Lab Practice
Karlsruhe Institute of Technology

The Optical Tweezer

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Contents

1 Experiment & Discussion

In this section we describe the experimental setup as well as the experiments that were conducted during the lab course. After finding the correct focus to ensure proper trapping of the spheres, we experimented with the optical trap to gain a better understanding of the trapping process. After that we analyzed the brownian motion and calculated the maximum trapping force.

1.1 Experimental Setup

The setup that was used is illustrated in Figure 1. The light from a simple high power diode laser ($\lambda = 638\,\text{nm}, P = 25\,\text{mW}$) is collected by a condensor lens (not in the image) and is then shaped by a telescope setup consisting of two lenses with different focal distances. The telescope is used to match the beam diameter to the aperture of the objective, hence utilizing the high numerical aperture and providing the strongest focus. The beam is then redirected by two plane mirrors. These mirror are not essential for the working principle, but their adjustment allows a much easier alignment of the setup. After passing the mirrors, the beam is divided by a beam splitter and reflected towards the objective. The objective focuses the beam into the sample that is mounted on a motorized translation stage. The stage controls all transverse motions (x,y and z- axis) and can be controlled using a simple software on the computer. The sample itself consists of a special microscope slide with a little reservoir that contains an emulsion of small latex spheres and that is sealed with a thin cover slip. An LED light source is used as a compact and intense back light. With this light source, the setup acts as a standard microscope. The white light that is scattered and refracted by the sample is imaged by the objective onto a CCD camera. Due to the high intensity of the laser beam, a red filter is used to attenuate the wavelength of the laser.

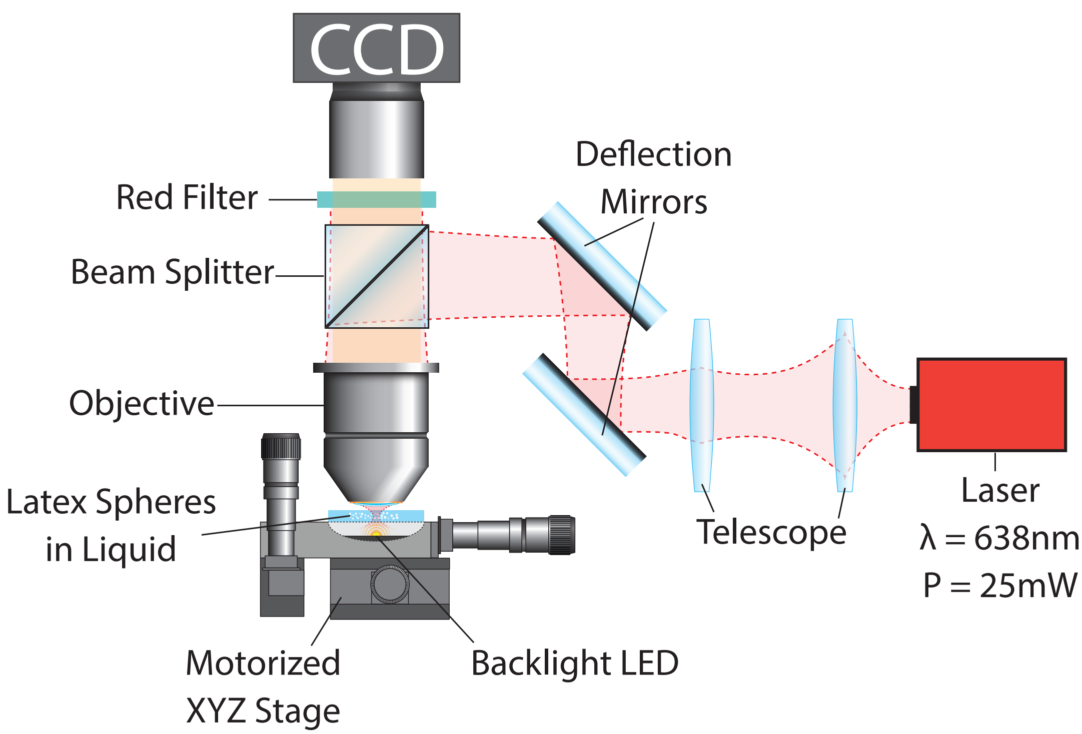


Figure 1: Experimental setup for simple optical trapping experiments.

