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## **Investigations of radiation pressure : optical side-band cooling of a trampoline resonator and the effect of superconductivity on the Casimir force**

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**Author:** Eerkens, H.J.

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## Optical Side-band Cooling of a Low Frequency Optomechanical System

For experimental investigations of macroscopic quantum superpositions and the possible role of gravitational effects on the reduction of the corresponding quantum wave function it is beneficial to consider large mass, low frequency optomechanical systems. We report optical side-band cooling from room temperature for a  $1.5 \times 10^{-10}$  kg (mode mass), low frequency side-band resolved optomechanical system based on a 5 cm long Fabry-Perot cavity. By using high-quality Bragg mirrors for both the stationary and the micromechanical mirror we are able to construct an optomechanical cavity with an optical linewidth of 23 kHz. This, together with a resonator frequency of 315 kHz, makes the system operate firmly in the side-band resolved regime. With the presented optomechanical system parameters cooling close to the ground state is possible. This brings us one step closer to creating and verifying macroscopic quantum superpositions.

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## 2.1 Introduction

In optomechanics, interesting phenomena occur when the photon-phonon coupling is sufficiently large. Amongst other things side-band cooling to the quantum mechanical ground state [27, 28], electromagnetically induced transparency (EIT) [31, 32] and coherent state transfer [34, 35] have been demonstrated. For all these experiments good optical and mechanical quality of the set-up is required.

To use side-band cooling to reach the quantum mechanical ground state of a mechanical resonator, the cavity linewidth  $\kappa$  needs to be smaller than the mechanical resonator frequency  $\Omega_m$  (side-band resolved regime) [56, 57]. This condition is not sufficient, since it does not specify the number of photons required, the maximum environmental temperature and the requirements for the mechanical damping rate  $\Gamma_m$ . A more suitable parameter is the multi-photon cooperativity:  $C = 4g_0^2\bar{n}_{cav}/(\kappa\Gamma_m)$  with  $g_0 = (\omega_{cav}/L)\sqrt{\hbar/2m\Omega_m}$  the optomechanical coupling rate,  $\omega_{cav}$  the cavity resonance frequency,  $L$  the cavity length,  $m$  the mode mass and  $\bar{n}_{cav}$  the mean cavity photon number. When  $C + 1 \gg \bar{n}_{th}$ , with  $\bar{n}_{th}$  the mean phonon number of the environment, optical cooling to the ground state is possible [25].

From the cooperativity it is clear that indeed a good mechanical (small  $\Gamma_m$ ) and optical quality factor (small  $\kappa$ ) are needed. It also follows that when the mode mass of the mechanical resonator becomes larger, the requirements on the other parameters become more strict. Therefore most of the optomechanical devices investigated so far operate in the small mass (below  $\sim 1 \times 10^{-12}$  kg), high frequency (above 1 MHz) range [27, 28, 58–62]. However, to investigate the possible involvement of gravity in the quantum to classical transition of macroscopic superpositions, large mass resonators are essential [21–24]. Another difficulty in using large mass resonators for these purposes is the low mechanical frequency, which makes reaching the side-band resolved regime difficult.

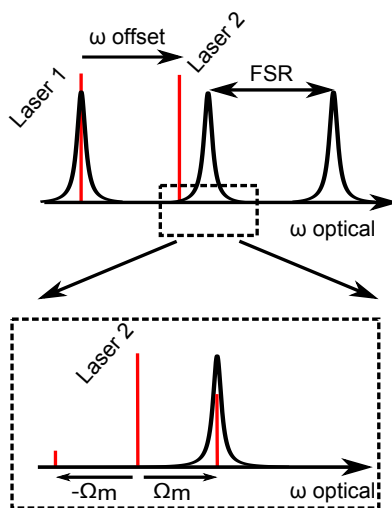
Here we present a 315 kHz optomechanical system that is sufficiently side-band resolved for ground state cooling. We have constructed an optomechanical system based on a Fabry-Perot cavity with a trampoline resonator as moving end mirror [63]. The trampoline resonator consists of a circular mirror (diameter 70  $\mu\text{m}$ ) hanging from four 200  $\mu\text{m}$  long  $\text{Si}_3\text{N}_4$  arms. High-quality Bragg mirrors (alternating  $\text{Ta}_2\text{O}_5/\text{SiO}_2$  layers with 22 ppm transmission loss and order ppm absorption) on both the stationary and the micromechanical mirror allow us to construct a side-band resolved cavity with  $\Omega_m/\kappa \approx 13.5$ .

