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Optical actuation of a macroscopic mechanical oscillator

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ABSTRACT An intensity-modulated HeNe-laser beam was utilized to optically actuate the mechanical resonance of a macroscopic torsional silicon oscillator ($f_0 = 67\,700$ Hz, $Q = 42\,100$ at $p = 1$ mbar and $T = 300$ K). Both radiation pressure and photothermal effects may cause optical actuation of a mechanical device. Both excitation effects were studied. In actuation through radiation pressure, the actuating laser beam was focused on the high-reflectivity-coated oscillator surface. In the case where the intensity-modulated laser beam was incident on the uncoated silicon surface the photothermal effect was shown to be the dominating excitation factor. Oscillation amplitudes due to the actuation through radiation pressure and photothermal effects were $\Delta x_{\mathrm{rad}} = 1.4$ pm and $\Delta x_{\mathrm{ph}} = 4.3$ pm with the same optical power of 1.5 mW. The measured resonance frequency and quality value were not changed when purely mechanical and radiation pressure actuation mechanisms were compared. With photothermal actuation the absorbed optical power heats the oscillator, introducing a slight decrease in the resonance frequency. Our experiments demonstrate that optical actuation combined with sensitive optical interferometric measurements can be utilized to perform dynamic vibration analysis of micromechanical components. Prospects of using micromechanical devices for observing extremely weak external forces are discussed.

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1 Introduction

Optical actuation of mechanical components has been widely studied during recent years [1–3]. Lasers and consequent radiation pressure have been used, e.g. in optical levitation of small particles [4] and in laser cooling and trapping of atoms and molecules [5, 6]. Moreover, radiation pressure has been utilized in cooling of macroscopic objects such as vibrational modes of movable mirrors of optical cavities [7–9]. In cold damping a viscous feedback force is used to freeze the mirror motion by applying an additional radiation pressure on the oscillating mirror [8, 9]. Another possibility is to produce squeezed states of the thermal noise by using parametric amplification in which one quadrature of the thermal noise is cooled at the expense of the other, i.e. the other quadrature is heated [10]. It has been discussed how sensitivities of interferometric measurements can be increased by reducing the quantum back action noise [11]. In the quantum locking technique, an active feedback control locks the moving mirror with respect to the position of another less noisy reference mirror and the radiation pressure noise in the interferometer can be reduced.

The subject of using optical coupling to the mechanical oscillator for observing fundamental quantum-mechanical effects is some tens of years old. One example is the observation of macroscopic superpositions of a mirror in an optomechanical system through interaction of photons with a micromechanical oscillator mirror as part of a high-finesse cavity [12]. Also, the demonstration of the appearance of the Einstein–Podolsky–Rosen (EPR) paradox when an optical radiation field impinges on a movable mirror of an optomechanical system has been discussed [13, 14]. Such an experiment would demonstrate whether radiation pressure can induce quantum-mechanical entanglement via a macroscopic object, i.e. if the entanglement can be realized at a distance between two spatially separated subsystems.

An array of optically actuated micromechanical devices has been proposed to be used in such applications as large-bandwidth photodetectors, miniaturized spectrum analyzers, polarization analyzers and even in optical computing [3]. One interesting aspect of the optical actuation is the possibility to perform on-wafer testing, analyzing and dynamic measurements of micromechanical components during the fabrication process. On the other hand, the response of a mechanical oscillator can be regulated by applying a force feedback through the photothermal effect. Such a photothermal feedback offers possibilities, e.g. to improve the measurement characteristics in atomic force microscopy [15].

In this work, the interaction of light with a microfabricated high-Q mechanical silicon oscillator is studied. Radiation pressure, i.e. the transfer of the momentum of light, introduces very weak forces that are typically not sufficient to produce observable displacements of macroscopic objects. Therefore, optical actuation is typically applied to very small devices such as micromechanical cantilevers [16–19]. The actuation of micromechanical components is usually realized by using capacitive coupling or mechanical actuators, e.g. piezo

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transducers or deformable micromembranes [20]. However, capacitive coupling requires additional electrodes, which are usually rather strongly coupled to the moving part and affect the performance of the component under study. The deposition of additional electrodes and conductors complicates the fabrication process or may even prevent some special component designs. Electrodes and conductors may increase sensitivity to electromagnetic disturbances. Piezo actuation is robust and easy to implement, but actuators are typically much larger in size compared to the dimensions of micromechanical components. Moreover, the bandwidth of the piezo actuators is typically limited to a few hundred kHz.

Optical actuation is typically provided by laser light. Thus, a remote and external light source can be used and the exciting force is directly applied to the chosen part of the component. The optical actuation method is non-contact in nature, meaning that it does not degenerate the intrinsic properties or performance of the measured component. However, optical actuation requires direct beam access that may not always be possible but, on the other hand, enables simultaneous interferometric measurement of the mechanical displacement as a function of time. In this work, laser light is utilized both to provide actuation for the mechanical oscillator and as the interferometric probe beam of an optomechanical sensor to detect the displacements in the oscillator position.

