Marie Curie ITN cQOM
Summary of the Scientific Achievements

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Start Date of ITN Fellowship: 01/10/2015
End Date of ITN Fellowship: 31/05/2016
Date of Report: 25/06/2016

1. Description of research work

My main project is to try and achieve multimode coupling within the membrane-in-the-middle setup. More specifically, coupling multiple optical modes within the cavity via a single mechanical mode. I will explain the motivation for this research in more detail in the subsequent section. This work is closely related to iQUOEMS, another European project, aimed at developing a coherent transducer between radio and microwave frequencies and the optical domain, which is expected to be of use in the framework of quantum computing. Within the membrane-in-the-middle setup, which we use, it could be realized by metalizing one side of the membrane and using it as one plate of a capacitor, the capacitance of which depends on the membrane's position. The position, in turn, is affected by light, thus achieving the coupling.

Currently I am also working on the HUMOR project, an Italian INFN project, aimed at observing nonlinearities in the dynamics of a quantum-mechanical oscillator, putting an upper bound on the effects due to quantum gravity.

2. Goals achieved and/or progress towards them

In an optomechanical system one can observe heating or cooling of a selected vibrational mode of the mechanical element by appropriately tuning the laser frequency. In particular, red-detuning the laser for an amount equal to the mechanical mode frequency (Ω_m) with respect to a given optical cavity mode, the mechanical mode is effectively cooled down (cf. left part of fig. 1). Owing to this effect, ground-state cooling of a mechanical mode has been achieved. What we aim to do in Camerino is to achieve coupling between one mechanical mode of the membrane and multiple cavity modes. Namely, the cavity actually supports infinitely many modes with a different spatial profile, the frequency of which depends on the membrane position along the cavity axis, as shown in the right part of fig. 1. For the moment we are focused on the triplet, which can be seen in the lower right. If we go back to part (b) of the left side of the figure, tuning the separation between the triplet modes to Ω_m would amount to more efficient cooling, since the laser can remain resonant with another triplet mode. Furthermore, if the third mode is yet further left, there would be an interplay between cooling and heating, amounting to a robust tripartite entanglement of the optical modes via the mechanics. This is very interesting from the aspect of quantum information, as entanglement can be a means to develop a communication channel which is protected from eavesdropping on a quantum-mechanical level.

A prerequisite for achieving multimode coupling with our system is having a very precise control of the membrane position, since it determines the separation of cavity modes in a particular multiplet, which needs to be set to the mechanical frequency of interest. For that we use another phase modulated beam and another feedback loop, similar to that used for locking the laser to the cavity, this feedback acting on the piezo on the membrane mount. However, the setup seems to be extremely sensitive and we are still trying to achieve a stable lock.

