Optical levitation of transparent microspheres.

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1 Resumen

Una trampa óptica es un dispositivo diseñado para confinar un pequeño dieléctrico, esto se consigue focalizando la luz de un láser monocromático en una pequeña región (llamada spot) con la ayuda de una lente, la cual debe estar aislada para cubrir posibles perturbaciones externas. En este trabajo en concreto, la luz se propaga de forma vertical, perpendicular al suelo. Dos fuerzas son las que provocarán que el objeto dieléctrico no caiga, permaneciendo levitando durante un periodo de tiempo extenso. La fuerza de dispersión, que 'empuja' al dieléctrico (microesfera de Sílica) ejerciendo una fuerza vertical en el sentido de propagación de la luz láser, esta fuerza puede imaginarse como si bombardeáramos con fotones a la microesfera; y la fuerza de gradiente, la cual atrae al dieléctrico a la zona donde la densidad de energía de la luz es mayor, para comprender esto es necesario puntualizar que aunque la luz procedente del láser posee una distribución gaussiana (manteniendo una simetría más o menos homogénea) al pasar por una lente la distribución de dicha gaussiana cambia, focalizando en un único punto donde en comparación con sus proximidades su valor es muy alto, es decir existe un valor máximo de gradiente en el spot y los objetos serán atraídos hacia esa región.

A pesar de tener un funcionamiento sencillo existen bastante inconvenientes difíciles se sortear debido a complicaciones experimentales. Lograr que una microesfera pase por una sección pequeña del espacio requiere tiempo y técnica, además cuando esto se consiga realmente no estará situada en el spot, si no en zonas superiores, que dependiendo de la divergencia de la trampa (un parámetro relacionado con la fuerza de gradiente), puede alejarse de la aproximación lineal que aborda este trabajo.

Tras construir la trampa óptica usando el material del laboratorio, y alguna que otra pieza hecha de forma artesanal, se procede a la preparación de una muestra. Las muestras de las que se habla no son otra cosa que microesferas, para lograr atrapar una es necesario soltar muchas de ellas cerca del spot y esperar que alguna pase justo por esa región tan pequeña, teniendo en cuenta que la potencia aplicada sobre ella sea la justa como para que no caiga o salga disparada por exceso de potencia. Para preparar dicha muestra se realiza una mezcla de isopropanol y microesferas, con ayuda de un gotero se esparce por un vidrio rectangular y se calienta, esperando que el isopropanol se evapore y deje distribuida de forma uniforme las microesferas por la superficie. Experimentalmente se comprobó que si la muestra era demasiado homogénea despegarlas del vidrio era más complicado, por lo que se intentó realizar en pequeñas aglomeraciones.

Una vez preparada la muestra, se coloca boca abajo dentro de la cabina de confinamiento y se le propina un golpe, con lo que las microesferas consiguen despegarse, formando con suerte una pequeña nube que pase por el spot.

Durante este trabajo se produjeron dos atrapamientos; en el primero de ellos, aunque efímero se consiguió atrapar un sistema de tres microesferas, dos de ellas pegadas y la otra levitando sobre estas últimas. Aunque singular, este evento no sirvió para aportar medidas, ya que era demasiado inestable, solo se consiguió fotografiar gracias a una cámara que apuntaba al spot. El segundo

y último de ellos fue más fructífero, se atrapó una sola microesfera y usando una cámara de mayor resolución espacial se realizaron videos de su movimiento cambiando la potencia aplicada, finalmente cayó debido a que se bajó la potencia demasiado, provocando que la esfera dejase de levitar. A continuación, se realizó el procesamiento de los datos, el video se descompuso en fotogramas y con la ayuda de un programa de Mathematica se hizo un rastreo del centroide que aportaba la imagen, asignando coordenadas espaciales acorde a su posición y de tiempo según el orden de estas. Usando Python se representaron en gráficas el movimiento de oscilación de todas las medidas tomadas, realizando un ajuste gaussiano a la probabilidad de presencia para saber la amplitud de la trayectoria seguida por la microesfera. No sin antes corregir fallos evidentes en las medidas tomadas, eliminando su contribución.

Uno de los objetivos de este trabajo es calcular la fuerza y constante elástica que caracteriza a la trampa. Para el cálculo de la constante y fuerza elástica, se aproximó la microesfera levitando a un oscilador armónico, por lo que hallando su frecuencia y su masa basta para conseguir los resultados. La frecuencia fundamental de oscilación se consiguió estimar haciendo una transformada rápida de Fourier, atendiendo a sus picos más altos, la masa y radio se estimó usando la media que ofrecía el bote de muestras de microesferas de sílica.

Si bien armar una trampa óptica y ponerla a funcionar ya es un logro, antes del inicio de la cuarentena se habían programado muchas más medidas, sencillas de realizar con elementos ya disponibles en el laboratorio, el aspecto teórico ya había sido estudiado y solo faltaba realizar nuevas capturas de microesferas. Se resumen todos los conceptos teóricos y comportamiento experimental esperados usando como referencia artículos científicos de la bibliografía. Por último, se habla sobre las posibles mejoras realizables, para obtener mayor calidad en futuros experimentos y abriendo posibilidades a nuevas ideas a las que sacar partido.

2 Objectives of the work

Resumen. *Explicar conceptos teóricos empleados para entender el experimento, calcular a partir de las medidas la fuerza y constante elástica de la trampa construida y por último ofrecer futuros experimentos usando esta trampa o una con ciertas mejoras.*

The functioning of the main elements that are part of the experiment will be explained in a simple and concise way. The functioning of the laser, the principles that support the optical levitation and process involved in luminescence and the total internal reflection that give rise to the "Whispering Gallery Modes".

In this work an optical trap will be built using a high power tunable laser. Transparent silica beads will be used to analyse their behaviour in the optical trap. The position of the bead will be measured as a function of the power applied, with the aim of determining its oscillation amplitude, its force and elastic constant.

In order to carry out these calculations it will be necessary to subject the data to certain corrections beforehand. The average oscillation amplitude will be given by a Gaussian fit (because it is oscillating with respect to its equilibrium position), according to its presence probability. For the force and elastic constant it will be necessary to find the frequency of oscillation. Finally, we offer a wide range of improvements and measures to be carried out.

3 Teorical Background.

Resmen. *En este apartado del trabajo se explica de forma sencilla y concreta los diferentes componentes del experimento, prestando especial atención en los conceptos físicos que describen a los micro-resonadores y el laser (naturaleza gaussiana y procesos que ocurren en éste).Todo ello con el objetivo de explicar el funcionamiento de la trampa óptica que se ha construido para levitar microesferas y estudiar su movimiento.*

3.1 Microresonators

Optical microresonators are devices that allow to keep light rays inside, either within a reflective cavity or a dielectric surface. They are small transparent structures (cell-size) that confine light inside them (by successive reflections) so that it travels the equivalent of several meters inside their micrometric structure. Moreover, this only happens at certain frequencies (resonant frequencies), which would be the equivalent of a musical instrument with its fundamental frequency and harmonics, but changing the instrument for the micro-resonator and the sound for the light.

This ability to store light allows a very strong interaction with matter that composes the micro-resonator, allowing a series of phenomena to occur, such as causing mechanical vibrations by the action of the radiation pressure of the laser light we inject into the resonator.

The optical resonators are characterized by two parameters, which provide information of the degree of light confinement in spatial terms (modal volume) and temporal (quality factor Q).

In particular, a spherical dielectric resonator keeps the light inside by total internal reflections. Due to this confinement a wave is generated with a characteristic number of oscillation modes also called resonant modes.

3.2 Gaussian beam

During this work it has been assumed that the nature of the Gaussian radiation profile is ideal. But the calculations have not considered the divergence it suffers during the optical path, the distance it travels is 1.4 meters so it is not possible to consider it negligible. This work approximates that dispersion as negligible. The procedure for the precise calculations is defined below. The Gaussian irradiance profiles are symmetrical around the center of the light beam and decreases with distance in the direction of light propagation.

$$y\left(r\right) = y_0(w(z))e^{-\dfrac{2r^2}{w(z)^2}} \tag{3.1}$$

We see that it does not remain constant as it advances along the propagation axis denoted by z. Due to diffraction, a Gaussian beam will converge and diverge from w_0 where the waist of the beam reaches a minimum value. The beam will converge and diverge equally on both sides of its waist with a θ angle. The variation of the beam diameter in the beam-waist region is defined by:

$$w(z) = w_0\sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2} \tag{3.2}$$

$$\theta = \frac{\lambda}{\pi w_0} \tag{3.3}$$

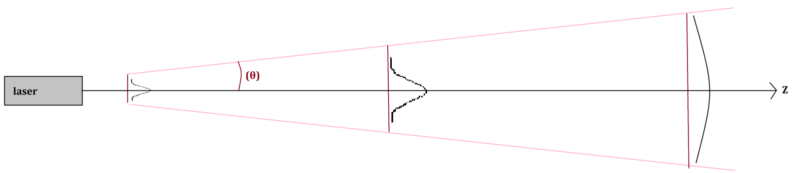


Figure 1: Scheme of a laser desviation with z

It is also possible to estimate what happens in the irradiance profile after passing through a thin lens. Typically you have equation 3.4, but it is also possible to arrive at a correction by assuming that the waist of the beam is the object, arriving at equation 3.5.

$$\frac{1}{s'} = \frac{1}{s} + \frac{1}{F} \tag{3.4}$$

$$\frac{1}{s'} = \frac{1}{s + \frac{\pi^2 w_0^4}{\lambda^2 (s+F)}} + \frac{1}{F} \tag{3.5}$$

Where w_0 is the width of the initial Gaussian and F the focal point of the used lens.

Although no calculation has been made on what the Gaussian beam of light looks like before it reaches the lens, nor how it is concentrated on the spot, these equations could serve to make a much more accurate analysis of the situation and not make any approximations. For this it would be necessary to use a simulation program. [1]

3.3 Optical Tweezing.

This technique, also called "optical trapping", is used to manipulate small dielectric objects of the order of micrometers or nanometers. The physics of this process consists of achieving an equilibrium in the forces of the particle by using the scattering force to compensate for the force of gravity.

