nature physics

ARTICLES

PUBLISHED ONLINE: 11 OCTOBER 2009 | DOI: 10.1038/NPHYS1425

Near-field cavity optomechanics with nanomechanical oscillators

G. Anetsberger[1], O. Arcizet[1], Q. P. Unterreithmeier[2], R. Rivière[1], A. Schliesser[1], E. M. Weig[2], J. P. Kotthaus[2] and T. J. Kippenberg[1,3]*

Cavity-enhanced radiation-pressure coupling between optical and mechanical degrees of freedom allows quantum-limited position measurements and gives rise to dynamical backaction, enabling amplification and cooling of mechanical motion. Here, we demonstrate purely dispersive coupling of high-Q nanomechanical oscillators to an ultrahigh-finesse optical microresonator via its evanescent field, extending cavity optomechanics to nanomechanical oscillators. Dynamical backaction mediated by the optical dipole force is observed, leading to laser-like coherent nanomechanical oscillations solely due to radiation pressure. Moreover, sub-fm Hz$^{-1/2}$ displacement sensitivity is achieved, with a measurement imprecision equal to the standard quantum limit (SQL), which coincides with the nanomechanical oscillator's zero-point fluctuations. The achievement of an imprecision at the SQL and radiation-pressure dynamical backaction for nanomechanical oscillators may have implications not only for detecting quantum phenomena in mechanical systems, but also for a variety of other precision experiments. Owing to the flexibility of the near-field coupling platform, it can be readily extended to a diverse set of nanomechanical oscillators. In addition, the approach provides a route to experiments where radiation-pressure quantum backaction dominates at room temperature, enabling ponderomotive squeezing or quantum non-demolition measurements.

Nanomechanical oscillators[1,2] possess wide-ranging applications in both fundamental and applied sciences. Owing to their small mass, they are ideal candidates for probing quantum limits of mechanical motion in an experimental setting. Moreover, they are the basis of various precision measurements[3–5]. Significant attention has been devoted to developing sensitive readout techniques for nanomechanical motion over the past decade. A natural scale for comparing the performance achieved with systems of different size and mass is given by the variance of the mechanical oscillators' zero-point motion $\langle x(t)^2\rangle_{zp} = \hbar/(2m\Omega_m)$ ($\hbar$: reduced Planck constant; m, $\Omega_m/2\pi$, Q: mass, resonance frequency, quality factor of the oscillator). In Fourier space, the zero-point motion can be described by a corresponding single-sided spectral density $S_{xx}[\Omega]$, which at the mechanical oscillator's resonance is given by $S_{xx}[\Omega_m] = 2\hbar Q/m\Omega_m^2$ and coincides with the SQL of continuous position measurement[6–9]. So far, the most sensitive transducers for nanomechanical motion have been based on electron flow using a single-electron transistor[10] or atomic point contact[11] coupled to a nanomechanical string in a cryogenic environment and have achieved a position imprecision of order 10^{-15} m Hz$^{-1/2}$. An imprecision at the level of the SQL, however, has not yet been achieved. In contrast, parametric motion transducers based on photons in a cavity—which are the basis for laser gravitational wave interferometers—provide quantum-limited measurement imprecision exceeding 10^{-18} m Hz$^{-1/2}$ (refs 12, 13) being at or even below[14] the zero-point fluctuations of the respective mechanical oscillator but are typically orders of magnitude less sensitive when applied to less massive, nanomechanical oscillators owing to the optical diffraction limit[15]. Moreover, cavity–optomechanical coupling of mechanical oscillators allows the exploitation of radiation-pressure dynamical backaction[16,17] that is associated with the momentum transfer from the photons involved in the measurement to the probed object and provides a mechanism for cooling[18–20] or coherent amplification[21] of mechanical motion. As such, an ideal platform would combine the quantum-limited detection and control afforded by cavity–optomechanical coupling with nanoscale mechanical oscillators which, owing to their small masses, provide large zero-point motion and high force sensitivity. Such an approach may therefore have promising implications for probing quantum phenomena of mechanical systems[22] and equally in precision experiments, such as mass spectroscopy[3], charge sensing[4] and single-spin detection[5] that are based on ultra-sensitive nanomechanical oscillators.

Efficient optomechanical interaction with nanomechanical oscillators requires avoiding introducing losses to the high-finesse optical cavity by the nanomechanical object, while maintaining large optomechanical coupling and mitigating thermal effects. Here, we demonstrate this combination, by evanescently coupling high-Q nanomechanical oscillators to the tightly confined optical field of an ultrahigh-finesse toroidal silica microresonator. Purely dispersive radiation-pressure coupling to the nanomechanical strings is observed and allows sub-fm Hz$^{-1/2}$ displacement imprecision (at room temperature), equal to the SQL, which previously has not been possible[10,11,23–25]. In contrast to the recently developed optomechanical zipper cavities[25], which also operate at the nanoscale, the reported near-field approach moreover decouples optical and mechanical degrees of freedom and thus provides a versatile platform to which diverse nanoscale oscillators, such as nanowires[26], graphene sheets[27] or carbon nanotubes, can be tunably coupled, extending cavity optomechanics[17] into the realm of nanomechanical oscillators. In particular, it enables simultaneously high mechanical and optical Q, giving access to the

[1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany, [2]Fakultät für Physik and Center for NanoScience (CeNS), Ludwig-Maximilians-Universität (LMU), Geschwister-Scholl-Platz 1, 80539 München, Germany, [3]Ecole Polytechnique Fédérale de Lausanne, EPFL, 1015 Lausanne, Switzerland. *e-mail: tobias.kippenberg@epfl.ch.

