Optical cooling of a micromirror of wavelength size

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The authors report on the passive optical cooling of the Brownian motion of a cantilever suspended micromirror. They show that laser cooling is possible for a mirror of size in the range of the diffraction limit (at $\lambda = 1.3$ μm). This represents the tiniest mirror optically cooled so far, with a mass of 11.3 pg, more than four orders of magnitude lighter than current mirrors used in cavity cooling. The reciprocal effect of cooling is also investigated and opens the way to the optical excitation of megahertz vibrational modes under continuous wave laser illumination. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2711181]

The chase after gravitational waves using optical interferometers detectors has led to the investigation of optomechanical couplings in Fabry-Pérot cavities.[1,2] In such detectors, one of the mirrors at least is mounted on a compliant suspension allowing motion along the cavity axis. The optomechanical coupling arises because on the one hand the photon field building up in the cavity exerts a force on the mirrors that displaces them, and on the other hand the intensity of the field in the cavity depends on the mirror position and velocity. The force mediating the coupling is either due to radiation pressure[3] or to photothermal pressure.[4] In the meantime the study of cavities with flexible mirrors strongly interacting with light has extended to submillimeter sized systems,[4] and it was recently demonstrated that optomechanical couplings can be harnessed to either cool or excite the Brownian fluctuations of an atomic force microscope cantilever that constitutes one of the two mirrors of the cavity.[5] The prospect of optically cooling vibrational fluctuations down to their quantum limit has stimulated recent work.[5–8] The quest for the quantum limit imposes to use the lowest possible mirror masses by minimizing their size. The mirror size, however, cannot be indefinitely reduced. In order to ensure high enough reflectivity, the mirror needs to have an area larger than the diffraction limit of the light mode in the cavity and must be thick enough to reduce cavity losses by transmission. In this letter, we investigate the smallest mirror cooled in such an optical cavity cooling scheme. The mass of our mirror (11.3 pg) is at least four orders of magnitude smaller than in previous works.[5–9]

Each of our paddle micromirrors, shown in Fig. 1(a), consists of a suspended squared silicon mirror ($2.4\ \mu\text{m} \times 2.4\ \mu\text{m} \times 100$ nm) covered with 90 nm of gold and attached to the end of a silicon lever of thickness $t = 100$ nm, width $w = 200$ nm, and length l ranging from 1 to 6 μm. These single sided clamped mechanical resonators are fabricated out of a silicon-on-insulator wafer with 100 nm Si layer and 500 nm SiO_2 sacrificial layer using electron-beam lithography (EBL) and reactive ion and wet etching. The gold mirror is first fabricated using conventional EBL and subsequent gold lift-off. In a second EBL step, the etch mask is defined for reactive ion etching. The sacrificial layer is then removed in hydrofluoric acid, leaving freestanding suspended paddles that are released in air using a critical point dryer.[10]

Given the very small size of the paddles, it was essential to construct a Fabry-Pérot cavity able to use them as efficient mirrors, providing an overall reasonable cavity finesse. We have already established[5] that the cavity cooling efficiency increases with the cavity finesse. The challenge was thus to design a cavity focusing the light modes on the paddle in order to reduce losses. In our optical setup, the gold coated Si paddle constitutes the back mirror of the Fabry-Pérot cavity. The input mirror of the cavity is the flat polished ending of an optical fiber coated with 32 nm of gold. A narrow band ($\leqslant 1$ MHz) single mode ($\lambda = 1.3$ μm) diode laser (Sacher TEC 500) is coupled to the other free end of the fiber. The light emerging from the input mirror is collimated and focused by a microscope down to an optical spot with a $1/e^2$ beam radius of 1.35 μm. An xyz piezopositioning block (Attocube ANP 100) allows placing the mirror paddle at the focal point of the microscope over a range of 5 mm in each direction. The light reflected from the cavity is collected through a 2×2 fiber beam splitter on a GaInAs p-i-n photodiode (Thorlabs PDA400). Recording the reflected light upon the xy position of the mirror paddle allows us to obtain first its confocal image [Fig. 1(b)], and then to positioning it accurately in conjugation with the fiber ending M1. We obtain this way a diffraction-limited confocal Fabry-Pérot cav-