2 Position of the oscillator in the optical actuation measurements

2.1 *Optical actuation through radiation pressure force*

As the laser beam is focused on the oscillator surface, the oscillator is exposed to the mechanical momentum transferred by the reflected and absorbed photons. The photons that reflect from the oscillator surface transfer a mechanical momentum p_{rad},

$$p_{\text{rad}} = 2\frac{h}{\lambda}\cos\theta, \tag{1}$$

where h is Planck's constant, λ is the wavelength of the laser light used and θ is the angle of the incident laser beam with respect to the normal direction. Absorbed photons transfer mechanical momentum that is half of the momentum transferred by the reflected photons. The number of photons n incident on the oscillator surface per unit time can be calculated from the optical power $P = nhc/\lambda$. The radiation pressure force F_{rad} applied to the oscillator due to the transferred mechanical momentum is [16]

$$F_{\text{rad}} = [2R + (1-R)]\, np_{\text{rad}} = (1+R)\,\frac{P}{c}\cos\theta, \tag{2}$$

where R is the power reflection coefficient of the oscillator mirror surface and $1-R$ is the absorbed fraction of the incident light. The displacement of the oscillator due to an external force $F(\omega)$ is

$$\begin{aligned}\Delta x\,(\omega) &= |\chi\,(\omega)|\; F\,(\omega)\\ &= \frac{1}{m_{\text{eff}}\sqrt{(\omega_0^2-\omega^2)^2+(\frac{\omega\omega_0}{Q})^2}}F(\omega),\end{aligned} \tag{3}$$

where $\chi(\omega)$ is the mechanical susceptibility and m_{eff} is the effective mass of the oscillator. At resonance ($\omega = \omega_0$), the displacement $\Delta x_{\text{rad}}(\omega_0)$ due to the modulated monochromatic radiation pressure force $F_{\text{rad}}(\omega_0)$ is

$$\begin{aligned}\Delta x_{\text{rad}}\,(\omega_0) &= |\chi\,(\omega_0)|\; F_{\text{rad}}\,(\omega_0)\\ &= \frac{Q}{m_{\text{eff}}\omega_0^2}\,(1+R)\,\frac{P_{\text{rms}}\,(\omega_0)}{c}\cos\theta.\end{aligned} \tag{4}$$

In order to be able to provide a sinusoidal actuation effect a dc optical power component P_{dc} must be involved. The dc optical power causes a small static deflection in the oscillator position, which can be considered as a new equilibrium position around which the oscillator is vibrating when the intensity-modulated laser beam is applied. The displacement due to the constant radiation pressure force $F_{\text{rad,dc}}$ is

$$\Delta x_{\text{rad,dc}} = \frac{F_{\text{rad,dc}}}{k} = \frac{(1+R)P_{\text{dc}}}{m_{\text{eff}}\omega_0^2 c}\cos\theta, \tag{5}$$

where k is the spring constant of the torsional oscillation mode.

Laser light contains intrinsic noise, which is based on the quantum nature of light. Shot noise of the laser beam arises from the fluctuations in the number of photons n, introducing an uncertainty in the optical measurements through an additional radiation pressure noise. Because of the Poisson distribution the standard deviation of the number of photons is equal to the square root of the mean number of photons in a laser beam, $\sigma_{\text{n}} = n^{1/2}$. The square root of the spectral power density S_{SN} of the shot noise is

$$\sqrt{S_{\text{SN}}} = \sigma_n hf = \sqrt{\frac{P\lambda}{hc}}\frac{hc}{\lambda} = \sqrt{\frac{Phc}{\lambda}}, \tag{6}$$

where hf is the energy per photon. Thus, the shot noise introduces a deviation in the oscillator position $\Delta x_{\text{SN}}(\omega)$:

$$\Delta x_{\text{SN}}\,(\omega) = |\chi\,(\omega)|\,(1+R)\sqrt{\frac{PhB}{\lambda c}}\cos\theta, \tag{7}$$

where B is the measurement bandwidth.

Besides quantum noise, laser light contains technical intensity noise [21]. According to the specifications of the HeNe-laser used the spectral density of the technical noise S_{tech} of the laser is less than $9\times10^{-18}\ \text{W}^2/\text{Hz}$ at frequencies below 10 MHz. Thus, the uncertainty in the oscillator position due to the technical noise of the laser can be estimated to be

$$\Delta x_{\text{tech}}\,(\omega) = |\chi\,(\omega)|\,\frac{(1+R)\sqrt{S_{\text{tech}}B}}{c}\cos\theta. \tag{8}$$

