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Towards Spatio-Temporal Control in Optical Trapping

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Abstract

Using both continuous-wave (CW) and high repetition rate femtosecond lasers, we present stable 3-dimensional trapping of 1 μ m polystyrene microspheres. We also stably trapped 100nm latex nanoparticles using the femtosecond mode-locked laser at a very low average power where the CW lasers cannot trap, demonstrating the significance of the fleeting temporal existence of the femtosecond pulses. Trapping was visualized through dark-field microscopy as well as through a noise free detection using two-photon fluorescence as a diagnostics tool owing to its intrinsic 3-dimensional resolution. Comparison between a Gaussian versus a flat-top Gaussian beam profile demonstrates the importance of laser spatial mode in optical trapping.

Keywords

Optical trap; femto-second laser; peak power; Rayleigh particles; two-photon fluorescence

1. INTRODUCTION

In optical tweezer or single beam gradient optical trap [1], a tightly focused laser beam with transverse Gaussian intensity profile is used to trap particles of various sizes starting from few micro meters to few nanometers. As of now, continuous-wave (CW) lasers are generally used for optical trapping. Over last few years femtosecond lasers are being used to trap dielectric microspheres because they produce very high peak power compared to their averaged power due to their fleeting existence. The high peak power of the femtosecond lasers can also produce two-photon fluorescence when two-photon fluorescent dye coated polymer microspheres are trapped [2].

Usually near infra-red (NIR) CW lasers are used to trap particles of diameter (d) being one order smaller than the laser wavelength (~ 800 - 1100 nm). In this situation, the particle can be treated as a point dipole and the radiation force (F) acting on the particle, according to Rayleigh scattering, is given by [3]:

$$F = \frac{\alpha}{2} \nabla E^2 \quad (1)$$

Where E is the electric field and α is the polarizability and is equals to:

$$\alpha = \frac{n^2 - 1}{n^2 + 2} r^3 \quad (2)$$

Where $n = n_1/n_2$ is the refractive index of the particle with respect to its environment, n_1 , n_2 are the refractive index of the particle and its surroundings respectively and r is the radius of the trapped particle. To maximize the gradient force, we have to maximize the gradient of the laser intensity by using a high numerical aperture (NA) objective. For trapping of Rayleigh particles using CW laser beam, the minimum laser power used is ~100-200mW.

On the other hand, the electric field of a paraxial pulsed Gaussian beam is [4]:

$$\vec{E}(\rho, z, t) = \hat{x} E(\rho, z, t) \\ = \hat{x} \frac{iE_0}{i + \frac{2z}{kw_0^2}} \exp \left[i\omega_0 t - ikz - \frac{i2kz\rho^2}{(kw_0^2)^2 + 4z^2} - \frac{(kw_0^2)^2 \rho^2}{(kw_0^2)^2 + 4z^2} \right] \exp \left[-\frac{(t-z/c)^2}{\tau^2} \right] \quad (3)$$

Where w_0 is the beam waist at the plane $z=0$, ρ is the radial coordinate, $\hat{x}$ is the polarization vector along the x direction, $k = 2\pi/\lambda$ is the wave number, τ is the pulse duration and ω_0 is the carrier frequency and the pulse spectrum width is much smaller than ω_0 . In such condition, the gradient force is a type of ponderomotive force, which in dilute solution is the Lorentz force. The value of the gradient force is given by [4]:

$$\vec{F}_{grad} = -\frac{\hat{a}\hat{c}}{\rho} 2\alpha I(\rho, z, t) \frac{\hat{a}\hat{c}}{\rho} / [cn_2\varepsilon_0 w_0 (1+4z^2)] \quad (4)$$

Where $I(\rho, z, t)$ is pulse intensity, $\hat{\rho}$ is the unit vector along the radial direction.

In this paper we have shown that the Gaussian beam is a better choice than the flat-topped Gaussian beam in the field of optical trapping. We also show that the escape speed of a trapped 1nm polystyrene sphere is more for a pulsed optical trap compared to a CW optical tweezer at the same power level indicating the importance of the instantaneous force of the individual pulses. In addition, we also trapped 100 nm latex nanoparticles at a very less average power, where CW laser cannot trap them. The two-photon fluorescence from the trapped particle gives us a unique method to observe them.

2. METHODOLOGIES

Our experimental set-up is made up on an optical tabletop to make it isolated from the vibrations. The schematic of it is given in figure 1, which is modified from our previous experimental set-up [5]. The laser system used in the experiment is a Ti:saph laser (Mira 900-F pumped by Verdi5, Coherent Inc.) that produces NIR (centered at 780 nm) ~120 fs mode-locked pulse trains at 76 MHz repetition rate. The laser can also operate in CW mode. The beam coming out of the oscillator is divided into two parts using a beam splitter. They were recombined again by another beam splitter after both the beam travels same path length. One of the splitted beams was passed through a retro-reflecting mirror that was mounted on a mechanical stage (UE1724SR driven by ESP300, Newport). Part of the collinearly propagating beam was collected through a Si- amplified Photo Diode (PDA100A-EC. Thorlabs Inc.) connected to a digital oscilloscope (TDS 224, Tektronix).

The delay stage and the oscilloscope were interfaced through a computer having GPIB card (National Instruments). The data was collected using LabVIEW software.

