHz

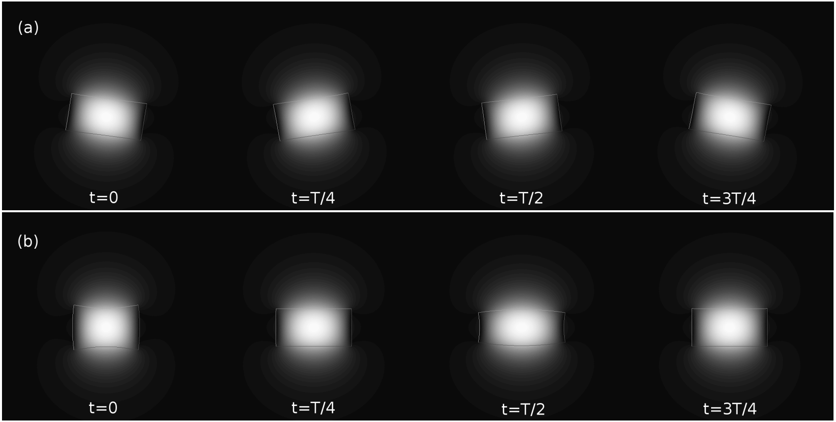
- Mostly thickness extensional motion (u_z).
- Phonon distribution at 9.4 GHz is (weakly) confined laterally in response to the optical force distribution.
- These phonons **are not** normal modes of the holey membrane.

Silicon waveguide, $w = 450$ nm and $h = 220$ nm



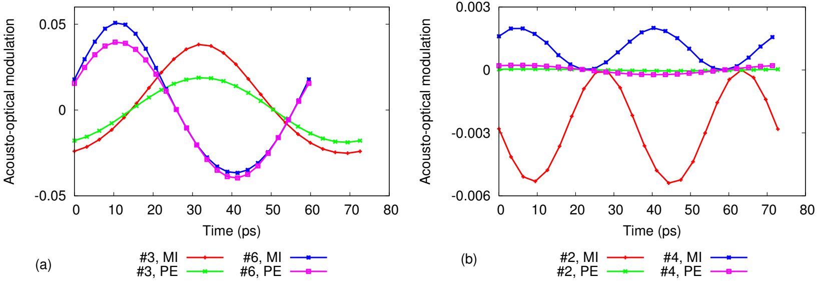
fundamental TE mode, $\lambda = 1.55$ μm

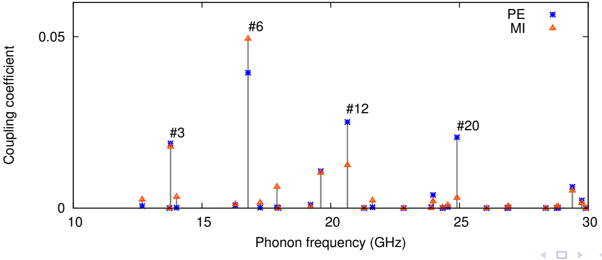
Waveguide deformation within one acoustic period



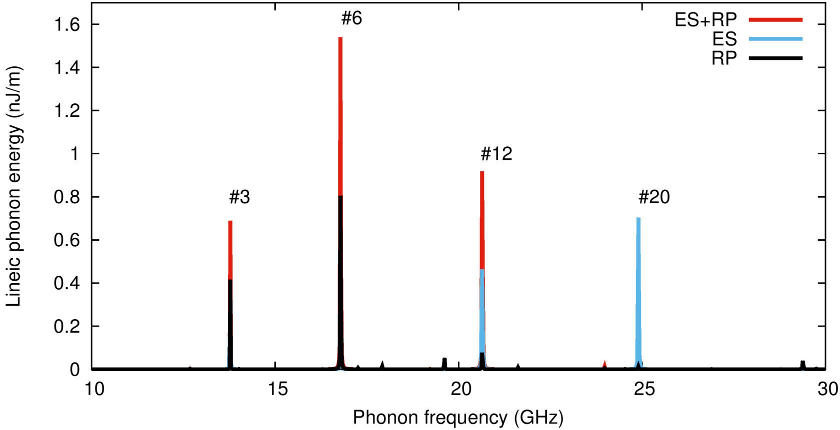
(a) mode #2 (b) mode #3

MI and PE modulations (acousto-optics)





Phonon generation including bulk and surface contributions



Conclusion

- **Lagrangian** (energetic, variational) formulation of photon-phonon interaction in dielectrics
  Laude & Beugnot, New J. of Physics **17**, 125003 (2015)
  - Leads to efficient finite element implementation
  - Both (bulk) electrostriction and radiation pressure are included.
  - Applies to both waveguides and cavities
- Explains very well Brillouin scattering gain in optical fibers
- Various acoustic phonons (elastic waves) can be excited all-optically, including surface waves
- Comparison with experiments in optomechanical cavities still pending