Two- and three-beam interferometric optical tweezers

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Abstract

We present an experimental demonstration of multiple optical tweezers based on interference of two co-propagating beams that intersect at a given angle and form interference fringes (asymmetric optical traps) at the focal plane of a focusing lens. Since this arrangement provides only two-dimensional trapping when the objects are pushed against the coverglass, we added the third counter-propagating beam. This beam did not interfere with the previous two but compensated their radiation pressure. Therefore, stable three-dimensional confinement into multiple fringes is achieved. We quantified experimentally the maximal optical forces exerted on 1\,\mu m polystyrene bead in both configurations and compared them with theoretical predictions. Reasonable good coincidence was found especially for two-dimensional trapping.

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1. Introduction

Despite the fact that the history of optical tweezers (OT) \cite{1} is about 20 years old, new and tremendous activities in this field occurred recently. Nowadays, OT is not just a single beam tool for manipulation of dielectric particles or living cells \cite{2} and measurement of tiny forces in the range from pN to nN acting between objects and molecules \cite{3–6} but it is also an optical tool for generation of optical lattices \cite{7,8} and arrays of confined or rotating objects \cite{9–12}, for creation of optical matter \cite{13,14} and colloidal crystals \cite{15} and for optical separation of microobjects \cite{16–18}.

In this article, we present a general way how to generate an interference field created by two or three beams having their optical axes in one plane. Firstly, we analyse an arrangement where two co-propagating laser beams intersect at an angle and interfere there. The fringes so produced behave...
as an array of two-dimension (2D) optical traps because the objects confined in the fringe are pushed against the rear coverglass of the sample cell by the radiation pressure. This set-up is similar to the so-called interferometric tweezers [19,20] but we quantified the properties of these traps by measurement of the maximum forces exerted on 1 μm-latex beads in the plane of the rear coverglass. These forces were determined for each of the generated fringes using the dragging Stokes method [21,22]. Moreover, we added the third counter-propagating beam that balanced the radiation pressure of the other two beams but did not interfere with them. In this arrangement we confined polystyrene beads at a given distance between the two surfaces of the sample cell. To the best of our knowledge this should be the first demonstration of three-dimensional (3D) trapping in interferometric tweezers.

2. Experimental set-up

The apparatus for interferometric optical tweezers (IOT) is schematically shown in Fig. 1. With respect to the directions of axis $r_2$ and $r_3$ let us define the axial and lateral directions along axis $r_3$ and in the plane $r_1r_2$, respectively. The set-up is essentially based on two main blocks: a Mach–Zehnder interferometer producing interference fringes and a focusing-imaging optical system providing trapping and imaging of latex microspheres. In the frame reported in Fig. 1 the gravity acts along the direction $r_2$. As a laser source we use a

![Fig. 1. Experimental set-up for interferometric optical tweezers based on an Ar+ laser: M, mirrors; BS1–BS2, beam-splitters; L1–L3, lenses; T, telescope; DM, dichroic mirror; F, filter; VNDF, variable neutral density filter; HWP, λ/2 plate; PZT, nano-positioning piezo-system. Beam Nos. 1 and 2 are linearly polarized along $r_2$ and beam No. 3 is polarized along $r_1$ axis.](image-url)
single frequency Ar\textsuperscript{+} ion laser (Coherent INNO-VA 90-3) emitting a TEM\textsubscript{00} beam with a maximum power of 800 mW at 514 nm. In order to improve the spatial quality of the beam, it is spatially filtered by using a 50 \(\mu\)m-diameter pin hole. The emerging beam from the telescope T has a diameter close to 5 mm and is split by the entrance beam-splitter BS\textsubscript{1} into two beams approximately of the same power \((P_1 \approx P_2)\). The output beam-splitter BS\textsubscript{2} joined both beams and translating it along the \(r_1\) axis we could adjust the distance \(D\) between the beam centres. Once the distance \(D\) is fixed, the two beams are aligned symmetrically with respect to the rest of the optical system. The beam intensities are changed with a variable neutral density filter (VNDF). Both beams are focused by the 25-cm-focal-length lens \(L_1\) on the image plane (IP) of the objective \(O_1\) (Olympus UPLAN 40x/NA-0.75, infinity-corrected) placed at a distance \(L\) of 31.5 cm from the lens \(L_1\). Therefore, the interference pattern created at the IP plane is reproduced in a reduced scale by the objective lens \(O_1\) on the conjugated sample plane (SP). More details about this optical scheme are depicted in Fig. 2. Following a simple geometrical optics approach and sine condition for \(O_1\) it can be shown that the angle \(\psi\) subtended by each of the two interfering beams and the optical axis in the SP is given by:

