

Phase-adaptive cooling of fringe-trapped nanoparticles at room temperature in hollow-core photonic crystal fiber

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Active feedback cooling of levitated dielectric particles is a pivotal technique for creating ultrasensitive sensors and probing fundamental physics. Here, we experimentally demonstrate phase-adaptive feedback cooling of silica nanoparticles optically trapped in standing-wave potential formed by two co-linearly polarized counterpropagating diffraction-free guided modes in a hollow-core photonic crystal fiber at room temperature. Unlike standard laser intensity- or Coulomb force-based feedback, our approach modulates the relative optical phase between the counterpropagating fiber-guided fundamental modes proportionally to the particle's axial momentum. This generates a Stokes-like dissipative force that effectively damps the center-of-mass motion without introducing excess recoil heating and can also work with uncharged particles. At 2 mbar air pressure, the axial center-of-mass temperature of a 195 nm silica particle is reduced by half upon application of the feedback and to 58.6 K at 0.5 mbar. The measured mechanical spectra agree well with our analytical model, validating the cooling mechanism. We envision that this approach will open up pathways toward long-range, coherent control of mesoscopic particles inside hollow-core fibers, offering a fiber-integrated versatile platform for future quantum manipulation.

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I. INTRODUCTION

In recent decades, substantial progress has been made on long-standing challenges in both applied and fundamental physics, notably design of sensors with exceptionally high sensitivity and exploration of quantum mechanics in gravitating objects. Optomechanics [1] offers an experimental testbed connecting these seemingly distant branches of physics. As a leading platform in optomechanics, optical levitation in vacuum [2] allows suspension of solid-state particles of sizes ranging from nanoscale to macroscale using light-induced forces, providing a high degree of isolation from its thermal environment. These optically trapped mechanical oscillators have become central to a diverse range of applications, including probing limits of quantum mechanics at mesoscopic scales [3], sensing ultraweak forces [4,5], and testing models of wavefunction collapse [6,7].

Realizing the full potential of levitated systems requires precise control over the particle's center-of-mass (CoM) motion, necessitating suppression of both thermal and quantum fluctuations. Various cooling strategies have been developed for this purpose, including passive sideband cooling in high-finesse cavities [8–11] and active feedback schemes [12] such as parametric feedback [13] and cold damping [14–17]. However, these methods face key limitations. Optical implementations relying on laser *intensity* modulation inherently introduce recoil heating [18], while electrostatic cooling techniques [17], though offering an alternative to optical methods, are restricted to charged particles and remain susceptible to stray electric fields. Hybrid approaches have also been demonstrated in which optical sidebands are generated via phase modulation, yet feedback cooling is achieved through the amplitude modulation of these sidebands [19].

These limitations have motivated the theoretical development of phase-adaptive feedback [20–22]—a conceptually distinct cooling technique in which continuous adaptation of optical *phase* of the trapping light, in response to the particle's motion, serves as the *sole* actuator for phonon energy extraction. This excess-recoil heating-free technique enables velocity-dependent damping without modifying the trapping potential, offering a pathway to all-optical and intensity-noise immune cooling even for uncharged particles. While theoretical bounds of the phase-only feedback have been established in the dual-beam tweezer configuration [21], its experimental validation remains limited.

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In this paper, we report an experimental realization of phase-adaptive feedback cooling, demonstrated on mesoscopic dielectric particles trapped in a hollow-core photonic crystal fiber (HC-PCF). Particles are confined at the antinode of a standing-wave trap (SWT), formed by the interference of two co-linearly polarized counterpropagating, fiber-guided LP₀₁ modes. In response to the axial momentum of the particle, we shift the SWT by dynamically adapting the relative phase between the guided beams. Unlike prior amplitude-based techniques, which introduce excess recoil [18], the SWT actuation generates a Stokes-like dissipative force proportional to the particle's axial velocity [21] without altering the depth of the trapping potential, thus providing a route to suppress thermal noise at room temperature and high vacuum.

Beyond demonstrating the principle, feedback implementation in HC-PCF further ushers additional advantages: Particles can be stably confined over multiple Rayleigh lengths [23–26] with low leakage loss [27] and in tunable environments [23,28]. The experimental configuration also supports scalable array of particles along the fiber axis [29], offering a powerful platform for exploring cooperative phenomena [30]. This synergy of a conceptually distinct cooling mechanism with a versatile fiber-based trap creates a toolkit for levitated optomechanics. Phase-adaptive cooling in HC-PCF enables the preparation of dielectric particles in low motional states at designated fiber positions. This includes systems with internal degrees of freedom, e.g., nitrogen-vacancy centers [31]. Once prepared, these can be transported using an optical conveyor belt along the HC-PCF [32] over long distances, even along curved trajectories, with minimal decoherence, enabling readout, and entanglement protocols at remote sites [33]. With these capabilities, we establish an innovative framework for long-range control of mesoscopic particles and open avenues toward mobile quantum probes and distributed fiber-based quantum technologies [34].

The paper is organized as follows: In Sec. II, we provide details of the experimental setup for the phase-adaptive feedback cooling of an optically trapped nanoparticle inside an HC-PCF. Section III demonstrates the cooling performance of this feedback scheme. Subsequently, Sec. IV outlines the discussions on the issue of internal bulk temperature and a potential route toward quantum ground state. The concluding remarks are finally presented in Sec. V.

II. EXPERIMENTAL SETUP

A schematic of our experimental apparatus is depicted in Fig. 1(a). The setup combines the SWT inside an HC-PCF with an active feedback loop to achieve phase-adaptive cooling of a levitated nanoparticle. To reduce gas damping and external perturbations, the system is enclosed in a vacuum chamber. The specific configurations for optical trapping, detection of eigenmotions, and feedback implementation are described below.

A. Optical trapping

A 10 cm long twisted single-ring HC-PCF [35], with a core diameter of 44 microns and an outer diameter of 270 microns, is placed inside a vacuum chamber. A scanning electron micrograph image of the fiber cross section is shown

