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Optical micromanipulation using a Bessel light beam

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Abstract

We demonstrate a technique for optical manipulation of micron-sized particles, including biological samples, using a zeroth-order Bessel light beam. The central maximum of such a beam offers a "non-diffracting" focal line of light. This line focus is well suited to rotationally align rod-like particles along the beam direction and to build stacks of particles. We have stacked up to nine 5 μm spheres above one another and manipulated this particle chain as a whole. Furthermore, we have observed laser guiding (transport) of 1 μm particles along the Bessel beam axis over 1 mm, which is over 10 times the Rayleigh range for a comparable Gaussian beam. © 2001 Elsevier Science B.V. All rights reserved.

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Optical forces at a dielectric interface arise due to radiation pressure and refraction, both of which can be exploited for the trapping and manipulation of small micron-sized particles. Ashkin et al. [1] first demonstrated the optical trapping in three dimensions of micron-sized spheres using a single light beam focused tightly with a microscope objective. These optical tweezers have found widespread application for manipulation of biological and dielectric samples. There has also been considerable interest in the guiding of particles. In this instance the particle is confined in two dimensions and radiation pressure can propel it along a laser beam [2]. The divergence of a laser beam has limited such all-optical guiding to the order of the Rayleigh range [3]. Hollow-core fibres have recently been used to guide particles, where one of the main motivations is to exceed the Rayleigh range limitation of a Gaussian beam [4]. In this work we make use of Bessel light beams for optical manipulation of particles. We observe alignment of long rod-like samples, stacking and manipulation of multiple spheres and guiding of micron-sized spheres along the extended line focus of the Bessel beam. In the latter case the guiding distance exceeds the Rayleigh range of Gaussian beam with the same spot size by more than an order of magnitude, offering significant improvements in guiding particles between two specific points in the sample chamber.

The zeroth-order Bessel light beam is a solution of the scalar Helmholtz equation [5]. It is sometimes termed "non-diffracting" or propagation invariant because the transverse profile of the beam remains unaltered during free-space propagation.

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The electric field amplitude of a zeroth-order Bessel beam is given by

$$E(r,z) = A\exp(\mathrm{i}k_z z)J_0(k_r r). \quad (1)$$

Here J_0 is the zeroth-order Bessel function and k_r and k_z are the radial and longitudinal components of the free-space wave vector k, where $k = 2\pi/\lambda$. An ideal zeroth-order Bessel beam would consist of an infinite number of rings around a central maximum, which can be very small (radius $= 2.405/k_r$). However, such a beam would require infinite energy. A finite approximation to a Bessel beam can be realised efficiently using a conical glass element known as an axicon [6]. An incident Gaussian light beam is refracted by such an element and the emergent beam has wave vectors lying on a conical surface. Such a distribution of wave vectors is a defining characteristic of a Bessel light beam [5]. The axicon-generated beam is a close approximation to a Bessel light beam over a limited propagation distance. However, the intensity of the central maximum is not constant with propagation but varies smoothly, peaking after about half the maximum propagation distance [7]. For an axicon of opening angle γ and refractive index n, illuminated with a Gaussian light beam of beam waist w_0 the propagation distance can be estimated by

$$z_{\max} \approx \frac{w_0}{(n-1)\gamma}. \quad (2)$$

The central maximum propagates without appreciable spreading (i.e. it is non-diffracting) over this distance and thus offers a focal line of light. It is this feature, coupled with small transverse dimension of the central maximum, that we exploit for optical micromanipulation in this work.

Fig. 1 shows the experimental set-up for optical micromanipulation using the Bessel light beam. We illuminate an axicon having an opening angle of 1° with the expanded Gaussian output beam of a Nd:YVO_4 laser (1 W@1064 nm). We use a telescope to reduce the size of the central maximum of the generated Bessel beam and obtain a suitable propagation distance. We used Bessel beams with central maxima of 6–10 μm in diameter for the

