How to use laser radiative and evanescent interference fields to control movement of the sub-micron objects.

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ABSTRACT

We present how to use the transfer of the momentum from the spatially periodic interference field to submicrometer-sized particles. The interference field is obtained by interference of co-propagating nondiffracting beams and counter-propagating nondiffracting and even evanescent fields. These types of trapping fields enable spatial organization of submicrometer-sized objects into one-dimensional arrays containing even thousands of objects, their controlled delivery over a distance of 1 mm, their sorting according to the size of refractive index. Moreover, the particle tracking enables to study the Brownian dynamics, jumps between neighboring optical traps and interactions between the objects. We present a group of new experiments studying particle behavior in such fields.

Keywords: random motion, optical force, colloidal particle, interference optical trap, optical conveyor belt

1. INTRODUCTION

We focus here on the submicrometer-sized objects immersed in the fluid. Therefore these systems suffer by strong thermal (Brownian) motion which determines their behavior and which should be partially overcome to obtain a sort of deterministic movement of these objects. The optical trapping of nano-scale or micro-scale objects employs the transfer of momentum from the light to the object via scattering of the light. Pioneering experiments were performed by A. Ashkin and they lead to the demonstration of optical tweezers - a tool where single focused laser beam provides spatial confinement of nanoobject, microobject, and even living cells or sub-cellular structures inside living objects. Optical tweezers combined with a sensitive method detecting the position of the trapped object enabled measurement of tiny forces acting on an optically trapped object. This object served as a handle with one component of molecular motor complex attached to it. Therefore, tiny forces acting at the level of single molecule were measured. Various molecular motors were investigated using this scheme - kinesin-microtubul, myosin-actin, nucleic acid-based enzymes, bacteriophage DNA packaging, mechanical DNA unzipping, mechanical unfolding of chromatin fiber.

Gradually the progress in the construction of optical tweezers enables generation of two optical traps via polarization beam separation or many traps using time-sharing of single beam among many traps. The development of spatial light modulator technology brought this device to the market and enabled construction of advanced so called holographic optical tweezers. They enable static and even dynamic generation of several optical traps spatially distributed in 3D, generation of optical vortices and complicated spatial distribution of the light intensity. Alternative methods used interference of co-propagating Gaussian beams to get interferometric optical tweezers and interference of counter-propagating Gaussian beams to get standing waves.

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wave traps aligned along the beam propagation. Usage of co-propagating and counter-propagating non-diffracting beams removed the strong axial dependence of the optical traps depth in focused Gaussian beams and enabled generation of an axial array of almost identical optical traps.

2. AXICON-GENERATED RADIATIVE FIELDS

2.1. Bessel beam introduction

Almost twenty years ago the concept of the so-called non-diffracting propagation of electromagnetic waves was proposed. These beams are formed by an interference of plane waves of wave vectors covering a conical surface. This interference is responsible for very narrow core of these beams (linear focus), their non-diffracting propagation and the ability to reconstruct itself after passing through a disturbing obstacle. This feature is especially useful for multiple confinement of micro-objects. The side effect of the interference is that the beam energy is split almost equally into several lateral rings and therefore only its fraction is available in the intense central core. The most simple non-diffracting beam is called the Bessel beam because its radial spatial profile is described by the Bessel function of the first kind and the zero order. Bessel beam represents the most simple scalar solution of the the Helmholtz equation whose temporally independent complex amplitude has a mode-like form $E(x, y, z) = E_B(x, y; k_r) \exp(-ik_z z)$ where $k_r$ and $k_z$ are related to the wave number $k$ as $k_r^2 = k^2 - k_z^2$. During propagation along the $z$-coordinate, the field exhibits phase oscillations given by the propagation constant $k_z$ but its longitudinal component of the Poynting vector $S_z$ remains unchanged. In the first work on scalar non-diffracting beams, the amplitude $E_B$ was obtained in the form of the the Bessel function giving the name of this type of the beams. Experimentally so called pseudo-non-diffracting beams can be generated only. These beams do not exist in the whole unlimited space but only in the spatially limited volume. One can use an annular aperture placed at the focal plane of a lens, hologram or an axicon (conical lens) (see Fig. 1) to obtain such beams.

