Marie Curie ITN cQOM
Summary of the Scientific Achievements

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Academic / Industrial Institution: EPFL
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1. Description of research work

Establishing quantum control of engineered mechanical systems is a long-standing goal in the field of quantum optomechanics. The controlled preparation and readout of nonclassical states of motion in macroscopic mechanical systems would indeed enable fundamental tests of quantum mechanics, while opening new avenues for the development of quantum technologies. The work is to design and fabricate optomechanical photonic crystal nanobeam (WP5) with mechanical vibrations in the GHz range and to perform fundamental optomechanical experiments using tapered optical fibers (WP5) in He3 buffer gas refrigerator (WP4) in the quantum regime, such as ground state cooling (WP4) and single phonon Fock state generation (WP4).

2. Goals achieved and/or progress towards them

Since the start in October 2014, we have optimized the fabrication process flow especially for the Electrom Beam Lithography and the Reactive Ion Etching steps, with detailed SEM analysis of the nanobeam structure. In addition, we designed and fabricated a novel coupling scheme by introducing a waveguide which the tapered fiber directly touches instead of the cavity, as shown in Figure 1.B and 1.D. In such way, the mechanical vibration is not perturbed by the strain induced by the taper. By changing the number of holes of the front mirror and thus the external coupling rate, we can tune between the overcoupling regime and undercoupling regime, while still preserve the mechanical Q as shown in Figure 1.A and 1.C. This enables us realize the optomechanical crystal in the resolved-sideband regime with optical loss $\kappa = 0.98GHz \times 2\pi$ and mechanical frequency $\Omega_m = 5.4GHz \times 2\pi$ and with single photon optomechanical coupling rate $g_0 = 1MHz \times 2\pi$.

One main goal for the project is to achieve single phonon Fock state generation. In this scheme, a weak blue detuned pumping laser is applied to generate phonon-photon pairs with perfect time correlations. The detection of the generated photon with a single photon detector then heralds the addition of a single phonon into the mechanical mode. After applying the readout pulse on the red mechanical sideband, the expected second-order correlation function conditioned on the detection of the heralding photon, showing a large degree of antibunching, due to the single-phonon character of the prepared state. To perform this experiment, we need to prepare the mechanical oscillator deep in the ground state.

Firstly, we performed the measurements at 4K in a helium4 cryostat. The intrinsic mechanical loss is decreased to $250KHz \times 2\pi$. Besides, we observed the optomechanically induced transparency because of the radiation-pressure coupling of an optical and a mechanical mode. This destructive interference leads to a transparency window for the probe beam, whose depth and the width are tunable by the power of the control beam. We reached a cooperativity of 5, corresponding to mean phonon occupation around 5.

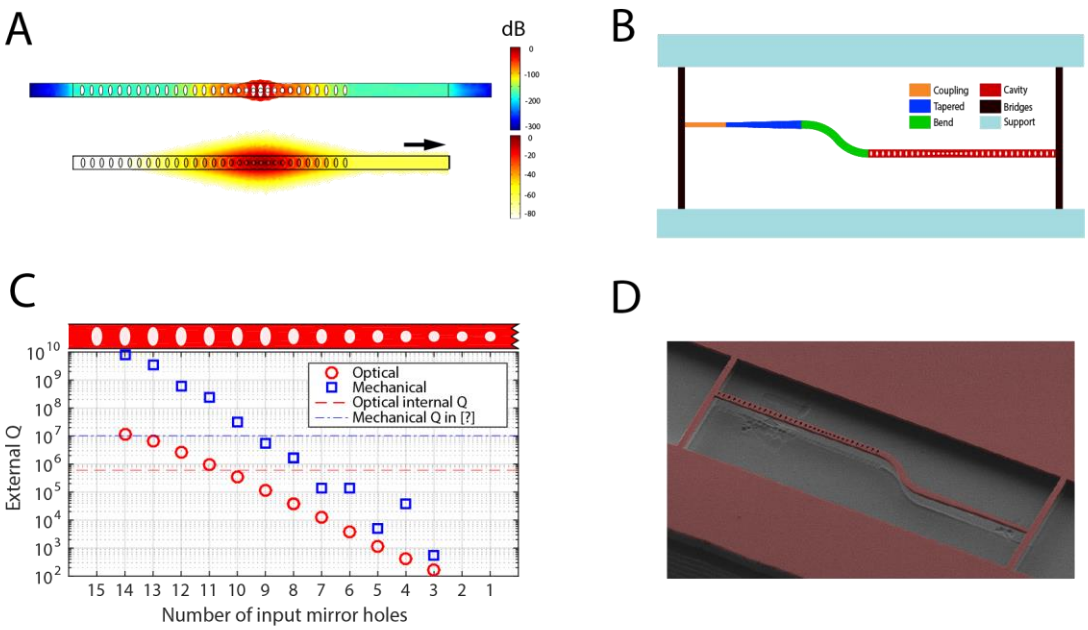

Figure 1. A) Simulated mechanical and optical field distribution, where the mechanical motion is perfectly confined while the optical field can be coupled in and out from one side of the cavity. B) Design of the device, which includes supporting pad, bridges, coupling waveguide, tapered waveguide, bended waveguide and one-sided photonic crystal. C) Simulations of the external optical Q and mechanical Q with different holes number for the input mirror. D) SEM picture of the actual device.