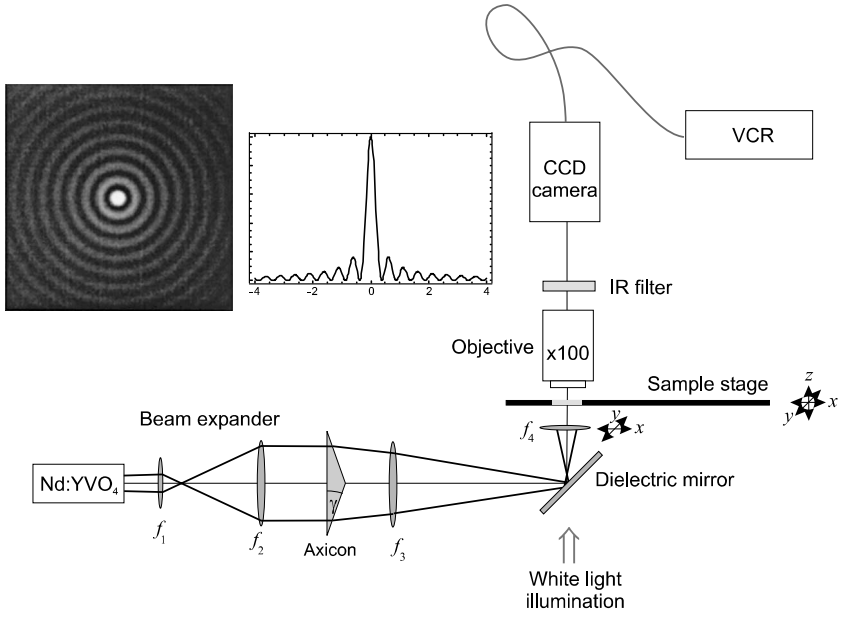

Fig. 1. Experimental arrangement for Bessel tweezing: Lenses $f_1 = 50$ mm and $f_2 = 250$ mm expand the beam to illuminate the axicon, which generates the Bessel beam. Lenses $f_3 = 250$ mm and $f_4 = 25$ mm reduce this Bessel beam to one with a central maximum of ≈9.4 μm diameter. Lens f_4 is adjusted to manipulate the particles. The inset shows a picture and cross-sectional profile of the Bessel light beam which propagates in the vertical direction.

work presented here. It is important to note that we can vary both this central maximum size and overall propagation distance by judicious choice of optics and beam parameters. This allows maximum flexibility in an experimental arrangement. The Bessel beam is directed vertically onto a sample slide holding the particles of interest in solution. Beam manipulation was performed by fine manipulation of the last lens of the optical system. We point out that the relatively large distance between the last lens and the sample of about 20 mm makes it possible to manipulate particles which are remote from the final optic and from any confining walls of the sample cell. A microscope objective ($\times 40$ or $\times 100$) and CCD camera were placed above the sample solely for observation of the trapped particles. A variety of particles were used in the experiments including silica spheres of 1 and 5 μm diameters, elongated glass fragments, chromosomes and *E. coli* bacteria cells.

For low laser powers of about 35 mW, which corresponds to a power of only about 4 mW in the central maximum of the Bessel beam, we were able to two dimensionally tweeze and manipulate 5 μm diameter silica spheres, *E. coli* and Chinese hamster chromosomes at speeds of about of the order of 10 $\mu m\, s^{-1}$.

At higher laser powers (typically greater than 60 mW) additional forms of particle manipulation were realised, namely guiding, alignment and stacking of particles. Given that the central maximum of a Bessel light beam is non-diffracting, it offers a narrow line of light which is equivalent to an enhanced depth of focus for a light beam. We used a Bessel beam with a central maximum of 9.4 μm diameter and a propagation distance of $z_{max} = 2.8$ mm. This propagation distance is approximately 40 times the Rayleigh range of a Gaussian beam with a 5 μm beam waist (at 1064 nm, the Rayleigh range is 74 μm). Although the on-axis intensity of an axicon-generated Bessel beam varies on propagation [7], it can be considered practically constant throughout the sample cells (100 μm high) used. Only in the guiding experiments discussed later on, where the sample cell becomes comparable in height to the maximal propagation distance z_{max}, this intensity variation becomes noticeable. We also note that the Bessel beam propagation distance can be extended with different choices of beam parameters and telescope systems.

As a result of its form the Bessel beam can be used as single beam line tweezers without need for any moving parts in the apparatus. To demonstrate this with a Bessel light beam we simultaneously trapped and manoeuvred several 5 μm spheres in unison. This was performed by trapping the sphere at a power level at which it was guided upwards by the Bessel light beam along its propagation direction and then translating the beam over another particle which was then also trapped. This action was repeated to trap up to nine particles in our experimental Bessel beam tweezers. The stack of spheres can be translated as a whole in the transverse plane. Fig. 2 shows an example of five spheres stacked on top of one another. We note that stacking in a Gaussian beam has previously been investigated theoretically [8] and our experimental results on stacking using a Gaussian beam will be published elsewhere [9]. The ability to construct particle chains could be of great importance in colloid physics, for example to study of binary colloid suspensions [10].