![Figure 1](image.png)

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.

In the paraxial approximation and for linearly polarized Gaussian beam the final field distribution behind the axicon can be described as:

$$E(\rho, z) = E_0 \sqrt{\frac{2\pi k_z}{\cos(\alpha_0)}} \sin(\alpha_0) e^{-\left(\frac{z \tan(\alpha_0)}{w}\right)^2 - \frac{z^2}{w^2}} J_0(k\rho \sin(\alpha_0)) e^{ikz \cos(\alpha_0)}.$$ (1)
where $k$ is the wavevector length, $\alpha_0$ is the angle which a vector normal to the conical surface of wavefront includes with the $z$ axis, $\alpha_0 \simeq (n_a - n_s)(\pi - \tau)/(2n_s)$, where $n_a$ is the refractive index of the axicon, $n_s$ is the refractive index of the surrounding medium (air), and $\tau$ is the apex angle of the axicon. It is clearly seen that the part $J_0(k\rho \sin(\alpha_0)) e^{ikz \cos(\alpha_0)}$ in (1) is the description of an ideal paraxial Bessel beam and that the factor $E_0 \sqrt{2\pi k \sqrt{\cos(\alpha_0) \sin(\alpha_0)}} e^{-\left(\frac{\zeta \tan(\alpha_0)}{w}\right)^2}$ is an axial beam envelope. For the on-axis intensity we obtain:

$$I(\rho = 0, z) = I_0 \frac{2\pi k z}{\cos(\alpha_0)} \sin(\alpha_0)^2 e^{-2\left(\frac{\zeta \tan(\alpha_0)}{w}\right)^2},$$

where $I_0 = \frac{1}{2} c \varepsilon_0 E_0^2$ is the on-axis intensity of the incident Gaussian beam. The distance of the Bessel beam existence is usually defined as $z_{\text{max}} = w/\tan \alpha_0$. The position of the intensity maximum and the distance of the Bessel beam existence are important especially if two and more Bessel beams are used experimentally.

### 2.2. Counter-propagating Bessel beams and “Optical conveyor belt”

The setup of two interfering counter-propagating Gaussian beams with the same size and position of the waists gives a rise to strong periodical intensity oscillations in the area near the beam waist. Therefore due to the strong intensity gradients and elimination of scattering forces this setup offers a possibility of much stronger particle confinement comparing to the single beam trap. The whole structure of such a standing wave (system of intensity maxima and minima) can be shifted altering the phase of one of the interfering beams. This setup was initially proposed for atom cooling\(^{39}\) and recently for deterministic delivery\(^{40}\) of single atoms. The possibility to use the Gaussian standing wave for confinement of high-index nano-particles and sub-micron particles was theoretically analyzed and successfully experimentally realized in the last decade.\(^{31,32}\) However, due to the very short Rayleigh range of a focused Gaussian beams one obtains relatively short longitudinal range where the on-axial intensity of standing wave is sufficiently strong for particle confinement.\(^{41}\)

The counter-propagating geometry with two Bessel beams results in a very long chain of standing wave traps and indeed overcomes the issue of the short Rayleigh range for focused Gaussian beam. The sliding Bessel standing wave (the system with alterable phase of one beam) thus offers a long extended axial region of optical traps for delivery of micro-objects so called “The Optical Conveyor Belt”\(^{33}\) obviating the drawbacks of a the sliding Gaussian standing wave.

Generally the easiest way how to obtain well-aligned counter-propagating beams is to use retro-reflection of the incident beam on the mirror\(^{32}\) (see Fig. 2 a). Such setup for Bessel beams was used in our preliminary experiments,\(^{42}\) however in this instance the positions of the standing wave nodes and anti-nodes are fixed with respect to the mirror thus prohibiting the axial motion and delivery of particles. Therefore we developed a different arrangement (see Fig. 2 b) where the sliding Bessel standing wave is created from two independent counter-propagating Bessel beams with alterable phase shift between them.