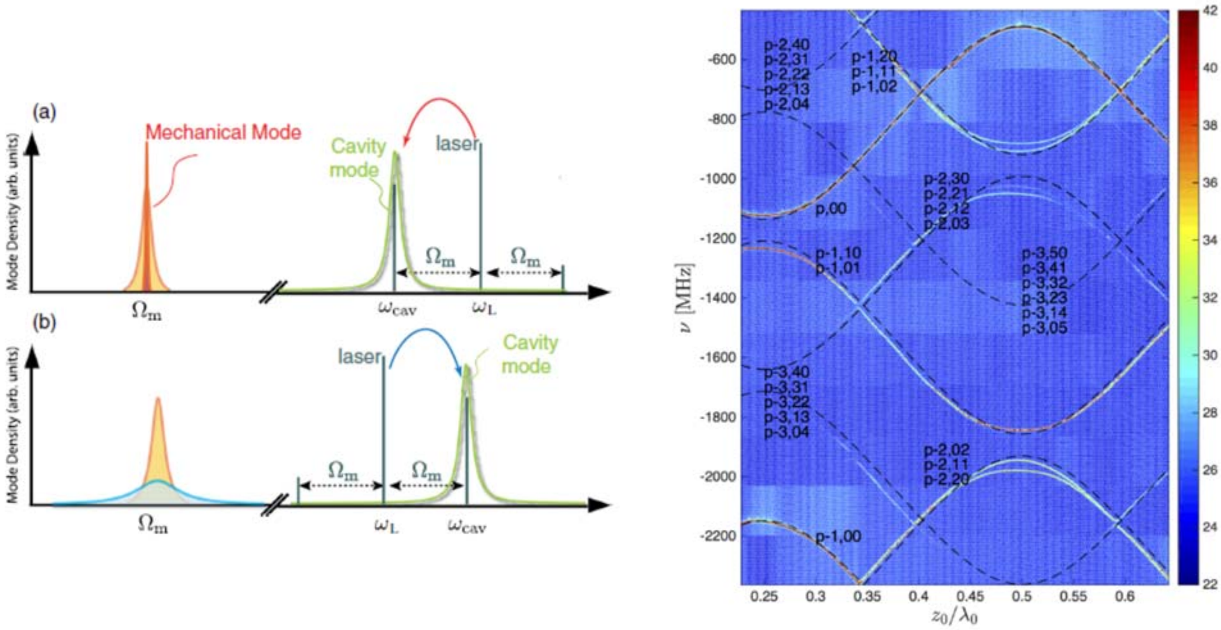

Figure 1. *Left* – A schematic of the heating (a) and cooling (b) of a particular vibrational membrane mode by blue- or red-detuning the laser for the mechanical frequency with respect to an optical mode supported by the cavity[1]. This is due to the resonant enhancement of either the Stokes or anti-Stokes sideband, both of which arise because of the presence of the membrane. *Right* – An example of a so-called cavity scan: frequencies of different cavity modes as a function the membrane position.

The HUMOR project, on the other hand, is aimed at observing nonlinearities in the dynamics of a quantum-mechanical oscillator, for the purpose of setting an upper bound on the parameters quantifying the deformation of the standard quantum-mechanical position-momentum commutator. To this end, we made a new, smaller cavity, gaining approximately a factor of 20 in the photon-phonon cooperativity with respect to the previous one (fig. 2). This is crucial since the cooperativity determines one's ability to cool the mechanical mode down to the quantum regime. This cavity, however, cannot be placed in a cryogenic environment, so we are using it for preliminary tests. The input light is sent into (and the reflection and transmission extracted from) the cavity via optical fibers and we managed to find a way to send them into the vacuum chamber. On the other hand, very recently we received the new cryostat from Leiden and are currently running tests for cooling. Meanwhile, we made the design for another, bulk cavity roughly the same size, which would be completely closed apart from the space needed for the fibers, therefore suitable for a cryogenic environment and ultimately for testing quantum gravity.

[1] Image taken from M. Aspelmeyer, T.J. Kippenberg, F. Marquardt, Rev. Mod. Phys., Vol. 86, No. 4 (2014), p. 1412

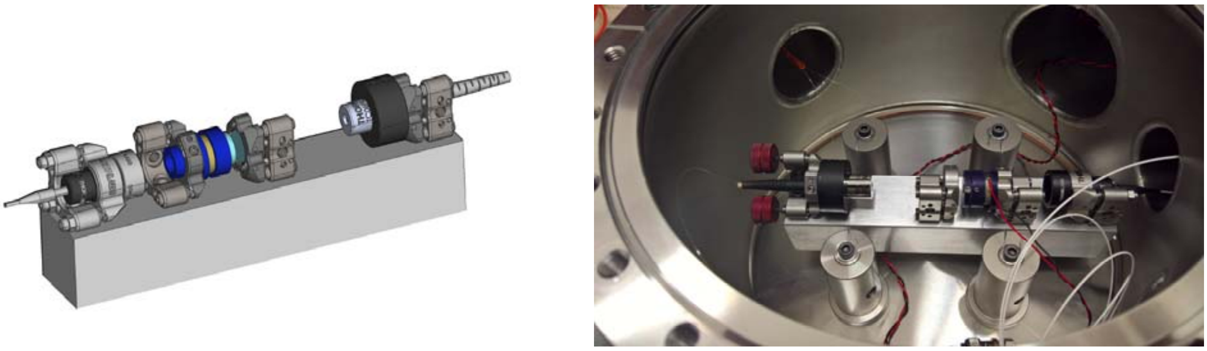

Figure 2. *Left* – An axonometric view of the cavity CAD project. *Right* – A photograph of the cavity inside the vacuum chamber. It is suspended on two pendula which serve as a low-pass filter. One can also see the input and output fibers and the wires for the piezo.

