

Cooling of an Optically Levitated Nanoparticle via Measurement-Free Coherent Feedback

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We demonstrate coherent, measurement-free optical feedback control of a levitated nanoparticle, achieving phonon occupations down to a few hundred phonons. Unlike measurement-based feedback, this all-optical scheme preserves the correlations between mechanical motion and the feedback signal. Adjustment of the feedback phase and delay provides precise and tunable control over the system dynamics. The ultimate cooling performance is currently limited by phase noise, which we analyze within a theoretical framework that outlines the constraints and prospects for reaching the motional ground state. Our results establish coherent feedback as a powerful tool for quantum control of levitated systems, extending beyond center-of-mass cooling.

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Active feedback control is a cornerstone of modern experimental physics widely used to stabilize and manipulate a broad range of systems, ranging from atomic ensemble [1,2], over mechanical oscillators [3–5] to space rockets [6]. In quantum optomechanics, it has been crucial for cooling the motion of mechanical systems to their quantum ground state [7,8] and for state control [9]. Such measurement-based feedback extracts information via photodetection which is processed electronically and used to generate corrective forces. While effective, this approach introduces fundamental and technical limitations: measurement backaction disturbs the system [10,11], and electronic noise is reintroduced through the feedback loop [5], degrading quantum coherence [12]. Coherent feedback offers a fundamentally different approach—one that avoids measurement altogether [13]. Instead, a light field interacts with the system and is redirected through an optical feedback loop to produce control forces without photodetection. This measurement-free scheme inherently preserves quantum correlations of light and motion, and avoids the introduction of classical noise through electronics, making it particularly attractive for quantum-limited control. Coherent feedback has already demonstrated promise in the control of light squeezing [14], atomic spin systems [15–17], solid state qubits [18], and membranes in optical cavities [19], while maintaining quantum coherence.

We explore the application of coherent feedback to a levitated nanoparticle system, a platform that combines excellent environmental isolation [20] with dynamic control over the potential landscape [21–27]. Recent advances have demonstrated motional ground-state cooling through active, measurement-based feedback [28–30] and via passive optical cavities [31–34]. In contrast, here we present the theoretical framework and the experimental realization of measurement-free, coherent feedback to manipulate the center-of-mass (c.m.) motion of an optically trapped nanoparticle. Controlled c.m. cooling is achieved by adjusting the feedback delay and phase via an optical fiber delay line.

General concept—To assess the relevance of coherent feedback in levitation optomechanics, we demonstrate c.m. cooling via linear cold damping and study the limitations toward ground-state cooling. Figure 1 illustrates our coherent optical feedback loop for a dielectric particle trapped in a single-beam optical tweezer (solid beam).

The particle motion $z_p(t)$ is imprinted on the phase of the scattered light $\phi_p(t)$. The backscattered light (arrows) is partially collected and redirected through an optical feedback loop back onto the particle, counterpropagating to the trapping beam. This feedback beam interferes with the trapping light, creating an interference pattern determined by the relative phase $\phi(t) = \phi_p(t - \tau) + \phi_0$ where ϕ_0 is the phase accumulated along the feedback loop. The interference pattern shifts the equilibrium position $z_{eq}(t)$ of the trapping potential, resulting in a position-dependent force. The new equilibrium position $z_{eq}(t)$ is now linked to the particle position in the past $z(t - \tau)$, with τ being the delay through the loop. Assuming a harmonic oscillator, a delay $\tau = \pi/2\Omega$ generates a velocity-dependent force, $F(t) \propto v_z(t)$, which can cool the particle's motion [35–37].

