Light manipulation of microparticles: Optical Tweezers

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Abstract

In this paper, optical tweezers are discussed. The physical phenomena of light manipulation of particles is explained. The state of the art of systems using this phenomena and some applications it finds in some fields are reviewed. It is also demonstrated a simple optical tweezers setup using basic optical components. Its different parts are explained and the alignment process and control of the system are described. Observations made using this setup are presented and improvement of the functioning of the setup is discussed.

1 Introduction

Light based techniques have huge implications in our life and in science. For example, passive imaging techniques such as confocal imaging [2] are widely used in fields like biology and chemistry. With the invention of the laser, our way of doing science changed and once again the natural sciences were revolutionized. One of the properties of light that has been highly investigated and used is that light is able to move, hold and apply very well calibrated and controlled forces on micrometric objects. This is optical manipulation of particles, known as optical tweezers.

1.1 Theoretical description and considerations

Light can exert forces that induce different behaviours on microparticles. In this field, a traditional and convenient way of dividing them is into scattering forces and gradient forces [5]. The latter have the direction of light propagation and can be thought as the push photons give to the particle. The former have the direction of the spatial light gradient and appear due to the force a dipole experiences in an electric field, which near the focus of a laser light beam is proportional to the gradient of the light intensity [6]. The scattering forces are the dominant ones, except in a focus point of a light beam, where the gradient force traps the particle. This is the basics behind optical trapping.

In a theoretical treatment of optical trapping, three regimes are usually considered [2].

Mie regime ($d \gg \lambda$)

This regime is applied to particles of dimensions much higher than the light wavelength. In this regime, ray tracing optics is valid and the particle is seen as a microscopic lens that moves to the position of highest light intensity. This is depicted in Figure 1.1 [1]. In this figure, the resultant forces in three situations with a different relative position between the centre of mass of the particle and the focal point are represented using ray optics. They are obtained by using the Fresnel equations [2] to describe the reflection and refraction of the light rays on the particle.

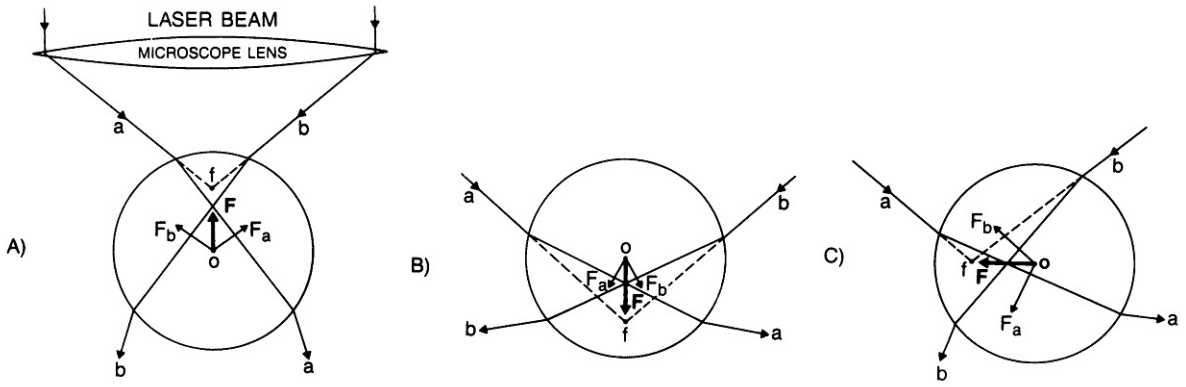


Fig. 1.1: Ray optics description of a particle in an optical trap.

It is seen that the particle feels a force that pushes it to the focal point, namely the point of highest light intensity.

Rayleigh regime (d≪λ)

This regime is used for particles of dimensions much lower than the light wavelength of an optical trap. The particle is seen as an induced point dipole that minimizes its energy in the electric field of the electromagnetic light wave. The energy of the induced dipole is proportional to the intensity of the light and thus the dominant force is the scattering force proportional to the gradient of the field. This a first order approximation of the Lorentz force that acts on the particle and in high intensity fields, a more precise approach is needed [3].

Lorentz-Mie regime (d≈λ)

This is the intermediate regime between the two approaches already presented, where both of them fail to give an accurate description of the phenomena. A full theoretical description in this regime is more complex to produce. A complete treatment of the electromagnetic interaction with the particle is needed to supply such an accurate description. There has been some progress in calculating the force exerted on a particle in this size range [5] but so far a more general description is not yet available.

