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LETTERS

Self-cooling of a micromirror by radiation pressure

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Cooling of mechanical resonators is currently a popular topic in many fields of physics including ultra-high precision measurements[1], detection of gravitational waves[2,3] and the study of the transition between classical and quantum behaviour of a mechanical system[4–6]. Here we report the observation of self-cooling of a micromirror by radiation pressure inside a high-finesse optical cavity. In essence, changes in intensity in a detuned cavity, as caused by the thermal vibration of the mirror, provide the mechanism for entropy flow from the mirror's oscillatory motion to the low-entropy cavity field[2]. The crucial coupling between radiation and mechanical motion was made possible by producing free-standing micromirrors of low mass ($m \approx 400$ ng), high reflectance (more than 99.6%) and high mechanical quality ($Q \approx 10{,}000$). We observe cooling of the mechanical oscillator by a factor of more than 30; that is, from room temperature to below 10 K. In addition to purely photothermal effects[7] we identify radiation pressure as a relevant mechanism responsible for the cooling. In contrast with earlier experiments, our technique does not need any active feedback[8–10]. We expect that improvements of our method will permit cooling ratios beyond 1,000 and will thus possibly enable cooling all the way down to the quantum mechanical ground state of the micromirror.

Radiation-pressure forces inside optical cavities are known to pose an ultimate limit on the sensitivity of interferometric measurements[11,12]. However, less well known is the fact that radiation pressure can also be used for the opposite, namely to counteract the dynamics of a cavity mirror by means of dynamical back action[2,7,13]. In a recent experiment a passive cooling mechanism for a micromechanical oscillator based on bolometric back action was presented[7]. Even though this scheme has intrinsically limited cooling capability because it ultimately relies on heating by absorption, it might permit a quantitatively significant reduction of the oscillator's thermal motion. A more powerful scheme is provided by the use of radiation pressure as a feedback force[2]. In this case, optical absorption does not impose a fundamental limit. The difficulty in using radiation pressure for this cooling purpose is that it calls for stable control of the detuning of a high-finesse cavity, strong optomechanical coupling and a low mass of at least one cavity mirror, thus requiring nanomechanical or micromechanical systems of high optical and mechanical quality (characterized by the cavity finesse F and the mechanical quality factor Q). Although cavity-induced radiation-pressure effects have already been used to modify elastic properties of mirrors[7,14–16] and to enforce mechanical instabilities[14,17–19], none of the previous experiments was able to combine these strict requirements. We have overcome this limitation by developing a method to produce free-standing micromirrors of low mass (about 400 ng), high reflectance (more than 99.6%) and high mechanical quality ($Q \approx 10^4$). The use of such micromirrors in a detuned optical cavity allows us to observe for the first time self-cooling in a regime in which, although photothermal effects are still present, radiation pressure participates significantly in the self-cooling process.

Radiation-pressure forces in an optical cavity arise from the momentum transfer of photons reflected from the mirror surface. For certain cavity detuning—that is, if the cavity angular frequency ω_c is off resonance with the frequency ω_l of the pump laser, the radiation pressure is highly sensitive to small displacements of the cavity mirror. This is a consequence of the fact that the energy stored in a cavity field varies strongly with detuning. As a consequence, the dynamics of an oscillating mirror inside a detuned cavity is modified by a mechanical rigidity that depends on the detuning. For a high-finesse cavity, the radiation-pressure-induced back action can act on the mirror motion in such a way as to induce low-noise damping. This is the general concept of dynamical back action[13]. A simple classical description of the dynamics of the mirror shows that both the resonance frequency ω_M and the natural damping rate γ of the mirror motion are modified by radiation pressure to ω_{eff} and γ_{eff}, respectively[2,7]. In particular, within the classical framework, the modified damping rate follows

$$\gamma_{\text{eff}} = \gamma + \frac{\beta(\Delta)}{2m}\frac{2\kappa}{(2\kappa)^2 + \omega_M{}^2} \tag{1}$$

with the cavity decay rate $\kappa = \pi c/2FL$, the cavity finesse F, the cavity length L and the speed of light *in vacuo*, c. Optimum damping is achieved when $1/(2\kappa)$ is of the order of ω_M, which for ω_M in the megahertz range requires a high-finesse cavity. Equation (1) depends on $\beta(\Delta)$, the spatial gradient of the radiation force evaluated at a (spatial) detuning $\Delta_x = L\Delta/\omega_l$. Here Δ is the effective detuning between cavity and laser frequency, including the effect of radiation pressure[20]. The contribution β, induced by radiation pressure, can be positive or negative depending on the sign of Δ. It is straightforward to show that $\beta(\Delta)$ is negative for $\Delta < 0$, corresponding to $\gamma_{eff} < \gamma$. In this regime, the system can enter instability. The focus of this work is the investigation of the opposite regime ($\beta(\Delta) > 0$) in which $\gamma_{eff} > \gamma$. This low-noise damping results in a reduction of the mirror temperature, and hence self-cooling is achieved. The previous self-cooling experiments based on bolometric forces[7] were operated in the regime of negative detuning, where radiation pressure counteracts the cooling.

