Using a laser to delay a particle

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We tried to find how the motion of a polystyrene sphere was affected by a focused laser. A laser was used as a tweezer to trap a tiny polystyrene sphere, which was suspended in distilled water. Although the trapping strength was not strong, we were able to delay the movement of the sphere against gravity. The movement of the sphere was recorded as a video. We tracked the position of the sphere through pixels in each frame. The sphere was clearly delayed by the laser. An analysis of the position change with time was performed. In order to find how strong the trap was, the standard deviation of the sphere's positions was calculated which is 6.34×10^{-7} m. The spring constant of the x axis due to the effect of the optical trap is $(1.03 \pm 0.5) \times 10^{-8}$ kg/s^2.

INTRODUCTION

In 1967, Dr. Arthur Ashkin did an experiment at Holmdel, a Bell Labs facility. He used a laser beam to push a small polystyrene sphere in water against gravity. Then Ashkin found that he could hold the sphere without touching it if there was another beam from the opposite side also shot on the sphere. These two laser beams formed an optical trap. This finding was published in 1970 in *Physical Review Letters* [1].

But Ashkin encountered difficulty because the atom was too hot to be held. As technology developed, in 1984, Ashkin successfully made the atom cool enough to be trapped. Soon afterwards, he furthered this study and focused on a more complicated situation: using a focused laser beam to trap a cooled atom. The result was published in 1986 [2].

An optical tweezer is a tool that is used by a wide range of researchers and studies to manipulate microscopic objects. They are used to hold, trap, and investigate small particles, including dielectric and absorbing particles. In pharmacology, optical tweezers can be used to capture bacteria and viruses. In medicine, it helps increase the efficiency of treatment by making drugs more targeted.

In the present experiment, polystyrene spheres were put in the water. A laser beam was used to trap a sphere in the solution.

THEORY

When light enters into a material with a higher refraction index, n, the speed of light will decrease while frequency stays the same, shown in Fig 1, which causes the light to bend to the side of the normal. From Snell's law,

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2). \quad (1)$$

Putting n_1 and n_2 on the same side of the equation,

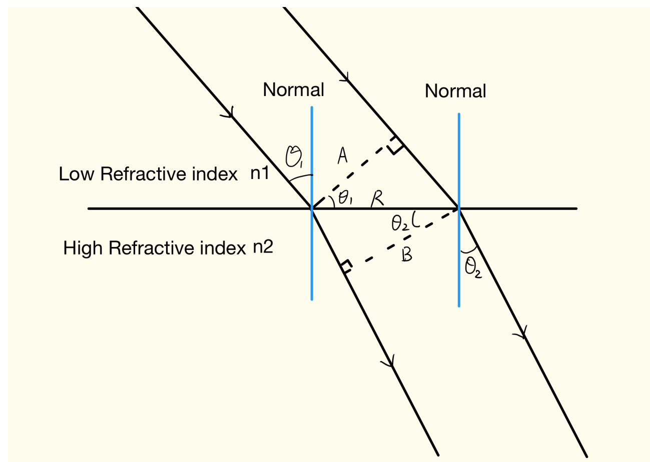

FIG. 1: Schematic showing the light was bent to the side of normal when it went through a material with a higher refractive index.

resulting in

$$\frac{n_1}{n_2} \sin(\theta_1) = \sin(\theta_2), \quad (2)$$

which means if the light enters a material with a larger index of refraction, the light will be bent to the side of the normal. When two paralleled laser beams enter a sphere from both sides, the two laser beams both are bent toward the center of the sphere because of the geometry of the sphere, like Fig 2. As the laser has a higher intensity in the center of the beam, the less intense beam always refracts towards the center of the laser, whereas the more intense beam placed closer to the center bends towards the outside of the laser. As we know, the photons leave the light source carrying momentum, and the momentum is transferred to the sphere when the light is refracted. As the momentum of photons is conserved, when light is bent by the polystyrene sphere to one side, a force on the opposite direction will be exerted on the sphere, just like Fig 3. As the more intense light contains more photons, which contain more momentum, a greater force can be exerted on the sphere than the less intense light. The total force on the sphere is towards the center of the laser.