The motion of any particle in an optical trap can be described by the theory of Brownian motion of Einstein-Ornstein-Uhlenbeck in the potential formed by the light beam [2]. This theory is mathematically described by the following Langevin equation:

$$m\frac{\partial^2 x}{\partial t^2} + \gamma_0 \frac{\partial x}{\partial t} + kx = (2k_B T \gamma_0)^{1/2}\,\eta(t)$$

where x is the position of the particle with relation to the focal point, m the mass of the particle, γ_0 the viscous damping of the medium where the particle is moving, k_B the Boltzmann constant, T the temperature of the medium and $\eta(t)$ the stochastic process of motion of the particle as a function of time. It is considered that the optical forces exerted on the particle are hookean in nature. With this, the optical force on the particle is proportional to its displacement and the constant of proportionality is k, the trap stiffness, which is is proportional to the laser power. The term on the right is the random Gaussian noise process and accounts for all the Brownian forces on the particle.

In order to have stable trapping, two things must be taken into account [6]. First, it is the damping that allows trapping. If the medium did not offer damping, the particle would enter and leave the trap because the optical force is conservative. With

the damping, the particle loses energy when entering the trap, not being able to escape it. Second, the fluctuation-dissipation theorem dictates that the damping is accompanied by fluctuations. Due to this, in order to have a stable trap, the depth of the generated light potential must be much higher than the energy associated with thermal motion $k_B T$.

Certain characteristics of the trap can be obtained from these descriptions. Its maximum force is given by [1]:

$$F = Q\frac{n}{c}P$$

where n is the refractive index of the medium, c the light velocity in vacuum, P the incident power on the particle and Q a scaling constant that measures how well the optical trap field couples to the particle. Q depends on the particle size, refractive index differences, aberrations and the trapping system itself. The Q factor has typically values around 0.1-0.2. [2,6]. Furthermore, it is expected by the equipartition theorem that the particle position will have a probability that obeys the Boltzmann law, being proportional to $\exp(-U(x)/k_B T)$, where $U(x)$ is the potential produced by the light trap. By studying the position of the particle, it is then possible to obtain the trap potential, expected to be proportional to the light intensity and quadratic in the particle position.

Besides the trap characteristics, the particles themself must have some properties. The most important one is that it should be transparent to the wavelength of the light being used. This improves the trapping process. It also gives advantages to the optical tweezers technique due to being a non invasive and non damaging technique to study different micrometer objects.

1.2 State of the art and applications

The typical optical tweezers setup is represented in Figure 1.2 [6]. Usually, a single light beam is incident in an high numerical aperture objective that tightly focuses the light in the particles plane inside the sample. In order for the best trapping possible, the source should be chosen according to the particles to be manipulated. A continuous wave laser is the most commonly used with the wavelength dependent on the particles to be trapped. The beam should be expanded to have a width equal to the diameter of the objective. this setup has founded a high number of applications in a variety of fields.

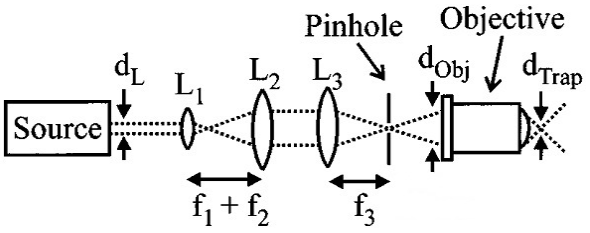


Fig. 1.2: Diagram of a standard optical tweezers setup.

When manipulation of more than on particle is needed at the same time, the typical setup fails to provide the needed traps. To compensate for this, dual beam optical traps were developed. These dual traps can be obtained by, for example, time-sharing the beam with an acousto-optic deflector or by separating the beam with a Mach Zender arrangement [2]. There are other methods that produce various traps such as discrete traps or arrays of traps. These use, for example, holographic trapping [5].

In order to obtain an even more reduced trapping region, what is called near-field trapping can be used [2]. The trapping forces result from evanescent waves. Because the strength of an evanescent wave decays with the distance from where the wave was generated, the region of optical trapping is drastically reduced. However, due to the nature of this waves, it is also difficult to achieve trapping in three dimensions. Various methods can be used to overcome this difficulty.

