Non-diffracting beam synthesis used for optical trapping and delivery of sub-micron objects

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ABSTRACT

We demonstrate the use of interference between non-diffracting Bessel beams (BB) to generate a system of optical traps. They offer sub-micron particle confinement, delivery and organization over a distance of hundreds of μm. We analyze system of two identical counter-propagating BBs and the case of two co-propagating BBs with different propagation constants separately. In both of these cases, the interference results in periodic on-axis intensity oscillations involving particle confinement. Altering the phase of one of the interfering beams, the whole structure of optical traps can be shifted axially. Implementing this conveyor belt enables the particle delivery over the whole distance where the optical traps are strong enough for particle confinement. Experimentally we succeeded with generation of both of these systems. In case of two counter-propagating BBs we observed a strong sub-micron particle confinement, while in case of co-propagating BBs the confinement was observed only with help of fluid flow against the radiation pressure of both beams.

1. INTRODUCTION

The transfer of momentum from photons to micro-objects, nano-objects and even atoms enables their spatial confinement. During the past 20 years it led to many unique experiments in many branches of physics, biology, and engineering[1,2] The most popular setup for 3D manipulation is based on a single focused laser beam so called optical tweezers.[3] Via movement of the laser focus, this tool enables manipulation with particles of sizes from tens of nanometers to tens of micrometers immersed in water. The distance of the transport is given by the field of view of the microscope in lateral and axial plane together with low optical aberrations. Gradually more complicated experimental arrangements were presented, generally they are based on the interference of several light beams. The most impressive example is the holographic optical tweezers, that employed the Spatial Light Modulators to dynamically rearrange tens of optical traps.[4,5] This is especially useful for handling of micro-particles and living cells.

Almost twenty years ago, the concept of the so-called non-diffracting propagation of electromagnetic waves was proposed. This special type of the beam is produced as the result of interference of plane waves whose wave vectors cover the conical surface. Therefore these beams do not change their intensity spatial profile over a region of their existence and, moreover, the radius of their central core can be very narrow (in units of wavelength). The longitudinal region where this non-diffracting beam keeps its properties depends on the lateral extend of the field that interferes. Usually it exists over much longer distance than the Gaussian beams of comparable beam waist. Several methods have been described how to experimentally generate this beam[6] but the most simple and powerful one is to use an axicon (see Fig. 1). It provides the lowest losses and so the power in the central core is sufficient for lateral confinement of sub-micron objects. Longitudinal confinement in single BB is possible only if other forces like gravity, hydrodynamic drag force or glass are used to compensate the

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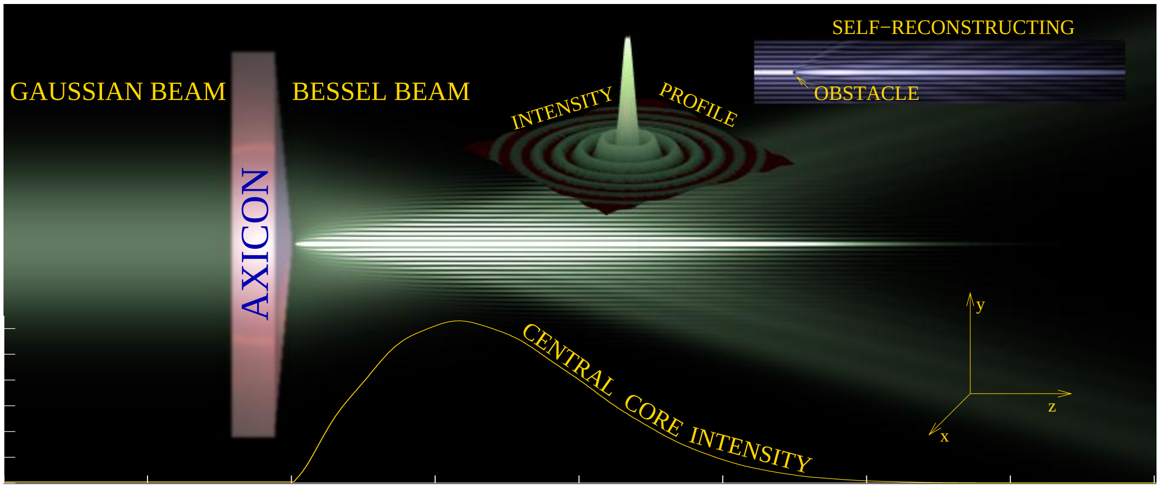

