Novel Micromanipulation Techniques For Optical Tweezers Using Spatial Beam Patterns

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Abstract

In this paper we describe trapping of micro-particles in a focused Gaussian laser beam with the help of basic optical tweezers set-up. Various methods to generate novel spatial beam patterns are discussed. Spatial Beam pattern are generated using virtual lab simulation and realized experimentally as well using interferometric approach. Novel Beam shapes increases the efficiency of optical tweezers. A low cost method using cracked glass plate to generate spatial beam patterns is also developed. Rotation of birefringent particle is achieved using circularly polarized light.

Key Words: Optical Tweezers, Spatial Beam Patterns

1. INTRODUCTION

The origin of optical trapping of micro-particle is based on the forces arising due to the momentum of electromagnetic radiation. The advent of lasers in 1960 enabled researchers to study radiation pressure through the use of intense, collimated source of light. V.S Lekhotov in 1968 proposed that light beam could be used to trap atoms. With laser, one can make these forces large enough to accelerate, decelerate, deflect, guide and even stably trap small particles. [1-3]

In 1970, Arthur Ashkin [4-5] at Bell labs discovered that laser light has the ability to apply forces on particle of size of tens of nanometers to tens of micrometers. In 1978 two counter propagating Gaussian beams [6] were used to trap spheres of high refractive index material than the surrounding medium. Sphere is held in stable equilibrium position by the opposing radiation force of two counter propagating beams.

The next advance in optical trapping and manipulation was the demonstration of levitation trap in air, under condition in which gravity plays a role. Ashkin and Dzeidic [7] performed the optical levitation experiment for the first time in 1971. In the levitation trap, a single vertical beam confines a microscopic particle where gravity and the upward scattering force balance.

Optical Tweezers, also known as optical traps, are three dimensional traps that use a focused laser to trap and manipulate microscopic objects, such as small dielectric spheres. In an optical tweezers trap two forces are involved: Gradient Force arising due to intensity gradient of the beam which is directed towards high intensity gradient and the Scattering Force arising due to the radiation pressure of the laser beam acting towards the beam propagation [8]. For a stable trap, gradient force must overcome the scattering force.

2. TRAPPING OF MICRO-PARTICLE IN BASIC OPTICAL TWEEZERS SET-UP

Basic Optical Tweezers set-up requires a laser beam that is suitably expanded, shaped and focused through a high numerical aperture (NA) microscopic objective. The same objective serves the purpose of imaging of the trapped particle. A laser power ~ 10-100 mw at the microscope is sufficient for basic trapping experiment. The preferred laser wavelength depends on the intended use of the trap. For inanimate objects like polystyrene spheres, visible lasers can be used. For biological specimen [9], the absorption of such tightly focused is large enough to damage the specimen. The absorption of infrared light is significantly less so source with wavelength between 700 – 1300 nm is often chosen.

A laser for optical trapping should operate in a continuous wave (CW) mode as pulsed lasers will damage specimens due to their high energy.

Another important factor to consider when using optical tweezers is the profile of the laser beam. TEM00 mode Gaussian beams are most commonly used in optical tweezers systems. The irradiance of a Gaussian beam decreases exponentially towards the edges of the beam and thus provide the transverse optical gradient required to trap particle in a three dimensional optical trap. Stable three dimensional trapping is achieved in a focused laser beam if the gradient force is large enough to overcome the scattering force. This is achieved by using a high numerical aperture microscope objective lens, which creates steep gradient. The focused spot should be symmetric and with minimum aberration [10-11].

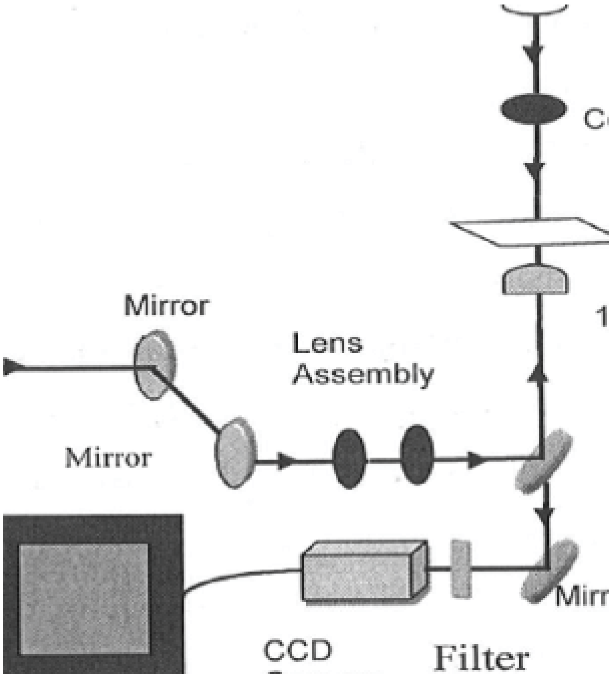

Fig. 1:
Basic Optical Tweezers set-up used for trapping micro-particles.