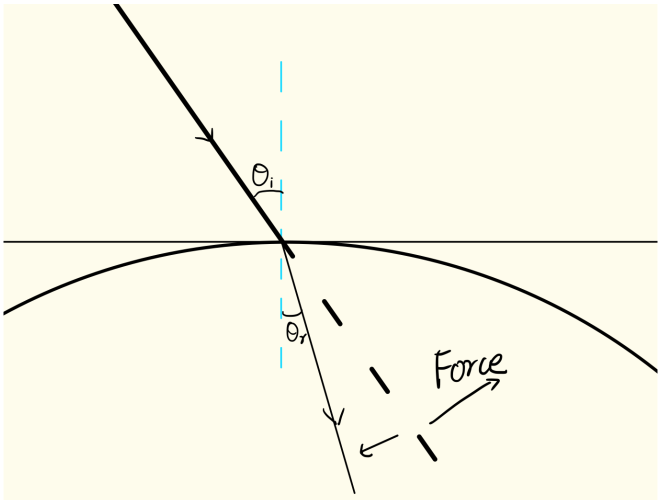

FIG. 2: Schematic showing light is bent toward the center of the sphere due to the geometry of the sphere.

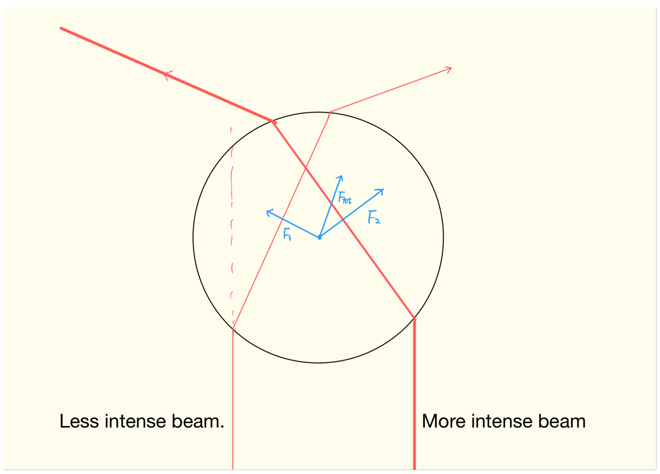

FIG. 3: Schematic showing the force exerted on the ball when the laser was not focused

So the sphere stays at the center of the beam and moves with the light.

In Fig 4, the laser is focused at the focal point f, so the intensity of the light is highest at its focus. If the light beams are refracted by the sphere before it reaches the focus, Light beam 1 will give the sphere a force to the upper left due to the conservation of momentum. Light beam 2 will give the sphere a force to the upper right. If the sphere is at the center of the light beam, the force to the left and to the right will be canceled. But the force upward will be added together, so the total force on the sphere moves upward to the focal point. Similarly, when the sphere is above the focus, Light beam 1 gives the sphere a lower right force, and Light beam 2 gives the sphere a lower left force due to the conservation of momentum. The total force that is exerted on the sphere points downward, and will push the polystyrene sphere

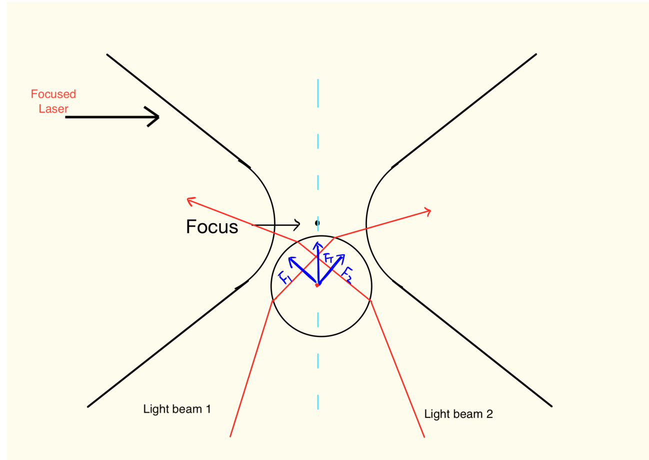

FIG. 4: Plot showing the force exerted on the sphere when the laser was focused and the sphere was under the focal point

