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Sub-kelvin optical cooling of a micromechanical resonator

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Micromechanical resonators, when cooled down to near their ground state, can be used to explore quantum effects such as superposition and entanglement at a macroscopic scale[1–3]. Previously, it has been proposed to use electronic feedback to cool a high frequency (10 MHz) resonator to near its ground state[4]. In other work, a low frequency resonator was cooled from room temperature to 18 K by passive optical feedback[5]. Additionally, active optical feedback of atomic force microscope cantilevers has been used to modify their response characteristics[6], and cooling to approximately 2 K has been measured[7]. Here we demonstrate active optical feedback cooling to 135 ± 15 mK of a micromechanical resonator integrated with a high-quality optical resonator. Additionally, we show that the scheme should be applicable at cryogenic base temperatures, allowing cooling to near the ground state that is required for quantum experiments—near 100 nK for a kHz oscillator.

Using a laser tuned to the resonance fringe of a high finesse optical cavity, it is possible to observe very small fluctuations in the length of the cavity due to brownian motion of one or both of the end mirrors. We have developed an optical cavity with one rigid large mirror, 6 mm in diameter and with a 25 mm radius of curvature, and one tiny plane mirror, 30 μm in diameter, attached to a commercial atomic force microscope cantilever of dimensions $450 \times 50 \times 2$ μm with a fundamental resonance of 12.5 kHz (Fig. 1b). An optical finesse of 2,100 and a mechanical quality factor of 137,000 have been achieved with the system[8]. The motion of the tiny mirror/cantilever is monitored by measuring the transmission of the cavity at a frequency on the side of an optical resonance peak. To do this, we use about 1 mW from a 780 nm tunable diode laser which is locked to the resonance fringe using the integrated signal from a photo-multiplier tube which monitors the light transmitted through the cavity (Fig. 1a). The time derivative of this signal is proportional to the velocity of the cantilever tip and is used to modulate the amplitude of a second, 980 nm, diode laser focused on the cantilever less than 100 μm away from the tiny mirror. The radiation pressure exerted by this feedback laser counteracts the motion of the mirror and effectively provides cooling of the fundamental mode.

The effective feedback gain can be varied over several orders of magnitude by sending the feedback laser through a variable neutral density filter. The average power in the feedback beam when it reaches the cantilever is of the order of 1 mW at the highest gain settings and proportionally lower otherwise. The mean modulation depth of the feedback beam varies from nearly 100% to less than 5% as gain is increased. The vibration spectrum of the cantilever as a function of gain is shown in Fig. 2. The r.m.s. thermal amplitude of the cantilever without feedback is 1.2 ± 0.1 Å. From this value, one can calculate that the spring constant of the cantilever is $0.15 \pm 0.01\ \mathrm{N\,m^{-1}}$, in agreement with the manufacturer-specified range, and the effective mass of the cantilever fundamental mode is $(2.4 \pm 0.2) \times 10^{-11}$ kg.

To determine the effective gain of the feedback loop and the temperature of the fundamental mode, we fit a lorentzian plus a constant background to the vibration spectrum of the cantilever for each value of feedback gain. The temperature is determined from the area under the lorentzian without the background, while the gain is determined by the width of the resonance. The linewidth provides a good measure of gain because it is directly determined by the damping rate whereas the cantilever amplitude may be affected by other sources of noise in the feedback loop. Cooling is observed over more than three orders of magnitude. The lowest temperature we are able to measure is 135 ± 15 mK, or a cantilever r.m.s. amplitude of 0.023 ± 0.002 Å, with a gain (the ratio of feedback to mechanical damping) of $g = 2{,}490 \pm 90$ (Fig. 2b). The lowest trace in Fig. 2b, indicating an even lower temperature, cannot be reliably fitted owing to the laser noise floor. Since the optical finesse is not the current limiting factor, we operate the opto-mechanical system at a finesse of only 200,