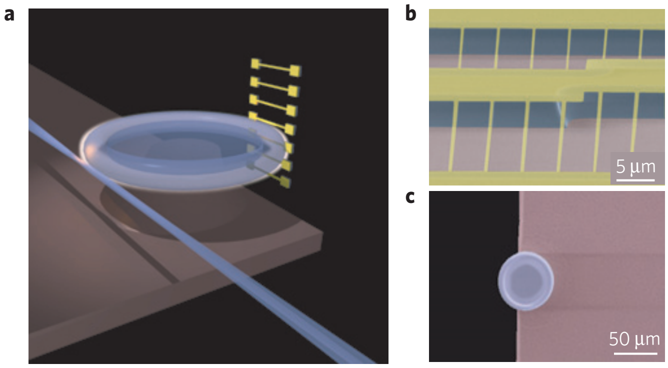

Figure 1 | Evanescent coupling of nanomechanical oscillators to an optical microresonator. a, Schematic of the experiment, showing a tapered-fibre-interfaced optical microresonator dispersively coupled to an array of nanomechanical oscillators. **b**, Scanning electron micrograph (false colour) of an array of doubly clamped SiN nanostring oscillators with dimensions 110 nm × (300–500) nm × (15–40) µm. **c**, Scanning electron micrograph (false colour) of a toroid silica microcavity acting as an optomechanical near-field sensor.

resolved-sideband regime[14,28,29]. By detuned excitation, dynamical backaction mediated by the optical dipole force is demonstrated, which leads to radiation-pressure-induced coherent oscillations of the nanomechanical oscillator, whereas thermal effects are negligible. Equally important, the combination of picogram and high-quality-factor nanostrings[30] with an ultrahigh-optical-finesse microresonator provides a route to the remarkable regime where radiation-pressure quantum backaction is the dominant force noise on the mechanical oscillator even at room temperature and might thus allow quantum optomechanical experiments such as ponderomotive squeezing[31], quantum non-demolition (QND) measurements of photons[32,33] or optomechanical entanglement[34] at ambient temperature.

Figure 1a shows a schematic of the experimental set-up. We use an array of nanomechanical oscillators in the form of high-Q, tensile stressed and doubly clamped SiN strings[15,30] such as shown in Fig. 1b. The strings have typical dimensions of 110 nm × (300–800) nm × (15–40) µm, effective masses of $m_{\mathrm{eff}} = 0.9$–5 pg and fundamental resonance frequencies $\Omega_{\mathrm{m}}/2\pi = 6.5$–16 MHz with mechanical quality factors of $Q = 10^4$–10^5 (see Supplementary Information). Following a special fabrication process (see Supplementary Information) indeed allows using the tightly confined optical modes of toroid silica microcavities as near-field probes (see Fig. 1c) that interact with the nanomechanical oscillator through their evanescent field decaying on a length scale of $\alpha^{-1} \approx (\lambda/2\pi)/\sqrt{n^2-1}$ (that is, approximately 238 nm for the refractive index of silica $n = 1.44$ and a vacuum wavelength of $\lambda \approx 1{,}550$ nm used throughout this work).

Optomechanical coupling rate

First, we study the strength of the optomechanical coupling of the nanomechanical oscillators to the optical mode of a 58-µm-diameter microcavity (showing an unloaded optical linewidth of 4.9 MHz, that is, a finesse of $\mathcal{F} = 230{,}000$). The presence of a dielectric oscillator in the evanescent cavity field, at a distance x_0 to the microresonator surface, can in principle give rise to both a reactive and dispersive contribution to the optical-cavity response[35]. The former would be characterized by increased cavity losses owing to scattering or absorption, given by a position-dependent cavity linewidth $\kappa(x_0)/2\pi$. The latter can be described by an optical-frequency shift $\Delta\omega_0(x_0)/2\pi = (\omega_0(x_0) - \omega_0)/2\pi$ caused by the increased effective refractive index sampled by the evanescent fraction of the mode (ω_0 denotes the unperturbed cavity frequency with the nanomechanical oscillator being removed). Using energy considerations the (small) shift can be approximated by:

$$\Delta\omega_0(x_0) = -\frac{\omega_0}{2}\frac{V_{\mathrm{nano}}}{V_{\mathrm{cav}}}(n_{\mathrm{nano}}^2 - 1)\xi^2 \mathrm{e}^{-2\alpha x_0} \quad (1)$$

where V_{nano} is the volume of the nanomechanical oscillator (refractive index n_{nano}) sampled by the microcavity with mode volume V_{cav}. The magnitude of the cavity field at the toroid/vacuum interface divided by the maximum electric field inside the cavity is denoted by ξ (see Supplementary Information for a more detailed analysis). To probe this static interaction, we position the nanomechanical strings tangentially to the optical whispering-gallery mode trajectory and vary their distance (see Fig. 2a, inset) to the cavity using piezoelectric positioners. Note that all experiments are carried out in this horizontal configuration of the nanostrings as well as in vacuum with a pressure $<10^{-4}$ mbar unless otherwise specified. As shown in Fig. 2a, the interaction with a nanomechanical string (110 nm × 800 nm × 25 µm) induces the expected optical frequency shift that exponentially increases as the distance x_0 is decreased and reaches the gigahertz range. The measured decay length of 110 nm is in good quantitative agreement with the value $1/(2\alpha)$ expected from equation (1). Importantly, we do not measure any degradation of the optical linewidth (see Fig. 2a) even for the strongest coupling. Our measurement accuracy of changes in the cavity linewidth $\Delta\kappa/2\pi < 0.5$ MHz allows an upper bound of 0.5 ppm equivalent optical loss induced by the SiN nanomechanical oscillator to be inferred. Thus, the optomechanical coupling is purely dispersive and can therefore formally be described by the dispersive Hamiltonian $\widehat{H}_0 = \hbar\omega_0(x_0)\hat{a}^\dagger\hat{a}$, where $\hat{a}^\dagger\hat{a}$ denotes the intracavity photon number. Linearized for small fluctuations $x \ll \alpha^{-1}$ around x_0, for example, the Brownian motion of the string placed at x_0, the interaction Hamiltonian reads: $\widehat{H}_{\mathrm{int}} = \widehat{H}_0 + \hbar g(x_0)\hat{x}\,\hat{a}^\dagger\hat{a}$ with the optomechanical coupling rate $g(x_0) = \mathrm{d}\omega_0(x_0)/\mathrm{d}x_0$.