1.2 Finding the Correct Focus

Before finding the focus plane, the sample slide was prepared. First of all, a droplet of the sample solution was dropped using a burette into the circular area located in the center of the microscope slide. Secondly, a cover slide was put onto the microscope slide starting from one side. Lastly, four corners of the cover slide were pressed against the microscope slide in order for the sample droplet to spread over the circular area of interest. It should be noted that the sample solution should not reach the edge of the cover slide thus not generating a flow which could tamper with the Brownian motion of the particles.

The sample slide was then mounted onto the positioning stage below the microscope objective. To find the focal plane, we moved the sample slide towards the objective from an initial position distant from the objective while observing the CCD image on the monitor. A bright image of the laser spot was firstly observed due to the reflection on the upper surface of the cover slide. The lower surface of the cover slide would not generate a bright reflection as the refractive index difference between the cover slide and the sample solution was not significant enough. The second focal spot image was observed when the laser spot hit on the sample. Meanwhile, clear image of the sample beads could be observed on the monitor indicating the focus was at the correct height, as shown in Fig. 2. As the focus plane was very close to the objective, extreme caution must be taken while positioning the stage as not to break either the slide or the objective.

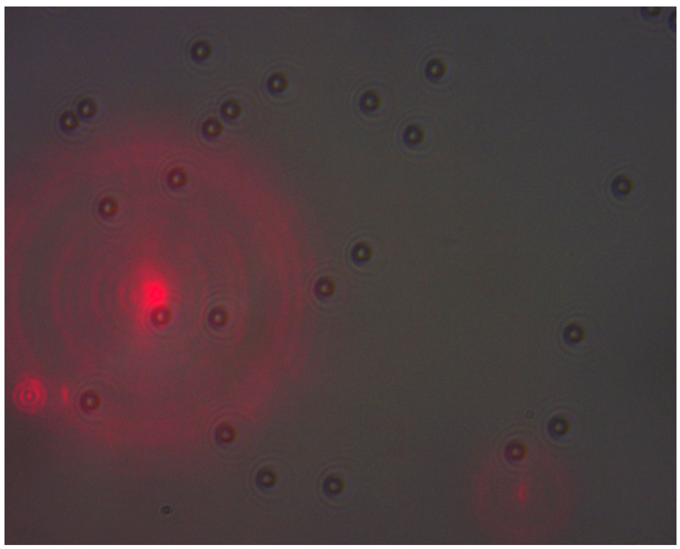


Figure 2: Image of focal plane

1.3 Simple Optical Trapping

After the focal plane was found, the focal spot of the laser could be used to manipulate sample beads. By moving the stage, we moved the target bead towards the focal spot. The the bead was close enough to the laser focal spot, it seemed as if being suched into the focal spot and thus was trapped. After getting trapped, the beam would stay inside the focal spot as long as the sample was moving below a certain maximum speed and the bead did not hit any obstacles (another beam or dust in the solution).

1.4 Brownian Motion

Brownian motion refers to the random moving of particles which are suspended in a fluid (a liquid or a gas) due to their bombardment by the fast-moving atoms or molecules in the gas or liquid [1].

To study the Brownian motion of the sample solution, two video clips targeting different areas were recorded using the camera software. From the video clips, totally six particles were chosen to be analyzed. Positions of these particles were traced, generating an average mean square displacement of the particle as a function of time.

In order to obtain the conversion factor between pixel number and length, we chose a large stationary dust in the sample as a reference. By moving it from one side of the monitor screen to another, which correspond to 1024 pixels, we recorded a distance of 0.3452 mm - 0.2468 mm = 0.0984 mm.

