SORBONNE UNIVERSITÉ

Sorbonne Université/ China Scholarship Council program 2020

Thesis proposal

Title of the research project: **Two-dimensional phoXonic crystals**

Keywords: **Acoustics, phononic crystals, localization, light and sound coupling**

Joint supervision: **no**

Joint PhD (cotutelle): **no**

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Institution: **Sorbonne Université and CNRS**

Doctoral school (N°+name): **ED 391 – Sciences Mécaniques, Acoustique, Electronique et Robotique de Paris**

Research laboratory: **Institut des Nanosciences de Paris – INSP UMR 7588**

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Subject description (2 pages max):

1) Study context

The study of acoustic or optical waves in complex media has considerably evolved over the last decades. Actually, the study of artificial periodic structures known as phononic and photonic crystals, has largely contributed to break conventional physical limitations, achieving remarkable manipulation of waves such as the negative refraction, the sub-wavelength focusing, the cloaking[1,2] or more recently the topologic insulator demonstration[3,4]. Basically, all these phenomena relate to the spatial periodicity of some physical properties of the structure: mass density and elastic modulus in the case of phononic structures or dielectric constant and magnetic permittivity for photonic structures.

In parallel, the coupling of phonons and photons in the same platform has aroused a great deal of works, giving rise to a new class of metamaterials, the phoXonic crystals[5] which simultaneously exhibit the properties of phononic and photonic crystals. Recent works in the field have shown that sound and light interactions may be enhanced inside a phoXonic cavity and high optomechanical (OM) coupling rate were obtained[5]. The physical demonstration of the phenomenon was done both theoretically and experimentally and the interest is now turned toward applications such as the integration of phoXonic devices inside OM circuits for information transport[6]. However, in most of these works, investigations were done in the context of periodic structures and only few studies report on the effect of disorder[7,8] despite this latter could lead to still unexplored new effects. Actually, it has been shown recently that the disorder resulting from fabrication imperfections was leading, for GHz phonons and hundreds of THz photons, to OM coupling rates $g_{OM}/2\pi$ of few hundreds of kHz while the perfectly engineered cavity in the same structure was offering a maximum coupling rate of few tens of kHz[9,10]. This was explained in the frame of classical theories: when such an artificial crystal is perturbed by some structural imperfections, the ideally propagating waves may get affected and Bloch modes undergo multiple random scattering, especially at the edges of the band gap, similarly to what happens in a crystalline solid with defects[11]. Even, a phase transition may occur when the disorder is sufficiently high and the modes become localized states, decaying exponentially and interacting together with a characteristic length scale. This disorder induces narrow resonances which populate the spectrum around the band edges, forming a band of localized modes known as the Lifshitz tail[12], which broadens with increasing disorder.

This type of confinement, also known as Anderson localization, was initially proposed in the context of electronic transport to explain the metal-insulator phase transition induced by structural defects in a semiconductor. The PhD thesis will extend this concept to both phonon and photon and will investigate their co-localization in mechanical resonators randomly distributed on the surface of two-dimensional structures.

2) Details of the proposal

This PhD research is a part of a large project involving five French teams. The main goal of this project is to investigate the effects of a mathematically controlled disorder on the co-localization of phonons and photons. In this framework, the PhD thesis only addresses the localization of phonons in structures where the localization of photons has been demonstrated already. This is a very challenging goal that requires good skills in mechanics and numerical simulations.

For this project to be successful, the proposed work plan should be as follows:

From a theoretical point of view, the candidate will calculate the eigenmodes of the resonators as well as the phase of their vibrations. Because of the coupling between close neighbors, it is expected that the eigenfrequencies, and in turn the localization of phonons, depend on the local resonators distribution. It is therefore of major importance to investigate how the disorder type affects the localization efficiency.

From the experimental side, one must accurately record the acoustical displacements field, amplitude and phase, on vibrating objects and in their immediate vicinity. The envisaged applications of these phoXonic structures being new OM components working at the telecom wavelength, the typical dimensions of the resonators will be of a few hundreds of nanometers and the acoustic frequencies involved will be of a few GHz. The experiments will be performed using several experimental techniques, including picosecond ultrasonic and transient grating techniques which both are available in our laboratory. PhoXonic crystals, also named optomechanical crystals, have been first proposed[13] in 2006 and provide since then a new tool to control light and sound. However, these artificial metamaterials have been considered since then only from the perspective of periodically patterned structures. With this PhD thesis, we propose a totally new approach that consists of taking advantage of Anderson localization, which is a phenomenon intrinsically linked to disordered media, to obtain properties usually observable in cavities set in purpose in very well-ordered systems. Because of the strong localization of both elastic and electromagnetic fields inside the resonators, or the cluster of resonators, it is expected that OM coupling efficiency is much better with such a random structure than it is with a more conventional periodic phoXonic crystal.

This PhD thesis has strong analytical and experimental features. The PhD candidate will first draw on the expertise of our group to calculate the shape, dimensions and frequency resonances of the actual resonators to be studied. In particular, it requires calculating the effect of the disorder type on the sound localization efficiency, and checking the compatibility of the projected designs with the light localization. To this end, the PhD student will use the finite element techniques available in our group. At the same time, he/she will develop a method to optimize the shape, size, geometry…of the samples in order to insure their relevance for the co-localization of phonons and photons.

The samples will be elaborated in the clean room facility available in Sorbonne Université, by means of isotropic dry etching and photolithography processes. Based on our experience, the most promising random phoXonic structures feature pillars on a plate. Such pillar based samples, which require an excellent accuracy, will be fabricated with the help of technical staff which has great expertise and skills for this task.

For the experimental part of his/her doctoral research, the PhD student will use two experimental methods, both well mastered by the host team, to investigate the suitability for sound localization of the fabricated structures. Both methods are based onto both the excitation and the detection of the elastic displacement field with optical lasers beams. The first one is the so called "picosecond ultrasonic technique". It allows to map the elastic displacement field as a function of time, on a surface of typically 200×200 μm^2 and for frequencies up to several tens of GHz. The technique gives direct view of the sites where the elastic field is localized. The second experimental bench is the "transient grating technique" that allows to measure the transmission of an elastic waves through the phoXonic crystal. It is expected that the decaying *vs* time of the transmitted waves departs from an exponential behavior when Anderson localization occurs in the random set of resonators. In turn, the outputs of both techniques will help to refine the analytical calculations. Hopefully, unexpected experimental results will show up, and they allow the PhD student winning further knowledge and understanding of this very new and topical class of artificial materials.

3) References

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4°) Profile of the Applicant (skills/diploma…)

The candidate must hold a master degree in Physics or Mechanics and have a taste for experimental approaches. The prior knowledge of phononic crystals is not mandatory but will be highly appreciated.

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