Transfer of a levitating nanoparticle between optical tweezers.

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We demonstrate and characterize the transfer of a levitating silica nanosphere between two optical tweezers, at low pressure. Both optical traps are mounted on the heads of optical fibers and placed on translation stages in vacuum chambers. Our setup allows to physically separate the particle loading environment from the experimental chamber, where the second tweezer can position the particle inside a high Finesse optical cavity. The separation prevents from spoiling the cavity mirrors and the chamber cleanliness during the particle loading phase. Our system provides a very reliable and simply reproducible protocol for preparing cavity optomechanics experiments with levitating nanoparticles, opening the way to systematic studies of quantum phenomena and easing the realization of sensing devices.

I. INTRODUCTION

Quantum optomechanics has recently expanded the range of explored and exploited systems to nanoparticles levitating in vacuum, trapped and oscillating in the potential created by an optical field. In particular, the topic of cavity optomechanics is very intriguing for the possibility of realizing quantum coupling between photonic field and the particle motion, where the latter is strongly decoupled from environmental thermal noise by operating in high vacuum.

Most proposals and experiments, aiming to cool the dynamics of a levitating nanoparticle inside an optical cavity are based on the dispersive coupling of its motion to the electromagnetic field, a technique well investigated in optomechanics. A different mechanism of cavity cooling, relying on coherent trapping of light scattered by a levitating nanoparticle into an optical cavity, has been recently realized and allowed to achieve motional cooling of a levitated nanoparticle to a phononic occupation number below unity. In any case, accurate positioning of the nanoparticle inside the cavity is crucial to tune and optimize the optomechanical coupling.

To optically trap a neutral nanoparticle, a laser beam is tightly focused in a chamber, in the presence of gas containing suspended particles. If their motion is sufficiently damped by collisions with the background gas, trapping occurs as one particle crosses the focused beam and releases its kinetic energy fast enough to be captured by the optical potential. To implement cavity optomechanics experiments, it is then necessary to place the levitating particle into the region defined by a field mode of a high finesse optical cavity, with submicrometric precision. The position must be stably and accurately maintained, avoiding excess mechanical and acoustic vibrations. A prerequisite is loading the dipole trap (optical tweezer) without spoiling the cavity mirrors, something that easily occurs due to particle deposition on the mirrors surface. Finally, high vacuum conditions must be achieved in reason-
The crucial stage in our scheme is the transfer of the nanoparticle between two optical tweezers, in a low pressure environment. In the following we characterize in detail this procedure.

II. EXPERIMENT

The setup is shown in Fig. 1. Nanoparticles are caught in chamber A, then transferred to the second trap in chamber B. The optical tweezer that capture the particles is realized with a fibered 976 nm laser diode (LD). The light delivered by a single-mode fiber is collimated and focused using an optical system (F1) composed of two aspheric lenses, having nominal focal length and numerical aperture of respectively 15.4 mm (N.A. 0.16) and 3.1 mm (N.A. 0.68). The two lenses are screwed on the fiber head connector. The beam at the focus is elliptical with waists of 0.96 µm and 0.92 µm, as deduced from the particle oscillation frequencies at the typical output power of 250 mW. The fiber head with the optics is mounted at the end of a 500 mm long, X-shape aluminum rod screwed on the moving flange of a bellowed sealed linear shift mechanism (HV Design) that allows to manually translate it between chambers A an B. We note that this support is sensitive to mechanical vibrations, making this trap unsuitable for stable cavity optomechanics experiments.

A drop of aqueous solution of silica nanospheres (9% of particles, in mass) of radius ∼85 nm is injected inside chamber C, that is filled with clean nitrogen while chamber A is evacuated. The valve separating the two chambers is opened and dust of nanoparticles is introduced in chamber A, carried by the gas turbulence produced by the pressure unbalance. Trapping by the optical tweezer occurs when a pressure of ∼100 mbar is achieved in chamber A, typically within few minutes.

With a particle trapped, before opening the gate G, residual wandering nanoparticles are pumped out from chamber A, whose pressure is gently decreased down to the mbar level. The chamber is then slowly refilled with pure nitrogen up to 30 mbar, and the gate is opened to equilibrate the pressure between chamber A and B. The optical tweezer is translated to chamber B and positioned in front of the second optical trap. We remark that at this pressure the nanoparticle motion is over damped, and we can keep the levitating particle during the translation without using any active feedback.