\[
\sin \psi = \frac{D}{2n_m} \frac{L - f_{L_1} - f_{O_1}}{f_{L_1} f_{O_1}},
\]

where \(f_{O_1}\) is the objective \(O_1\) focal length \((\approx 4.5\ \text{mm in our case})\), and \(n_m\) is the refractive index of the medium where the particles were dispersed (distilled water). The fringes separation \(p\) can be estimated assuming the interference produced by two plane waves:

\[
p = \frac{\lambda_{\text{vac}}}{2n_m \sin \psi},\]

where \(\lambda_{\text{vac}}\) is the wavelength in vacuum (514 nm). The number of interference fringes \(N_{\text{fringes}}\) produced by two interfering Gaussian beams is:

\[
N_{\text{fringes}} = \frac{2w}{pcos \psi},
\]

where \(w\) is the Gaussian beam waist at the SP. To obtain a reasonable number of interference fringes we chose \(w \approx 3.4\ \mu\text{m}\) and \(D = 7\ \text{mm}\ (\psi \approx 7^\circ)\). With these parameters, Eqs. (2) and (3) provide \(p = 1.6\ \mu\text{m}\) and \(N_{\text{fringes}} = 4.25\) which is in good agreement with the observed pattern. Typical measured and calculated interference pattern is shown in the lower part of Fig. 3. This pattern, as it will be discussed later, serves as an array of lateral optical traps (2D traps) since the axial restoring force coming from the axial intensity gradient is
too weak and the objects are pushed against the rear cell wall. In order to obtain an array of 3D traps a third laser beam was focused with the objective $O_2$ (Swift 40x/NA-0.65) at the same focal plane of the objective $O_1$ (see dotted line in Fig. 1); its polarization was rotated by $\pi/2$ using a $\lambda/2$ waveplate (HWP) to avoid the formation of standing-wave interference along the axis $r_3$. The lens $L_3$ (50 cm focal length) focuses this third laser beam at a distance of a few cm from the back aperture of $O_2$. Therefore, a spot size comparable with those of the two counter-propagating beams is produced at the focal plane. The observation part consisted of the objective $O_2$ (Swift 40x/NA-0.65), the dichroic mirror DM, and the lens $L_2$ that imaged the interference pattern and the sample on a CCD camera. Finally, the images were captured by a computer.

Fig. 3. (a) Sketch of 2D trapping: two laser beams having wave vectors $\vec{k}_1$ and $\vec{k}_2$ create an interference pattern in proximity of the coverslip where latex beads are optically trapped in the $r_1r_2$ plane. In this case the positive axial optical force pushes the bead onto the surface of the rear coverslip. (b) Picture showing a computer simulation of the fringe pattern (right part) and experimental confinement of four beads in four different fringes (left part). Laser power used is $P_{\text{tot}} = 58 \text{ mW}$. 
The sample cell consisted of two microscope cover-slips separated by 50 μm mylar strip, filled with calibrated latex beads of 1.01 μm in diameter (Serva Electrophoresis) diluted in distilled water. The cell was sealed and then fixed to a computer-controlled three axis piezoelectric actuator (Physik Instrumente mod.611 Nanocube).

3. Theoretical calculations

We wanted to compare the measurement with theory to better understand the properties of this type of trap. Up to our knowledge similar configuration was studied in detail for Rayleigh [23] and Mie [24] particles but only for interfering plane waves. Since we used several Gaussian beams in the experiments, we modified the Barton’s method of the calculation of optical forces acting on bigger spherical objects [25] so that the final incident electric and magnetic field is done by the sum of electric and magnetic components of all Gaussian beams corrected up to the fifth order [26].

The numerical calculations are rather lengthy and so we calculated the forces in 3D cube consisting of 17 positions of \( r_1 \) between 0 and 1 \( \frac{\lambda_{\text{vac}}}{n \sin \psi} \), for five positions along \( r_2 \) axis between 0 and 1.5 \( \frac{\lambda_{\text{vac}}}{n \sin \psi} \) and for seven points along \( r_3 \) axis between −50 and 50 μm. Since the problem is completely symmetric or antisymmetric along \( r_1 \) and \( r_2 \) axes, the data were expanded to symmetric negative regions of \( r_1 \) and \( r_2 \). Finally, the interlaying data points were interpolated using splines.

4. Results

4.1. 2D trapping

We started our investigations with two-beam configuration. We observed that trapping occurred only if particles were quite close to the surface of the rear cover of the sample cell (the bottom coverslip in Fig. 3). That is ascribed to the fact that, under our experimental conditions, the axial field gradient was weaker than the radiation pressure exerted by both beams. Therefore, the particles were accelerated along the axis \( r_3 \) and collected on the rear cover slip.