To observe the self-cooling effect a read-out scheme of the mirror motion is required. For this purpose it is sufficient to measure the statistical properties of the optical field that leaks out of the cavity. In a way, the output cavity field represents a 'blank sheet' on which the dynamics of the mirror can be written. It is possible to briefly sketch the main idea of our self-cooling read-out process by exploiting a

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simple (but for our purposes sufficient) semiclassical picture. A full quantum mechanical framework, which generalizes the classical picture for self-cooling proposed so far in the literature[2,10], is presented elsewhere[21]. Not only is this (more general) approach in agreement with the classical picture taken into account by equation (1) but it also paves the way towards the rigorous study of the limitations imposed on self-cooling by the influences of quantum noise[21]. The total energy of a cavity consisting of a fixed mirror and a movable mirror driven by an input laser field of power P is given by[20,21]

$$U=\frac{\hbar}{2}(\omega_{\mathrm{c}}-\omega_{\mathrm{l}})(X^2+Y^2)-\hbar\frac{\omega_{\mathrm{c}}}{2L}(X^2+Y^2-1)q+\frac{1}{2}\left(\frac{p^2}{m}+m\omega_{\mathrm{M}}^2q^2\right)+\sqrt{2}\hbar EY \qquad (2)$$

where X and Y are the quadratures of the cavity field, p and q are the momentum and position quadratures of the oscillating mirror, and $E=\sqrt{2\kappa P/\hbar\omega_{\mathrm{l}}}$ is the coupling rate between the cavity and the input laser field. If the timescale set by the cavity decay rate is the shortest in the dynamics of the system—that is, $\kappa\gg\omega_{\mathrm{M}}$—the cavity field follows the mirror motion adiabatically. As a consequence, the fluctuations δY_{out} of the field leaking out of the cavity are directly related to the fluctuations of the mirror's position quadrature as $\delta Y_{\mathrm{out}}(t)=A(\Delta,\kappa,E)\delta q(t)$ (refs 22, 23), where we have neglected any noise in the system. For the parameter regime of our experiment the signal-to-noise ratio of the contribution given by the mirror's spectrum is as large as 10^7. The dynamics of the output field quadrature is thus entirely determined by the mirror motion by means of the function $A(\Delta,\kappa,E)$. A phase-sensitive measurement of the output field quadrature δY_{out} is therefore capable of 'monitoring' the full mirror dynamics. It is particularly interesting to measure the power spectrum because $S_{Y_{\mathrm{out}}}=\int \mathrm{d}t'\mathrm{e}^{i\omega t'}\langle\delta Y_{\mathrm{out}}(t)\delta Y_{\mathrm{out}}(t+t')\rangle=T(\Delta)S_{\mathrm{q}}$, where S_{q} is the spectrum of the mirror motion. In other words, the quadrature power spectrum of the mirror motion S_{q} and of the output cavity field $S_{Y_{\mathrm{out}}}$ are directly related by means of a transfer function $T(\Delta)$. This correspondence is at the basis of our read-out scheme. Note that the full transfer function has to take into account the sensitivity of the specific detection scheme used.

This detection strategy allows us to infer the effective temperature of the mirror's brownian motion through the study of its displacement power spectrum; that is, its frequency-dependent mean-square displacement. The power spectrum follows a lorentzian distribution centred on $\omega_0=\sqrt{\omega_{\mathrm{eff}}^2-2\gamma_{\mathrm{eff}}^2}$ with a full-width at half-maximum (FWHM) $w_{\mathrm{FWHM}}\approx 2\gamma_{\mathrm{eff}}$ (for $\omega_0^2\gg\gamma_{\mathrm{eff}}^2$), thus proportional to the introduced damping. The area of the power spectrum, $\langle x^2\rangle=\int_{-\infty}^{+\infty}\mathrm{d}\omega S_{\mathrm{q}}$, is proportional to the mean energy $\langle U\rangle$ of the vibrational mode and hence, by the equipartition law, to the effective temperature of the mirror, because $\langle U\rangle=m\omega_{\mathrm{M}}^2\langle x^2\rangle=k_{\mathrm{B}}T_{\mathrm{eff}}$. The relative change in area underneath the power spectrum is therefore a direct measure of the change in effective temperature.

