Trapping sub-micron Size Particles in Holographic Optical Tweezers

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Abstract. Trapping of sub-micron size particles is of interest to the biological community as well as to nanoelectronic research and industry. We have employed spatially modified Gaussian beam to generate narrow optical traps within diffraction limitation. A spatial light modulator is addressed with the spatial frequencies of the required optical traps. The inverse Fourier transform is obtained at the trap plane of the optical tweezers. We have demonstrated the trapping of sub-micron particles in multiples traps, patterned numerically which is addressed to a spatial light modulator. The trap is vary stable and the particles are trapped for more than 120 seconds.

1. Introduction

Optical tweezers are tools that use optical pressure in trapping micro objects including living cells and micro-organisms, and also in directionally rotating artificial micro-objects fabricated by micro-machining. Given their non-contact and non-invasive nature, optical tweezers are useful particularly in biological processes. The field of optical tweezers has enjoyed a wide range of applications since its invention in the early 1970s. By using light to trap microscopic objects non-invasively, optical tweezers provide a unique tool for ultrafine positioning, measurement, and control. Particle positioning and detection capabilities are on a spatial scale of micrometers down to few angstroms [1, 2].

The emerging applications of laser based optical traps are quite diverse and extensive, ranging from atomic physics to the medical sciences. As a result, optical tweezers have been a focal point for interdisciplinary science. Trapping apparatus ranges from simple, lens-based traps to complex instrumentation integrating multiple optical technologies [3]. A variety of noble techniques have been developed for rapid position detection, trap stiffness determination, and applying controlled, calibrated forces. Instrument advances, such as the use of multiple laser beams, computerized automation of laser beams and sample positioning, and optical tweezers used in combination with other methodologies, such as fluorescence spectroscopy, micro-pipettes, and optical micro-beams, have all helped to make optical tweezers an extremely versatile tool. Owing to their exquisitely controllable force exerting properties, optical tweezers are useful for a variety of nano-mechanical measurements, particularly those with biological applications.
Objects such as bio-polymers e.g., micro-tubules, DNA molecules, lipid membranes, intact or fractionated cells, and single biological macromolecules have all been studied successfully with optical tweezers [4].

In an optical tweezers, a highly focused laser beam creates a large gradient in an optical field, resulting in stable particle trapping at the beam focus. Since the trapping occurs only at the focal point, true 3 - D trapping can occur. Particles in scale from cells (µm) to individual molecules (nm) are routinely studied with this technique. However, due to the large amounts of optical power necessary to create traps of adequate stiffness, large optical intensities are necessary (∼ 10^6 W/cm²). This makes it difficult to create and control multiple traps on the same device hence multiple high powered lasers and/or holography techniques must be employed.

2. Theory
For dielectric particles larger than the wavelength we use simple ray optics to study radiation pressure forces exerted on the particle from scattering of light momentum. The early models for trapping were either all optical two beam traps or single beam levitation traps which required gravity or electrostatic force for their stability.

For particles in the Rayleigh regime, where the size (a) is much less than the wavelength (λ), the particle acts as a dipole. The force acting on dipole divides itself into two components: one is the scattering force that acts in the direction of incident light beam and other is the gradient force component pointing towards the maximum intensity region of light. The balance between the two forces results in trapping of the particle. Optical tweezers was originally designed to work in Rayleigh regime. Conceptually and practically single beam laser traps are one of the simplest lasers trapping model. Its stability in Rayleigh regime is the result of dominance of gradient force that pulls the particle towards the focus and maximum intensity region, over the scattering force that tries to push the particle away from the focus in the direction of incident light beam.

For Rayleigh particle, the scattering force component is given as [5]

$$F_{sca} = \frac{I_0 128 \pi^5 r^6}{3 \lambda^4} \frac{m^2 - 1}{m^2 + 2} n_b$$

with r is the size of the particle, m is the ratio of refractive indies of medium and particle. The gradient force is given as

$$F_{grad} = -\frac{n_b^3 r^3 m^2 - 1}{2} \frac{m^2 - 2}{m^2 - 2} \nabla |E|^2$$

The figure shows the trapping forces acting on the particle. The particle is placed at different positions from the focus of incident laser beam. Each time the resultant force acts on the particle such that the particle is displaced towards the focus of the laser beam and when the forces are balanced the particle gets trapped inside the trap volume.