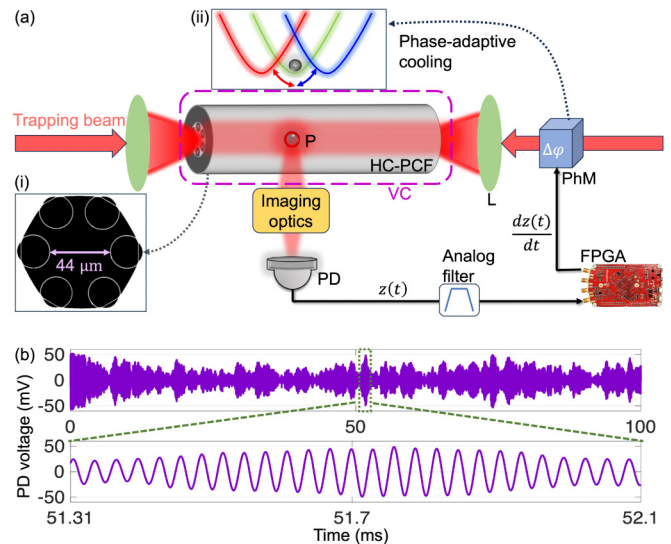


FIG. 1. (a) Schematic of phase-adaptive active feedback cooling in a dual-beam tweezer setup. P: levitated particle, VC: vacuum chamber, HC-PCF: hollow-core photonic crystal fiber, L: 75 mm lens, PD: photodiode as motion detector, PhM: phase modulator, FPGA: red-pitaya STEMLab-125. The trapping beam is a 1064 nm continuous-wave laser. The total trapping power is 0.75 W. The imaging optics are a combination of spatial aperture, telescope, and lenses. The position signal is processed using a second-order Butterworth electronic bandpass filter close to the axial eigenfrequency of the trapped particle. The feedback logic processes time-dependent position $[z(t)]$ in order to produce a feedback signal proportional to the filtered axial velocity ($\frac{dz(t)}{dt}$) of the particle. (i) Scanning electron micrograph of the HC-PCF. (ii) Working principle of phase-adaptive cooling. The optical potential is dynamically adjusted by detuning the relative phase between the counterpropagating trapping beams. (b) The demodulated photodiode electrical signal close to the axial eigenfrequency (33.7 kHz) of a 195 nm silica particle at 2 mbar pressure featuring stochastic oscillations on a diffusive time scale (top figure). Note that this is a single trajectory of the oscillator. For timescale shorter than the mechanical decoherence time (γ^{-1}), the oscillator features damped deterministic harmonic oscillations (bottom figure).

in Fig. 1(a)(i). The twist rate is 0.5 rad/mm and the circular birefringence of the fiber is 10^{-9} RIU. The eigenmodes of the helically twisted fiber are circularly polarized [36]. Thus, if co-linearly polarized laser beams are launched from each end of the fiber, the propagating modes will preserve the ellipticity and will suffer identical polarization rotation at every location inside the fiber. This allows generation of standing wave pattern over long distances along the fiber.

Laser light at 1064 nm (λ) is coupled to the fundamental LP₀₁ mode of the fiber from each side. The spacing between two adjacent nodes or antinodes is 532 nm. The coherence length of the laser is 5 km ensuring high-quality fringe visibility over long distances. The trapping experiment is performed using silica nanoparticles (Kisker GmbH PSI-5%) of various sizes as long as the particles can be trapped by standing wave fringes (see Appendix A). We start our description of trapping and cooling with 195 nm silica particles. The initial solution is diluted with isopropanol to a mass concentration of 10^{-8} and

loaded into the optical trap by aerosol launching technique [37] until one particle gets trapped in front of the fiber facet. By reducing the power in one of the tweezer arms, the particle is pushed inside the hollow core of the fiber.

B. Detection scheme

The scattered light from the particle coming through the semitransparent fiber cladding is collected using a telescope and a variable spatial aperture. It is simultaneously focused on a fast camera and an InGaAs (indium gallium arsenide) amplified photoreceiver. The spatial aperture size can be adjusted in order to maximize the amount of scattered light from the particle reaching the detector while minimizing the impact of the stray light from the semitransparent fiber cladding. At low pressure, the particle's motion is driven by thermal noise. The dipole radiation from the moving particle interferes with the cladding stray light and parts of the guided fiber modes, resulting in brightness modulation of the detected light on the photodiode (see Appendix B). This electrical signal contains motional information about both the radial (transverse) and the axial eigenmodes. The radial eigenfrequency of the 195 nm silica particle at 0.75 W of trapping power is ~ 1.3 kHz, whereas the axial eigenfrequency ($\frac{\Omega}{2\pi}$) is ~ 33.7 kHz (see Fig. 6 in Appendix B). Due to the large disparity in confinement scales, i.e., the fringe spacing of 532 nm along the axial direction versus the fiber core diameter of 44 μm along the radial direction, the radial optical forces are roughly three orders of magnitude weaker than the axial forces. The output signal of the photodiode is filtered with a second-order analog bandpass Butterworth filter close to the axial eigenfrequency (33.7 kHz). Figure 1(b) shows the resultant electrical signal. In time domain, the CoM motion of an underdamped optically trapped particle in high vacuum exhibits two well-defined dynamical regimes [38] depending on the mechanical damping rate (decoherence rate γ). At short timescales, $t \ll \gamma^{-1}$, the eigenmotion of particle retains phase coherence, and exhibits ballistic (inertial) behavior characterized by deterministic harmonic oscillations at the mechanical eigenfrequency [Fig. 1(b), bottom]. However, at longer timescales, $t \gtrsim \gamma^{-1}$, residual gas collisions progressively randomize the phase of the particle motion and damp its coherent oscillations. In this limit, random thermal fluctuations dominate the dynamics, and the motion transitions to a stochastic regime governed by Brownian thermal noise. The particle's position therefore exhibits stochastic diffusive behavior, characteristic of a thermally driven damped harmonic oscillator [Fig. 1(b), top].

C. Feedback implementation

Before detailing the experimental feedback loop, we first outline the mechanism of our phase-adaptive cooling technique. In our feedback implementation [21], the relative phase between the counter-propagating optical modes is modulated as

$$\phi(t) = \frac{C}{\Omega} \times \lim_{dt \rightarrow 0} \frac{q_{\text{det}}(t) - q_{\text{det}}(t - dt)}{dt}, \quad (1)$$

where dt is the time increment between measurements and the measured (dimensionless) position $q_{\text{det}}(t) = q(t) + \eta W^{\text{det}}(t)$ includes additive detection noise characterized by amplitude

η and Wiener increments $W^{\text{det}}(t)$. The parameter C quantifies the feedback strength. The principle behind this feedback mechanism is illustrated in Fig. 1(a)(ii), where the optical potential is shown to adapt dynamically to the particle trajectory. As the particle drifts away from the potential minimum of the axial trap, the fringe position is dynamically shifted by controlling the relative phase between the trapping beams. This, in turn, generates a viscous drag force [see Eq. (C1) in Appendix C], thereby damping the CoM motion.

Experimentally, the feedback signal is generated by passing the filtered photodiode output through a feedback logic circuit [see Fig. 1(a)]. The feedback circuit can be analog or digital. The analog circuit was implemented by using operational amplifiers in the beginning and later on digital feedback control is performed with Red Pitaya FPGA (STEMlab 125-14). The analog circuit consists of a unity gain derivative circuit, a phase shifter for additional adjustment of the phase delay, an inverter to switch from cooling to heating and a switch for turning off/on the feedback logic. For FPGA implementation, we used in-phase and quadrature module (IQ-module) from Pyrp1 package [39]. The module performs convolution of the input signal with reference sine and cosine functions and can be modified to be used as a narrow-bandwidth bandpass filter. We set the center frequency of the filter to be the axial eigenfrequency (33.7 kHz) of the oscillator. We also provide a suitable phase shift to delay the output by $\frac{\pi}{2\Omega}$ from the input signal so that it can work as a feedback signal in the cold-damping regime. Finally, a gain factor is set to adjust the strength of the applied feedback. Additionally, if the oscillator's eigenfrequency is low, one can also use a usb-daqcard to implement the feedback logic.

In order to control the relative phase between the trapping beams, a lithium niobate phase modulator is installed in one of the tweezer arms. The modulator is driven by the amplified feedback signal using a high-voltage amplifier. After trapping the silica particle, the fiber is evacuated using a turbo-molecular pump. At low pressure, inertial motion of the particle becomes underdamped featuring mechanical eigenresonances (see Fig. 6 in Appendix B). We observed slight variation in the trapping frequencies (0.8 kHz) over the course of experiment, most likely caused by the intensity fluctuations of the trapping laser. The feedback is switched on when the particle's motion becomes ballistic [13], usually below 5 mbar.