The scattering force can be explained as the thrust exerted by the photons on impact with the micro-sphere, this force will be in the direction of the propagation of the incident light. It is clear that even though the incident light has a specific direction. The result will be a transfer of momentum in the direction of propagation if the light is isotropic.

$$F_{scatt} = \frac{I_0 \sigma n_m}{c} \qquad \sigma = \frac{128\pi^5 a^6}{3\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2 \tag{3.6}$$

The scattering force is usually dominant, but not for our experimental case, as there is a pronounced intensity gradient in the vicinity of the spot. The gradient force is produced by the interaction of a dipole with an inhomogeneous electric field, in the experiment the laser produces a field concentrated in a width region, therefore it is not homogeneous, producing a force in the direction of the spot.

$$F_{grad} = \frac{2\pi\alpha}{cn_m^2}\nabla I_0 \qquad \alpha = n_m^2 a^3 \left(\frac{m^2-1}{m^2+2}\right) \tag{3.7}$$

For a trapping it is necessary that the axial component of the scattering force, which is achieved with an intense gradient produced by a high NA of the laser. It is necessary that the dispersion is homogeneous so that the net force is in the direction of propagation. This is achieved when the wavelength of the incident light is much bigger than the radius 'a' of the micro-sphere.

The mathematical expression for the physic's effects are describedin Equations 3.6 and 3.7. Where n_m is the index of refraction of the medium, σ is the scattering cross section of the sphere, m is the ratio of the index of refraction of the particle to the index of the medium and α is the polarizability of the sphere [2].

As seen in Figure 2, the narrowest part of the beam, achieved by focusing, is called a beam waist and has a very high field gradient. This will cause the particles found in areas of lower gradient to be attracted to the center and keeping them suspended at that point by a force similar to the Hooke's law. That mean that the force in the near the beam waist is has a linear dependence to the displacement of the particle.

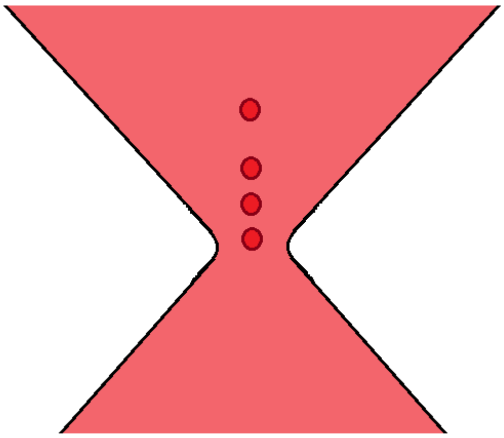


Figure 2: Scheme of a laser trap, the bead can ascend in the trap if the power applied is increased.

3.4 Equipartition Theorem

A microsphere trapped in an optical trap in thermal equilibrium (or in the case we are working, a proximate equilibrium due to thermal oscillations of the laser due to a breakdown in the cooling system), moves in a Brownian way near the spot where it is confined. The fluctuations that are observed in the movement can give us information about the optical potential to which it is subjected. As expected from the use of Boltzmann statistics, there is a Gaussian function that establishes the probability of the particle's presence.

If the probability of presence measured in the laboratory is represented in a histogram, this Gaussian appears as expected, with a higher probability of presence where the optical potential is lower. This Gaussian nature can be used to find out how stiff the buffer is by using the temperature parameter, as shown in the equation 3.8 and 3.9, where σ is the width of the histogram. Therefore it is possible by measuring its temperature to know its elastic constant or to estimate at what temperature the microsphere is if the elastic constant is obtained by other means.

$$\rho = e^{(k/2k_B)(x-x_0)^2} \tag{3.8}$$

$$k = \frac{k_B T}{\sigma^2} \tag{3.9}$$

Reconstructing the optical potential using Boltzmann statistics can be used to describe any achievable capture, provided that the temperature parameter is available. Unfortunately, any Gaussian noise will make the experimental histograms wider, obtaining a not very accurate measure of the elastic constant [3].

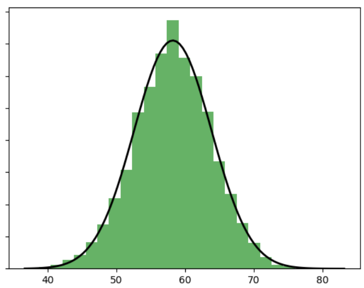


Figure 3: Example of experimental histogram

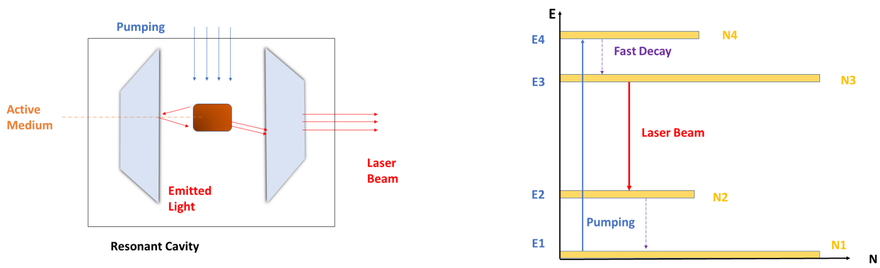
3.5 Laser

First of all it's necessary to differentiate two types of transitions, radiative transitions (emission and absorption of photons spontaneously or induced) and non-radiative ones (variations in temperature due to changes in the phonon -network-).

A laser is formed by three main components, a resonant cavity prepared to amplify the light that arrives, an electron pump system and an active medium, that will be responsible for emitting the light using a properly power in the pump system. After the first emission of light by the active system it begins to reflect in the cavity causing a waterfall effect that amplifies the generated light, one of the mirrors of the cavity has a certain transmissivity that allows to obtain a beam of light, like Figure 4 (a) shows.

A laser will only be able to emit light if it meets certain conditions. The most important condition it is the level inversion, this means that the radiative transition just happend between a very populated excited level and another one with less energy and population, this condition it's impossible for two-level systems. Population is understood as the amount of electrons in a level and it's call N.

For the case study in the laboratory it will be used a four-level system laser. You can see the behavior of this level system in Figure 4 (b).



(a) Components of a laser (b) Transitions in a laser

Figure 4: Operation of a laser

In Figure 5 you can see the tunable laser used for the experiment, you can see the laser structure explained above but with a new element, this laser is peculiar because it allows you to change the wavelength to which you are lasing using a birefringent crystal. Normally, to change the wavelength in a laser, the optical path is changed by moving the mirrors or with a diffraction network, however, this laser achieves the same effect with this crystal.

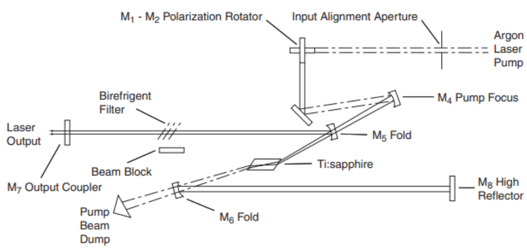


Figure 5: Operation of the Titanium Sapphire Laser

4 Methodology and experimental procedures.

Resumen. *Se indica el proceso seguido a la hora de construir la trampa óptica, hablando de los elementos que forman todo el sistema óptico, desde la fuente de luz, pasando por los espejos y lentes usadas. Una de las partes más importantes del experimento son los ajustes previos a la levitación y la preparación de las muestras, puesto que si no se realiza de forma óptima, atrapar microesferas se convierte en cuestión de suerte y no un proceso que se pueda repetir con asiduidad. Por último se nombra como se han tomado los datos y las fuentes de error que hay presentes en el experimento y escapan hasta cierto punto de nuestro control.*

The first part of this work corresponds to the experimental set-up and processes prior to the measurements.

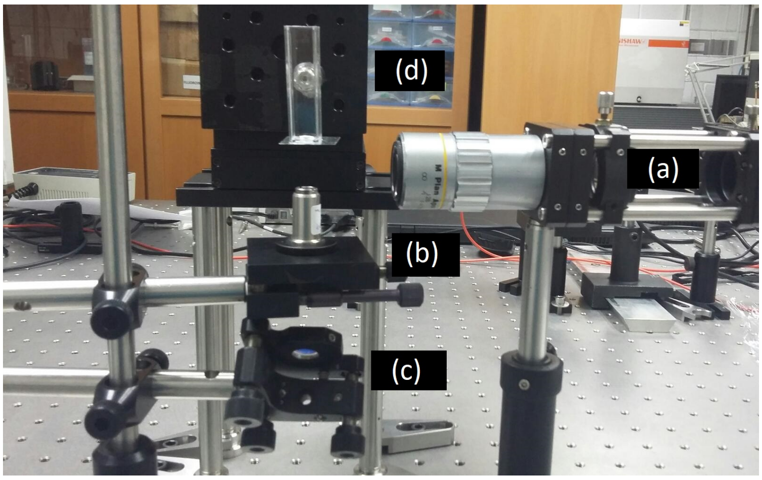


Figure 6: Optic Trap: (a)Camera (b)Lens (c)Mirror (d)Trap

As far as the experimental assembly of the optical trap is concerned, it turns out to be a simple procedure once you have all the necessary components to assemble the optical system. The precision with which the elements was aligned on the table is quite high, since a metric optical bench is used, with the capacity to screw the necessary optical supports without having to be aware of alignment problems. Among the elements used, the chamber support (observed system), the camera support system (measurement system) and the laser are emphasized.

Developing the three parts of the set up a little more.

The lighting system is formed by two lasers, one that pumps (millenia) to the other that acts as a wavelength tuner (sapphire titanium) which is fixed at λ=726 nm. Both systems are refrigerated to maintain a stable temperature that allows the most reliable measurements possible, and also covered by an extractor so that the minimum possible dirt is deposited on them.

The area where the micro sphere is to be enclosed is built by hand. The chamber (d) consists of a small rectangular prism with two entrances, one of which has been sealed using a cover slice (corresponding to the lower part of the prism) and the other has been left unsealed in order to drop the beads, although a cover slice was used again as a cover. This container has been fitted with a nut so that it can be screwed onto an XYZ, so that the chamber can be moved without dismantling the set up, if the situation requires it.