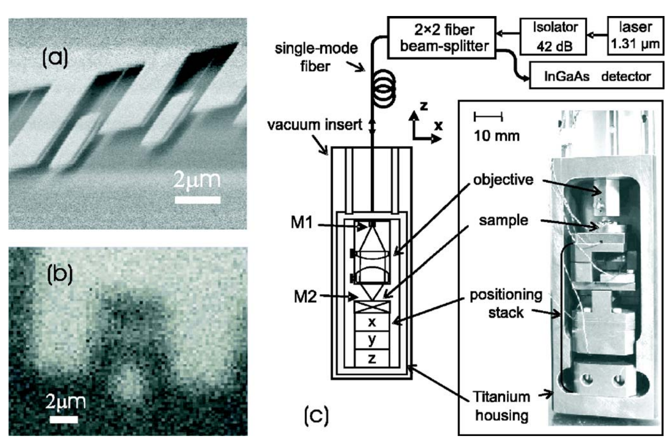

FIG. 1. (a) SEM picture of the paddle micromirrors. (b) Cavity *in situ* optical imaging of one micromirror. (c) Setup.

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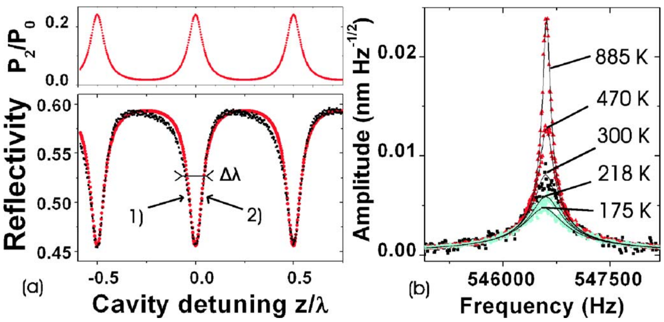

FIG. 2. (a) Bottom: Measured (squares) and modeled (circles) reflectivity of the cavity. Top: Simulated ratio of the light power sent on the cavity which impinges on the mirror paddle M2. (b) Brownian motion amplitude spectra at low laser power P1 (squares labeled 300 K) and at higher laser power for negative detuning 1 (circles labeled 218 and 175 K, respectively, for P2 and *P*3) and positive detuning 2 (triangles labeled, respectively, 470 and 885 K for P2 and P3). The continuous lines are fits using Eq. (2).

ity with an effective mirror separation of 33.6 mm and an adjustable length z. As seen in Fig. 1(c), the whole arrangement is very compact and operation in cryogenic environment will be possible at a later time. In addition to measuring the continuous level of the photodiode signal, we used a spectrum analyzer (Rohde and Schwarz FSP 3 GHz) to record the noise power spectra and a lock-in amplifier (Stanford Research 844RF) to measure the frequency response of the cavity reflectivity to a weak modulation of the input laser intensity.

Figure 2(a) shows Fabry-Pérot resonances in the reflectivity of the cavity, with a corresponding cavity finesse of $(\lambda/2)/(\Delta\lambda)=5.85$.[11] The reflectivity does not vanish at resonance because of the strong absorption in the mirrors. We have measured an absorption of 19% through the input mirror. Using this value, a reflectivity of 0.75 on each mirror and intracavity losses of 4 m^{-1}, we modeled accurately the measured reflectivity and simulated the fraction of the optical power sent onto the cavity falling on the mirror paddle [Fig. 2(a)]. This modeling enabled us to monitor quantitatively the amplitude of the Brownian motion of the mirror paddle through the reflectivity signal. In order to do so and to optimize the signal sensitivity to the paddle displacements, we slightly detuned the cavity to the points of extremal reflectivity slope dR/dz [positions 2 and 1 in Fig. 2(a) corresponding to $z/\lambda=\pm 0.039$]. In this configuration the spectrum of the Brownian motion was directly obtained in the photodiode signal [shown in Fig. 2(b)] and measured at 10^{-5} mbar for three different laser input powers impinging on the cavity (P1=18.5 μW, P2=320 μW, and P3=530 μW). For each power we measured the spectrum at positions 1 and 2 for cavity detuning. For the lowest laser power P1, the Brownian motion spectrum did not depend on the cavity detuning [spectrum labeled 300 K in Fig. 2(b)] and could be analyzed by describing our resonator as a mechanically damped harmonic oscillator consisting of a mass m (the mirror of the resonator in first approximation[12]) held by a spring K (the lever). At low power, the light signal serves just as a readout of the mirror fluctuations. The expression for the mean squared amplitude in a frequency window δf is[5]

$$\langle z_\omega^2\rangle = \frac{4k_BT}{K}\frac{\omega_0^2\Gamma}{(\omega_0^2-\omega^2)^2+(\Gamma\omega)^2}\delta f. \tag{1}$$

