

# Stable, mode-matched, medium-finesse optical cavity incorporating a microcantilever mirror: Optical characterization and laser cooling

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A stable optical resonator has been built using a 30- $\mu\text{m}$ -wide, metal-coated microcantilever as one mirror. The second mirror was a 12.7-mm-diameter concave dielectric mirror. By positioning the two mirrors 75 mm apart in a near-hemispherical configuration, a Fabry-Pérot cavity with a finesse equal to 55 was achieved. The finesse was limited by the optical loss in the cantilever's metal coating; diffraction losses from the small mirror were negligible. The cavity achieved passive laser cooling of the cantilever's Brownian motion. © 2007 American Institute of Physics.

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## I. INTRODUCTION

The coupling of micromechanical structures to light via radiation pressure has been a topic of considerable interest in recent years. Much of this interest has been driven by the goal of observing and exploiting quantum aspects of either the radiation pressure or the micromechanical structures themselves. Outstanding goals in this area include laser cooling micromechanical systems,<sup>1,2</sup> quantum-limited displacement measurements,<sup>3,4</sup> generating squeezed<sup>5</sup> and entangled<sup>6</sup> light, and studying macroscopic quantum phenomena.<sup>7</sup> Each of these goals requires a high-finesse optical cavity in which one of the cavity mirrors is mounted on a micromechanical structure such as a cantilever. This is a challenge because the cavity's finesse may be limited by diffraction losses from a mirror small enough (approximately tens of micrometers) to be mounted on a cantilever.

In previous work this issue was partially addressed by forming a cavity between the surface of a cantilever and the cleaved end of an optical fiber.<sup>2</sup> Since such a cavity is formed by two parallel-plane surfaces it is not a stable resonator and hence cannot achieve high finesse. This instability can be partially compensated for by bringing the two mirrors very close, and in Ref. 2 a finesse  $\mathcal{F}=3.3$  was achieved for a cavity of length  $L=34\ \mu\text{m}$ . However, cavities with substantially higher  $\mathcal{F}$  will most likely require mirrors which form a stable optical resonator.

Stable optical resonators are also appealing because they allow for longer cavities. Since the figure of merit for the particular application of radiation pressure cooling is proportional to  $L\mathcal{F}$ ,<sup>3</sup> increasing  $L$  will lead to improved laser cooling.

Here we describe the construction and characterization of a stable Fabry-Perot optical cavity in which one mirror is formed by a micromechanical cantilever. By carefully positioning the cantilever mirror near the center of curvature of a concave mirror, we create a stable cavity with  $L=75\ \text{mm}$  and  $\mathcal{F}=55$ . This value of  $\mathcal{F}$  is consistent with the reflectivities of the mirror coatings and is not limited by diffraction losses from the cantilever mirror. The nonadiabatic response of the

cantilever to the light in this cavity leads to passive laser cooling of the cantilever's Brownian motion. This allows us to lower the cantilever's noise temperature by roughly a factor of 5.

## II. APPARATUS

The cavity is shown schematically in Fig. 1. It is formed by a microcantilever and a concave dielectric mirror. The cantilever is a commercial atomic force microscopy (AFM) cantilever (Olympus AC240TM), 240  $\mu\text{m}$  long, 30  $\mu\text{m}$  wide, and 2.7  $\mu\text{m}$  thick. It is made of Si, and the surface facing the input coupler is coated with Al while the opposite surface is coated with Pt. It has a measured resonance frequency in its lowest flexural mode of  $\nu_0=67\ 110\ \text{Hz}$  and is specified to have a spring constant  $k=2\ \text{N/m}$ . We measured the reflectivity of the cantilever at  $\lambda=532\ \text{nm}$  to be  $R_2=0.83\pm 0.05$ .

The dielectric mirror (which serves as the cavity input coupler) is a 12.7-mm-diameter concave mirror (CVI PR1-532-99-0537-0.075cc). Its radius of curvature is specified to be  $r=75\ \text{mm}$ . We measured its reflectivity at  $\lambda=532\ \text{nm}$  to be  $R_1=0.995$ . Thus the cavity is undercoupled.