To be able to take measurements, different cameras were used throughout the work, in order to achieve a higher resolution. The system consists of a microscope lens (a) that will provide an enlarged image of the experiment and a light filter so as not to saturate and the camera.

Finally, to finish the set up of the experiment, the laser light has to be brought to the optical trap, which is oriented vertically. For this purpose, a system of mirrors was prepared, one of them folding, which allows changing the direction of the laser light towards the section of the table where the trap is located or using it for some other purpose, optimizing the capacity of the table and making it possible to use the laser for other experiments. And another mirror(c) placed in the lower part of the chamber that changes the direction of the laser 90 degrees from the vertical. Finally, after travelling 140 cm it reaches the convergent lens (b)(focal: 15.29 mm) located above the mirror that focuses the laser light into the chamber.

When working with a vertical laser, light is necessary to take many precautionary measures especially at the time of alignment, as it can happen that is not well placed causing the laser to get a dangerous inclination for the eyes of experimenters. Henceforth actions are taken such as use power reduction glasses, avoid using reflective objects and close the laser shutter when you want to align the vertical setting.

Before performing the measurements, it is necessary to carry out a series of pre-adjustments, in addition to preparing the sample.

To make the corresponding measurements with the high-resolution camera, it is necessary to focus the camera on the laser spot, since when the beads are caught it will be necessary to provide the greatest possible stability to the table, to avoid them coming out of the trap or accidentally hitting the set up.To properly focus on the spot, the XYZ and a piece of black cardboard will be used. The spot will be searched manually by moving the XYZ after focusing on the card.

If the camera is focusing on the place there are several signs. Among them are the following: the spot projected on the card should be as small as possible, since it is an area of high energy concentration the card will start to burn slightly, releasing some smoke. And most importan, taking into account the interferometry of the speckles, when the speckles become noticeably larger it means a greater proximity to the spot zone.

In Figure 7 the spot is projected on the black cardboard. The surface is sightly tilted because the camera need some angle to get the picture.

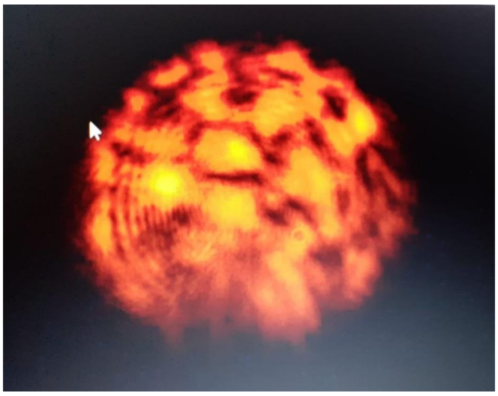


Figure 7: Spot laser projected on a black surface

Before taking the data, the camera had to be readjusted, because the microsphere is not exactly in the spot, but close to it. It must also be said that the camera is not well supported and allows rotation but no translation, this may cause it to be unintentionally off-center moments before the capture. To make the measurements, the camera is connected to a lap top located near the experiment. A capture program is used to display the data provided by the camera, make small contrast and brightness adjustments and define the parameters for recording the experiment .

The first step after having the setup of the optical trap mounted, is the preparation of samples. The dielectric microspheres used are made of silica, a solution of these is prepared in isopropanol and placed in a very thin cover slice, once the isopropanol has evaporated (Using a hot plate), it is verified that the microspheres are not agglomerated enough using microscope, in Figure 8 (b) an example. Knowing how to prepare the sample correctly was a challenge, making it in an optimal way so that when hitting the cover slice a homogeneous cloud of microspheres is formed that descends through the chamber, and catches some of them in the spot was something that was achieved after multiple trial and error. It became evident that small decisions like preparing the sample have a great impact on the success of the experiment. In the first place, it could be thought that the sample should be distributed as homogeneously as possible over the surface (Figure 8(a)), since if it is too agglomerated, when falling in the spot the weight of the clast will prevent it from levitating or in case of levitating it will be hit by a neighboring clast (Figure 8(c)). The ideal shape is found in a mixture of both.

With the laser activated, the cover slice is placed upside down, then a small hit is provided, that produce the falling of microspheres. For trapping microspheres they must fall forming a small cloud, this is the most complicated part of this experiment, because the microsphere should pass through the spot,a very small region, furthermore with a specific power so that the microspheres do not shoot upwards or on the contrary slow down their drop. It is also possible for several microspheres to pass through the spot, causing shocks that prevent them from being trapped.

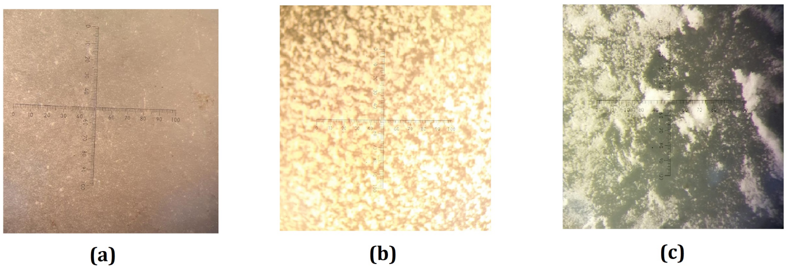
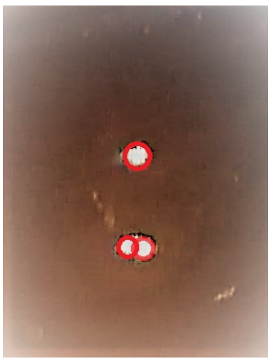


Figure 8: Proper Microesphere Sample Preparation

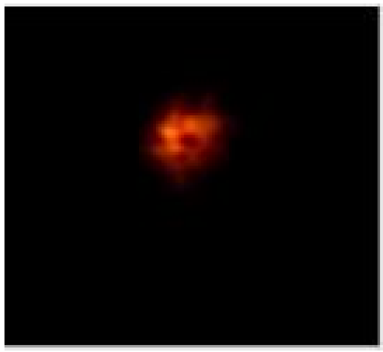
4.1 Measurements

After many tries, the stable power was found to allow the levitation of spheres. The pump power of the laser was at 2.95 W in the first and 3.00 W in the second capture. It is possible that the heating of the laser due to a long time trying to catch some sphere modifies the power at which the capture was recorded.

As seen in Figure 9, the particles trapped in the laser focus shine with great intensity, as they receive all the power concentrated in a single point. As mentioned in previous sections of this work, this point is actually a wide region in which more than one bead can be trapped, the hope is that a set of these will be found to study their mechanics more thoroughly. In addition the spheres will have moment of inertia causing rotation and there will be fluctuations due to the stability of the laser.



(a) Three particles , first catch

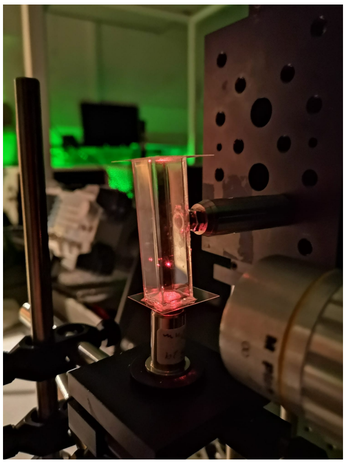


(b) One particle , second catch

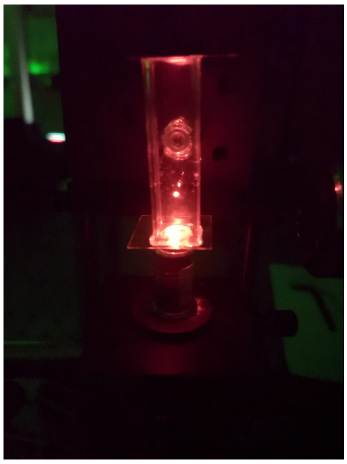
Figure 9: Images from the camera

Catching beads is a fairly slow process as the ideal conditions described above must be present. Two traps were performed:

The first, in which a system of three microspheres was trapped. Unfortunately, the camera used at that time did not have the necessary resolution to make reliable measurements, only one capture could be made in which the system was clearly observed. Although there was no data stored, it was observed that two of the spheres were forming a binary system, surely they were in contact, the third sphere was floating erratically above the binary system, the low stability of the sphere made it fall leaving only the binary system, which also ended up falling due to a small blow to the chamber trying to bring the camera closer. As expected, in the experimental development events arise that were not foreseen, part of the learning process is trial and error. The events of the first capture made the next one improve, not only in the camera used but also in small details when preparing the experiment and meditating a strategy of execution.



(a)



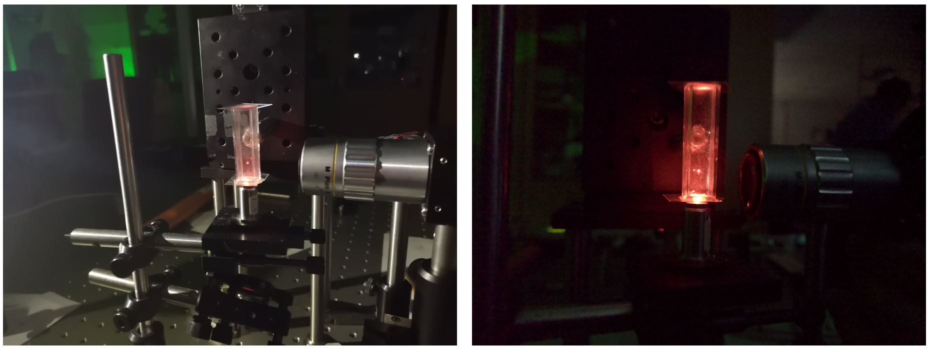
(b)

Figure 10: Laser trap in operation, first catch

The second trapping only caught a microsphere. After checking that the camera was working properly, the following measures were taken. The first one consisted in making a pixel-micrometer scale. Since for the subsequent data processing it was necessary to work on the SI. To make it three captures were taken in which the sphere does not suffer any change, simply the camera was moved by 50 in 50 micrometers to see later how many pixels correspond to 50 micrometers of displacement.

The second measurement consisted of a two-minute video at a fixed power, in order to have a long-lasting measurement that serves as a reference.