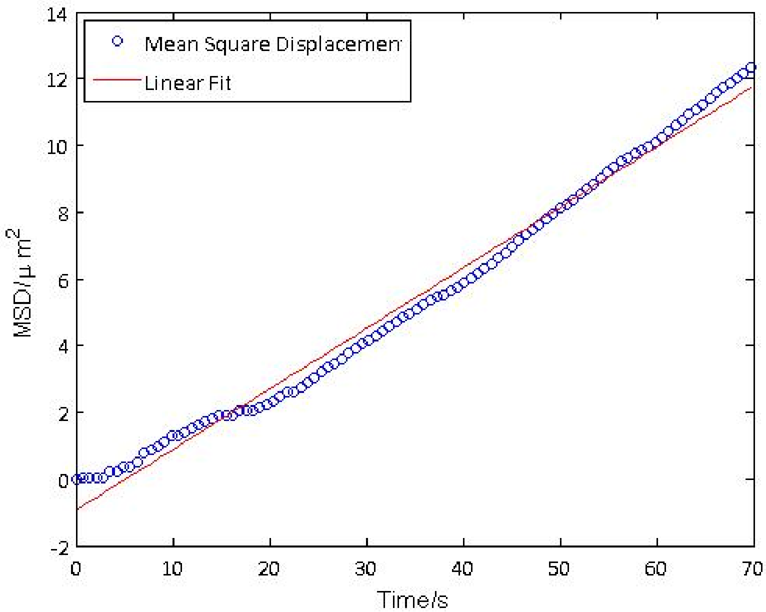


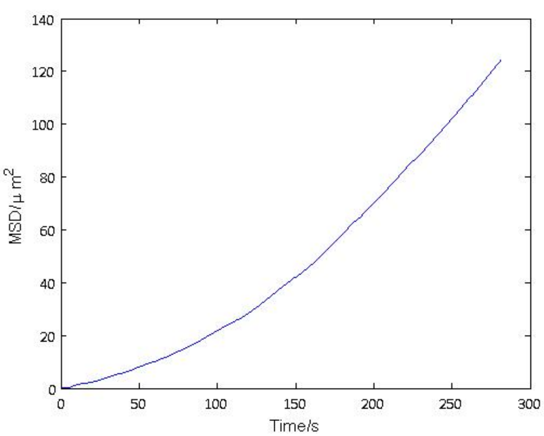
Figure 3: Mean Square Displacement as a function of time.

As illustrated in Fig. 3, the mean square displacement grows linearly with time. The linear fitting can be expressed as:

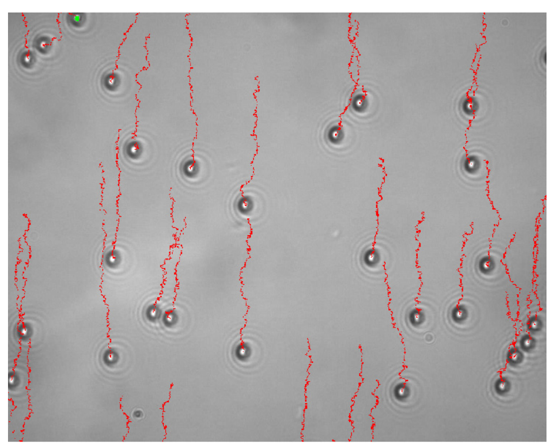
$$y_{fit} = 0.1819 \times x - 0.9423 \tag{1.1}$$

where the slope $m = 0.1819$ ($\mu m^2 \cdot s^{-1}$).

However, with a longer observation time, the particles seem to be drifting with an accelerated speed (Fig. 4(a)). In this case, the movements of the particles are no longer Brownian. This is also demonstrated on Fig. 4(b) as particles are moving in same direction. The red tails indicate the traces of each particle. On one hand, this phenomenon might be caused by an uneven thermal distribution of the solution. On the other hand, part of the solution might have reached the edge of the cover slide, which could have led to a flow which dragged the particles.



(a) Long time MSD versus time



(b) Long time drifting of particles

Figure 4: Long time observation of drifting particles

1.5 Maximum Trapping Force

As the target can be considered as a laminar current, we can obtain maximum trapping force by computing the maximum Stokes friction force.

$$F_{T,max} = 6\pi\eta_{eff}av_{max} = 6\pi\frac{2k_BT}{3\pi am}av_{max} = \frac{4k_BTv_{max}}{m} \tag{1.2}$$

where $m = 0.1819\mu m^2 \cdot s^{-1}$ (see (1.1)) and $v_{max} = 50\mu m \cdot s^{-1}$ in both x and y directions from measurement .