Figure 1 shows the basic optical tweezers set-up used for trapping silica particles. Frequency-doubled Nd:YAG laser (λ = 532 nm , power = 600mw) is used for trapping 3μm size silica spheres dispersed in water. A telescopic system is used to collimate the beam and make it correct diameter for filling the rear aperture of the microscopic objective. A dichroic mirror placed at 450 directs the incident laser beam into the microscopic objective but allows white light to pass through and an image to be formed on charged coupled device (CCD) camera that can be viewed on a monitor and recorded on a video recorder. Incoherent illumination of the sample is provided from above the sample cell using a fiber. The microscope objective has a high numerical aperture of 1.3 that gives a tightly focused trapping beam. A 100X objective is used to give the smallest spot size. Sample cell are created using a microscope slide, spacer and a small cover slip on top. A drop of index matching liquid is placed on the top of the objective. The sample is placed on the translational stage and the beam can be moved in the sample by translating the stage. Figure 2 shows the trapped silica sphere in focused Gaussian Laser beam.

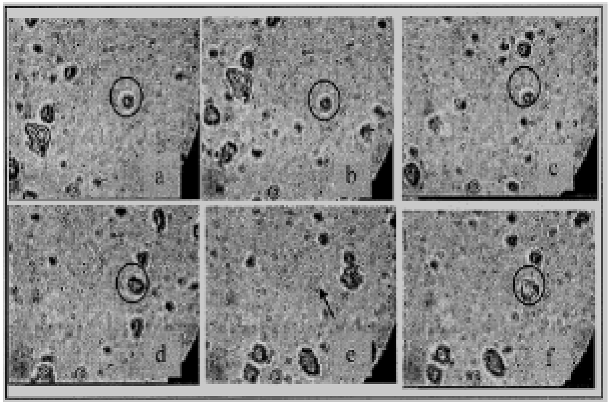

Fig. 2 : a-d)
CCD images with time showing encircled trapped silica particle. Other particles are seen moving in the area.
e) Arrow shows a particle approaching towards the laser focus **f)** Particle trapped at focus

3. GENERATION OF NOVEL BEAM SHAPES

Novel Beam shapes extend the trapping efficiency of optical tweezers set-up. Laguarre Gaussian [LG] beams are a family of circularly symmetric modes denoted as LGpl with mode indices l and p. In LGpl beam with azimuthal index l, the phase circulates by 2πl in one complete loop where p is the radial index and p +1 gives the number of radial nodes in the mode profile. LG beam possesses angular momentum due to an eilφ phase term in mode description where φ represents the azimuthal phase. For trapping and manipulation of particles this phase variation can be converted to intensity variation by adopting a suitable interferometric set-up [12-13].

An LG beam, also known as vortex, has a dark at the centre which results in the reduction of on-axis radiation pressure, and as a result, can be used to improve axial trapping. Low refractive index particle can be trapped in LG beams. Angular momentum of these beams can be transferred to objects by absorption of light [14]. Microscopic particles are partly absorbing as well as partly transparent, can be made to rotate in a Laguerre Gaussian optical trap. LG beams are generated using phase holograms [15]. Figure 3 shows the formation of LG beams from Gaussian laser beam using computer generated phase holograms.

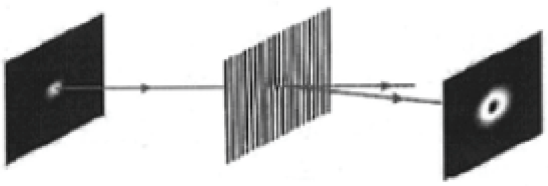

Fig 3:
Formation of LG beams using computer generated phase holograms. Input beam is Gaussian laser beam and Output beam is LG beam.

LG beams can also be generated using spatial light modulators (SLM) as well [16].

Spatial beam patterns also significantly enhance the capability of optical tweezers set-up. A range of particle from low refractive index to high refractive index and particles of different shapes can be confined within these beam patterns. Various spatial beam patterns are simulated with the help of Virtual Lab1.0 software. Different field patterns are created and further the interference between these fields is obtained. Some of the generated pattern is shown in figure 4.

