# Optical tweezers in hollow-core photonic crystal fibers: Nonlinear motional dynamics and phase-adaptive feedback cooling

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**Résumé**

Optical tweezer (1) in hollow-core photonic crystal fibers (HC-PCFs) has emerged as a powerful technique, spanning over multiple disciplines including metrology, biophysics, and fundamental physics (2, 3). Here, we report on the nonlinear motional dynamics and phase-adaptive center-of-mass (CoM) cooling of a 195 nm silica particle. The particle is optically levitated inside a HC-PCF by a standing wave pattern, generated by interfering two co-linearly polarized, counter-propagating, fiber-guided modes. By introducing a constant phase shift (4) between the counter-propagating modes, the interference fringes along with the trapped particle are set into uniform motion. At ambient pressure, the dynamics of the particle result from the interplay between the axial optical trapping force and the viscous drag force from the environment. As the fringe velocity increases, viscous drag causes the particle to slip away and fall of a fringe; after which it is captured by an adjacent fringe, where it experiences renewed acceleration due to the trapping force until it slips again, repeating the cycle. Remarkably, the experimental observations are well-described by a nonlinearly-driven damped harmonic oscillator model.
By monitoring the location of the particle and adapting the optical conveyor belt through the phase of one of the counter-propagating beams, we can operate feedback cooling of the noise-driven CoM motion of the nanoparticle. Upon application of the phase-adaptive force, we show that the CoM temperature is reduced to 58 K at 0.5 mbar pressure for a 195 nm diameter particle (5, 6). Finally, by adjusting the stiffness of the optical trap at twice the mechanical frequency, we can access nonlinear parametric heating or cooling and even prepare classical squeezing of the CoM motion. The work adds to the collective effort in exploring macroscopic quantum mechanics using levitated particles.

References

(1) A. Ashkin, "Acceleration and trapping of particles by radiation pressure", Phys. Rev. Lett. **24**, 156 (1970).

(2) D. S. Bykov *et al.*, "Flying particle sensors in hollow-core photonic crystal fibre", Nat. Photon. **9**, 461 (2015).

(3) C. Gonzalez-Ballestero *et al.*, "Levitodynamics: Levitation and control of microscopic

*Intervenant

objects in vacuum", Science **374**, eabg3027 (2021).

(4) S. Chakraborty *et al.*, "Velocity-modulated drag-trapping of nanoparticles by moving fringe pattern in hollow-core fiber", arXiv:2506.04770 (physics.optics) (2025).

(5) P. Kumar *et al.*, "Prospects of phase-adaptive cooling of levitated magnetic particles in a hollow-core photonic-crystal fiber", Phys. Rev. Res. **7**, 023191 (2025).
(6) S. Chakraborty *et al.*, "Phase-adaptive cooling of fringe-trapped nanoparticles at room temperature in hollow-core photonic crystal fiber", Phys. Rev. Res. **7**, 043301 (2025).