Other novel ways of trapping micro-objects is by using different light modes. Usually, a Gaussian beam with a single transverse mode output such as TEM_{00} is used. However, with this mode the trap region is

ellipsoidal with the major axis of the ellipse being the beam propagation direction. By using Laguerre-Gaussian beams [2], improved axial trapping can be obtained due to the mode having a low intensity centre with the beam periphery retaining the majority of the intensity. Low refractive index particles can also be trapped using such beams. Another type of beams very interesting for optical trapping is Bessel beams [2] that allow the formation of a periodic potential, where different particle behaviours can be studied.

Optical tweezers find applications in a variety of fields. In physics, optical tweezers are studied in order to characterize an optical trap. They are also a way of studying Brownian motion. With optical tweezers, transfer of angular momentum between light and a material can also be made [4]. Some colloidal systems are studied using optical tweezers and the results can produce some insights into condensed matter [2]. Chemistry also uses optical tweezers. Chemical reactions can be analysed with higher detail, such as liposomes reactions [2], and elasticity of molecules can also be studied [6]. Biology is also a field that explores optical tweezers, being behind some of its developments. This technique is widely used due to being non damaging. The DNA and its reactions can be studied with optical trapping [2]. Mobility, morphology and elasticity of cells studies can be performed using light manipulation [6].

In this paper, a simple optical tweezers setup is developed. Its alignment and control is explored and observations using this simple setup are made, showing that even with a simple optical system, optical trapping can be obtained.

2 Simple Optical Tweezers

In order to achieve manipulation of microparticles, an experimental setup had to be developed. This simple setup uses the physical principle described above, allowing the observation of light manipulation of particles.

2.1 Experimental setup

The developed experimental setup is represented in Figure 2.1. A continuous wave laser, with a wavelength of 532 nm and a power of 100 mW (Changchun New Industries Optoelectronics Technology Co., Ltd., model MSL-FN-532), was used for manipulation of the particles. The laser could be attenuated according to our needs. This laser was chosen for standard manipulation of microparticles [6], considering its wavelength and beam shape (transverse mode output TEM_{00}).

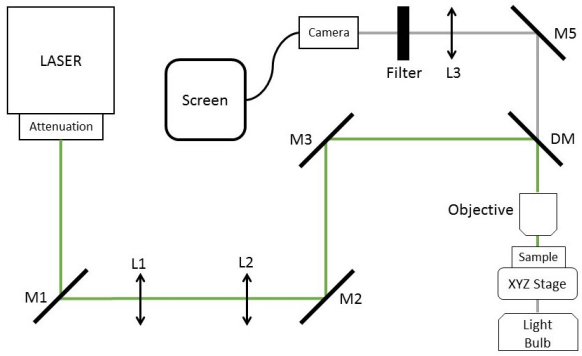


Fig. 2.1: Diagram of the optical tweezers setup. (M: mirror, L: lens, DM: dichroic mirror)

The experimental setup is divided in 5 parts:

1. Beam expansion: The lens L1 and L2 (Melles Griot Fl 150) form a telescope. With these, the beam is expanded to completely fill the aperture of the objective to ensure the tightest possible beam focus at the sample plane, thus achieving a full 3D trapping.

2. Beam angle adjustment and steering: The mirror DM adjusts the incident angle at the objective and the lens L1 adjusts the direction of the beam. They are used to steer the beam in the sample plane in order to manipulate the particles by changing the position of the beam focus.

3. Beam focusing: The objective (microscope objective 100x) focuses the beam at the sample

plane. By using the objective, we increase the focusing of the beam, increasing the gradient of light intensity and thus obtaining a better trapping of the particle.

4. Sample control: The sample is mounted on a XYZ stage (Melles Griot) that allows the positioning of the sample. By changing the z position of the sample, we change the position of the focal point inside the sample, which should be in the sample plane and not to deep in the solution of the sample, to avoid aberrations [6].

5. Imaging: In order to see the manipulation of the sample particles, the sample is illuminated from its bottom by a white light bulb. The light from the light bulb that passes through the sample and the laser light reflected at the sample pass through the objective and are then separated at the dichroic mirror DM. The white light then continues to the camera (KOCOM CCTV Camera, model KCB-278), first passing the lens L3 (Melles Griot) to focus the beam at the camera and the filter to reduce the light intensity. The camera is then connected to a screen, where the manipulation is observed.