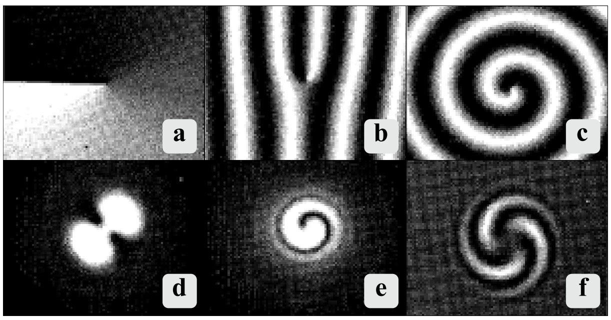

Fig. 4 : a) Phase distribution of a vortex beam **b)** Intensity distribution of Interference pattern between tilted plane and vortex beam **c)** Intensity distribution of Interference pattern between spherical and vortex beam **d)** Intensity distribution of Interference pattern between LG02 and Gaussian beam **e)** Intensity distribution of Interference pattern between LG01 and spherical beam **f)** Intensity distribution of Interference pattern between LG03 and spherical beam

Spiral beam patterns and fork patterns have also been experimentally generated using Mach-Zhender Interferometric set-up as shown in figure 5. Phase hologram is inserted in one of the arm of interferometer and other arm is either a plane beam or a spherical beam. Fork pattern is generated by the interference of vortex beam with tilted plane wave and spiral beam pattern is generated by interfering spherical beam with vortex beam. These generated spatial beam patterns are used in optical tweezers set-up to trap and manipulate the micro-particles.

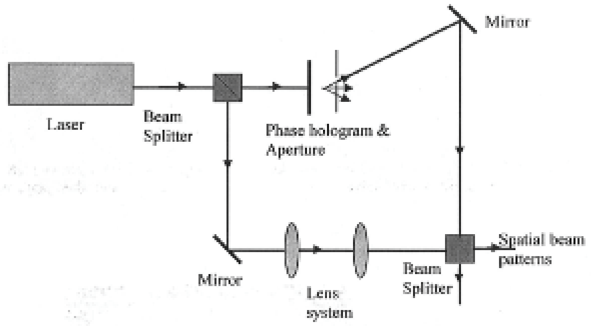

Fig 5: Interferometric setup to generate spatial beam patterns

Intensity profile of generated LG01 and LG03 , in one of the arm of interferometer, is shown in figure 6.

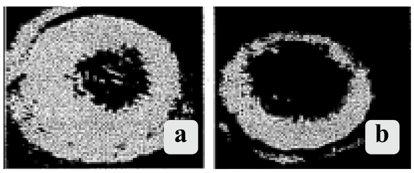

Fig. 6: Intensity profile of experimentally generated a) LG_0^1 and b) LG_0^3 beams

These generated LG beams are interfered with tilted plane beam and spherical beam and as a result triple charged fork pattern (three phase singularity) and triple charged spiral patterns are clearly seen in fig. 7 a, b.

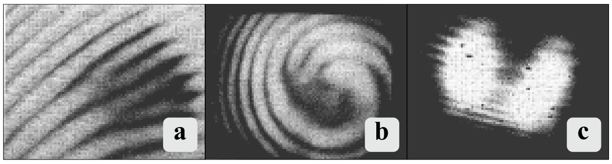

Fig. 7: a) Fork Pattern generated by interference of plane tilted beam with LG03 beam **b)** Spiral pattern generated by interference of spherical beam with LG03 beam **c)** Interference pattern between two Gaussian beams

4. AN ALTERNATIVE LOW COST METHOD FOR THE GENERATION OF SPATIAL BEAM PATTERNS

Spatial beam patterns can be generated using an inexpensive energy-efficient method [17]. This method is used to generate spiral or fork patterns by inserting cracked plexi glass plate in one of the arm of Mach-Zhender interferometer instead of computer generated hologram (CGH). It has many advantages over CGH. It has high efficiency due to no loss of energy in different diffraction orders and one does not have to undergo a complex and expensive fabrication process. It is simply adjustable and can be used at any wavelength in the wavelength region where the material transmits.

A spiral phase retarder $\varphi(r,\theta) = m\theta$ is constructed by using the crack in plexi glass plate. By changing the degree of deformation, the retarder can be adjusted. It can be used at any wavelength and the value of the phase step can be chosen. The plate is constructed from a parallel-sided transparent plexi glass sheet in which a crack is induced starting at one edge and terminating close to the center. The plate is mounted on a rigid frame and, by use of a set of screw, one edge of the crack is twisted relative to the other.

