Enhancing thermally induced effects on atomic force microscope cantilevers using optical microcavities

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Bimetallic cantilevers have recently been applied to chemical and biological sensing, leading to significant progress in increasing power resolution; in particular, picowatt resolution has been achieved.\(^1\)–\(^3\) In these cantilevers, difference in thermal expansion of thin films constituting the beam changes the deflection and frequency. A change of mass on the order of picograms can also be detected by micromechanical resonators coated with a chemoselective polymer\(^4\) or by a V-shaped cantilever.\(^5\) Difference in thermal expansion of layers also gives rise to a stress at the contact surface between layers; for large expansion (large bending), this can destroy the cantilever beam\(^6\) once the strain force exceeds the binding force between layers. Furthermore, increasing cantilever sensitivity is challenging because cantilever bending is dependent on the material of metallic films; hence, methods for controlling the deflection and enhancing cantilever sensitivity are of interest.

Recently, Hiroshima et al.\(^7\) used a Ti-coated multiwall nanocarbon nanotube cantilever and enhanced the photo-thermal vibration amplitude by 10–50 times. In another study where a metallic cantilever was used to enhance photothermal effects, Stievater et al.\(^8\) has examined the concentration of toluene vapor by detecting the change in added mass to the cantilever. By monitoring the cantilever frequency shift \(\delta f\), a sensitivity of \(1.5 \times 10^{-11}\) kg (1.5 pg) has been achieved (\(\delta f \simeq 120\) Hz for a resonance frequency of \(304\) kHz). For finer mass resolution, higher frequency resolution is required. In this study, a theoretical model of an optical microcavity (OMC) for enhancing the response of a cantilever (deflection and frequency shift) with respect to the input power is proposed. The response is affected directly by the intensity of the stored power and cantilever mechanical properties, e.g., the effective mass when chemical molecules are attached, or the heat convection when the cantilever surface is modified. Therefore, by examining the behavior of the cantilever as a function of optical power, we can extract information of the ambience, such as the density or adhesion of molecules. We will show that \(\delta f\) can be enhanced an order of magnitude from \(10\) to \(200–300\) Hz for \(\sim 200\)-\(\mu m\)-long cantilevers. This enhancement allows for detecting of mass with higher resolution and facilitates the fabricating process. Furthermore, having a deflection controlled simultaneously by thermally induced and radiation-pressure-induced forces can help tune amplitude setpoints in amplitude modulation mode atomic force microscope (AFM) besides using feedback from the \(z\)-piezo extension\(^8\) to achieve piconewton precision for the applied force on the sample.

An OMC is a system of several metallic thin films arranged in parallel to enhance the optical field stored between the films. OMCs have been used widely to study laser cooling of optomechanical systems, such as mirrors\(^9\)–\(^11\) or membranes\(^12\) put inside OMCs. The first mirror is a metallic thin film coated at the end of a fixed optical fiber and the second mirror is the silicon cantilever of an AFM coated by another metallic thin film, as shown in Fig. 1. We will show that the response of this OMC-based cantilever is increased several times compared with that of a directly irradiated cantilever (without OMC). This effect results from the enhancement of the optical field trapped inside the OMC and of the absorbed power on the metallic film (of thickness \(t_c\)). For cavity length \(L_c \approx n\lambda/2\), where \(\lambda\) is the wavelength of the input laser and \(n\) is an integer, the enhancement ratios for the absorbed power \(P_h\) and cavity-induced radiation force (CIRF) can reach \(\sim 7\) and \(\sim 10\), respectively,\(^13\) which can strongly alter the cantilever dynamics via the appearance of optical rigidity. This rigidity arises from a nonlinear change in the CIRF caused by cantilever deflection and can be used to cancel the thermally induced frequency shift caused by bending.\(^14\)

Using a specific property of the OMC, i.e., the stored power follows a Lorentzian dependence on the position of the...
movable mirror making the cantilever and is enhanced orders of magnitude, we show that the cantilever has a higher absorption than that under direct irradiation. This absorption is maximum when the mirror is at the resonance position $z_p$ [see Eq. (2)] and decreases with increasing mirror displacement. Furthermore, the decrease in the absorbed power with increasing $z$ ensures the stability of the cantilever with respect to the input power.

Analytically, a system of the Maxwell equations for the electromagnetic field $E(z)$ inside parallel layers of fiber-end coating, vacuum, and cantilever are derived. The average field intensity ($\beta \sim |E|^2$, where $E$ is the field amplitude inside the metallic film) when the OMC is used is shown in Fig. 2(a) (black squares) to compare with that under direct irradiation (without OMC, red circles). The quality factor for the noc.it deiscsion of round trips the light (photon) travels before escaping the OMC, which represents the possibility of trapping and enhancement, as deduced from the Maxwell stress tensor $\mathbf{T}$, i.e.,

$$F(z) = \left( \int_S \mathbf{T}(\mathbf{r}, t) \cdot \mathbf{n}(\mathbf{r}) \, dS \right).$$  

where the thickness-dependent parameter $\beta$ represents the enhancement ratio of the absorbed power to the input power $P_i$ and $P_\beta$ is the full width at half maximum (FWHM) of $P(z)$. Figure 2(b) shows $P(z)$ for the two cases stated above. An absorption power up to $\sim 38\%$ (or $\beta \sim 0.38$) corresponding to an enhancement ratio up to 7 for $t_1 > 100$ nm is obtained [see Fig. 2(c), triangles, left axis].

