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Intracavity feedback optical trapping

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Summary. — Several research groups have integrated feedback control with optical trapping to improve performance, *e.g.*, for force or position control. Among the different proposed approaches, using the feedback when trapping inside a laser cavity stands out for several reasons, namely, trapping can occur at lower optical intensities, reducing photodamage, and with low numerical aperture lenses, simplifying setup design. This is possible because the trapped particle position alters the cavity losses, triggering an intrinsic feedback on the trapped particle. Here, we analyze the behaviour of intracavity optical trapping with a single beam and with counter-propagating beams. The single-beam configuration features a well-known nonlinear feedback effect, because the beam power changes as the square of the particle displacement from trapping position. Instead, the counter-propagating-beam configuration feedback effect acts on both beams and can not be described by the same model.

1. – Introduction

Optical tweezers are a powerful tool to study micro- and nanoparticles confined by tightly focused laser beams [1]. Since Ashkin's pioneering studies [2, 3], optical tweezers have been used in many areas of science, such as physics, chemistry, biology and medicine [4]. For example, optical tweezers are used for trapping nanometric objects [5], proteins and molecules [6], and, very recently, for particles cooling [7]. In many applications, high trapping stiffnesses are required. However, it is often necessary to limit the amount of laser power because high laser power can damage the systems under investigation. This can be done using an extrinsic feedback mechanism based on acusto-optic deflectors or electro-optic modulators [8]. Recently, optical trapping inside a laser cavity has been proposed and implemented [9], demonstrating that the intrinsic feedback caused by the cavity itself can increase trapping efficiency. Here, we extend this study from the case of a single beam inside the cavity to the more general configuration with two counter-propagating beams.

2. – Experimental setup

Our experimental setup (fig. 1) comprises a continuous wave ring cavity fiber laser with a trapping system inside. The Yb-doped gain fiber is pumped by a 976 nm single-mode fiber-coupled diode laser by a wavelength-division multiplexing (WDM). A band-pass filter allows selecting the laser wavelength at $\lambda = 1030\,\text{nm}$. After the band-pass filter, a fiber coupler is employed to split the beam into two parts. The smaller part is sent to the bottom photodiode ($_B$) for monitoring and the larger one is sent to a single mode fiber coupled collimator placed in the bottom (BC). The output from the collimator is sent to the trapping system consisting of two aspheric lenses L1 and L2 ($f = 9.6\,\text{mm}$ and $NA = 0.3$). Two dichroic mirrors DM1 and DM2 are used for illumination and visualization of the particles. The top collimator (TC) couples the beam from free space to the fiber. The intracavity optical trapping switches from unidirectional (single beam) to bi-directional (counter-propagating beam) by inserting or removing a free space optical isolator (ISO) inside the cavity. The experimental setup is mounted in such a way that the z-axis coincides with the direction of gravitational acceleration $\vec{g}$. Thus, in the counter-propagating beam configuration, the beam that travels from BC to TC (bottom beam) is opposite to $\vec{g}$, while the beam that travels from TC to BC (top beam) has the same direction as $\vec{g}$. The power of the two beams, P_B and P_T, was monitored using two photodiodes, $\mathrm{PD_B}$ and $\mathrm{PD_T}$. $\mathrm{PD_B}$ monitors the power of the bottom beam through the 5% coupler port, while $\mathrm{PD_T}$ the top beam through the 6% pellicle beam splitter PBS.

The sample consists of a small cell containing a distilled water solution of $2.31\,\mu$m diameter silica particles. It is placed at the focal plane of the lenses L1 and L2. The sample temperature was kept constant during the experiments at $T = 24.0 \pm 0.7\,^\circ$C.

