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'Optical Cogwheel' And 'Defocused Beam' for 2D Multiparticle Patterned Trapping

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Abstract

Size selective and patterned optical trapping of polystyrene beads has been demonstrated using spatially structured beams of shape of 'optical cogwheels' and 'defocused beam'. 'Optical cogwheels' – are collinear superpositions of two doughnut beams of equal and opposite helical index, have been generated experimentally using diffractive optical element, i.e., phase-plate. They exhibit the characteristic light intensity modulation around the circumference of a sphere periodically. 'Defocused beam' has been created experimentally by defocusing the focus spot down the focal plane along propagation axis. 'Optical cogwheels' are able to trap only those particles of size exceeding the 'ring' diameter by certain amount, thus enabling a passive sorting for particles of differing sizes.

1. Introduction

Optical tweezers (OT) is a proven versatile tool for trapping and manipulation of mesoscopic particle with its potential application in physical sciences and in particular, biological sciences [1-3]. Conventionally, a Gaussian profile of trapping beam is conversed to a diffraction limited focus spot using high numerical aperture (NA) >1.0 objective lens so as to achieve higher magnitude of attractive Gradient force over destabilizing scattering and absorption forces to trap the dielectric particles of higher refractive index than the surrounding medium [4]. But this approach could enable the trapping of a very few particles because of concentration of almost all laser power at the center of Gaussian beam. This is why it is not viable to investigate the biological samples due propensity of photo damage. For multiparticle and patterned trapping, it requires the spatial beam shaping routes, such as; commercially available spatial light modulator (SLM), phase plates, two or three beam interferometry, tapered fiber bundle, micro lenses etc. In most of these cases, light structures are dynamically changed for micro-manipulations. Similarly, control over the phase of laser beam enables the transformation of laser modes which facilitate multiparticle trapping. Transformation of fundamental

Gaussian mode TEM_{00} to doughnut-shaped Laguerre-Gaussian mode by introducing a helical phase structure $\sim\exp(il\theta)$, where l is an integer corresponds to so-called azimuthal mode index, sometimes also called the 'topological charge' and θ is the polar angle around beam axis. Spatial modulation of wavefront of a laser beam using diffractive optical elements creates arbitrary light intensity distributions at the object plane of microscope before it enters to create various shapes of optical trap [5] or arrays of traps with individually steerable spot positions [6, 7]. Apart from diffractive optical elements, stressed optical waveguide [8, 9**]** are another efficient schemes for the generation of–so called optical vortex modes which facilitate more efficient trapping and sorting of high and low refractive index particles than normal TEM_{00} modes [6, 10]. In addition each photon of optical vortex beam carries angular momentum of $l\hbar$ causing the rotation of trapped objects around beam axis [11, 12].

Fundamentally, such doughnut modes when focused, retains its intensity null along longitudinal direction and creates a sharp bright ring of width of the order of wavelength. The diameter of intensity null depends linearly on the helical pitch index l of the doughnut mode, light wavelength and reciprocally on the numerical aperture of the microscope objective. This opens the avenues of creating optical traps with a precisely defined size [10].

$$R_l = a\frac{\lambda f}{\pi\Sigma}\left(1+\frac{l}{l_0}\right) \qquad (1)$$

where $a = 2.585$, $l_0 = 9.80$, Σ is the radius of optical trains' effective aperture (3.5 mm for our system), λ is the wavelength of trapping laser (632nm for this case) and f is the focal length of MO. Rearranging the terms in above Eq. (1) for NA of MO ($NA = 1.25$ for this case), we get

$$R_l = a\frac{\lambda}{\pi NA}\left(1+\frac{l}{l_0}\right) \qquad (2)$$

When this doughnut mode is collinearly superimposed with a second doughnut mode of opposite helical pitch index 'l', which results periodic intensity modulation located on the ring circumference – formation of so called 'optical cogwheel'. In contrast to a doughnut mode, such 'cogwheel' mode carries no net orbital momentum [13].

In other modality of multiparticle patterned trapping presented in this letter, a 'defocused beam' has been adjusted at back focal plane of microscope by defocusing the laser focus spot down the focal plane along propagation axis as shown in Fig. 5a. In this spatially structured image plane, width of bright fringes can be altered by defocusing the beam only but at the cost of reduced intensity. Inherently, creation of this structured image plane does not require any optical device yet it facilitated multiparticle trapping of polystyrene spheres with additional feature of altering their number.

2. Experimental Set-Up

Figure 1 shows the schematic of experimental set-up calibrated for multiparticle patterned trapping by spatially structured beam of 'optical cogwheel' mode generated by diffractive optical phase plate.