The FWHM values of $P(z)$ for various $t_1$ are shown in Fig. 2(c) (blue stars, right axis). For a very thin film, the confinement of the optical field is weak, leading to a slow change in the stored and absorbed powers; therefore, the FWHM values are large, i.e., $\gamma_P \sim 20$ nm for $t_1 < 30$ nm. Moreover, $\gamma_P$ decreases with increasing $t_1$ and for $t_1 \gg t_c$, the asymptotic value $\gamma_P \approx 8.75$ nm is seen.

We assume that the size of the laser beam waist is small enough so that it creates a heat point at the cantilever end. The temperature distribution has the form $T(x) = T_0 + P_m \sinh(mx)/[2hu_0 \cosh(mL)]$, where $T_0$ is the reference temperature at $P = 0$, $m^2 = 2/h(\lambda_1 t_1 + \lambda_2 t_2)$, $h$ is the convection heat transfer coefficient, $w$ is the cantilever width, and $\lambda_1(2)$ and $t_1(2)$ are the thermal conductivity and thickness of the metallic (Si) layer, respectively. The cantilever deflection $z$ under directly irradiated (without OMC) can be known from $15,17$ $d^2z/dx^2 = N[T(x) - T_0]$, and the result is $z(L) = NP[\sinh(mL)/m - L]/[2hu_0 \cosh(mL)]$, where $N = 6(\gamma_2 - \gamma_1)(r + 1)/(t_2K)$. $\gamma_1(2)$ is the thermal expansion coefficient of the metallic (Si) layer, $r = t_1/t_2$ has been used for brevity, $K = 4 + 6r + 4r^2 + (E_1/E_2)^3 + (E_2/E_1)/r$, and $E_1(2)$ is the Young’s modulus of the metallic (Si) layer. The nonlinearity of $P(z)$ [see Eq. (2)] makes the equation for $d^2z/dx^2$ a second-order autonomous differential equation and hence an analytic solution of $z(L)$ cannot be obtained. Here, numerical calculations have been done to produce results of $z(x)$.

In Fig. 3, a clear increase of $z(L)$ for various thicknesses is seen, e.g., for $P_i = 10\mu W$ and $t_1 = 140$ nm $z(L)$ increases from 3.1 nm under direct irradiation (red circles) to $\sim 18$ nm when the OMC is used (black squares).

Heating cantilever implies a higher thermal noise in vibration, as deduced from the fluctuation–dissipation theorem, $(1/2)K'(\delta z^2) = (1/2)k_B T$, where $K$ is the mechanical rigidity. The vibration amplitude is $A_0 = \sqrt{2(\delta z^2)}_{300K} \approx 0.67$ nm. However, an increase of 1 K in the temperature does not enhance this noise much at normal experimental conditions. Only at very low temperatures does the heating have an effect on $A_0$, e.g., at $T_0 = 4\, K$, $A_0 \approx 0.077$ nm and the thermal noise enhances $A_0$ by $\sim 11\%$ to $\approx 0.086$ nm. The CIRF can be calculated by substituting the solutions for the Maxwell equations with appropriate boundary conditions into the Maxwell stress tensor $\mathbf{T}$, i.e.,

$$F(z) = \left( \int_S \mathbf{T}(\mathbf{r}, t) \cdot \mathbf{n}(\mathbf{r}) \, dS \right).$$
where \( \langle \cdots \rangle \) is the time-averaged CIRF and \( \mathbf{n}(r) \) is the normal vector on \( S \), the closed surface surrounding the cantilever. It was shown that \( F(z) \) peaks every \( \lambda/2 \) for increasing \( L_c \) and at each peak it follows a Lorentzian form \( F(z) = \alpha(P_i/c)\gamma L_c/[c(z - z_0)^2 + \gamma^2] \), where \( \alpha \) is the enhancement factor, \( z_0 \) is the resonance position, i.e., the position where \( F(z) \) is maximized, and \( \gamma \) is the FWHM of \( F(z) \), i.e., \( \gamma = \gamma_p \). In fact, a nonlinear \( F(z) \) has been measured in a recent experiment.\(^{18}\) The displacement can be obtained from \( F(\delta z) = K \delta z \), where \( K \) is the mechanical rigidity,

\[
\Delta z = \frac{1}{6} \left\{ \frac{2^{4/3}(z_0 - 3\gamma P_i)}{\sqrt{z_0^2 - 4(z_0^2 - 3\gamma P_i) + z_0}} \right\}^{1/3} - \frac{2^{2/3}[(z_0^2 - 4(z_0^2 - 3\gamma P_i) + z_0)^{1/3}]}{} ,
\]

and \( z_0 = -2\gamma\alpha(P_i/c)\gamma L_c/K + 2z_0^3 + 18z_0\gamma^2 \). In Fig. 4, the CIRF and the corresponding \( \delta z \) are shown. For the same input power used in the previous measurement (~10\,\mu W), \( \delta z \) is too small compared with the deflection caused by heating. Therefore, we can use solely thermal bending in the calculation of deflection with high accuracy in this range of input power.

