Self-rotation of an assembly of two or more cylindrical objects in optical tweezers: A simple approach for realization of optically driven micromotors

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We show that an assembly of two or more cylindrical objects rotates by itself when trapped in conventional optical tweezers. The rotational speed and direction of rotation were observed to depend on the asymmetry of the structure, and for a given structure the speed was found to increase linearly with increase in the trapping beam power. A ray optic model was also developed for the assembly of rods. Its predictions on the direction of rotation and the optical torque on the assembly were in qualitative agreement with the experimental observations. Such an assembly of rods may provide a convenient and dynamically reconfigurable approach for optically driven micromotors.

**Keywords:** Microfluidics, micromotors, optical trapping, optical tweezers.

There exists considerable interest on the development of optically driven micromotors as these could be driven remotely by laser beams and thus could play an important role in various microfluidic applications. A variety of methods have therefore been developed for rotation of optically trapped objects. One approach actively pursued towards this objective is to fabricate structures that experience windmill-type torque by transfer of linear momentum from the trapping beam and thus rotate. However, fabrication of such special structures is complicated and costly, and may limit the use of this approach. We show in this communication that an assembly of two or more cylindrical objects provides a convenient and dynamically reconfigurable approach for optically driven micromotors. Further, the individual rods can be transported through narrow channels (with width smaller than the size of the micromotor), either by microfluidic flow or by laser tweezers to the desired location where they can be assembled to construct micromotors and dismantled after use. We also describe a ray optic model for the assembly, which accurately predicts the direction of rotation as well as dependence of the torque on the asymmetry of the structure.

We used a conventional inverted optical tweezers setup for studies on the dynamical behaviour of an assembly of cylindrical rods when subjected to a trapping beam. The output of a 1064 nm, TEM_{00} mode, cw Nd : YAG laser (Solid State Laser Division, Raja Ramanna Centre for Advanced Technology, Indore, India) was coupled to a 100X/1.3 microscope objective (Carl Zeiss GmbH, Jena, Germany) and used as the trapping beam. The sequence of digitized images, acquired using a CCD camera and frame-grabber, was used for studying the dynamical behaviour of the assemblies of micro-rods. To prevent the backscattered laser light from reaching the CCD detector, an IR cut-off filter was used. The laser beam power was measured at the back aperture of the microscope objective using a power meter (Coherent Inc., USA). The trapping beam power at the sample plane was estimated using the transmission factor of the objective (57%) that was determined using the dual objective technique described by Misawa et al. The glass rods (Nippon Electric Glass Co Ltd, Japan) used in the study had diameter of \(-5 \mu m\) and lengths varying from 10 to 30 \(\mu m\).

It is known that when placed in a point optical tweezers, a cylindrical rod gets aligned along the axis of
the laser beam that is normal to the plane of the micro-
scope stage. The behaviour of an assembly of two similar
rods when trapped simultaneously in the same trapping
beam (120 mW) is shown in Figure 1. As can be seen in
Figure 1, one of the two rods (marked by arrow) gets ori-
ented along the axis of the laser beam and the other rod
remains almost horizontal and rotates in the clockwise di-
rection about the rod aligned along the laser axis. Figure
2 shows the variation of rotational speed of this rod as-
sembly as a function of the trapping beam power. The ro-
tational speed was observed to increase linearly with a
slope of ~1.50 rpm/mW.

It is pertinent to note that the assembly of two cylindri-
ical rods placed in the same trap beam, shown schematically
in Figure 3a, results in a structure that resembles one of
the four arms of the structure investigated in detail by
Higurasi et al.7 and Gauthier9. In conformity with their
analysis, the origin of the torque in the present assembly
appears to arise due to asymmetry of the structure (the
two long sides of the horizontally placed cylinder not be-
ing symmetrical with respect to the rod trapped vertically
along the laser beam). An exact modelling of the torques
induced by the trapping beam on the assembly of two cy-
lindrical objects will be complicated. In order to keep the
simulation simple, we ignored the effect of the vertically
oriented rod on the propagation of the trap beam and used
the theoretical model developed earlier by Gauthier et al.9–11 to estimate the torque on the horizontal cylindrical
rod as a function of its position with respect to the trap
beam focal point. Following Gauthier9, the z-axis directed
TEM00 unpolarized Hermite–Gaussian laser beam can be
treated as a stream of photons, which are made incident
on the cylindrical object. As the photon undergoes reflection
and refraction at the point of incidence, there is a transfer
of momentum. If \( l_i, m_i, n_i \), \( l_r, m_r, n_r \) and \( l_t, m_t, n_t \) are
the direction cosines for the incident, reflected and re-
fracted rays, the momentum transferred to the object from
the reflected photon is:

\[
\frac{h n_r}{\lambda} \{ (l_i - l_r) \hat{x} + (m_i - m_r) \hat{y} + (n_i - n_r) \hat{z} \}. \quad (1)
\]

and from refracted photon is:

\[
\frac{h n_t}{\lambda} \{ (l_i - n_{rel} l_i) \hat{x} + (m_i - n_{rel} m_i) \hat{y} + (n_i - n_{rel} n_i) \hat{z} \}. \quad (2)
\]

