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Prospects for cooling nanomechanical motion by coupling to a superconducting microwave resonator

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Abstract. Recent theoretical work has shown that radiation pressure effects can in principle cool a mechanical degree of freedom to its ground state. In this paper, we apply this theory to our realization of an optomechanical system in which the motion of mechanical oscillator modulates the resonance frequency of a superconducting microwave circuit. We present experimental data demonstrating the large mechanical quality factors possible with metallic, nanomechanical beams at 20 mK. Further measurements also show damping and cooling effects on the mechanical oscillator due to the microwave radiation field. These data motivate the prospects for employing this dynamical backaction technique to cool a mechanical mode entirely to its quantum ground state.

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1. Introduction

Despite the recent progress in the fabrication, control and measurement of macroscopic mechanical objects, a mechanical oscillator is yet to be observed in its motional ground state. This long standing goal is a necessary prerequisite for many experiments that explore and make use of the quantum nature of motion, such as entanglement, squeezing and quantum measurement. Standard dilution refrigeration techniques can cool sufficiently high frequency mechanical resonators to their ground state; however, these small, stiff oscillators are exceedingly difficult to measure with enough sensitivity to resolve the zero point motion. Furthermore, many current experimental realizations are incompatible with operation in a dilution refrigerator. In these situations, feedback (either passive or active) seems to offer the most feasible route to ground state cooling. In active feedback, a force is applied to the oscillator that is proportional to its velocity using the information acquired from a precise measurement of the mechanical motion. This force can then damp the thermal, Brownian motion and cool the oscillator by coupling to the effectively 'colder' bath of the measurement. In this way, the fundamental limit of this cooling technique is the sensitivity of the measurement. In fact, it is only a Heisenberg-limited measurement that could completely cool to the quantum ground state [1]. So while this technique has been used to greatly reduce the effective temperature of a mechanical mode [2]–[4], true ground state cooling is not a realistic possibility until a quantum limited measurement has been achieved.

While mesoscopic measurement techniques that can couple to lighter and smaller resonators have produced the closest approach to this measurement limit [5, 6], technical issues have prevented measuring at the quantum limits of displacement sensitivity. More recently, there have also been proposals to couple mechanical motion to superconducting quantum interference devices (SQUIDs) [7, 8]. In contrast to these mesoscopic methods, the most precise measurements in terms of absolute displacement sensitivity use interferometric techniques with visible light to infer the mechanical position [2]. This strong interaction between an electromagnetic resonance and mechanical motion offers another method for cooling. This passive cooling can be achieved by engineering a system where the delayed radiation pressure of the light field serves to damp the oscillator's motion. Recent experimental [9]–[12] and theoretical [13]–[15] progress on the use of this dynamical back-action indicates that this method is poised to achieve true ground state cooling. This paper explores these possibilities for cooling in our particular realization of this system, whereby a nanomechanical beam is embedded in a superconducting, microwave cavity [16].

2. Theory of optomechanical effects

The Hamiltonian that describes an electromagnetic resonance whose resonant frequency is parametrically coupled to the motion of a mechanical oscillator is

$$H = \hbar\omega_0 \left(a^{\dagger}a + \frac{1}{2}\right) + \hbar\omega_m \left(b^{\dagger}b + \frac{1}{2}\right) - \hbar g a^{\dagger}a \left(b^{\dagger} + b\right) \delta x_{zp}.$$
 (1)

Here a^{\dagger} (b^{\dagger}) is the creation operator for the electromagnetic (mechanical) mode and ω_0 (ω_m) is the frequency of the unperturbed electromagnetic (mechanical) resonance. In the presence of a mechanical beam, the electromagnetic cavity resonance frequency is perturbed to ω_c . The dispersive effect of a displacement $\hat{x} = (b^{\dagger} + b)\delta x_{zp}$ on the cavity resonance frequency is given



Figure 1. Measurement schematic. In this simplified circuit diagram, the microwave cavity is represented by an *LC* resonator capacitively coupled to a feedline. The motion of a nanomechanical beam modulates this cavity resonance frequency by capacitively loading the circuit. Thus, by measuring the phase, ϕ , of the transmitted microwave signal via homodyne detection, the mechanical motion may be inferred.

by $g = -\frac{\partial \omega_e}{\partial x}$. This coupling implies that the light can be used to infer the displacement of a mechanically compliant object, and that photons in the cavity in turn exert a force on the mechanical oscillator. If the mechanical resonance frequency is greater than or comparable to the energy decay rate of the cavity, γ , this force becomes substantially out of phase with the physical motion. Recently, a fully quantum theory of this damping has shown that this effect is capable of cooling a mechanical mode to its ground state [13, 14, 17, 18].