The last one consisted in taking 20 seconds videos at different applied powers, with the objective of seeing the displacement in the Y axis with the increase of the power and also to see how this power affects the oscillation of the microsphere (or what is the same to its elastic constant or confining force). Despite wanting to take more measurements, by varying the power of the laser, and reaching a lower power, not only higher than the initial power (since the interesting thing is to observe large oscillations, which occur at low power), the microsphere ended up falling because it did not have the necessary power to levitate.



(a) (b)

Figure 11: Laser trap in operation, second catch

The process that follows the measures would be to treat the data to find possible errors, and to be able to improve the conditions of the third capture. But due to the beginning of the state of alarm and with it the decree of quarantine it was not possible to resume future measures.

Specific Parameters in the set up

The calculation of width of the spot is given by equation 4.1, where F is the focal of the lens ($15.29mm$) and D is the diameter of the Gaussian profile ($0.95mm$).

$$2\omega_0 = \frac{4}{\pi}\frac{\lambda F}{D} \tag{4.1}$$

Using the specific parameters given previously $2W_0$ is $7.377\mu m$. Therefore it is possible to calculate the energy density in the area of the spot $1.77 \cdot 10^9 W/m^2$.

4.2 Sources of Error: Sealed and Thermal Unstability

If the chamber where the light trap takes place is not well sealed, it could happen that at the point where the beam is focused, it warms up, causing the air temperature to increase, generating an upward current of air that makes it difficult to trap microspheres. We cannot therefore be certain that the chamber was hermetically sealed and convection currents add a small error.

The time between measurement of 2 minutes and 20 seconds was quite long so, as is to be expected, the laser has suffered a considerable overheating, so the pump power of 2.90 W no longer corresponds to 44.20 mW of applied power, and given that it is impossible to measure the applied power without the trap stopping working. The exact location of the working power region in the captures is displaced without being able to quantify the error; however for short measurements we can say with certainty is that they are separated from 0.5 to 0.5 W(pump power). The thermal instability added to the output of the linear regime becomes even more evident at 84.40 mW. Figure 21 (b) shows how the temperature increases at the end of the measurement.although it could be thought a priori that it is due to a blow to the measurement table.

5 Results and discussion.

Resumen. *Tras medir los movimientos de la microesfera, los datos son trasladados a un formato más cómodo para trabajar, convirtiendo los videos en frames y los frames en coordenadas de posición, usando un programa de rastreo hecho en Mathemathica. Cambiando ahora un lenguaje más conocido, Python, los datos son corregidos y representados en varias gráficas. Se realizan histogramas para saber cuantitativamente cuanto se desplaza en su oscilación y se representa su evolución temporal. Para hallar los parámetros necesarios para el cálculo de la constante elástica se realiza una transformada rápida de Fourier, lo que permite saber su frecuencia de oscilación. Si el sistema es considerado como un oscilador armónico simple es posible calcular la constante y fuerza elástica de la trampa. La medida de mayor potencia no sigue el comportamiento esperado a pesar de tener en cuenta los posibles errores cometidos a la hora de tomar las medidas.*

The VLC player, Wolfram Mathematica 11, and Python were used to process the data from the various videos and screenshots taken.

The first step is to convert the videos into images, which is done by dividing them into as many frames as possible, using the VLC player. The need to see how the sphere moves led to the search for the best way to automatically track the position of the sphere. The solution was given by Wolfram alpha 11, which has a command ,"IntensityCentroid", that assigns the centroid of a given imagen. The positions of each centroid were given in pixel coordinates and saved in a data file. Python was used in order to work with this files. A pixel-micrometer scaling was done using the captures. After finding the first degree polynomial fit, the initial data was modified to work with micrometers.

By plotting the data, it was found that some of the position points did not correspond to the movement of the sphere (in other words, the tracking had some errors). A filter was applied to eliminate the few points that presented a clear failure in the tracking. The number of deleted points is very small compared to the total number of points.

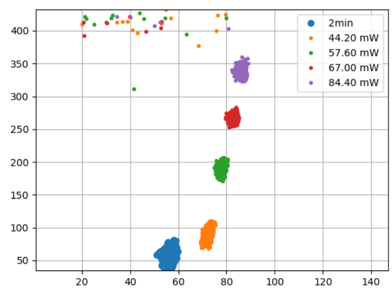
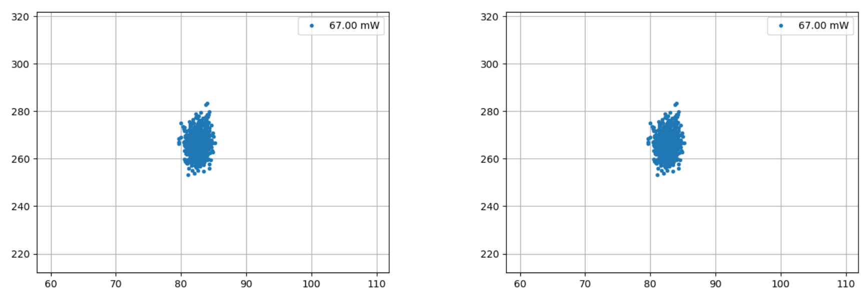


Figure 12: Before correction

Once an array of data was obtained according to what is expected from the movement, an angular correction was made, since a small deviation of the vertical axis was detected as the sphere was subjected to more power. This tilt is due to a camera inclination, because aligning it vertically with great precision was complicated. After finishing the correction of the available data, a Gaussian fit was made, to be able to see the probability of presence of the sphere along its oscillation. Finally, a Fourier analysis of the oscillating movement of the sphere was performed. In Figure 12 the two-minute measurement is offset horizontally from the 20-second measurement because the X-axis was reset before the measurement was changed

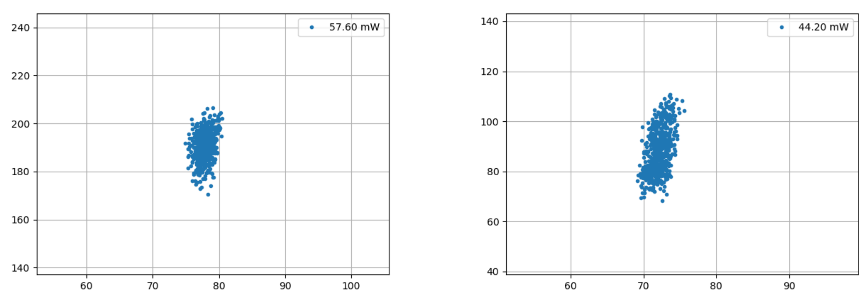
5.1 Laser Trap Elastic Constant with applied power

As can be seen in the graphs, the movement of the sphere is represented in microns, being able to distinguish how the movement is delimited due to the elastic behavior of the trap.The assigned coordinates are from the center of the image.



(a) (b)

Figure 13: Laser trap at 84.40 and 67.00 mW



(a) (b)

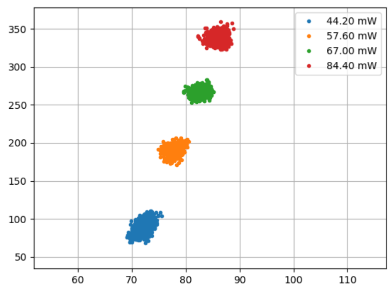
Figure 14: Laser trap at 57.60 and 44.20 mW

To place us in the order of power with which the laser hits the microsphere, we will use the linear relationship that exists between the pumping power of the laser and the power applied by the laser; in other circumstances a beam sample would have been measured experimentally or would have been added a beam sampler in the experimental setup to be able to simultaneously measure the power applied, but due to the quarantine only two data are available, when the laser starts and when it starts levitating; with the adjustment equation we have an extrapolation that shows in the Table 1.

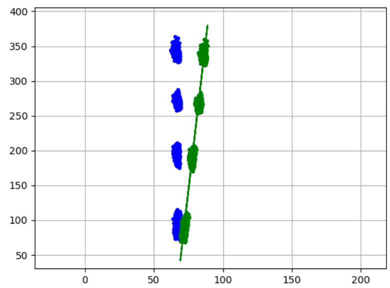
Pump Power[W]	Applied Power[mW]
2.75	0.00
3.00	67.00
2.95	57.60
2.90	44.20
3.05	84.40

Table 1: Estimated powers

A deviation in the measurements from vertical axis is observed in Figure 15 (a), this may be due to problems with the alignment between the camera and the microsphere. This deviation has been corrected by rotation; fitting data and extracting its inclination or the degrees of deviation from the vertical. After knowing this angle, the data has been passed to polar coordinates, adding the corresponding correction, and has been converted to Cartesian again. The final result it is showed in Figure 15 (b).



(a) Four captures



(b) Angular Optimization (3.34 degrees)

Figure 15: Evolution of system with mW; the position coordinates are not with respect to the spot, but to the total plane where the image was taken.

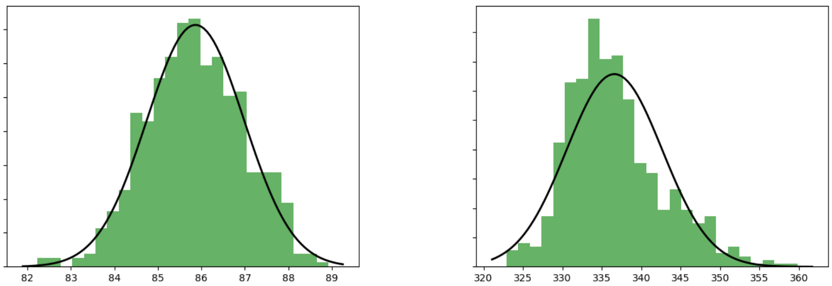
Table 2 serves as a final conclusion to analyze the behavior of the microsphere subjected to changes in the applied power. As expected, the vertical oscillation is bigger when there is less power, because less force is used to confine it. The horizontal oscillation does not change much, one could say that it remains almost constant. The variation in positions is one of the magnitudes needed to calculate the elastic constant and confinement force.

However, the higher power measurement does not match the expected behavior. Without a clear response to this deviation in behavior, one can venture that it is either due to a measurement error or that it is far from the linear behavior region.