The second tweezer is formed by the light of a Nd:YAG laser, delivered by a polarization maintaining fiber. The focusing optical system screwed on the fiber head (F2) is the same of the first tweezer, and is positioned on a three-dimensional miniature linear stage (PI Q-522). The beam waists at the focus are 1.02 µm and 0.93 µm, the typical optical power is 200 mW. Fibered beam-splitters allow to collect the light arriving from the fiber heads. With the help of dichroic mirrors, we can thus measure the transmitted and back-scattered light of both sources.

To transfer the particle between the two tweezers, we have to superpose the positions of their intensity maxima with sub-micrometric precision. This procedure is performed by moving the second fiber head. Its transverse position with respect to the optical axis is optimized by maximizing the light transmission between the two fibers, while the distance between the two fiber heads must take into account the chromatic aberration, as sketched in Fig. 2(b). We remark that the light of the second tweezer remains off during the whole procedure, to avoid the accidental formation of an unstable potential by the superposition of the two intensity profiles.

To define the optimization procedure, we have performed a preliminary characterization of the optical coupling between the two fibers, at the two used wavelengths. The transmitted power of the Nd:YAG light through the first fiber, and that of the LD light through the second fiber are reported in Fig. 2(a). The transverse position of the fiber head is kept optimized during the measurement, while the two fiber heads are moved closer at ∼1.1 µm steps. The solid line, for each of the two wavelengths, is given by the overlap integral of the two counter-propagating modes, fitted to the experimental data.

We find a distance of 9.8 µm between the positions of the foci for the two wavelengths. As shown in the scheme of Fig. 2(b), assuming two identical focusing systems the optimal distance to transfer the particle between the tweezers is halfway between the transmission maxima at the two wavelengths (this position is labeled as P2 in the figure). The operative procedure is then the following: we optimize the transmission of the LD light through the second fiber by moving the fiber head in the three directions, and afterwards we increase the fiber heads distance by ∼10 µm.

To load the second trap, we boost the Nd:YAG power and slowly turn off the LD. With the described protocol, we can reliably transfer the particle between the two traps. In Fig. 3 we show a photo of the two optical systems and the levitating nanoparticle before and after the transfer. The power spectra of the light collected by the fibers in the back and forward di-

![Experimental setup. Nanoparticles are injected in chamber C, then transported in a gas flux toward chamber A where they are captured by the tightly focused light of a laser diode delivered by a single-mode fiber. The fiber head with the focusing system (F1) is mounted on the tip of a rod (R) that can be manually translated between chambers A and B through the gate G. The second optical tweezer is formed by the light of a Nd:YAG laser, delivered by a similar optical system (F2) mounted on a three-axis miniature linear translation stage (MLS). The focus can be positioned inside the optical cavity (OC) with sub-micrometric precision.](image-url)
FIG. 2. (a) Transmitted power of the laser light from the two sources through the two optical fibers and the corresponding F1 and F2 optical systems. Green dots: Nd:YAG light. Orange squares: LD light. Data are recorded approaching the two fiber heads at 1.1 µm per step, and normalized to the maximum transmitted power for each wavelength. Abscissa represents the variation of fiber heads distance, with the origin set halfway between the two maxima. Solid lines: overlap integral between the propagating field modes, fitted to the experimental data. (b) Schematic drawing of the two focusing systems during the measurement. Green (orange) rays represent the Nd:YAG (LD) beam propagation, with arrows indicating the direction. P2 indicate the optimal position to transfer the particle, as the two focuses are spatially overlapped. At relative position P1(P3) the two focusing systems are optimally placed to couple the Nd:YAG (LD) optical power. In that case, the distance between the two traps is 9.8 µm.

FIG. 3. Left panel: the light back scattered (B.S.) from the particle is collected from the trapping fibers during the transfer between the LD and the Nd:YAG tweezers. Orange: LD light signal (scale on the bottom axis). Green: Nd:YAG light signal (scale on the top axis). Central panel: images of the Nanoparticle trapped by the LD (bottom picture) and the Nd:YAG (top picture) optical tweezers. Bright spots, also shown in the enlarged insets, are due to the particle dipole emission, and scattered light allows to identify the edges of the focusing lenses. Brightness difference between the two traps is due to the different camera sensitivity at the two wavelengths. Right panel: spectra of the back and forward scattered light, collected by the fibers and acquired at a background pressure of 2 mbar, exhibiting spectral peaks corresponding to the three eigenfrequencies of the particle motion. Bottom graph: spectra of the forward scattering (upper trace) and back scattering (lower trace) of the LD light, with the particle on the first tweezer. Top graph: spectrum of the forward scattering of the Nd:YAG light, with the particle trapped by the second tweezer. Vertical dashed lines display the particle oscillation frequencies.