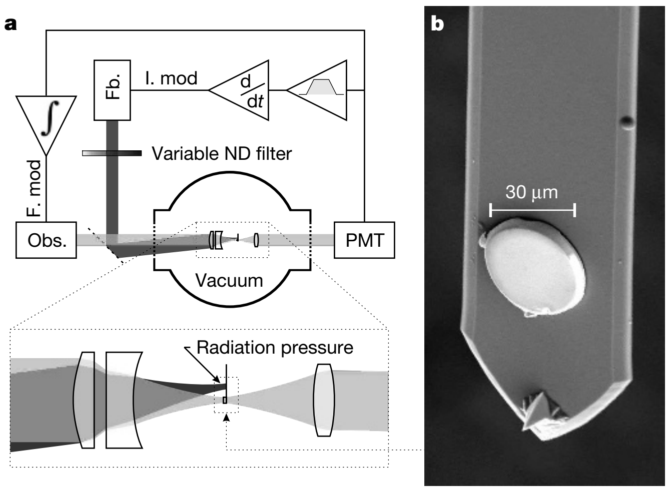

Figure 1 | The experimental system. **a**, Diagram of the feedback mechanism: a 780 nm observation laser (Obs.) is frequency locked to the optical cavity (shown magnified at bottom) with an integrating circuit (via the laser frequency modulation input, f. mod), using the signal from a photomultiplier tube (PMT). This signal is also sent through a 1.25 kHz bandpass filter at 12.5 kHz and a derivative circuit (d/dt) to provide an intensity-modulating signal (I. mod.) for the 980 nm feedback laser (Fb.). The feedback laser is attenuated with a variable neutral density (ND) filter to adjust the gain of the feedback. The feedback force is exerted on the cantilever via this laser's radiation pressure. **b**, Scanning electron microscope image of the tip of the cantilever with attached mirror.

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produced by slight cavity misalignment, which makes the system less sensitive to transient vibrations.

The amplitude of the mirror motion can be calculated in the presence of feedback by assuming that the Langevin force—the effective thermal force that maintains brownian motion—remains constant while the mechanical susceptibility of the mirror is reduced by the dissipation due to the radiation feedback pressure. It suffices to consider only the fundamental mode of the mirror motion, represented by a damped harmonic oscillator. In this approximation, the power spectrum of the mirror's motion in the presence of feedback becomes[9]:

$$S_x^{\mathrm{fb}}[\Omega] = \frac{2\Gamma_0 k_B T_0}{M}\frac{1}{(\omega^2-\Omega^2)^2+(1+g)^2\Gamma_0^2\Omega^2} \quad (1)$$

where Ω is the observation frequency, ω is the resonator frequency, Γ_0 is the mechanical damping factor, M is the effective mass of the resonator mode, k_{B} is Boltzmann's constant, T_0 is the bulk temperature of the resonator and g is the gain. $g=0$ corresponds to the vibration spectrum in the absence of feedback. The motion of the oscillator in the presence of feedback is the same as that of an oscillator with lower temperature and a higher damping constant:

$$T_{\mathrm{fb}} = (1+g)^{-1}T_0 \quad (2)$$

$$\Gamma_{\mathrm{fb}} = (1+g)\Gamma_0 \quad (3)$$

The optical feedback scheme, when analysed in terms of noiseless classical light fields, can be seen as a virtual viscous force, which unlike a real viscous force creates dissipation without introducing fluctuations. As discussed below, the cooling temperature as demonstrated here is limited by laser frequency fluctuations. Ultimately, optical cooling should be limited by the balance of residual heating and quantum noise in the observation and feedback laser signals.

For a signal-to-noise ratio of one in spectral density at the peak of the mechanical resonance, the temperature of the cantilever would be (as can be derived from equation (1)):

$$T_{\mathrm{min}} \cong \sqrt{\frac{T_0 M\omega^3 S_{\mathrm{noise}}}{2k_{\mathrm{B}}Q}} \quad (4)$$

where S_{noise} is the equivalent position noise in the interferometer measurement and $Q=\omega/\Gamma_0$ is the mechanical quality factor. For higher values of gain, the feedback signal is mostly noise and lower temperatures can not be conclusively demonstrated. For our experiment, the equivalent noise level is $\sqrt{S_{\mathrm{noise}}} \approx 10^{-3}\,\mathrm{\AA\,Hz^{-1/2}}$. This corresponds to the expected noise due to the frequency fluctuations of a free running tunable laser diode, which are of order $10^3\,\mathrm{Hz\,Hz^{-1/2}}$ at the resonance frequency of 12.5 kHz (ref. 10). With the system in vacuum at pressures of 10^{-6} mbar, so as to maximize the mechanical quality factor of the cantilever, this noise level corresponds to a minimum temperature of the order of 100 mK, in good agreement with the experimental data.