Applied Power[mW]	$\Delta Y[\mu m]$	$\Delta X[\mu m]$
84.40	36.91	6.69
67.00	30.02	5.60
57.60	35.91	5.61
44.20	42.62	6.41

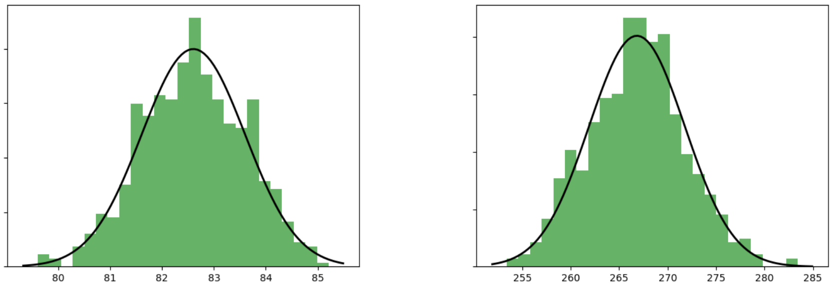
Table 2: Variation in positions

To make a better analysis of the oscillation in both axes, a Gaussian fit has been made for the data, this provides a more approximate measure of the variations in position, removing the contribution of the less probable points. The next Figures shows the probability distributions in each axis and their respective Gaussian fit. Finally the Gaussian width is the position variation. The results of this fits are in Table 3, these are some of the parameters required to calculate the elastic constant.



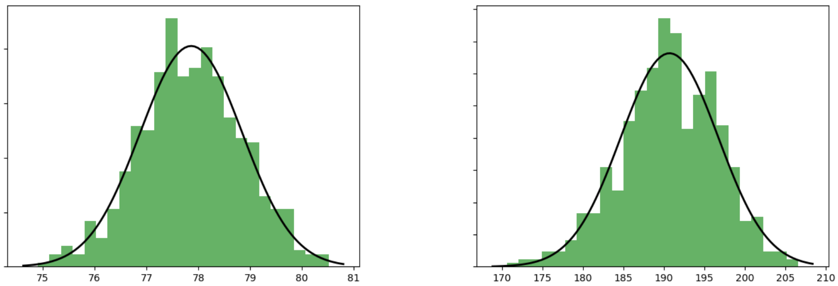
(a) X-axis (b) Y-axis

Figure 16: Probability distribution in space and fit in 84.40 mW



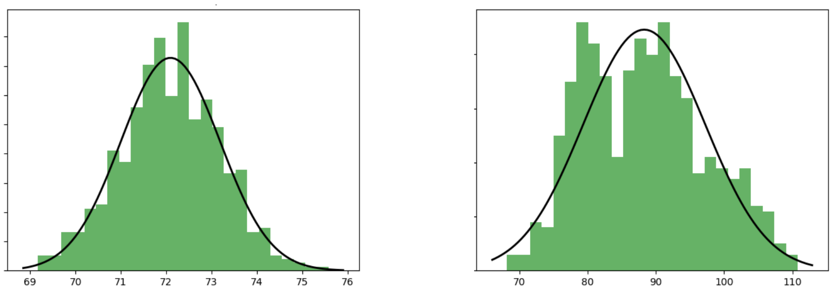
(a) X-axis (b) Y-axis

Figure 17: Probability distribution in space and fit in 67.00 mW



(a) X-axis (b) Y-axis

Figure 18: Probability distribution in space and fit in 57.60 mW



(a) X-axis (b) Y-axis

Figure 19: Probability distribution in space and fit in 44.20 mW

Representing position versus time, the time array will not be the same for each capture, as some data has been removed, for this reason it is important

Applied Power[mW]	$\Delta Y[\mu m]$	ΔX[μm]
84.40	14.29	2.63
67.00	11.67	2.35
57.60	14.16	2.31
44.20	21.07	2.58

Table 3: Variation in positions using Gaussian fit

to mention that the time arrays used will be adapted to the number of data available; dragging a small error.

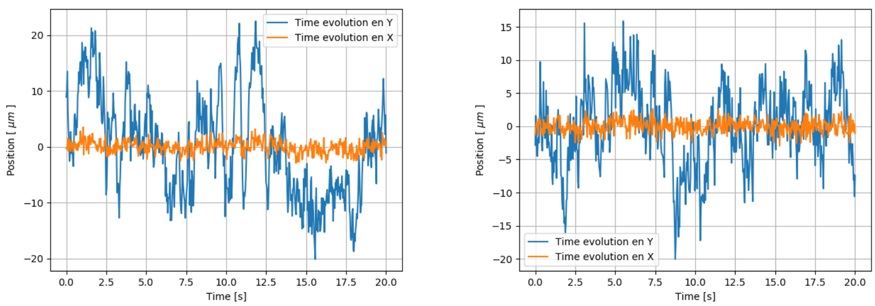
The trap's elastic constants and elastic force can be calculated using the equations 5.1 and 5.2 for a harmonic oscillator.

$$\omega = \sqrt{\frac{K}{m}} \tag{5.1}$$

$$F = K \cdot x \tag{5.2}$$

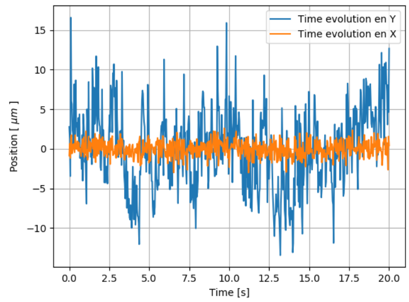
Where the mass of the microsphere has been estimated from the average volume offered by the manufacturer and the desnsity of the silica that composes it. These values are $r = 5$ [μm] and $\rho = 2.65$ [g/cm^3].

To calculate K and F, it is necessary to know the frequency of oscillation of the harmonic oscillator. To do this, a Fast Fourier Transform of the temporal evolution of all catches was carried out. Working in this new space makes it easier to find out at which fundamental frequency and in which corresponding harmonics it oscillates.

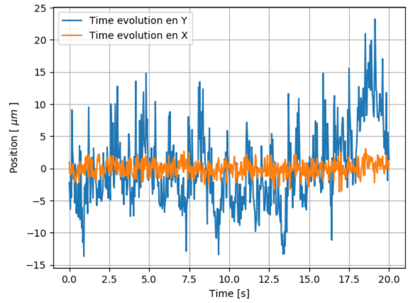


(a) 44.20 mW (b) 57.60 mW

Figure 20: Temporal evolution respect to equilibrium

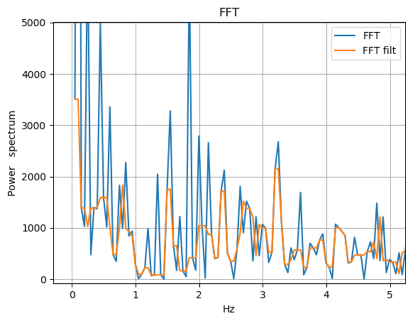


(a) 67.00 mW

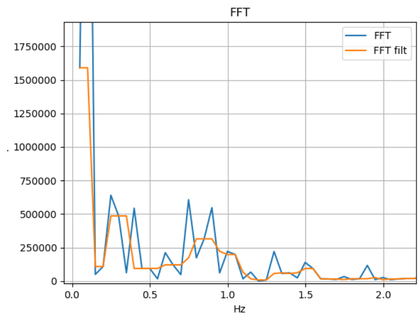


(b) 84.40 mW

Figure 21: Temporal evolution respect to equilibrium

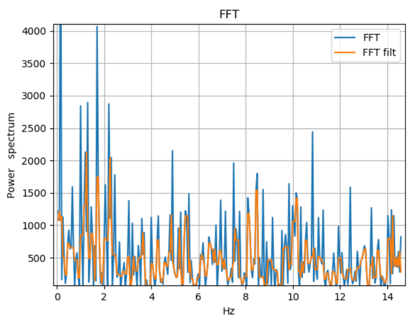


(a) FFT X 44.20 mW

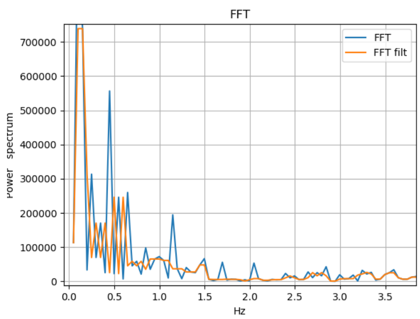


(b) FFT Y 44.20 mW

Figure 22: Fundamental Frequency $[Hz]$; $f_x = 1.85$ $f_y = 0.30$

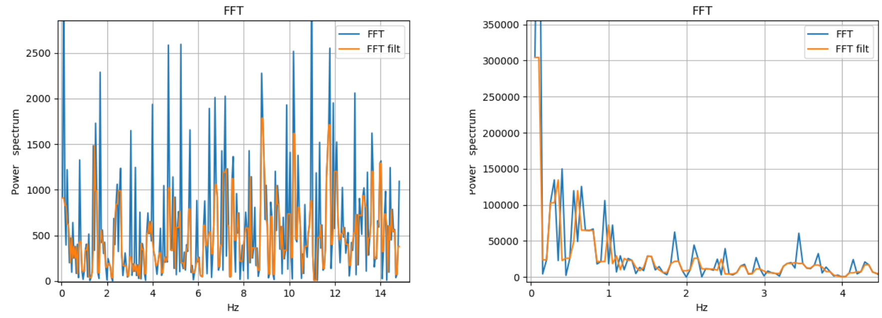


(a) FFT X 57.60 mW



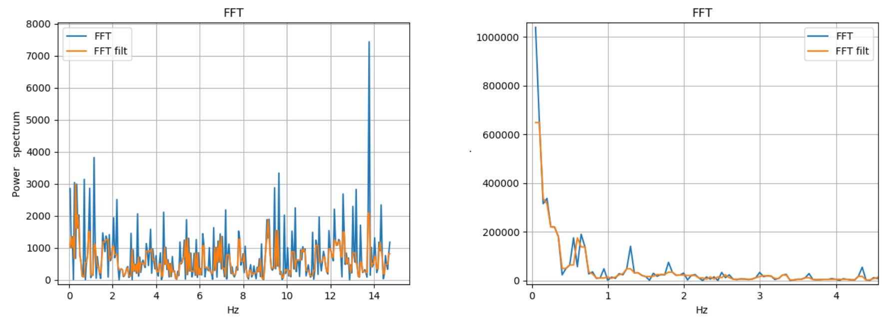
(b) FFT Y 57.60 mW

Figure 23: Fundamental Frequency $[Hz]$; $f_x = 1.70$ $f_y = 0.44$



(a) FFT X 67.00 mW (b) FFT Y 67.00 mW

Figure 24: Fundamental Frequency $[Hz]$; $f_x = 1.55$ $f_y = 0.56$



(a) FFT X 84.40 mW (b) FFT Y 84.40 mW

Figure 25: Fundamental Frequency $[Hz]$; $f_x = 1.15$ $f_y = 0.60$

The peak taken corresponding to the fundamental frequency to calculate the elastic constant and its force is represented in Table 4. The data was taken from the previous figures.The y-axis values have not been normalized due to the great difficulty involved, since the valuable information is on the x-axis.