The system under investigation is a doubly clamped cantilever used as the end mirror of a linear optical cavity driven by an ultra-stable Nd:YAG laser (see Fig. 1). The input mirror of the cavity is attached to a piezoelectric transducer, which is fed by a control loop allowing us to lock the precise length of the cavity either at resonance or detuned (off resonance) with respect to the laser frequency. The error-signal input to the control loop is obtained with the Pound–Drever–Hall (PDH) technique[24]. It has been shown[23] that the PDH error signal is proportional to the phase quadrature of the output field Y_{out} and hence to the mirror motion (see above). An intuitive way to view it is that the error signal is proportional to the variation of the cavity length. Above the cutoff frequency of our control loop, the fluctuations in the error signal are therefore directly related to the thermal noise of the cantilever (the input mirror is assumed to be fixed).

We measured the PDH power spectrum for different input powers and cavity detunings. The detuning was achieved by adding an offset to the error signal. With this method, the mechanical damping can be measured directly by determining the FWHM of the resonance peak of the observed mechanical mode. To obtain the effective temperature of the mode one has to calculate the area underneath the resonance peak and account for the sensitivity of the error signal. This is done by normalizing the measured mirror amplitudes by the gradient of the PDH signal. The results are summarized in Figs 2–4.

Figure 2 shows the noise spectrum of the oscillator for two different detunings at 2 mW input laser power. The width of the peak increases and the area of the peak decreases, which is indicative of both overdamping and cooling of the mechanical mode. This behaviour is in full agreement with the theoretical model presented above. We investigate the specific variation of both mechanical damping and of self-cooling with detuning for different input laser powers of 1 and 2 mW, respectively (Figs 3 and 4). Figure 3 shows the change in width of the mechanical mode. For positive detunings, the peak is broadened from a natural width of 32 Hz to well above 800 Hz, corresponding to an extra damping of the mode. At large detuning

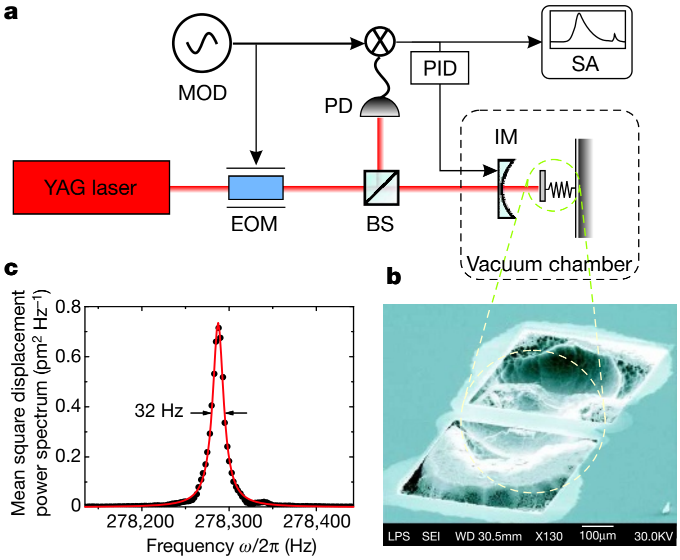

Figure 1 | Sketch of the experimental setup. **a**, A cavity was built between the cantilever and a regular concave mirror of 25 mm focal length and 99.3% reflectivity. The cavity length was slightly shorter than 25 mm so as to obtain a waist of about 20 μm at the location of the surface of the cantilever. In this configuration we measured a cavity finesse of 500. To minimize damping of the mechanical mode due to gas friction, the cavity was placed in a vacuum chamber kept at 10^{-5} mbar. The cavity was pumped with a Nd:YAG laser at 1,064 nm. The beam was phase modulated at 19 MHz (MOD) by a resonant electro-optic modulator (EOM) before it was injected into the cavity by means of the input mirror (IM). The beam reflected from the cavity was sent through a beam splitter (BS) onto a high-speed PIN photodiode (PD). After amplification of the photocurrent, its AC part was demodulated with the initial modulation frequency to obtain the PDH error signal. This error signal was then used to feed a low-frequency control loop (PID) to stabilize the cavity length by means of a piezo actuator. In addition, the error signal was fed to a spectrum analyser (SA) to record the dynamics of the mechanical mode. **b**, The cantilever was a doubly clamped free-standing Bragg mirror (520 μm long, 120 μm wide and 2.4 μm thick) that had been fabricated by using ultraviolet excimer-laser ablation in combination with a dry-etching process[30]. The reflectivity of the Bragg mirror was 99.6% at 1,064 nm. **c**, Power spectrum of the micromirror. We isolated a mechanical mode at 280 kHz with a natural width of 32 Hz, corresponding to $Q\approx 9{,}000$. All measurements presented here were made on this mode. Experimental points correspond to a temperature of 300 K; solid lines are lorentzian fits to the data.