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**Figure 2.** The two types of Bessel standing wave generation - retroreflection at the mirror(left) and interference of counter-propagating beams (right).
Even though we successfully built up a setup for sliding Bessel standing wave at the University of St. Andrews,\textsuperscript{33} we have not reached the maximal value of possible particle delivery which such setup offers. It was caused due to the fact that we did not use the identical optical components in both arms of the setup and therefore the resulting Bessel beams did not exist over the same distance. In this case the scattering forces could be compensated over a short part of Bessel beam existence only (see Fig. 3).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{The demonstration of the overlap of counter-propagating Bessel beams for case of the St. Andrews setup (top) and for the case of the optimized one (bottom). The red dashed lines define the range where the difference of the intensities in both beams does not exceed the limit of 10\%.}
\end{figure}

The optimized experimental setup of the optical conveyor belt demonstrates Fig. 4. The used laser source is Verdi V5 (Coherent) with maximal output power equal to 5.5 W, working on $\lambda_{\text{vac}} = 532$ nm. In both arms the output Gaussian beam is transformed by axicons (A1, A2) EKSMA 170° into Bessel beam and consequently modified by the telescopes (T1, T2) consisted of doublet lenses (L1, L2) $f = 30$ mm and aspherical lenses (AL1, AL2) $f = 8$ mm. The motion of the movable mirror M3 was controlled by the piezoelectric accurator PiFoc (Physik Instrumente).

We succeeded in the generation of 1 mm long array of nano-traps filled with polystyrene beads of radius 175 $\mu$m (see Fig. 5). At the moment we do not fully understand the phenomenon of the dark places in the particle chain. The 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 6 proves the delivery of polystyrene beads of radii 100 nm over a distance of 60 $\mu$m. Since both Bessel beams axially overlapped over a distance exceeding 1 mm (see the bottom plot of Fig. 3, we have used the mechanism of optical conveyor belt to deliver the same objects over this distance.

2.3. Co-propagating interfering Bessel beams

Very promising effects appear if two or more co-directional non-diffracting beams interfere. If their propagation constants are properly chosen, the non-diffracting beams exhibit constructive and destructive interference at the distances repeating with the period $z_T$ - historically known as "Talbot distance".\textsuperscript{43} As a consequence, the longitudinal component of the Poynting vector exhibits a longitudinal periodicity known as the self-imaging,
Figure 4. The optimized experimental setup of optical conveyor belt. M1–M3 – metal mirrors; A1, A2 – axicons; T1, T2 – telescopes formed from doublet lenses L1, L2 and aspherical lenses AL1, AL2; LDO+CCD – long working distance objective and CCD camera; PBS1, PBS2 – polarizing beam splitters; $\lambda/2$, $\lambda/4$ – wave plates; C – cuvette.

Figure 5. 1 mm long array of polystyrene particles of 175 nm in radius captured in the Bessel beam generated standing wave with about 5000 optical traps. The top image is composed of 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. The bottom image shows part of one unscaled frame corresponding to the white rectangle from the top image.
Simultaneous confinement and delivery of polystyrene particles of radius 100 nm in a movable standing Bessel beam (optical conveyor belt).

\[ S_z(x, y, z) = S_z(x, y, z + z_T). \] This effect was first analyzed and measured in 1996\(^{44} \) for two beams, later on it was studied in more details and workout for more beams including rotating ones.\(^{45-48} \) For two interfering beams, the total field has a cosine longitudinal evolution but for more beams strong intensity peaks appearing periodically along the propagation direction can be observed.

We present here the usage of self-imaging for generation of periodic one dimensional array of three dimensional optical traps separated by several micrometers. 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 and causes the tilt of the axial potential profile. To confine the particle, the longitudinal component of the gradient force has to balance the scattering force and therefore, the longitudinal oscillation of the field (Talbot distance\(^{43} \)) has to be as short as possible.

