Simulation and optimization of the trapping efficiency in optical tweezers

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The system integration of optical tweezer setups introduces restrictions in terms of laser power and available space or demands extended working distances and trapping under special conditions. We present a simulation tool and design considerations for integrated optical micromanipulation.

1 Introduction

Under laboratory conditions many ways for optical manipulation have been demonstrated. However in many real life applications in microfluidics, certain design criteria need to be kept in mind. Many microfluidic chips, for instance, require channel thicknesses for mechanical stability which exeed the working distances of the common tweezing setups. While it is quite convenient to use off-the-shelf components it becomes nescessary to develop elements to achieve new functionalities in optical micromanipulation. The goal of our work is the design of tweezing setups which maintain the characteristics of laboratory setups in field test conditions.

2 Optical manipulation

Optical forces are a widely known phenomenon. These forces result from the momentum transfer of light during the interaction with microscopic particles. In highly focused laser beams a stable 3D-equilibrium of the optical and gravitational forces can be achieved. For the calculation of these forces severel mathematical models have been developed [1]. The determining parameter for the validity of these models is the size of the considered particles. The forces acting on large particles (d»λ) can be calculated in the geometric optics domain. The total force contribution of a single ray is the result of several interactions of the beam with the surface of the microparticle.

$$d\vec{F} = \frac{n}{c} dP \cdot d\vec{Q} \tag{1}$$

The efficieny of the force generation is given by the local efficieny factor dQ which mainly depends on the angle of incedence of the ray on the particle. The local efficiency factor takes into account the Fresnel coefficients and the refractiv indices of the particles and the surrounding media.

3 Simulation Tool

For the qualitative studies and comparison of arbitrary trap geometries, we have developed a raytracing simulation tool in Matlab®. We assume rather large biological specimen, therefore the geometrical optics approach gives a good approximation of the real behaviour of the trap [2]. The software allows to simulate arbitrary intensity fields. Effects like abberations can be simulated by adjusting the initial vectorfield which represents the intensity profile. To this end the corresponding wavefront needs to be sampled adequately. The simulation tool provides the calculation and visualization of axial and lateral trapping forces. It is possible to plot the local efficiency factor dQ for each ray in order to study the effects of deliberate modifications of the trap geometry. Absorption and polarized light can not be simulated yet, but the implementation of these options has been prepared during the software design

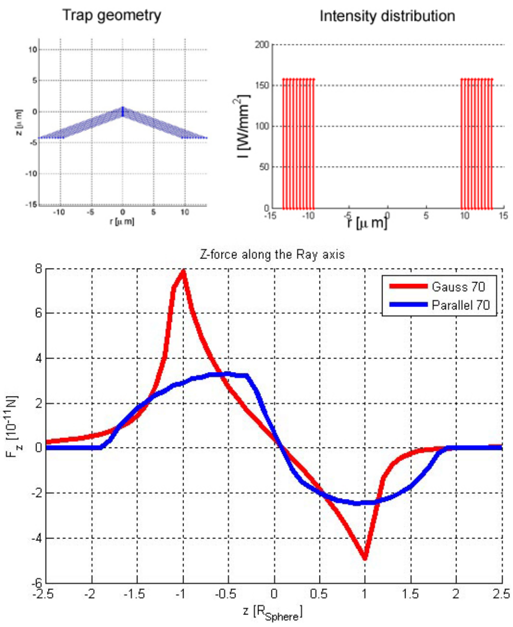

Fig. 1 *Comparison of two different trapping geometries. The red curve represents the axial force distribution of a standard Gaussian trap. The blue curve shows the result for the simulation of a ring illumination with parallel rays. With the same total laser powers in both disributions, the parallel ring trap shows a smaller maximum power but a higher slope (stiffness) around the equlibrium and an extended attracting force*

4 Trap geometries

While the efficiency of the entire intensity distribution Q has been used in many papers, we also look at the local efficiency factors dQ. This allows a separate investigation of geometries and opens up a new way of tailoring intensity fields for optical manipulation. In very good agreement with values given in [2], the simulations of uniform and doughnut intensity distributions show higher trapping efficiencies. It is interesting to see, that the axial force curves are quite similar as long as the geometry is maintained and only the intensity is changed. Other geometries show different behaviour which is depicted in Fig. 1 for a ring illumination where all rays have the same angle towards the optical axis and the same intensity. The motivation for simulating such an exotic geometry was the question if it is possible to extend the axial trapping region. In this intensity distribution rays of the highest local efficiencies hit the particle at different locations along the optical axis. It can be seen, that the region of attracting the forces becomes larger at the cost of the maximum force dropping to about a third of force of the Gaussian beam.

5 System optimization

As mentioned in the introduction, the main objective of this work is the analysis of influences on the trapping forces and the optimization of the total system efficiency. To this end all components of the tweezing setup need to be examined. As an example the focusing unit of a tweezing setup is discussed. It is known that shifting the laser power in the high angles of the objectives increases the efficieny of the trap. In practice this is realized by increasing the waist of the laser beam up to two times the diameter of the objective's entrance pupil [3]. This way the beam profile is flattened. However, the laser power used for trapping decreases when the overfilling factor is increased. The result (Fig. 2) of these opposing parameters is an optimum which suggests that it is best to choose an overfilling factor slightly below unity.

The forces for hollow doughnut mode beams were simulated as well. The resulting curve showed 24% higher trapping forces in axial direction. So if the conversion of a Gaussian beam to a doughnut mode can be achieved with losses smaller than 24% an improved system efficiency is achieved.

6 Conclusion

We have developed a tool which allows the calculation and qualitative comparison of optical forces of arbitrary optical trap geometries. It is very instructional to study the design of special intensity distributions in order to achieve a desired trap behaviour. However, for the design of integrated optical tweezers it it seems to be more target-oriented to focus on the optimization of the experimental setup itself. The fact, that the usual optical components such as microscope objectives are not optimized for optical trapping opens up a field for new specialized designs.

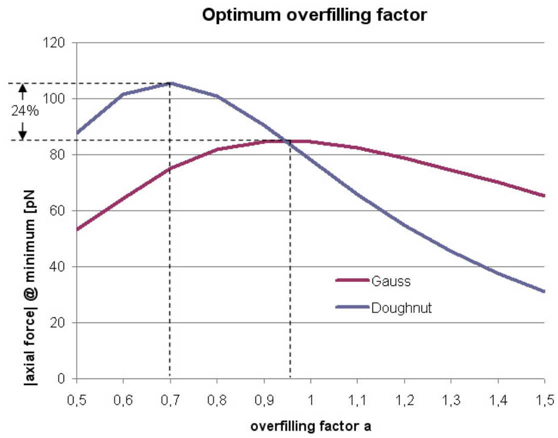

Fig. 2 *Optimal usage of avialable laser power for different overfilling factors* $a = \omega_0/d_{pupil}$*. The source delivers constant power. With increasing overfilling, the fraction of entering the focusing optics decreases. The graphs show a force maximum for overfilling factors below 1 and 24% higher forces for a doughnut mode*

7 References

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