Here \( \lambda \) is the wavelength of the trapping laser beam in
vacuum, \( h \) is the Plank constant and \( n_{rel} = n_2/n_1 \), where \( n_2 \)
is the index of refraction of the object and \( n_1 \) that of the
ambient medium. Thus the total force exerted by all the
photons reflected or refracted at the interface of the cyl-
inder and ambient medium can be written as:

\[
F = \sum F_i = \sum N_i \{ R_{avg} \frac{h n_i}{\lambda} \{ (l_i - l_r) \hat{x} + (m_i - m_r) \hat{y} + (n_i - n_r) \hat{z} \} + (1 - R_{avg}) \frac{h n_i}{\lambda} \{ (l_i - n_{rel} l_i) \hat{x} + (m_i - n_{rel} m_i) \hat{y} + (n_i - n_{rel} n_i) \hat{z} \} \}. \quad (3)
\]

\( N_i \) is the number of photons per second incident at the
point centred on the ith elemental area of the rod, and
\( R_{avg} \) is the average of the reflection coefficients (calcula-
ted using Fresnel formula) for the two orthogonal polariza-
tions (TE and TM) of the laser beam. The summation is
over the entire elemental area of the rod. It is known that
a cylinder placed in a laser trap localizes such that its
overlap with the high-intensity region is maximized.
Therefore, for the two-rod assembly, one of the rods
aligns along the trap beam and the other will try to orient
about this rod such that it also maximizes overlap with
the region of high intensity. The experimental results
(Figure 1) suggest that the second rod is almost horizon-
tal. Therefore, to keep simulation tractable, we assumed
the other rod to be exactly horizontal. The torque on the
horizontal rod as a function of its position in the XY-
plane can be calculated as:

\[
\tau = \Sigma (\hat{\tau} \times d \hat{F}). \quad (4)
\]
Figure 3. a. Schematic of side view of the cross-section of the two-rod assembly. Solid circles show the vertical position of the horizontally placed rod where the whole width of the rod interacts with the beam. Dashed circles show the closest position of the horizontal rod in the Y-direction. b. Estimates for torque on the horizontally placed rod (L = 15 µm), when the axis of the rod was 4 µm above the plane of focus. Trap beam power was taken to be 120 mW. Torque was calculated only for the positive displacement (from 2.5 to 6 µm in the Y-direction) of the centre of the cylinder with respect to the beam.

Here $r_i$ is the radial distance of the $i$th element from the origin (centre of the beam waist) and $dF_i$ is the force on this element. Since at $Z = 0$, the rod will have negligible interaction with the trap beam, it has to be located at a plane above or below $Z = 0$. As we move vertically up/down in the Z-plane, the interaction of the rod with the beam emerging out of the vertically trapped rod increases. A simple calculation shows that the whole width of the rod in transverse direction interacts with the trap beam at a plane located at $\pm 6$ µm from the focal plane. This is shown in Figure 3a by solid circles. However, the intensity of the trap beam decreases rapidly as we move away from the focal plane. The stable trap position for the rod is, therefore, expected to be in the region lying between planes $Z = 0$ µm and $Z = 6$ µm. Our experimental results suggest that this was $\pm 4$ µm. We therefore calculated the torque acting on a horizontally placed rod (radius: 2.5 µm and length: 15 µm) at a plane 4 µm above the plane of focus. For a laser beam power of 120 mW, the results are shown in Figure 3b. Since the horizontal rod cannot come closer than 2.5 µm (shown by dashed circles in Figure 3a) in the Y-direction due to the presence of the vertical rod, the lower Y-limit of calculations was kept at 2.5 µm. A perusal of Figure 3b shows that the torque on the rod is zero when it is placed symmetrically with respect to the centre of the beam waist and increases in magnitude as the asymmetry of the assembly increases by displacement of the rod in the X-direction on either side. Further, it is important to note that the sign of the torque changes in (+) and (–) X-quadrants, suggesting that the displacement of the horizontal rod in (+) or (–) X-direction from the beam waist determines the sense of rotation. This is consistent with the experimental results presented in Figure 1.

The dynamics was even more interesting when two rods of unequal lengths were trapped. The behaviour of an assembly of two unequal rods trapped simultaneously in the same trapping beam (80 mW) is shown in Figure 4a–f. In this case, it was observed that the bigger rod was always aligned along the laser beam axis even if at first the smaller rod was so aligned. To understand this, we would like to point out that in case of a single trapped rod, the equilibrium is obtained only when the rod is aligned along the trap beam. In such an orientation, the effective potential energy of the rod inside the trap is minimized as it ensures maximum overlap of the rod with the trap beam. Using the same arguments, we believe that in case of a two-rod assembly, aligning of the longer rod with the trap beam axis ensures minimization of potential
An assembly of more than two cylindrical rods shows even richer dynamics. When two additional rods were trapped near an already trapped and aligned rod (marked by arrow), such as a red blood cell (RBC), was used to monitor the flow direction and rate. The drag forces induced by the rotating assembly caused the rod to change direction in the surrounding medium to follow a circular path. From the movement of the tracer object (RBC, assuming to be a disk of diameter ~8 μm and width ~3 μm), the fluid flow rate induced by rotation of a two-rod assembly was found to be ~5 nl/h.

To conclude, we have shown that an assembly of two or more cylindrical rods rotates when trapped by optical tweezers. Such an assembly of rods may provide a convenient and dynamically reconfigurable approach for optically driven micromotors.


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