Power	f_x[Hz]	f_y [Hz]	$K_x[kg/s^2]$	$K_y[kg/s^2]$	$F_x[J/m]$	$F_y[J/m]$
84.40	1.15	0.60	$7.19 \cdot 10^{-11}$	$1.96 \cdot 10^{-11}$	$1.89 \cdot 10^{-16}$	$2.79 \cdot 10^{-16}$
67.00	1.55	0.56	$1.31 \cdot 10^{-10}$	$1.70 \cdot 10^{-11}$	$3.07 \cdot 10^{-16}$	$1.99 \cdot 10^{-16}$
57.60	1.70	0.44	$1.57 \cdot 10^{-10}$	$1.05 \cdot 10^{-11}$	$3.63 \cdot 10^{-16}$	$1.49 \cdot 10^{-16}$
44.20	1.85	0.30	$1.86 \cdot 10^{-10}$	$4.89 \cdot 10^{-12}$	$4.80 \cdot 10^{-16}$	$1.03 \cdot 10^{-16}$

Table 4: Results

As expected, the results for the y-axis agree with the initial hypothesis, the elastic constant and the force increase when the power applied on the micro-sphere is increased.

For the x-axis a failure is clearly seen for the higher power measurement, possibly at the unreliability of the oscillation frequency, since its fft presents a large amount of noise.

After these results, special attention is given to the 84.40 mW measurement, its behavior is not under the initial hypothesis. A possible explanation is explained at the end of this section.

5.2 Laser Trap Elastic Constant for a long measurement

The same procedures as in the previous subsection have been followed but for a measurement that lasts 2 minutes instead of 20 seconds. This longer measurement was proposed in order to obtain more reliable values. Comparing with the same power measured previously it will be possible to see the improvement. However, as explained in the section dedicated to experimental errors, the power of this measurement is not the same, due to the overheating of the laser as it has been on for so long, making impossible to compare.

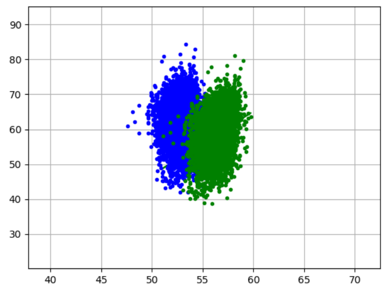
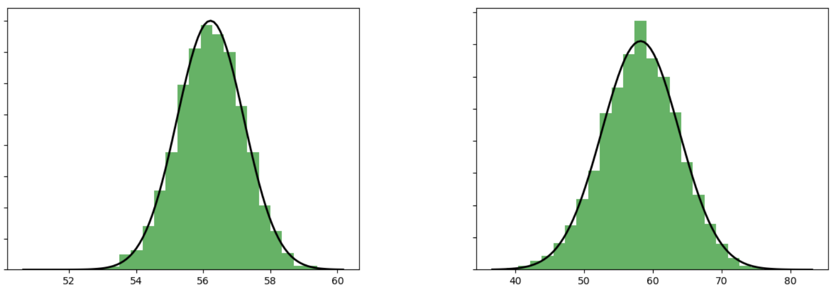


Figure 26: Angle correction measurement two minutes (3.34°)

The angular correction applied is the same as the four captures, but because the number of points is much higher, the weight of the measurements is far from the desired adjustment. It is therefore assumed that the camera is still turned at the same angle as for the previous captures, the correction of the data shows in Figure 26 that this assumption was correct.



(a) X-axis;width: 2.34 μm

(b) Y-axis;width: 13.22 μm

Figure 27: Probability distribution in space and fit in the longest measurement

It is appreciated that the Gaussian adjustment fits very well in Figure 27, this is because the measure has a greater number of data.

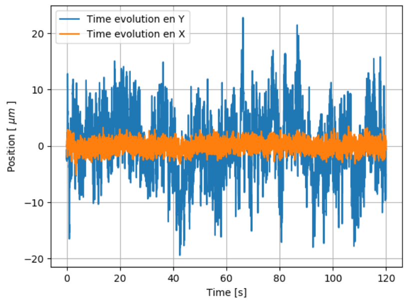
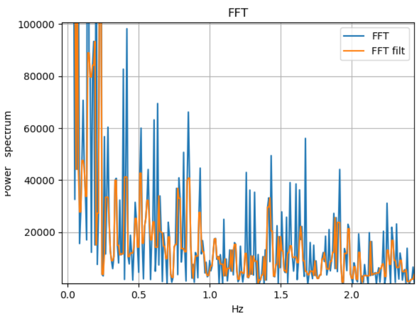
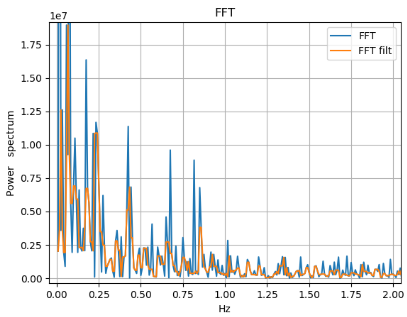


Figure 28: Temporal evolution of the longest measurement



(a) FFT in x-axis



(b) FFT in y-axis

Figure 29: Fundamental Frequency $[Hz]$; $f_x = 0.85$ $f_y = 0.43$

f_x[Hz]	f_y [Hz]	$K_x[kg/s^2]$	$K_y[kg/s^2]$	$F_x[J/m]$	$F_y[J/m]$
0.85	0.43	$3.93{\cdot}10^{-11}$	$1.00{\cdot}10^{-11}$	$9.19{\cdot}10^{-17}$	$1.33{\cdot}10^{-16}$

Table 5: Results of the longest measurement

5.3 Higher power measurement

As it has been mentioned many times throughout this work, the data collected on the 84.40 mW power presents a very wide movement on the Y axis. This result is a priori inconsistent. The initial hypothesis is that the more power, the greater the confinement; although this is true for the other measurements, the microsphere of greater power does not follow the same criteria.

To be able to explain the great oscillation movement of the sphere, it is necessary to talk about the characteristics of our trap. Unlike other optical traps, this one has a low confining power due to a low divergence. This was something done on purpose, since it achieves a greater spot width, which increases the probability that a sphere is trapped, but sacrificing confinement power

In order to explain how the divergence of a trap affects its confining power, attention is paid to the region adjacent to the spot. A trap with high divergence provides an adjacent zone with a weak gradient force, making it more difficult for the microsphere to get out. On the other hand, if the trap has low divergence, the zones near the spot do not change drastically their gradient force, and it is easier to move the sphere because it is less confined. To visualize this concept, Figure 30 is helpful.

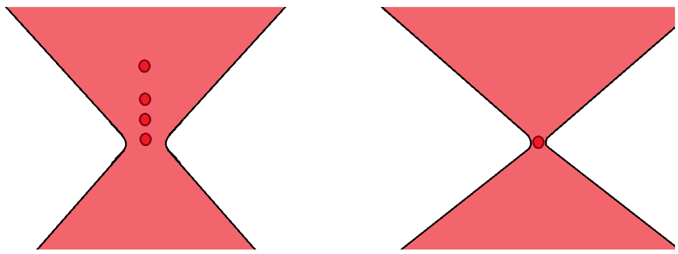


Figure 30: Optical trap divergence

When a sphere ascends to an area far enough from the spot, which is relatively easy, due to the low divergent power of the trap, two phenomena occur that explain the results obtained for the vertical and horizontal movements of the highest power. The vertical oscillation movement no longer follows a linear elastic force, since the microsphere is subjected to notable changes in its gradient force (the maximum elongation is very different from the minimum elongation due to the dependence of the gradient force on the y-coordinate). Horizontal movement is affected by the Gaussian nature of the laser beam. In the spot the beam is highly concentrated, causing the Gaussian that characterizes its distribution to be in a small region. A narrow gaussian function makes it possible to approximate a linear elastic force. When we move away from the spot the light diverges, causing a flattening in the gaussian so now it is not possible to consider the elastic force linear. Scheme of the explanation in Figure 31.

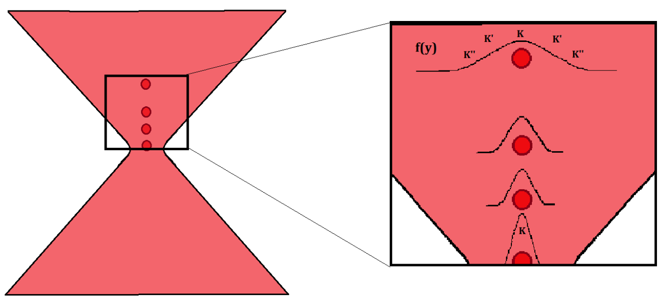


Figure 31: Gaussian dispersion

The measures taken have a great error, since to produce the levitation of the sphere it is necessary that the weight of the sphere is equal to the vertical elastic force. It moves away several orders of magnitude because the calculations made start from an approximation, the microsphere is not really in the spot, in fact it is farther than expected, because of the low divergence of the trap, in addition to what is explained in this subsection. Although the data and its analysis are correct, to obtain a more reliable measurement it is necessary to go deeper into the 3.5 equations, which really show the potential that governs the system. For future work using the information collected, it is necessary to use the corresponding simulations to accurately find the strength of the trap.