3. Holographic Optical Tweezers
Computer-generated holograms can transform a single laser beam into number of independent optical traps, each with different spatial characteristics, arrayed in arbitrary two dimensional configurations. Holographic optical tweezers use a computer designed diffractive optical element (DOE) to split a single collimated laser beam into several separate beams, each of which is focused into an optical tweezers by a strongly converging lens. Originally demonstrated with micro-fabricated DOEs, holographic optical tweezers have since been implemented with computer addressed liquid crystal transmissive spatial light modulators (SLM). Projecting a sequence of computer designed holograms reconfigures the resulting pattern of traps.
The gradient force same as exploited in single beam optical tweezers also worked in holographic optical tweezers. The dielectric particle, approaching towards the focus of the beam, is pulled into the region of maximum intensity by gradient force. The scattering force competes with this gradient force and tries to displace the trapped particle along the beam axis. Hence, optical tweezers are usually designed around microscope objective lenses whose large numerical apertures and minimal aberrations optimize axial intensity gradients. An optical trap can be placed anywhere within the objective lens’ focal volume by appropriately selecting the input beam’s propagation direction and degree of collimation [8, 7].

Multiple beams simultaneously entering the lens’ input each form optical traps in the focal volume, each at a location determined by its degree of collimation and angle of incidence. This is the principle behind holographic optical tweezers. The figure shows the custom designed optical traps demonstrated using SLM. The first column is the design; middle column shows the Fourier Transform of the objects in first column. The last column shows the trap positions generated using the SLM at trap plane. The particles are trapped, manipulated in three dimensions using the setup.

4. Experiment and Results
The experiment setup consists of three parts, viz., (i) Generating of FFT of desired spatial profile numerically (ii) design of single beam optical tweezers and (iii) guiding the spatially modified beam profile through the beamline without violating Helmholtz equation.

**Figure 1.** Schematic of experimental setup of Optical Tweezers used to trap particles in a manipulated optical trap.

**Figure 2.** Snaps of trapped particle taken every 10s using setup shown in Fig. 1.

The spatial profile of the desired geometry are designed using appropriate software with 2 bit encoding (B/W) having image size of 256×256 pixels. The image is Fourier transformed using software code written using LabVIEW. The phase information of FFT are distributed spatially. The amplitude part of the FFT are ignored and phase only is considered. The phase is unwrapped suitable to remove any overflow of phase information [6].

The setup of single beam optical Tweezers is shown in Fig. 1. The setup has five ports represented by A-E. The ports A and B guides a He-Ne laser and a Nd:YAG laser to the optical trap. The port C is a imaging port having a 4 mega pixel CCD (Apogee). The port D is the optical tweezers, where two lasers and a white light source illuminate the particle while the backscattered light detected at port C. The port E has the spatial light modification using a setup of inverted telescopes and a SLM. In Fig. 2, snaps taken at an interval of 10 s are displayed.
A particle of sub-micron size (160nm) is shown in the pictures. The trap is found to be stable for more than two minutes times. However, thermodynamic changes and coagulation of particles makes it difficult to keep the trap stable for longer time durations.

In Figs. 3 and 4, we exhibit the manipulation of submicron sized particles in a pre-decided patterned manner. The First column shows the 2-bit spatial profile of the pattern to be generated. The SLM is address with FFT of information obtained from data in the first column, the FFT are shown in second column. The third column shows the reconstructed profiles at the trap plane.

![Figure 3](image1.png)

**Figure 3.** The original image, FFT and reconstructed profile are shown in first, second and third columns, respectively.

![Figure 4](image2.png)

**Figure 4.** Same as Fig. 3, but the particles are manipulated in a circular path.

The demonstration of optical traps in a predefined pattern promises the utilization of the present setup for various applications. Addition of suitable spectrograph to the system makes the possibility of a micro-photoluminescence studies at single atom level (single electron devices), appropriate manipulation of the beam positions may be used to maneuver DNA and sequencing studies.

5. Conclusions
A single beam optical tweezers is modified to have multiple traps. The spatial profile of the TEM\(_{00}\) mode of the laser beam is spatially modified with the FFT of the required pattern. Particles are trapped at the pre-decided positions. Polystyrene spheres of sizes 1µm and 160nm have been successfully trapped using current Optical Tweezers setup. The trapped particles are manipulated in 3-Dimensional positions using SLM.

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