Finally, with $T = 300K$, the maximum trapping force can be calculated to be 4.55×10^{-12} N.

2 Conclusion

Through this labwork, we have firstly gained a better understanding of the physical backgroudn of optical tweezer with different interpretations. Secondly, by doing the experiments in the lab, we have learnt both the principles of a simple optical tweezer setup and procedures of manipulating micro objects with the tweezer. Finally, the Brownian motion of the sample beads is observed and studied, yielding a maximum trapping force of 4.55×10^{-12} N for the experimental setup. To achieve a higher trapping force, the laser should be tightly focused through a high NA objective lens and the sample plane should be as close as possible to the focal plane of the laser.

3 Introduction and Physical Principles

When light is reflected or absorbed by a material, then the momentum that was carried by the light must be transferred to that material and a force will act on that material. While the exerted forces are so small that they can be neglected[1] in our daily lives, they can still be utilized. Since radiation is typically incident on an area, this force per are is consequently called radiation pressure. Large solar sails utilize this pressure exerted on their enormous surface and are able to accelerate a payload in space without the need of any propellant. In 2010 NASA launched the "'NanoSail-D sail"', a $10\,\mathrm{m}^2$ solar sail, into earths orbit to validate the technology [2]. NASA is also currently exploring the possibilities of this technology for deep space exploration missions (Figure 5).

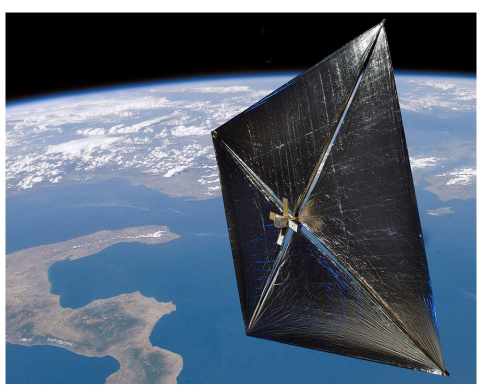


Figure 5: A solar sail as it will be used in the Sunjammer project to demonstrate propulsion by radiation pressure. [3]

Solar sails overcome the problem of little pressure by simply increasing the surface area exposed to the radiation. However, there is another approach to utilize the force exerted by radiation. Instead of using a larger area, the intensity of the light can also be increased to achieve considerable effects. If implemented in the right way, the force created by the radiation can be used to create optical traps in which small

[1] The radiation pressure on earth due to absorbed sun light is only about $4.6\,\mu\mathrm{Pa}$.

particles can be trapped. This is used in modern optical tweezers that are nowadays a versatile tool in science and technology.

This report describes the experiments conducted using a simple optical tweezer setup based on a microscope design on samples made of latex spheres. The first chapter present a short historical introduction, describes the diverse applications of optical tweezers and provides a simple physical understanding of to the topic. The latter provides a qualitative understanding of both the geometrical optics model as well as the scattering model to understand the optical trapping.

3.1 History of the Optical Tweezer

In 1619 German mathematician and astronomer Johannes Kepler tried to explain the specific shape of comet tails by the pressure of solar beams on particles in the tail. Being more of an educated guess[2] by Kepler, it took almost another 400 years before the linear momentum connected to radiation was explained by the electromagnetic theory by Maxwell in 1873 [4]. But even with the theoretical prediction that light does exert pressure on a material, the experimental proof was hard due too the extremely small forces and weak light sources at the time. Another 30 years later in 1901, and using a 30 Ampere arc lamp, the skillful Russian scientist Lebedev showed that the effect does actually exist [5]. While Lebedev was only able to show the existance of the effect, two years later Nichols and Hull were able to measure and compare numerical values to the theory [6].