To demonstrate the capabilities of our system, we perform a side-band cooling experiment where we have  $\sim\text{kHz}$  resolution of the pump laser frequency with respect to the cavity resonance. We match the experimental results to theory and find excellent agreement. The system parameters found with the side-band cooling experiment are in good agreement with parameters found from characterization measurements. These results show that with a lower base temperature, ground state cooling should be achievable. This brings investigation of the quantum to classical transition with large mass resonators one step closer.

## 2.2 Experiment

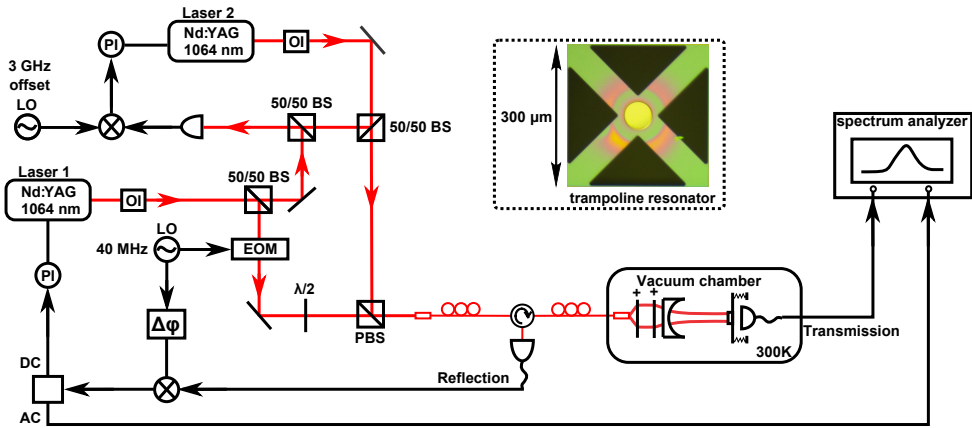
Our system consists of a 5 cm long Fabry-Perot cavity, operating around 1064 nm, with a trampoline resonator as the moving end mirror [63]. The trampoline resonator used in the experiments presented here has a mirror diameter of  $70 \mu\text{m}$ , a resonance frequency of 315 kHz, and a mode mass of  $1.5 \times 10^{-10}$  kg (determined using COMSOL). The optical quality of the cavity is obtained by measuring an optical cavity ring-down. For this, a resonant laser beam is quickly shut down with an acousto-optical modulator (AOM) and the decaying intensity of the transmitted light is recorded. Characterization of the mechanical resonator is done by measuring its mechanical thermal noise spectrum with a laser locked to a cavity resonance using the Pound-Drever-Hall (PDH) technique [64]. The laser power is kept sufficiently low to avoid optomechanical effects on the mechanical linewidth.

Optical side-band cooling occurs when a laser is placed precisely one mechanical frequency below a cavity resonance (see inset in Figure 2.1). Interaction of the laser with the mechanical resonator leads to up- and down-conversion of the laser frequency, creating an upper and lower side-band. The upper side-band is resonant with the cavity and the up-conversion process is therefore enhanced compared to the down-conversion process. The net effect is the extraction of energy (phonons) from the mechanical mode of the resonator.



**Figure 2.1:** The laser scheme used for side-band cooling. Laser 1 is locked to a cavity resonance and laser 2 is locked to the first laser with a variable offset. Inset: Laser 2 is placed precisely one mechanical frequency below a cavity resonance for optimal cooling.

Since the experiment is carried out at room temperature, thermal drift and low frequency mechanical noise can potentially limit the measurement time. To compensate for these, a measurement scheme containing two lasers is used. The frequency of one laser, laser 1 in Figure 2.1, is locked to a cavity resonance using the PDH tech-



**Figure 2.2:** Simplified schematic of the optical set-up. The frequency of laser 1 is locked to the optomechanical cavity using the Pound-Drever-Hall (PDH) technique. Laser 2 is locked to laser 1 via an optical phase-locked loop (OPLL). Laser 2 is tuned one free spectral range (FSR) apart from laser 1 to avoid interference at frequencies relevant to the experiment. The components displayed are: LO: local oscillator, BS: beam splitter, PBS: polarizing beam splitter, EOM: electro-optical modulator, OI: optical isolator and PI: proportional-integral feedback controller. Inset: optical image of the trampoline resonator.

nique. This laser follows slow changes in the cavity length and provides a frequency reference for the second laser, laser 2 in Figure 2.1. This second laser is locked with a tunable frequency difference to the first laser with an optical phase-locked loop (OPLL) operating around 3 GHz. The frequency offset is chosen such that the second laser is close to the next cavity resonance, one free spectral range (FSR) away, to avoid unwanted interference of the two lasers at frequencies relevant to the experiment.