The mechanism for cooling via radiation damping can be understood as a Raman process whereby the parametric coupling allows drive photons to inelastically scatter to another frequency. This process preferentially scatters photons to the cavity resonance frequency, as this is where the final photon density of states is maximal. If an excitation frequency, ω_e , is red detuned from cavity resonance by $\Delta = \omega_e - \omega_c < 0$, the mechanical motion will be both damped and cooled. In this paper, we will consider these quantum results within the weakcoupling limit [13], where the cavity linewidth is always greater than the mechanical linewidth. This regime is sufficient for all experimental parameters considered in this paper.

In general the radiation force is a complex quantity that can affect both the damping and the spring constants of the mechanical system. For an ideal, single-port cavity, the additional mechanical damping, Γ , and the mechanical frequency shift, $\delta\Omega$, due to the radiation field are given by

$$\Gamma = A \left[\frac{1}{\gamma^2 + 4 \left(\Delta + \omega_{\rm m} \right)^2} - \frac{1}{\gamma^2 + 4 \left(\Delta - \omega_{\rm m} \right)^2} \right],\tag{2}$$

$$\delta\Omega = \frac{A}{\gamma} \left[\frac{\Delta + \omega_{\rm m}}{\gamma^2 + 4 \left(\Delta + \omega_{\rm m}\right)^2} + \frac{\Delta - \omega_{\rm m}}{\gamma^2 + 4 \left(\Delta - \omega_{\rm m}\right)^2} \right],\tag{3}$$

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where

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$$A = \frac{8g^2 P \gamma^2}{m\omega_{\rm m}\omega_{\rm c}(\gamma^2 + 4\Delta^2)},\tag{4}$$

P is the incident power, m is the effective mass and γ is the cavity linewidth [13, 14].

In the absence of mechanical damping, the effective temperature of the mechanical degree of freedom is completely determined by the cavity-filtered photon shot noise. Following the formalism of Marquardt *et al* [13], the equilibrium number of thermal phonons, \bar{n}_p , for a given relative detuning, is completely determined by the ratio of ω_m and γ .

$$\bar{n}_{\rm p} = -\frac{\gamma^2 + 4\left(\Delta + \omega_{\rm m}\right)^2}{16\omega_{\rm m}\Delta}.$$
(5)

As $\omega_{\rm m}$ becomes comparable to or greater than γ , one enters the so-called good cavity limit. The quantity, $\bar{n}_{\rm p}$, can be made less than unity only in this resolved sideband limit with a properly chosen red-detuned carrier. The optimal detuning for the lowest effective temperature is given by

$$\Delta_{\rm opt} = -\frac{1}{2}\sqrt{\gamma^2 + 4\omega_{\rm m}^2}.\tag{6}$$

Thus, in the bad cavity limit ($\omega_m \ll \gamma$), $\Delta_{opt} \simeq -\gamma/2$ and $\bar{n}_p \simeq \gamma/(4\omega_m) \gg 1$. However, in the good cavity limit, $\Delta_{opt} \simeq -\omega_m$ and $\bar{n}_p \simeq \gamma^2/(16\omega_m^2) \ll 1$. It is important to note that, once in the good cavity limit, the frequency shift has zeros exactly at the points of maximal damping, $\Delta = \pm \omega_m$. Thus, the effect of the radiation at these values of the detuning is purely a damping component.

In order to determine the final temperature in the presence of both a thermal reservoir and this effective photon temperature, one must weight each temperature by the strength with which it is coupled to the mechanical oscillator. Thus, the final steady-state occupancy of the mechanical oscillator, $\bar{n}_{\rm f}$, is

$$\bar{n}_{\rm f} = \frac{\Gamma \bar{n}_{\rm p} + \gamma_{\rm m} \bar{n}_{\rm T}}{\Gamma + \gamma_{\rm m}}.\tag{7}$$

Here, γ_m is the intrinsic mechanical damping, and \bar{n}_T is the mean number of thermal phonons determined by the bath temperature. As this final phonon number, \bar{n}_f , becomes less than unity, this mode of the mechanical oscillator asymptotically approaches its quantum mechanical ground state.