The experimental setup is shown in Fig. 7. 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 tuned 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 again 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. The apaxes 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. Unfortunately 50% of the trapping power is wasted here.

If the cuvette C was missing, each of the beams was imaged on the calibrated CCD. By fitting the optical intensity at the detector to the data from these figures we found that the radius of the central high-intensity ring...
Figure 7. Experimental set-up. $M_{1-3}$ - mirrors, $\lambda/2$, $\lambda/4$ - wave plates, $PBS_{1,2}$ polarizing beam splitters, $L_{1-4}$ - lenses, $A_{1,2}$ - axicons, $P$ - polarizer, $C$ - cuvette filled with water. The inset shows the water circulation caused by laser heating.

The distance between neighboring optical traps is bigger in the co-propagating beams comparing to the counter-propagating ones. Therefore, the self-reconstructing property of Bessel beams$^{36,49}$ restores the original
Figure 8. Examples of several objects of different sizes confined in two co-propagating and interfering Bessel beams. Weak water flow against the beams propagation was generated by laser heating of the fluid. It pushed the object closer to the on-axial intensity maxima so that they were better confined laterally.

Figure 9. An example of the delivery of 5 polystyrene beads of diameter 520 nm over a distance of 80 μm by changing the phase of one Bessel beam.

Bessel beam profile at the place of the next trapped object for the object diameters used in the experiments.

3. EVANESCENT INTERFERENCE FIELDS
3.1. Evanescent standing-wave and “evanescent conveyor belt”
Up to these days, the interference of counter-propagating evanescent waves was generated using a retro-reflecting mirror and it was used for generation of periodic light pattern for near-field microscopy experiments. In

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contrast to the previous methods of the generation of a periodic near-field interference pattern by a retro-
reflecting mirror we used a setup with two independent counter-propagating Gaussian beams that were
focused on the top surface of the prism. Tuning the incident angle may result in either a surface patterned
evanescent fields (evanescent standing wave - ESW) or a propagating light field just above the surface (see Fig.
10). Moreover this set-up enables us to alter the relative phase between the two beams in a controlled fashion
by a movable mirror. Its movement results not only in the motion of the standing wave but also in motion of
the objects confined in this standing wave.

Figure 10. Experimental setup. Linearly polarized beam (Verdi, 5 W, $\lambda_{\text{vac}} = 532$ nm) is 3 $\times$ enlarged passing through
telescope T, the following half-wave plate $\lambda/2$ rotates the polarization so that the beam is separated into two parts.
One is reflected on the polarizing beam splitter (PBS), changed to circularly polarized on $\lambda/4$ plate, reflected on the
movable mirror MM, changed to linearly polarized beam after passing again through $\lambda/4$ plate. Its polarization is now
perpendicular to the original one reflected to this arm and so the beam passes through the PBS to the mirror M2 and
is focused by lens L2 on the surface of the prism PR. The second beam passed through the PBS, the mirror M1, and
the lens L1 and overlapped on the top surface of the prism PR with the first beam. The lower plot shows the side view
with the edges we used to block the major part of the beam that formed the propagating wave transmitted through the
prism.

Therefore, the evanescent field was generated mainly by the high intensity core of the Gaussian beam close
to the critical angle. Overlapping of both beams gave elliptical spot 40 $\mu$m long and 10 $\mu$m wide with standing
wave fringes separated by 200 nm. Movable mirror MM was controlled by a PIFOC (Physik Instrumente) which
provided fast movement over 150 $\mu$m very precisely.

Applying the mechanism of the optical conveyor belt we were able to move particles from 350 nm to 800 nm
in diameter over a range of about 40 $\mu$m on the surface (Fig 11a). However particles of size 410 nm and 750 nm
in contrast did NOT follow the motion of standing wave and were unaffected by its presence (see Fig. 11b,
11c).
Figure 11. Particle delivery and particle affinity to the surface conveyor belt. a) A polystyrene sphere of diameter 520 nm is delivered over a distance of 36 µm. b) Mixture of spheres of sizes 410 nm (left) and 520 nm (right). While the larger moves with the conveyor belt, the smaller keeps its original position unaffected by the standing wave. c) Mixture of polystyrene particles of diameters 350 nm and 750 nm where the smaller one follows the motion of standing wave. The larger sphere remains unaffected until it is in close proximity of the smaller sphere (‘binding’ interaction).