2.2 *Measurement of the oscillator position*

The Heisenberg uncertainty principle places a fundamental limit on the sensitivity in measuring the position of a free mass [22]. This limit is called the standard quantum limit (SQL). In measuring the position of a small oscillator with a mass m at a certain resonance frequency ω_0, the minimum detectable displacement Δz_{SQL} is given by [23]

$$\Delta z_{\text{SQL}} = \sqrt{\frac{\hbar}{2m\omega_0}}. \tag{9}$$

The laser beam P_i that is utilized as an interferometric probe beam to detect oscillator displacement contains quantum fluctuations in intensity and phase. The laser intensity noise introduces an oscillator displacement through radiation pressure, which is referred to as quantum back action of the measurement. At optical resonance the total optical power P_c circulating inside a low-loss Fabry–Pérot cavity compared to the incident power P_i is given by [24]

$$\frac{P_c}{P_i} = \frac{t_1 t_2}{(1-r_1 r_2)^2} = \frac{1-R}{(1-R)^2} \approx \frac{\mathcal{F}}{\pi}, \tag{10}$$

where t_1 and t_2 are the amplitude transmission coefficients, r_1 and r_2 are the amplitude reflection coefficients, R is the power reflection coefficient of the two cavity mirrors ($t_1 \approx t_2$ and $r_1 \approx r_2$) and $\mathcal{F}$ is the finesse of the cavity. In other words, the optical power inside the cavity is enhanced by the finesse and an estimate for the uncertainty in the oscillator position due to the quantum back action can be written as

$$\Delta x_{\mathrm{QBA}}(\omega) \approx |\chi(\omega)|(1+R)\sqrt{\frac{P_i h B}{\lambda c}\frac{\mathcal{F}}{\pi}}. \tag{11}$$

On the other hand, the phase noise of the probe laser beam leads to an uncertainty in the measurement of the displacement of the oscillator position [22, 23]. The phase noise corresponds to the position uncertainty of

$$\Delta x_{\mathrm{PN}} \approx \sqrt{\frac{hc\lambda B}{P_i}\frac{1}{4\mathcal{F}}}. \tag{12}$$

The best measurement accuracy is obtained with the optical power that minimizes the sum of the noise terms due to the quantum back action $\Delta x_{\mathrm{QBA}}(\omega)$ and the measurement uncertainty Δx_{PN}. This optimum power level gives a minimum uncertainty in the oscillator position measurement which is of the order of the SQL.

In practical measurements quantum noise is typically buried under classical noise sources. However, quantum noise must be carefully considered when realizing optomechanical systems working at the quantum limit, e.g. when the measurement accuracy is reaching the SQL or in realizing gravitational wave detectors based on optical interferometry [11, 22, 25–28]. Thermal noise limits the sensitivity of the measurements performed with our experimental setup at room temperature. The thermal noise force F_{th} acting on the silicon oscillator is

$$F_{\mathrm{th}} = \sqrt{\frac{4k_B T m_{\mathrm{eff}}\omega_0 B}{Q}}, \tag{13}$$

where k_B is the Boltzmann constant and T is the temperature. Oscillator displacement due to the thermal excitation (Brownian motion) is

$$\Delta x_{\mathrm{th}}(\omega) = |\chi(\omega)|\sqrt{\frac{4k_B T m_{\mathrm{eff}}\omega_0 B}{Q}}. \tag{14}$$

2.3 *Optical actuation through photothermal effect*

The photothermal effect introduces thermoelastic fluctuations that arise from heating of the oscillator due to the absorbed photons from the incident light [25, 28]. Typically, the laser beam heats the localized spot and the temperature gradient leads to a deformation and bending of the oscillator via thermal expansion. In a simple case when a laser beam is incident on the surface of an absorbing body, a fluctuating photon number Δn will induce fluctuations in the temperature ΔT and the corresponding displacement Δx_{ph} due to the photothermal effect is [28]

$$\Delta x_{\mathrm{ph}} = d\alpha\Delta T = d\alpha\frac{hf\Delta n}{\rho C V}, \tag{15}$$

where d is the thickness of the oscillator, $\alpha(T)$ is the linear thermal expansion coefficient, ρ is the density, $C(T)$ is the specific thermal capacity and V is the volume. The magnitude of the photothermal effect depends strongly on the ambient temperature, material parameters, geometric dimensions of the oscillator structure and spot size and position of the actuating laser beam [16–18]. Moreover, photothermally induced deflection will become saturated when higher modulation frequency, higher laser power or larger spot size r_0 are used [18]. The thermal relaxation time τ_c of the oscillator determines the critical frequency ω_c for the response to the optical power fluctuations [29]:

$$\omega_c = \frac{1}{\tau_c} = \frac{\kappa_T}{\rho C r_0^2}, \tag{16}$$

where $\kappa_T(T)$ is the thermal conductivity of the oscillator. If the modulation frequency is high compared to the critical frequency, the oscillator is affected by an averaged temperature because of the finite thermal time constant associated with heating.

3 Experimental setup

Our experimental setup (Fig. 1) consists of three main elements. The first is a torsionally vibrating *high-Q mechanical oscillator* that is the object for the actuating optical power. A laser beam is modulated by *an intensity modulator* which is based on a Michelson interferometer. A very sensitive *optomechanical sensor* measures the motion of the actuated silicon oscillator. The high-Q mechanical silicon oscillator and the optomechanical sensor are discussed in more detail in Ref. [30].

