# Optical conveyor belt for delivery of submicron objects

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We demonstrate an optical conveyor belt that provides trapping and subsequent precise delivery of several submicron particles over a distance of hundreds of micrometers. This tool is based on a standing wave (SW) created from two counter-propagating nondiffracting beams where the phase of one of the beams can be changed. Therefore, the whole structure of SW nodes and antinodes moves delivering confined micro-objects to specific regions in space. Based on the theoretical calculations, we confirm experimentally that certain sizes of polystyrene particles jump more easily between neighboring axial traps and the influence of the SW is much weaker for certain sizes of trapped object. Moreover, the measured ratios of longitudinal and lateral optical trap stiffnesses are generally an order of magnitude higher compared to the classical single beam optical trap.
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The optical dipole or gradient force may be used for confinement of atoms, biological and microscopic objects at the region of highest light intensity. The use of the dipole force for delivery of particles has been already demonstrated in some forms. A single focused laser beam (optical tweezers) enabled three-dimensional (3D) confinement and manipulation of particles or even living cells over a distance related to the field of view of an optical microscope. Interferometric techniques can potentially enhance such extended transport. The sliding Gaussian standing wave (SGSW) was initially proposed for atom cooling[1] and recently for deterministic delivery[2] of single atoms. To date, however, no form of deterministic delivery of submicron objects or biological specimens has been demonstrated. Additionally, due to the very short Rayleigh range of a tightly focused Gaussian beam (GB), one obtains a relatively short longitudinal range where the on-axial intensity is sufficiently strong for particle confinement.[3] Therefore, the SGSW does not provide at the same time precise object confinement laterally and long distance of transport. Almost 20 years ago the concept of the so-called diffractionless propagation of electromagnetic waves was proposed by Durnin.[4] These propagation invariant light fields have a lateral beam intensity profile described by zero-order Bessel functions and the longitudinal beam properties remain constant over the region of beam propagation. The drawback of this Bessel beam (BB) is that the total power is split almost equally into several lateral rings and therefore only the optical intensity in the central core is available for object trapping. The multitude of rings, however, is key to a very useful property of this nondiffracting beam: the ability to reconstruct itself after passing through a disturbing obstacle.[5] This is especially important if several objects aligned longitudinally should be manipulated in unison. These attributes of a single BB were employed for two-dimensional manipulation and delivery of microobjects in distinct sample cells displaced even by several millimeters.[6] Since the single BB has no intensity gradient along the propagation axis, it cannot be used for pure optical 3D confinement of objects. However, if the interference of two coherent counter-propagating BB is employed, the axial intensity of the total field is strongly peaked at the planes located periodically along the propagation axis of both beams. It should therefore result in a very long line of SW traps, and indeed overcome the issue of the short Rayleigh range for a tightly focused GB that would result in solely one or two trap sites. The sliding Bessel standing wave thus offers a long extended optical conveyor belt for trapped objects obviating the drawbacks of the SGSW. In this Letter, we demonstrate and characterize such a system.

In contrast to the usual generation of the SW using retroreflection of the incident beam on the mirror[7,8] we present in this Letter a different arrangement where the SBSW is created from two independent counter-propagating BBs with alterable phase shift between them (see Fig. 1). While slightly different optical components were used in both paths at the time of this experiment, the estimated widths and propagation distances of both counter-propagating BB are very close to each other. From the parameters of the optical system the diameters of the central BB cores are equal to 2.24 $\mu$m and 2.14 $\mu$m for the first or the second path, respectively. The cuvette was 5 mm long, made from 1-mm-thick BK7 glass. It was filled up with $D_2O$ which has lower absorption at the trapping wavelength and so the heating and unwanted convection of the liquid was suppressed. The microparticles were put into the cuvette and the light scattered perpendicularly to the propagation of the beams was observed by a microscope objective with a long working distance and charge coupled device camera.

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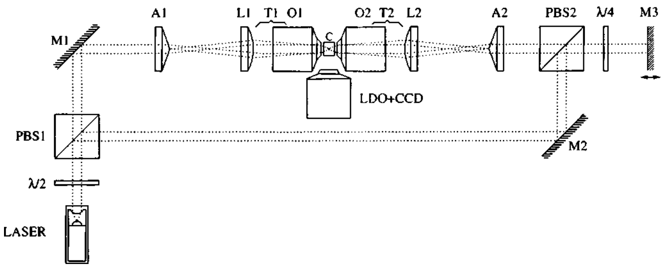