The modified resonance frequency is known from the deflection \( z(L) \). For small bending, we have\(^{19}\) \( \omega_R = \sqrt{\omega_0^2 + D_R^2} \), where \( \omega_0 = \sqrt{K/m_0} \) is the original resonance frequency, \( D_R^2 = E/[(1 - \nu^2)\rho R^2] \), \( \nu = (\nu_1 + \nu_2)/\nu_1 + \nu_2 \) is the effective Poisson ratio, \( \rho = (m_1 + m_3)/[Lw(t_1 + t_2)] \) is the mass density of the beam, \( R \) is the average cantilever radius \( [R \approx L^2/(2c) \text{ for } z/L << 1] \), and \( K \) and \( m_0 \) are the effective rigidity and mass, respectively. Here, the effective Young’s modulus\(^{20}\) \( E \) has been used. Changes in Young’s moduli\(^{21}\) with respect to the temperature are negligible for a small temperature gradient of the cantilever of ~1 K/200\,\mu m. The change in the frequency with respect to the input power \( S = \delta(\delta \omega) / \delta P_i \) as a measure of the efficiency for this measurement model can be obtained by evaluating the change in \( \omega_R \) as

\[
S = \frac{\partial(\delta \omega)}{\partial P_i} \approx \frac{D_R^2/2\omega_0^2}{L^2(1 - \nu^2)\rho_0^2 P_i} \frac{z^2}{} .
\]

Figure 5 shows the enhancement of the frequency shift caused by bending for three values of \( t_1 \). For example, for \( P_i = 10\,\mu W \) the frequency shift is increased from ~10 to ~300\,Hz.

We have compared the thermally induced shift with that of the directly irradiated cantilever \( S_0 \) and figured out the enhancement ratio \( S/S_0 \) for the two cases. It is seen that \( S \) can be enhanced at least an order in magnitude once the OMC is used, as shown in Fig. 6. Particularly, as \( t_1 \) increases \( S/S_0 \) approaches an asymptotic value of ~36 for a predetermined fiber-end coating of 5\,nm in thickness. The role of \( t_c \) should be further studied to reveal this enhancement factor. In fact, we use the experimental value from recent works\(^{10,11}\) as an example; a more detailed study of \( t_c \) will be examined later.

In summary, we showed that using an OMC, the response of an AFM cantilever with respect to the input power can be enhanced up to an order of magnitude from ~10 for 40-nm-thick coating to ~36 for thicker coating. The absorbed power in this bimetallic cantilever has been significantly increased because of confinement of the optical field. This leads to an increase in cantilever deflection compared with the case of direct irradiation by a laser beam in normal measurements. Furthermore, the Lorentzian dependence of the absorbed power on the deflection ensures the stability of the cantilever with respect to overheating. This model helps fabricate a
detecting system of low input power and high sensitivity by indirectly boosting the frequency resolution. The cantilever is 233 µm in length and 23 µm in thickness similar to the one used in Ref. 10. The mechanical properties of the thin films are calculated based on Ref. 24. The parameter values are shown in Table I; the other parameters are $h = 1670$ W m$^{-2}$ K$^{-1}$, taken from Ref. 6, $\omega_0 \approx 54.62$ kHz, and $z_p \approx 21$.

**Table I.** Parameters used in the simulation.

<table>
<thead>
<tr>
<th></th>
<th>Au</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus$^{10}$ $E$ (GPa)</td>
<td>61.3</td>
<td>190.0</td>
</tr>
<tr>
<td>Thermal conductivity$^{6,22}$ $\lambda$ (W m$^{-1}$ K$^{-1}$)</td>
<td>320</td>
<td>100</td>
</tr>
<tr>
<td>Thermal expansion coefficient$^{23}$ $\gamma$ (10$^{-6}$/K)</td>
<td>14.2</td>
<td>2.6</td>
</tr>
</tbody>
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**Fig. 6.** Ratio of the enhancement of the frequency shift $S/S_0$. For small thickness $t_1$, $S/S_0$ keeps unchanged with increasing input power. For $t_1 \geq 80$ nm, $S/S_0$ approaches an asymptotic value; for $t_C = 35$ nm, $S/S_0$ is $\sim 36$.

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