We suppose that a similar trapping condition was also realized in the experiments described in [19,27], although that is not explicitly discussed. We could trap single particle or several particles and simultaneous confinement of four beads is shown in Fig. 3(b) (the laser power at the sample was \( P_1 = P_2 = 29 \) mW for each beam). We also succeeded in trapping of up to four beads into a single fringe aligned along \( r_2 \)-axis (not shown in figure).

By translating the sample in the lateral plane \( r_1r_2 \) we checked that these beads stayed at the intensity maximum of interference fringe. To characterize the IOT, we measured the maximum lateral forces acting on the trapped bead along \( r_1 \) and \( r_2 \) axes using the drag-force method. At this purpose, the sample stage was translated along positive direction of \( r_1 \) axis or reversed direction of \( r_2 \) axis at a given constant velocity \( v \). The trapped sphere was deviated from the centre of the fringe by the drag (Stokes) force \( F_s = 6 \pi \eta R v \) (\( \eta \) is the viscosity of the fluid surrounding the sphere and \( R \) is the sphere radius) and settled in a new equilibrium position where drag force was compensated by the optical force of opposite direction. The lowest velocity, when this equilibrium position is not established, is called the escaping velocity \( v_{\text{escape}} \) and it enables to quantify the maximal optical force via the maximal drag force \( F_{\text{max}} = 6 \pi \eta R v_{\text{escape}} \). In particular in Fig. 4 there are plotted the absolute values of optical forces measured along \( r_1 \) having latex beads in each fringe (\( P_1 + P_2 = 58 \) mW). As it was expected, the maximum forces were obtained in the central fringes \#3 and \#4 where the laser intensities are the highest and consequently their spatial gradients along \( r_1 \) axis are bigger, too.

We observed also proximity effect. After a certain time the trapped beads stuck on the surface. A direct consequence of the bead–surface interaction is the fact that the drag force balances the sum of the elastic optical force and the friction force due the surface proximity. In order to reduce this unwanted interaction we covered the coverslip with a teflon coating which considerably elongated the period (up to about one hour) of bead attaching.
We compared the experimental data with theoretical model but we had to take into account that these experimental results are presented in Fig. 4 in their absolute values. The correct sign of the experimental data has to be chosen with respect to the orientation of co-ordinate system and direction of the stage movement in our case negative. These are shown in Fig. 5 as circles. The full line corresponds to the theoretical profile of the optical force acting on sphere placed into Gaussian beams of the same parameters as in the experiment. Since the magnitude of the optical forces at any position along \( r_1 \) is nearly done by a product of sine function forming the fringes and Gaussian envelopes of each beam (see for example the first and principal term of Eq. (B.2) in [23]), the measured maximal lateral forces should roughly follow the Gaussian profile of the beams supposing they are of the same width. A beam waist of \( w = 3.4 \mu m \) was found from a fit of Gaussian to measured maximal optical forces showed as circles in Fig. 5. Together with optimal laser power in one beam equal to \( P_1 = 6.3 \) mW we obtained very convincing coincidence with the measured profile (see Fig. 5).

It should be noted that the fringes placed symmetrically with respect to the centre of the interference pattern do not exhibit the same force in experimental data and even in theoretical results. To understand this effect let us remind that this measured data were obtained only for unidirectional movement of the stage (along positive direction of \( r_1 \)) and that the interference fringes were created from Gaussian beams having their overlaid intensity maxima at the centre of the interference pattern (\( r_1 = 0 \) in Fig. 5). Therefore, the sinusoidal interference fringes are modulated by Gaussian envelope. The positive drag force pushes the sphere placed in negative region of \( r_1 \) (fringes \#2 and \#3 in Fig. 3) to the centre of the interference fringes (towards \( r_1 = 0 \)). But the same drag force pushes the sphere placed in positive region of \( r_1 \) (fringes \#4 and \#5) away from the centre of the interference fringes where, due to the Gaussian envelope, the optical forces are smaller.