A very good fit of the experimental spectrum was obtained using a mechanical resonance frequency $f_0=\omega_0/2\pi=546.6$ kHz, $K=0.134$ N/m, and a mechanical damping $\Gamma=1871$ Hz, corresponding to a mechanical quality factor $Q=2\pi f_0/\sqrt{3}\Gamma=1059$ [Fig. 2(b)]. Four similar mechanical resonators showed resonances in the same frequency range but values of Q ranging from 20 to 1100. The paddle mass could be extracted from f_0 and K, $m=K/(2\pi f_0)^2$, giving $m=11.4\pm 1$ pg, in good agreement with the expected value of 11.3 pg if assuming the densities of 2329 kg/m^3 for silicon and 19 300 kg/m^3 for gold. Using continuous elasticity theory,[12] the effective spring constant of a beam-shaped lever is $K=(E/4)w(t/l)^3$. With a young modulus $E=1.6\times 10^{11}$ Pa for silicon, we determined an effective lever length $l=3.9$ μm.

At higher laser powers P2 and P3, the Brownian motion amplitude spectrum depended strongly on the cavity detuning, revealing an important coupling between the mechanics of the micromirror and the optics of the cavity [Fig. 2(b)]. At position 1, the spectrum broadened when increasing the laser power (circles), whereas it narrowed substantially at position 2 (triangles). This striking phenomenon was first reported in Ref. 5 and originates from a cavity-induced modification of the mechanical properties of the resonator at high laser power: the supended mirror paddle has an optically modified mechanical damping Γ_{eff}, a modified resonance $f_{\text{eff}}=\omega_{\text{eff}}/2\pi$, but an unmodified spectrum of thermal random driving forces. Its Brownian motion spectrum becomes[5]

$$\langle z_\omega^2\rangle = \frac{4k_BT}{K}\frac{\omega_0^2\Gamma}{(\omega_{\text{eff}}^2-\omega^2)^2+(\Gamma_{\text{eff}}\omega)^2}\delta f, \tag{2}$$

which corresponds to Brownian fluctuations at an effective temperature $T_{\text{eff}}=T(\Gamma/\Gamma_{\text{eff}})$. Using the above equation to fit our experimental results [Fig. 2(b)], we concluded that we could cool the mechanical motion of our micromirror down to an effective temperature of 175 K. In contrast, at position 2, the spectrum narrowing revealed a heating of the motion to 885 K. This demonstrates the feasibility of optical cooling and heating of the motion of such a small mechanical resonator, with an eigenfrequency in the megahertz range.

Passive cavity cooling of a mirror,[5] in contrast to active cooling,[9] relies on the existence of a delay in the optomechanical coupling between the mirror motion and the cavity field. In order to understand the optomechanical coupling taking place here and to measure the corresponding delay time, we performed a measurement of the frequency response function of the paddle microresonator. Working at position 2 and average laser power P3=530 μW, we modulated the laser intensity by an amount $\beta=3\%$ around the continuous wave intensity I_0 in order to modulate the photoinduced forces in the cavity around an average dc force F. We then performed a lock-in analysis of the in-phase ($\Re$) and out-of-phase ($\Im$) components of the light intensity reflected by the cavity. The real part $\Re$ of the demodulated signal consists of two parts. The first part $\Re 1$ reveals the effect of the laser-induced forces on the position of paddle. The second part $\Re 2$ is always present, even in a rigid cavity, and corresponds to the laser intensity modulation itself. In our experiment, the imaginary part did not have a component directly related to the laser intensity modulation because the delay caused by the cavity storage time (about 10^{-10} s) was much shorter than the period of the modulation. The imaginary part $\Im$ of the signal was dominated by the retarded effect of the photoinduced forces acting on the mirror paddle.

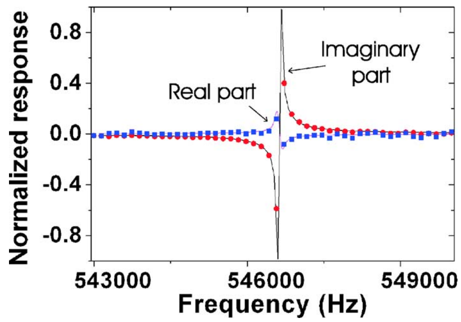

FIG. 3. Measured real and imaginary parts (squares and circles) of the normalized response function of the light intensity reflected on the cavity. The continuous lines are fits using Eq. (3) and the expression for Λ_ω.