One of the beams was sent to the home built tabletop inverted microscope via a telescope with two steering mirrors. For the trapping purpose we used a 100x oil-immersion objective (UPlanSApo 1.40 NA, Olympus Inc.). Before the microscope, a dichroic mirror with ~95% reflectance was placed. The two-photon fluorescence and the back-scattered light were collected after the dichroic mirror. The two-photon fluorescence was collected using a photomultiplier tube (PMT) and the back-scattered signal was collected by a Silicon-amplified Photo Diode (PDA100A-EC, Thorlabs Inc.) after using proper band-pass filters. Both the PMT and the Photo Diode signals were collected by an automotive oscilloscope or 'picoScope' (Pico Technology Ltd) triggered by a rotating-disk optical chopper (having 30 slot wheel) run by a tunable frequency driver (MC1000A, Thorlabs Inc.) operating at 800 Hz. Using our set-up, we can collect the two-photon fluorescence and back-scattered light simultaneously to observe the trapping event in both methods. Furthermore, we can also capture the video of the trapping event under bright field illumination (not shown) and dark field fluorescence. Polystyrene microsphere with 1 μm diameter (F8820, Molecular probes Inc.) and latex beads of diameter 100nm (F8800, Molecular Probes Inc.) were used to trapping. Both the beads were coated with fluorophore with single photon absorption maxima at 540 nm and emission maxima at 560 nm. Diluted and slightly alkaline solution of the samples were well sonicated and immediately used for trapping. The sample stage was attached to a mechanical stage (UE1724SR driven by ESP300, Newport) which was connected to a tunable velocity motion controller/ driver (ESP 300, Newport). By putting two cylindrical lenses, separated by their sum of focal distance, in the beam path we generated top hat Gaussian beam.

3. RESULTS AND DISCUSSIONS

The beam profile of the flat-topped Gaussian beam is given in the figure 2. Using this beam, we were unable to trap both 1 μm and 100 nm beads, even at very high laser powers. This can be understood from equation (1), where the ∇E^2 is zero and hence there is no gradient force available to drag the beads for getting trapped. This is also in accordance with the theoretical prediction [6].

We trapped 1 μm particle using both the CW and mode-locked laser and found that the escape velocity of the particle is more in case of pulsed laser optical trap compared to the CW one at the same power level (Figure 3), which essentially shows that the force acting on the 1 μm particle is higher in the pulsed laser situation, as the force acting on the trapped particle is given by:

$$F = 6\pi r \eta v \quad (5)$$

Where r is the radius of the particle, η being the dynamic viscosity of water and v is the escape velocity.

For the 100 nm beads, at ~ 10 mW average powers at the sample tweezer occurred, which can be shown from the random spikes and few trapping instances stable for few seconds

(Figure 4). The spikes were formed due to the biased diffusion of the nano particles into the trapping zone [7]. The peak height correspond the number of particles that are trapped simultaneously. At a higher average power (~ 30 mW at the sample), a stable trap was observed. Both back-scattered and fluorescence signal showed the signature of stable trapping (Figure 5a, 5b). Figure 5b also shows that stable trap of one particle followed by another, as the fluorescence intensity increased by a factor of ~ 2 clearly telling that two particles got trapped during that time period. On the other hand, when the laser was switched to the CW mode, the tweezing action started at ~ 100 mw power, whereas the stable trap and multiple particles trapping event occurred at a much higher power (~ 200 mw). This result also confirms the temporal effect of the femtosecond laser pulses in the optical trapping.

Figure 6 is the field autocorrelation trace of the trapping beam. The autocorrelation width is found to be ~ 270 fs and thus the pulse width is ~ 190 fs. The laser repetition rate is 76 MHz, thus the time lag between two consecutive pulses is ~ 13 ns. Due to the fleeting temporal existence of the pulses with high repetition rate, the ratio of the peak power to the average power is about $10^5 : 1$. This gigantic peak power allows us to trap the 100nm latex beads at a very low average power where CW laser could not trap them. Due to this huge peak power of the femtosecond laser, when the pulse is 'on', there is a huge flux, which in turn increases the trap stiffness of the trapped particle to such a high extent that it can trap the 100 nm beads. In addition, due to the high repetition rate of the laser, even the 100 nm particle, which has higher Brownian speed, cannot leave the trapping zone, which is in turn the focal volume (~ 10 femto liter), while the light is 'off'. This effect of pulsed laser was also shown by Ambardekar et. al. in the context of levitating particle from the glass surface by overcoming its adhesive interaction, by using ~ 45 μ s pulses [8]. For 1 μ m bead, the force exerted on the particle is such high while the light is 'on', time averaged property, is higher for the pulsed laser so that, the escape velocity, which is compared to the CW laser optical trap (Figure 3).

4. CONCLUSIONS

Thus we have shown that using the very high peak power of the femtosecond laser having paraxial Gaussian profile, we can trap the Rayleigh particles stably at the low average power level. However the effects of pulse width, laser repetition rate on femtosecond laser tweezer are currently being pursued in author's laboratory.

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Figure 2.
Beam profile of flat-topped Gaussian beam.

Figure 3. Power vs. Escape Velocity plot for 1 μm bead trapped using both CW and mode-locked lasers.

Figure 4. Fluorescence signal for trapping of 100 nm beads at 10mW power for mode-locked laser: frequent spikes due to biased diffusion, ~ 150 sec, particle was trapped for ~1 sec.

Figure 5a.

Back-scatter signal for stable trap of 100nm bead at 30mW power using mode-locked laser.

Figure 5b.

Fluorescence signal for stable trap at 30mW power using mode-locked laser.

Figure 6.
Field auto correlation trace.