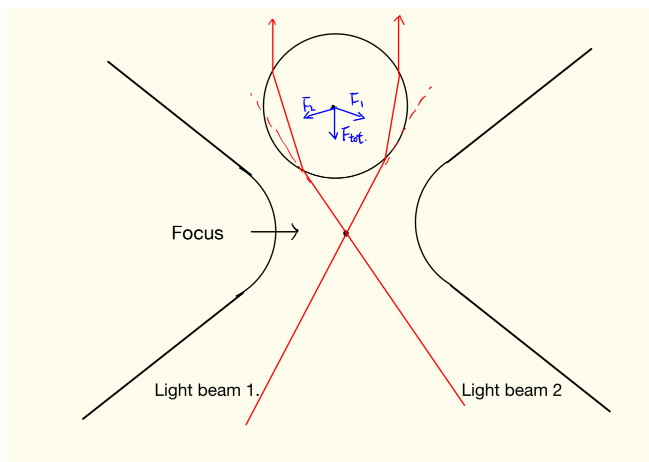

FIG. 5: Plot shows the force exerted on the sphere when the laser was focused and the sphere was above the focal point

to the focal point. So if the laser is strong enough, the sphere will be held at the focal point of the laser, which works as a tweezer.

In this experiment, the laser was used to trap a polystyrene sphere against the gravitational force.

PROCEDURE

All the equipment has already been set up by a supervisor, and all the lenses should not be moved. Fig 6 shows how the components of a microscope were rotated to be put in to one plane. A laser is focused by the microscope objective lens, which formed a trap on the sample slide. The optical components were arranged in the the order in Fig 6 to change the path of the laser beam and also make it to be more tightly focused. The two mirrors were used to reflect the laser beam, which increased the

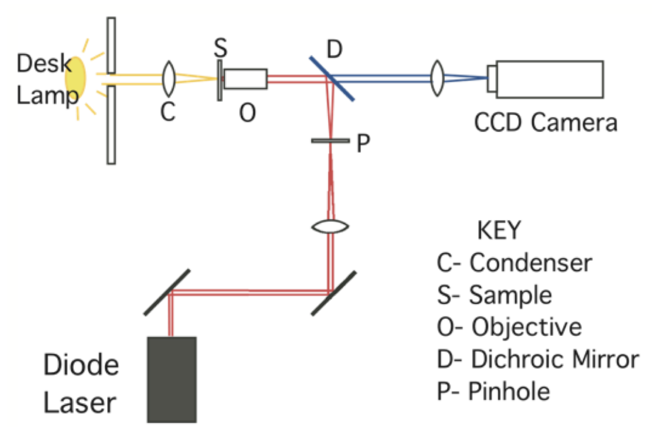

FIG. 6: shows the components of the experiment. Two mirrors were used to change the laser beam path. Dichroic mirror was used to reflect the laser to the objective lens and let the light from the sample slide pass through to the CCD camera.The figure is reproduced from reference[3]

steering ability. The beam was focused when it passed through a converging lens. Then, the focused laser beam went through a pin hole which acted as a spatial filter that assured the shape of the laser beam was circular. A circular shape can focus the laser beam more tightly than other shapes.

The laser beam diverged after it went through the pin hole and there was a dichroic mirror behind the pin hole. The dichroic mirror only reflected light with a certain wavelength. It reflected the laser beam to the objective lens, whereas the light from the sample slide went through it to the web camera. This allowed the movement of the polystyrene sphere to be observed by the web camera. Light from the desk light was focused by the condenser to provide enough light to illuminate the sample slide, which worked as a condenser on the microscope.

The first step in this experiment was to make a test slide. After cleaning the slide, laboratory film was cut into a U shape which provided some space between the microscope slide and glass cover and also prevented leaking of the solution. We placed one or two drops of polystyrene solution on the slide and covered it with a microscope cover glass. Then we put the slide on the stage and moved it until spheres were clearly able to be seen by the web camera. Adjusting the position of the sample slide, the spheres in the solution can be clearly observed.