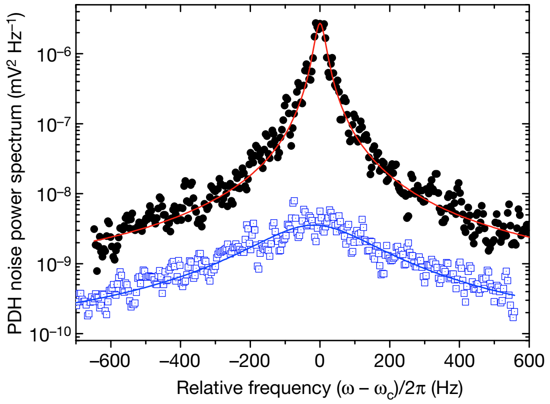

Figure 2 | Power spectrum of the mechanical mode at two different relative detuning levels Δ of the cavity for an input power of 2 mW. The data were obtained from the PDH power spectrum, which was directly proportional to the displacement power spectrum of the micromirror. Experimental points (black, $\Delta = 0$; blue, $\Delta = 0.44\kappa$) were taken with the spectrum analyser, averaged over 30 consecutive measurement runs. Solid lines are lorentzian fits to the data. The areas obtained from the fit correspond to temperatures of 300 K (red) and 8 K (blue).

values the stability of the locking limits the precision of the measurements. For negative detuning (not shown) we observed a narrowing of the peak, associated with an amplification of the mirror motion (that is, 'negative' damping), which rapidly leads to a self-oscillation region. In Fig. 4 the same data set is used to obtain the corresponding cooling ratio from the relative change in area of the power spectrum, because the total peak area is a measure of temperature. As expected, the increase in damping is accompanied by a cooling of the mechanical mode. At large detuning, the cooling effect is slightly enhanced compared with our simple model, which might be due to the reduced contribution of thermal background of other oscillator modes. The best experimental cooling ratio in our detuning range is more than 30. Because our experiment was performed at room temperature, this corresponds to a cooling of the mode from 300 K to less than 10 K (Fig. 2).

We explicitly compare the experimental results for positive detuning with the theoretical predictions obtained if the effect is due only to radiation pressure. To do that, we have independently evaluated the effective mass participating in the dynamics of the system, which leaves no free parameter for the evaluation of radiation-pressure forces and hence allows a full quantitative treatment. The effective mass can be much smaller than the total mass of the cantilever[19,25]. For our mirror, an independent assessment both by means of spatial tomography of the vibrational mode and by means of a calibrated reference results in a value of 22 ± 4 ng at the probing point (see Supplementary Information). This results in a theoretically expected cooling that is less strong than the experimentally observed one. To get a clear, immediate figure of the 'strength' of the radiation pressure effect required to replicate the experimental data we assume a fixed effective mass and permit variation of the input power. We find that, for effective masses of 18 and 26 ng, a power respectively 2.2-fold and 3.3-fold the nominal value used in the experiment is required to match the theoretical predictions with both the observed damping and cooling (Figs 3 and 4). In other words, radiation pressure accounts for at least 30% of the observed cooling but may be as strong as 50%; that is, there is cooling by a factor between 8 and 12. We attribute the additional cooling in our setup to the presence of photothermal effects. In a similar manner to the bolometric forces reported in ref. 7, differential heating of the outer layers of the dielectric Bragg mirror can result in time-delayed changes in the cavity length, eventually introducing a retarded force that can contribute to the self-cooling mechanism. In a thin-layered medium the delayed force induced by photothermal effects can have typical time constants on the order of several tens of nanoseconds (see Supplementary Information), which is fast enough to compete with the timescale of radiation pressure effects of $1/(2\kappa)$ (about 13 ns in our experiment). The direction of the force depends on the specific material properties of the expanding layers. In our case, and in contrast with previous experiments, it assists the cooling effect of radiation pressure present for positive detuning.