Figure 2.2 shows a simplified schematic of the optical set-up. For clarity, the optical components needed for the optical cavity ring-down measurement are omitted. The optomechanical cavity is placed inside a vacuum chamber ( $p < 10^{-5}$  mbar) with several eddy current dampers and springs. Two  $\sim$ kHz linewidth piezo-tunable Nd:YAG lasers operating at 1064 nm are used. To realize the PDH locking scheme, laser 1 is sent through an electro-optical modulator (EOM) [64]. The light reflected from the cavity is, via a fiber circulator, picked up with an avalanche photodiode (APD). The electrical signal is mixed with the local oscillator (LO) at 40 MHz that also drives the EOM. The low-frequency part is routed to a PI controller ( $\sim$ 30 kHz bandwidth) to lock the frequency of laser 1 to a cavity resonance. The high-frequency part is sent to a spectrum analyzer to record the mechanical thermal noise spectrum of the mechanical resonator, both for the mechanical characterization and for the side-band cooling experiment.

To lock laser 2 with a variable frequency difference to laser 1 via an OPLL, the beat signal of laser 1 and 2 is continuously monitored using a fast PIN diode. This signal is mixed with a local oscillator around 3 GHz to provide the error signal for

the OPLL, which is directed to a fast PI-controller. By adjusting the frequency of the OPLL LO, laser 2 can be set to a specific cavity detuning.

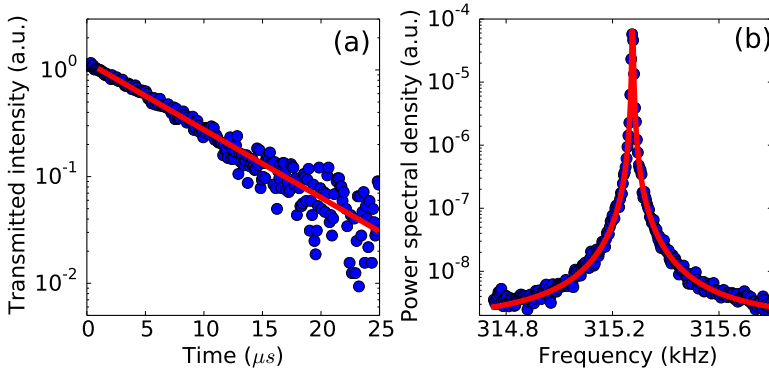
By using a cavity resonance as frequency reference, any thermal drift is compensated for. The frequency tunable range of the lasers via the piezos is limited to approximately 10 MHz. However, both lasers are also temperature tunable over a broader frequency range ( $\sim 1$  GHz), although with  $< 1$  Hz bandwidth. We have therefore implemented a slow temperature feedback loop for each laser that enables us to measure for many hours with a fully automated measurement protocol.

## 2.3 Results and discussion

First we show the results of the optical and mechanical characterization. This provides information about the mechanical frequency  $\Omega_m$ , mechanical linewidth  $\Gamma_m$  and optical linewidth  $\kappa$ . From the optical cavity ring-down measurement in Figure 2.3(a) we obtain a cavity linewidth  $\kappa$  of  $2\pi \times 23.2 \pm 0.1$  kHz, which corresponds to a finesse of 129000. Given the small diameter of the mirror and the multiple clean room fabrication steps it went through, it is remarkable that the optical finesse almost reaches the theoretical maximum of 140000 set by the coating of our Bragg mirrors. For the mechanical characterization, the mechanical thermal noise spectrum is recorded and a Lorentzian is fitted to it, as is shown in Figure 2.3(b). From the fit we find  $\Gamma_m = 2\pi \times 3.3 \pm 0.14$  Hz, corresponding to a mechanical quality factor of 95000. From the optical and mechanical characterization alone it is clear that our optomechanical system is in the side-band resolved regime with  $\Omega_m/\kappa \approx 13.5$ . The small linewidth of the optical cavity allows for a large intracavity laser power with only modest input. Since the light is circulating in vacuum, rather than for example silica, secondary effects due to absorption do not play a role, as in [60]. These two ingredients contribute to a large intracavity photon number and therefore also to a large multi-photon cooperativity. We estimate, using the current system parameters, that a cooperativity of  $10^5 - 10^6$  is possible depending on laser input power.