Experimentally, the position-dependent optomechanical coupling rates of the nanomechanical string to the microcavity can be obtained by taking the derivative of the measured static frequency shifts, that is, $g(x_0) = \mathrm{d}\omega_0(x)/\mathrm{d}x|_{x=x_0}$. These statically determined coupling rates reach values up to $g/2\pi = 10$ MHz nm^{-1} (see Fig. 2a). For comparison, also data obtained with a two-dimensional (2D) nanomechanical oscillator in the form of a 30 nm × 40 µm × 50 µm sheet of Si_3N_4 are shown, which also show purely dispersive coupling (see Fig. 2b) of up to $g/2\pi = 20$ MHz nm^{-1}. This sizeable coupling is due to the small mode volume V_{cav} of toroid microcavities because the optomechanical coupling scales as $g \propto (V_{\mathrm{nano}}/V_{\mathrm{cav}}) \cdot \omega_0/l$, where l is the characteristic length scale, which in our case is given by the field intensity decay length, that is, $l = 1/(2\alpha) \approx 110$ nm (see Supplementary Information for analytical expressions of g). Yet higher optomechanical coupling rates can be attained in our system by reducing the size of the microcavity and the wavelength of the used light. An integrated photonic-crystal device with a larger ratio $V_{\mathrm{nano}}/V_{\mathrm{cav}}$, recently allowed remarkably large coupling rates of about 100 GHz nm^{-1} to be obtained[25]. It however also entailed the difficulty of obtaining sufficiently high optical Q in photonic-crystal cavities such that the resolved-sideband regime where the optical linewidth is comparable to or smaller than the mechanical oscillation frequency could not be achieved in ref. 25. The approach presented here, in contrast, separates optical and mechanical degrees of freedom. As the nanomechanical oscillators do not induce any measurable losses to the ultrahigh-finesse microresonators, it thus particularly allows combination of the toroids' high optical Q ($>10^8$) with high mechanical Q and falls naturally into the resolved-sideband regime, which enables ground-state cooling[28,29] or backaction-evading measurements[6].

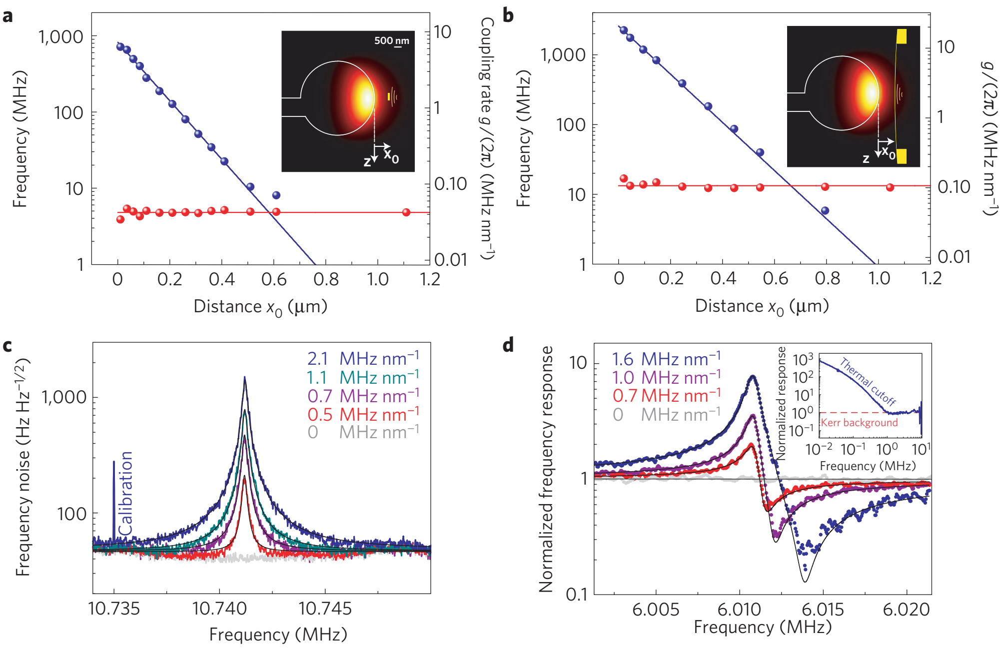

Figure 2 | Characterization of the optomechanical coupling. a,**b**, The dependence of a 58-μm-diameter optical microcavity's linewidth (red) and negative optical frequency shift (blue) as a function of the distance x_0 to nanomechanical oscillators in the form of a doubly clamped SiN string (110 nm × 800 nm × 25 μm (**a**)) and a 2D Si_3N_4 sheet (30 nm × 40 μm × 50 μm (**b**)). The data reveal in both cases purely dispersive coupling without introducing a measurable degradation of the microcavities' optical decay rate. The right axes show the static optomechanical coupling rates $g(x_0) = d\omega_0(x_0)/dx_0$, as given by the negative derivative of the fitted frequency shift data (blue alone). Coupling rates $g/2\pi$ of order 10 MHz nm^{-1} are achieved. **c**, The Brownian noise associated with the nanomechanical oscillator of **a** transduced by the optical cavity for different oscillator positions. The respective dynamical coupling rates $g/2\pi$ are derived from the calibrated frequency noise spectra $S_{\omega\omega}[\Omega]$ as explained in the text. **d**, The interference of the nanomechanical oscillator's force and the microcavity's Kerr response to a modulated laser field, confirming the attractive nature of the dipole force. This measurement represents a third, independent method to determine the optomechanical coupling rates (see text and Supplementary Information). Inset: Broadband response of the nanomechanical oscillator–microcavity system, showing thermal cutoff and Kerr background as well as the first low-Q mechanical modes of the microcavity. It is noted that the presence/absence of the nanomechanical oscillator does not alter this broadband, off-resonant response.