3.1 *High-Q mechanical oscillator*

The high-Q mechanical silicon oscillator with a dielectric high-reflectivity (HR) coating used in this work is illustrated in Fig. 2. The oscillator is a balanced torsionally vibrating rectangular silicon vane ($1.4 \times 2.3 \times 0.38\ \mathrm{mm}^3$), which is mounted with narrow bridges to several surrounding frames. Oscillators were produced from double-sided-polished (DSP), (100)-oriented single-crystal silicon wafers (p-type, 5–10 Ω cm) by etching from both sides simultaneously in a 25% tetra-methyl ammonium hydroxide (TMAH) solution at 85°C. A thermally grown silicon oxide layer was used as an etching mask. The oscillator can be considered to behave like a one-dimensional mechanical harmonic oscillator in a pure torsional mode. At low pressure

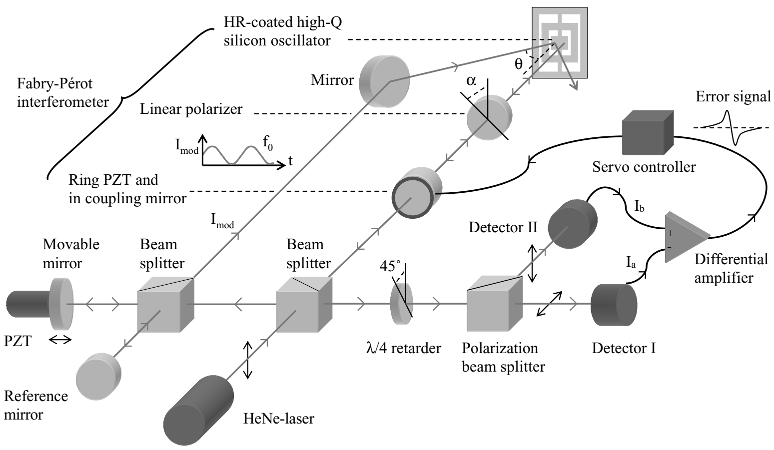

FIGURE 1 The Hänsch–Couillaud locking and intensity-modulation schemes. The locking method is based on polarization spectroscopy. The dispersion-shaped resonances provide the error signal for the electronic servo loop

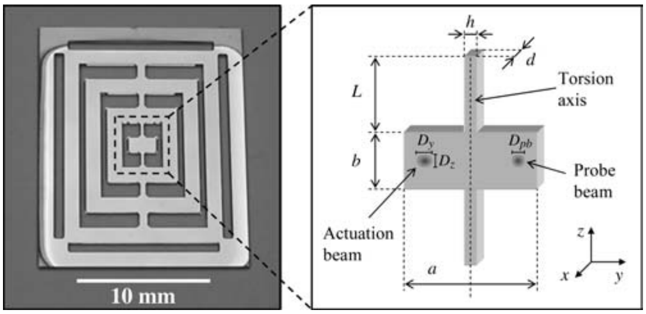

FIGURE 2 Design of a torsional mechanical silicon oscillator used in this work. The oscillator size is specified by the parameters $a = 2.3\,\text{mm}$, $b = 1.4\,\text{mm}$, $h = 200\,\mu\text{m}$, $d = 380\,\mu\text{m}$ and $L = 1.2\,\text{mm}$. Spot sizes of the actuation and probe beams at the oscillator are $D_y = 270\,\mu\text{m}$, $D_z = 205\,\mu\text{m}$ and $D_{pb} = 186\,\mu\text{m}$

($p < 10^{-3}$ mbar) the resonance frequency and Q value of the HR-coated oscillator were measured to be $f_0 = 67\,707\,\text{Hz}$ and $Q = 42\,100$, respectively. The resonance frequency and Q value make it possible to determine the measurement bandwidth $B = f_0/Q = 1.6\,\text{Hz}$. The effective mass was determined to be $m_{\text{eff}} = 0.59\,\text{mg}$. The thickness of the oscillator in our configuration is $d = 380\,\mu\text{m}$ and is much larger compared to the inverse of the absorption coefficient of silicon at the HeNe-laser wavelength ($\gamma \sim 10^5\,\text{m}^{-1}$) [31]. Thus, practically no light is transmitted through the oscillator.

In our configuration the angle of the incident actuating intensity-modulated light beam is $\theta = 40^\circ$ and the power reflection coefficient of the HR-coated oscillator surface is $R = 0.98$. We used HeNe-laser light with maximum optical power of 1.5 mW. The laser beam was sinusoidally modulated and the modulation depth was almost 100%. The actuating rms optical power was determined to be $P_{\text{rms}} = 0.5\,\text{mW}$. By using Eq. (4) and the numerical values given above, we find that the theoretical value for the displacement due to the radiation pressure of 1.5-mW laser light is $\Delta x_{\text{rad}}(\omega_0) = 1.0 \times 10^{-12}\,\text{m}$.