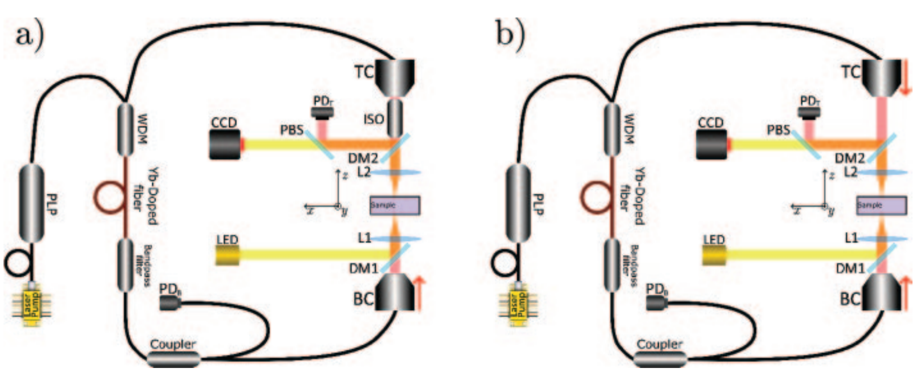

Fig. 1. – Intracavity optical trapping schemes: single beam (a) and counter-propagating beams (b). The transformation from (a) to (b) occurs by removing the optical isolator (ISO) placed inside the laser cavity. PLP indicates a Pump Laser Protection, PD a photodiode, DM1, DM2 dichroic mirrors, PBS a pellicle beam splitter, L1 and L2 the lenses, and CCD a charge-coupled device camera. The solid red lines indicate the beam direction.

3. – Data acquisition and analysis

Particle trajectories in the xy-plane were acquired by video-tracking [10] using a CCD camera at 10 frames per second. To monitor the feedback effect, we synchronized the photodiodes signals with the CCD acquisition using a hardware trigger. The particle displacement from the equilibrium position, $r = \sqrt{x^2 + y^2}$, is shown in fig. 2(a) for the single-beam configuration and in fig. 3(a) for the counter-propagating beam one.

Single-beam configuration. – In the single-beam configuration, we used the bottom beam to trap the particle. In agreement with [9], we found that the optical power inside the laser cavity P_B is proportional to r^2 (fig. 2(c)). This dependency is also confirmed by the correlation coefficient between P_B and r^2, *i.e.*, $C_{r^2 P_B} = \frac{1}{N-1}\sum_{i=1}^{N}\left\langle \frac{r_i^2 - \mu_{r^2}}{\sigma_{r^2}}\right\rangle \left\langle \frac{P_{B,i} - \mu_{P_B}}{\sigma_{P_B}}\right\rangle \simeq 0.9$, being μ_{r^2,P_B} and σ_{r^2,P_B} the mean and the standard deviation of r^2 and P_B respectively. Moreover, using the equipartition theorem [1], we estimated the trapping stiffness along the x and y axes: $k_x^{single} = (7.7 \pm 0.6) \cdot 10^{-8}$ N/m and $k_y^{single} = (14.1 \pm 0.2) \cdot 10^{-8}$ N/m, obtained with a mean measured optical power $P_B \simeq 2\,\mathrm{mW}$.

