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Soumya Chakraborty

soumya.chakraborty@mpl.mpg.de

Max Planck Institute for the Science of Light

Pardeep Kumar

Max Planck Institute for the Science of Light <https://orcid.org/0000-0002-9706-040X>

Gordon Wong

Max Planck Institute for the Science of Light

Claudiu Genes

TU-Darmstadt

Nicolas Joly

University of Erlangen-Nürnberg

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Spatial delocalization of cold oscillators in hollow-core fibers

Soumya Chakraborty (Corresponding author),^{1,2,*} Pardeep Kumar,²

Gordon K. L. Wong,² Claudiu Genes,³ and Nicolas Y. Joly^{1,2}

¹*Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 7, D-91058 Erlangen, Germany*

²*Max Planck Institute for the Science of Light, Staudtstraße 2, D-91058 Erlangen, Germany*

³*TU Darmstadt, Institute for Applied Physics, Hochschulstraße 4A, D-64289 Darmstadt, Germany*

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Trapped particles in hollow-core fibers enable long-range sensing, though advanced control of their in-fiber motion, such as multimodal cooling and squeezing, remains challenging. Here, we present optical interference-based adaptive techniques for controlling the motion of a fringe-trapped silica nanoparticle inside a fiber. After feedback-cooling its axial and radial motion, we induce axial delocalization (position anti-squeezing) via two complementary approaches. First, non-adiabatic fringe suppression expands the position variance by 11.83 (± 0.7) dB to that of the initial cold-state while retaining Gaussian statistics. Second, multi-pass particle positioning at dark fringes increases the delocalization to 13.23 (± 0.5) dB relative to the cold-state's variance via dark inverted optical potentials, in agreement with our Wiener stochastic model. Stronger delocalization produces non-Gaussian states of motion. Unlike prior inverted-trap implementations, our method requires neither auxiliary optical traps nor charged particles in Paul traps. Our results demonstrate fringe-trapped particles in hollow-core fibers as a versatile platform for long-range sensing and macroscopic quantum physics.

I. INTRODUCTION

Optomechanics [1, 2] with optically trapped nanoparticles is opening new opportunities in metrology and tests of quantum physics, including gravity-induced wavefunction collapse. Recent advances include ground-state cooling [3–6], quantum-limited force sensing [7, 8], and preparation of atypical motional states [9–13].

Building on these foundations, highly delocalized motional states, characterized by anti-squeezing along the position quadrature, provide a pathway toward surpassing standard quantum limits in force sensing [8] and preparing nanoparticles in macroscopic quantum superpositions [14]. In optical tweezers [15], motional delocalization is typically achieved through non-adiabatic modulation of the trapping power, which changes the mechanical frequency [9, 13, 16] and has yielded up to 7.2 dB of quantum squeezing [17, 18]. Dark inverted traps offer an alternative path to squeezing with near-zero quantum backaction and rapid state expansion, but existing implementations rely on auxiliary traps [19, 20] and charged particles in Paul traps which are sensitive to stray electric fields [21].

These limitations motivate alternative architectures, such as standing-wave fringe traps formed by interfering counterpropagating fiber modes in hollow-core photonic crystal fibers (HC-PCFs). These diffraction-free traps [22–24] enable long-range particle transport [25], while the relative phase and polarization of the counterpropagating modes independently control the particle position and axial stiffness. We recently demonstrated axial feedback cooling through the relative phase control [26, 27];

however, advanced control, including multidimensional cooling and squeezing, remains unexplored.

Here, we demonstrate adaptive control of the dissipative and conservative optomechanical dynamics of a 234-nm silica nanoparticle trapped in an HC-PCF under high vacuum. We combine phase-adaptive cold damping of the axial mode with parametric feedback of the radial mode [16, 26–28], reducing their center-of-mass (CoM) temperatures near 1 K at 10 μ bar pressure. After cooling the particle's motion, we demonstrate two complementary protocols for axial thermomechanical delocalization (position anti-squeezing). A sudden polarization change produces a nonadiabatic axial frequency jump *without* changing the trapping power, increasing the position variance of the state by 11.83 (± 0.7) dB relative to the variance of a cold (7.8 K) thermal state while preserving Gaussianity. This delocalized state subsequently relaxes toward the initial thermal state under thermal noise and damping, as accurately captured by our stochastic Wiener evolution. Independently, rapid phase control transports the particle to and fro between bright and dark optical fringes, where the dark inverted potential produces hyperbolic motional evolution and exponential phase-space delocalization. Repeated phase-synchronized excursions between dark and bright fringes increases the position variance of the thermal state by 13.23 (± 0.5) dB relative to the initial state's variance, *without* requiring auxiliary traps [20] or charged particles [21]. Beyond the linear regime, further increases in dark fringe excursion delocalize the particle enough to probe the nonlinearities of the optical fringe potential, giving access to non-Gaussian motional dynamics [11].