The phase noise of the trapping laser can limit the feedback cooling (see Appendix D). It induces CoM heating particularly at low-phonon occupancy, when heating from other sources, such as background gas, reduces. This effect can be mitigated with advanced laser phase stabilization techniques such as Pound-Drever-Hall technique [19] and phase-noise eater based on imbalanced Mach-Zehnder interferometers [40,41].

III. RESULTS

We now demonstrate active feedback cooling of the CoM motion of the fringe-trapped optomechanical system. The protocol dynamically adjusts the optical phase via a feedback loop, modulating the trapping potential in a velocity-dependent manner to enhance damping. The cooling

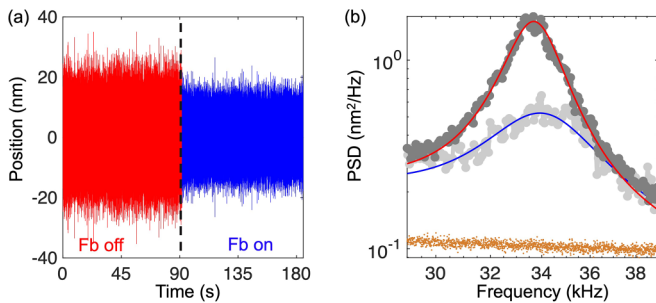


FIG. 2. (a) Long-time traces of axial motion of 195 nm silica particle with (blue) and without (red) feedback (Fb) cooling at 2 mbar. The sharp spikes in the time trace are caused by detectors and electronics. (b) Axial mechanical spectra of the particle at 2 mbar with (light-gray) and without (dark-gray) feedback cooling are shown. The axial eigenfrequency is 33.7 kHz. The copper line indicates the noise floor of the detection scheme. The spectra are fitted with Eq. (2).

performance of this phase-adaptive technique is then quantified through the spectral analysis.

A. Cooling action

The effect of the feedback cooling at 2 mbar along the axial direction is shown in Figs. 2(a) and 2(b). The time-domain traces of oscillation of the particle without (red) and with (blue) feedback cooling are shown in Fig. 2(a). The signal is calibrated using equipartition theorem [42] in the absence of feedback. Upon activation of the phase-adaptive feedback, the root-mean square (RMS) amplitude of the motion reduces, indicating an increase in the natural damping rate γ .

A complementary frequency-domain representation is shown in Fig. 2(b). The dark-gray curve shows the position power spectral density (PSD) of the particle motion without feedback, while the light-gray curve corresponds to the PSD under feedback cooling. The copper-colored line marks the detection noise floor when there is no particle present in the optical trap. The application of feedback results in a broadened spectrum and reduced peak amplitude, reflecting increased damping and suppressed fluctuations. Moreover, the integrated area between the position PSD and the noise floor—proportional to the particle’s potential energy (CoM temperature) along the axial direction—is significantly reduced, confirming that thermal energy is extracted from the system by the feedback mechanism. In principle, further reduction in temperature is possible until the PSD goes below this noise floor ($0.4 \text{ nm}/\sqrt{\text{Hz}}$).

Our single-pixel amplified photodiode-based side-scattered detection resembles in-loop detection schemes [17]. To accurately model the experimental spectra near resonance, we now introduce the effects of detection and feedback noises in the phase-adaptive cooling protocol. Sources of these noises likely include the detected and amplified stray extraneous scattered light from the fiber cladding, as well as intrinsic laser noises. For particles of mass m , the scattering cross section decreases as $\sigma_{\text{scat}} \propto m^2$ [13,43], requiring a wider collection aperture to gather sufficient signal for imaging smaller particles. However, increasing the aperture also admits more extraneous light,

thereby enhancing the amplified noises. Ultimately, when feedback is applied, this noise is reinjected into the trap, manifesting as feedback-induced noise.

In order to model the motional PSD under phase-adaptive cooling, the governing coupled stochastic difference equations [see Eq. (C1) in Appendix C] are discretized and analyzed in the long-time limit to capture the system’s steady-state behavior. In this framework, the detected dimensional position signal is expressed as $z_{\text{det}}(t) = z(t) + q_{\text{zpm}}\eta W^{\text{det}}(t)$, where $z(t)$ captures the thermal and feedback-induced fluctuations, while the second term accounts for additive detection noise [44]. Here, q_{zpm} denotes the zero-point motion amplitude of the axial mode. Incorporating these contributions, the PSD near the axial mechanical resonance takes the form (see Appendix C):

$$S(\omega) = \frac{2\gamma k_B T_{\text{th}}/m}{(\omega^2 - \Omega^2)^2 + (\gamma + \beta C)^2 \omega^2} + \left(\frac{\hbar}{m\Omega}\right) \frac{\eta^2}{\omega^2} + \left(\frac{\hbar}{m\Omega}\right) \left[\frac{(\eta\beta C)^2}{(\omega^2 - \Omega^2)^2 + (\gamma + \beta C)^2 \omega^2} \right], \quad (2)$$

where k_B is the Boltzmann’s constant. The above spectrum comprises three distinct contributions: The first term represents the desired feedback-damped mechanical response, characterized by the parameter $\beta = 4.49 \text{ GHz}$, which is associated with the trap stiffness (κ) and the wavevector (k_0) of light. The second term accounts for detection noise of magnitude η and contributes an apparent amplitude offset near resonance. Its ω^{-2} scaling arises from additive noise in the position measurement [44], consistent with the discrete-time stochastic model (see Appendix C). The third term denotes the undesired feedback heating arising due to the amplified detection noise being fed back into the optical trap. Away from the resonance, the spectrum is limited by the base electronic noise floor of the detector. The feedback gain C governs a critical performance trade-off: increasing C enhances cooling rates but amplifies feedback noise contributions.

We fit the position PSD in Fig. 2(b) for feedback-off (solid red line) and feedback-on (solid blue line) conditions using Eq. (2), extracting $\gamma = 2\pi \times 2 \text{ kHz}$, $\eta = 9.4 \times 10^6 \sqrt{\text{Hz}}$, and $C = 3.84 \times 10^{-6}$ through a two-step procedure: first, the feedback-off spectrum determines η , Ω , and γ ; second, with these fixed, the feedback-on spectrum yields C . The value of η is independently verified via thermal occupancy measurements under feedback cooling.

In our experiment, particle loss typically occurs below 1 mbar due to the absence of full three-dimensional cooling. Nonetheless, in certain cases, stable trapping is maintained down to 0.5 mbar. The CoM temperature of the axial eigenmode is proportional to the integrated area between the measured spectrum and the noise floor, using the feedback-off spectrum as a reference at 293 K. As shown in Fig. 3(a), the temperature decreases linearly with pressure, consistent with the expected suppression of Brownian noise.