FIG. 1. Experimental setup. Linearly polarized beam (IPG, 10 W, $\lambda_{vac}=1.070\ \mu$m) passed through half wave plate $\lambda/2$ and was divided by a polarization beam-splitter PBS1 into two paths with controllable power ratio. The first *p*-polarized beam is reflected on metallic mirror M1, transformed to the BB by an axicon A1 (Eksma 130-0270). The core of this BB is decreased by a telescope T1 formed by lens L1 (f=38 mm) and microscope objective O1 (Newport, M-40X, N.A. 0.40). The second *s*-polarized beam is reflected on the metallic mirror M2 and on a polarization beam-splitter PBS2, passed through the quarter wave plate $\lambda/4$ to the axially movable mirror M3 controlled by stepmotor (Newport ESP 300), reflected back through the same $\lambda/4$ (the beam became *p* polarized) and transformed to the BB by an axicon A2 (Eksma 130-0260) and narrowed down by T2 made from lens L2 (f=38 mm) and microscope objective O2 (Newport, M-20x, N.A. 0.40). Both BBs interfere with the cuvette C. The particles in the cuvette are observed by a microscope objective with long working distance LDO (Mitutoyo MPlan NR50) and CCD camera.

The movement of mirror M3 causes the phase shift between both counter-propagating beams to change in a controlled fashion and this resulted in the movement of the whole SW structure together with the confined submicron particles—a sort of optical microconveyor belt. Since the positioning accuracy of the stepmotor is 1 $\mu$m, we could precisely deliver a number of confined particles over a distance much longer than it was possible in GB of width comparable to the core of the BB. In our case, two 410 nm polystyrene spheres were moved over a distance of more than 250 $\mu$m (see Fig. 2) while the distance between them kept constant. This is a demonstration of controlled 3D delivery of submicron particles using SBSW and at the same time an example of 3D optical confinement of the smallest particles using nondiffracting beams. We note, too, that we can induce a continuous phase shift between the two beams using the angular Doppler effect for continuous delivery of microparticles.[9]

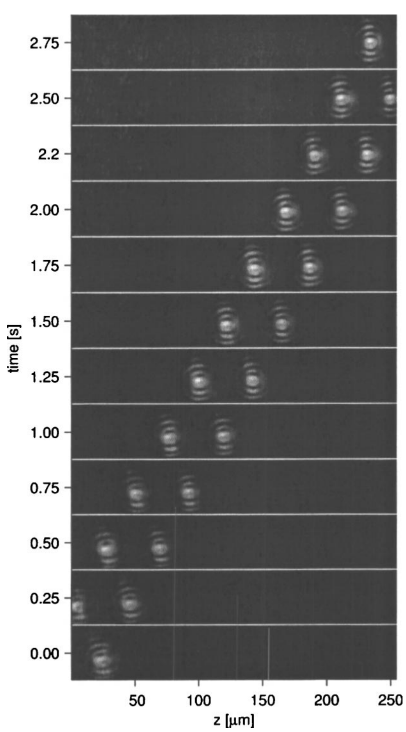


FIG. 2. Demonstration of an optical microconveyor delivering two polystyrene spheres of 410 nm diameter over a distance 250 $\mu$m using a sliding Bessel standing wave.

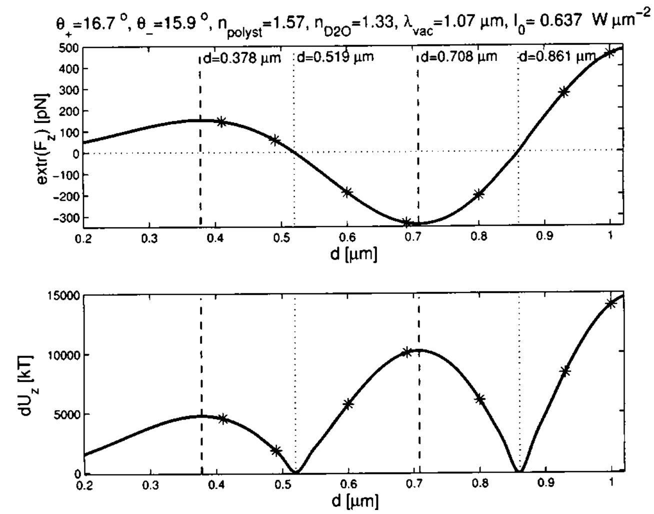


FIG. 3. The theoretical dependence of the extremal (maximal or minimal) axial optical force (top plot) and trap depths $dU_z$ (bottom plot) in the Bessel standing wave as a function of polystyrene beads diameter. Particles were confined in $D_2O$ using on-axis optical intensity $I_0=0.637$ W $\mu m^{-2}$ in each beam (equivalent to on-axis intensity in Gaussian beam of beam waist 1 $\mu$m and power 1 W) of the idealized Bessel beam created by the same optics as in the experiment. The negative values of extremal forces indicates that the bead is trapped with its center at the node of the SW. Stars denote the bead sizes used in experiments. Vertical dotted lines indicate bead sizes that do not feel the Bessel standing wave and therefore cannot be confined in this periodic structure (see Ref. 10).