The input coupler is mounted in a tilt stage (ThorLabs KM05) and affixed to one end of an Invar spacer. The cantilever is mounted on a second tilt stage which in turn is mounted on a piezoelectric stick-slip  $x$ - $y$ - $z$  translation stage (AttoCube ANP100 series). This translation stage provides several millimeters of travel and submicrometer positioning accuracy in all three axes. The translation stage is mounted to the end of the Invar spacer opposite the input coupler. The spacer is mounted inside a 150-mm-diameter vacuum chamber which provides optical access to both ends of the cavity via antireflection-coated windows. Data were taken with the chamber at a pressure of  $\sim 1\ \text{Torr}$ .

The cavity is illuminated by  $\lambda=532\ \text{nm}$  light from a highly stable, doubled cw Nd:YAG (yttrium aluminum garnet) laser (Innolight Prometheus). The collimated laser beam is expanded to a  $1/e^2$  diameter of  $\omega_{\text{in}}=13.5\ \text{mm}$  and mode

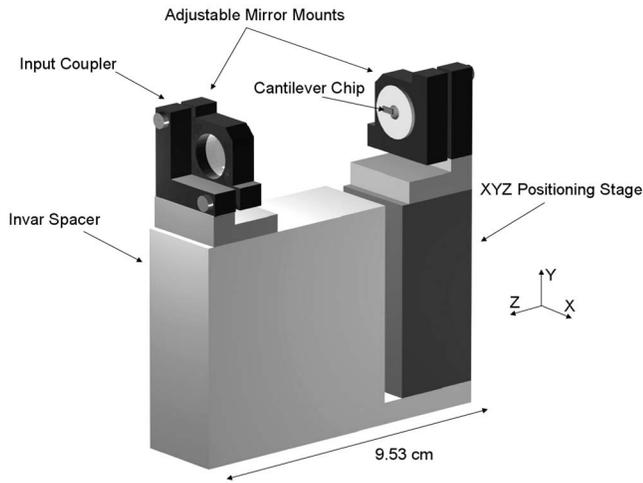


FIG. 1. Scale drawing of the cavity. The cantilever chip is visible at the right-hand side of the drawing; the cantilever itself is not visible at this scale. Also shown is the orientation of the coordinate system used in the text. The coordinate system's origin is at the center of curvature of the input coupler. The force of gravity points along the negative  $y$  direction.

matched to the cavity by a 50 mm diameter, 175 mm focal length lens positioned in front of the vacuum chamber.

Throughout this article we use a coordinate system  $\{x, y, z\}$  whose origin  $\{0, 0, 0\}$  is defined to be the center of curvature of the input coupler. The orientation of the  $x$ ,  $y$ , and  $z$  axes is shown in Fig. 1. Since the cantilever mirror is approximately planar, all the cavity modes have waists at the cantilever. In order to minimize the diameter of the cavity mode waists, we position the cantilever very close to  $\{0, 0, 0\}$  (i.e., near-hemispherical geometry). Thus the cavity length  $L=r=75$  mm. This is achieved by first aligning the mode-

matching lens so that the beam waist is roughly at  $\{0, 0, 0\}$ . Using the piezotranslation stage, the cantilever is adjusted in the  $x$ - $y$  plane until it partially obscures the beam (as monitored via light transmitted through the cavity). Then the  $z$  position of the cantilever is adjusted until it approaches  $\{0, 0, 0\}$ . We determine the optimal alignment by scanning the cantilever position through a few cavity resonances (using the  $z$  piezo of the AttoCube) and extracting the finesse from the reflected signal.

### III. OPTICAL PROPERTIES

Figures 2(a)–2(c) show the reflected signal  $P_r$  as a function of the displacement  $\delta z$  when the cantilever is in different positions along the  $z$  axis. At positive displacements along  $z$  (i.e., toward the input coupler from  $\{0, 0, 0\}$ ), the cavity satisfies  $0 < (1 - L/r) < 1$  and so is nominally stable<sup>8</sup> (although the diffraction losses may still be large). This is illustrated by the data in Fig. 2(a). As the cantilever is moved closer to  $\{0, 0, 0\}$  the finesse increases and the transverse mode spacing decreases. The increasing finesse presumably results from the fact that the diffraction losses decrease as the spot size at the cantilever decreases. The decrease of the transverse mode spacing is expected for a cavity as the mirror positions approach a hemispherical geometry, and when the hemispherical geometry is reached, the transverse modes should become degenerate.<sup>9</sup> Figure 2(b) shows the reflected signal when the transverse modes are approximately degenerate. We interpret this as a sign that the cantilever is very close to  $\{0, 0, 0\}$ , and hence that the cavity is roughly hemispherical.