The reduction in CoM temperature [42] can be visualized in phase space [see Fig. 3(b)]. The red and blue distributions correspond to the cases without and with feedback, respectively. These are obtained by sampling the mechanical trajectory over a time interval much longer than the oscillation period, using a sampling rate that exceeds the mechanical

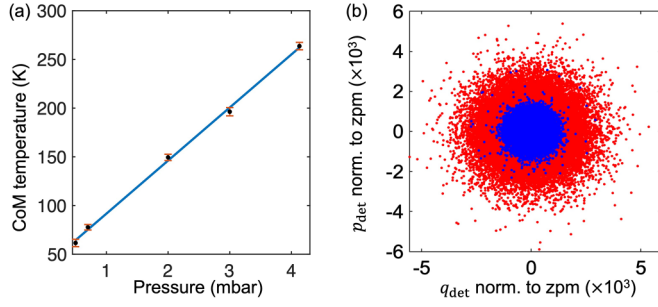


FIG. 3. (a) CoM temperature as a function of pressure. The CoM temperature is proportional to the integrated area between the measured spectrum and the noise floor, after calibrating them with uncold spectral area at 293 K. The error bar indicates standard deviation of temperature calculated by measuring the spectrum consecutively 32 times at a given pressure. (b) Experimental phase-space distributions at 0.7 mbar with (blue) and without (red) feedback cooling. The detected position (q_{det}) and momentum (p_{det}) quadratures are normalized to the zero-point motion (zpm) of the oscillator in motional ground state, where $q_{\text{zpm}} = 8.22$ pm and $p_{\text{zpm}} = 12.1$ yN/s.

decoherence time, $1/\gamma$. The experimentally measured phase-space distribution was recorded at a pressure of 0.7 mbar, based on continuous time traces exceeding 120 s. In the absence of feedback (red points), the oscillator exhibits a broad thermal Gaussian distribution, characteristic of the bath temperature T_{th} . When feedback is applied (blue points), the distribution contracts significantly, indicating a reduction in CoM temperature. This compression in phase space reflects a decrease in thermal energy and remains consistent with energy equipartition, even under externally applied damping.

B. Cooling larger particles

A disadvantage of single-pixel detection using an amplified photodiode is that the extraneous light, which comes out of the fiber cladding gets collected and amplified, setting up a strong detection noise background, ultimately contributing to the feedback noise. One way to tackle this problem is using a larger 400 nm silica particle, which scatters more light due to an increase in scattering cross section ($\sigma_{\text{scat}} \propto m^2$) and thereby allowing us to close the spatial filter in front of the photodiode, offering a lower noise floor. The detection floor in this experimental configuration is $26 \text{ pm}/\sqrt{\text{Hz}}$. The particle could be stably trapped down to 0.5 mbar. Figure 4 shows the feedback cooling in action for a bigger 400 nm particle. The axial eigenfrequency of the 400 nm silica particle at 0.75 W of trapping power is ~ 24.7 kHz. All the spectra are fitted with Eq. (2) for negligible η . The red fit indicates PSD of position of the oscillator at 2 mbar in the absence of feedback cooling, while the blue curve indicates spectrum with feedback cooling at 2 mbar. The spectrum fitted in magenta is recorded at 0.5 mbar with feedback cooling on. The fitting parameters are $\beta = 8$ GHz and $C = 4.1 \times 10^{-7}$. The corresponding CoM temperature for the larger 400 nm particle is 11.3 K at 0.5 mbar.

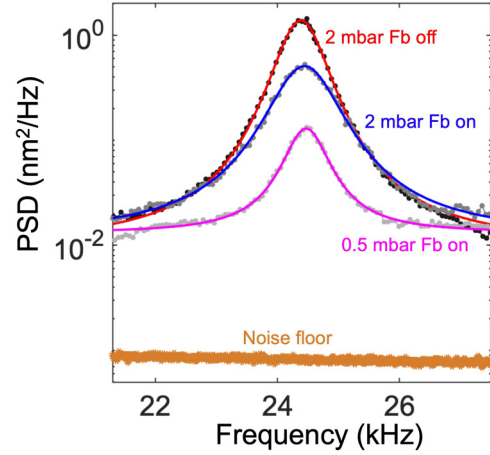


FIG. 4. Measured spectra of axial mechanical motion of a 400 nm silica particle. The spectra are fitted with Eq. (2). The spectra without Fb cooling at 2 mbar is shown in red, with feedback cooling at 2 mbar is shown in blue, and at 0.5 mbar with feedback is shown in magenta. The detection noise ($26 \text{ pm}/\sqrt{\text{Hz}}$) without any particle in the optical trap and with the spatial aperture closed is shown in copper color.

IV. DISCUSSION AND OUTLOOK

A. Thermal bulk temperature consideration

The ultimate achievable CoM temperature is limited by the loss of the particle in high vacuum, possibly due to an increase in internal bulk temperature (see Appendix E) of the nanosphere [45–47] and insufficient viscous damping at low pressure. Additional damping can be provided in the radial directions by using phase-adaptive parametric feedback [13,20], while cooling efficiency can be improved by enhancing the oscillator's quality factor (eigenfrequency)—for instance, by trapping it in a tapered HC-PCF [48,49]. The phase-adaptive cooling in a hollow-core fiber can facilitate probing distributed weak magnetic field [50] using ultracold magnetic particle in an optical conveyor belt. Potential internal heating (see Appendix E), which may destabilize particles [47,51], can be mitigated by doping the dielectric material with rare-earth ions, enabling thermal energy redistribution through solid-state refrigeration [52].

B. Toward preparation of motional ground state

Beyond these thermal considerations, our platform can be extended toward quantum ground-state operation (see Appendix F). Recent studies have shown that an HC-PCF can maintain pressure gradient between ultrahigh vacuum (UHV, 10^{-9} mbar) and atmospheric pressure [26]. Operating hollow-core fibers under UHV presents challenges due to outgassing and slow evacuation rate [53]. To reduce the risk of outgassing, we thoroughly remove all polymer coating and use single-ring HC-PCFs with fewer cladding capillaries to reduce the internal surface area as compared to photonic bandgap (PBG) [25,53] and Kagome-type fiber [23]. We further avoid chlorine treatment during fiber fabrication [54]. Prebaking the fiber can also help to lower residual gas release. Additionally, the larger core of single-ring HC-PCF increases molecular

flow conductance [55], facilitating faster evacuation of the fiber. In order to avoid the long evacuation time (on the order of weeks) to reach UHV from atmospheric pressure, the fiber can be maintained in UHV and particles can be dry launched, for example, by shaking them off a polytetrafluoroethylene (PTFE) substrate [56] in UHV.

In UHV, photon recoil becomes the dominant heating mechanism; for a 195-nm silica particle in our HC-PCF trap, we estimate a recoil heating rate [18] of ~ 5 kHz at 1064 nm, which lies below the optimal feedback cooling rate of 7.2 kHz [21]. The ultimate quantum limit of feedback cooling is governed by the trade-off between measurement imprecision and measurement backaction. While backaction noise can be suppressed by optimizing trap power and operating at longer wavelengths, imprecision noise suppression requires improving scattered-photon collection. Our current collection efficiency of $\sim 1\%$ can be enhanced to $\sim 24\%$ by integrating a high-NA (0.85 NA) objective to image the particle, bringing performance in line with state-of-the-art free-space experiments [17]. Together with optimal spatial filtering, balanced detection using quadrature photodiode and enhanced photon collection, these measures would bring the oscillator close to its motional ground state.

V. CONCLUSION

We have experimentally demonstrated a phase-adaptive feedback cooling technique by trapping silica nanoparticles in interference fringes inside the hollow core of a photonic crystal fiber. The cooling method involves modulation of the phase of fringe trap. This technique may provide a remedy for extraneous recoil heating often associated with traditional techniques involving intensity modulation. This work opens up opportunities for long-range precision sensing and coherent manipulation of mesoscopic quantum systems in HC-PCF.