We also succeeded in 3D optical trapping and delivery of bigger polystyrene beads of diameters 490, 600, 800, 930, and 1000 nm. Notably from this selection of particles sizes, those of diameter $d=490$ and 800 nm jumped much more easily between neighboring longitudinal optical traps and stayed confined in one trap for significantly shorter time scales. This behavior coincides with theoretical predictions based on the generalized Lorenz-Mie scattering theory applied on the calculation of the optical forces in counter-propagating BB. The detailed description of this method will be the subject of future work but results related to this present experiment are shown in Fig. 3. We note from this figure that there are bead sizes that may not even be trapped in this interferometric scheme. In turn this opens up the prospect of selectively trapping and transporting submicron objects of given sizes and a method of optically sorting them based upon their affinity to this periodic light pattern. This discrimination between particles of differing size is a key feature of a SW geometry.[10]

In order to compare theory with experimental results more precisely, we applied the correlation algorithm[11] to track the particles' trajectory along both the *x* and *z* axis from the video records. The results shown in the insets of Fig. 4 support the conclusions that the smaller sphere is strongly confined since it stayed in one trap. On the other hand, plenty of jumps between neighboring longitudinal traps occurred for bigger sphere and the distances between them fit very well to the distance between two neighboring SW antinodes

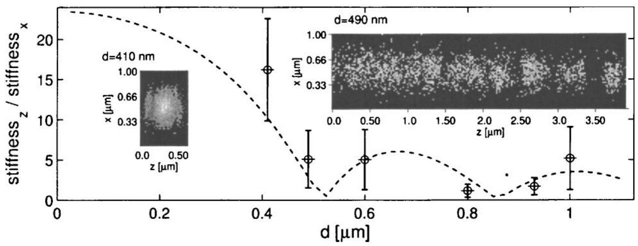


FIG. 4. Comparison of the ratio of longitudinal and lateral stiffnesses $\kappa_z/\kappa_x$ obtained from the theory (the same parameters as in Fig. 3) and experiment. The error bars correspond to the 90% confidence level. Insets show the $x-z$ record of positions of single polystyrene bead of diameters 410 nm (over a period of 166 s) and 490 nm (over 127 s) confined in Bessel standing wave.

$\delta z = 419$ nm. Unfortunately, this experimental system was not stable enough and the small drift of the longitudinal traps smeared the clear distinction between neighboring traps during repeated particle returns to the same trap.

We calculated the trap stiffness from the time record of $x$ and $z$ bead positions. We chose ranges of the same number of consecutive positions (50), eliminated the drift by fitting a line and calculated root-mean-square deviations (RMSD) $\langle x^2 \rangle$ and $\langle z^2 \rangle$ from this line. The trap stiffness is inversely proportional to the RMSD. Unfortunately, we could not compare the experimental stiffness with theoretical predictions because we did not know the exact trapping laser intensity at the place of particle confinement. This quantity is not experimentally available since the ideal BB is in reality longitudinally modulated by Gaussian envelope and so it is dependent on the axial position of the bead. For this reason, during the exchange of the bead sizes we tried to put the cuvette in the same region of the beam each time and retained the same laser powers. Nevertheless, we could compare the ratio of stiffnesses $\kappa_z/\kappa_x = \langle x^2 \rangle / \langle z^2 \rangle$, which is insensitive to trapping power (see Fig. 4). We believe that this comparison reflects the theoretical trends even though the error bars indicate that much more attention must be paid to the stability of the system in future measurements. The ratio is bigger than 2 for the majority of studied particle diameters and therefore the objects are confined tighter longitudinally than laterally. In contrast, for a single focused GB, this ratio lies between 0.68 for $d = 400$ nm and 0.2 for $d = 1000$ nm,[13] respectively. For any given size of trapped bead, if a GB is simply focused to a diffraction limited spot, there is a fixed relation between the maximum trapping force and the stiffness of the trap. However, the elasticity of biological molecules is very nonlinear and to get higher grade information, there is a need to locate the molecules more precisely in one dimension than another and an asymmetry in stiffness in the optical trap as demonstrated here might facilitate such studies.

In conclusion, we have demonstrated how two counterpropagating Bessel beams can be used to create a standing wave where the submicron particles can be 3D confined and precisely delivered over a distance of hundreds of $\mu$m by sliding the Bessel standing wave. This optical conveyor belt may have potential for the delivery of biological and colloidal microparticles and indeed a variant of this system may also be used for deterministic delivery of cold atoms.

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