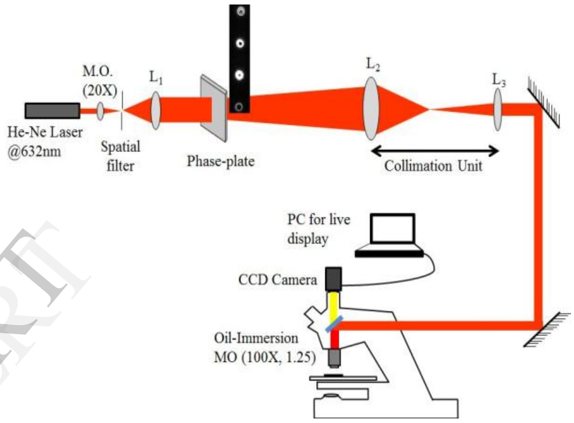


Figure 1. Schematic diagram of optical tweezers set-up.

First, laser beam (632nm, 10mW) was spatially filtered using 20X MO and then was collimated by lens L1. The collimated beam was finally projected on phase-plate (purchased from RPC Photonics, NY USA) that generated various diffracted beams as shown in Fig. 2.

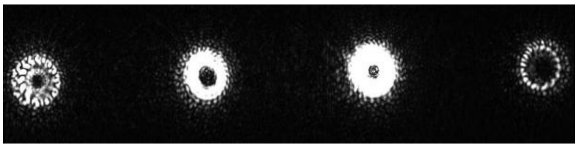
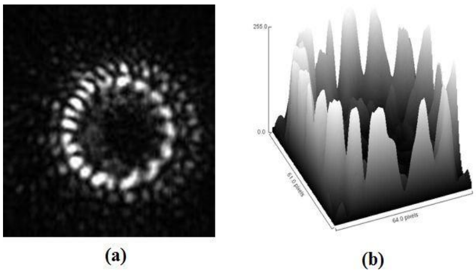


Figure 2. Various diffraction orders from phase-plate.

One of the various diffracted orders shown in Fig. 2 is chosen and its 3D intensity plot is shown in Fig 3(a), Fig 3(a), respectively. This diverging but modulated wavefront (Fig. 3a) after phase-plate was again collimated to approximately 7mm beam-diameter by assembly of lenses L2 and L3 so that it can slightly overfill the back aperture of 100X MO (5.9mm diameter) for steep focusing. Here, the same MO is acting for both the focusing and imaging. The light collected by MO was made to pass through neutral density (ND) filter to eliminate the trapping wavelength (632nm) from reaching to CCD camera to prevent the saturation of images. Sample cell was prepared by sandwiching the Mylar spacer between glass plate and cover slip (Corning glass, No. 1.5) maintaining the channel depth of 20μm. Sample was prepared by shaking vigorously a drop of Polystyrene spheres (Polysciences, Washington) in 1ml. of distilled water with a drop of Triton X (to prevent from auto-aggregation) and was injected into cell via micropipette.



(a) (b)

Figure 3. Spatially modulated wavefront generated by diffractive optical element phase-plate (a) 'Optical cogwheel' of mode index $l = 9$ and (b) its 3D intensity plot.

3. Results and Discussion

We discuss our experimental results on 'optical cogwheel' and 'defocused beam' driven optical tweezers in the standard geometries. Standard geometry is the methodology of instrumental calibration for trapping of micro-particles against the gravity using upright microscope. Figure 4 shows the results of trapping of polystyrene spheres realized first using modulated 'optical cogwheel' beam of periodic intensity distribution around the ring circumference. As evident from Fig 3b, there are 18 intensity maxima points distributed on the circumference of the 'cogwheel'. To substantiate this, the image (Fig. 3a) was further analyzed for intensity distribution (using ImageJ software) and the obtained result (see Fig 3b) confirms the number of intensity peaks to be 18. We discuss the intensity distribution of 'optical cogwheel' on the circumference of ring diameter which has resulted from superposition of two 'optical vortex' beams of equal but opposite helicity.

A helical mode $\psi_l(\vec{r})$ is distinguished by a phase factor proportional to the polar angle θ around the beam's axis.

$$\psi_l(\vec{r}) = u(r,z)e^{-ikz}e^{il\theta} \tag{3}$$

Here, $\vec{k} = k\hat{z}$ is the beam's wavevector, $u(r,z)$ is the field's radial profile at position z, and l is an integral winding number known as the topological charge. All phases appear along the beam's axis $r = 0$, and the resulting destructive interference cancels the axial intensity. When two helical modes of equal but opposite helicity, propagating in the same direction are superimposed, the resulting field distribution is

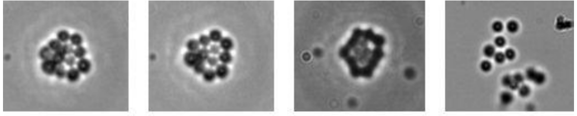
$$\psi_{resulting}(\vec{r}) = 2u(r,z)e^{-ikz}\left(\frac{e^{-il\theta} + e^{il\theta}}{2}\right) \tag{4}$$

which gives a

$$\psi_{resulting}(\vec{r}) = 2u(r,z)e^{-ikz}\cos(l\theta) \tag{5}$$

As obvious from Eq. (5) that resultant field and thus intensity on the circumference of the 'optical cogwheel' should be periodically distributed. The very same is substantiated from the result analysis shown in Fig. 3(b).

