Orientation and rotation of trapped microparticles in optical tweezers

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Introduction

The dynamic evolution and wide spreading of microtechnology and optical micromanipulation took place in the last two decades and the progress is continuous. The driving forces behind microfabrication are the peculiar properties arising from the small size while the possibility of convenient noncontact manipulation by light (which can be used simultaneously with traditional microscopy) offers great prospects. The combination of these two techniques promises numerous possibilities and a bright future can be envisioned both for the scientific research and applications. We think that our work can contribute to the progress in this direction.

The work on biological, biomedical microdevices has a great importance. Such structures can promote basic science and they could contribute to applications in medical diagnosis, too. One of the most complicated and most intensely studied area is called "lab-on-a-chip”. The expression stands not only for complex microscopic devices capable of performing complete analytical and diagnostical tasks but also for the theory of their function and the technology for producing them.

Such microdevices have several advantages: very small sample quantity is required, single particles (cells, bacteria, or macromolecules) can be studied, and several analytical steps can be performed parallel when using many copies of a device at the same time.

Optical micromanipulation proved to be an effective method for studying microscopic objects. Laser tweezers can fix or move microparticles by the phenomenon of optical trapping. The trap is formed by a focussed laser beam with high numerical aperture. The interaction of the beam and a microscopic body results in forces that pull the particle towards the focal point where it becomes trapped. External forces acting on a trapped particle change its equilibrium position. By measuring the position change the magnitude of the external force can be determined. This makes optical tweezers suitable for measuring forces in the 1 pN – 100 pN range.

Bringing together microtechnology and optical micromanipulation seems to be a plausible goal. The magnitude of forces and torques required by moving micromachines makes direct optical driving possible. However, until now small effort and progress was made in this direction.

Our work is partly the utilization the above-mentioned possibility. In addition, our results show that optical tweezers can be used for more complex and comprehensive studies than before.

The following questions can be answered based on our studies:

Is photopolymerization suitable for producing microparticles on which the impact of the shape on the behaviour in the optical trap can be studied?

How is it possible to precisely control the orientation of a trapped particle in optical tweezers? How can we model the phenomenon quantitatively in a simple way?

Does it offer a possibility to measure external torques exerted on the trapped microparticles?

Certain bodies tend to rotate when grabbed by laser tweezers. What is the origin of this phenomenon? What is the relation between the shape of the body, the power of the trapping beam and the characteristics of the rotation? What is the magnitude of the torque exerted by the light?

How is it possible to control the rotation direction of the light driven microrotors? What simple model can explain the phenomenon?

Can the light driven microrotors be used as power sources (engines) of mechanical microdevices?

Methods

Among the various experimental and data analysis methods we used perhaps the photopolymerization based microfabrication technique is the most remarkable.

Photopolymers are clear viscous liquid mixtures of various chemicals that undergo polymerization (solidification) upon illumination.

Curing the material with a strongly focussed beam of proper wavelength and power results pinpoint solidification at the focal point. By moving the sample arbitrary three dimensional shapes can be "drawn" into the photopolymer. Appropriate organic solvents dissolve the unpolymerized fraction while the cured shapes remain intact.

We used the Norland NOA 63 commercial optical adhesive as photopolymer. We cured the material by a focussed 514 nm beam of an Ar-ion laser. The focusing was done by a high numerical aperture microscope objective. The desired shape was drawn by computer controlled movement of the sample with submicron precision.

The microscopic objects produced by this method were suitable for subsequent studies using optical tweezers.

Results

1. We studied the orienting effect of optical traps made by linearly polarized laser beam. We showed that elongated particles always assume a position in the trap parallel to the direction of polarization. This "angular trapping" offers a possibility to control the orientation of various biological objects, too. We successfully manipulated chloroplasts and chromosomes by this method. (I.)

2. We determined how the relative position of a cross shaped test particle and the polarization affects the orienting torque exerted by the trapping beam. We worked out a suitable measurement principle. Rotating the polarization direction by a spinning half-wave plate caused the rotation of the trapped body with the same speed. However, a phase shift emerged due to drag. Calculating the latter gives the magnitude of the torque originating from the light beam. Performing the measurement at different rotation speeds made it possible to determine the dependence of the light torque on the relative orientation of the particle with respect to the polarization. (I.)

3. We performed simple model calculations in order to explore the physical processes behind the phenomenon. We used raytracing to track a large number of

individual rays of the laser beam to calculate the torque emerging from the interaction of the rays with the trapped particle. The polarization effects were considered through the Fresnel formulae. The results agreed well with the measurement data. New methods can be designed based on our work by which it is possible to measure or exert microscopic torques on the trapped objects. Investigations on the torsional properties of giant biomolecules (e. g. DNA) can be realized this way. (I.)

4. We studied the spinning of different shapes in the optical trap. The rotation was a consequence of the mechanical interaction between the trapping light and the trapped body. The shape of the latter determined the characteristics of rotation. The helicity present in the case of the helices and the propellers is the origin of the spinning. The rotation of spinklers was traced back to the component of the momentum current perpendicular to the optical axis. In all cases we found a linear dependence of the rotation speed on the laser power. At constant power the propeller proved to be the most effective rotor and the spinkler turned to be the most ineffective one. (II., IV.)

5. We also studied the rotation rate for different helix sizes. The results showed that the period of rotation scales with the inverse square of the diameter. We explained this behaviour with simple arguments. (II.)

6. We gave a rough estimate of the torque exerted on the propeller by the laser beam for the highest rotation speed observed. The torque turned to be in the order of 10^{-17} Nm. This result is in agreement with the data found in the literature for

other particles and rotational mechanisms and points towards possible applications. (IV.)

7. It can have a great importance to be able to control the rotation direction of a micropropeller. To achieve this property we designed a light driven microrotor that is rotated by the momentum current components perpendicular to the optical axis. We showed that a body with arms following the line of a 45° logarithmic spiral is ideal for our purpose. Further design considerations ensured that the arms were positioned on one side of the focus (closer to the objective, here the beam converges) upon trapping. The rotor spinned in one direction. By lowering the objective the particle was pushed against the microscope coverslip and changed its position to the other side of the focus (where the beam diverges). The rotation direction reversed. This was caused by the fact that the relevant momentum current components were opposite on the two sides of the focus. We also measured the rotation rate at different positions of the particle with respect to the focal point. (III.)

8. We made calculations the results of which were compared to the measurement data. We used raytracing to calculate the relative magnitude of the torque exerted by the beam on the trapped rotor. We made qualitative comparison to the measurement data and a satisfactory agreement was found. (III.)

9. We performed experiments to prove if the light driven rotors can be used as the power source for microscopic size mechanical machines. We produced several cogwheel-like structures that were able to rotate freely around an axis fixed to the

coverslip surface. The propeller was trapped by the optical tweezers and we engaged it with the cogwheels. It was able to rotate the passive structures, the gearing worked, the machine functioned. We realized this in different configurations: the trapped rotor was able to rotate one or two cogwheels via direct coupling or the propeller moved a gear indirectly through an intermediate one. The systems worked well in all cases. (IV.)

Publications related to the thesis:

I. Galajda P., Ormos P., Orientation of flat particles in laser tweezers by linearly polarized light *manuscript* (2002)

II. Galajda P., Ormos P., Rotation of microscopic propellers in laser tweezers
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III. Galajda P., Ormos P., Rotors produced and driven in laser tweezers with reversed direction of rotation
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