Transduction of nanomechanical motion

The optomechanical coupling rate transduces the motion of the nanomechanical oscillator's eigenmodes (characterized by the displacement spectral density $S_{xx}[\Omega]$) into frequency noise $S_{\omega\omega}[\Omega]$ of the optical cavity mode. Figure 2c shows the Brownian motion of a nanostring at room temperature (110 nm × 800 nm × 25 μm, $\Omega_m/2\pi = 10.74$ MHz, $Q = 53{,}000$, $m_{eff} = 3.6$ pg, $x_{rms} = 16$ pm) imprinted into cavity frequency noise, probed by a laser locked to cavity resonance and calibrated using a known external frequency modulation[13,14]. The nanostring's room-temperature Brownian noise $S_{xx}[\Omega]$ can thus be used to directly determine the optomechanical coupling $g = \sqrt{S_{\omega\omega}/S_{xx}}$ in a second, independent way. We refer to this as a dynamic measurement. Both for the SiN nanostring and the 2D Si_3N_4 nanosheet, the values obtained for the dynamically measured coupling rates are in good agreement with the statically determined values (see Supplementary Information). It is important to note that this identity of static and dynamic coupling rates is in agreement with the expectation for optical dipolar interaction, which should give rise to frequency-independent optomechanical coupling rates g. The non-measurably small optical losses (<0.5 ppm) induced by the nanostrings also indicate that dissipative coupling mediated by thermal effects caused by light absorption has an insignificant role. Indeed, differentiating radiation pressure from thermal effects is a challenge that has eluded researchers for centuries. A prominent example is the light mill that can be driven by thermal heating, rather than by radiation pressure. More recently, thermal effects have been shown to have a significant role in micro- and nanomechanical systems[25,36,37]. It is, however, only the conservative Hamiltonian of radiation pressure that allows phenomena such as ponderomotive squeezing[31] or QND measurements of photons[32]. Therefore, it is central to clearly identify the origin of the optomechanical interaction.

Demonstration of radiation-pressure interaction

The optomechanical coupling not only gives rise to a differential cavity-frequency shift that transduces the nanostring's mechanical motion but also conveys the per-photon force $-\hbar g(x_0)$ inevitably acting on the mechanical degree of freedom, as expected for any linear continuous position measurement. As proof that the optical dipole force mediates the optomechanical coupling—rather than thermal effects[36,37]—we carry out a pump–probe measurement that probes the force response of the nanomechanical oscillator. A resonant, intensity-modulated pump laser provides the modulated force $\delta F[\Omega] = -\hbar g \delta N[\Omega]$ (where N is the intracavity photon number) acting on the nanomechanical oscillator while a second, weak probe laser measures the response of the cavity resonance frequency. The measured data (see Fig. 2d) consist of the nanomechanical oscillator's force response, interfering with the constant background due to the Kerr nonlinearity of silica (that is, its intensity-dependent refractive index, see Fig. 2d and ref. 20). Note that the data for different optomechanical coupling rates are scaled to the constant Kerr background, which allows an accurate determination of the magnitude of the nanomechanical oscillator's response. Two important conclusions can be drawn from this measurement. First, the shape of the interference in Fig. 2d implies that the force experienced by the nanomechanical oscillator is attractive (that is, pointing towards higher intensity) as expected for an optical-gradient force. Below its

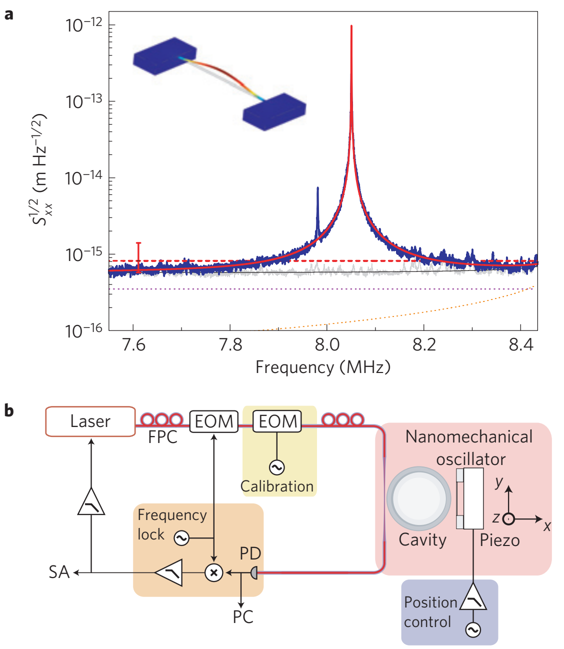

Figure 3 | Displacement measurement of a nanomechanical oscillator with an imprecision at the SQL. a, Room-temperature Brownian noise of a nanomechanical string with a fundamental resonance frequency of 8 MHz and dimensions 110 nm × 800 nm × 35 µm ($m_{\rm eff} = 4.9$ pg, $Q = 40{,}000$). For an input power of 65 µW, the displacement imprecision reaches a value of 570 am Hz$^{-1/2}$ (grey line), 0.7 times the SQL, that is, the oscillator's expected zero-point fluctuations of 820 am Hz$^{-1/2}$ (red dashed line). The large dynamic range across the wide frequency window gives rise to a 1.5 dB error bar for this value (shown in red). The background is due to laser shot-noise (purple dotted line) with smaller contributions from thermal noise of the cavity (orange dotted line), thermorefractive and detector noise (not shown). The second, 20 dB smaller peak is attributed to a second resonator in the toroid's field of view. Inset: Finite-element simulation of the string's fundamental mode. **b**, A schematic of the measurement set-up used to attain an imprecision at the SQL using a low-noise fibre laser emitting at 1,548 nm and locked to cavity resonance ($\kappa/2\pi = 50$ MHz for the measurement shown in **a**). PD: photodiode, PC: personal computer, SA: spectrum analyser, EOM: electro-optic modulator, FPC: fibre-coupled polarization controller.