It is worth to underline that since the trapping occurred close to the cell cover, the Stokes force should be corrected giving three times bigger values [28]. Therefore, the real optical forces acting on the object should be three times bigger, too. That is why the theoretical power has to be also three times higher \( P_1 + P_2 = 37.8 \) mW to obtain good overlap of the theoretical and experimental data in this case. However, this value still differs from the experimental one (58 mW). It is probably caused by the fact, that in reality the beams did not perfectly overlap.
We used the found beam waist to study the properties of maximal (minimal) optical forces along axis $r_1$ or $r_2$ which correspond to the stage movement along negative (positive) direction of $r_1$ or $r_2$ axis. We assumed the same two-beam configuration and analysed the forces as a function of the object position along $r_3$ axis. These results are plotted in Fig. 6. Subplot (a) shows how the maximal and minimal force $F_{r_1}$ depends on the position along $r_3$ axis. Experimentally this correspond to various positions of the trapping cell along $r_3$ axis. As it was mentioned above it is seen that even though the problem is symmetric along $r_1$ axis, the maximal forces in the symmetrically placed fringes are not the same (+ versus ○, or × versus *). As it could be expected from the symmetry of the fringes, we see that $F_{r_1\text{max}}(#3) = -F_{r_1\text{min}}(#4)$ and $F_{r_1\text{min}}(#3) = -F_{r_1\text{max}}(#4)$. The same is valid for fringes #2 and #5. From subplot (b) we find that for $r_2$ axis similar relations hold: $F_{r_2\text{max}}(#3) = -F_{r_2\text{min}}(#3) = F_{r_2\text{max}}(#4) = -F_{r_2\text{min}}(#4)$ which are valid even for fringes #2 and #5. Subplot (c) shows how the positions $r_{1\text{max}}$ and $r_{1\text{min}}$ (where the extremal forces $F_{r_1}$ were found) and equilibrium position $r_{1\text{eq}}$ (where the extremes of $F_{r_2}$ were looked for) changes along $r_3$ axis. These changes are less than 100 nm for central fringes (#3 and #4) and less than 200 nm for peripheral fringes (#2 and #5).

Fig. 7 shows how the ratios of extremal forces along $r_1$ and $r_2$ axes $F_{r_1\text{max}}/F_{r_2\text{max}}$ and $|F_{r_1\text{min}}/F_{r_2\text{max}}|$ in each fringe depend on the position along axis $r_3$. Again we find that the symmetrically placed fringes have the same ratios but with interchanged role of $F_{r_1\text{max}}$ and $F_{r_1\text{min}}$. We see that these ratios as a function of $r_3$ change more in peripheral

![Fig. 6](image-url)
fringes #2 and #5 and less in central fringes #3 and #4.

We also compared the optical forces measured along positive direction of \( r_1 \) axis (\( \text{IOT} F_{r_1} \)) and reversed direction of \( r_2 \) axis (\( \text{IOT} F_{r_2} \)). In particular, Fig. 8 (left part) shows the behaviour of such forces as a function of the total laser power \( P_{\text{IOT}} = P_1 + P_2 \) for the fringe #4. As expected, \( \text{IOT} F_{r_1} > \text{IOT} F_{r_2} \) since the optical gradient is larger along the nodes–anti-nodes line. Using data from Fig. 8 we get \( \frac{\text{IOT} F_{r_1}}{\text{IOT} F_{r_2}} = 3.4 \). The corresponding theoretical results presented in Fig. 7 gives for \( \frac{|F_{r_1\text{min}}/F_{r_2\text{max}}|}{r_3} \approx 4 \). Since we found convincing coincidence between experimental and theoretical values of \( F_{r_1\text{min}} \) (see Fig. 5), we conclude that the experimental beams had elliptical beam profile with smaller beam width along \( r_2 \) axis or the beams along \( r_1 \) did not overlap perfectly. This would provide bigger \( F_{r_2\text{max}} \) and smaller ratio \( F_{r_1\text{min}}/F_{r_2\text{max}} \).

For comparison in the left part of Fig. 8 (line c) is also reported the behaviour of the optical force measured along the axis \( r_2 \) with a single laser beam (single beam tweezers, SBT). In this case, one of the interfering beams was blocked while the laser power was increased so that the forces measurements were performed with the same incident power as in the presence of two beams (\( P_{\text{SBT}} = P_{\text{IOT}} = 2P_1 \)). From Fig. 8 we get for the ratio of \( \frac{\text{IOT} F_{r_1}}{\text{SBT} F_{r_2}} \approx 2 \). Since the laser intensity in the interference maximum of 2 beams (IOT) is four times higher than the intensity of the single beam and in SBT we used single beam with 2 times higher intensity, this result is quite consistent with our expectations.