To demonstrate the “side-band resolvedness” of our system, we perform a side-band cooling experiment. We change the laser detuning of the strong pump beam (laser 2) in small steps of 5 kHz by varying the OPLL LO and measure the mechanical thermal noise spectrum. The laser power of the pump beam is about 50 times higher than the power of the read-out laser. In Figure 2.4(a) the mechanical thermal noise spectrum together with a Lorentzian fit is shown for two specific detunings. The top curve shows the spectrum for  $\Delta = \omega_{laser} - \omega_{cav} = -2\Omega_m$  and the bottom curve shows the spectrum for  $\Delta = -\Omega_m$ .

Clearly the linewidth is larger and the integrated area smaller for the bottom mechanical thermal noise spectrum, indicating both damping and cooling. The integrated area can be related to an effective temperature via the equipartition theorem since  $\langle x^2 \rangle = \frac{k_B T}{m\Omega_m^2}$ . When the pump laser is off, the mechanical resonator is not cooled, so its effective temperature is equal to the environmental temperature of 300 K, assuming good thermalization with the environment. Therefore we set the related integrated area to correspond to an effective temperature of 300 K. When the pump laser is on, the effective temperature for each specific detuning is obtained



**Figure 2.3:** Characterization of the optomechanical system: (a) Optical cavity ring-down measurement with an exponential fit; (b) Mechanical thermal noise spectrum at 300 K with a Lorentzian fit.

by comparing the integrated area of each mechanical thermal noise spectrum to the integrated area of the mechanical thermal noise spectrum at 300 K. The effective optomechanical linewidth  $\Gamma_{eff}$ , which is broadened due to optical damping according to  $\Gamma_{eff} = \Gamma_m + \Gamma_{opt}$ , and the frequency shift due to the optical spring effect are also obtained from the Lorentzian fit. The results are shown in Figure 2.4(b)–2.4(d) together with a fit according to the equations (see for example [25]):

$$T_{eff} = \frac{\hbar\Omega_m}{k_B} \frac{\bar{n}_{th}\Gamma_m + \bar{n}_{min}\Gamma_{opt}}{\Gamma_m + \Gamma_{opt}}, \quad (2.1)$$

$$\Gamma_{eff} = \Gamma_m + \frac{P_{in}\kappa_{ex}\omega_{cav}}{2L^2m\Omega_m(\Delta^2 + \kappa^2/4)} \left[ \frac{\kappa}{(\Delta + \Omega_m)^2 + \kappa^2/4} - \frac{\kappa}{(\Delta - \Omega_m)^2 + \kappa^2/4} \right], \quad (2.2)$$

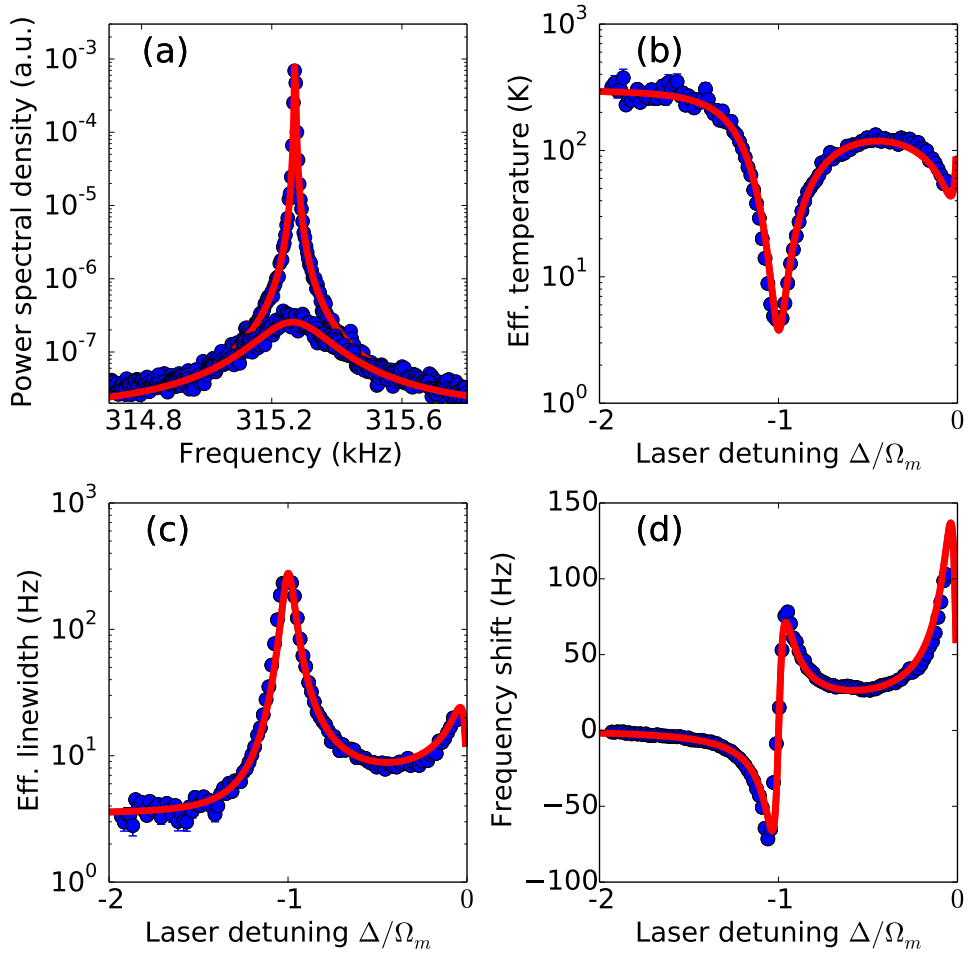
$$\delta\Omega_m = \frac{P_{in}\kappa_{ex}\omega_{cav}}{2L^2m\Omega_m(\Delta^2 + \kappa^2/4)} \left[ \frac{\Delta + \Omega_m}{(\Delta + \Omega_m)^2 + \kappa^2/4} + \frac{\Delta - \Omega_m}{(\Delta - \Omega_m)^2 + \kappa^2/4} \right], \quad (2.3)$$