The experimental data are consistent with radiation-pressure cooling assisted by photothermal effects. Residual heating of the cantilever due to absorption was not observed (see Supplementary Information). Improvements in the reflectivity of the Bragg mirror will further reduce and eventually eliminate photothermal contributions to the cooling because it will permit a higher finesse to be achieved and the optical absorption to be limited. An interesting analogy by which to understand this cooling mechanism can be found in thermodynamics. If a system (the mirror), initially at

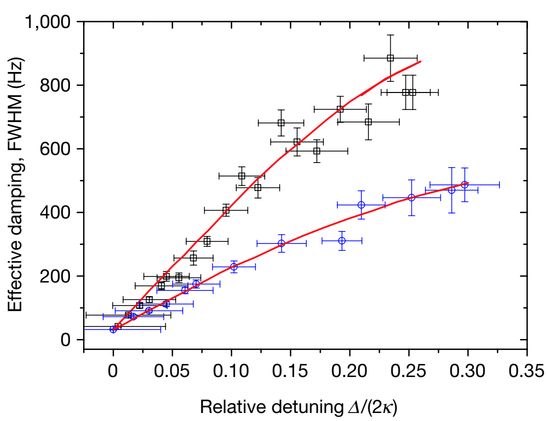

Figure 3 | Radiation-pressure-induced damping of mirror dynamics. The measured width of the mechanical mode at 278 kHz is shown at different detuning levels of the cavity and for input laser powers of 1 mW (blue points) and 2 mW (black points). The data are obtained directly from lorentzian fits on the measured power spectra of the PDH error signal. Error bars represent absolute errors based on experimental uncertainty. Solid lines represent theoretical predictions of purely radiation-pressure effects for $F \approx 500$, $Q \approx 9{,}000$ and an effective mass of 9 ng. The inferred effective mass of 22 ± 4 ng indicates the presence of an additional damping force of photothermal nature (see the text).

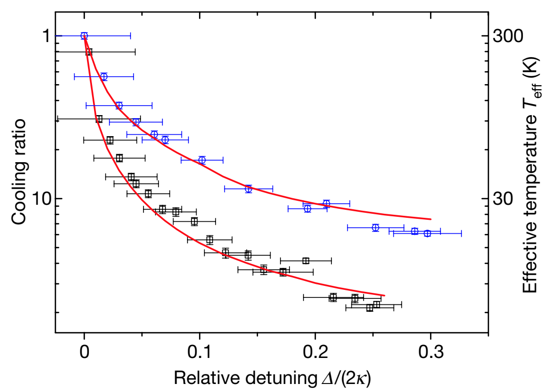

Figure 4 | Self-cooling of the mechanical resonator. The cooling ratio of the mechanical mode is shown as a function of detuning and for input laser powers of 1 mW (blue points) and 2 mW (black points). The data are obtained as the normalized area of the measured PDH power spectrum, compensated for the detuning dependent sensitivity of the PDH cavity response. Error bars represent absolute errors based on experimental uncertainty. The self-cooling effect increases for increasing laser power and detuning, in agreement with the theoretical predictions (solid lines). The right ordinate shows the inferred effective temperature of the mechanical oscillator. Radiation pressure contributes between 30% and 50% to the overall cooling, which is assisted by photothermal effects.

thermal equilibrium with a bath at ambient temperature (its environment), is strongly coupled to another bath with a very low temperature (the low-noise laser), its temperature will decrease so as to bring it to equilibrium with both baths. The current technical limitation for observing a lower temperature is the stability of the detuned locking and the base temperature from which the self-cooling starts. For example, with a cavity finesse $F = 6{,}000$ and an input optical power of 1 mW we expect a pure radiation-pressure cooling ratio of 1,500 for a smaller mirror oscillating at 1 MHz with an effective mass of 5 ng and $Q = 10^5$. Starting from 5 K, one should achieve cooling to 3 mK—below the base temperature of a dilution fridge. We are confident that the quantum ground state may be reachable with state-of-the-art optics and microfabrication techniques[26].

We have observed self-cooling of a low-mass micromirror sustained by radiation pressure. The cooling of mechanical oscillators is a key requirement for many open problems of modern physics ranging from the performance of shot-noise-limited position measurements[1] to the study of gravitational waves[2,3] and dynamical multistability in micro-optical systems[27]. The possibility of lowering the temperature of an oscillator to its quantum mechanical ground state paves the way to the implementation of quantum state engineering involving macroscopic systems[21,28,29], a closer study of the boundary between classical and quantum physics[6] and, ultimately, the observation of non-classical correlations between macroscopic objects[26]. In the long term it may also provide new methods of integrated quantum (mechanical) information processing.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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