The demonstrated delocalized thermal states open a unique route for precision force and displacement sensing [8] with trapped nanoparticles. In our system, the achieved ~ 13 dB squeezing of velocity variance corre-

* soumya.chakraborty@mpl.mpg.de

sponds to a nearly 4.5-times enhancement in force sensitivity when compared to the original cold thermal state. Dark-fringe particle placement also enables rapid delocalization of the particle's CoM wavepacket [21]. This capability is valuable for matter-wave interferometry [14] and the generation of motional cat states with increasingly massive objects, as the dark fringe provides a sign-insensitive position measurement. This connection between adaptive control, precision sensing, and quantum state engineering establishes HC-PCF-based fringe trapping as a versatile platform for fiber-integrated metrology and optomechanics.

II. RESULTS

With the particle stably trapped in the hollow-core fiber, we first establish active control over its CoM motion. We simultaneously cool the axial and radial modes by combining phase-adaptive cold damping with parametric feedback, preparing a cold thermal state for the delocalization protocols that follow. We then delocalize the axial motion through polarization-adaptive and dark-fringe-adaptive protocols, and finally exploit the anharmonicity of the fringe potential to prepare a non-Gaussian motional state.

A. Cooling action

A schematic of the experimental setup is shown in Fig. 1. A 1064 nm (λ) Nd:YAG laser with 1.5 W total trapping power is split into two equally intense, co-polarized beams and coupled into the fundamental modes of a twisted hollow-core fiber (t-HCF) [27] with a 44 μm core diameter. The fiber is mounted inside a vacuum chamber to control the gas damping of the trapped particle's motion. Scattered light from the particle, together with the cladding stray light, is collected by a 0.26 NA objective and detected using a camera and two fast photodiodes. The photodiode signals are obtained through interference between particle-scattered and cladding light [27]. The in-loop photodiode (IPD) provides the signals for field-programmable gate-arrays (FPGAs)-based feedback control, while the out-of-loop photodiode (OPD) is used for independent motion detection. The particle is loaded at atmospheric pressure by nebulizing a highly diluted silica suspension. At around 5 mbar, the axial mode is observed at $\Omega = 2\pi \times 55$ kHz. The radial mode is at $\Omega_r = 2\pi \times 1.3$ kHz. The motional signals are calibrated using equipartition theorem [29].

The IPD signal, which contains both axial and radial eigenmodes, is digitally filtered in real time at the respective eigenfrequencies with sufficient bandwidth. For axial cooling, a Red Pitaya FPGA uses its IQ module to generate a feedback signal at the axial frequency Ω , with a phase shift of $\pi/2$ relative to the measured motion. This signal drives a phase modulator that dynamically adjusts

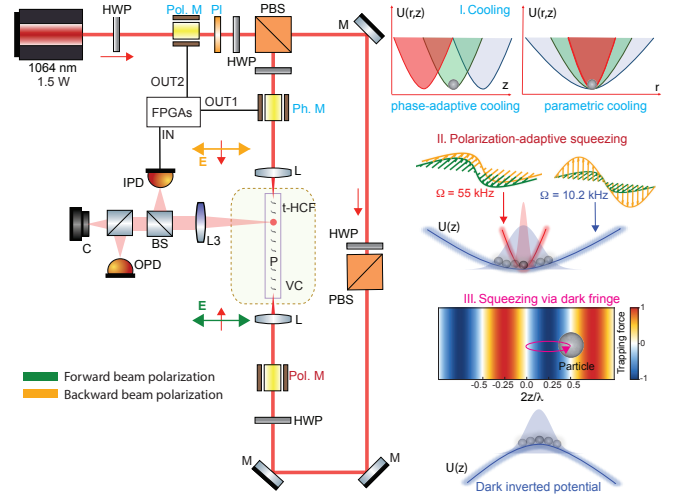


FIG. 1. **Schematic of the HC-PCF dual-beam optical tweezer for multimode cooling and axial delocalization;** P: levitated particle, HWP: half-wave plate, PBS: polarizing beam splitter, Pl: Polarizer, BS: beam splitter, C: camera, M: mirror, VC: vacuum chamber, t-HCF: twisted hollow-core fiber, L: 75 mm lens, L3: 0.26 NA objective, OPD: out-of-loop photodiode, IPD: in-loop photodiode, Pol. M: Polarization modulator, Ph. M: phase modulator, FPGAs: Moku:Lab and Red Pitaya STEMLab-125. The forward (left $\rightarrow$ right direction) and backward (right $\rightarrow$ left direction) beams' polarizations (electric field orientations) are shown in green and yellow colors, respectively. Active feedback cools the axial motion by modulating the standing-wave position (position of the axial potential $U(z)$) via the relative phase of the counterpropagating beams, and the radial motion by modulating the radial trap stiffness (slope of the radial potential $U(r)$). Mechanical anti-squeezing is realized either by transiently suppressing the standing wave using nearly-orthogonally polarized trapping beams which reduces the axial stiffness or by momentarily placing the particle at a dark fringe, therefore creating an inverted axial optical potential.