3. Training received (complementary/soft skills, ITN workshops attended)

I have attended three ITN workshops during the course of my MSCA fellowship. The first one was held at the IBM research center in Rueschlikon, in the vicinity of Zurich, at the end of November 2015, and the second one in Diavolezza in February 2016. Of these I would like to point out the latter, since the idea of the workshop is that the talks are given by the fellows, and I had the possibility to present the work we did in Camerino. Perhaps even more importantly, it serves to gain experience in presenting, in this case to a scientific audience. The most recent workshop took place in Ghent, Belgium, in May 2016 and culminated with a visit to the state-of-the-art facilities of IMEC and the famous 300 mm clean room. While CMOS fabrication is not among my proficiencies, I enjoyed hearing about the obstacles and recent improvements in the field. Much like the one at IBM, the Ghent workshop presented an opportunity to look at research from a slightly different viewpoint than I am used to, to look at research which probably has, or will have, a more immediate impact on everyday life. I believe this is beneficial for, somehow, keeping things in perspective. In general, all of the organized workshops were extremely useful not only due to the possibility to see what other people in the same or similar research and interest field are working on, but also from the aspect of making their acquaintance and establishing or deepening professional relationships.

The School of Advanced Studies (SAS) at the University of Camerino (UNICAM) frequently organizes courses for PhD students to acquire transferable skills. Of these I would like to point out several on writing a grant proposal, specifically in the context of MSCA and Horizon 2020 projects. More precisely, this was a series of five talks until now, spanning from October 2015 to May this year, with more to follow. Two talks were given by Dr Ciro Franco, the Director of STPVR (an Italian office for promotion and valorization of research) and a reviewer within the Horizon 2020 network, and one by Dr Daniela Corda, director of the Institute for Protein Biochemistry, CNR Napoli and the Italian representative for Horizon 2020 ERC and MSCA. These were complemented by talks by two successful IF MSCA applicants, Angela Bellia and Sara Caviola. I stress this series of talks because grant proposals are a vastly important part of a researcher's career. Accordingly, knowing how to write a good proposal is an invaluable skill. My feeling is, conversely, that one is often forced to learn this "on the fly", which is why hearing from both the reviewers' and the applicants' point of view was very helpful, and why I am glad the talks on this subject will continue at UNICAM.

Within the SAS transversal activities program I also attended two lectures by Luisa Currado and Elena Silva on intellectual property and communicating to diverse audiences, respectively.

4. Participation and role in dissemination and outreach activities

One of the deliverables of this ITN project is improving the Wikipedia webpage on cavity optomechanics to which I have contributed by writing the basis for two chapters: linearization of the optomechanical Hamiltonian and solving the quantum Langevin equations.

I participated at the 5th Scientific day at UNICAM, presenting a poster regarding our work on testing circular SiN membranes for optomechanical applications (cf. publications).

I am currently making arrangements for a small public talk concerning the problem of strong CP violation and my work within the search for axions at the CERN CAST experiment. The experiment is also related to optomechanics since it is being upgraded in an effort to detect (currently only presumed) chameleons via radiation pressure with a membrane-in-the-middle setup. The talk is to be held at the Astronomical Centre in Rijeka, Croatia, probably in late August this year.

5. List of conferences attended

During my fellowship I have only attended the cQOM workshops listed above. However, shortly before the beginning of my ITN fellowship, in August 2015, I attended the Les Houches summer school on optomechanics and electromechanics. I intend to participate in the iQUOEMS conference entitled "Quantum Interfaces with Nano-opto-electro-mechanical devices: Applications and Fundamental Physics", organized among others by Prof. Vitali as coordinator and to be held in Erice, Sicily, from 31 July to 5 August 2016. The iQUOEMS project is coordinated by Prof. Vitali and has collaborated with the cQOM ITN project.

6. Publications (with links)

E. Serra, M. Bawaj, A. Borrielli, G. Di Giuseppe, S. Forte, **N. Kralj**, N. Malossi, L. Marconi, F. Marin, F. Marino, B. Morana, R. Natali, G. Pandraud, A. Pontin, G. A. Prodi, M. Rossi, P. M. Sarro, D. Vitali and M. Bonaldi. *Microfabrication of large-area circular high-stress silicon nitride membranes for optomechanical applications.* AIP Advances 6, 065004 (2016). http://dx.doi.org/10.1063/1.4953805

7. Career plans after ITN

My primary goal is to finish my PhD research and thesis at the University of Camerino. I expect the experimental part, i.e. the data taking, to be concluded by March 2017, with a couple of extra months for adding the finishing touches to the thesis itself. Afterwards, my intention is to remain in academia and have a postdoc position within the field of cavity optomechanics if possible, at an institution yet to be determined at this point.