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The authors declare that they have no conflicts of interest, financial or otherwise, related to the work presented in this manuscript.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

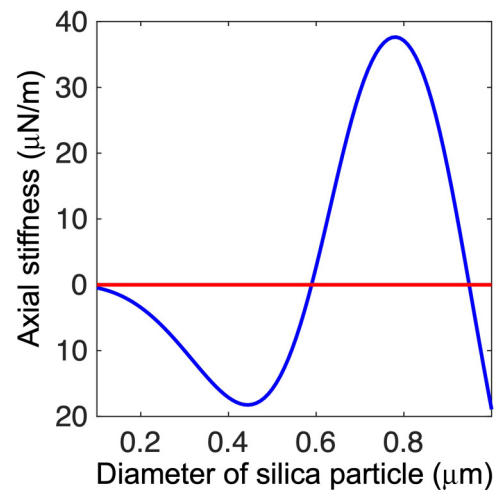


FIG. 5. Axial stiffness is plotted (blue curve) as a function of silica particle diameter. Parameter used in the simulation are NA of the fiber = 0.03, density of silica = 2000 kg/m^3 , refractive index of silica = 1.43, and total trapping power = 1 W. The simulation is performed using optical tweezer toolbox [57]. The red line at zero stiffness indicates the sizes of the particle, which do not feel any axial gradient force and therefore cannot be cooled down.

APPENDIX A: AXIAL SPRING CONSTANT AS A FUNCTION OF PARTICLE DIAMETER

In our experiment, we have trapped and cooled CoM motion of silica particles of various sizes. The trapping mechanism of larger particles is governed by generalized Lorentz-Mie theory [57,58]. The silica particles can be high-field seeker (trapped at antinode) or low-field seeker (trapped at node) depending on their sizes and experimental parameters [59]. In Fig. 5, we show the simulated axial optical spring stiffness (blue curve) as a function of silica particle diameter. It can be seen that the particles larger than fringe spacing can also be cooled down; however, the direction of the phase change has to be adjusted depending on the particle diameter. Certain sizes of particles do not feel any axial gradient force (red line), thus cannot be cooled down using phase-adaptive technique.

APPENDIX B: SIDE-SCATTERED LIGHT DETECTION FOR A STANDING-WAVE TRAP

For a Rayleigh particle trapped (particle diameter $d \ll$ wavelength λ) in a standing-wave optical potential formed by y-polarized electric fields propagating along z, the incident field is

$$\mathbf{E}_{\text{inc}}(\mathbf{r}(t)) = E_0 \hat{\mathbf{y}} \cos[kz(t)], \quad (\text{B1})$$

where E_0 is the total electric field amplitude and $k = 2\pi/\lambda$, the wave number.

The trapping field-induced dipole moment can be written as

$$\mathbf{p}(t) = \alpha \mathbf{E}_{\text{inc}}(\mathbf{r}(t)) = \alpha E_0 \hat{\mathbf{y}} \cos[kz(t)]. \quad (\text{B2})$$

The far-field scattered radiation along direction $\hat{\mathbf{r}}$ (unit vector from the particle to the detector) is given by [60]

$$\mathbf{E}_s(\mathbf{r}, t) = \frac{k^2}{4\pi\epsilon_0 r} \{\hat{\mathbf{r}} \times [\hat{\mathbf{r}} \times \mathbf{p}(t)]\} e^{ikr}. \quad (\text{B3})$$

The far-field scattered electric field along a side detector (angle θ from x) is

$$\mathbf{E}_s(t) \approx E_{s0} \hat{\mathbf{y}} \cos[kz(t)] e^{-ikz(t) \sin \theta} + (\partial_x E_s) \hat{\mathbf{y}} x(t), \quad (\text{B4})$$

where E_{s0} is the scattered field amplitude.

For small displacements around a trap antinode z_0 ($z(t) = z_0 + \delta z(t)$, $|\delta z| \ll \lambda$) and for small displacement $\delta x(t)$ along radial direction from the center of the core (x_0), we linearize

$$\cos[kz(t)] \approx \cos(kz_0) - k \sin(kz_0) \delta z(t), \quad (\text{B5a})$$

$$e^{-ikz(t) \sin \theta} \approx 1 - ik \sin \theta \delta z(t), \quad (\text{B5b})$$

$$x(t) \approx x_0 + \delta x(t). \quad (\text{B5c})$$

Multiplying and keeping terms linear in δz and δx :

$$\begin{aligned} \mathbf{E}_s(t) \approx E_{s0} \hat{\mathbf{y}} [1 - k \sin(kz_0) \delta z(t) - ik \sin \theta \delta z(t)] \\ + (\partial_x E_s) \hat{\mathbf{y}} \delta x(t). \end{aligned} \quad (\text{B6})$$

The scattered light interferes with the coherent fiber mode $\mathbf{E}_f = |E_f| e^{i\phi_f} \hat{\mathbf{y}}$, where $|E_f|$ is the amplitude of the guided mode at the detector and determines the strength of the interference signal with the particle-scattered light and ϕ_f is the relative phase of the fiber mode with respect to the scattered field at the detector. This phase critically sets the magnitude of the linear response to axial motion. The scattered light also interferes with the partially polarized cladding light $\mathbf{E}_g = |E_g|(\sqrt{\kappa} \hat{\mathbf{y}} + \sqrt{1-\kappa} \hat{\mathbf{e}}_x(t))$, where $|E_g|$ is the amplitude of the cladding light reaching the detector, κ is the fraction aligned along y , and $\hat{\mathbf{e}}_x(t)$ is a random unit vector perpendicular to y . The photodiode measures

$$I(t) \propto |\mathbf{E}_s(t) + \mathbf{E}_f + \mathbf{E}_g|^2. \quad (\text{B7})$$

Averaging over random perpendicular components and keeping terms linear in x and δz , the intensity becomes

$$\begin{aligned} I(t) \approx I_0 + 2\Re[\underbrace{(\partial_x E_s)^*(E_f + \sqrt{\kappa} E_g)}_{\mathcal{G}_x} \delta x(t) \\ + 2\Re[\underbrace{(-k \sin(kz_0) - ik \sin \theta) E_{s0}^*(E_f + \sqrt{\kappa} E_g)}_{\mathcal{G}_z} \delta z(t) \\ + s(t)], \end{aligned} \quad (\text{B8})$$

where $s(t)$ is detector noise. Here, $\mathcal{G}_x$ is the transverse linear response. $\mathcal{G}_z$ includes both amplitude modulation from the standing wave $[-k \sin(kz_0)]$ and phase modulation from detector tilt $(-ik \sin \theta)$. Axial motion can produce a measurable linear signal even at $\theta = 0$ if the particle is displaced from an exact antinode.