the relative phase of the counterpropagating trapping beams, producing a viscous damping force on the axial CoM motion. For radial cooling [Fig. 2(a)], a Moku:Lab FPGA generates a phase-synchronized modulation signal at $2\Omega_r$ with appropriate damping using its phasemeter module. This signal drives an amplitude modulator to parametrically control the trap stiffness, increasing the confinement as the particle moves away from the trap center and reducing it during the return motion, resulting in net damping of the radial eigenmode. As shown in Fig. 2(b), the radial motional peak appears at Ω_r and the power modulation appears at $\sim 2\Omega_r$. The power-modulation peak is broader than the radial peak because the feedback signal decays twice as fast as the radial motion. This is because the feedback modulation follows the CoM energy, which oscillates and decays twice as fast as the position oscillation [16]. At a given pressure, axial cold-damping cooling is approximately five times more efficient than radial cooling as measured through feedback-induced broadening of the corresponding spec-

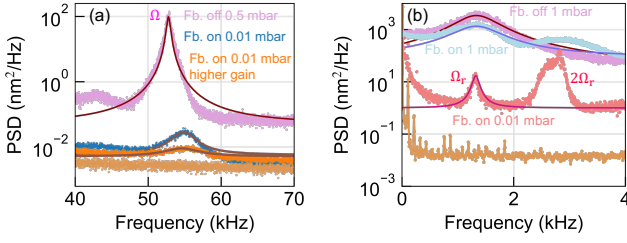


FIG. 2. **Simultaneous cooling of two eigenmodes;** (a) Axial PSD shown at 0.5 mbar without feedback cooling (plum colored). The blue and orange PSD at 0.01 mbar are recorded with feedback cooling for two different feedback cooling rates of 4 kHz and 7.2 kHz, respectively. (b) Parametric feedback cooling of the radial eigenmode of a 234 nm silica particle. The plum-colored spectra are recorded in the absence of parametric cooling at 1 mbar of air pressure. The steel-blue and coral-red-colored spectra are recorded at 1 mbar and 0.01 mbar air pressure in the presence of feedback cooling featuring second harmonic feedback signals at $2\Omega_r$. All the spectra are fitted with Lorentzian curves.

tral linewidths. The axial and radial temperatures are reduced to 0.7 K and 2.9 K, respectively, at 10 μ bar pressure (Fig. 2). The particle remains stably trapped down to 10 μ bar which is the current limit of our vacuum system. The temperatures are measured by comparing the area under the feedback-cooled spectra to the spectra in the absence of cooling. The noise floor obtained near the axial trapping frequency is 49 pm/ $\sqrt{\text{Hz}}$. The slight change in trapping frequencies are most likely caused by trapping laser power fluctuations and power modulation over the duration of experiment [16].

From the cold thermal state we then engineer, using two different protocols, an axially delocalized harmonic oscillator. The delocalization experiments are performed at a slightly higher pressure and an axial CoM temperature of 7.8 K to increase the delocalized-state's decay time, which scales inversely with pressure, thereby reducing the measurement time.

B. Polarization-adaptive delocalization

In the first protocol, we prepare a delocalized thermal state by impulsively reducing the axial optical confinement through rotating the relative polarization angle (θ_p) between the trapping beams from 0° to $\sim 88.3^\circ$. The axial frequency depends on the relative polarization angle as $\Omega = \Omega_0 \sqrt{\cos \theta_p}$ [see Sec. I of Supplementary Materials (SM) [30]]. At $\theta_p = 88.3^\circ$, the axial and radial frequencies decrease to 10.2 kHz and 0.92 kHz, respectively [23]. The shift in the radial eigenfrequency indicates that polarization rotation also modifies the radial trap, consistent with an approximately $1/\sqrt{2}$ reduction in the total on-axis electric-field intensity [see Sec. I of SM [30]]. The time scale of the switch between collinear to nearly-orthogonal polarization states of the trapping beams is determined

by the electro-optic modulator bandwidth, which is more than 100 MHz and therefore much larger than the trap frequencies (kHz).

For axial delocalization, the feedback is then switched off after cooling the particle, and the standing-wave trap is transiently suppressed, reducing the axial frequency to $\Omega_1 = 2\pi \times 10.2$ kHz. The particle evolves in the shallow potential for one-quarter of the corresponding oscillation period, producing motional delocalization through the sudden frequency change. The standing-wave trap is subsequently restored, and feedback cooling is reactivated to reinitialize the particle. This sequence is repeated 3000 times, while the particle position and velocity are extracted from the real-time filtered OPD signal using a FPGA-based lock-in method [10, 21, 31] around the axial frequency, and continuously recorded. These position and velocity data yield the motional phase-space trajectory. Further details regarding the data processing are provided in the Methods section.

