Theoretical analysis of advanced optomechanical nanostructures

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Engineering the coupling of electromagnetic radiation (photons) to vibrations (phonons) is at the heart of solid-state physics. Phonon transport at different frequencies governs crucial physical phenomena, ranging from thermal conductivity to the sensitivity of nano-electromechanical resonators. To engineer and control the overlap of light with the mechanical vibrations of matter in an efficient manner, we make use of very precisely fabricated nanometer-scale devices. The standard way of achieving this control is to use patterned structures - optomechanical crystals - where the electromagnetic field and the mechanical displacement are confined simultaneously within the same small volume thus enhancing their interaction [1, 2]. Despite its extraordinary potential, these structures are very difficult to model due to its complexity and to the lack of analytical or semi-analytical calculation methods. This limits the analysis of existing structures and, at the same time, the design and optimization of novel systems.

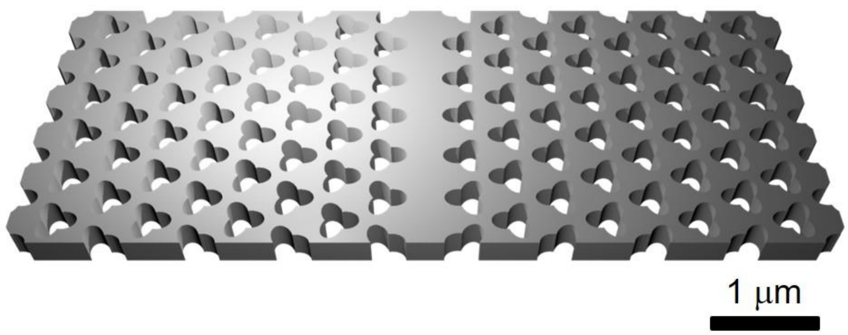

Figure: Optomechanical waveguide fabricated on silicon. This will be our basic geometry to study.

Project description and goals

Our main objective is to implement advanced calculation methods for optomechanical nanostructures and use them to design systems with an enhanced optomechanical coupling. The current approach to calculate the eigenmodes and corresponding photonic and phononic fields of fully three-dimensional complex nanostructures (see the Figure) relies on using finite elements. The relevant equations (Maxwell equations for the electromagnetic field and elastic wave equation for the vibrational displacement) are solved imposing periodic or other boundary conditions. This brute-force approach requires heavy calculation resources and limits the complexity of the systems that can be tackled. Typically, the solving times of few (10) eigenmodes for nanostructures similar to the one shown in the Figure are on the order of 10 – 20 hours which obviously rules out any realistic optimization approach.

An alternative to existing methods is to use an approximation method: a guided-mode expansion. This method is a modified version of a plane-wave expansion where the modes in the vertical direction are taken just as the guided modes of the unstructured slab. This method is very convenient for planar structures like the one shown in the Figure, as the pattern is engineered only within the plane. So far, the photonic part has been already implemented in python [3]. Now, we lack the implementation of the phononic part [4] and the combination of the photonic and phononic solutions to calculate optomechanical couplings in the form of overlap integrals between the confined electromagnetic and displacement calculated fields. This would be the task of this project which would allow us to reduce the calculation times to minutes, to recover the full photonic and phononic dispersion relations of the structures under study and to develop design methods to maximize the optomechanical coupling.

Our main goals are, therefore:

- To implement a guided-mode for phonons following Ref. [4] in python.
- To combine the phononic and phononic guided-mode expansions.
- To apply the resulting script to different optomechanical and phononic nanostructures.
- To calculate the optomechanical coupling in different nanostructures.

The student will be supervised in a daily-basis by Dr. P. David García [5] (pd.garcia@csic.es with strong background on finite elements and experimental optomechanics) and by Dr. Daniel Torrent [6] (dtorrent@uji.es with a strong background on analytical and semi-analytical methods for acoustics and phononics). The student will acquire knowledge on nanophotonics, nanophononics and optomechanics. We also have access to the experimental characterization of these nanostructures to complement the view of a cutting-edge research field.

References

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