As with many other optical technologies, the invention of the laser in 1957 was needed to transform an interesting study object into a versatile tool. It was now for the first time possible to create light intensities high enough to easily observe the pressure due to radiation. The first scientist to use lasers for optical acceleration and stable trapping of particles was Arthur Ashkin in 1970 [7]. While his approach is somewhat different from the modern approach (as described in section 3.3) the underlying phenomena are the same. Ashkin also developed his initial ideas further and created a single beam gradient force trap, now known as optical tweezers [8].

3.2 Application of Optical Tweezers

Optical tweezers are especially useful to control the movement of single particles with sizes of a few micrometer. Hence, they are extremely useful to control the movement of single cells which is an extremely useful tool for biologist, as described in an review article by Svoboda and Block[9] . There is simply no comparable tool available that enables the handling of single cells or macromolecules with such a flexibility and precision. Furthermore, the interaction is completely contact free, so that the sample can not be contaminated. It is also possible to measure and exert extremely small forces, again with very high precision.

In addition to biological applications, there are many other fields in which optical tweezers are used. Applications include colloidal sciences, microfluidics, microscopic alignment, particle separation, molecular motor dynamics as well as the study of the transfer of optical angular momentum, hydrodynamic interactions as well as light-matter interaction (see [4, 10] and references therein).

3.3 Physical Principles of Optical Tweezers

In modern optical traps, the beam is highly focused and a minimum of Energy, i.e. a potential well, is created using only one laser beam[3]. This well effectively traps the particle in three dimensions with the use of only a single laser beam from one direction.

There are two models that are generally used to describe the optical trapping. Scattering theory is applied for objects that are small compared to the wavelength while a geometrical optics approach is used for objects larger then the wavelength.

[2]The shape of comet tails is actually caused by solar wind rather then the momentum of the sun light.

[3]Which is in contrast to the original approach by Atkins in 1970 where either the glass interface or a second beam was used for the actual trapping. [7]

The scattering model is based on the Lorentz force, which directly calculates the force on the objects resulting from rescattering. The incident light induces a dipole moment in the material, $\vec{P}$, which is proportional to the electric field $\vec{E}$. The total energy can then be expressed as

$$U = -\vec{P} \cdot \vec{E} \propto -\vec{E} \cdot \vec{E} \propto -I \tag{3.1}$$

since the intensity I is proportional to the square of the electric field. Therefore the energy of the particle is minimum where the intensity is maximum. For a focused light beam, the maximum intensity is at the focus, which thus attracts particles.
The two important forces are the trapping force and the friction force due to movement in the suspension. In a laminar current, the Stokes friction force F_{Stokes} is adopted, which can be expressed as

$$F_{Stokes} = 6\pi\eta_{eff}av \tag{3.2}$$

where η_{eff} is the effective viscosity of the suspension, a is the radius of the spheres and v is the movement speed.

The geometrical optics model calculates the change in the momentum of the light due to the reflection and refraction of the light by the objects, and then used momentum conservation to calculate the force on the objects [11]. As shown in Figure 6, a qualitative understanding of the trapping force on a dielectric sphere can be achieved by considering the momentum change between two symmetrical incident rays and their first reflected and refracted rays.

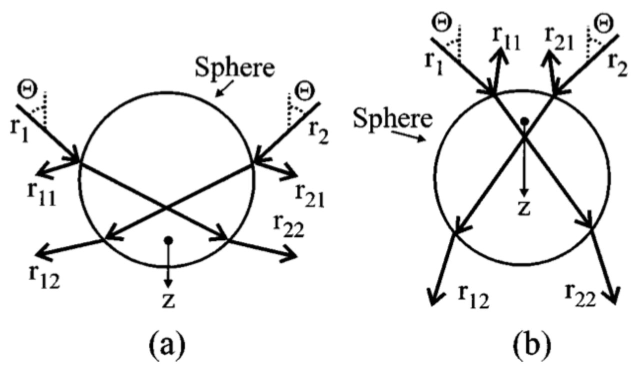


Figure 6: Simplified ray tracing diagram of the net force on a dielectric sphere displaced above (a) and below (b) the focus of the rays in the absence of the sphere. [11]

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