Equation (B8) indicates that the detected position signal of a trapped particle is a superposition of displacements along multiple eigendirections of the optical potential, with each component oscillating at its respective eigenfrequency. The total motional PSD at 1 mbar of a 195 nm silica particle at 0.75 W of trapping power is shown in Fig. 6. The first peak from the left side of the spectrum at ~ 1.3 kHz corresponds to the radial eigenresonance originating due to the transverse confinement from the Bessel-like [61] guided fiber mode, the

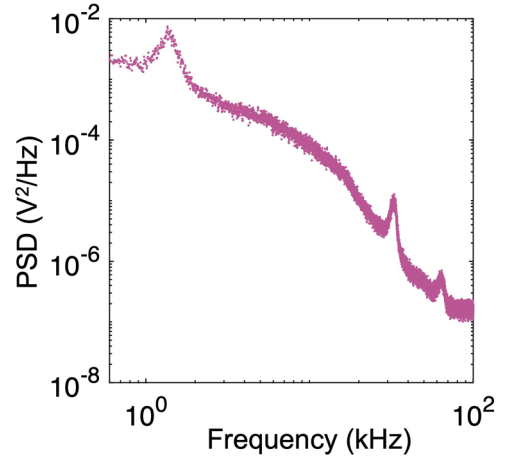


FIG. 6. The total thermally driven mechanical spectrum of the trapped 195 nm silica nanoparticle at 1 mbar pressure as detected from the side-scattered light featuring transverse (1.3 kHz) and axial eigenresonances (33.7 kHz). The third right-most peak at 67 kHz represents the second harmonic of the axial eigenmode.

second peak at ~ 33.7 kHz corresponds to the axial eigenresonance from the standing-wave trap, and the third peak at ~ 67 kHz is the second harmonic of the axial resonance.

To experimentally verify the axial eigenmode, we apply a small sinusoidal phase modulation to the standing-wave optical trap at a background pressure of 45 mbar. This pressure is chosen deliberately to ensure the particle motion remains sufficiently damped, thereby suppressing unwanted ballistic excursions that could lead to particle loss. The scattered light from the particle is collected on the photodiode and analyzed using a lock-in amplifier synchronized to the modulation frequency, enabling sensitive detection of the particle's motion even at small amplitudes. The resulting PSD, plotted as a function of lock-in reference frequency in Fig. 7(a), shows a clear resonance at ~ 33.7 kHz, corresponding to the axial eigenfrequency of the trapped particle.

The verification of the transverse (radial) eigenmode is achieved by utilizing the static charges on the nanoparticle [62] and electrically driving its radial mechanical response by a pair of electrodes at low pressure. The radial trapping forces are roughly three orders of magnitude weaker than the axial forces of the fringe trap in the HC-PCF, which necessitates reducing the background gas damping in order to start observing the thermally populated radial eigenmode. Furthermore, the net number of elementary charges on the particle is very small (in the order of $5-10e^-$). Thus, the radial mode detection experiment is conducted at a lower pressure of 10 mbar, as compared to 45 mbar used for axial mode detection. At this pressure, the thermally driven transverse eigenmotion is slightly underdamped and the viscous damping is reduced to allow measurable mechanical response to the ac electric field drive, while still preventing particle loss due to ballistic motion. The corresponding motional PSD in the presence of the ac drive is obtained from the side-scattered light detected by the photodiode and is plotted in Fig. 7(b) with high resolution in the low-frequency region of the spectrum. The sharp peak at 2 kHz corresponds to the electrically driven mechanical response, the weaker sharp peak at 4 kHz is

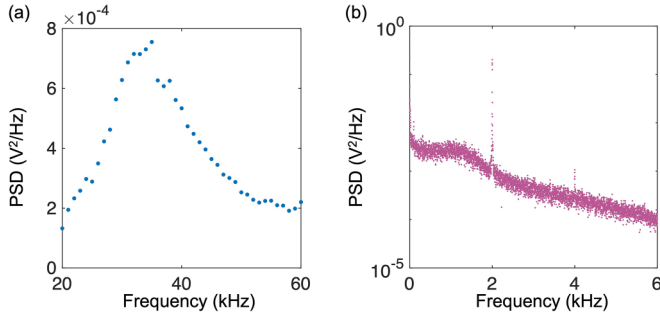


FIG. 7. (a) Axial eigenfrequency (33.7 kHz) verification by applying small-signal sinusoidal phase modulation to the standing-wave trap at 45 mbar, with the scattered-light power spectral density measured using lock-in detection. (b) Radial eigenfrequency (1.3 kHz) verification by recording high-resolution motional spectrum in the low-frequency region by radially driving the trapped particle with ac electrical excitation at 10 mbar. The sharp peak at 2 kHz corresponds to the electrically driven mechanical response, while the broad resonance near 1.3 kHz indicates the thermally driven radial eigenmode. The second harmonic of the AC response at 4 kHz is likely caused by large anharmonic displacement of the particle compared to the core center due to strong electrical drive.

likely due to residual anharmonicity in the radial trap caused by the drive. The damped thermally driven eigenmode is at ~ 1.3 kHz.

APPENDIX C: DERIVATION OF THE POSITION SPECTRUM

To derive the steady-state position spectrum under phase-adaptive feedback, we follow the formalism introduced in Ref. [21]. In this framework, the stochastic dynamics of a trapped particle subjected to phase-adaptive feedback along the axial (z) direction is described by coupled difference equations expressed in terms of dimensionless position and momentum quadratures, defined as $q = z/q_{\text{zpm}}$ and

$p = p_z/p_{\text{zpm}}$, where $q_{\text{zpm}} = \sqrt{\hbar/(m\Omega)}$ and $p_{\text{zpm}} = \sqrt{m\hbar\Omega}$ denote the zero-point position and momentum scales, respectively. The equations of motion read

$$dq = \Omega p dt, \quad (\text{C1a})$$

$$dp = -\gamma p dt - \Omega q dt - \beta \phi(t) dt + \sqrt{2\gamma n_{\text{th}}} dW^{\text{th}}(t). \quad (\text{C1b})$$

Here, the system is subject to two dominant stochastic processes: (1) Thermal noise from background gas collisions couples the oscillator to a bath at temperature T_{th} (occupancy n_{th}), introducing pressure-dependent damping (γ) and fluctuations modeled via Wiener increments $dW^{\text{th}}(t)$ satisfying $\langle (dW^{\text{th}}(t))^2 \rangle = dt$ (timestep); (2) feedback force $-\beta\phi(t)$ with $\beta = m\Omega^2\lambda/(2\pi p_{\text{zpm}})$ (λ : laser wavelength) generated through phase control.

Our phase-adaptive feedback cooling implementation modulates the relative phase between the counter-propagating fiber modes as

$$\phi(t) = \frac{\mathcal{C}}{\Omega} \times \lim_{dt \rightarrow 0} \frac{q_{\text{det}}(t) - q_{\text{det}}(t - dt)}{dt}, \quad (\text{C2})$$

where the measured position $q_{\text{det}}(t) = q(t) + \eta W^{\text{det}}(t)$ includes additive detection noise characterized by amplitude η and Wiener increments $W^{\text{det}}(t)$. The feedback gain $\mathcal{C}$ governs a critical performance trade-off: Increasing $\mathcal{C}$ enhances cooling rates but amplifies noise contributions. Note that, substituting Eq. (C2) into Eq. (C1) reveals an enhancement of the mechanical damping from γ to $\gamma + \beta\mathcal{C}$. This feedback mechanism corresponds to cold damping.