3.2 *Intensity modulation*

A laser beam was intensity modulated by a Michelson interferometer. The position of the movable mirror Δx_{mm} can be controlled with a piezo actuator, which is driven with a signal generator. The output intensity of the Michelson interferometer can be written as

$$I_{\text{out}}(\Delta x) = \frac{1}{2}\left[I_0 + I_0 \cos\left(\frac{4\pi\,\Delta x_{\text{mm}}}{\lambda}\right)\right], \qquad (17)$$

where I_0 is the intensity of the incident light. The piezo actuator is driven at the level which allows the movable mirror to be displaced one-quarter of the wavelength ($\Delta x_{\text{mm}} = 0, \ldots, \lambda/4$). This gives the output beam a maximum modulation ($I_{\max}$ in Fig. 3). An additional dc offset voltage is used to control the equilibrium position of the movable mirror so that the modulation takes place in the linear region. The position of the movable mirror due to the sinusoidal driving signal and dc offset is

$$\Delta x_{\text{mm}}(t) = \frac{\lambda}{4} c_1 \frac{1}{2}\left[\sin(\omega t) + c_2\right], \qquad (18)$$

where the parameters c_1 and c_2 are related to the modulation amplitude and the dc offset voltage level, respectively. The parameter c_1 is set by adjusting the amplitude of the signal that drives the piezo actuator, whereas the parameter c_2 is matched by the dc offset level control. Mathematically, c_1 must be equal to the inverse of c_2. The modulated output intensity $I_{\text{mod}}(t)$ is a close approximation to a pure sinusoidal signal (Fig. 3).

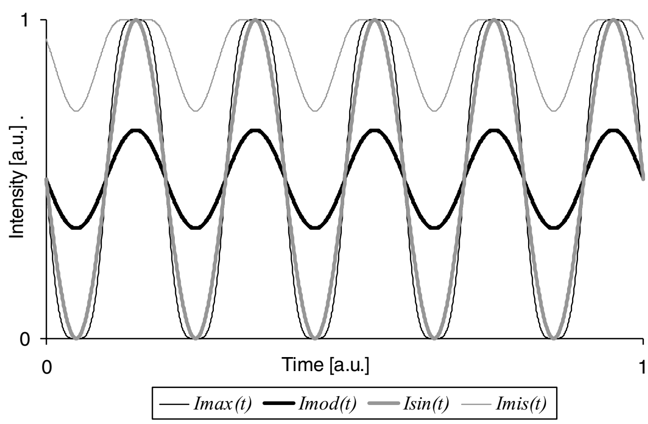

FIGURE 3 An intensity modulation in a Michelson interferometer gives a close approximation to a sinusoidal signal. $I_{\sin}$ is an ideal sinusoidally modulated intensity, $I_{\max}$ is an actual intensity with maximum modulation depth, I_{mod} is a moderately modulated intensity with the dc level shifted to the linear region and I_{mis} shows a modulated intensity with a misadjusted dc offset voltage level

The curve I_{sin} in Fig. 3 shows an ideal sinusoidally modulated output intensity $I_{sin}(t) = (-\sin(\omega_0 t) + 1)/2$. In comparison, I_{mis} in Fig. 3 shows a modulated signal with an incorrect dc offset voltage level and slightly distorted shape.

3.3 *Optomechanical sensor*

In order to observe small displacements in the position of a high-Q mechanical oscillator, a sensitive and low-noise detection system is required. A convenient detection can be realized by using optical interferometry, in which a mechanical oscillator is integrated into the optical resonator as one of the two mirrors. In our configuration, a HR-coated silicon oscillator is employed as a planar rear mirror in a Fabry–Pérot interferometer. Physical oscillations of the mechanical oscillator change the interferometer response.

A HeNe laser provides linearly polarized 5-mW optical power (TEM_{00} mode) at the wavelength of $\lambda = 632.8$ nm. The optical finesse is $\mathcal{F} = 100$ and is limited by the linear polarizer in the cavity. We use the Hänsch–Couillaud locking method [32] to provide the error signal for the active stabilization of the optical cavity (Fig. 1). The error signal contains information of dynamic length variations of the optical cavity. The slope of the error signal at optical resonance was determined to be 1.5 nm/V by using the known free spectral range as a length reference.

We have demonstrated earlier [30] that our optomechanical sensor can be used for high-precision sensing applications. In our case the smallest measurable displacement in the oscillator position is limited by the thermal noise to the level $\Delta x_{th} = 1.6 \times 10^{-13}$ m at room temperature. However, the measured noise floor of the interferometer response next to the oscillator resonance peak indicates that the sensitivity of the optomechanical sensor is $\Delta x_{min} = 1.7 \times 10^{-14}$ m. It can be calculated that Δx_{min} could be reached if the ambient thermal noise is reduced by cooling the oscillator from room temperature to 7 K, because the oscillator displacement due to the thermal noise scales with $T^{1/2}$.

4 Measurements

4.1 *Intensity-modulation measurements*

The intensity modulation takes place on a separate optical table that is not in direct mechanical contact with the optomechanical sensor. This is necessary because otherwise the mechanical motion of the movable mirror of the Michelson interferometer was mechanically coupled to the extremely sensitive high-Q oscillator. In order to reveal the possible unwanted mechanical, acoustic or electrical coupling, the intensity modulator was driven in such a way that the modulation frequency was swept over the resonance frequency of the mechanical oscillator and the laser beam was cut after the intensity modulator. Thus, the beam did not hit the oscillator at all. At the same time, the oscillation amplitude of the mechanical oscillator was detected by monitoring the error signal with the lock-in amplifier. As shown in the frequency response in Fig. 4, there was no resonance peak in the oscillation amplitude and the phase response is random throughout the frequency sweep. It was concluded that there is no excitation due to the operation of the intensity modulator itself.