When the cantilever is translated beyond  $\{0, 0, 0\}$  (i.e., to

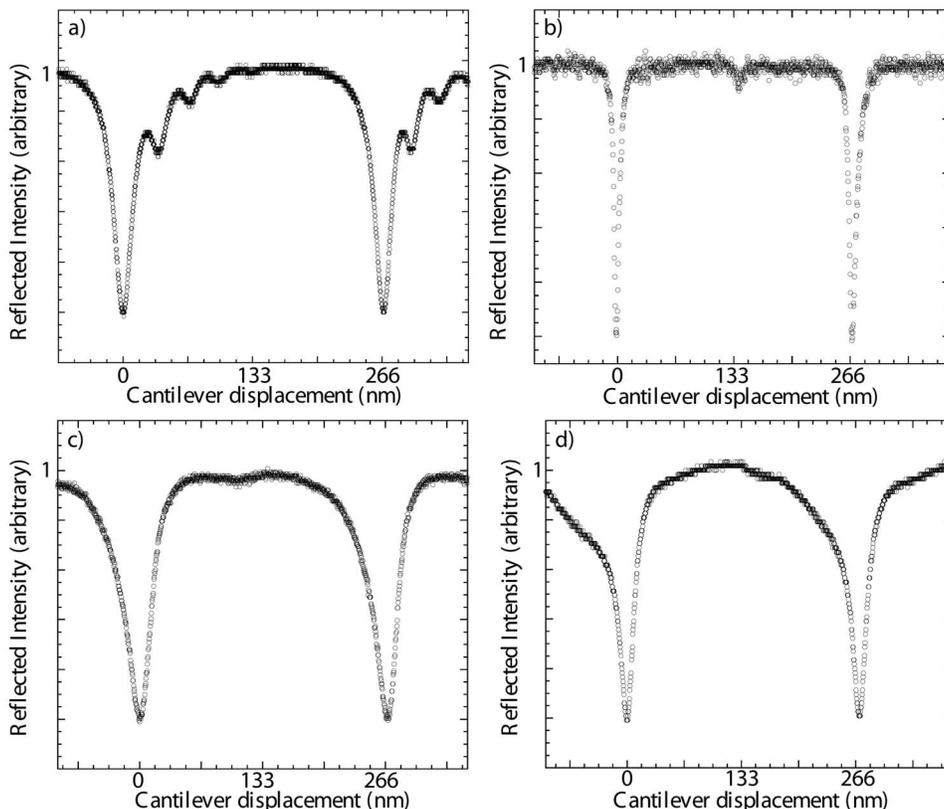


FIG. 2. Reflected intensity as a function of cantilever displacement for four different cavity geometries. In (a) the cantilever is positioned at approximately  $\{0, 0, 400 \mu\text{m}\}$ , i.e., 400  $\mu\text{m}$  towards the input coupler from the input coupler's center of curvature (the coordinate system is given Fig. 1). The cavity is nominally stable, but diffraction losses appear to limit the finesse. Multiple transverse modes are visible within each free spectral range. In (b) the cantilever is approximately at  $\{0, 0, 0\}$ , i.e., the hemispherical configuration. Here the finesse is at its maximum and the transverse modes visible in (a) have become degenerate. In (c) the cantilever is at  $\{0, 0, -500 \mu\text{m}\}$ . This renders the cavity unstable and leads to a low finesse. In (d) the cantilever is approximately at  $\{0, 35 \mu\text{m}, 0\}$ . Here the input beam only partially overlaps with the cantilever.