Furthermore, Bessel beam tweezers can be used to align elongated particles. Several biological specimens have an elongated or rod-like form and Fig. 3(a) and (b) shows rotational orientation of *E. coli* bacteria and a 50 μm long fragment of a glass fibre respectively in the Bessel beam tweezers. The particles, originally in the horizontal plane, are rotated by the Bessel beam and placed upright, aligned with the propagation direction of the central maximum of the beam, which is vertical in this instance (Fig. 3). Chinese hamster ovary chromosomes, suspended in phosphate buffer solution, were also vertically oriented and elevated. Subsequently, we were able to manoeuvre these upright rod-like samples around on the slide.

Vertical alignment of rod-like particles in a Gaussian beam has been reported recently [11]. We note that vertical alignment in a Bessel beam is different from that in a Gaussian beam, as the rod-like element is trapped along its entire length in a Bessel beam. Vertical alignment and subsequent manipulation could allow one to readily isolate and transfer elongated samples from one sample

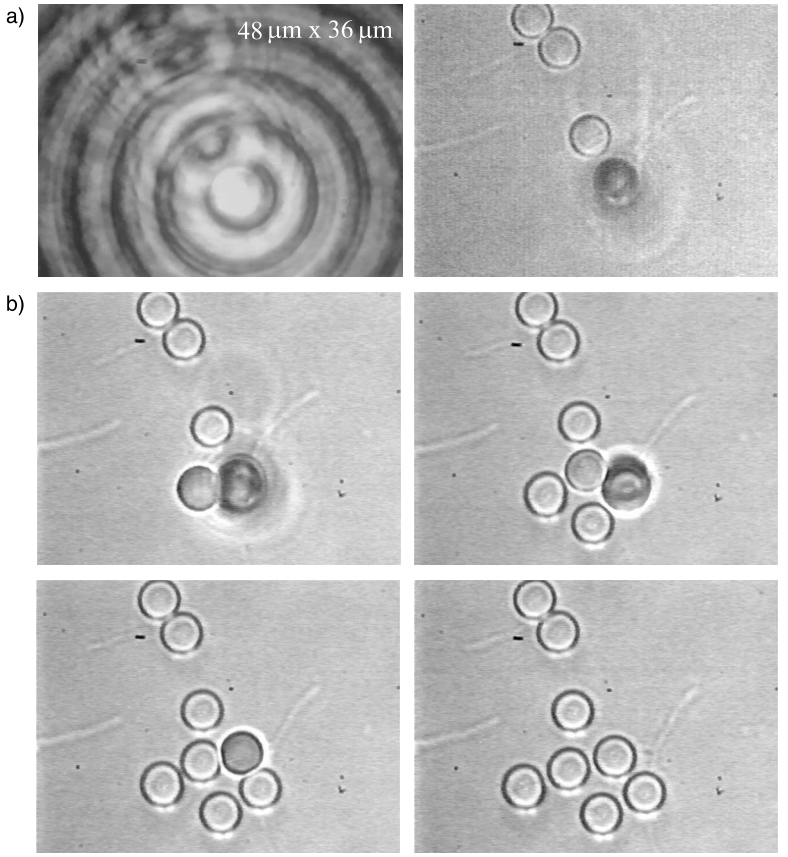

Fig. 2. The stacking of five 5 μm spheres aligned along the Bessel beam: (a) The stack is held vertically by the Bessel beam and can be translated in the transverse plane. (b) A sequence of frames showing the collapse of the five stacked spheres after blocking the beam.

chamber to another. Utilising the Bessel beam, a vertically aligned sample could easily be transferred through a channel in the trapping well whose size would not allow passage of the sample in its horizontal orientation. In chromosome studies for example, this is of direct importance in that chromatid fragments need typically to be spatially separated to a chamber to perform polymerase chain reactions [12].

Finally, we describe the application of a zeroth-order Bessel light beam as an all-optical guide for trapped particles. All-optical guiding relies on the gradient force to confine a particle axially in two dimensions and the radiation pressure to propel the particle along the length of the laser beam. Such transport of microscopic particles is important for many interdisciplinary areas including aerosol science and biology. All-optical guiding has been demonstrated previously using a standard Gaussian beam [3].