6 Scheduled experiments and improvements

Resumen. *Se recopila todas las medidas y experimentos programados para este trabajo, ofreciendo una breve introducción del fenómeno a observar y como se vería en el experimento usando bibliografía.*

As expected, the extraordinary circumstances experienced in the last part of this year had a negative impact on this experimental work. Although it is true that we managed to obtain data to work with, many interesting things remained unexplored. The main objective of this work was the construction of an optical trap and its operation, this process was achieved with much effort, time and countless attempts. While the first capture was made almost by chance (as the samples were not made in an optimal way), the second capture took quite a while to arrive, going through a learning process that ended with the preparation of samples in an optimal way. After reaching this point of experimental knowledge, levitating a sphere would become a process, within the complicated, more enjoyable to achieve.

With the arrival of the confinement, the possible measures to be carried out, remained in that, in only possible. In this section I will talk about all the measures that were programmed to be done with the material that was already in the laboratory and about future improvements to the experiment.

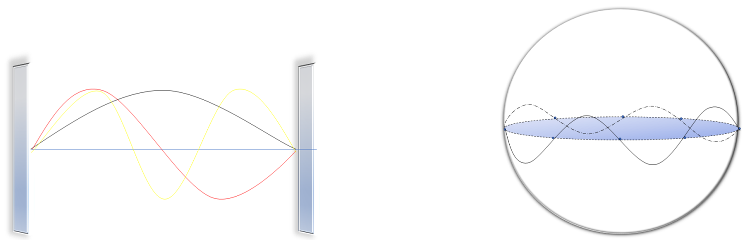
To begin with I will talk about a fairly simple measure that could have been done in the second capture, which was not possible due to the fall of the object of study.

Change the wavelength value and see how this affects the microsphere, because we are dealing with an optical micro-resonator we can give a quite approximate answer to what we could see. To do this it is necessary to explain a concept called Whispering Galary Mode.

Whispering Galary Mode

As we have already said, the microsphere behaves like a light container, this is achieved thanks to total reflections inside it, creating an internal standing wave characterized by very specific modes of vibration.

The mathematical characterization of the resonant modes for each type of resonator, can be modelled using a wave trapped between two parallel mirrors Figure 32 (a), since it is possible to make approximations to obtain an expression for the microsphere Figure 32 (b).



(a) Ideal planar mirror (b) Ideal spherical resonator

Figure 32: Geometric analogue between resonators

In order to obtain the oscillation modes for the parallel mirror system, it is necessary to solve an a very simple equation in partial derivatives, Equation 6.1, using the boundary conditions for the previously named resonator, Equation 6.2. Assuming that the light has the form of Equation 6.3 you get to Equation 6.4. For more extended explanation go to [4].

$$\nabla^2 U + k^2 U = 0 \tag{6.1}$$

$$U\left(r = 0\right) = 0 \quad U\left(r = d\right) = 0 \tag{6.2}$$

$$U\left(r\right) = A \sin\left(kz\right) \tag{6.3}$$

$$d = m\lambda \tag{6.4}$$

Assuming that the number of nodes present in the sphere is high,as show the Figure 33. Is obtained Equation 6.5 where 'R' is the radius of the sphere and 'm' the number of nodes.

$$P \approx 2\pi R = m\lambda \tag{6.5}$$

The last equation can be set to parameters known in the laboratory as the refractive index.

$$\nu = \frac{n 2\pi R}{m} \tag{6.6}$$

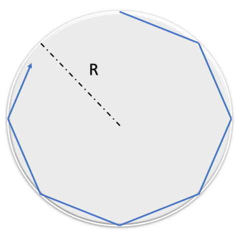


Figure 33: Wave travel inside the microsphere

Once this concept has been explained, it is known that the microsphere being levitated will have a characteristic resonant frequency. If the sphere is illuminated with monochromatic light, tuning the frequency used with the resonant, something very interesting is seen.

Using Figure 34 as a reference in the bibliography, one could venture an increase in the force experienced by the trap. This paper analyzes, using Mie's theory, the experimental behavior of a microsphere levitating in an optical trap when it is subjected to changes in the wavelength that illuminates the sphere.

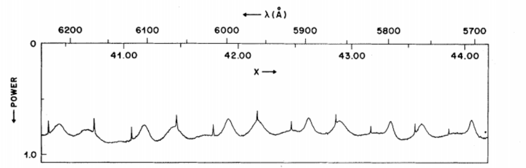


Figure 34: Measured power for levitation λ vs X (size parameter) [5]

It is logical to think that this behavior could be repeated in our experiment, changes in the strength of the trap will be observed (translated into movement) if we approach resonant frequencies of the microspheres. To do this it is necessary to vary the micrometric screw that regulates the Titanium Sapphire used in the experiment.

Among the many options that could have been explored with the resources of the laboratory, the most notable is the replacement of silica microspheres with rare earth doped ones. The simple fact of changing the original sample for one with a luminescent nature gives way to an interesting study of its behavior. As it was done before in this section, theoretical concepts related to the possible measurement, and the result that would be reached, are introduced.

Up Conversion

It is a process whereby after illuminating a photoluminescent material whit a specific wavelength, a shorter wavelength is earned. This process is achieved with a sequential absorption of several photons, which manage to excite the material, when returning to the fundamental state, a more energetic light is obtained. This excitation, entered in more specific details, it happen in two steps; first excites the fundamental level at a metastable excited level and then, with another photon of the same wavelength as the previous one, excite it to a higher level (more energetic). The results of this excitation in different fragments is a more energetic emission. The difference with the conventional photoluminescence is that there is no interaction with the phonon network (Figure 35).

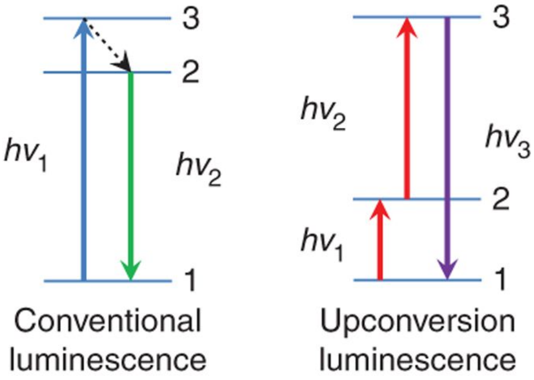


Figure 35: Scheme of up conversion

In order to measure the up conversion, a spectrograph is usually used to capture the two wavelengths present in the process. There are two ways of attaching this to our experimental setup, removing the camera to place the spectrograph there, as it allows much easier focusing on the microsphere, or using a fiber optic, which allows easier installation despite how difficult it would be to align this instrument with the laser spot.

Luminescence.

Among the interactions that exist between radiation and matter, it is important to deepen the luminescence because it provides a source of non-thermal radiation that allows observing the processes that occur in the interior of the microsphere. This process can have different origins, in nature is easy to find biological organisms capable of generating light, but for the experiment bioluminescence is not interesting, luminescence is produced in materials doped with rare earth. It is called photoluminescence and is produced by emissions of photons of the material obtained in transitions of excited levels of electrons to lower levels, this previous excitation is achieved in our case with laser radiation.

According to the nature of the excited state and ground state, its possible differentiate two types of photoluminiscense as show Figure 36. The difference between Figure 36 (a) 'fluorescence' and Figure 36 (b) 'phosphorescence' it is the rate of emission.

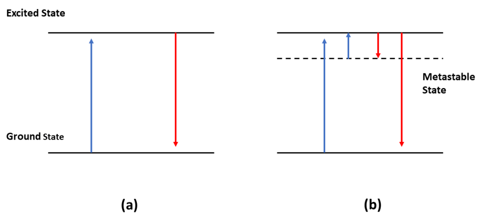


Figure 36: Types of Luminescence

The light coming from the laser does not cross the sphere and creates a stationary wave, the process is different, because light needs the same wave vector direction that the dielectric (something quite unlikely and that happens by diffusion). But when increase the laser power, it is more possible that some light will penetrate the microsphere and exciting the luminescent ions, this emission of photons is what will eventually cause the stationary wave enclosed in the microsphere.

Optical cooling

The explained concepts of fluorescence and up conversion are used to explain optical cooling. The initial objective will be to see how the microsphere experiences a cooling due to the interaction with the laser light, this can occur in different ways. There are many laser cooling techniques such as Doppler cooling or Sisyphus cooling, however the technique used in this type of experiment will be ones of the Raman Effects ,anti-Stokes fluorescence. Raman's effect describes the inelastic scattering in solids, usually when light hits in matters it is reflected (light has the same energy) but a really small part is absorbed by phonon network producing variation on temperature, that have a important consequences in energy emitted light. Can be differentiated two types of Raman's effects or Stokes's Scattering according to absorption or emission of phonons like shows Figure 37.

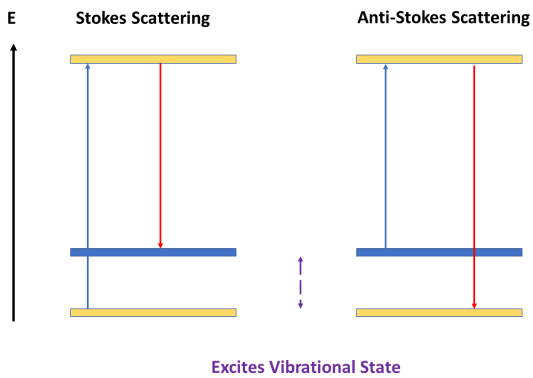


Figure 37: Types of Raman's effects

To be able to measure an optical cooling using doped spheres it is necessary to have a trap that works in vacuum since if it is done in air the results will not be noticeable. As shown in Figure 37, the anti-stoke cycle absorbs the energy needed to reach the excited level of the photon network, that is, it uses the vibration energy of the sphere (temperature) to achieve it. The cooling is also due to another phenomenon produced by the electronic levels of the doped material, following the same principle as up-conversion cooling but with electronic levels.