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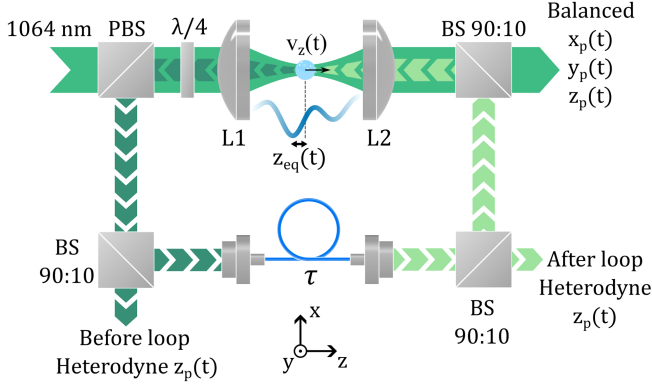


FIG. 1. A particle is trapped at a laser focus (wavelength $\lambda = 1064$ nm, NA = 0.77, elliptical polarization). The forward scattered light is collected by lens 2 (L2, NA = 0.55) to detect the particle's motion along x , y , z using balanced detection. The backward scattered light (arrows, dark green) is collected by the trapping lens (L1), separated from the trapping light by a polarizing beam splitter (PBS) and transmitted by an optical fiber of length $L \approx 1.3$ km. After a time τ the scattered light is focused back onto the particle using lens L2 (arrows, light green). The interference of counterpropagating scattered and trapping light creates an optical potential (blue curve) with shifted equilibrium $z_{\text{eq}}(t)$. The particle's position along $z_p(t)$ is detected via a heterodyne measurement using part of the backscattered light either before the delay line or after the delay line. Additional balanced forward detection of $x_p(t)$, $y_p(t)$, $z_p(t)$ is used to apply electrical cold damping.

Theory—The equation of motion of a particle trapped by the optical tweezer is

$$\ddot{z}_p(t) + (\Gamma_0 + \Gamma_c)\dot{z}_p(t) + \Omega^2 z_p(t) = \frac{F(t)}{m}, \quad (1)$$

where $z_p(t)$ is the particle's position at time t , m its mass, and Ω its mechanical eigenfrequency accounting for additional frequency shifts (see Ref. [38]). The damping coefficient $\Gamma_0 = \Gamma_m + \Gamma_r + \Gamma_d$ stems from the surrounding gas Γ_m [42], the optical trap Γ_r [43], and electrical linear feedback Γ_d [35]. The damping due to the coherent feedback $\Gamma_c = \beta\Omega \sin(\Omega\tau)$ depends on β , relating the delayed particle position and the equilibrium position through $z_{\text{eq}}(t) = \beta z_p(t - \tau)$. The parameter β depends on the feedback loop efficiency η , the accumulated phase ϕ_0 , the relative power of the trapping and feedback beams, their polarization and spatial overlap, and the numerical aperture of the lenses (see Ref. [38]). For small η , β changes sign for $\phi_0 = 0$ to π (see Ref. [38]).

The stochastic external force $F(t) = \sigma_m \chi_m(t) + \sigma_r \chi_r(t) + \sigma_c \chi_c(t)$ relates to residual gas collisions with $\sigma_m = \sqrt{2mk_B T \Gamma_m}$ [42], photon recoil with $\sigma_r = \sqrt{(2/5 + A^2)\hbar 2\pi P_d / (c\lambda)}$ [44], and phase noise in the feedback beam with $\sigma_c = m\beta\Omega^2 \sigma_\phi / B$ (see Ref. [38]). The geometrical factor A relates to the Gouy phase, P_d

to the scattered power, B to the phase of the collected light and the particle's position through $\phi_p(t) = Bz_p(t)$, while σ_ϕ^2 relates to optical phase fluctuations. We assume $\chi_i(t)$ to have zero mean and their respective autocorrelation functions to be delta functions.

From Eq. (1) we observe cooling (heating) of the particle motion for $\Gamma_c > 0$ ($\Gamma_c < 0$). The effect is the largest for maximum interference at $\phi_0 = 2\ell\pi$, with $\ell \in \mathbb{Z}$, where β reaches its extreme values (for other cases, see Ref. [38]).