These equations may be summarized by noting that the requirements for reaching the ground state are threefold. Firstly, the intrinsic mechanical quality factor must be larger than the initial number of thermal phonons in the mechanical mode ($\bar{n}_T < Q_m$). Secondly, the effective temperature of the photon bath must be sufficiently cold. From equation (5), this implies that the system must be sufficiently in the good cavity limit ($\omega_m \gtrsim \gamma$). The last requirement is that the optical damping is strong enough to overwhelm the coupling to the thermal bath ($\Gamma \gtrsim \gamma_m \bar{n}_T$). Unlike optical systems, for which achieving the good cavity limit is the primary challenge, our microwave implementation naturally falls in this regime. However, for our system, it is the last requirement on the coupling that sets the practical limit on temperatures attainable with passive cooling. One additional caveat is that the ratio between the initial and final temperatures cannot exceed the ratio of the resonance frequency of the electromagnetic and mechanical modes ($\bar{n}_T/\bar{n}_f \leq \omega_c/\omega_m$) [18]. While this restriction could in principle preclude ground state cooling, it is not a limiting factor for the experimental parameters considered in this paper.

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Figure 2. Images of the device. These scanning electron microscope (SEM) images show both a portion of the microwave cavity (left) and the nanomechanical oscillator (right) fabricated out of aluminium. The cavity consists of a $\lambda/4$ resonator that is capacitively coupled to a CPW feedline. A 50 μ m long, suspended beam is placed at the voltage antinode of the cavity so that its vibrational motion modulates the resonance frequency of the cavity.

3. Device implementation and measurement scheme

In our system, the motion of a freely suspended, nanomechanical beam modulates the resonance frequency of a superconducting microwave cavity [16]. As shown in figure 2, this cavity takes the form of a $\lambda/4$ coplanar waveguide (CPW) resonator that is capacitively coupled to a feedline. Such CPW resonators simultaneously provide many desirable characteristics and have been utilized in several recent experiments in fields such as radio-astronomy [19, 20] and quantum computing [21]. These include ease of fabrication, cryogenic operation, small mode volume and low loss ($Q > 10^5$). Because the mode volume is so small, even the nanomechanical motion of picogram oscillators can significantly influence the electromagnetic resonance.

A high aspect-ratio, nanomechanical beam is placed at a voltage antinode within the cavity. These devices are fabricated in the JILA clean room using a combination of optical and electronbeam lithography to pattern a resist mask on an ultrahigh resistivity silicon substrate. Both the mechanical beam and the microwave cavity structures are created by a single evaporation step of 120 nm of aluminium. In order to release the nanomechanical beam, a reactive ion etch is used to remove the silicon substrate below the mechanical oscillator. The resulting beam is freely suspended and held at a distance of roughly 1 μ m from the ground plane. Typical mechanical oscillators range in length from 10 to 50 μ m and have resonance frequencies from 0.1 to 6 MHz. The microwave cavities are designed to have a quarter wave resonance between 4 and 10 GHz and a coupled quality factor of approximately 10⁴ so that internal cavity losses do not dominate. While these Q values are modest compared to optical Fabry–Perot cavities used to measure micromechanical oscillators, it is the cavity linewidth that determines if the system is in the good cavity limit. Thus, by using microwave frequencies and superconducting resonators, linewidths can readily be made less than 1 MHz.

All measurements are performed in a dilution refrigerator whose base temperature is approximately 20 mK. In order to measure the mechanical displacement, a microwave tone is

applied to the device using a commercial, low-noise signal generator and 40 dB of cryogenic attenuation. The transmitted signal is then amplified with a cryogenic, high electron mobility transistor (HEMT) amplifier within the inner vacuum chamber of the cryostat. The signal is further amplified at room temperature and demodulated with standard homodyne detection. An in-phase quadrature (IQ) mixer is used to recover both the amplitude and phase of the the microwave signal. In this configuration, the low-frequency mechanical motion of the beam gives rise to a phase shift in the transmitted microwave signal as shown in figure 1. Further details regarding both the fabrication and the experimental setup are described in previous work [16].

As the dynamical backaction cooling relies on the cavity being excited with a purely coherent excitation, this places stringent requirements on both the thermal population of the cavity modes and the noise of the signal generator. By operating at cryogenic temperatures where $k_{\rm B}T \ll \hbar\omega_{\rm c}$ and ensuring all microwave lines have enough cold attenuation to reduce the room temperature Johnson noise to a negligible level at the device, the thermal population of the cavity can be made less than unity. While both amplitude and phase noise of a signal generator could also prevent cooling to the mechanical ground state, for our current and future device parameters, the specified noise level of the commercial microwave generator (<140 dBc Hz⁻¹ at 1 MHz) is sufficiently small that it will not preclude ground state cooling.