In this framework, to derive an analytical solution for the optomechanical system subject to phase-adaptive feedback, we discretize the time interval $[0, t]$ into n steps of duration $dt = t/n$, following the effective numerical scheme of Ref. [21]. This discretization reformulates the stochastic equations of motion [Eq. (C1)] into recurrence relations that incorporate both thermal fluctuations and feedback-amplified detection noise at each timestep. Applying recursive back-substitution in the long-time limit yields the following steady-state expressions for the position and momentum quadratures:

$$q(n) = \frac{2\Omega}{\bar{\gamma}_+ - \bar{\gamma}_-} \lim_{n \rightarrow \infty} \sum_{j=0}^{n-1} (\bar{\lambda}_-^j - \bar{\lambda}_+^j) [\sqrt{2\gamma n_{\text{th}}} dW_{n-j-1}^{\text{th}} + \mathcal{A} dW_{n-j-1}^{\text{det}}], \quad (\text{C3})$$

$$p(n) = \frac{1}{\bar{\gamma}_+ - \bar{\gamma}_-} \lim_{n \rightarrow \infty} \sum_{j=0}^{n-1} (\bar{\gamma}_+ \bar{\lambda}_+^j - \bar{\gamma}_- \bar{\lambda}_-^j) [\sqrt{2\gamma n_{\text{th}}} dW_{n-j-1}^{\text{th}} + \mathcal{A} dW_{n-j-1}^{\text{det}}], \quad (\text{C4})$$

where the effective damping rates $\bar{\gamma}_{\pm} = \bar{\gamma} \pm \bar{\Omega}$ are defined in terms of $\bar{\Omega} \equiv \sqrt{\bar{\gamma}^2 - 4\Omega^2}$, which characterizes the system's dynamical response. Here, $\bar{\gamma} \equiv \gamma + \beta\mathcal{C}$ represents the total effective damping rate, combining intrinsic viscous damping and phase-adaptive dissipation. The coefficients $\bar{\lambda}_{\pm} = 1 - (\bar{\gamma}_{\pm}/2)dt$ determine the decay weights for past noise contributions, $\mathcal{A} = \eta\beta\mathcal{C}/\Omega$ scales the detection noise amplification in the feedback loop.

Position power spectral density

In our formalism, the detected oscillator position after feedback is activated and expressed as $\tilde{q}_{\text{det}}(t) = q(t) + \eta W^{\text{det}}$, where $q(t)$ represents the position including thermal noise and feedback contributions and ηW^{det} denotes additive detection noise. In dimensional form, we can express it as

$$z_{\text{det}}(t) = \tilde{z}(t) + q_{\text{zpm}} \eta W^{\text{det}}(t),$$

where $\tilde{z}(t) = q_{\text{zpm}}q(t)$ is the modified position quadrature due to applied phase-adaptive contribution. Here, $q(t)$ can be obtained by using Eq. (C3) in the large n limit.

Within the discretized approach, the position PSD is defined by the Fourier transform:

$$S(\omega) = \lim_{dt \rightarrow 0} dt \sum_{n'=-\infty}^{\infty} e^{-i\omega n' dt} \langle z_{\text{det}}(n) z_{\text{det}}(n + n') \rangle. \quad (\text{C5})$$

Summing over n' and taking the $dt \rightarrow 0$ limit yields the following form of the PSD:

$$S(\omega) = \frac{2\gamma k_B T_{\text{th}}/m}{(\omega^2 - \Omega^2)^2 + (\gamma + \beta C)^2 \omega^2} + \left(\frac{\hbar}{m\Omega} \right) \frac{\eta^2}{\omega^2} + \left(\frac{\hbar}{m\Omega} \right) \left[\frac{(\eta\beta C)^2}{(\omega^2 - \Omega^2)^2 + (\gamma + \beta C)^2 \omega^2} \right]. \quad (\text{C6})$$

Above position noise spectrum comprises three physically distinct components. The first contribution originates from stochastic thermal forces due to collisions with the background gas at temperature T_{th} . This thermal noise exhibits a Lorentzian profile centered near the mechanical resonance frequency Ω , with its magnitude proportional to the thermal energy $k_B T_{\text{th}}$ and damping rate γ . The spectral lineshape is modified by the total effective damping $(\gamma + \beta C)$, representing the combined effect of intrinsic viscous drag and feedback-induced dissipation.

The second component constitutes the base detection noise floor, which dominates the off-resonant spectrum at low frequencies ($\omega \ll \Omega$). Characterized by a $1/\omega^2$ frequency dependence, this term is independent of both mechanical parameters (Ω , γ) and feedback settings (C), representing a fundamental limit determined solely by the detection noise performance η .

The third contribution arises from detection noise amplified through the feedback loop. Scaling quadratically with both the feedback gain C and detection noise amplitude η , this term represents a fundamental trade-off: While higher gain enhances cooling efficiency, it simultaneously injects additional noise. This feedback-amplified component shares the Lorentzian resonance profile of the thermal noise and dominates near the mechanical resonance ($\omega \approx \Omega$), directly competing with thermal fluctuations.

APPENDIX D: EFFECT OF LASER PHASE NOISE

In interferometric systems such as dual-beam optical tweezers, fluctuations in the phase of the trapping laser (i.e., phase noise) manifest as variations in the effective trapping frequency. The laser field can be represented as having a constant amplitude with a stochastically varying phase,

$$\mathcal{E}_0 = |\mathcal{E}_0| e^{i\phi_l(t)}, \quad (\text{D1})$$

where $\phi_l(t)$ is modeled as a Gaussian random variable with zero mean and variance σ_{ϕ_l} . The influence of this stochastic phase can be incorporated through ensemble averaging [21]. Invoking Gaussian statistics yields

$$\langle e^{i\phi_l(t)} \rangle = e^{-\sigma_{\phi_l}/2}, \quad (\text{D2})$$

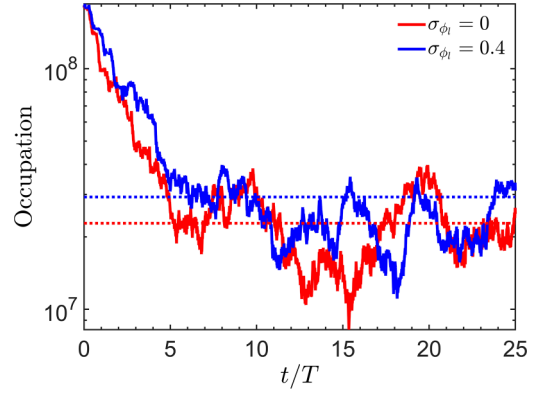


FIG. 8. Effect of trapping laser phase noise on system dynamics for a pressure of 0.1 mbar. Solid lines represent simulated phonon occupation for phase-noise variances $\sigma_{\phi_l} = 0$ (red) and 0.4 (blue), corresponding to trap frequency changes of 0% and $\sim 18\%$, respectively. Dotted lines denote the analytically predicted steady-state average occupancy values [21]. The parameters are 195 nm silica particle with density 2000 kg/m^3 trapped in 0.75 W of trapping power at 0.1 mbar, detection noise amplitude $\eta = 9.4 \times 10^6 \sqrt{\text{Hz}}$, feedback gain $C = 3.84 \times 10^{-6}$, and the oscillation time period is $T = 2\pi/\Omega$, where the eigenfrequency of the oscillator is $\Omega = 2\pi \times 33.7 \text{ kHz}$.

where the averaging is performed over many realizations. Propagation of these fluctuations through the governing dynamical equations reveals that phase noise suppresses both the trapping frequency and the cooling rate: The natural frequency is renormalized from Ω to $\Omega e^{-\sigma_{\phi_l}/2}$, while the cooling rate decreases from $\bar{\Gamma}$ to $\bar{\Gamma} e^{-\sigma_{\phi_l}}$ [21]. The impact of σ_{ϕ_l} is illustrated in Fig. 8, where phonon occupation exhibits excellent agreement with the analytical predictions [21], displaying a systematic decline in cooling rate as the phase variance increases. This trend is quantitatively reflected in the negative slope of the plotted curves. While the influence of phase noise on the CoM temperature is relatively minor when the oscillator resides far above its motional ground state—where thermal and detection noise dominate—it becomes pronounced in the near-ground-state regime. In such conditions, the implementation of advanced laser phase-stabilization techniques offers a viable route to mitigating noise at the motional eigenfrequency [19,40,41].