resonance frequency, where the mechanical oscillator responds in phase with a modulated force, it is pulled towards the optical mode, which leads to an increased redshift, adding to the in-phase redshift due to the Kerr contribution. Above its resonance frequency where the nanomechanical oscillator responds with a phase lag of 180°, the attractive force leads to destructive interference with the in-phase Kerr response. Second, the ratio of the mechanical to the Kerr nonlinearity response constitutes a relative measure[20] and allows derivation of the per-photon force acting on the nanomechanical oscillator independent of the optical parameters (cavity linewidth, coupling conditions, input power). The coupling rates g independently measured in this per-photon-force measurement match the values determined by both methods presented earlier (see Supplementary Information for more details). This measurement thus unambiguously demonstrates that the interaction of the nanomechanical oscillator and the optical cavity is mediated by the dispersive, ponderomotive radiation-pressure interaction, that is, the optical dipole force. No thermal forces are observable.

Measurement imprecision at the SQL

Having established its ponderomotive origin, we use the optomechanical coupling to obtain a high-sensitivity readout of nanomechanical motion with an imprecision at the SQL. To this end, we use a low-noise fibre laser that is quantum-limited in both amplitude and phase at the Fourier frequency of the mechanical oscillators (>6 MHz), resonantly locked using a Pound–Drever–Hall technique[12]. The experimental set-up is shown in Fig. 3b. Remarkably, using a $\kappa/2\pi = 50$ MHz optical mode, more than 60 dB signal to background ratio can be obtained when measuring the Brownian motion $S_{xx}[\Omega_{\rm m}]$ of nanomechanical strings at room temperature. In an ideal measurement, the background of the measurement is given only by laser shot-noise, which limits the single-sided displacement sensitivity attainable for an input power $P_{\rm in}$ and an impedance matched cavity to[12]:

$$\sqrt{S_{xx}[\Omega]} = \sqrt{\frac{\hbar\omega_0}{P_{\rm in}}}\,\frac{\kappa/2}{\sqrt{2}g}\sqrt{1+4\frac{\Omega^2}{\kappa^2}} \qquad (2)$$

The best single-sided displacement sensitivity (as determined from the background of the measurement) that was achieved amounts to $S_{xx}^{1/2} = 570$ am Hz$^{-1/2}$, as shown in Fig. 3a, using an 8 MHz doubly clamped nanomechanical SiN string (110 nm × 800 nm × 35 µm, $m_{\rm eff} = 4.9$ pg, $Q = 40{,}000$), 65 µW input power and a coupling rate of $g/2\pi = 3.8$ MHz nm^{-1}.

To allow a comparison of the attained imprecision with values obtained using other nanomechanical motion transducers, we scale it to the nanomechanical oscillator's zero-point fluctuations, which for the nanostring of Fig. 3 amount to 820 am Hz$^{-1/2}$ (single-sided). Thus, our measurement imprecision amounts to only 0.7 times the oscillator's zero-point fluctuations, that is, 0.7 times the SQL. Interestingly, the condition for a measurement with an imprecision better than the zero-point fluctuations can (for both single- and double-sided spectra) be recast into the condition of a signal-to-background ratio greater than $\sqrt{2k_BT/\hbar\Omega_{\rm m}} \cong \sqrt{2\bar{n}}$, where $\bar{n} \cong k_BT/\hbar\Omega_{\rm m}$ denotes the average phonon occupation number of the mechanical mode (T: temperature, k_B: Boltzmann constant). Such an imprecision had so far never been achieved, neither with the best transducers of nanomechanical motion based on electronic current flow using single-electron transistor[10], atomic point contact[11] and superconducting quantum interference device[23] sensors operating in a cryogenic environment, nor with integrated photonic-crystal systems[25]. Thus, although higher absolute sensitivity has recently been obtained for an oscillator that is ten times heavier[25], our approach for the first time allows the measurement of nanomechanical motion with an imprecision at the SQL.

Although the current measurement allows inferring an upper bound of 380 am Hz$^{-1/2}$ for the shot-noise limit (in agreement with equation (2), see Supplementary Information), our measurement is at present also partially limited by detector noise, which can be eliminated by means of straightforward technical amendments. Moreover, further improvements are readily feasible. Using smaller microcavities and a shorter optical wavelength may allow an increase of g by up to one order of magnitude. Thus, displacement sensitivities at the level of 10^{-17} m Hz$^{-1/2}$ may be attainable, which would allow measurements with an imprecision far below the SQL. Ultimately, the background afforded by mechanical modes of the cavity[13,38] (see Fig. 3a) and thermorefractive noise[13,39] of the cavity will limit the sensitivity. These noise sources can, however, in principle be suppressed by cryogenic operation, which toroid microcavities have been shown to be compatible with[40].