In order to trap the spheres, the beam was placed in their path so that when they entered the fringes of the laser, their movements were delayed due to the force that pulled them to the focus. When a polystyrene sphere was trapped, video was recorded by Photo Booth. Then we found a fixed point on the sample slide that could move along with the slide. A photo was taken to record the initial place of the fixed point. Then the slide was moved

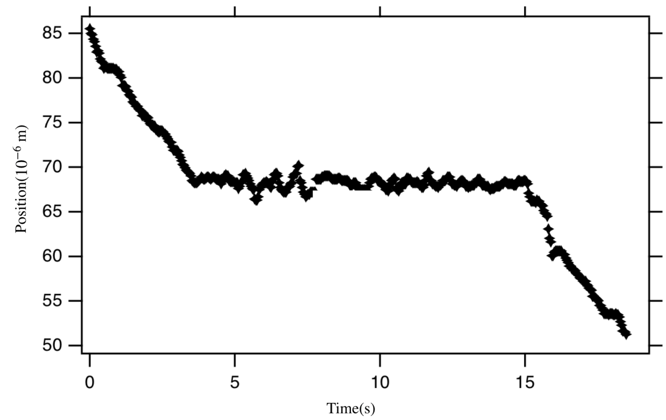

FIG. 7: Plot of x value of the position of the sphere versus time. The motion of the sphere in the x direction was halted between a time of 4 s and 15 s because of the effect of the laser beam.

0.001 inch. A photo was taken to show the final position of the fixed point. These two photos were used to analyze the distance that the sphere traveled.

RESULT

During the experiment, it showed that the focused laser beam had some effects on direction and speed of the polystyrene sphere's movement. A laser with higher energy could create a higher strength trap that can act as a tweezer that can move the sphere.

Photo Booth was used to record a video of the sphere movement. Capstone was used to track the position of the sphere in each frame. By clicking on the sphere in the frame, capstone created a coordinate in pixels. In order to find the relationship between pixels and real length, a fixed point on the sample slide was found. Then, the slide was moved by 0.001 inch. The pictures of initial position and final position were taken. By tracking the initial and final position, the relation between pixels and real distance was determined.

Due to the gravity, the polystyrene sphere was moved in x direction and the movement in y direction is ignorable from the position we tracked.Using Capstone, the x position of the trapped sphere was tracked. We exported the x value and time in Igor and the plot of x versus time was presented as in Fig 7, which clearly showed how the movement of the sphere was delayed from the 5th second to the 14th second. The sphere's x position was changing initially. Then the sphere was interfered by the laser beam so its x position held steady. But the trap is not strong enough to be held against the gravity, the sphere's x position started changing again. We found the strength of the trap through the standard deviation of the x value when the sphere was trapped, which is 6.34×10^{-7} m.

Then insert the standard deviation value into

$$\frac{1}{2}k_x < x^2 >= \frac{1}{2}k_B T \tag{3}$$

where k_x is the spring constant for the trap along the x axis, $< x^2 >$ is the standard deviation of the sphere from its average position, k_B is the Boltzmann's constant, and T is the absolute temperature in kelvin which was predicted to be 300 K, the spring constant of the trap along x axis can be calculated as $(1.03 \pm 0.5) \times 10^{-8}$ kg/s^2.

The main uncertainty in this experiment was how to track the position of the sphere in Capstone properly. Because I needed to click the sphere in every frame to get its coordinate in pixels, and the sphere was not well focused, it is hard to track the position with the cursor. It was hard to find the corresponding point in the video when we were trying to find the relationship between pixels and position.

CONCLUSION

In this experiment, a laser was reflected to go through an objective lens of a microscope. The laser was focused on the sample slide behind the objective lens and was used to affect the movement of a polystyrene sphere. The motion of the sphere went through a focused laser and was recorded as a video. Using Capstone to track the motion of the sphere, the effects on the motion of the sphere was demonstrated. From the graph, it is clear that the PS sphere was held against gravity. In order to find how strong the trap was, standard deviation of position on the x axis was calculated to be 6.34×10^{-7} m. The spring constant of the trap, which shows how strong the trap is, was determined to be $(1.03 \pm 0.5) \times 10^{-8}$ kg/s^2.

[1] Steven Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable. Experimental observation of optically trapped atoms. *Phys. Rev. Lett.*, 57:314–317, Jul 1986.

[2] Arthur Ashkin, 2019. Online; accessed 18-September-2019 http://www.laserfest.org/lasers/pioneers/ashkin.cfm.

[3] The College of Wooster Physics Department. *Junior IS Lab Manual, Ashkin: optical tweezers*, 2019.