The effective temperature of the c.m. motion is given by the equipartition theorem $T_{\text{eff}} = m\Omega^2 \langle z_p(t)^2 \rangle / k_B$ where k_B is the Boltzmann constant and $\langle z_p(t)^2 \rangle$ corresponds to the integral of the displacement power spectral density (PSD) $S_{zz}(\omega)$ given by

$$S_{zz}(\omega) = \frac{2(\sigma_m^2 + \sigma_r^2 + \sigma_c^2)}{m^2[(\Omega^2 - \omega^2)^2 + \omega^2(\Gamma_0 + \Gamma_c)^2]}. \quad (2)$$

The effective temperature is given by

$$T_{\text{eff}} = \frac{m\Omega^2}{2k_B} \left(\frac{\sigma_m^2 + \sigma_r^2}{m^2\Omega^2(\Gamma_0 + \Gamma_c)} + \frac{\sigma_\phi^2\Omega^2}{B^2} \frac{\beta^2}{\Gamma_0 + \Gamma_c} \right). \quad (3)$$

Hereafter, we need to distinguish two cooling scenarios: for weak cooling (small β), the second term in Eq. (3) is negligible, in contrast to strong cooling (large β) where both terms contribute similarly. For weak cooling with small β , Eq. (3) takes the well-known expression [42]

$$T_{\text{eff}} = \frac{T_0\Gamma_0}{\Gamma_0 + \Gamma_c} = \frac{\sigma_m^2 + \sigma_r^2}{2k_B m[\Gamma_0 + \beta\Omega \sin(\Omega\tau)]}, \quad (4)$$

where T_0 is the temperature in the absence of coherent feedback ($\beta = 0$ or $\Omega\tau = \pi$). Equation (4) suggests that the temperature decreases for increasing β and is optimized for a delay $\tau = \pi/(2\Omega)$ corresponding to a quarter oscillation period.

In contrast, for strong cooling with large β , the feedback force noise correlates with the particle motion, since the equilibrium position $z_{\text{eq}}(t)$ is dominated by phase noise, similar to measurement-based cold damping [35].

Since the two terms in Eq. (3) scale differently with β , an optimal feedback strength $\beta_{\text{opt}} = \sqrt{\sigma_m^2 + \sigma_r^2} B / (m\Omega^2 \sigma_\phi)$ exists for which a minimum temperature

$$T_{\text{eff,min}} = \frac{\sigma_\phi \Omega \sqrt{\sigma_m^2 + \sigma_r^2}}{k_B B \sin(\Omega\tau)} \quad (5)$$

is achieved assuming $\Gamma_0 \ll \Gamma_c$. From Eq. (5), we observe an increase in $T_{\text{eff,min}}$ with increasing noise σ_ϕ , σ_m , σ_r and $\sin(\Omega\tau) < 1$. Increasing beyond β_{opt} ultimately heats the particle and the detected PSD shows signatures of noise squashing (see Ref. [38]).

Experimental implementation—To study the effect of coherent feedback, a charged silica nanoparticle of radius $R \approx 97$ nm and mass $m \approx 7.07$ fg is trapped by an optical tweezer along the optical axis z (green beam) of elliptically polarized light at wavelength $\lambda = 1064$ nm, focused by lens 1 of numerical aperture $NA_1 = 0.77$ and the geometrical factor due to the Gouy-phase $A_1 = 0.83$ as depicted in Fig. 1. At the power $P_t \approx 300$ mW, the mechanical resonance frequencies of the particle are $(\Omega_x, \Omega_y, \Omega)/2\pi \approx (187, 162, 47)$ kHz. The light scattered forward by the particle is collected by lens 2 with numerical aperture $NA_2 = 0.55$ and used to detect the particle position in a balanced detection scheme [42]. This position measurement stabilizes the particle in 3D to a base temperature $T_0 \ll 300$ K by means of linear electrical cold damping ($\Gamma_d > 0$) [25,35].

The light scattered backward by the particle (dark green arrows) is collected using lens 1 and separated from the trapping beam by a polarizing beam splitter (PBS). This feedback beam passes through a single-mode fiber of length $L \approx 1.3$ km and refractive index $n_{\text{eff}} \approx 1.46$, causing a delay time $\tau = Ln_{\text{eff}}/c \approx 6.34$ μ s. The collected light (light green arrows) is focused on the particle by lens 2, closing the feedback loop with a total efficiency η . The trapping light is excluded from entering the feedback loop due to its polarization (see Supplemental Material, Fig. S6 [38]). The accumulated phase ϕ_0 along the feedback loop is controlled by changing the beam path length with a mirror placed on a piezoelectric element. For the coherent feedback, we use part of the feedback light in an additional heterodyne measurement [28,29] to detect the particle motion along z (see Fig. 1). The heterodyne detector is placed either in front of or after the delay line. All data presented in this Letter are acquired in backward heterodyne detection before the delay line unless specified differently.