The first 3 parts are related with the production and movement of the trap for microparticles, considering the theory behind this phenomena. The fifth part allows the user of this system to see the control of the microparticles by the use of light.

2.2 Setup alignment and control

The experimental setup described in the previous subsection allows for micromanipulation. However, in order to have a setup with proper functioning, alignments have to be made. To start with, all elements and components were cleaned using alcohol and proper optical wipers.

With the objective covered by a mirror, all mirrors (except M5 in Figure 2.1) were align. With the laser attenuated, but still visible with the naked eye, the beam was centred in all mirrors. It was also verified that the light reflected returned through the same path. After the alignment of the mirrors, the telescope alignment was verified, namely the distance between the lens (coincident image and object focal points).

The imaging system was also adjusted in the same conditions. However, for this adjustment the attenuation was smaller due to the small laser intensity that passes through the dichroic mirror DM. With this, it was required special attention and care handling the optical system (optical protection glasses). The distance between the camera and lens L3 was adjusted. The mirror M5 was aligned and then the filter was placed after the lens L3 in front of the camera.

Following all these adjustments, the objective could be align. First, with the laser on, the mirror DM was aligned with the objective, by verifying if the beam was incident in the objective. By placing a mirror in the sample stage, it was also verified again if the reflected light travelled back through the same path. Second, with the laser off, without a mirror in sample stage and with the light bulb on, the imaging system was again verified.

Having the experimental setup aligned, the samples could be place in the stage. An index matching liquid (Richard-Allan Scientific Resolve Microscope Immersion Oil M2000 n=1.5150) was placed on top of the sample, to have a better conduction of light. Final adjustments still had to be made to the setup. With the laser and light bulb on, it was verified both reflections at the top and bottom of the sample, by movement in the z direction of the sample stage. When the particles were observed, further refinement in the z position of the sample was made in order to have the beam focus in the sample particles plane.

With all these adjustments, trapping and manipulation of the particles could be performed. The sample could be moved in the x and y direction in order to find the best region or to verify if particles were being trapped. With the sample fixed, the manipulation of the particles was achieved by controlling the position and incident angle at the objective, by moving lens L1 and the mirror DM.

3 Observations

With a functional optical tweezers experimental setup, manipulation of microparticles could be performed. Two types of particles were observed and manipulated: bread yeast and PMMA microspheres. The particles were in an aqueous solution that was placed between a microscope slide and a cover slip. On top of the cover slip, a drop of the index matching liquid was placed. Both type of particles had micrometer dimensions and were transparent to the laser beam light.

3.1 Bread yeast

It was provided particles of bread yeast in an aqueous solution. It were made two observations of these particles. In Figure 3.1, it is represented the first observation made. It is verified that the concentration of particles is high. Due to this, it was not possible to observe trapping and manipulation of the particles.

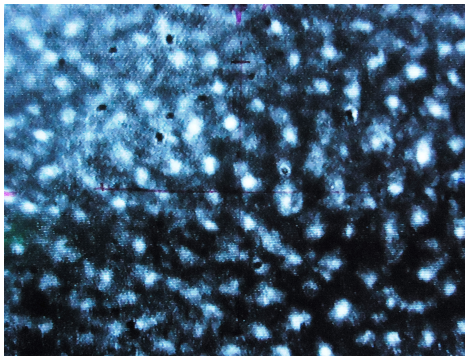


Fig. 3.1: First observation of bread yeast particles.

In order to avoid an high concentration of particles, the solution was diluted in water. The observations carried out with this solution are presented in Figure 3.2 and 3.3. A set of images of the sample being moved are presented in Figure 3.2. It is observed that the concentration of particles has decreased. One also sees trapping of one particle at the focal point, pointed out by the arrow, while the sample was moved. In the third image, it is observed a collision with other two particles and in the following image it is verified that the trapping was maintained. This shows that the forces in play in this optical trapping were stronger than collision forces.

In Figure 3.3, a set of images of the sample fixed but the focal point moved is represented. It is verified that a particle was trapped and manipulated by changing the position of the focal point. It is also observed that the trapping of the particle occurred in the X and Y direction, confirming the theoretical description of this phenomena. However, with these experimental setup, it was not possible to manipulate a particle further in the X and Y direction than the distance presented in these observations. It is also not possible to verify the more weak trapping in the z direction. These are limitations of our simple setup that could be corrected by improving the imaging system and the focusing of the beam.