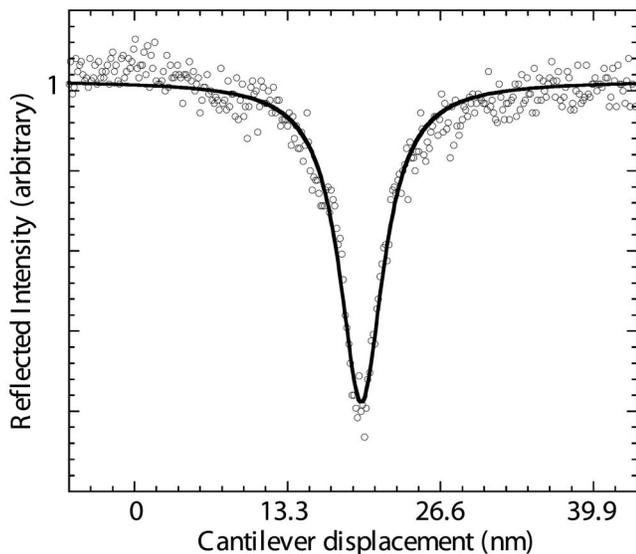


FIG. 3. A more detailed scan of the cavity reflection peak. Here the cantilever is positioned at approximately  $\{0,0,0\}$ , i.e., in the hemispherical geometry. The solid line is a fit to the formula given in the text and corresponds to a finesse  $\mathcal{F}=55$ .

negative  $z$ ), the finesse drops rapidly [Fig. 2(c)]. This is because  $0 < (1 - L/r) < 1$  is no longer satisfied and the cavity is not stable.

When the cantilever is positioned at the optimum  $z$  but displaced in the  $x$ - $y$  plane the finesse also drops. Figure 2(d) shows  $P_r(z)$  for the cantilever displaced by approximately  $35 \mu\text{m}$  along its narrowest dimension (i.e., to  $\{0, 35 \mu\text{m}, 0\}$ ). Although this displacement implies that a large fraction of the input laser beam does not intersect the cantilever, the finesse still remains relatively high ( $\sim 10$ ), due to the fact that the transverse shape of the cavity modes adjust to minimize diffraction losses.<sup>9</sup>

Figure 3 shows a finer scan of the cantilever position around  $\{0,0,0\}$ . Fitting the data to the expression<sup>8</sup>

$$P_r(z) = 1 - \varepsilon \left( 1 + \left\{ \frac{2\mathcal{F}}{\pi} \sin \left[ \frac{2\pi(L + \delta z)}{\lambda} \right] \right\}^2 \right)^{-1},$$

where  $\mathcal{F}$  and  $\varepsilon$  are fitting parameters giving a value for the finesse of  $\mathcal{F}=55$ . This is roughly consistent with  $\pi(R_1 R_2)^{1/4} / (1 - (R_1 R_2)^{1/2})$ , the value expected in the absence of diffraction losses.

#### IV. LASER COOLING

Although many of the long-term goals for these devices involve quantum effects, micromechanical optical cavities like the ones described here can also exhibit interesting classical effects. One example is cooling of the cantilever's Brownian motion. Cooling of the Brownian motion is achieved when the optical force acting on the cantilever has a phase lag relative to the cantilever motion. A negative phase lag increases the cantilever's damping without necessarily adding fluctuations. As discussed extensively elsewhere,<sup>2,10</sup> this corresponds to a change in the effective temperature of the cantilever.

Figure 4 shows the power spectral density of the cantilever's undriven Brownian motion. These data are acquired

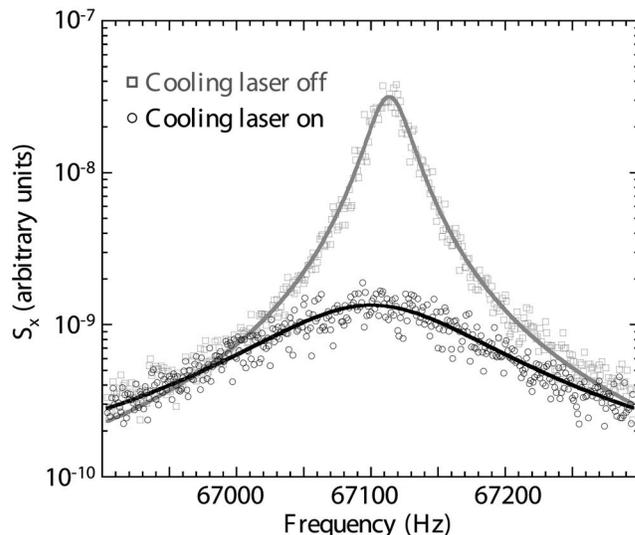


FIG. 4. Laser cooling of the cantilever. The power spectral density of the cantilever displacement,  $S_x$ , is plotted with the 532 nm cooling laser off (squares) and on (circles). The solid lines are fits to the expected form for a damped harmonic oscillator. With the cooling laser off, the fit gives  $Q = 1925$ . With the cooling laser on,  $Q_{\text{loaded}} = 370$ .