Firstly, we used the same set-up as shown in Fig. 1 to guide 1 μm spheres vertically upwards. We used various thicknesses of sample cells (100 μm up to over a 1 mm) and guided over the almost full extent (height) of the cell, from near the bottom to a position just below the surface of the cover slip (see Fig. 4). Notably, we are able to guide several spheres simultaneously in the beam. We have experimentally recorded the times required for extended guiding using the Bessel beam. We note that the particle velocity varies during the guiding process, typically ranging between 5 and 10 $\mu m\,s^{-1}$. The back-scattered component of the light incident on the particle causes it to accelerate

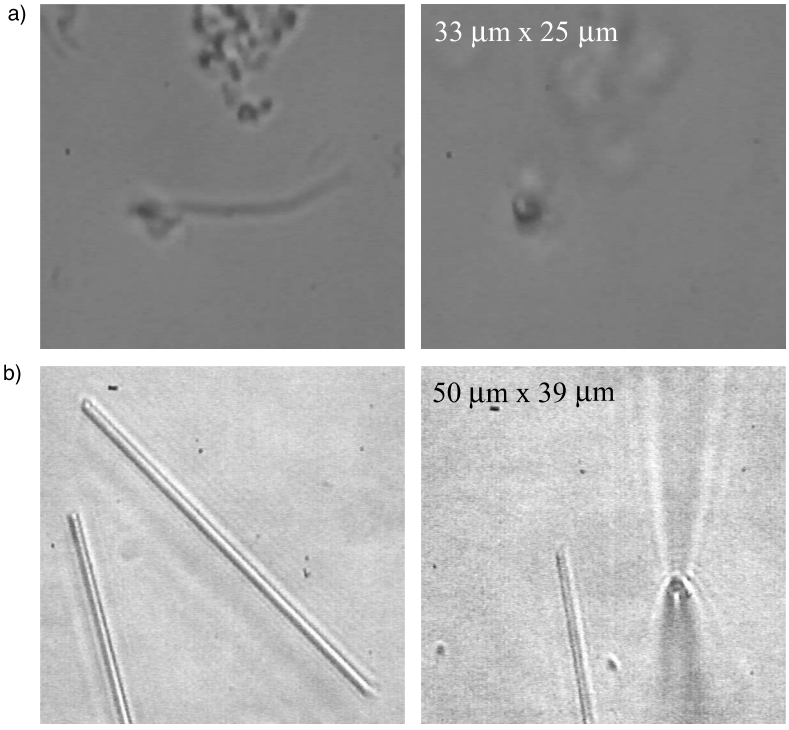

Fig. 3. Rotational orientation through 90° of (a) a *E. coli* bacterium (the second frame is focused about 15 μm higher, at the top of the upright bacterium) and (b) a 50 μm fragment of a glass fibre. Both samples could subsequently be manipulated once in the upright position.

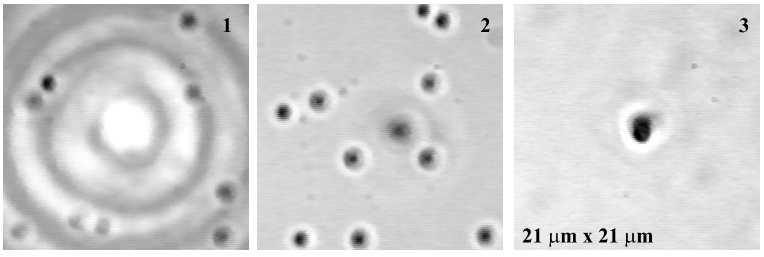

Fig. 4. The three frames show the behaviour of a guided 1 μm particle. In frame 1 we see the Bessel beam superimposed on the particle. In frame 2 we can see that the particle is guided upwards and goes out of focus. Note that the particles in the background change position due to Brownian motion of the 1 μm spheres suspended in water. In frame 3 we refocus the camera at the top of the sample cell (100 μm in this instance) and see the guided particle just below the cover slip.

in the direction of beam propagation until this force is compensated by gravity and Stokes drag. However, the radiation pressure force itself varies due to the on-axis variation of the intensity of the axicon-generated Bessel beam, giving rise to a variation of the particle velocity as a function of guiding distance. We have also guided 5 μm spheres in our set-up. Calculations show that with increased laser power and propagation length of the Bessel beam we should be able to observe guiding of larger microscopic particles over much longer distances.