To ensure the linear cooling regime described by Eq. (4), the feedback beam is optically attenuated, reducing $|\beta|$. For a delay $\tau\Omega \approx \pi/2$, a velocity dependent force heats ($\Gamma_c < 0$) or cools ($\Gamma_c > 0$) the particle motion, depending on ϕ_0 as depicted in Fig. 2. In comparison to the motion in the absence of coherent feedback (dark green), the coherent feedback cools for $\phi_0 = 0$ with $\Gamma_c > 0$ (light green, circle) and heats for $\phi_0 = \pi$ with $\Gamma_c < 0$ (blue, square), represented by the decreasing or increasing area of the PSDs. The observed damping rate reaches $(\Gamma_0 + \Gamma_c)/2\pi \approx 1.92$ kHz at maximum cooling, corresponding to $\beta \approx 4.10 \times 10^{-2}$, while the omnipresent damping rate equals $\Gamma_0/2\pi \approx 78$ Hz (see Ref. [38]). Note that the motion along x, y remains unaffected for $\Gamma_c \neq 0$.

To demonstrate the effect Ω on the cooling efficiency, we measure T_{eff} for varying Ω which corresponds to different $\Gamma_c \propto \Omega \sin(\Omega\tau)$. The resonance frequency Ω is varied by changing the optical tweezer power such that β remains constant (see Ref. [38]). We double the delay to $\tau' = 2\tau$ by

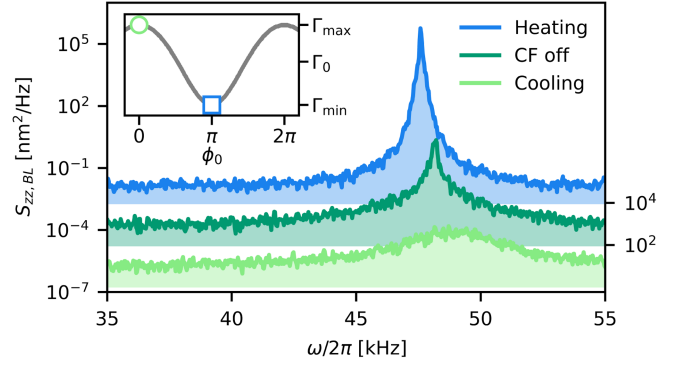


FIG. 2. PSD of particle displacement with coherent feedback at $p = 1 \times 10^{-4}$ mbar. Depending on the phase ϕ_0 , the coherent feedback cools (light green, circle) or heats (blue, square) the particle motion in comparison to the absence of feedback light (dark green). The individual particle displacements are offset to increase visibility. Inset: for $\phi_0 = 2n\pi$, the damping $\Gamma_c > 0$ is maximal (light green circle), while for $\phi_0 = (2n + 1)\pi$, $\Gamma_c < 0$ is minimal (blue square).

placing a retroreflector at the end of the delay line followed by a circulator (see Supplemental Material, Fig. S6 [38]). The phase ϕ_0 remains now uncontrolled. Figures 3(a) and 3(b) display $T_{\text{eff}}(\Omega)$ in time for two different $\Omega\tau$. We estimate $T_{\text{eff}}(\Omega)$ from the area of the PSD of the particle displacement (see Ref. [38]). ϕ_0 governs if the particle motion is cooled or heated. For a delay $\Omega\tau' > \pi$ at $\Omega/(2\pi) = 48$ kHz, as in Fig. 3(a), the lowest temperature and pronounced temperature variations are observed, suggesting strong coherent feedback ($\Gamma_c \gg \Gamma_0$). In contrast, for $\Omega\tau' \approx \pi$ at $\Omega/(2\pi) = 39$ kHz, as in Fig. 3(b), the particle motion remains mainly unaffected for all time as expected from a weak feedback strength ($\Gamma_c \approx 0$).