Fig. 7. Dependence of the absolute value of the ratio of maximal forces \( |F_{r_1\text{max}}/F_{r_2\text{max}}| \) in each fringe. Since the problem is symmetrical the ratios for both peripheral (#2 and #5) and both central (#3 and #4) fringes are the same but only the role of \( F_{r_1\text{max}} \) and \( F_{r_2\text{max}} \) is interchanged.
4.2. 3D trapping

In order to get a 3D confinement we introduced a third counter-propagating beam according to the geometry shown in Fig. 1. The power $P_3$ of the beam No. 3 was varied to a proper value to balance the radiation pressure acting along $r_3$. For instance, keeping $P_1 = P_2 = 10$ mW, we found experimentally that this balancing condition was achieved for $P_3 \approx 38$ mW.

Fig. 9 proves the experimental 3D confinement. Four frames correspond to different distances of the trapped bead (indicated by the arrow) from the rear cover that were reached using the piezoelectric translator moving the sample cell along $r_3$ axis. The frame 1 shows the trapped bead near the coverslip together with another bead stuck to the surface. The subsequent frames 2 and 3 show the trapped bead in axial positions more distant from the coverslip (now the stuck bead is not focused). Frame 4 shows the situation when the motion of the piezoelectric translator was reversed and the sample cell was moved back toward the initial position (the original stuck bead became again visible).

Similarly to the case of 2D IOT, we measured the maximum lateral trapping forces in 3D IOT configuration for both $r_1$ and $r_2$ directions. In 3D case, the trapped bead was approximately kept in the middle between the cell covers, i.e., about 25 µm from the surfaces, and therefore surface...
proximity effects are negligible. The measured forces as a function of the total laser power $P_1 + P_2$ are shown in the right part of Fig. 8 for a bead confined in the fringe #4. If we compare the forces measured in 2D and 3D IOT shown in Fig. 8, we find that for a given laser power the forces measured in 3D traps are slightly larger than those obtained in 2D traps (for both $r_1$ and $r_2$ axes). This can be explained by the contribution of the force coming from lateral intensity gradient of the third beam.

Fig. 10 shows the directions of optical forces in $r_1r_3$ and $r_1r_2$ planes, equilibrium positions of the spherical particle, and the places of zero forces $F_{r_1}$ (top and bottom, dashed line), $F_{r_2}$ (bottom, full line), and $F_{r_3}$ (top, full line). Intersections of these dashed and full curves determine the stationary points. But only those of them become equilibrium points where the forces push the object back if deviated from this equilibrium position. These positions – optical traps are marked by bigger and smaller black circles in the top figure. It is seen that the peripheral traps are located at different $r_3$ positions. This plot could help us to understand what will happen if the drag force is applied along the direction of $r_1$ axis (similarly as in the experiment). In this case the full lines (showing the places of $F_3 = 0$) will stay at the same positions but dashed lines will be moved along the positive direction of $r_1$. Therefore, new equilibrium positions are established at the intersections of both types of curves. The originally symmetrical arrangement of the optical traps in central and peripheral fringes is lost and they will be localized

Fig. 10. Theoretical simulations showing the positions of optical traps, direction of relevant forces (arrows) and positions of zero values of forces $F_{r_1}$ (top and bottom, dashed line), $F_{r_2}$ (bottom, full line), $F_{r_3}$ (top, full line). Lighter regions correspond to the places of higher intensities.
at different positions not only along $r_1$ axis but also along $r_3$ axis. From this example it is seen that meaningful comparison theory with experiment needs measurements of 3D positions of the trapped particle. Unfortunately this have not been done in our experiments and therefore in this article we could not provide reasonable comparison. The two lower figures show the cross-sections of the situation at both equilibrium positions along $r_3$ axis (the left section for central fringes and the right one for peripheral fringes). Despite the fact that in these sections we could find more equilibrium positions than the marked ones, they would not be the equilibrium points along $r_3$ axis.

5. Conclusion

In this article, we have reported the first experimental quantification of optical forces acting on polystyrene particles of diameter 1.01 μm placed into so-called interferometric optical tweezers which was created by two interfering laser beams. Using the viscous-drag method we measured the maximal optical forces acting on a particle two-dimensionally confined (pushed against the coverslip in the third dimension) in each of six interference fringes. These forces were compared with the theoretical model which gave reasonable coincidence with the measurement if the same beam waists and laser powers in both beams were used as the only free parameters. At the same time this article presents also the first experimental demonstration of 3D optical tweezers using the interference pattern generated by three-beam interference and the first theoretical predictions about the behaviour of the confined object under influence of drag force.

This technique is suitable to trap and manipulate two or more symmetrical particles, moreover, if the interference pattern is rotated, confined elongated particles start to rotate as well. If the three beams had the same polarization, this three-beam geometry would provide several equilibrium conditions along the axial direction and a planar optical lattice of three-dimensional optical tweezers could be realized in this way.

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