4. Results

Initial measurements have yielded very encouraging results for the low temperature mechanical properties of beams made entirely out of evaporated aluminium [16]. Figure 3 shows the range of mechanical resonance frequencies and quality factors for devices at a cryostat temperature of 20 mK. These measurements include both doubly clamped beams and cantilever style oscillators. These beams range in length from 9 to 50 μ m and have a height and width of roughly 100 nm. Some of the doubly clamped beams were thermally annealed before they were released in order to place them under tensile stress. Tension not only increases the mechanical resonance frequency, but also greatly increases the mechanical quality factor as well. This effect is analogous to Fabry–Perot experiments in which the optical spring effect is exploited to increase the mechanical stiffness without changing the damping [4]. Similar results have recently been observed in silicon nitride beams and membranes where quality factors exceed 10^6 at room temperature [22, 23] and 10^7 at 300 mK [24]. While our beams without tension tend to have quality factors less than 10^4 , tension reproducibly results in oscillators with $Q > 10^5$.

From equation (5), one can show that passively cooling to a thermal occupancy of less than one phonon is theoretically possible for a ratio of $\omega_m/\gamma > 1/\sqrt{32}$. This requirement is easily met for all beams and cavity parameters shown above. The limit of the cooling in our system is not the effective temperature of the radiation effects (i.e. reaching the good cavity limit), but rather how strongly the radiation can be coupled to the mechanical motion. It is only if the radiation damping, Γ , is much larger than the intrinsic damping, γ_m , that the mechanical oscillator decouples from its thermal environment. In theory, weak coupling can be overcome by increasing the circulating photon power. In practice, this quantity is limited by the critical current of the superconducting film. For our aluminium cavities, the microwave resonance becomes nonlinear at a circulating power of order 1 μ W.

One device showed coupling that is of an order of magnitude greater than expected. Later SEM imaging indicated that this is due to part of a doubly clamped beam actually touching the adjacent ground plane. While this configuration makes it difficult to know the precise mode



Figure 3. Mechanical resonance frequencies and quality factors. This plot shows 18 mechanical oscillators that have been measured with our microwave interferometric technique at a cryostat temperature of 20 mK. For the doubly clamped geometry, film tension can be used to greatly increase both resonance frequency and the the quality factor of the mechanical mode. The black line shows the $Q_{\rm m}$ one would expect if the beam tension were only changing the spring constant and leaving the mechanical damping, $\gamma_{\rm m}$, constant.

shape or effective mass, the driven response of this 50 μ m long beam shows a clear mechanical resonance at 1.41 MHz with a quality factor of 3800. Due to this large coupling, there is clear evidence of dynamical backaction in both the quality factor and effective temperature of the beam even at low microwave powers. For this device, the cavity resonance frequency is 7.55 GHz with the quality factor of 25 000. Figure 4 shows the mechanical quality factor as a function of microwave carrier detuning while maintaining a constant circulating power. This experiment is well in the good cavity limit ($\omega_m = 4.7 \times \gamma$) as is immediately evident from figure 4. There is a sharp peak (dip) in the mechanical quality factor when the carrier is blue (red) detuned by the mechanical resonance frequency. The black line shows a fit to equation (2), which reproduces the independently determined values for ω_m and γ .

This change in the mechanical quality factor implies that the thermal motion of the beam should also be affected. In order to measure this effect, the cryostat is held at a temperature of 200 mK so that the thermal motion of the beam is clearly visible. As shown in figure 5, the spectral density is measured as a function of frequency with the carrier both red and blue detuned by the mechanical resonance frequency. The area of the Lorentzian peak is proportional to the rms motion of this mode of the beam, and hence its effective temperature. These data show a 50% reduction in this area between the blue and red detuning. Thus, for the blue detuning, the beam is coupled to a negative temperature bath (as given by equation (5)) and the temperature increases from 200 to 280 mK. Analogously, in the case of red detuning, the beam cools to an effective temperature of 140 mK. While this level of cooling is far from what is required for ground state cooling, it clearly demonstrates the dynamical backaction of the





Figure 4. Detuning dependence of the mechanical quality factor. The mechanical quality factor, Q_m , displays the expected effects of radiation damping. As the microwave carrier is red (blue) detuned from the cavity resonance by $\pm \omega_m$, the dynamical backaction results in a maximal decrease (increase) in the mechanical quality factor. The width of these peaks in Q_m is set by the cavity linewidth, which clearly shows that this device is well in the good cavity limit.