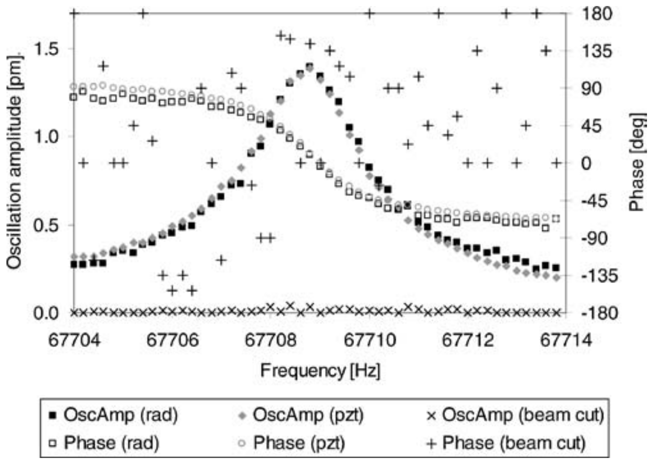

FIGURE 4 High-Q oscillator was optically actuated through radiation pressure (rad). In comparison, the resonance was excited mechanically by a piezo actuator (pzt). The operation of the intensity modulator alone had no measurable influence on the mechanical oscillator (beam cut)

4.2 *Radiation pressure measurements*

The oscillator actuation through radiation pressure was demonstrated. The measurements were carried out at a low pressure of $p = 1$ mbar because it was evident that the weak radiation pressure effect would be buried under the gas damping at the atmospheric pressure. The intensity-modulated laser beam was guided onto the HR-coated surface of the mechanical silicon oscillator. The beam was focused by using a single lens with the focal length of 100 mm. The beam diameter at the oscillator was measured to be $D_i = 205$ µm by using the knife-edge scanning technique. Due to the off-axis incidence, the spot size at the oscillator is $D_y = 270$ µm in the y direction and $D_z = 205$ µm in the z direction (Fig. 2). In order to excite the torsional oscillation mode the laser beam was focused $l = 1$ mm aside from the torsion axis of the oscillating vane. The modulation frequency was swept over the mechanical resonance of the oscillator. The oscillation amplitude was measured by monitoring the error signal with the lock-in amplifier. It was demonstrated by altering the modulation depth that the radiation pressure force increases linearly with the applied optical power. Mechanical actuation by using a piezo actuator was also applied and the amplitude of the piezo drive signal was normalized to give a similar oscillation amplitude as the radiation pressure actuation (Fig. 4).

The oscillation amplitude due to the radiation pressure was measured to be $\Delta x_{rad} = 1.4$ pm. This value is 40% larger than the predicted value that was based on the theoretical consideration discussed in Sect. 3.1. At least part of the inaccuracy can be explained by the difficulties in determining the error signal slope with high precision, because the peak-to-peak value of the error signal may drift slightly from one measurement to another. Another possible reason is related to the contribution of the photothermal effect and will be discussed in Sect. 4.5.

According to the radiation pressure measurements, the resonance frequency and the width of the resonance were equal to those results obtained by mechanically exciting the oscillator with a piezo actuator. Both actuation methods give equal Q values of $Q = 42\,100$.

4.3 *Photothermal effect measurements*

In order to study optical actuation through the photothermal effect the experimental setup was modified in such a way that the 1.5-mW intensity-modulated laser beam was guided on the uncoated back side of the silicon oscillator. The laser beam was focused approximately 1 mm aside from the torsion axis in order to introduce an exciting torque for the torsional oscillation. In this configuration, the incident optical power of the laser beam was partially absorbed and partially reflected from the silicon surface. The power reflection coefficient of the polished silicon surface for the HeNe-laser wavelength is $R_{\mathrm{Si}} = 0.34$ and thus approximately two-thirds of the incident optical power was absorbed by the oscillator material. Radiation pressure is still involved but it is now smaller than with the HR-coated surface.

The modulation frequency was swept over the mechanical resonance of the oscillator and the frequency response was stored from the error signal by the lock-in amplifier (Fig. 5). The oscillation amplitude due to the photothermal effect of an absorbed intensity-modulated optical power of 1.0 mW was measured to be $\Delta x_{\mathrm{ph}} = 4.3$ pm. The small contribution of radiation pressure was neglected here. It was noticed by altering the modulation depth that the photothermal actuation force increases linearly with the optical power. The result was compared to the frequency response which was attained by mechanically exciting the torsional resonance with a piezo actuator. The frequency responses of oscillation amplitude and phase are similar in both actuation methods, but the resonance frequency was decreased by 0.6 Hz when optical actuation through the photothermal effect was used (Fig. 5). Absorbed optical power heats the oscillator, which affects the elastic properties of silicon. The shear modulus of elasticity of silicon