The feedback-cooled particle initially has a circular phase-space distribution as shown in Fig. 3(a), where potential and kinetic energies are balanced. A sudden change of the trap stiffness via relative polarization rotation rapidly changes the potential energy without changing the particle's instantaneous motion. The subsequent evolution converts this imbalance into correlated position and momentum quadratures, stretching the thermal distribution into an ellipse. This redistribution of fluctuations between the two quadratures produces an anti-squeezed motional state. We observe up to 11.83 (± 0.7) dB of delocalization of the trapped particle, as shown in Fig. 3(b), inferred from the phase space dynamics 9 μ s after the two frequency jumps ($\Omega_0 \rightarrow \Omega_1 \rightarrow \Omega_0$). The uncertainty is obtained by fitting the position quadratures of the phase-space distributions with a Gaussian function. At this point, we observed a strong correlation between the position and momentum of the trapped particle V_{qp} which decays as a function of time due to collision from the background gas molecules as shown in Fig. 3(d-e).

We describe the measured dynamics by the covariance matrix $V(t) = \langle \mathbf{u}(t)\mathbf{u}^T(t) \rangle$, where $\mathbf{u} = (q, p)^T$ denotes the vector of dimensionless position and momentum quadratures, and $\langle \dots \rangle$ denotes the ensemble average over independent realizations of the stochastic dynamics. The system evolves under deterministic dynamics and stochastic thermal fluctuations [see Sec. II of SM [30]]. Starting from thermal equilibrium at trap frequency Ω_0 , we apply a square polarization pulse that rapidly changes the trap frequency from Ω_0 to Ω_1 at t_1 and restores it to Ω_0 at t_2 . Since both polarization rotations are fast compared with the mechanical period, they act as instantaneous symplectic transformations. The first quench maps the covariance as $V(t_1^+) = S(r)V(t_1^-)S^T(r)$, with $S(r) = \text{diag}(e^r, e^{-r})$ and $r = \ln(\sqrt{\Omega_1/\Omega_0})$, where and throughout the analysis the superscripts $\mp$ denote instants immediately before and after the quench, respectively. It thereby transforms the initially isotropic thermal distribution into an elliptical phase-space distribution.

During the pulse, the covariance ellipse rotates at Ω_1 , while damping and thermal diffusion progressively reduce its anisotropy,

$$V(t) = e^{-\gamma\tau_1} \mathcal{R}(\Omega_1\tau_1) V(t_1^+) \mathcal{R}^T(\Omega_1\tau_1) + \mathcal{Q}_1(\tau_1), \quad (1)$$

where $\tau_1 = t - t_1$, $\mathcal{R}$ describes harmonic phase-space rotation and $\mathcal{Q}_1$ is the thermal covariance. To enhance anisotropy upon the return quench, we set the pulse duration to $T_1/4$ ($T_1 = 2\pi/\Omega_1$). This quarter-period evolution eliminates the position-momentum correlation, leaving $V(t_2^-)$ diagonal with unequal variances. The inverse transformation $V(t_2^+) = S(-r)V(t_2^-)S^T(-r)$ then amplifies this asymmetry. Subsequent evolution at Ω_0 follows Eq. (1) with $\Omega_1 \rightarrow \Omega_0$ and $\mathcal{Q}_1 \rightarrow \mathcal{Q}_0$. Following this sequence, the transient dynamics as shown in [Fig. 3(d)] feature a coherently rotating ellipse whose anisotropy decays to equilibrium via damping and diffusion.