using an incident power  $P_{\text{in}} = 0.18 \text{ mW}$  of 633 nm light from a HeNe laser. The dielectric mirror's reflectivity at 633 nm is only 0.27, so the 633 nm light sees a low-finesse (and over-coupled) cavity. Since the optical damping of a cantilever scales strongly with  $\mathcal{F}$ , the lower  $\mathcal{F}$  for the 633 nm laser helps to ensure that it does not perturb the cantilever motion.

The data indicated by square points were taken with the 532 nm laser shuttered. Fitting these data to the expected form for a damped harmonic oscillator gives a value of the cantilever's intrinsic quality factor  $Q_0 = 1925$ .

The data indicated by circular points were taken with 4.53 mW of 532 nm light incident on the cavity and slightly red detuned from the cavity resonance. Fitting these data gives  $Q_{\text{loaded}} = 370$ . This implies a reduction of the cantilever's effective temperature by the same factor, i.e.,  $1925/370 \sim 5.2$  or from 300 to  $\sim 60 \text{ K}$ . The cooling can also be estimated from integrating the curves in Fig. 4 which are proportional to  $\langle x^2 \rangle$ , the mean-squared amplitude of the cantilever's Brownian motion. When the 532 nm laser is on,  $\langle x^2 \rangle$  is decreased by a factor of 6.2, roughly consistent with the ratio of  $Q_0/Q_{\text{loaded}}$ .

The optical forces acting on the cantilever are expected to arise from two sources: radiation pressure and photothermal forces. Either of these forces can lead to cooling of the cantilever if it lags behind the cantilever motion. In the case of radiation pressure, the lag is due to the ringdown time of the optical cavity  $\tau_{\text{opt}} = L\mathcal{F}/\pi c$ , which for our setup is 4.4 ns. The cooling resulting from this lag can be calculated *a priori*<sup>2</sup> to be  $\sim 2.5\%$ , i.e., cooling from 300 to 293 K. Although a small effect, this is substantially greater than the expected radiation pressure cooling in the setup described in Ref. 2, where the relevant figure of merit  $L\mathcal{F}$ <sup>3</sup> is roughly six orders of magnitude smaller than for the setup described here.

The actual cooling observed in Fig. 4 is much greater than the predicted radiation pressure cooling. We believe that

this additional cooling is due to the photothermal force. This force is caused by the inhomogeneous thermal expansion of the cantilever upon absorbing light from the cavity field. The phase lag associated with this force arises from the thermal time constant of the cantilever, which was measured to be  $\sim 1$  ms in a similar cantilever.<sup>2</sup> The cooling due to this effect is difficult to predict *a priori*, as it depends on the thermal expansion coefficients, thermal conductivities, and specific heats of the evaporated metal films and the cantilever itself. However, the cooling arising from this photothermal force seems to be of the same order of magnitude as in Ref. 2, once the different cantilever  $\nu_0$  and mirror reflectivities are taken into account.

## V. DISCUSSION

We have constructed an optical cavity which incorporates a micromechanical cantilever as one mirror. The cavity demonstrated here is a stable optical resonator and achieves a finesse 20 times higher in a cavity  $2 \times 10^3$  times longer than in previous microcantilever cavities. In addition, the optical stability of the cavity implies that the finesse can be further improved with better mirror coatings. Both the increased finesse and cavity length will be important for studying quantum optical effects in optomechanical cavities.

*Note added in Proof.* After the submission of this article a number of other groups also described stable optical cavities incorporating micromechanical cantilevers and exhibiting laser cooling (see Ref. 11).

## ACKNOWLEDGMENTS

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