Experimentally our observations concur with the theory for mono-disperse (in size) or diluted samples on the top of the prism and we can readily observe the differing affinity of the particles to the SW pattern similar to Figs. 11b, 11c. However, dense colloidal samples suffered from inter-particle interactions. An example of this can be seen in Fig. 11c where the insensitive larger particle starts to move even before physical contact with the smaller particle. This is attributed to an optical binding type interaction where scattered light from the particle selected by the standing wave affects the optical forces experienced by the unaffected particle.

3.2. Optical static sorting of particles

Recent work has shown the experimental demonstration of optical separation using an extended optical lattice or holographic methods in the presence of a laminar flow and it has been followed by theoretical analyses. In these studies the particles are not trapped per se but rather their differing affinity to a periodic light pattern (landscape) were exploited. This sensitivity is very high and potentially offers a new non-invasive method for optical separation.

In contrast to the above mentioned methods our setup brings the possibility of the optical separation of sub-micron particles in the absence of any imposed flow by exploiting the varying affinity of objects to this spatially modulated light pattern. In our case the sorting was provided exposing a diluted sample to a tilted washboard potential, created by introducing a slight intensity asymmetry between the counter-propagating waves. This asymmetry created a differential optical gradient along the standing wave and if this was moved “up the hill”, it resulted in the particle sorting demonstrated in Fig. 12. Figure 13 demonstrates that the method is able to separate objects of sizes differing by just 60 nm.

4. CONCLUSION

An overview of three types of experiments is shown demonstrating submicrometer-sized particle confinement and delivery using interference fields obtained by two counter-propagating Bessel beams, two co-propagating Bessel beams and two counter-propagating evanescent waves. The system of counter-propagating Bessel beams generates thousands of optical traps separated by 200 nm and spread over 1 mm. Thousands of submicrometer-sized particles can be localized in these traps and delivered simultaneously over the region of 1 mm. Unfortunately
Figure 12. An example of a new method of optical sorting of colloids. The imbalance between the intensities generates the imbalance between the radiation pressures coming from both counter-propagating waves and tilts the landscape. Consequently, the particles that are not affected by the standing wave are pushed in the direction of the tilted potential (to the left here). On the contrary, the spheres affected by the standing wave follow its motion and they are delivered against the tilted potential landscape. The sample presented here consisted of a mixture of polystyrene particles of diameter 750 nm (left, insensitive to standing wave) and 350 nm (right, sensitive to standing wave) dispersed in water.

Figure 13. Examples of sorting of colloids of different sizes. Polystyrene beads of diameters 350 nm and 410 nm. The beads of diameter 350 nm are delivered by the conveyor belt in the positive direction of the z axis, the others are insensitive to the periodic modulation of the potential and therefore they fall down due to the potential tilt.
strong interactions between neighboring objects occur. The system using co-propagating Bessel beams creates many optical traps with similar properties separated by several micrometers. This is far enough to suppress the mutual interactions between neighboring objects and due to the self-reconstructing property of the non-diffracting beams the significant interaction between confined objects starts only when the object leaves the trap and approaches to its neighbor. Optical sorting using evanescent conveyor belt is used to separated objects differing in size by only 60 nm.

These experiments competed by fast CCD camera detection provide an interesting tool to study the dynamics of the stochastic motion and especially the problem of the first escape from the trap in periodic potential. It can be easily studied in two dimensions (axial and radial) without enormous demands on the stability of the system and resolution of the position detection. The other system using counter-propagating evanescent waves can be used to study the particle behavior in static periodic potential, tilted periodic potential, and even periodic potential in motion giving a new optical realization of optical ratchets.

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