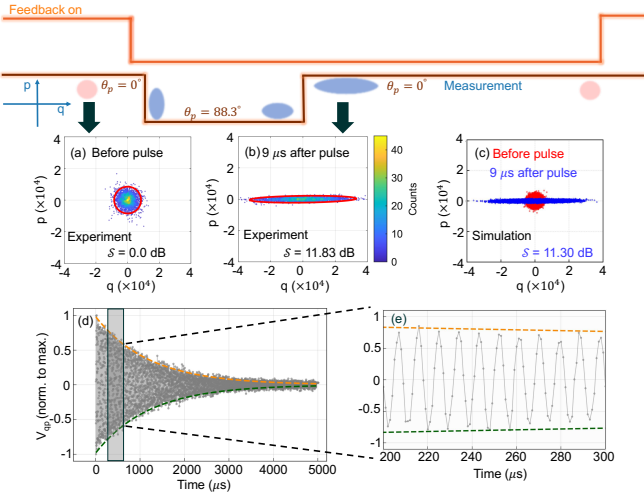


FIG. 3. Evolution of delocalized thermal states; Experimental (a-b) and simulated (c) phase-space distributions normalized to the zero-point motion (zpm), showing the anti-squeezed state under thermal noise. The position and momentum zpms are $q_{\text{zpm}} = 4.43$ pm and $p_{\text{zpm}} = 22.5$ yN.s. The red circle (ellipse) on top of (a) and (b) are the analytical distributions using Eq. (4). The experimental data and the numerical data are taken over 3000 and 20000 realizations, respectively. (d-e) Thermal decoherence of the position-momentum correlation (V_{qp}), shown at times starting 9 μs after application of the polarization-rotating pulse. The time 0 μs refers to the end of the pulse. The red and blue envelop are the fit to the gas damping [29]. (e) is the magnified view of (d).

Diagonalizing the post-pulse covariance matrix yields the variances of the squeezed and anti-squeezed quadratures, $\Lambda_{\min}(t)$ and $\Lambda_{\max}(t)$. We quantify the transient position anti-squeezing (delocalization) in decibels as [32],

$$S(t) = -10 \log_{10} \left[\frac{\Lambda_{\min}(t)}{n_{\text{th}}} \right], \quad (2)$$

where n_{th} is the initial thermal variance. Including damping and thermal noise, the minimum variance immediately

following the pulse is

$$\Lambda_{\min} = e^{-\gamma T_1/4} n_{\text{th}} e^{-4|r|} + n_{\text{th}}^{\Omega_1} (1 - e^{-\gamma T_1/4}) e^{-2|r|}, \quad (3)$$

where $n_{\text{th}}^{\Omega_1}$ is the phonon occupation at Ω_1 . For our single pulse protocol (frequency jumps from 55 to 10.2 kHz, back to 55 kHz), Eq. (2) predicts 11.96 dB of delocalization immediately after the pulse as shown in Fig. 3(c). At longer times, damping and thermal diffusion erase this anisotropy, restoring equilibrium and returning squeezing to zero. The numerical simulation and analytics involving the thermal noise and damping shows excellent agreement with the experimental results.

Because the particle remains confined to a single fringe, the potential is well approximated as harmonic and the dynamics remain linear. The phase-space distribution remains Gaussian and is fully characterized by the covariance matrix,

$$P(q, p, t) = \frac{1}{2\pi \sqrt{\det V(t)}} \exp \left[-\frac{1}{2} \mathbf{u}^T V^{-1}(t) \mathbf{u} \right], \quad (4)$$

providing a direct connection between the analytical covariance dynamics, which are shown in the red-colored ellipses in Fig. 3, and experimentally observed distributions.

C. Dark fringe-adaptive delocalization

An alternative to polarization-based delocalization is to place the particle at a dark fringe of the standing-wave trap, where the local intensity and hence recoil scattering are strongly suppressed, while the inverted optical potential enables accelerated squeezing. To generate anti-squeezing in the dark trap, we transiently shift the standing-wave pattern by $\lambda/4 = 266$ nm, transferring the particle from a bright to a dark fringe. The particle evolves in the dark potential for a duration $\tau_D = 1.8$ μs before the standing wave is shifted back, returning the particle to the bright fringe and preventing particle loss. After evolving in the bright potential for half a motional period ($\tau_B = T/2$), this dark-fringe excursion is repeated to accumulate squeezing. Each individual excursion from bright $\rightarrow$ dark $\rightarrow$ bright fringes is referred to as ‘dark pulse’. The motional state is measured when the particle is at the bright fringe, 2 μs after the end of each dark pulse, followed by feedback cooling to reinitialize the system. The full sequence is repeated 3000 times.

Building on the frequency-quench description, we now describe a complementary anti-squeezing route with a fixed axial frequency Ω , where phase-adaptive control rapidly transfers the particle from the bright to the dark fringe for duration τ_D . This fast transfer leaves the covariance continuous across the transition, $V(t_1^-) = V(t_1^+)$. At the dark fringe, the inverted potential amplifies displacements, so that the dynamics are described by the

hyperbolic propagator

$$\mathcal{O}_D(\Omega\tau_D) = \begin{bmatrix} \cosh(\Omega\tau_D) & \sinh(\Omega\tau_D) \\ \sinh(\Omega\tau_D) & \cosh(\Omega\tau_D) \end{bmatrix}, \quad (5)$$

whose eigenvalues $e^{\pm\Omega\tau_D}$ define expanding and contracting directions. Including damping and thermal fluctuations, the covariance in the dark-fringe evolves as

$$V(t) = e^{-\gamma\tau_D} \mathcal{O}_D(\Omega\tau_D) V(t_1^+) \mathcal{O}_D^T(\Omega\tau_D) + \mathcal{Q}_D(\tau_D), \quad (6)$$

with $\mathcal{Q}_D$ capturing the thermal noise [see Sec. III of SM [30]]. The dark interval is kept finite—sufficient for substantial delocalization, yet short enough to prevent too large displacements. Upon return to the bright fringe, the covariance remains unchanged, and the subsequent bright interval of duration τ_B evolves under Eq. (1).