Figure 3 shows the signals $\Re 1$ and $\Im$ normalized to $\Re 2$ as a function of the laser modulation frequency. Both show an asymmetric resonance at 546.64 kHz, revealing a mixing of the mechanical response of the mirror paddle with the dynamics of the photoinduced forces, as we now explain.

We consider a photoinduced force acting on the mirror paddle $F=\alpha P$, proportional to the light power P impinging on it and delayed with respect to the mirror motion. In the case of photon pressure, the delay is given by the photon lifetime in the cavity, in the case of photothermal pressure, by the thermal response time of the mirror paddle. We assume an exponential delay function of the form $1-e^{(-t/\tau)}$, where τ is the delay time. As mentioned earlier, the microresonator coupled to the optical cavity behaves as an effective harmonic oscillator. In this modulation experiment, it is driven by the sum of a photoinduced force F and a small modulated force $\Delta F=\beta F e^{i\omega t}$. The solution of the harmonic oscillator equation under these driving forces is in the frequency domain,[5]

$$z_\omega = \frac{(\beta\alpha P)}{K}\frac{1}{1+i\omega\tau}\frac{\omega_0^2}{\omega_{\text{eff}}^2-\omega^2+i\Gamma_{\text{eff}}\omega}. \qquad (3)$$

At position 2, the gradient of reflectivity upon mirror coordinate z takes its maximal value $(dR/dz)_2=1.41\times10^6\ \text{m}^{-1}$, $R_2=0.519$ being the reflectivity at position 2. The complex frequency component of the reflected light intensity Λ under modulated laser illumination at ω is

$$\Lambda_\omega = \beta I_0 R_2 + I_0(\nabla R)_2 z_\omega = \Re 2 + (\Re 1 + \Im). \qquad (4)$$

Since the ratio $(\Re 1+\Im)/\Re 2$ does not depend on β, we used it to fit the normalized response function of Fig. 3 and obtained an excellent agreement when using $f_0=564.6$ kHz, $f_{\text{eff}}=564.634$ kHz, and $K=0.134$ N/m extracted from our above analysis of the Brownian motion, together with a force delay time $\tau=1.26\ \mu$s, a force coefficient $\alpha=4.2510^{-6}$ N/W, and $\Gamma_{\text{eff}}=20$ Hz. The Γ_{eff} value, obtained here under a dynamical measurement, is substantially smaller than the one measured previously under continuous laser illumination. At high laser power indeed, the photoinduced pressure pushes the mirror paddle, so modulating the laser intensity at a frequency f ends up modulating the cavity detuning around position 1 or 2 at the same frequency. Since position 1 or 2 allows maximal optomechanical coupling, the optically modified mechanical properties of the mirror padlle are themselves modulated at the frequency $2f$. Such a condition is favorable for parametric amplification in the modulated experiment[13] and is presumably responsible for the observed additional line narrowing. In the case of radiation pressure acting on mirror paddle, the force coefficient α would be given by $(2R)/c$, resulting in our cavity ($R=0.75$) to a value of 870 times smaller than the one observed here. The time constant would be given by the storage time of photons in the cavity, about 10^{-10} s, whereas the τ value of 1.26 μs closely corresponds to the numerically simulated time of $\tau=2\ \mu$s heat takes to diffuse from the mirror paddle to the substrate. This shows that photothermal pressure rather than radiation pressure dominates the optomechanical behavior of the micromirror, most likely because of the presence of the 90 nm absorbing gold layer on the Si paddle forming a bilayer with different thermal coefficients.

In conclusion, we demonstrated the optical cooling and heating of a micromirror of size in the diffraction limit range, embedded in a Fabry-Pérot resonator. This provides an example of optical cooling of a very small mass mechanical resonator (11.3 pg). Small mass mechanical resonators are more sensitive to optomechanical effects and are thus promising candidates to reach very low temperatures by means of optical cooling. The converse effect of cooling reveals a convenient way to excite optically the vibrational and torsional motions of such a tiny resonator with megahertz eigenfrequency:[14–16] by positioning it in a strongly focused beam, we form an optical cavity which allows, under continuous laser illumination, us to enhance effectively the mechanical fluctuations of the resonator. A further increase of the cavity finesse would lead to its mechanical self-oscillation.

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