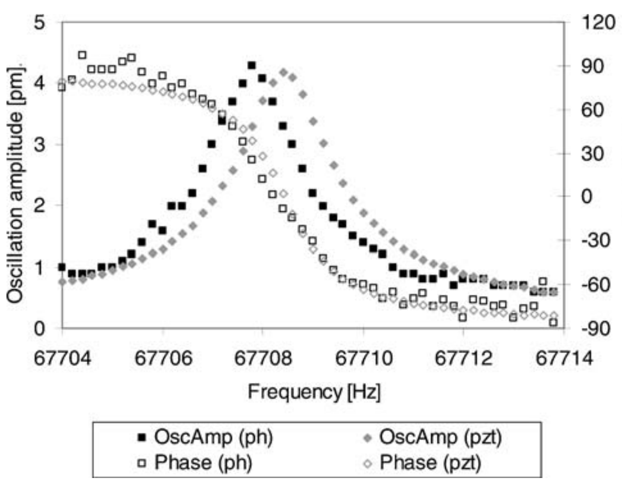

FIGURE 5 Piezo actuation and photothermal actuation were compared. The resonance frequency is decreased in photothermal actuation since the absorbed optical power causes oscillator heating

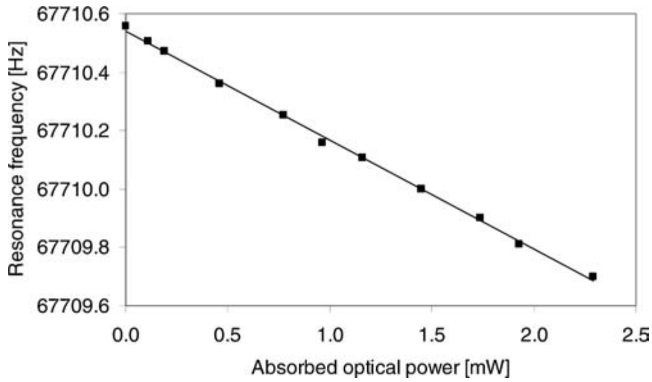

FIGURE 6 The resonance frequency depends linearly on the absorbed dc optical power applied to the piezo-actuated oscillator. Measurements were done at room temperature and at an air pressure of 1.5 mbar

decreases at higher temperatures [33]. Therefore, the spring constant k of the torsional oscillation mode reduces as well and the resonance frequency decreases as $\omega_0 = (k/m)^{1/2}$.

4.4 *Photothermal effect of the dc optical power*

The photothermal effect of the applied optical power was further studied. A 3.5-mW dc laser beam was focused on the uncoated back side of the silicon oscillator. The intensity of the applied linearly polarized laser light was adjusted by a rotating linear polarizer situated in the light path. Absorbed dc optical power was allowed to heat the oscillator locally until a steady-state situation and an equilibrium temperature were reached.

The high-Q oscillator was mechanically excited by a piezo actuator. Figure 6 shows the results of the measurements in which the resonance frequency was determined as a function of the absorbed optical power. The frequency dependence on the absorbed optical power was measured to be −5.5 ppm/mW, which corresponds to the slope of the linear fit in Fig. 6. Earlier measurements [30] indicated that the resonance-frequency dependence on the ambient temperature is −25 ppm/K. Therefore, it can be calculated that focusing an additional dc laser beam with an absorbed optical power of 2.3 mW on the oscillator increases the effective operating temperature by 0.5 K.

The photothermal heating effect can be utilized, e.g. in stabilizing the oscillator resonance frequency. The resonance frequency of a high-Q mechanical oscillator is extremely sensitive to small changes in the physical parameters of the environment. Therefore, the resonance frequency can be controlled or locked to a certain value very accurately by adjusting the operating temperature with the dc level of the incident laser power.

4.5 *Comparison of radiation pressure and photothermal effects*

Without the HR coating on the silicon oscillator the photothermal effect introduces the dominating excitation factor. A high-quality dielectric HR coating guarantees a very high reflection at the oscillator surface, but even a very

Oscillation amplitude [m]	
$\Delta x_{ph}(\omega_0)$	4.3×10^{-12}
$\Delta x_{rad}(\omega_0)$	1.4×10^{-12}
$\Delta x_{th}(\omega_0)$	1.6×10^{-13}
$\Delta x_{rad,dc}(\omega = 0)$	3.6×10^{-17}
$\Delta x_{PN}(\omega_0)$	3.4×10^{-17}
$\Delta x_{tech}(\omega_0)$	7.6×10^{-18}
$\Delta x_{QBA}(\omega_0)$	1.9×10^{-18}
$\Delta x_{SN}(\omega_0)$	5.5×10^{-20}

TABLE 1 Summary of various contributions in the interferometric position measurement