For a train of N_p dark-fringe pulses separated by bright intervals τ_B , the covariance V_j after the j -th pulse ($j = 1, \dots, N_p - 1$) obeys the recursive relation

$$V_{j+1} = e^{-\gamma(\tau_D + \tau_B)} \mathcal{M} V_j \mathcal{M}^T + \mathcal{Q}_{\text{cyc}}, \quad (7)$$

where $\mathcal{Q}_{\text{cyc}}$ collects the thermal covariance accumulated per cycle and $\mathcal{M} = \mathcal{R}(\Omega\tau_B) \mathcal{O}_D(\Omega\tau_D)$ represents a single dark-bright cycle. This map captures the phase-sensitive accumulation: τ_D controls squeezing strength, while τ_B sets the orientation of the anti-squeezed ellipse for constructive addition. From this recursion, anti-squeezing is quantified by Eq. (2), and the linear-Gaussian form of the distribution is preserved throughout the sequence [Eq. (4)].

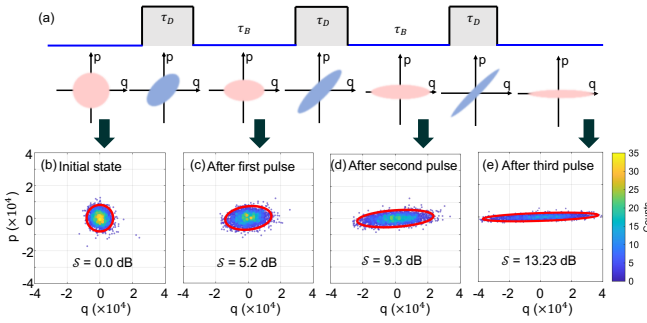


FIG. 4. Demonstration of nanoparticle motional delocalization using a transient inverted optical potential; (a–e) The standing-wave trap is shifted by to the dark fringe for three times in a row and measurement is done once the particle is transferred back to the bright region, producing an increase of the position variance by 13.23 (± 0.5) dB relative to the initial thermal variance. The bright and dark fringe particle placement durations are $\tau_D = 1.8 \mu\text{s}$ and $\tau_B = 9 \mu\text{s}$, respectively. The experimental distributions are normalized to the zero-point motion (zpm) and fitted with Eq. (4).

During the $1.8 \mu\text{s}$ interaction time, this inverted potential induces exponential stretching and compression of the motional phase-space distribution [see Fig. 4(a)]. To prevent the particle from reaching an adjacent bright

fringe as the position uncertainty grows, which would halt the intended exponential delocalization without a clear signature, we periodically return the particle to the bright fringe before transferring it back to the dark fringe. The period is chosen to be half the oscillation period, such that the delocalization generated during each dark-fringe trapping event accumulates over subsequent events, as shown in Fig. 4(c, d & e). This repositioning the particle at the dark fringes across multiple passes transiently increases the position variance up to 13.23 (± 0.5) dB relative to the initial thermal variance.

D. Non-Gaussian state preparation

With increasing position delocalization, the cold particle reaches the fringe-trap edges, where quartic and higher-order even terms introduce significant anharmonicity into the optical potential, modifying the restoring force and particle dynamics [see Sec. IV of SM [30]]. To capture this nonlinearity, we retain the full spatial dependence of the standing-wave intensity [26] rather than expanding about the trap minimum, giving a sinusoidal gradient force. Fig. 5 compares experiment and theory: a fourth dark pulse measures the motional state at $T/8 \sim 2 \mu\text{s}$ after the particle returns to the bright fringe (blue data), while numerical solution of the nonlinear stochastic equations [see Eqs. (S147-S148) in Sec. IV of SM [30]] of motion simulates the non-Gaussian state (orange data). Fitting the simulation to the experimental data gives the nonlinearity parameter $\eta = 2.69 \times 10^{-5}$, consistent with the theoretical expression $\eta = 2\pi q_{\text{zpm}}/\lambda$, where $q_{\text{zpm}} = \sqrt{\hbar/m\Omega} = 4.43 \text{ pm}$ is the zero-point position fluctuations with $\hbar$ being the reduced Planck constant.