In fact, particle diameter (2μm) is sufficiently large than the dimension of intensity maxima on the ring circumference. Therefore, sphere interacts with laser illumination only on ring circumference at 'cogs' and generates in-situ Gradient force for trapping. Figure 4 (a-c) shows ring geometry created from trapped polystyrene spheres (9 in numbers) similar to 'cogwheel'. One of the remarkable point worth to highlight here is that number of trapped particles does not correspond to the number of intensity maxima of 'cogwheels'. This is due to fact that alternate intensity maxima (18 in number and broader than minima) and minima generates the attractive and repulsive force covering a range of a fraction of particles' diameter on circumference, thus settling only 9 particles. From intensity profile of 'optical cogwheel' (see Fig. 3b), the azimuthal index number (l) can be deduced which is half of the number of intensity peaks, i.e., 9. As soon as laser beam was tuned off, all the trapped particles orphaned from attractive force and finally dispersed away as shown in Figure 4d.

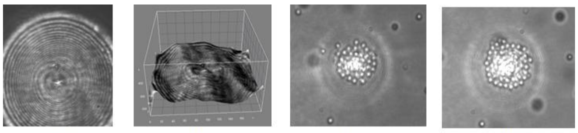


(a) (b) (c) (d)

Figure 4 Trapping of 2μm diameter polystyrene spheres with spatially modulated 'optical cogwheel'.

One of the limitations of presently used diffractive optical phase plate for modulation of wavefront is that the diameter of 'cogs' on ring circumference cannot be altered as per the requirement. So, the size selectivity of phase-plate generated 'optical cogwheel' was limited to only 2µm diameter polystyrene spheres, for present case.

In second scheme, a 'defocused beam' as obtained in our case (see Fig. 5a) is experimented for multiparticle trapping. Let’s us brief about 'defocused beam'. Any light beam is superposition of plane waves and when it propagates for a distance Δz, it undergo a phase shift $k_z \Delta z$, where k_Z is the wavevector of the beam in z-direction. In most of cases, each plane wave component suffers a different phase shift, and so the resulting beam—the interference pattern of the plane waves—changes shape. There are special beams where phase-shifts for each plane wave is same and do not change its shape on propagation. Such beams are called Bessel beams of non-diffracting nature and are generated by illuminating a conical shaped optical element, called an axicon with Gaussian beam [14, 15]. Wavefront of nondiffracting Bessel beam exhibits the characteristic concentric rings and regenerate itself after a certain distance [14]. But 'defocused beam' as obtained in our case (see Fig. 5a) does not exhibits the regenerative property, except similar in spatial intensity distribution at defocused plane, because it was achieved by defocussing the focus spot. Yet it facilitated multiparticle trapping of 2µm polystyrene spheres in a closely packed circular geometry (Fig 5c).



(a) (b) (c) (d)

Figure 5. (a) shows the 'defocused beam' captured at trapping plane, (b) 3D surface plot of the beam at trapping plane (analyzed by ImageJ), (c) multiparticle trapping of 2µm diameter polystyrene spheres, and (d) the numbers of trapped particle can be varied on defocussing the 'defocused beam' down the propagation axis.

The 'defocused beam' was further analyzed (using ImageJ) for 3D surface plot to show the flatness/uniqueness of trapping plane which is shown in Fig. 5b (values on X-Y-Z axes are in arbitrary units). This analysis becomes imperative because if 'defocused beam' would have been generated due to oblique incidence of laser beam, a 'comatic aberration' must be taken place. If so, a 3D surface plot of 'defocused beam' must result a cone formation rather a flat trapping plane as shown in Fig. 5b. The number of trapped particles further can be altered (see Fig. 5d) by defocussing the beam longitudinally provided sufficient power is retained in that particular plane. Interestingly, this approach does not require any spatial beam modulating optical devices but merely defocused spot is enough to foster.

4. Conclusion

Multiparticle trapping of dielectric polystyrene spheres (2µm diameter) in a circular pattern has been realized using 'defocused laser beam' created away from focal plane down the propagation axis. This approach is the simplest one because it does not require any optical components. Phase modulated wavefront -'optical cogwheels' has been shown for size selective trapping of dielectric polystyrene spheres (for this case, 2µm diameter only). Computer simulated optical vortex beams of variable topological charge could result variable 'cogs' and prove a versatile tool for size selective patterned trapping when interfaced with SLM.

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