Figure 5. Thermal noise of a mechanical resonance with red and blue detuning. For these curves, the microwave carrier is detuned by the mechanical resonance frequency so that the dynamical backaction has a maximal effect. The upper curve (shown in blue) is when the microwave carrier is blue detuned from the cavity resonance, increasing both $Q_{\rm m}$ and the rms motion of the oscillator. Likewise, the lower curve (shown in red) is red detuned, and the nanomechanical beam experiences damping and cooling.

microwave cavity on the temperature of the mechanical oscillator. While this is only a modest demonstration of cooling and heating effects, it serves as a proof of principle demonstration for our experiment. While the effect of the cooling scales with circulating power in the microwave cavity, our experiments are limited by the critical currents of the superconducting film. Despite this limitation, as recent data have shown that mechanical quality factors of greater than 10^5 are feasible, it is interesting to note that this would imply a hundredfold increase in the cooling effect for the same circulating power. It is with a device that possesses both a high mechanical quality factor and the large coupling seen in this particular measurement that ground state cooling becomes a foreseeable prospect.

5. Future prospects

In future experiments, we believe such large coupling strengths should be reproducibly achievable by implementing several improvements. The relative coupling constant, g/ω_c , depends on the *fractional* change in capacitance for a given mechanical displacement. Thus, the beam's effect on the cavity (and hence the cavity's effect on the beam) may be maximized in two ways. The first method is to increase the mutual capacitance between the mechanical oscillator and the cavity. While this can be accomplished by simply fabricating the suspended beam closer to the adjacent ground plane, this separation is limited, in a practical sense, by intrinsic floppiness of the mechanical oscillator. A more feasible option is to increase the length of the beam while using tension to obtain the desired mechanical resonance frequency. A second method for improving the coupling involves reducing the total capacitance of the electromagnetic resonance. This may be accomplished by increasing either the resonance frequency ($\omega_c \simeq (LC)^{-1/2}$) or the characteristic impedance ($Z_0 \simeq \sqrt{L/C}$) of the cavity. With all of these improvements, it is foreseeable that this total capacitance can be reduced by more than an order of magnitude from our current design [16].

To quantify the cooling potential of dynamical backaction, we consider a possible future device with optimized parameters. Figure 6 shows a theoretical prediction of the cooling that should be possible with several near term improvements. This assumes a 200 μ m long beam with a mechanical frequency of 1 MHz and a mechanical quality factor of 5 × 10⁵ is coupled to a microwave cavity with a resonance frequency of 10 GHz and a cavity quality factor of 4 × 10⁴. Figure 6 shows the theoretical final phonon occupancy as a function of red detuning. Here, a 1 MHz mechanical mode is assumed to be in thermal equilibrium with a dilution refrigerator at 50 mK (~1000 phonons). As the detuning reaches the optimal value, the beam would cool by the dynamical backaction to less than 50 μ K (1 phonon) with a microwave circulating power of 2 μ W in the cavity. This assumes that the coupling strength would be greatly increased to g = 80 kHz nm⁻¹ by making a longer nanomechanical beam (200 μ m) and by increasing the characteristic impedance of the microwave resonator to 300 Ω . While similar results could be achieved with a range of experimental parameters, this example serves to demonstrate the prospects for passive cooling in future experiments with realistic parameters.

In conclusion, we have applied the theoretical analysis of dynamical backaction to our microwave cavities to show that this technique is a feasible option for cooling a mechanical mode to its quantum ground state. These theoretical expectations are framed within the context of currently achievable experimental parameters. Our measurements have demonstrated nanomechanical oscillators with resonance frequencies between 0.1 and 6 MHz, exhibiting high-quality factors at cryogenic temperatures. Furthermore, preliminary experimental results

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Figure 6. Theoretical mechanical oscillator phonon number as a function of red detuning for possible future experimental parameters. This prediction shows the expected cooling that should be achievable given the experimental parameters listed in the text. By strongly coupling a high Q, 1 MHz mechanical resonator to an optimized microwave cavity, dramatic cooling should be possible in the near future. At the optimal detuning ($\Delta = -\omega_m$), the oscillator would cool from more than 1000 phonons to approximately 1.

on a system in the good cavity limit demonstrate radiation damping and cooling effects. Together, these results indicate that the appropriate combination of experimentally demonstrated parameters should allow cooling below dilution refrigerator temperatures, perhaps even to the ground state of the mechanical oscillator.

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