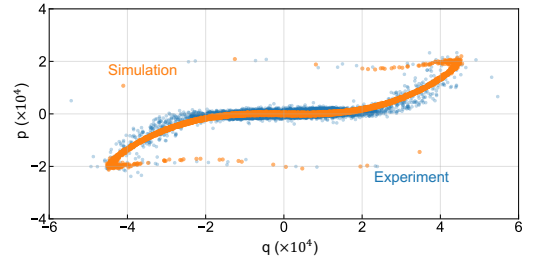


FIG. 5. Non-Gaussian motional state preparation; Numerical and experimental phase-space distributions of a non-Gaussian state generated through massive delocalization in the nonlinear optical trap using four consecutive dark-fringe placement events. The blue points are experimental data taken over 6000 realizations while the orange points are numerical solution of nonlinear motional dynamics taken over 20000 realizations.

As the highly anti-squeezed thermal state evolves in the bright anharmonic optical potential, its phase-space distribution develops extended, curved, and fanning tails [11]. While low-amplitude components of the distribution remain predominantly confined to the approximately har-

monic region of the potential, higher-amplitude components experience an amplitude-dependent oscillation frequency. Consequently, different parts of the distribution accumulate different dynamical phases and rotate through phase space at different rates. This differential rotation progressively shears and bends the outer regions of the distribution, producing the observed curved tails and transforming the initially Gaussian delocalized state into a distinctly non-Gaussian phase-space distribution.

III. DISCUSSION

Thermally delocalized motional states provide a practical resource for force and displacement sensing with trapped nanoparticles. For a charged 234 nm-diameter silica particle, placed in electric fields [27], assuming a mechanical resonance frequency of $2\pi \times 55$ kHz, a damping rate of $2\pi \times 200$ Hz, and a temperature of 7.8 K, the thermal force-noise power spectral density is approximately $S_F = 2m\gamma k_B T \simeq 4$ aN²/Hz [33]. Applying 13 dB of momentum squeezing reduces the force-noise amplitude spectral density by a factor of $10^{13/20} \simeq 4.47$, corresponding to a reduction of the force-noise power spectral density by a factor of $10^{13/10} \simeq 20$. Thus, $S_F^{(\text{sq})} \simeq 4/20 \simeq 0.20$ aN²/Hz, or, equivalently, the force-noise amplitude spectral density is reduced from 2 aN/ $\sqrt{\text{Hz}}$ to approximately 0.45 aN/ $\sqrt{\text{Hz}}$. This corresponds to a nearly fivefold improvement in force-noise amplitude sensitivity over the feedback-cooled thermal state.

Polarization-adaptive delocalization controls the axial trap stiffness without altering optical power which can increase the recoil heating rate at ultra-high vacuum [34] [3 times for $\theta_p = 88.3^\circ$, as shown in see Sec. V of SM [30]]. However, the standing-wave geometry provides an additional means of suppressing recoil heating. Near a dark fringe, the recoil rate scales as $k_l^2 \langle z^2 \rangle$ where $\langle z^2 \rangle$ is the position variance [see Sec. V of SM [30]], allowing strong suppression in the Lamb-Dicke regime ($k_l \sqrt{\langle z^2 \rangle} \ll 1$) while retaining finite trap curvature. As the delocalization increases, however, recoil heating grows, establishing a trade-off between motional delocalization and recoil heating.

The motional delocalization is strongest along the axial direction, with only a modest ≤ 1 dB radial anti-squeezing observed during the polarization-adaptive protocol due to the accompanying reduction in radial trap stiffness. Conversely, no radial delocalization is observed during dark-fringe adaptive protocols. At an optical node, the radial potential flattens ($U(r) \approx 0$), removing the radial restoring force without creating an inverted radial trap. Because the dark-fringe placement duration ($\tau_D = 1.8 \mu\text{s}$) is orders of magnitude shorter than the radial period ($T_r \approx 770 \mu\text{s}$), the particle undergoes negligible thermal drift, leaving the transverse phase-space distribution effectively frozen. To achieve simultaneous multi-mode squeezing, parametric power-modulation protocols [17, 18] can be

integrated with polarization- and dark-fringe-adaptive schemes to dynamically modulate trap stiffness across all motional degrees of freedom.

With ongoing improvements in our laboratory's vacuum technology, we estimate that an average phonon number below unity can be achieved at a pressure of approximately (10^{-7} mbar) which is demonstrated in hollow-core fibers [25, 35]. Beyond delocalization, the sign-insensitive response of the dark fringe provides a route toward measurement-induced spatial superpositions with ground-state cooled fringe-trapped particle. Since the dark fringe lies midway between two adjacent bright fringes, the particle-scattered light intensity follows $\hat{I}_d(\hat{z}) \propto \hat{z}^2$ which can enable a quadratic position measurement. Such measurement can then conditionally prepare a coherent spatial Schrödinger-cat state of two symmetric positions $\pm z_m$ [14]. Subsequent free evolution will cause the two components to overlap and produce matter-wave interference fringes. Therefore, dark fringes can prove to be a vital resource for testing macroscopic quantum physics.