with  $\bar{n}_{min} = (\kappa/4\Omega_m)^2$  the theoretical minimum phonon number in the side-band resolved regime,  $P_{in}$  the input power and  $\kappa_{ex}$  the input coupling loss rate. The fit is done simultaneously for all three curves with only the input power and cavity linewidth as free parameters. The parameters obtained from the fit are  $3.07 \pm 0.04 \mu\text{W}$  for the input power of the cooling laser and  $2\pi \times 23.7 \pm 2 \text{ kHz}$  for the cavity linewidth.

This value for the cavity linewidth is consistent with the value obtained from the optical cavity ring-down measurement. The excellent agreement between experiment and theory, as indicated by Figure 2.4(b)–2.4(d), and the good match between the two different methods for obtaining the cavity linewidth, shows the level of precision and control we have over the system.

We would like to stress that the sharp features resulting from the optical spring effect in Figure 2.4(d) around  $\Delta = -\Omega_m$  can only be visible with a high-finesse cavity and a narrow-linewidth laser, in combination with optimal performance of the entire





**Figure 2.4:** Optical side-band cooling: (a) Thermal mechanical noise spectra for  $\Delta = \omega_{laser} - \omega_{cav} = -2\Omega_m$  (top curve) and  $\Delta = -\Omega_m$  (bottom curve); (b) Effective temperature; (c) Effective linewidth as a result of optical damping; (d) Mechanical frequency shift due to the optical spring effect.

set-up and locking schemes. Although two narrow-linewidth lasers are used, excess laser phase noise could easily be introduced by e.g. an improper laser lock, which would blur out any sharp features such as in Figure 2.4(d) [65] and could potentially prevent ground state cooling. Observing these sharp features therefore demonstrates the cleanliness of the whole measurement chain consisting of lasers, photodetectors and feedback loops.

Although the goal of this paper is not to demonstrate large optical cooling factors, we are able to cool from room temperature to 4 K using modest laser power, as indicated in Figure 2.4(b). By increasing the laser power further, lower effective temperatures are achieved (not shown here). However, to reach the quantum mechanical ground state, the environmental temperature should be lowered significantly by placing the optomechanical cavity in a cryostat. Note that even in a cryogenic environment we can still use relatively high laser powers due to the low absorption of the mirrors. From the experimental parameters presented in this letter, we estimate that a multi-photon cooperativity of more than  $10^5$  is possible, indicating that a base temperature of 1 K is sufficient for ground state cooling. This is easily achievable in a variety of cryostats, bringing investigation of quantum to classical transition with low frequency resonators one step closer.

## 2.4 Conclusion

In this paper we have reported experiments with a high-finesse optomechanical Fabry-Perot cavity. By using high-quality Bragg mirrors for both cavity mirrors, we are able to demonstrate optical side-band cooling of a large mass, low frequency side-band resolved system ( $\Omega_m/\kappa \approx 13.5$ ). By locking a pump laser via an optical phase-locked loop to a probe laser, we are able to achieve  $\sim$ kHz resolution laser detuning. Not only do we find a good agreement between the experiment and theory, the obtained value for the cavity linewidth from the optical cooling experiment also matches the value obtained by a separate cavity ring-down measurement. With this we demonstrate the precision of our experiment. By lowering the environmental temperature significantly, optical cooling to the quantum ground state should be possible.