Figure 1. Schematic image of a non-diffracting beam generated by an axicon illuminated by a Gaussian beam. The generated beam has mainly properties of the ideal Bessel beam - radial intensity profile is done by the zero-order Bessel function and the width of the central core is constant over the whole Bessel beam existence. However, its intensity is influenced by illuminating Gaussian beam (see the bottom plot). The top-right part shows the property of self-reconstructing - the ability of non-diffracting beams to reconstruct itself after passing an obstacle.

radiation pressure that propels the object in the direction of beam propagation. To provide a gradient of the central core field strong enough for particle confinement, we have to use the interference of two or more BBs. In this paper we are focused on the most simple cases of this phenomenon - two identical counter-propagating BBs and two co-propagating BBs with different propagation constants (projection of k-vectors of generating plane waves into the z axis). The particle behavior in spatially periodic fields is strongly dependent on the particle refractive index and on the particle size. For certain diameters, the particles are insensitive to the field and cannot be trapped. This property can be employed for particle sorting. Changes in the phase in one of the interfering beams cause the spatial movement of the whole structure of nodes and anti-nodes of the periodical field. If a particle is confined near the node or anti-node, it follows it's motion. Therefore, by precise control of the phase it is possible to deliver simultaneously large amount of sub-micron objects[7] (optical conveyor belt). The non-diffracting beams are particularly suitable for generation of large systems of optical traps due to the property of self-reconstruction. Passing through the disturbing obstacle, the beam reconstructs itself on a very short distance. The presence of particle is responsible for modification of the trapping field which can influence behavior of other close particles. The property of self-reconstructing can help to suppress these effects.

2. CONFINEMENT OF OBJECTS IN COUNTER-PROPAGATING BBS

Using two identical BBs for particle confinement gives a conservative field of optical forces with a washboard like potential near the z-axis. Our previous experiment[7] proved that even though the affinity to the trapping field is strongly dependent on particle size and refractive index, majority of particles with size from hundreds of nm up to units of microns can be strongly confined using lasers with output power in units of watts. In this experimental work, we have presented the particle delivery over a distance of 300 μm. Even though this was an excellent result, the theoretical description of the trapping field evinced a possibility of particle delivery over a distance in order of millimeters. This motivated us to optimize our setup and to verify this occasion. This time we used two times shorter wavelength (532 nm) and identical optical components in both arms (see Fig. 2).

Since the movable mirror $M3$ changes the phase in one beam, the whole structure of intensity maxima and minima moves axially followed by the confined objects. Under the experimental conditions the overlap of BBs, where the traps were strong enough for particle confinement exceeded 1 mm (see Fig. 3). This whole distance could be used for transport of particles. One can observe empty (dark) places in the particle chain periodically distributed over the whole trapping area. At the moment we do not fully understand this phenomenon. The