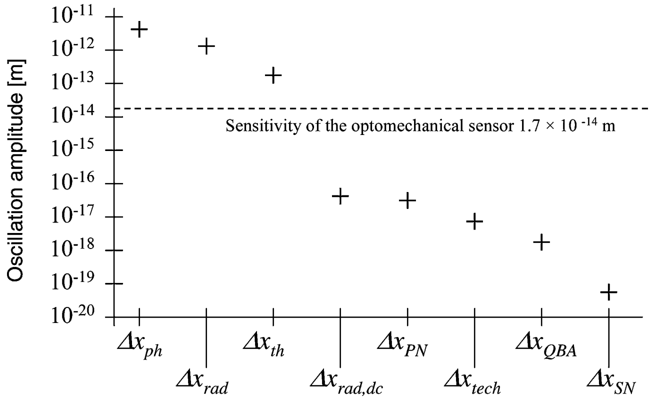

FIGURE 7 Comparison of oscillation amplitudes as a result of various excitation and noise mechanisms. The *dashed line* indicates the sensitivity of the optomechanical sensor used at room temperature, $\Delta x_{min} = 1.7 \times 10^{-14}$ m

small amount of absorbed optical power may cause the weak radiation pressure effect to be masked under the photothermal effect. As mentioned in Sect. 4.2, the oscillation amplitude due to the radiation pressure force was measured to be larger than the calculated one. However, the difference in the oscillation amplitudes cannot totally be explained by the photothermal effect that is introduced by the non-perfect reflection at the HR coating. The reflectivity of the HR coating is $R = 0.98$ and 2% of the incident optical power of 1.5 mW is absorbed by the oscillator. Therefore, in the radiation pressure measurements, the absorbed optical power would introduce an oscillation amplitude of 0.13 pm due to the photothermal effect. This is more than one order of magnitude less than the measured oscillation amplitude due to the radiation pressure force. This calculation was made on the basis of the fact that excitation forces of radiation pressure and photothermal effects increase linearly with increased optical power when moderate power levels are used. Moreover, the resonance frequency was shown to stay unchanged, indicating that the small fraction of absorbed power does not significantly heat the oscillator. In conclusion, the photothermal effect contributes only a little to the optical actuation of the HR-coated oscillator and the main excitation mechanism is the radiation pressure force.

4.6 *Summary of the measurements*

The oscillation amplitude depends on various mechanical and thermal effects that are related to the intensity-modulated laser beam, interferometric laser probe beam and Brownian motion of the oscillator. Oscillator displacements that were measured with the optomechanical sensor or discussed on a theoretical basis in this paper are listed in Table 1 and illustrated in Fig. 7. It can be seen that only oscillations due to the photothermal effect Δx_{ph}, radiation pressure Δx_{rad} and Brownian motion Δx_{th} can be detected within the present sensitivity of our optomechanical sensor.

5 Discussion

Creating practical and functional applications for the optical actuation depends on the ability to make use of very weak forces induced by the optical actuation, especially provided by the transfer of the electromagnetic momentum in the radiation pressure effect. Considering our experimental setup, higher sensitivities can be achieved by increasing the mechanical Q value of the oscillator or by modifying the optomechanical sensor to detect smaller displacements in the oscillator position. On the other hand, optical actuation can be enhanced by increasing the optical power of the light source. The wavelength, material and structural dimensions used may set limitations for the practical optical power. Very high optical power may cause the component to suffer or be damaged due to overheating even if high-quality HR coatings are used and only a fraction of the incident optical power is absorbed. Moreover, at very high optical power levels the intensity quantum fluctuations cause radiation pressure noise, which may lead to significant uncertainty in the oscillator position in high-precision measurements.

A theoretical discussion presented in Ref. [13] implies that the EPR paradox could be realized with the present technology. The discussion in Ref. [13] was based on the experimental setup described in Ref. [8] and calculations were done with the reasonable parameter values of oscillator mass $m = 3 \times 10^{-5}$ kg, resonance frequency $f_0 = 400$ kHz, oscillator mechanical quality $Q = 4 \times 10^5$, finesse $\mathcal{F} = 37\,000$, measurement temperature $T = 4$ K and optical power $P_0 = 27$ mW. If these values are compared to those presented in our work ($m_{eff} = 0.59$ mg, $f_0 = 68$ kHz, $\mathcal{F} = 100$ and $Q = 2.1 \times 10^6$ before the HR coating and at $T = 4.2$ K), it can be seen that the most severe limitation in our configuration is the modest finesse. It is limited by the optical losses in the intracavity linear polarizer that is required by the Hänsch–Couillaud locking method. It is evident that by performing the measurements at cryogenic temperatures, it is possible to improve the measurement sensitivity of our optomechanical sensor by several orders of magnitude.

6 Conclusions

It was experimentally shown that the mechanical resonance of a macroscopic torsionally vibrating high-Q oscillator can be optically actuated by using an intensity-modulated laser beam with a very moderate optical power of the order of 1.5 mW. Optical actuation happens through radiation pressure and photothermal effects, both of which were demonstrated.

At low pressure the radiation pressure of the intensity-modulated laser produced an oscillation amplitude of $\Delta x_{rad} = 1.4$ pm, whereas the oscillation amplitude due to the photothermal effect was $\Delta x_{ph} = 4.3$ pm. It was shown that the observed resonance frequency and Q value were equivalent in both radiation pressure and mechanical actuations. In the photothermal actuation, however, the absorbed optical power heats the oscillator, introducing a decrease in the resonance frequency when higher optical powers are used.

Optical actuation allows remote actuation and direct utilization of optical power without the need of using additional transducers. It was demonstrated that optical actuation combined with optical interferometric measurements can be utilized to perform versatile dynamic vibration analysis of micromechanical components and in high-precision sensing applications.

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