Radiation-pressure dynamical backaction

A second important ramification of the reported cavity–optomechanical system stems from the fact that the nanomechanical oscillators show oscillation frequencies that equal or even exceed the photon decay rate of the optical resonator, enabling access to the regime of dynamical backaction both in the Doppler[18–20] and

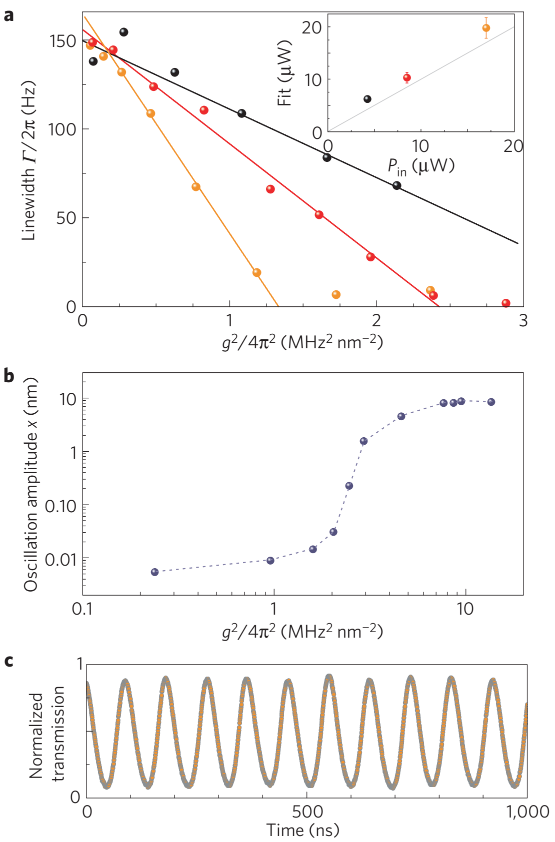

Figure 4 | Observation of radiation-pressure-induced dynamical backaction and coherent oscillations of a nanomechanical oscillator. **a**, Mechanical linewidth of a SiN nanostring (110 nm × 800 nm × 25 μm with a Q of 70,000 at 10.8 MHz and $m_{\rm eff} = 3.6$ pg) as a function of the optomechanical coupling rate for three different launched powers but fixed blue-detuning $\Delta = +\kappa/2$ ($\kappa/2\pi = 12$ MHz). The lines are fits to the dipolar force contribution using the input power as the only fit parameter, which is in good agreement with the actual input power used (inset). Regions where the linewidth drops to a value close to zero coincide with the onset of regenerative mechanical oscillations. **b**, The oscillation amplitude of the nanomechanical string (derived from a 30-Hz-bandwidth power measurement) as a function of the optomechanical coupling showing threshold and saturation at typical values of 10 nm. **c**, The transmitted power past the cavity (normalized by the off-resonant transmission) for a nanomechanical string in the regime of the parametric oscillation instability. The coherent mechanical oscillation of the 3.6 pg string at 10.8 MHz causes a close to unity modulation depth of the optical field transmitted by the cavity.

resolved-sideband[14,28,29] limits. To observe dynamical backaction, the optical microcavity is excited with a positive laser detuning $\Delta = \omega - \omega_0(x_0)$, which can lead to maser/laser-like amplification[41] of mechanical motion. Thereby, the mechanical oscillator resumes the role of the photon field in the laser and the cavity, in turn, has the role of the (phonon) gain medium. As in the case of a laser, the canonical signs of this phenomenon are linewidth narrowing, threshold behaviour and eventual saturation of the oscillation. All of these features are observed with the nanomechanical strings as shown in Fig. 4. For fixed detuning, the backaction gain rate $\Gamma_{\rm ba} \propto -g^2 P_{\rm in}/m_{\rm eff}$ (see Supplementary Information) grows linearly with increased g^2. In the experiment, the optomechanical coupling g is varied (for fixed detuning $\Delta = \kappa/2, \kappa/2\pi = 12$ MHz), giving rise to a narrowing of the total mechanical linewidth $\Gamma = \Gamma_{\rm m} + \Gamma_{\rm ba}$, as shown in Fig. 4a ($\Gamma_{\rm m}/2\pi$ denotes the intrinsic mechanical damping rate). The experimentally observed slopes $\partial\Gamma/\partial(g^2)$ are in good quantitative agreement with the theoretical expectation for the dipolar force (see inset Fig. 4a). When the backaction rate eventually equals the mechanical damping rate, the nanomechanical oscillator experiences net gain, which leads to the onset of coherent mechanical oscillations. A clear threshold of the mechanical oscillation amplitude as shown in Fig. 4b is observable, followed by a saturation of the mechanical motion once the frequency shift caused by the mechanical oscillator exceeds the cavity linewidth, leading to gain saturation. Indeed, the large coherent oscillations of several nanometres in amplitude can lead, remarkably and despite the nanoscale nature of the strings, to near-unity modulation depth of the optical-cavity transmission, as shown in Fig. 4c, when the oscillation amplitude is close to $(\kappa/2)/g$. The resulting radiofrequency signal may serve as a photonic clock[42] and is expected to show a linewidth limited only by thermal noise, as in the case of a maser[41]. The observation of dynamical backaction amplification (and coherent oscillations) constitutes the first report of dynamical backaction onto a nanomechanical oscillator using radiation pressure (in contrast to thermal effects[25,36]), and in particular using optical gradient or dipole forces. So far, in the field of nanomechanics, dynamical backaction cooling or amplification has been achieved only using microwave fields[43], which owing to the about $\times 10^4$ longer wavelength show lower coupling rates and do not allow access to quantum-limited displacement sensing yet (albeit significant progress is being made[44]).

Outlook

The extension of quantum-limited sensitivity with an imprecision at the SQL and dynamical backaction to nanomechanical systems manifests a promising realm for future studies explaining the quantum nature of optomechanical interaction. Remarkably, we note that combined with state-of-the-art nanomechanical strings[30], the ratio of radiation-pressure quantum backaction (the force noise provided by photon shot-noise) and thermal force spectral density can reach unity at room temperature owing to the very small (picogram) mass and ultrahigh finesse (>400,000) of the optomechanical system (see Supplementary Information). This brings the long sought-after[6,7] regime of quantum backaction into reach even at room temperature, which would allow ponderomotive squeezing[31] or QND measurements of the intra-cavity field[32,33]. A further distinguishing feature of the presented approach is that by coupling the nanostrings transversely to the direction of the whispering-gallery mode field, quadratic coupling to the position coordinate of the nanomechanical oscillators enabling QND measurements of mechanical motion[45,46] can be implemented by exploiting the standing-wave mode patterns that microresonators can show (see Supplementary Information).