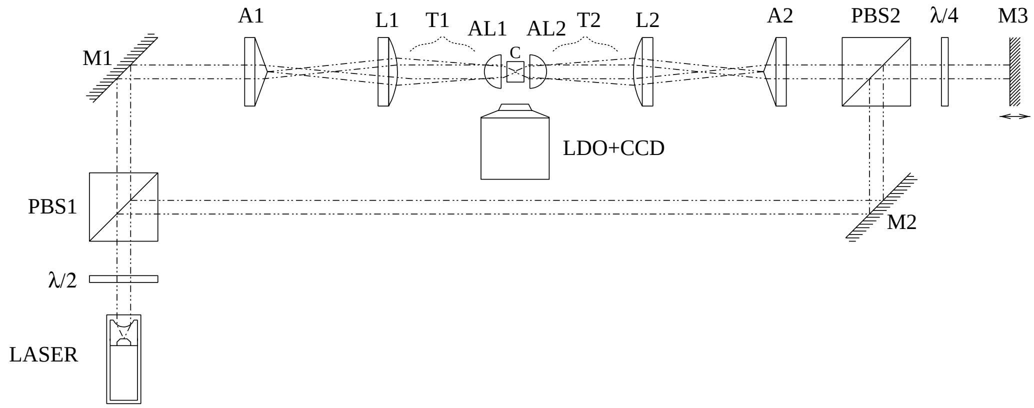

Figure 2. The experimental setup with two counterpropagating BBs. Polarization of the beam from the laser (Coherent Verdi V5, 5 W,$\lambda = 532$ nm) is tuned by the half-wave plate $\lambda/2$ to control power ratio of beams separated on the polarizing beam-splitter PBS1. First beam coming through PBS1 is reflected on the dielectric mirror M1 to the axicon A1 (EKSMA 170°) where is transformed into a BB. Its width is consequently decreased on a telescope T1 consisting from doublet lens L1 (f=60 mm) and aspherical lens AL1 (f=8 mm). The mirror M2 reflects the second beam towards the polarizing beam-splitter PBS2 which reflects the beam through the quarter-wave plate $\lambda/4$ to the movable mirror M3. Here is the beam reflected backwards through the $\lambda/4$ and PBS2 to the axicon A2 and telescope T2. The optical elements in both parts are the same and so both counterpropagating BBs have the same properties. Moving the mirror M3 the phase of the second beam can be tuned in a cuvette C. This causes the movement of the whole structure of standing wave nodes and anti-nodes together with confined objects. Trapped objects can be recorded by the imaging system consisting of microscope objective LDO and CCD camera.

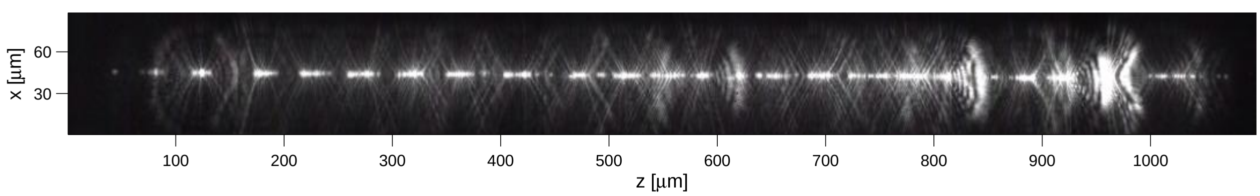

Figure 3. An 1 mm long array of polystyrene particles of 175 nm in radius captured in the Bessel beam generated standing wave. Image is composed from 10 frames taken at different positions of the imaging system (LDO + CCD). The recording started on the left side, and therefore it seems to be less saturated then the right side, where the amount of trapped particles grew during the recording.

diffraction on the axicon edges was negligible and we do not see any reason for the axial intensity modulation on this scale coming from the beam. We speculate it could be caused by the collective scattering of many confined particles. Figure 4 proves the delivery of polystyrene beads with 200 nm in diameter over a distance of $50\,\mu$m.

3. CONFINEMENT OF OBJECTS IN CO-PROPAGATING BBS

Since non-diffracting beams form an orthogonal base, they can be used to form an arbitrary longitudinal intensity profile. Interference of several non-diffracting beams exhibit constructive and destructive interference at the distances repeating with the period z_T - historically known as "Talbot distance".[8] As a consequence, the longitudinal component of the Poynting vector exhibits a longitudinal periodicity known as the self-imaging, $S_z(x, y, z) = S_z(x, y, z + z_T)$. This effect was first analyzed and measured in 1996[9] for two beams, later on it was studied in more details and workout for more beams including optical vortices.[10–13] For two interfering beams, the total field has a cosine longitudinal evolution. Several publications dealt with the interference of co-propagating Gaussian, Laguerre-Gaussian or Bessel beams of different widths. Even though they were more focused on the design of "bottle beams" - beams with intensity minimum surrounded by intensity maximum[14–20] majority of them mentioned optical tweezers and optical trapping as one of the possible fields of applications