An alternative approach to study the cooling is to analyse the temporal response of the system by gating the signal to the feedback laser. The characteristic time constant for the system to reach equilibrium after the cooling is turned on is given by:

$$\tau_{\mathrm{fb}} = \Gamma_{\mathrm{fb}}^{-1} = (1+g)^{-1}\Gamma_0^{-1} \quad (5)$$

To observe this behaviour, we monitor the cantilever over many 10 s periods during each of which the cooling is on for 3 s. Data for cooling to 1.8 ± 0.2, 4.0 ± 0.2 and 6.4 ± 0.1 K and returning to thermal equilibrium are shown in Fig. 3. The cooling times are measured to be 9.0 ± 0.5, 19 ± 1 and 27 ± 1 ms, respectively. The reheating time is found to be indistinguishable for all three gains with an average of $\tau_0 = 1.30 \pm 0.05$ s. This is in agreement with the linewidth of the cantilever measured without feedback, $\Gamma_0 = 680 \pm 50$ mHz. In

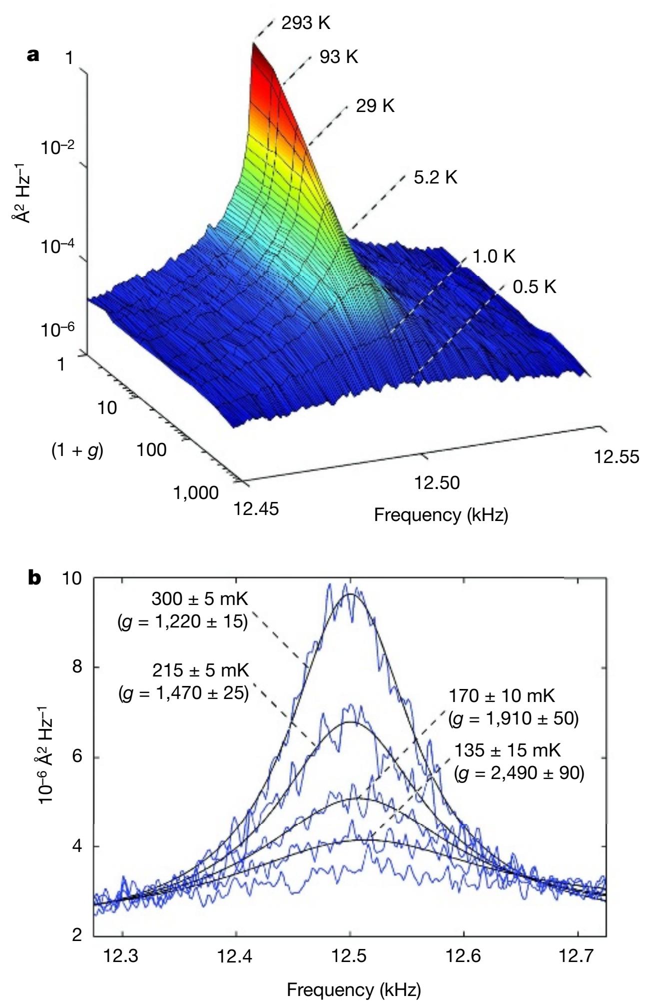

Figure 2 | Single-sided thermal vibration spectrum of the cantilever as it is cooled. g is the dimensionless gain factor, which is the ratio of feedback to mechanical damping. **a**, Spectrum at low to moderate gains. **b**, Spectrum near the background noise level for large gains. The blue curves correspond to experimental data, and the black curves to fits of a gaussian function plus a background. The lowest trace cannot be reliably fitted.

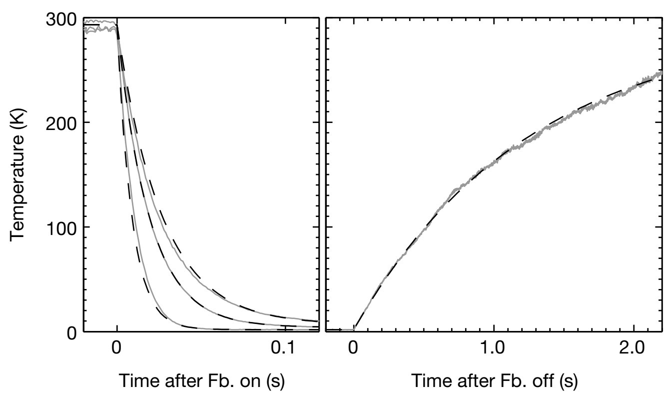

Figure 3 | Temporal response of the cantilever to cooling pulses. The temperature is determined by calculating the total vibrational amplitude of the cantilever between 12 and 13 kHz in 1 ms bins and subtracting the background. Each data set is the average of 1,000 samples. The three sets in the left panel correspond to cooling to 6.4, 4.0 and 1.8 K (solid lines, top to bottom). Heating is shown (right panel) for only one data set (1.8 K), as all three are nearly coincident. The dashed lines are fits to exponential decays, used to determine the cooled temperature and the cooling and reheating times. Fb. refers to the feedback system.

accordance with theory, the ratio of the reheating to the cooling times, τ_0/τ_{fb}, and the corresponding ratio of the spectral linewidths from the earlier measurements, Γ_{fb}/Γ_0, are found to be the same as the cooling factor, T_0/T_{fb}, within statistical uncertainties.