Figure 3(c) depicts $T_{\text{min}}(\Omega)$ in dependence of Ω , where each data point corresponds to the median of all instances of $T_{\text{eff}}(\Omega) < T_0(\Omega) + 2\Sigma[T_0(\Omega)]$ where Σ is the standard deviation (blue shaded region). Rearranging Eq. (4) allows to fit the data to

$$\frac{1}{T_{\text{eff}}(\Omega)} - \frac{1}{T_0(\Omega)} = \frac{\beta}{\Gamma_0(\Omega)T_0(\Omega)} \Omega \sin \Omega\tau' \quad (6)$$

shown as the green solid line, where the fitting parameters are $\beta/(\Gamma_0 T_0)$ and τ' . The fitted value $\tau' = 12.9 \pm 0.04$ μ s is in good agreement with the expected value $\tau' \approx 12.7$ μ s. From the fit we extract $\beta \approx (6.18 \pm 0.4) \times 10^{-4}$, corresponding to $\Gamma_c/2\pi \approx 20$ Hz for $\Omega\tau' \approx 3\pi/4$ [Fig. 3(a)] and $\Gamma_c/2\pi \approx 0.55$ Hz for $\Omega\tau' \approx \pi/2$ [Fig. 3(b)], where the feedback beam has been optically attenuated in comparison to Fig. 2.

To estimate the minimum achievable temperature $T_{\text{eff,min}}$ in our system, the feedback phase is stabilized at $\phi_0 \approx 0$ and Γ_c is adjusted by attenuating the feedback beam power, thereby emulating a variable feedback loop efficiency η ,

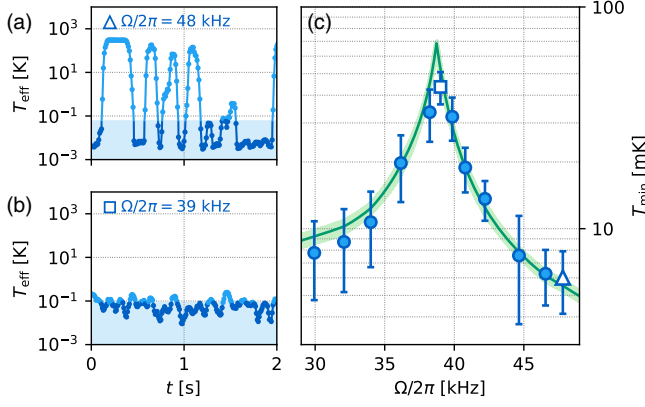


FIG. 3. (a),(b) Center-of-mass temperature without phase lock (free-running ϕ_0) leading to random cooling and heating in time. (a) At the resonance frequency $\Omega/(2\pi) = 48$ kHz with $\Omega\tau' > \pi$, strong coherent feedback manifests itself in high maximum and low minimum temperatures due to $\max(|\Gamma_c|) \gg \Gamma_0$. (b) The coherent feedback is ineffective for $\Omega/(2\pi) = 39$ kHz with $\Omega\tau' \approx \pi$ leading to a reduced variation in T_{eff} due to $|\Gamma_c| \ll \Gamma_0$. (c) Minimum achieved c.m. temperature T_{min} for different resonance frequencies Ω . For mismatched delays at $\Omega/(2\pi) \approx 39$ kHz the cooling is inefficient ($\Omega\tau' \approx \pi$). For smaller and larger Ω the delay is more optimized and the coherent feedback cools efficiently to lower T_{min} . The doubled length of the delay line leads to $\tau' = 12.7$ μs . Each point is the average of five measurements of T_{min} , and the error bars represent their standard deviation. T_{min} is the median of the blue shaded region in (a),(b) corresponding to $T_{\text{eff}} < T_0(\Omega) + 2\sigma[T_0(\Omega)]$. The data are fitted to Eq. (6) (green line) taking the fitting errors into account (green shaded area).