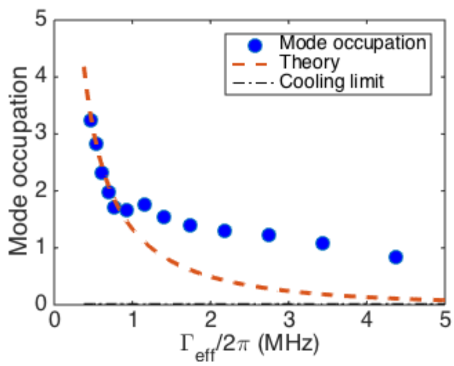

Figure 2. Mode occupation vs the effective damping rate of the mechanical oscillator through sideband cooling, in comparison to the theoretical mode occupation and sideband cooling limit.

Recently, with the new established He3 buffer gas cryostat, we systematically studied the optical on-resonance absorption heating behavior of the mechanical resonator in the cryostat where the He3 is condensed at different buffer gas pressure. We confirmed that the buffer gas cryostat provides us a unique approach for the cryogenic optomechanical experiments, unlike previous experiments with optomechanical crystal in dilution fridge, which suffer from large heating. The optimal working temperature is around 1.3K with buffer gas pressure around 30mbar, which not only provides sufficient thermalization (small heating) of the nanobeam and but also doesn't gas damp the mechanical oscillator. At such condition, we obtained mechanical linewidth $\Gamma_m = 70KHz \times 2\pi$, which enables us reach high cooperativity more than 20 and thus high fidelity ground state through sideband cooling, as shown in Figure 2.

Furthermore, we developed a novel heterodyne detection scheme where two additional diode lasers, as two local oscillator, are phase locked close to the upper and lower sideband of the probe laser, which is locked to the cavity resonance using a Pound–Drever–Hall technique. Because of the low on-resonance heating, we could directly monitor both the mechanical sidebands and thus observe the sideband asymmetry. Moreover, we split out power from the red detuned LO to cool the mechanical oscillator through sideband cooling. This provides an alternative approach towards ground state cooling where the laser detuning are much more stable. Meanwhile, we have started the preparation of the writing pulse and reading pulse sequences through MEMS switches and also cascaded filters with high suppression of the on-resonance pumping laser for the correlation measurements. These achievements and advances in device fabrication, cryogenic operation and measurement schemes during the last two years would provide us with a unique approach towards the mechanical Fock state generation.

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

ITN cQOM workshop "Finite Element Modeling"	Lausanne, Switzerland	21.-23.07.2014
Diavolezza 2015 annual ITN cQOM Workshop	Diavolezza, Switzerland	1-5.02 2015
Diavolezza 2016 annual ITN cQOM Workshop	Diavolezza, Switzerland	31.01.–04.02.2016
cQOM workshop:"Taking a Research Idea to a Product"	Rüschlikon, Switzerland	30.11.–01.12.2016
cQOM workshop:"From Photonics Research to CMOS-fab"	Ghent, Belgium	17-19.05.2016

4. Participation and role in dissemination and outreach activities

I anticipated the experiment preparations for “The Nuit de la Science” in July 2014, Geneva, Switzerland.

I provided support on Wikipedia article on “Cavity optomechanics”.

5. List of conferences attended

IBM Zurich Photonics Symposium, Rüschlikon, Switzerland, 16 July 2015

6. Career plans after ITN

I’m continuing my PhD thesis in cavity optomechanics at cryogenic temperature with photonic crystal at EPFL and will complete PhD by foreseen date of May 2018. With the multiple dimentional training I received with ITN cQOM in optics, mechanics, electronics, fluid dynamics and cryogenics, I plan to pursue my career in academia in the community of cavity optomechanics, which provides not only a unique approach to study fundamental quantum mechanics at macroscopic level but also potential applications in various sensing technologies with ultrahigh sensitivity.

Secondment:

The fabrication of one dimentional optomechanical crystals, which targets at nanometer resolution and high verticality and low roughness of the sidewall, is of great challenge, especially for the Electron Beam Lithography and Reactive Ion etching steps. IBM Zurich, specifically Paul Seidler's group, has established their expertise in their previous works on slotted photonic crystal with ultrahigh quality factor-to-mode volume ratio. Through the secondment with IBM Zurich, I benefited significantly from the nanofabrication expertise from both cleanrooms at EPFL and IBM Zurich. I presented my thesis work on cryogenic optomechanical experiments at the IBM Zurich Photonics Symposium and received valuable suggestions on the experiments. I also received the cleanroom training and precious advice on my fabrication process, especially for the SEM analysis, which in the end becomes one of the key steps in our optimized process flow. With more stabilized fabrication process, we are able to achieve high quality factor of optical and mechanical resonances of the optomechanical crystal with large optomechanical coupling rate.

Paul Seidler's group at IBM Zurich also started to look into interesting physics and potential applications with slotted photonics crystal cavity in cavity optomechanics. With the secondment, we also brought the expertise in optomechanics to IBM Zurich and provided ESR Katharina Schneider with help on both the simulations and characterization of the optomechanical coupling rate.

Through the secondment with IBM Zurich, we both shared and benefited from the expertise of each other, which led to a fruitful collaboration during the last two years.