

COOLING OF A MICRO-MECHANICAL OSCILLATOR USING RADIATION-PRESSURE INDUCED DYNAMICAL BACKACTION

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Abstract:

We demonstrate how dynamical backaction of radiation pressure can be exploited for *passive* laser-cooling of high-frequency (>50 MHz) mechanical oscillation modes of ultra-high-finesse optical microcavities from room temperature to 11 K.

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For more than three decades, *dynamical backaction* in the form of radiation pressure has been predicted to give rise to intricate coupled dynamics of the optical modes of a high-finesse cavity and the mechanical modes of its boundaries [1]. In particular, if the mechanical oscillation period is comparable to the cavity's photon lifetime, and the cavity is pumped with a red-detuned laser, the Brownian motion of the mechanical mode can be reduced, corresponding to an effective temperature reduction or cooling.

In this contribution, we report on the first the experimental observation of this phenomenon using very high-finesse toroidal silica microresonators[2]. These structures (Fig. 1A) possess whispering gallery type optical modes (with photon lifetimes up to 500 ns) while simultaneously exhibiting micro-mechanical resonances in the radio-frequency domain. Here we study the interaction of the intracavity light with the ~60 MHz radial breathing mode of the cavity, which has a Q-factor of about 3000 in ambient atmosphere. Due to the curved nature of the dielectric cavity, the circulating photons exert a radial force on the cavity sidewalls, thereby coupling the optical and modes as reported in prior work. [3-5]Consequently, this system is equivalent in its description to a Fabry P erot cavity with a movable mirror (Fig. 1B). Owing to the resonator's optical photon lifetime being similar to the mechanical oscillation period, these devices operate in a regime where cavity retardation effects cannot be neglected, which has previously enabled the study of radiation pressure induced oscillations [3-5]in an experimental setting.

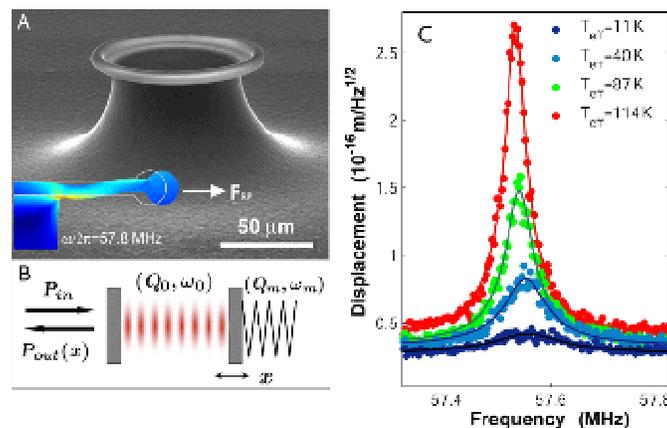


Fig. 1. (A): Scanning electron micrograph of a toroid microcavity on a chip. Inset: Finite element simulation showing the stress (color coded) and strain of the 57.8-MHz breathing mode of the device. The strain is exaggerated for clarity. Note that radiation pressure exerts a radial force owing to total internal reflection of the confined light. (B) Fabry-Perot equivalent diagram of the experiment. (C) Cooling of the mechanical mode as induced by a red-detuned 972nm laser at power levels of 0.25, 0.75, 1.25, 1.75 mW (red to blue curves). The effective temperature, as inferred from the modified mechanical damping, could be reduced down to 11 K.

Cooling (Fig. 1C) is achieved when the cavity is excited with a red-detuned laser with respect to the cavity resonance. A reduction in the displacement fluctuations (as monitored in the transmission signal of the cooling laser itself) is clearly observed, with a concomitant increase of the mechanical linewidth due to the additional dissipation

of the mechanical mode which is introduced by the cooling laser. For the maximum applied power of ~ 2 mW (at 972 nm), a reduction to an effective temperature of 11 K was observed.

By solving the equations of motion of the coupled optomechanical system using a perturbative approach, we were able to deduce analytical expressions for the radiation pressure force, cooling rates, mechanical resonance frequency shift and damping modification. In a series of experiments, very good quantitative agreement with these predictions was observed, constituting first evidence that the origin of the observed effect is indeed a radiation-pressure induced, cavity-delayed back-action of the displacement readout on the mechanical mode. In particular, a drastic change in the dynamics of the system is observed when changing no parameter except the (independently measured) optical cavity linewidth to values below twice the mechanical resonance frequency. In this regime, the resonance frequency shift is reversed for small detunings and has an additional pair of zeros for a specific laser detuning (Fig.2), indicating a purely viscous radiation pressure force. We note that this regime has not been entered by other recently reported cooling experiments[6, 7].

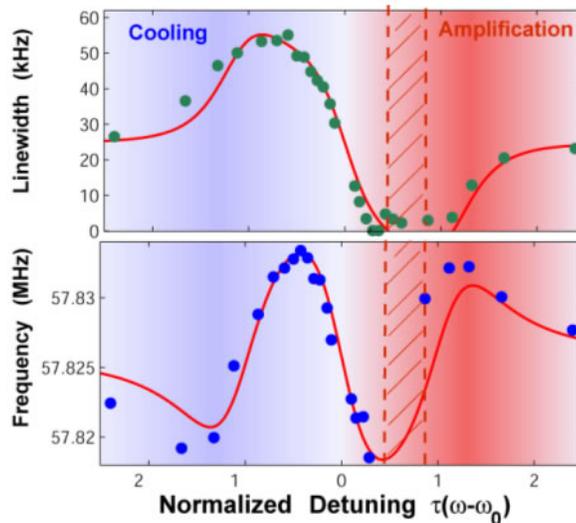


Fig. 2. Mechanical linewidth (upper panel) and resonance frequency (lower panel) of the 57.8 MHz radial breathing mode as a function of (normalized) detuning when the laser is tuned over a 50 MHz-wide optical resonance. For $(\omega-\omega_0)<0$, the resonance is being cooled. Solid lines are theoretical predictions based on our model.

Finally response measurements were carried out, where a strong, modulated pump laser drives the different nonlinearities present in the cavity (thermal effects, Kerr effect, radiation-pressure induced displacement), while a weaker probe laser reads out the induced resonance frequency shift. This has allowed to assess the contributions of thermal effects to the observed cooling to be on the 1% level.

We believe our result constitutes an important step towards the long-sought aim of cooling a micro-mechanical oscillator to its motional ground-state.

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