with $\Gamma_c \propto \sqrt{\eta}$ (see Ref. [38]). Additionally, we maximize Ω to benefit from lower phase noise. Figure 4(a) displays the linear decrease of $T_{\text{eff}}(\Omega)$ for increasing but small Γ_c (blue circles) as expected from Eq. (4). For large enough Γ_c , $T_{\text{eff}}(\Omega)$ starts leveling off despite increasing feedback gain. This effect is due to the fact that phase noise starts dominating over the phase imprinted by the particle motion $\phi_p(t)$, heating the particle motion as predicted by Eq. (3). At $p \approx 3 \times 10^{-7}$ mbar, we measure a minimum temperature $T_{\text{eff,min}} \approx 719 \pm 65$ μK at $\Gamma_c \approx 2\pi \times 893$ Hz, corresponding to $n_{\text{min}} = k_B T_{\text{eff,min}}/(\hbar\Omega) = 351 \pm 32$ phonons. The particle motion is predominantly cooled by coherent feedback with $\Gamma_c \approx 10\Gamma_d$. We fit the measured displacement PSDs to Eq. (2) accounting for additional detector noise. Using the fit parameters in Eq. (3), we calculate the effective temperature T_{eff} . We have only an indirect measurement of $\Gamma_c \propto c_h$ where $c_h = V(t)/z(t)$ relates the detected heterodyne voltage with the displacement. Fitting T_{eff} to Eq. (3) allows one to extract Γ_c . The fit (green solid curve) incorporates all dominating noise sources and captures the minimum temperature $T_{\text{eff,min}}$. According to Eq. (5), the minimum temperature (blue dotted line) equals $T_{\text{min}} = 847$ μK , which is in good agreement with the

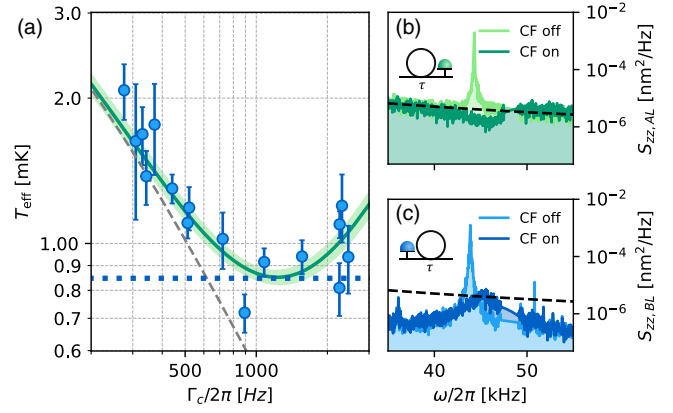


FIG. 4. (a) T_{eff} versus Γ_c by varying the feedback power. The minimum temperature achieved is $T_{\text{eff,min}} \approx 719 \pm 65$ μK , corresponding to $n_{\text{min}} = k_B T_{\text{eff,min}}/(\hbar\Omega) = 351 \pm 32$ phonons. Data and error bars represent the mean and standard deviation of five measurements. The data are fitted to Eq. (3) (green solid line) with the corresponding fitting error (light green shaded region). For negligible phase noise heating $\sigma_c = 0$, we recover the linear decay of T_{eff} with increasing Γ_c (dashed gray line). Equation (5) (blue dotted line) predicts the minimum reachable temperature. (b) PSD of the particle displacement detected after the delay line. Without coherent feedback (CF) for $\Gamma_c = 0$ (light green), the particle motion is clearly visible, while with CF for $\Gamma_c > 0$ (dark green), noise squashing indicates that the feedback is dominated by phase noise. The displacement noise due to the phase noise (black dashed line) matches the data [see Eq. (S37) in [38]]. (c) PSD of the particle displacement in front of the delay line. When the CF is on $\Gamma_c > 0$ (dark blue), the particle amplitude is reduced in comparison to $\Gamma_c = 0$ (light blue) but clearly visible. The peak value of the PSD matches the displacement noise observed in the detector after the delay line.

experiment. For $\sigma_c = 0$, we recover the linear decay of T_{eff} with increasing Γ_c (dashed gray line).