This cooling is a double-edged sword, since as the sphere cools it changes size, becoming smaller and collecting less light. To observe this effect is quite difficult in practice because of the limitation of resources and the contribution of thermal noise in the areas near the microsphere. [6]

In order to measure the temperature at which the micro-sphere is located, two methods can be used.

Fluorescence intensity ratio

Fluorescence intensity ratio is a kind of temperature determination technique based on the change in the band shape luminescence, generally from a RE doped material. The technique studies the relative intensities of two radiative transitions, one between the electronic energy levels E2 and E1 and the other from the upper energy level E3 to E1. The proximity between the electronic levels E2 and E3 allows the upper level to be populated from the E2 population by thermal redistribution. Thus, the intensity ratios of these transitions depend on the temperature (they are thermally coupled), but they are independent of the source power intensity since the population of each level it is also proportional to the pump power employed. As shown in Figure 38, experimentally a sphere doped with luminescent material has a measurable change in its Fluorescence intensity ratio. As before, this information is collected with a spectrograph, taking into account the relative intensity of the transitions of the thermally coupled levels.

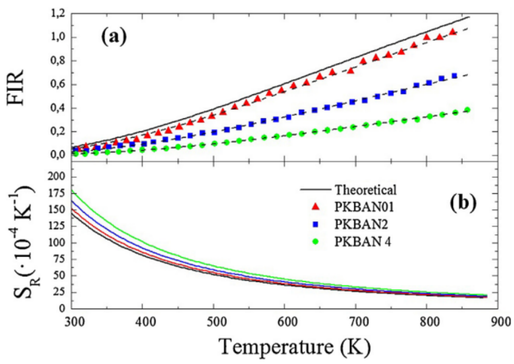


Figure 38: (a)Experimental fluorescence intensity ratio obtained versus temperature (b) Relative Sensitivity versus temperature [7]

Whispering gallery modes as a function of temperature

One of the possible measures that could be carried out in the laboratory, using existing measuring instruments and improving the optical trap (using vacuum) is to use a high-Q optical micro-resonator doped with a luminescent material as a temperature sensor exploiting the physical phenomenon of WGM. This technique is currently of great interest due to the high sensitivity it offers and the low uncertainty in the error.

The microspheres used present a phenomenon of total internal reflection that derives in a resonant behavior, the geometry of the resonator influences directly in the WGM, as it was seen in the theoretical background of WGM. The changes in temperature to which the sphere is subjected translate directly into dilations or contractions in the material, i.e. changes in its radius. These changes are noticeable in the resonant frequencies since they have required a modification in its resonance parameters [8]. In a system formed by a micro-resonator being hit by its resonant frequency there is an increase in its probability of emission, Purcell effect, with the help of a spectrograph you can see the intensity of the emission peaks, and most importantly, their position (which is translated into temperature).

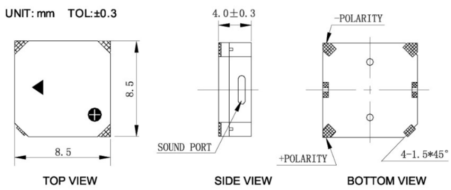
6.1 Improvements

Stabilize the trap

One of the biggest problems encountered when maintaining the microsphere levitating was the low stability of the laser and its heating due to a problem (at that time unknown) with the cooling system of the laser. The latter could have been solved with good maintenance of the laser cooling system. Increasing the stability would have been a little more complicated, one of the options considered was to use a second beam and cross it with the already present one, achieving a very stable spot where to levitate. But this would require dividing the beam, doubling the material used to focus it on the spot and a great effort to make both spots coincide in the same region of the space.

Vacuum seal

One of the implementations that can be made in this project is the replacement of the air optical trapping chamber with one that is vacuum sealed. This would facilitate the trapping of microspheres and the temperature stability of the chamber. This is due to the absence of thermal conductivity of the air, which allows not only to eliminate possible currents that may be generated but also to increase the precision of temperature measurement. However, this improvement of the experiment implies to devise a bead release system inside the chamber itself, which is quite complicated not only at a technical level but also in terms of resources. Although this was not an impediment to test it. The attempt to implement this improvement was based on coupling a piezoelectric (buzzer), with which it is intended to release the microspheres, tuning its characteristic frequency at the right time to produce a shock that would drop the microspheres that are weakly attached to the buzzer surface. This attempt was considered a failure since the microspheres did not fall homogeneously, something of vital importance to catch them. Therefore, trying to perform the experiment in a vacuum was discarded. The buzzer used appears in next Figure, it was dissected to expose the vibration zone, it was welded properly to connect it to a wave generator, and finally a silicone plug was created to couple it to the trap. This implementation did not work because the cloud microsphere dropped was heavy and agglomerated.



(a) Type of buzzer used

(b) Dissected and welded buzzer

Multiple captures

The study of isolated systems has always been very recurrent for physics, since it is possible to obtain a lot of information and compare it with theoretical developments. A great implementation for this experiment would be to trap two microspheres with two different light beams inside the same chamber with the intention of seeing how these two particles interact in a controlled levitation space.

This could be done by dividing the main beam to obtain two beams, these would be directed to the chamber. However, experimentally it would be very complicated to get two microspheres to fall in two different spots simultaneously. Moreover, after the experiment carried out in this work, it is most likely that the noise from external vibrations added to the individual oscillations, sometimes somewhat erratic, would make it impossible to obtain quality information. The whole experiment would have to be improved to carry out this study. One could also have studied how a binary system of microspheres trapped in the spot works. See how the behavior varies depending on their separation distance, or if the way of rotation and its changes in luminosity resemble a binary star system. In the first capture it was possible to catch a system of three spheres, two of them in a binary type arrangement, but as commented before it was impossible to mediate due to the sudden fall of all of them trying to change the camera. The third microsphere was above them levitating quite erratically, the nature of its strange oscillation would also have been of interest, in order to give an informed explanation.

Improve image quality

One implementation that wanted to be incorporated before the declaration of quarantine was to improve the chamber optical quality. The easiest to achieve, since the only thing that would be needed would be to cut and replace the piece of the chamber that faces the camera with a cover slice. The image would be much more defined because it possible focus on the bead directly, but without this improvement, the quality is doubtful.

7 Conclusions.

Resumen. *Para finalizar el trabajo se hace un recorrido por todas las secciones previas, recalcando que conocimiento he adquirido durante todo el experimento y mi experiencia a lo largo de todo el proceso.*

In conclusion, I would like to talk about everything I have learned during the execution of this work, which has had quite different sections when it came to dealing with it.

The first step that was taken for this work was to get to know the spectroscopy laboratory in depth, although I had already carried out some experiments in some practice subjects, I had not known it well until now. The environment of the experimental subjects throughout the grade had always provided us with the experiment already set up, and ready to be cached with it and a specific manual to guide you. Facing an empty table in the lab was unfamiliar to me. Learning the distribution of all the material in the laboratory was essential to be able to get the necessary elements to build the optical trap. Even though I initially had no idea how it was going to be built, knowing the available material helped in the construction process.

The lab is a place of multiple experiments, so it is important to keep an order at the work table and try to optimize my space as much as possible, so as not to disturb and make the experimentation easier for my lab colleagues. I achieved this by using a mirror that diverted the laser light only to my workplace, at the end this same mirror was removed from its optical support so that the laser was not monopolized only by me.

When I was building the experiment, I found that not everything is standardized, and that sometimes it is necessary to make certain modifications manually or use ingenuity, to get everything to fit. Like adjusting the trapping chamber to the XYZ, something that followed a totally handmade procedure. Once the optical trap was mounted, it was necessary to verify its operation, which took quite some time because even if the optical trap was well mounted, trapping beads is an art. To begin with, it was necessary to learn how to use the laser in the laboratory and discover at what power it is possible to achieve a trap. After making the first launches of microspheres, it was seen that when they passed through the laser spot (increasing its brightness much) if the power was not enough, they reduced the speed of their fall, on the contrary if you had an excess of power the bead was launched upwards.

When the ideal working power was finally found, the trapping took place. This first time, although it was not possible to make any measurements, it served to acquire experimental skill and to design with greater precision the tasks to be carried out after managing to trap. After much trying for a second catch, it was concluded that something was not working properly. The problem was that none or a very small number of microspheres passed through the laser spot, which was crucial for the trapping to take place, this event had to follow a statistical probability, something was wrong, so I paid attention to the sample preparation. The sample had to be evenly distributed over the surface of the cover slice so that when a hit was made, a homogeneous fall was produced. However, this was not the case, the beads clung too tightly to the surface, causing the cover slice to fall down with very few beads, or even to break due to the force of the impact. After several attempts I got the sample distributed in small clusters, small enough so that the microspheres would detach when hit, this increased considerably the number of useful hits to get trapping, forming clouds of microspheres that always passed through the spot, until getting the second trapping.

After carrying out the relevant measures, the data were managed to analyse that the measures taken did not present problems and, if not, to solve them in the next trap. The management and manipulation of the data, although it can be quite difficult, was not a problem, since thanks to the subjects of experimental techniques this process had been common throughout the degree and had enough experience and ease.

Unfortunately, the quarantine arrived and it was not possible to continue with possible measures.

After representing the data that had been obtained, it was found that the initial hypothesis was not fulfilled for all the measurements, increasing the power of the trap does not always achieve greater confinement. While this was true for almost all measurements, there had to be an explanation for the exceptions to this behavior. Although the basic theoretical concepts to explain the operation of the trap had been understood, it had been assumed that confinement was achieved near the spot, without changing its position. After understanding my failure, I went deeper into the events during the experiment, making it clear that the microsphere was never in the spot and that the higher the power, the further it went. This became evident in the measure of greater power, but the fact that at no time the microsphere was located in the spot carried an error in all the calculations because to be able to know with high precision the confinement force it was necessary by means of simulators to know of which form the laser behaved after moving away from the spot.

Although I think that the simple fact of building the optical trap and putting it into operation is already an achievement, the amount of possible programmed experiments that remained to be explored, produces a little frustration and uneasiness. I hope that in the years to come another student will be able to make the most of this experiment that I have invested so much time and dedication in, and of which I have good memories despite the setbacks and headaches that come with experimental work.

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