PROCEEDINGS OF SCIENCE

Advances in Optomechanics

Nenad Kralj[a,*]

[a] *Faculty of Physics and Center for Micro- and Nanosciences and Technologies, University of Rijeka, Radmile Matejčić 2, 51000 Rijeka, Croatia*

E-mail: `nenad.kralj@phy.uniri.hr`

I present a recapitulation of several advances in the design of SiN membrane resonators for use in optomechanical systems. The concomitant improvement in Q-factors has allowed two recent experiments to cool a vibrational mode of such a membrane close to its quantum ground state starting from room temperature, as well as to demonstrate that an optomechanical system comprising it can serve as a long-lived and efficient quantum memory for single photons.

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[*] Speaker

Optomechanical systems [1] have shown great potential as platforms for studying an array of topics. To name just a few, these range from fundamental tests of quantum gravity (e.g. [2, 3]), exploring the boundary between the quantum and classical world by optically cooling [4] increasingly massive objects to the ground state, over gravitational-wave detection in optical interferometers [5], to efforts towards long-distance quantum communication, such as the realization of a quantum memory [6] and quantum teleportation [7]. In this talk, we will discuss some of the recent advances in a particular type of system, one comprising a Fabry-Pérot optical cavity and a thin membrane made out of SiN placed inside it (so-called membrane-in-the-middle, MIM). We will also touch upon early tests of this setup as a platform for an optomechanical quantum memory.

Within a MIM system, the coupling between the membrane and cavity modes is typically dispersive: the membrane motion changes the cavity resonance frequency. Importantly, a coherent laser field impinging on such a cavity acquires sidebands on account of its phase being modulated at a certain mechanical mode frequency ω_m. The upper (anti-Stokes) sideband corresponds to the annihilation of phonons in the mechanical mode, whereas for the lower (Stokes) the excess energy is deposited as phonons in the mode. If the laser pump is red-detuned with respect to the cavity resonance, the former is amplified compared to the latter, resulting in net cooling of the mechanical mode. In short, the figures of merit for determining the lowest achievable occupancy are the coupling strength, the mechanical and optical decay rates, the temperature of the mechanical bath and the degree of resolution of the Stokes and anti-Stokes sideband by the cavity. A lower bath temperature clearly facilitates reaching a given occupancy. In fact, this is not only because the bath occupancy is lower, but also because mechanical Q-factors generally scale favorably with a decrease in temperature. On the other hand, from the perspective of practical applications, it would be advantageous to remove the need for cryogenic cooling. Towards that goal, it is beneficial to improve the mechanical Q-factor. SiN membrane resonators can be seen as owing their high Qs to three distinct realizations. The first boost is due to so-called dissipation dilution [8, 9]. Basically, while intrinsic losses cannot be acted upon, their effect can be reduced by increasing the overall stored energy, and this is done by introducing in-plane tensile stress. The second advancement was creating a periodic array of holes in the Si substrate, which serves as a radiative shield for the membrane modes [10]. Another substantial improvement in the recent years is due to the advent of "soft clamping" [11]. In soft-clamped membranes, the periodic array of holes (phononic crystal) is made in the SiN itself, whereas the effective membrane is a "defect" pad engineered at the crystal center. Apart from radiatively shielding the defect modes from the environment, this design has the added advantage of allowing them to exponentially decay into the crystal, before reaching the "hard" clamping boundary with the Si substrate. This significantly reduces bending losses and thus increases Q.

Soft-clamped membranes in conjunction with high-finesse cavities would in principle allow for the MIM setup to operate in the quantum regime, i.a. enabling ground-state cooling, even at room temperature. In practice, this is typically prohibited by cavity frequency noise. In a recent work [12], we have attempted to mitigate this by appropriately engineering the spectra of the two cavity end-mirrors. To that end, one of the mirrors was made by coating an optical fiber which had previously been ablated by a strong laser pulse. The idea behind that approach is making the mirror lighter, such that its fundamental vibrational mode is of significantly higher frequency than that of the membrane. In order to facilitate alignment, the other mirror was instead a flat one, comprising a Pyrex glass wafer bonded to a Si support structure acting as a radiative shield for the center of the wafer, ideally around the membrane mode frequency. Because of the fiber mirror's small radius of curvature, the cavity length was bound to be on the order of 100 µm. This, in turn, implies that the mechanical sidebands are not resolved, and additional cooling mechanisms are required to reach the ground state. Implementing a combination of sideband cooling and feedback cooling, we managed to cool the membrane mode to 30 phonons, which is still a record for real-time cooling of MIM systems from room temperature. Since then, a similar system has seen ponderomotive squeezing at room temperature, and the preparation of conditional motional states with below-unity occupancy [13].

The interaction underlying sideband cooling is an exchange of quanta between the mechanical and optical modes. This exchange can also be utilized to realize a type of quantum memory for single photons in optomechanical systems, commonly referred to as one based on optomechanically induced transparency (OMIT). It is also worth noting an OMIT memory is different from the one in [6], based on the two-mode squeezing interaction.

The storage protocol would be as follows: 1. the photon is converted into a phonon by a strong, red-detuned driving field; 2. the field is turned off, and the mechanical mode is left to evolve freely; 3. before the mechanical state has decohered, the field is turned back on and the phonon is converted back in to a photon. We have tested the performance of a MIM setup in this capacity, with classical coherent pulses emulating single photons [14]. At room temperature, we demonstrate a storage efficiency of $\eta \approx 40\,\%$ and a lifetime of $T_1 = 23\,\text{ms}$. An important prerequisite for the system to operate as a quantum memory is that the mechanical oscillator be initialized in the ground state before the arrival of the photon to be stored. Reaching this goal, either at cryogenic or room temperature, is one of the main goals of our current project funded by the Croatian Science Foundation.

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