In experiments where optical feedback is used on cantilevers with non-uniform composition, radiation pressure is typically overwhelmed by the photothermal force, which is an effective force due to thermally induced bending[5,6]. Although this is not the case for single-crystal silicon cantilevers, the addition of a tiny mirror on the tip of our cantilever should produce a weak photothermal force. This force can be distinguished from radiation pressure by its dependence on the intensity modulation frequency of the feedback laser. Whereas radiation pressure is independent of modulation frequency, the photothermal force is not, because it has a characteristic response time, τ, related to the thermal relaxation time of the cantilever. A simple model for the frequency dependence of the photothermal force, $F_{pt}(\Omega)$, gives:

$$F_{pt}(\Omega) \cong \int_0^{\infty} \frac{F_{pt}(0)}{\tau} e^{-\frac{t}{\tau}} e^{-i\Omega t} \mathrm{d}t = \frac{F_{pt}(0)}{1+i\Omega\tau} \qquad (6)$$

where $e^{-i\Omega t}$ corresponds to the input power modulation, and $e^{-\frac{t}{\tau}}$ is due to the thermal relaxation. This is consistent with the frequency dependence of the photothermal force as described in previous work[6]. To test for the presence of photothermal force in our resonator, the feedback laser was modulated at a range of frequencies from 100 Hz to 20 kHz and the mechanical response of the cantilever was measured as before (Fig. 4). The power in the feedback laser reflected from the cantilever was determined to have a mean of 2.7 ± 0.5 mW and a modulation amplitude of 1.0 ± 0.2 mW, independent of the modulation frequency. This results in a radiation pressure force of $F_{rad} = 2P_{mod}/c = 6.7 \pm 1.3$ pN(where P_{mod} is the amplitude of the power modulation and c is the speed of light) at the modulation frequency.

If the driving frequency is sufficiently far from the cantilever resonance, the mechanical damping constant can be ignored and the amplitude of the cantilever's motion should be of the form:

$$A(\Omega) = \left| \frac{\frac{A_{pt}}{1+i\Omega\tau} + A_{rad}}{1-\left(\Omega/\omega\right)^2} \right| \qquad (7)$$

where Ω is the driving frequency, ω is the resonance frequency, τ is the photothermal characteristic time, and A_{rad} and A_{pt} are the magnitudes of the motion due to the radiation pressure and photothermal force alone, at zero frequency. The term in the denominator is due to mechanical amplification by the cantilever resonance. This equation fits well to the measured response (Fig. 4), resulting in $A_{rad} = 0.470 \pm 0.005$ Å, $A_{pt} = -6.3 \pm 0.2$ Å and $\tau = 30 \pm 2$ ms. At frequencies greater than 5 kHz, radiation pressure is observed to be the dominant force mechanism, whereas the photothermal force is relevant only at lower frequencies.

Assuming the constant force background described by A_{rad} is entirely due to radiation pressure, one can calculate the spring constant of the cantilever at the position where the feedback laser is focused to be $k = F_{rad}/A_{rad} = 0.14 \pm 0.03\ \mathrm{N\,m^{-1}}$, in agreement with the value for the spring constant obtained earlier. Near the fundamental resonance of the cantilever, the radiation pressure is calculated to be almost 5 times larger than the photothermal force. Additionally, the two forces should be nearly 90° out of phase at this frequency, given that the time constant of the photothermal force is found to be 30 ± 2 ms. Thus the radiation pressure is responsible for almost all of the demonstrated feedback cooling; in the absence of photothermal force, the total feedback force would be reduced by less than 3%.

When optical cooling is active, the cantilever's motion is strongly damped, making it undesirable for many types of measurements. In some cases this problem can be overcome with a stroboscopic cooling scheme, where measurements are only made in the periods when the cooling is off. In addition to being of direct importance for the aforementioned massive superposition experiment, this scheme has already been theoretically shown to be useful for high sensitivity measurements of position and weak impulse forces[11]. Because the cooling is faster than the heating by a factor $(1 + g)$, a low temperature can be maintained even when the cooling is off the majority of the time. However, maintaining low temperatures requires that the measurement window be short; if it is, for example, one oscillation period long, the temperature of the oscillator will have increased by $\Delta T \approx 2\pi T_0/Q$ by the end of each measurement window, meaning that cooling past this point results in marginal improvement.