Counter-propagating configuration. – In this case, both the bottom beam and the top beam oscillate inside the cavity. The trapping stiffnesses resulted to be $k_x^{counter} = (8.7 \pm 1.4) \cdot 10^{-7}\,\mathrm{N/m}$ and $k_y^{counter} = (8.9 \pm 1.6) \cdot 10^{-7}\,\mathrm{N/m}$ with the mean measured optical powers $P_B \simeq 11\,\mathrm{mW}$ and $P_T \simeq 4\,\mathrm{mW}$. Unlike the case of a single beam, no correlation appears between r^2 and the powers of the two beams, as shown in fig. 3(b). In fact, the correlation coefficients were $C_{r^2 P_B} \simeq 0.1$ and $C_{r^2 P_T} \simeq 0.1$. To check if some correlation exists between the powers and the trajectory, we analyzed also the correlation with the coordinates x and y, finding $C_{xP_B} =\simeq 0.3$, $C_{xP_T} =\simeq 0.3$, $C_{yP_B} =\simeq -0.4$, and $C_{yP_T} =\simeq -0.2$. This confirms a weak correlation between the particle position and the optical powers of the two beams. Interestingly, the correlation coefficient between the powers of the two beams is $C_{P_T P_B} =\simeq -0.3$ suggesting that the two beams are weakly anti-correlated. The absence of correlation between the counter-propagating beams could be explained by the fact that the two beams attempt to exert independent feedback mechanisms and, as an overall effect, the particle finishes in a sort of frustrated state, which, at same condition of total intracavity power, results in more confinement. In fact, the standard deviations of the particle motion normalized to the laser power are: $\sigma_r^{counter} \simeq 4.42$ nm/mW and $\sigma_r^{single} \simeq 137\,\mathrm{nm/mW}$. Another interesting result concerns the behavior of the laser powers P_B and P_T, when the particle is present or not in the

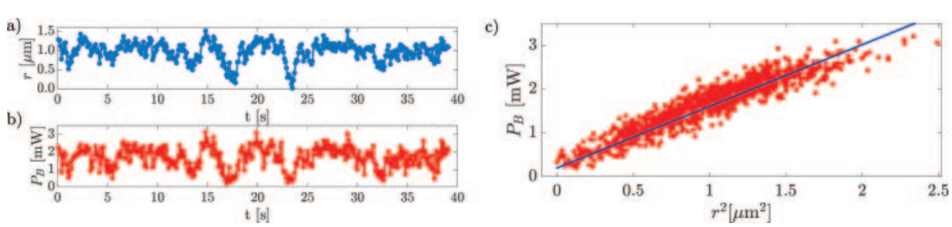

Fig. 2. – Displacement r from the equilibrium position of the particle (a) and optical power inside the ring cavity P_B (b) as a function of time t for 10 seconds of a 100 second trajectory. P_B as a function of r^2 (c). The solid line in panel (c) is the fit curve to check the linearity of our data.

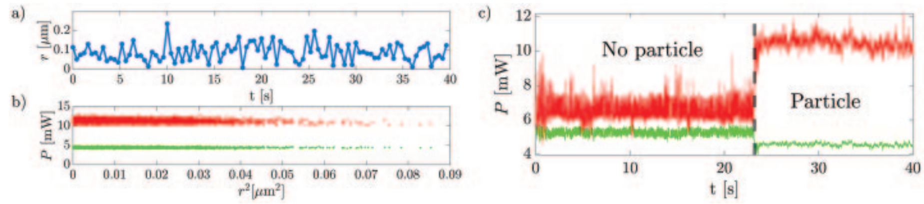

Fig. 3. – Displacement r from equilibrium position of the particle as a function of time t for 10 seconds of a 100-second trajectory (a). P_B (red) and P_T (green) as a function of r^2 (b) and as a function of time t for the non-trapped and trapped cases, respectively. The dashed black line delimits the transition between the non-trapped case and the trapped case.

cavity (fig. 3(c)). When the particle is trapped, P_T decreases while P_B increases, such that $P_B + P_T$ is greater than when the particle is not trapped. We hypothesize that the amplified spontaneous emission (ASE) could play an important role to explain this not yet understood phenomenon.

4. – Conclusion

In this work, we have analysed two optical configurations for intracavity optical trapping: a single-beam configuration and a counter-propagating-beam configuration. For the single-beam configuration, we confirmed the feedback mechanism leading to the trapping identified in [9]. For the counter-propagating configuration, we obtained some new results: the absence of correlation between the laser powers of the two beams and the particle displacements, and the anomalous increase of the total power inside the cavity. This suggests the appearance of new phenomena related to the competition between the two beams and the role of the ASE. Our plan is to extend the toy model proposed in [9] to the counter-propagating-beam scheme and to verify, also with accurate simulations, the experimental results.

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