3.2 PMMA Microspheres

The PMMA Microspheres were manufactured by Phosphorex Inc. and have a diameter of 8 μm. It was prepared an aqueous solution with these particles to be observed and manipulated with our optical tweezers system. The observations performed are presented in Figure 3.3. It was not observed trapping since it is seen the focus point moving but the particles fixed. This can be due to either the particles being stuck together or to the particles having higher dimensions than the dimensions the forces applied in this system are capable of manipulating. To obtain trapping, the microspheres could be diluted in a different solvent or the power of the laser beam should be increased, in order to achieve an higher gradient of intensity at the focal point thus increasing the strength of the trapping forces.

A deeper and more complete study of optical trapping could be performed by computerising the imaging system. Studies of the trapped particle position and also of the force it feels could be made and thus a full characterization of this optical trap could be obtained.

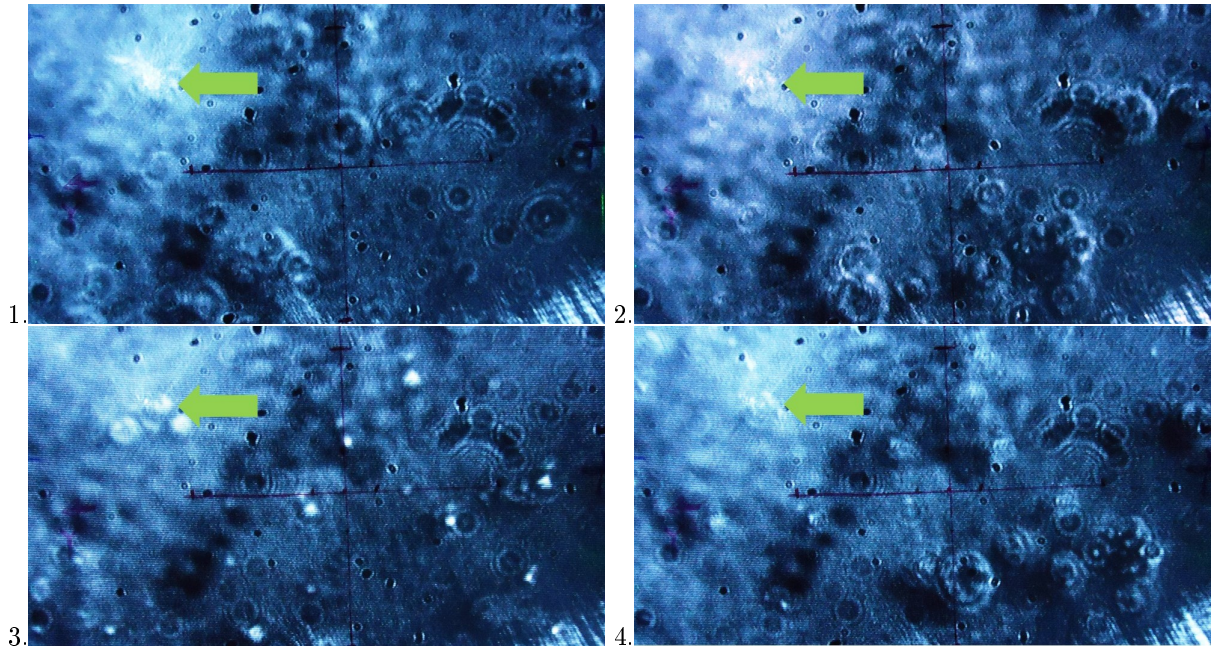


Fig. 3.2: Second observations of bread yeast particles: moving sample and fixed focal point.