We now evaluate the potential for reaching even lower temperatures for the purpose of studying quantum effects in similar systems. Reference 3 proposes an experiment: putting a mechanical oscillator in a quantum superposition of vibrating and not-vibrating by interaction with the light pressure of a single photon in an optical cavity of which one end mirror is attached to the oscillator. Appropriate for such a scheme would be a 250-μm-long silicon cantilever with a 20-μm-diameter dielectric mirror on the tip and a resonance frequency of 1 kHz. Because of the constraints of environmentally induced decoherence[12,13], the bulk temperature must be less than $T_{EID} = Q\hbar\omega/k_B = 8$ mK for the cantilever to remain coherent over one period, given $Q \approx 150{,}000$. This temperature is achievable by conventional means; nuclear adiabatic demagnetization of $PrNi_5$ (ref. 14) could be employed as the final, vibration-free, cooling stage, as it is able to be started from temperatures previously demonstrated

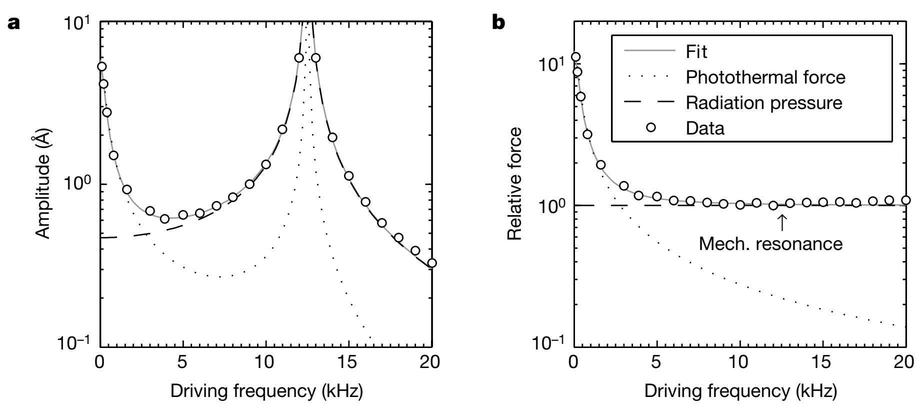

Figure 4 | Response of the cantilever to an external intensity-modulated laser. a, The amplitude of the cantilever's motion at the driving frequency. **b,** The force on the cantilever, calculated by dividing the amplitude by the mechanical amplification of the cantilever. In both graphs the magnitude of the contributions (ignoring phase differences) of the photothermal force and radiation pressure are shown as dashed and dotted lines, respectively. The slight deviation of the fit from the data at higher frequencies is due to higher-order flexural modes.

for vibration-isolated cold stages ($\sim$100 mK)[15,16]. The observation period for a massive superposition experiment is one oscillation long, thus the maximum useful cooling factor is $Q/2\pi \approx 25{,}000$ as discussed above. This corresponds with a temperature of 300 nK or a mean oscillator quantum number of only 2π.

It has been shown theoretically that optical feedback still works in the quantum regime, allowing cooling to the ground state[17]. Experimentally, cooling to the quantum regime requires the capability to accurately monitor the position of the cantilever without introducing significant heating. With an optical finesse $F = 5 \times 10^5$, which should be technologically achievable[8], an observation beam power of 1 aW, or about 5,000 photons per second, is enough to reduce shot noise to the appropriate level. Assuming the thermal conductivity of the cantilever is reduced to the one-dimensional quantum limit, the cantilever's thermal resistivity will be roughly 30 mK aW^{-1} (ref. 18). The heating from the feedback laser can be reduced by use of a sufficiently long wavelength laser so that absorption is negligible; this is not possible for the readout beam, which must be resonant with the optical cavity. Thus as long as the observation laser has relatively low absorption in the cantilever/mirror, it should not significantly affect the bulk temperature. This implies that cooling a kHz oscillator to near its ground state should be possible, drastically simplifying the experimental requirements to observe quantum phenomena in this system.

We have demonstrated active laser feedback cooling of a micromechanical oscillator, using only radiation pressure, from room temperature to 135 mK. Furthermore, we have shown that this cooling method could be used in addition to traditional cryogenics to reach much lower temperatures, even near the ground state of a kHz oscillator. This in turn would significantly aid the realization of proposals to create and investigate massive quantum superpositions.

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