APPENDIX E: ISSUE OF INTERNAL TEMPERATURE

For trapped particles in high vacuum, the steady-state bulk temperature is determined by processes involving heating due to optical absorption of the trapping light and blackbody radiation, and cooling through the emission of blackbody radiation [47]. In the Rayleigh regime, for a given particle and wavelength, the absorption heating rate is proportional to the local laser intensity on the particle. The absorbed power can be expressed as [47]

$$P_{\text{abs}} = \frac{12\pi I V_p}{\lambda} \text{Im} \left(\frac{\epsilon - 1}{\epsilon + 2} \right), \quad (\text{E1})$$

where $I = P_l/\sigma_w$ is the local beam intensity, P_l is the laser power, σ_w is the beam waist area, V_p is the particle volume, λ

is the trapping wavelength, and ϵ is the dielectric constant of the material. Thus, the heating is independent of the numerical aperture (NA) as with increasing NA and proportionally reduced power, the intensity remains constant.

1. Lateral confinements

For a high-NA (0.85) objective, the diffraction-limited waist diameter or mode field diameter is ~ 700 nm (waist area $\sigma_{wd} = \pi(0.35 \mu\text{m})^2$ [13]), whereas the fiber mode waist diameter is $\sim 40 \mu\text{m}$ ($\sigma_{wf} = \pi(20 \mu\text{m})^2$). At equal impinging laser power, the ratio of absorbed powers is

$$\frac{P_d}{P_f} = \frac{I_d}{I_f} = \frac{\sigma_{wf}}{\sigma_{wd}} \sim 3300, \quad (\text{E2})$$

so the absorbed power is much higher in the diffraction-limited focus. To equalize the absorption, the free-space trap would need to reduce its power by a factor of ~ 3300 , severely reducing its trap depth and stability.

2. Longitudinal confinement

In a standing-wave trap, the fringe spacing at 1064 nm is ~ 532 nm, closer to the diffraction-limited waist, so the internal heating can be comparable. In such cases, additional strategies such as antinode trapping [9,63] or rare-earth doping for solid-state refrigeration [64] can be used to suppress internal heating.

Thus, hollow-core fiber trap may enable weak trapping of particles with reduced internal heating, providing better thermal stability.

APPENDIX F: TOWARD MOTIONAL GROUND-STATE PREPARATION

Achieving the motional ground state of the particle requires ultrahigh vacuum (UHV) operation and significant improvements in detection efficiency. Here, we provide a roadmap that details the steps to bring our fiber-based phase-adaptive platform into the quantum regime. The major steps are as follows:

1. UHV operation and recoil heating

The first step in this roadmap is operating under UHV conditions, where gas collisions are suppressed and photon recoil heating becomes the dominant limitation. The recoil heating rate [18] is given by

$$\Gamma_r = \frac{2\pi P_s}{5mc\lambda\Omega}, \quad (\text{F1})$$

where λ is the trapping wavelength, P_s the scattered optical power (2.36 μW at 1064 nm and 0.247 μW at 1550 nm), m the mass of the particle, c the speed of light, and Ω the mechanical frequency. For a 195-nm silica sphere in our HC-PCF trap at 0.75 W of optical power, we estimate $\Gamma_r \approx 5.15$ kHz at 1064 nm, which decreases significantly to ~ 0.65 kHz at 1550 nm. Crucially, the optimal cooling rate in our system [21] is 7.2 kHz, thus feedback cooling is expected to suppress recoil heating effectively in the UHV regime.

2. Consideration of UHV conditions inside the fiber

A primary consideration is addressing the constraints imposed by ultra-high vacuum (UHV, 10^{-9} mbar) operation in hollow-core fibers [25,53], due to outgassing and long evacuation time. In our experiments, all polymer coatings, including the fiber jacket, are thoroughly removed to minimize outgassing. The single-ring HC-PCF used in this work, which features a reduced number of cladding capillaries and therefore smaller internal surface area, lowers the risk of outgassing compared to PBG [53] and Kagome-type hollow-core fibers [23]. During fabrication, the fiber is not treated with chlorine [54], which can exacerbate outgassing in UHV. Finally, prebaking (100° – 200° C) the fiber prior to mounting further reduces residual gas release.

Additionally, the larger core diameter (d_{core}), as compared to PBG and Kagome fibers, increases molecular flow conductance (C_v) [55], facilitating faster evacuation of the fiber. The flow conductance in free molecular regime, scales cubically with the fiber core diameter $C_v \propto d_{\text{core}}^3$ [25]. In order to avoid the long evacuation time (on the order of weeks) to reach UHV from atmospheric pressure, the fiber can be maintained in UHV environment and particles can be dry launched, for example, by shaking them off PTFE substrate [56] in UHV.

3. Quantum imprecision–backaction trade-off

Having addressed the UHV environment, the next fundamental consideration is the quantum limit of measurement itself. The ultimate phonon occupancy is determined by the balance between measurement imprecision noise and measurement backaction, which can be written as [65]

$$S_{\text{imp}} S_{\text{ba}} = \frac{\hbar^2}{4\zeta}, \quad (\text{F2})$$

where S_{imp} is the PSD of impression noise, S_{ba} is the PSD of backaction noise, and ζ is the measurement efficiency. Minimizing occupancy requires tuning these two contributions to be PSD equal and increasing η in order to operate at the Heisenberg limit [66]. Back action can be reduced by optimizing trap power and operating at UHV, where it is dominated solely by photon recoil. Imprecision can be improved by enhancing the collection and detection of scattered photons. This trade-off [67] defines the technical targets for our platform.

4. Increasing measurement efficiency

Therefore, a central pillar of our roadmap is an upgrade to our detection system. Our current setup, which collects only $\sim 1\%$ of scattered photons with a simple lens, serves as a proof of principle. Integrating a high-NA (0.85) objective lens above the fiber to directly image the particle would raise the collection efficiency to $\sim 24\%$. This order-of-magnitude improvement is on par with state-of-the-art free-space experiments [17] and would directly address the imprecision limit by substantially lowering its noise contribution.

5. Suppressing stray light and technical noise

Finally, the improved measurement efficiency must be paired with a reduction of technical noise to be fully effective. Key strategies to suppress stray scattered light and

lower the detection noise floor include: (a) optimal filtering, (b) optimized input coupling to minimize scattering from fiber imperfections, and (c) the use of balanced or quadrant photodiodes for common-mode noise rejection. Together, these measures will actively lower the detection noise floor and ensure that the gain in collection efficiency translates into a corresponding gain in signal-to-noise ratio.

By combining the steps outlined above, the imprecision-back-action product can be reduced to near the Heisenberg

limit, thereby fulfilling the criterion for ground-state cooling. It is important to emphasize that, although the present work primarily demonstrates the first realization of phase-adaptive feedback within a fiber-based geometry, the underlying architecture remains fully compatible with the aforementioned enhancements. In this respect, our platform constitutes not only an experimental system but also a scalable pathway toward quantum-limited force sensing and ground-state control of mesoscopic particles.

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