Pertaining to the wider implications, the presented approach allows coupling to virtually any dielectric nanomechanical oscillator. The ability to combine nanoscale mechanical oscillators—which are at the heart of proximity (Casimir) force sensors and a variety of other high-resolution measurement techniques[3–5]—with quantum-limited displacement sensitivity at the sub-fm $\rm Hz^{-1/2}$ level conceivably offers opportunities for improved performance in these research fields. Particularly interesting may also be the study of graphene sheets[27]. The possibility to couple several mechanical oscillators to a single optical mode may moreover provide a straightforward way to achieve optically mediated coupling between different mechanical oscillators. Finally, the used microtoroidal platform has already been demonstrated as an interface for atomic cavity quantum electrodynamics[47], enabling potentially the interaction of phonons, photons and atoms or qubits, as recently proposed[48,49].

Note added in proof. After submission of this work, a measurement of nanomechanical motion using microwaves with an imprecision at the SQL was reported[50].

Received 13 May 2009; accepted 4 September 2009; published online 11 October 2009

References

1. Craighead, H. G. Nanoelectromechanical systems. *Science* **290,** 1532–2537 (2000).
2. Ekinci, K. L. & Roukes, M. L. Nanoelectromechanical systems. *Rev. Sci. Instrum.* **76,** 061101 (2005).
3. Jensen, K., Kwanpyo, K. & Zettl, A. An atomic-resolution nanomechanical mass sensor. *Nature Nanotech.* **3,** 533–537 (2008).
4. Cleland, A. & Roukes, M. A nanometre-scale mechanical electrometer. *Nature* **392,** 160–162 (1998).
5. Rugar, D., Budakian, R., Mamin, H. & Chui, B. Single spin detection by magnetic resonance force microscopy. *Nature* **430,** 329–332 (2004).
6. Braginsky, V. B. & Khalili, F. Y. *Quantum Measurement* (Cambridge Univ. Press, 1992).
7. Tittonen, I. *et al.* Interferometric measurements of the position of a macroscopic body: Towards observation of quantum limits. *Phys. Rev. A* **59,** 1038–1044 (1999).
8. Caves, C. M. Quantum-mechanical noise in an interferometer. *Phys. Rev. D* **23,** 1693–1708 (1981).
9. Clerk, A. A., Devoret, M. H., Girvin, S. M., Marquardt, F. & Schoelkopf, R. J. Introduction to quantum noise, measurement and amplification. Preprint at <http://arxiv.org/abs/0810.4729v1> (2008).
10. LaHaye, M. D., Buu, O., Camarota, B. & Schwab, K. C. Approaching the quantum limit of a nanomechanical resonator. *Science* **304,** 74–77 (2004).
11. Flowers-Jacobs, N. E., Schmidt, D. R. & Lehnert, K. W. Intrinsic noise properties of atomic point contact displacement detectors. *Phys. Rev. Lett.* **98,** 096804 (2007).
12. Arcizet, O. *et al.* High-sensitivity optical monitoring of a micromechanical resonator with a quantum-limited optomechanical sensor. *Phys. Rev. Lett.* **97,** 133601 (2006).
13. Schliesser, A., Anetsberger, G., Riviere, R., Arcizet, O. & Kippenberg, T. J. High-sensitivity monitoring of micromechanical vibration using optical whispering gallery mode resonators. *New J. Phys.* **10,** 095015 (2008).
14. Schliesser, A., Rivière, R., Anetsberger, G., Arcizet, O. & Kippenberg, T. J. Resolved-sideband cooling of a micromechanical oscillator. *Nature Phys.* **4,** 415–419 (2008).
15. Unterreithmeier, Q. P., Weig, E. M. & Kotthaus, J. P. Universal transduction scheme for nanomechanical systems based on dielectric forces. *Nature* **458,** 1001–1004 (2009).
16. Braginsky, V. & Manukin, A. *Measurement of Weak Forces in Physics Experiments* (Univ. Chicago Press, 1977).
17. Kippenberg, T. J. & Vahala, K. J. Cavity optomechanics: Back-action at the mesoscale. *Science* **321,** 1172–1176 (2008).
18. Arcizet, O., Cohadon, P.-F., Briant, T., Pinard, M. & Heidman, A. Radiation-pressure cooling and optomechanical instability of a micromirror. *Nature* **444,** 71–74 (2006).
19. Gigan, S. *et al.* Self-cooling of a micromirror by radiation pressure. *Nature* **444,** 67–70 (2006).
20. Schliesser, A., Del'Haye, P., Nooshi, N., Vahala, K. J. & Kippenberg, T. J. Radiation pressure cooling of a micromechanical oscillator using dynamical backaction. *Phys. Rev. Lett.* **97,** 243905 (2006).
21. Kippenberg, T. J., Rokhsari, H., Carmon, T., Scherer, A. & Vahala, K. Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity. *Phys. Rev. Lett.* **95,** 033901 (2005).
22. Schwab, K. C. & Roukes, M. L. Putting mechanics into quantum mechanics. *Phys. Today* **58,** 36–42 (2005).
23. Etaki, S. *et al.* Motion detection of a micromechanical resonator embedded in a d.c. SQUID. *Nature Phys.* **4,** 785–788 (2008).
24. Poggio, M. *et al.* An off-board quantum point contact as a sensitive detector of cantilever motion. *Nature Phys.* **4,** 635–638 (2008).
25. Eichenfield, M., Camacho, R., Chan, J., Vahala, K. & Painter, O. A picogram- and nanometre scale photonic-crystal optomechanical cavity. *Nature* **459,** 550–555 (2009).
26. Cui, Y., Wei, Q., Park, H. & Lieber, C. M. Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species. *Science* **293,** 1289–1292 (2001).