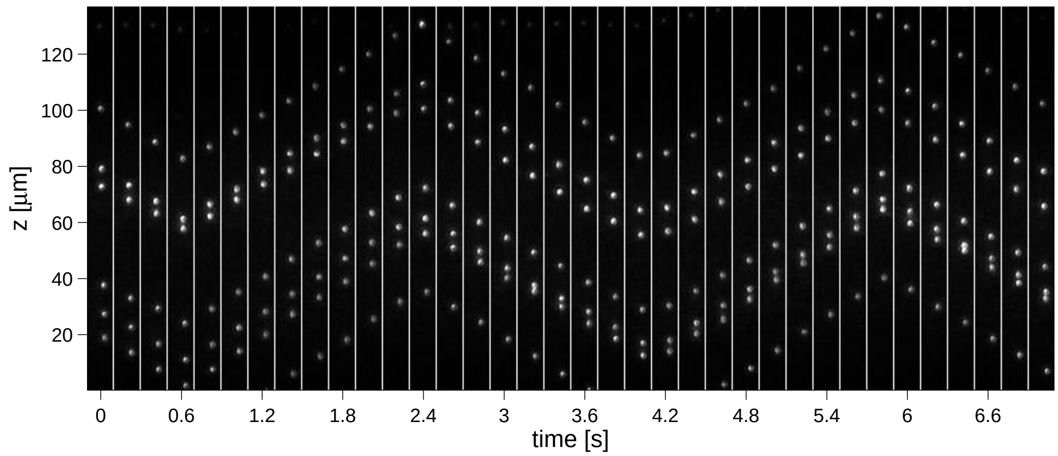

Figure 4. Simultaneous confinement and delivery of polystyrene particles of diameter 200 nm in a movable standing Bessel wave (optical conveyor belt).

because such a beam enables spatial confinement of micro-objects having refractive index lower comparing to surrounding medium or atoms into blue-detuned dipole trap. In contrast to above mentioned examples we present here the usage of self-imaging for optical three dimensional confinement of one order smaller particles (sub-micron ones) with refractive index higher comparing to the surrounding medium. In this case the longitudinal intensity changes give rise to gradient optical force pushing the object to on-axis intensity maximum. At the same time, the scattering force (radiation pressure) coming from both co-propagating beams pushes the particles in the direction of both beams. To confine the particle of radius a, the longitudinal component of the gradient force has to balance the scattering force and therefore, the longitudinal oscillation of the field (z_T) has to be as short as possible. On the other hand, the parameters of the interfering beams must be compromised with the available laser power and optical components. The setup we used for our experiments demonstrates Fig. 5. In our case the periodical field was generated by interference of BBs with central core radii equal to 0.437 μm and 1.156 μm which gave the field period equal to 7.34 μm in water. We used the Barton's method[21] to express the optical forces acting on spherical micro-particles placed into interference field of two co-propagating BBs with the same size-parameters that we used in our experiments. The result demonstrates Fig. 6. It's obvious, that without any force acting against the direction of BBs propagation our setup enables particle confinement up to radii of 300 nm. For bigger particles the gradient force cannot balance the radiation pressure so there is no stable equilibrium position of particle on the z-axis and the particle is accelerated in direction of BBs propagation. The chosen values of central core power used for the calculations are in ratio where the ideal destructive interference appears but they are much larger, then we can obtain using our equipment. Under our experimental condition the maximal depth of potential well is in order of units of k_BT.

For the experimental studies we used cuvette filled with H_2O and the height of the water inside the cuvette determines the thermal water motion caused by the laser beams. As expected, with no fluid flow we were not able to force the tested particles of radii $a = 100$, 175, 205, 260, 300 nm to stay in the optical trap long enough to prove they are trapped. All particles followed the direction of both beams but after a distance smaller than the Talbot one they left the beam center and departed laterally. To obtain the traps for strong particle confinement (10 k_BT of potential well) we had to use at least 3 times larger laser power, which could not be done with our equipment. The other complication is, that theoretical model deals with ideal destructive interference which we were not able to reach using our polarizing optics. An other deviation could be caused by aberrations of BBs.

To overcome this troubles we increased the amount of water inside the cuvette and weak thermal water circulation was generated by the laser. In this case, we were able to compensate the scattering force and to confine the objects near the on-axial intensity maxima. An array of organized polystyrene objects of all studied