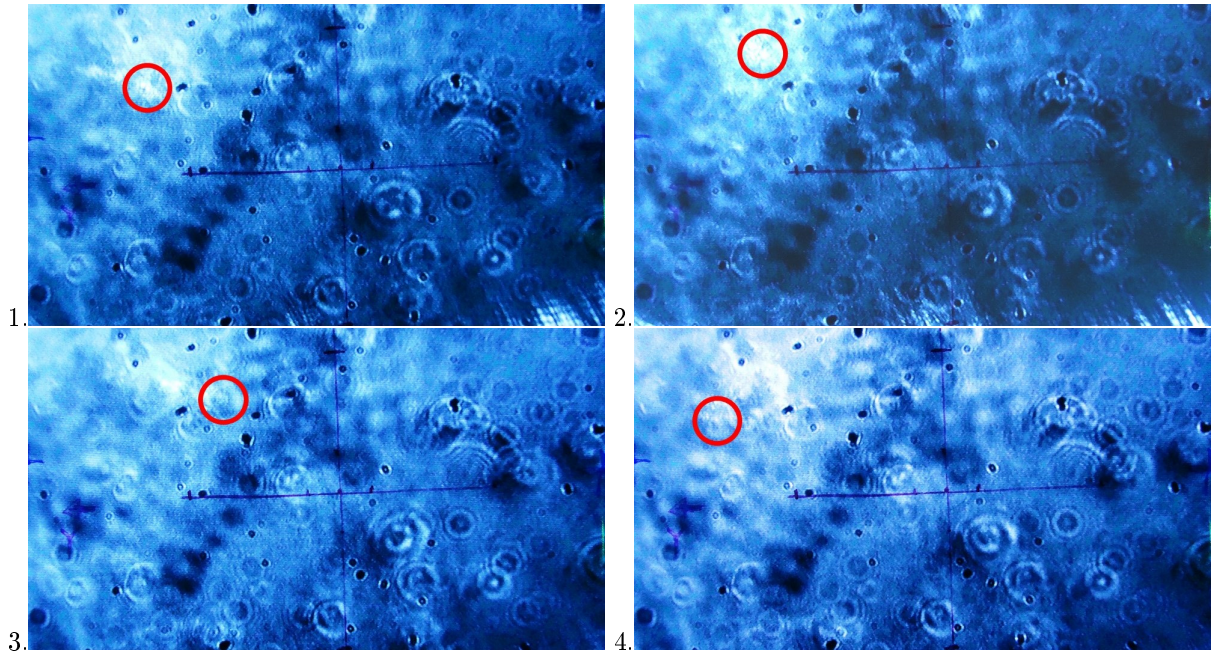


Fig. 3.3: Second observations of bread yeast particles: fixed sample and moving focal point.

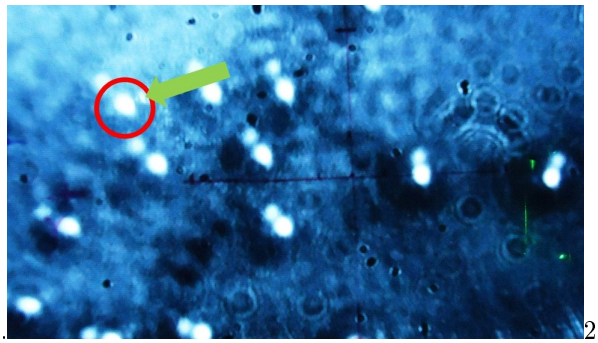
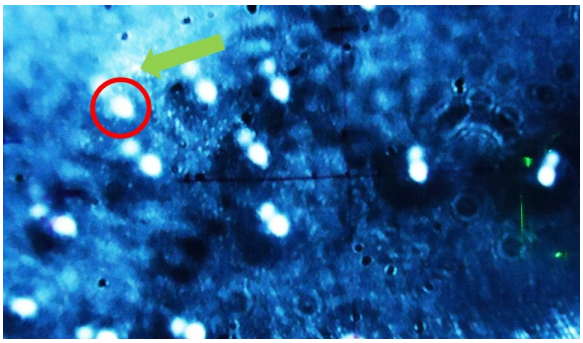
1.  2. 

Fig. 3.4: Observations of PMMA Microspheres

4 Conclusion

A study of optical tweezers and its application was made. It was concluded that optical tweezers have a simple physical principle behind with a complex theoretical description that allows light manipulation of a variety of particles. Furthermore, optical tweezers find applications in a wide range of fields such as chemistry and biology.

In this work, it was also developed a simple optical tweezers experimental setup for manipulating particles using light. With this setup, two types of particles were observed: bread yeast particles and PMMA microspheres. Trapping and manipulation were observed with bread yeast particles. However, with microspheres, trapping was not observed due to not having the best solvent of the microspheres' solution or not achieving enough strength to manipulate these particles. In order to improve our setup and observe trapping of particles like the microspheres, the laser beam intensity could have been higher thus increasing the strength of the forces that act on the particles. For a deeper study of the optical trap, an improved imaging setup should have been used.

In spite of this simple setup, it was verified what light manipulation is able to do, showing that it is possible to have a cheap and simple optical setup to control particles with light.

References

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