27. Bunch, J. S. *et al.* Electromechanical resonators from graphene sheets. *Science* **315,** 490–493 (2007).
28. Wilson-Rae, I., Nooshi, N., Zwerger, W. & Kippenberg, T. J. Theory of ground state cooling of a mechanical oscillator using dynamical backaction. *Phys. Rev. Lett.* **99,** 093901 (2007).
29. Marquardt, F., Chen, J. P., Clerk, A. A. & Girvin, S. M. Quantum theory of cavity-assisted sideband cooling of mechanical motion. *Phys. Rev. Lett.* **99,** 093902 (2007).
30. Verbridge, S. S., Craighead, H. G. & Parpia, J. M. A megahertz nanomechanical resonator with room temperature quality factor over a million. *Appl. Phys. Lett.* **92,** 013112 (2008).
31. Fabre, C. *et al.* Quantum-noise reduction using a cavity with a movable mirror. *Phys. Rev. A* **49,** 1337–1343 (1994).
32. Heidmann, A., Hadjar, Y. & Pinard, M. Quantum nondemolition measurement by optomechanical coupling. *Appl. Phys. B: Laser Optics* **64,** 173–180 (1997).
33. Verlot, P., Tavernarakis, A., Briant, T., Cohadon, P.-F. & Heidmann, A. Scheme to probe optomechanical correlations between two optical beams down to the quantum level. *Phys. Rev. Lett.* **102,** 103601 (2009).
34. Vitali, D. *et al.* Optomechanical entanglement between a movable mirror and a cavity field. *Phys. Rev. Lett.* **98,** 030405 (2007).
35. Favero, I. & Karrai, K. Cavity cooling of a nanomechanical resonator by light scattering. *New J. Phys.* **10,** 095006 (2008).
36. Zalalutdinov, M. *et al.* Autoparametric optical drive for micromechanical oscillators. *Appl. Phys. Lett.* **79,** 695–697 (2001).
37. Höhberger Metzger, C. & Karrai, K. Cavity cooling of a microlever. *Nature* **432,** 1002–1005 (2004).
38. Anetsberger, G., Rivière, R., Schliesser, A., Arcizet, O. & Kippenberg, T. Ultralow-dissipation optomechanical resonators on a chip. *Nature Photon.* **2,** 627–633 (2008).
39. Gorodetsky, M. L. & Grudinin, I. S. Fundamental thermal fluctuations in microspheres. *J. Opt. Soc. Am. B* **21,** 697–705 (2004).
40. Arcizet, O., Rivière, R., Schliesser, A., Anetsberger, G. & Kippenberg, T. J. Cryogenic properties of optomechanical silica microcavities. *Phys. Rev. A* **80,** 021803 (2009).
41. Schawlow, A. L. & Townes, C. H. Infrared and optical masers. *Phys. Rev.* **112,** 1940–1949 (1958).
42. Hossein-Zadeh, M., Rokhsari, H., Hajimiri, A. & Vahala, K. J. Characterization of a radiation-pressure-driven micromechanical oscillator. *Phys. Rev. A* **74,** 023813 (2006).
43. Teufel, J. D., Harlow, J. W., Regal, C. A. & Lehnert, K. W. Dynamical backaction of microwave fields on a nanomechanical oscillator. *Phys. Rev. Lett.* **101,** 197203 (2008).
44. Castellanos-Beltran, M., Irwin, K., Hilton, G., Vale, L. & Lehnert, K. Amplification and squeezing of quantum noise with a tunable Josephson metamaterial. *Nature Phys.* **4,** 929–931 (2008).
45. Thompson, J. D. *et al.* Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane. *Nature* **452,** 72–75 (2008).
46. Miao, H., Danilishin, S., Corbitt, T. & Chen, Y. Standard quantum limit for probing mechanical energy quantization. *Phys. Rev. Lett.* **103,** 100402 (2009).
47. Aoki, T. *et al.* Observation of strong coupling between one atom and a monolithic microresonator. *Nature* **443,** 671–674 (2006).
48. Hammerer, K., Aspelmeyer, M., Polzik, E. S. & Zoller, P. Establishing Einstein–Poldosky–Rosen channels between nanomechanics and atomic ensembles. *Phys. Rev. Lett.* **102,** 020501 (2009).
49. Rabl, P. *et al.* Strong magnetic coupling between an electronic spin qubit and a mechanical resonator. *Phys. Rev. B* **79,** 041302 (2009).
50. Teufel, J. D., Donner, T., Castellanos-Beltran, M. A., Harlow, J. W. & Lehnert, K. W. Nanomechanical motion measured with precision beyond the standard quantum limit. Preprint at <http://arxiv.org/abs/0906.1212v1> (2009).

Acknowledgements

T.J.K. acknowledges financial support by an Independent Max Planck Junior Research Group of the Max Planck Society, an ERC Starting Grant (SiMP), MINOS and a Marie Curie Excellence Grant as well as the Nanosystems Initiative Munich (NIM). J.P.K. acknowledges financial support by the Deutsche Forschungsgemeinschaft through project Ko 416/18, the German Excellence Initiative through the Nanosystems Initiative Munich (NIM) and LMUexcellent as well as LMUinnovativ. O.A. acknowledges financial support from a Marie Curie Intra European Fellowship within FP7 (project QUOM). T.J.K. thanks P. Gruss and the MPQ for continued Max-Planck support. The authors thank M.L. Gorodetsky for valuable discussions.

Author contributions

J.P.K. initiated the study and jointly devised the concept with T.J.K. G.A. and O.A. planned, carried out and analysed the experiments supervised by T.J.K. Q.P.U. and E.M.W. designed and developed suitable nanomechanical resonators. All authors discussed the results and contributed to the manuscript. R.R. contributed to the development of the experimental apparatus and A.S. assisted with the response measurements.

Additional information

Supplementary information accompanies this paper on www.nature.com/naturephysics. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to T.J.K.