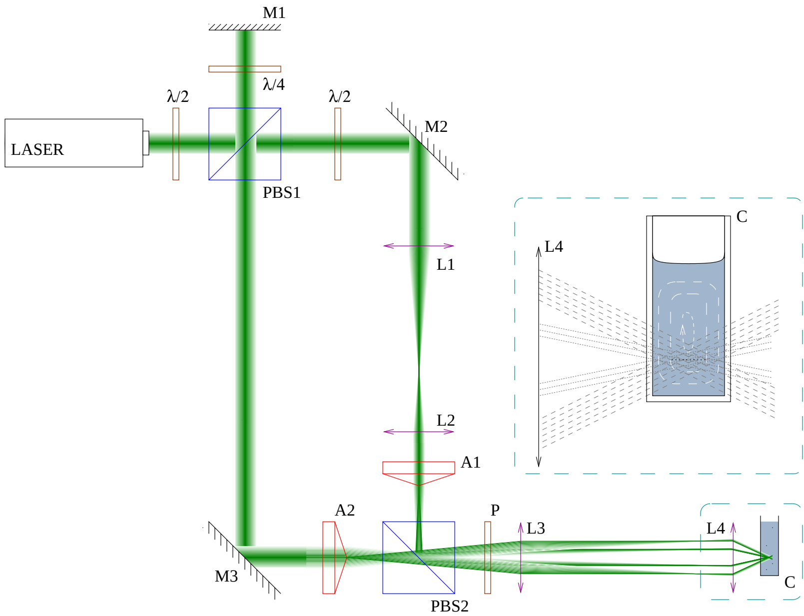

Figure 5. Experimental set-up of two co-propagating BBs. We used laser Verdi V5 (Coherent) having vacuum wavelength 532 nm and the maximal power 5.5 W. The beam passes through $\lambda/2$ wave plate tuning their linear polarization so that the powers in both beams obtained behind PBS1 can be set properly to get destructive interference on the optical axis behind L4. The first beam is reflected by PBS1, its polarization is changed to circular passing through $\lambda/4$, its direction is reversed on mirror M1 and its polarization is turned to linear passing again through $\lambda/4$. Axial motion of mirror M1 changes the phase of this wave. Since now the polarization is rotated by 90 degrees with respect to the original one, the beam passes through the PBS1, reflects on M3 and passes through an axicon A2 (Eksma 130-0260, apex angle equal to 160 degrees). Behind A2 a Bessel beam is formed with the core diameter equal to $4.9\,\mu$m. The second beam behind PBS1 passes through $\lambda/2$ plate changing its linear polarization by 90 degrees and reflects on M2. Its width is decreased 2 times by a telescope made from lenses L1, L2 and the beam passes through A1 (Eksma 130-0270, apex angle equal to 170 degrees). The Bessel beam is formed with a core diameter equal to $9.2\,\mu$m. Both beams are merged together by PBS2 and their widths are decreased $5\times$ by a telescope consisting of lenses L3 and L4 with focal lengths 40 mm and 8 mm, respectively. Measuring the decreased beam widths, we obtained values $0.437\,\mu$m and $1.156\,\mu$m. The apexes of both axicons are placed at the focal plane of L3 to get the axial overlap of the regions where both Bessel beams exist. Since the width of the second beam is decreased $2\times$, these regions are of about the same lengths for both beams. The polarizations of both beams behind the PBS2 are perpendicular and therefore the polarizer P is rotated by 45 degrees to get interference of both beams (half of the trapping power is wasted here). The cuvette C was filled by suspension of particles in water. The inset shows the water circulation caused by laser heating.

sizes was obtained. Since our set-up enables us to change the phase in one beam with respect to the other, we used the mechanism of conveyor belt just like in the case of counter-propagating BBs. If the optical traps are occupied, the confined objects can be delivered in this way over a region where both BBs overlapped (see Fig. 7). Measuring the distances between confined particles from the CCD record we obtained the value of $z_T = 7.68$.

4. CONCLUSIONS

We used an interference of counter-propagating and co-propagating Bessel beams to generate movable array of optical traps. Despite our theoretical results indicated possibility to trap sub-micron objects in both of these systems, in case of co-propagating BBs, we experimentally succeeded in particle localization only using liquid flow to compensate radiation forces. The reason was the poor quality of used optics and insufficient laser power.