We have compared qualitatively the guiding of particles in a Bessel beam with that in a Gaussian beam. Experimentally we find significant advantages in using the Bessel beam. Its non-diffracting

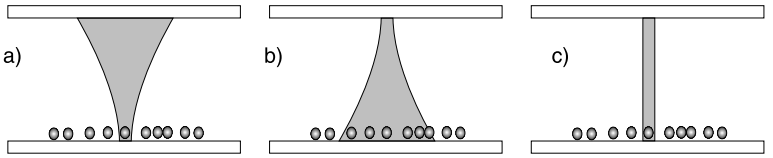

Fig. 5. For point-to-point guiding the Bessel beam is advantageous: With a Gaussian beam there is poor localisation at (a) the final destination or (b) the initial capture area. (c) The central maximum of a Bessel beam provides to good localisation throughout the sample cell.

nature means we are able to isolate and guide specific particles in the sample to a specified location. The Gaussian beam was unable to do this over an equivalent distance due to diffraction. The beam would either be unable to localise the particle at its final destination (Fig. 5(a)) or its initial capture area would be so large as to guide all specimens to the final destination (Fig. 5(b)). The Bessel beam (Fig. 5(c)) provides good two-dimensional localisation throughout the guiding distance.

Secondly, we looked at horizontal guiding of 1 and 5 μm spheres. We used a small cuvette (4 mm × 4 mm × 10 mm) containing the sample and directed a horizontal Bessel beam through this close to a bottom edge. We could track the guided particles by observing the scattered light through a ×10 microscope objective, looking orthogonal to the guiding direction. Typically, the guiding velocities are about twice as high as for vertical guiding, i.e. in the range of 10–20 $\mu m\,s^{-1}$. Fig. 6 shows 5 μm spheres guided sideways through the cell from left to right. In this particular instance it can be seen that the right-hand sphere moves slower than the sphere on its left. This effect has been reported and explained previously for guiding in Gaussian beams [3]: The first sphere scatters a considerable fraction of the beam away from the propagation direction, reducing the propulsion force on the right-hand sphere and thus allowing the left-hand one to catch up.

The ability to guide and deposit tissue into a specific 3D structure is of importance as certain tissues use specific cell–cell interactions that depend on the spatial ordering of multiple cell types. Recapitulating this spatial order in vitro will facilitate our understanding of function and failure in native and engineered tissue. One approach to achieving such high placement precision is to use optical forces to deposit cells directly [13]. We believe that the Bessel beam with its non-diffracting central maximum and vastly increased guiding distance offers an excellent choice for such studies.

We have demonstrated a number of optical micromanipulation techniques with Bessel light beams. All these techniques can be performed remotely, as no microscope objective is required to project the Bessel beam into the sample cell. The methods exploit the propagation invariance of the Bessel beam. One can realise single beam line tweezers, which is of particular interest for studying micromechanics with dipolar chains [14]. Multiple particles can be trapped vertically and the resulting stack translated as a whole. Rotational

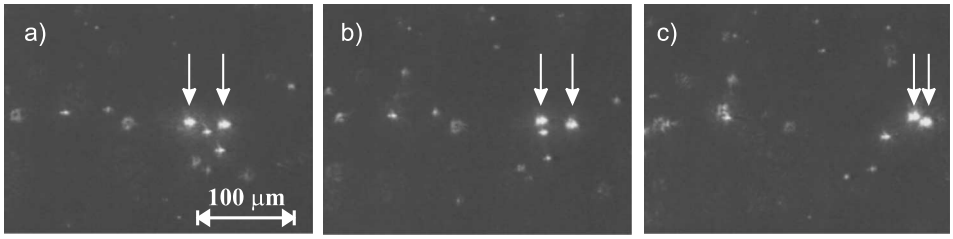

Fig. 6. Three frames ((a) $t = 0$ s, (b) $t = 1.8$ s, (c) $t = 4.34$ s) showing two 5 μm spheres guided horizontally from left to right. The second (left-hand) sphere catches up with the first. The right-hand sphere is also guided slightly below the left-hand one. This is again due to the distortion of the central maximum of the Bessel beam by the left-hand sphere.

orientation of elongated particles may also be achieved with the Bessel beam allowing alignment of very long (up to 50 μm) rod-like specimens with the central maximum of the beam. Guiding and transport of particulate matter over extended distances is also observed. Such guiding can be used in direct writing of structures and tissue engineering [13]. We are currently studying the use of such laser guiding for the separation and subsequent collection of laser microdissected chromatid fragments from the parent chromosome [12]. We believe this method of optical micromanipulation will find several interdisciplinary uses including optical micromachines, colloid research and biological studies.

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