IV. CONCLUSION

In summary, we demonstrated advanced optomechanical control of a levitated nanoparticle, trapped in the interference fringes of an HC-PCF. We achieved simultaneous feedback cooling of axial and radial modes and generated axial delocalization by both extinguishing the fringes and transporting the particle into and out of dark inverted optical fringes. We also demonstrated generation of a non-Gaussian motional state. Our measurements agree closely with a Wiener dynamics-based analytical model capturing deterministic evolution and stochastic thermal fluctuations. These results establish fringe-based optical traps hollow-core fibers as a versatile platform for deterministic control of levitated solid-state particles. We anticipate that our work will open a route toward fiber-based generation and transport of non-classical states of motion for enhanced sensing as well as advanced optomechanics experiments.

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AUTHOR CONTRIBUTIONS

S. C. and G. W. performed the experiments. P. K. developed the theoretical model and performed the numerical simulations. C. G. and N. J. supervised the project. All authors contributed in writing and editing the paper.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

The datasets generated in the current study are available from SC on reasonable request.

METHODS

The polarization-adaptive delocalization is performed using four consecutive steps, repeated over 3000 iterations.

(1) The particle is initialized in a low-energy motional state at a axial trap frequency of $\Omega_0 = 2\pi \times 55$ kHz under feedback cooling. The cooling ensures our homodyne-type detection remains in the linear regime. The feedback is then switched off for 20 μ s.

(2) The standing-wave pattern is transiently suppressed, therefore reducing the axial trap frequency to $\Omega_1 = 2\pi \times 10.2$ kHz for a duration of $T_1/4$ where $T_1 = 2\pi/\Omega_1$. The particle motion gets squeezed during the frequency jump. By choosing the evolution duration correctly in the shallow optical potential [18], we can maximize the amount of squeezing (see main text).

(3) The standing-wave trap is restored.

(4) The feedback is switched on and the system is allowed to reinitialize for 10 ms.

(5) The entire sequence is repeated 3000 times.

For the entire duration of the protocol, the axial position of the particle was monitored in real time using a FPGA-based lock-in amplifier around the axial eigenfrequency, providing continuous positional information through the orthogonal in-phase and quadrature components. The velocity can be reconstructed either by numerical differentiation of the measured position [9] or directly from the quadrature component [21]; both methods yielded consistent results for us. To account for the finite response of the detection chain, we further use the retrodiction protocol introduced in Refs. [10, 21, 31], in which the measured position is used to reconstruct the velocity at an earlier time. A retrodiction test, confirms that, except 1 μ s after the pulse, transients arising from AC coupling do not affect the reconstructed velocity. The resulting position and velocity define the motional phase-

space trajectory, and all phase-space data are processed using the same protocol. To correct for slow positional drift [21], the 3000 realizations are divided into 100 groups of 30 consecutive realizations, with each group spanning more than 300 ms. For each group, the mean position is calculated, and the resulting 100 group means are linearly fitted to determine the positional drift. The fitted drift is then subtracted from the mean position of each group before constructing the phase-space distributions. This correction centers the groups at a common position and prevents slow positional drift from artificially increasing the measured position variance and, consequently, from leading to an overestimation of the inferred squeezing.

Here we detail the protocol for squeezing in dark trap which is repeated 3000 times.

(1) Starting from the cold thermal state and keeping the feedback off, the standing-wave pattern is transiently shifted by $\lambda/4 = 266$ nm, transferring the particle to a dark optical fringe.

(2) The particle evolves in the dark fringe for 1.8 μ s. For longer dark-pulse durations, we observe that the particle becomes axially unstable, as indicated by sharp, irregular excursions in the measured position.

(3) The standing-wave pattern is shifted back, returning the particle to a bright optical fringe and thereby preventing particle loss. The particle subsequently evolves for $T/2$, where T is the motional oscillation period.

(4) Afterwards the particle is returned back to the dark fringe where it is allowed to evolve for another 1.8 μ s, following its subsequent return to the bright fringe. One full excursion from bright $\rightarrow$ dark $\rightarrow$ bright fringes is referred to as ‘dark pulse’. The motional state is measured after returning the particle to the bright fringe after each dark pulse. The velocity was constructed as before using the position data.

(5) The maximum motional squeezing was observed for three consecutive dark pulses while maintaining Gaussian statistics.

(6) The entire sequence is repeated 3000 times.

(7) Feedback cooling is switched on, and the system is allowed to reinitialize for 10 ms.

For the dataset capturing the non-Gaussian motional state using four consecutive dark pulses, 6000 experimental realizations were recorded. For this specific protocol, feedback cooling was reactivated 5 μ s after measuring the non-Gaussian state (see Fig. 5) to maintain stable particle trapping at low pressure.

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