The main limitation of the minimal effective temperature $T_{\text{eff,min}}$ is the phase noise σ_ϕ introduced by the delay line. We compare the PSD of the particle's displacement after [Fig. 4(b)] and before the delay line [Fig. 4(c)] with (dark points) and without coherent feedback (light points). Here, Γ_c equals the largest value used in Fig. 4(a). The detector after the delay line shows noise squashing, a dip below the noise floor (dashed line), due to increased phase noise once coherent feedback is applied (dark green). At the detector in front of the delay line, the signal-to-noise ratio remains well above one even with coherent feedback (dark blue). The particle is always exposed to the accumulated phase noise, since the delay line is required for cooling. The displacement noise at Ω for β_{opt} is extracted from a fit to the noise floor of the detector after the delay line to $S_{zz,\text{AL}}(\Omega) \approx 2\sigma_\phi^2/B^2 = 4 \times 10^{-24}$ m^2/Hz (dashed line), corresponding to the phase noise contribution [see Fig. 4(b)].

Discussion—To reach ground state with coherent feedback, the minimum achievable phonon occupation $n_{\text{min}} = k_B T_{\text{eff,min}}/\hbar\Omega$ described by Eq. (5) shows that

lowering phase noise σ_ϕ , residual gas collisions σ_m , and photon recoil σ_r is beneficial. Increasing Ω leads to an overall decrease in the minimum phonon number by $\propto 1/\Omega^2$, assuming $1/f$ phase noise and $\sigma_\phi \propto L \propto 1/\Omega$ due to a shorter delay line. In a backaction-limited experiment, smaller particles are also advantageous due to $n_{\min} \propto R^3$ and enhanced collection efficiency further contributes positively. In current levitation experiments, phase noise [34,45] and residual gas pressure [20,28,46] have shown significant improvements. Assuming a phase noise reduction by 30 dB [47,48], and a $2.5\times$ smaller particle promises at $p = 1 \times 10^{-8}$ mbar [20,28] a minimum phonon occupation of 0.9 phonons, reaching ground state. In the absence of external decoherence ($\sigma_\phi, \sigma_m = 0$), we recover the fundamental limit of measurement-based feedback $n_{\min} = (1/\sqrt{\eta_{\text{det}}} - 1)/2$ [19] which arises from the imprecision noise in the position being mapped to the equilibrium position via $z_{\text{eq}}(t) \propto z_p(t - \tau)$.

Outlook and conclusion—In summary, we have demonstrated the impact of measurement-free coherent feedback on the motion of a levitated particle. Our implementation employs an all-optical feedback loop that can preserve the correlations between the mechanical motion and the feedback signal. By tuning the feedback phase and its delay, we achieved full control over the system dynamics. Furthermore, we presented a theoretical framework that outlines the fundamental limitations to ground-state cooling. Levitated nanoparticles are inherently low-frequency oscillators, which necessitates longer feedback delays compared to other optomechanical systems [19]. This extended delay introduces increased phase noise, which scales with the delay line length. In many practical applications, phase noise may also be frequency dependent, often becoming more significant at lower frequencies. As a result, levitation may initially appear less suitable for coherent feedback cooling. However, levitation in high-frequency regimes—such as librational degrees of freedom [34,49–51], levitation in standing-wave optical traps [45], or using high-refractive-index materials [52–54]—offers more promising prospects. Additionally, unique three-dimensional cooling of levitated particles could be enabled through multidirectional detection schemes [55], such as those implemented on integrated platforms [56]. Importantly, coherent feedback has applications beyond cooling. It can be employed to engineer a variety of system interactions, including dissipative and nonreciprocal dynamics [57–60], optomechanics with Fano resonators [61], and motional entanglement [13,62,63]. Some of these approaches may circumvent the need for long delay lines and thus avoid the associated phase noise, making coherent feedback a powerful tool for advancing quantum control of levitated particles.

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Data availability—The data that support the findings of this article are openly available [64].

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