We often observe that the particle scattered light changes suddenly during the transfer. On the other hand, a transfer between potential wells having the same minimal point should be characterized by a continuous change in the apparent particle brightness, following the varying light intensity. The observed abrupt changes indicate that the nanoparticle jumps between two potential minima, that are not perfectly superimposed due to an uncertainty in the positioning of the order of few hundred nanometers, and to the optics mechanical vibrations. While turning off the LD, the potential barrier from the first to the second trap, as well as the depth of the first trap, become vanishing small. A reliable transfer occurs if the jump rate (favored by the lowering barrier) is higher enough than the loss rate (increased by the lowering well depth) and the motion is damped enough that the particle can lose its kinetic energy during the transfer. Our double tweezer is a versatile system to investigate the stochastic motion of a particle in a variable three-dimensional potential that is however beyond the scope of the present article and is left to further works. At the purpose of providing useful information for the reproduction of our method, we describe in the following a semi-quantitative investigation of the pressure and misalignment ranges that allow a reliable transfer.

We first characterize the relative mechanical vibrations of the two trapping optics on the plane perpendicular to the optical axis. The two focusing systems are first placed at the position that maximizes the transmitted Nd:YAG power through the two fibers. The transmitted signal is then recorded while moving the second fiber head in the vertical direction. Hence, the fiber head is set at the position that halves the transmitted power, and the time trace of the transmitted signal is acquired and calibrated in terms of displacement fluctuations using the previously recorded transmission curve (as illustrated in the right inset of Fig. 4). The same procedure is repeated for the horizontal displacement. In Fig. 4 we show the calculated displacement noise spectra. The main spectral feature is a double peak at ~ 50 Hz for the vertical direction, whose
we have placed an optical axes, or ∼ 50 mm (root means square), much smaller than the beam waists. A simulation with a Finite Element Model shows that the two peaks are due to flexural modes of the rod that sustains the first fiber head.

In order to define the pressure range that allows a reliable transfer, we have repeated at least three times the transfer back and forth between the two traps, at the pressure values of 100, 75, 50, 25 and 15 mbar. We actually lost the particle during the fourth attempt at 10 mbar. We notice that at 10 mbar the damping rate is about Γ ≃ 2π × 10 kHz, thus the particle motion is weakly damped.

At 50 mbar we have then evaluated the tolerance in the misalignment between the two fiber heads. Starting from the optimal position, we could transfer the particle three times back and forth in different relative positions, until the two focuses were misplaced by ∼ 3 μm on the plane perpendicular to the optical axes, or ∼ 10 μm along the optical axes. For the latter case, we show in Fig. 3 on the left panel, the time evolution of the backscattered light during a transfer from the LD to the Nd:YAG tweezers. The visible steps indicate a jump between the two potential wells occurring in a time shorter than 0.1 ms.

After having defined the above described transfer protocol, we have placed a ∼ 50 mm long optical cavity (Finesse 54000) inside the chamber B. The cavity spacer has a 20 mm diameter radial hole that allows to place on the cavity optical axis the nanoparticle trapped by the Nd:YAG tweezer. We have captured and transferred several particles from the LD to the Nd:YAG trap at a background pressure of 30 mbar. Even after ten complete cycles we could appreciate no degradation of the cavity finesse, as shown in Fig. 5 where we report two recordings of the cavity transmission function, acquired before the first, and after the last transfer operation. The measured width is respectively 57 ± 1 kHz and 56 ± 1.5 kHz.

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We have described a robust method to systematically capture and place a levitated nanoparticle with sub-micrometric precision inside an optical cavity, without spoiling the cavity optical quality and the environment of the experimental chamber. We have indeed observed that the optical cavity can be repeatedly loaded without degrading its performance. A key element of our protocol is the transfer of the loaded particle between two, completely independent optical tweezers, that we realize and characterize, and that is performed without the necessity of stabilizing feedback loops. Hence, the second tweezer can be mounted on stable nano-positioners, that allow a reliable and systematic investigation of the coupling between the nano-particle and the cavity optical field. Our system provides a very reliable and simply reproducible protocol for preparing cavity optomechanics experiments with levitating nanoparticles, opening the way to systematic studies of quantum phenomena and easing the realization of sensing devices.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.
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