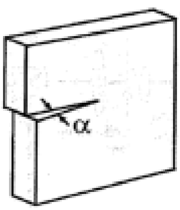

Fig. 8: Spiral phase plate

The plate is inserted in one arm of the Mach-Zhender interferometer as shown in figure 9. One beam is allowed to pass through this cracked plate and other beam through the plane sheet of same thickness. Interference patterns such as spiral pattern and fork patterns are generated by varying the angle at the crack.

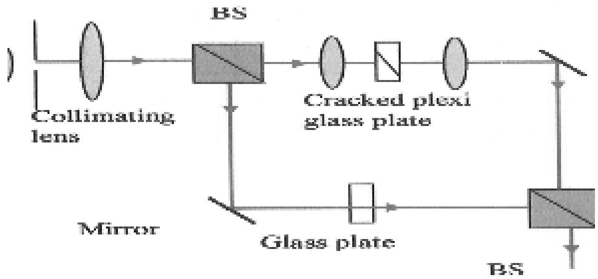

Fig. 9 : Mach-Zhender Interferometric set-up to generate spatial beam patterns using cracked plexi glass. Red color line showing the use of He-Ne laser for generating spatial beam patterns

Fork pattern and spiral patterns are generated using the interferometer and shown in fig. 10 and results of trapped particles are shown in fig.11.

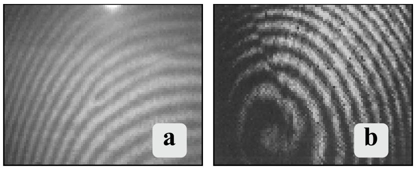

Fig. 10: a) single charged Fork pattern **b)** Spiral pattern generated using cracked glass plate in one arm of the Mach-Zhender interferometer

Micron size silica particles were trapped when these patterns were input to the optical tweezers set-up.

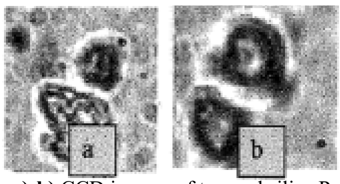

Fig. 11: a)-b) CCD images of trapped silica Particle in pattern shown at fig. 7c

5. ANGULAR MOMENTUM TRANSFER TO OPTICALLY TRAPPED PARTICLE

The ability to controllably rotate micro-particles in optical tweezers adds another level of manipulation to the translation motion already possible in a single beam optical trap [18]. Experiments by several groups have also shown that orbital angular momentum can be transferred by absorption or scattering [19]. These rotating particles could be used to derive micro-machine element such as micro-pumps and micro-stirrer for micro-fluidic device, or used as instrument to measure torsional properties of biological polymers [20].

We have used basic optical tweezers setup (as shown in figure 1) with a quarter wave plate (QWP) and trapped birefringent calcite particles in circularly polarized light.

Frequency doubled Nd:YAG laser ($\lambda = 532$ nm , power = 700mW) is used for trapping crushed calcite particles dispersed in water. CCD images of rotating calcite particle are shown in figure 12. It has been observed that two-three particles out of ten particles rotate while trapped. It may be due to the dependence of transfer of angular momentum on the shape of birefringent particle. The speed of rotation achieved is of the order of ten cycles per second.

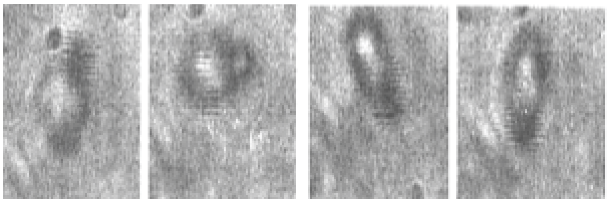

Fig. 12: CCD Images of rotating calcite particle trapped in circularly polarized light

6. CONCLUSION

We have demonstrated trapping of micro-particle in optical tweezers set-up. Spatial Beam patterns are generated with the help of computer generated hologram. A low cost method of generating spatial beam patterns using cracked glass plate is demonstrated. Efficient trapping of micron size silica particle is done successfully. At last, controlled rotation of birefringent calcite particle is also achieved with the help of circularly polarized light.

In conclusion, novel laser beam improves the efficiency significantly and led to the enhancement of optical tool-kit by utilizing these beams for cutting tweezing and rotating microscopic particles.

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