Theoretical predictions have shown, that under the studied conditions using co-propagating BBs, the particle confinement is possible for very small objects only. To confine bigger object it is necessary to use BBs with smaller propagation constants. This can be done in setup without cuvette and replacing the telescope lens L4

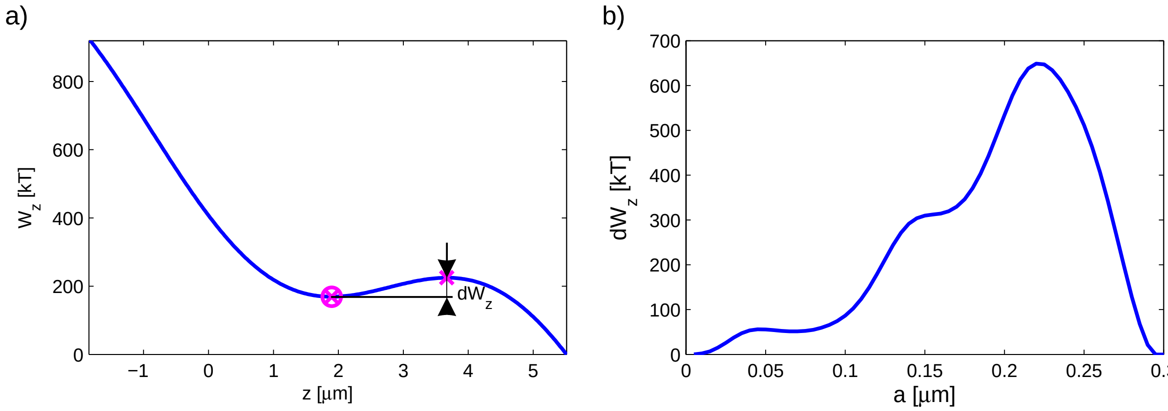

Figure 6. Results of numerical calculations of optical forces acting on micro-particle for radii of BB cores $r_1 = 0.437$ μm and $r_2 = 1.156$ μm and for the central core laser powers $P_1 = 0.323$ W and $P_2 = 2.263$ W. a) The on-axis potential energy of particle with 50 nm in radius. b) The depth of potential well dependence on particle radius

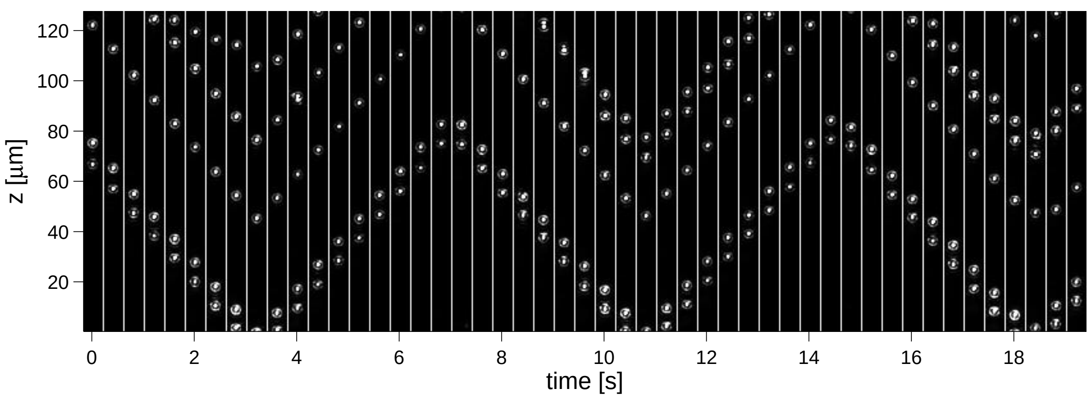

Figure 7. Delivery of polystyrene beads of diameter 410 nm over a distance of 80 μm in co-propagating BBs generated interference traps.

by a high numerical aperture objective optimized for water immersion sunk directly into studied suspension. However, in this case, the side observing of trapped object could be much more complicated.

Both of this systems are unique tools for long-distance precise particle delivery that can be applied in other branches. In the case of Counter-propagating BBs, the period of the field is very close to the limiting case of $\lambda/2$ and therefore the stiffnesses in z-direction achieves a very large values. Comparing to the classical optical tweezers this system offers much larger ratio of longitudinal and lateral stiffnesses, which might play an important role in Biology. Counter-propagating BBs can serve also as a device for sub-micron particle sorting according to their size or refractive index due to very variant particle affinity to the field.

Since the distance between optical traps in co-propagating beams is at least 20 times bigger than in the case of counter-propagating ones, the dynamics of stochastic motion and especially the problem of the first escape from the trap in periodic potential can be easily studied in two dimensions (longitudinal and lateral) without enormous demands on the stability of the system and resolution of the position detection. Due to this larger distance and the self-reconstructing property of the non-diffracting beams the interaction between objects confined in adjacent traps is not significant.

5. ACKNOWLEDGMENT

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