Optical Trapping of mesoscopic objects

Report submitted by: **Md Majid Hussain**[a] **and Yazhini A R**[a]
Under the guidance of **Dr. Deepak Kumar Gupta**[b]

[a]*Summer Training in Physics and Chemistry (STIPAC)-2025* , [b]*CMPD, Materials Science Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu-603102.*

Abstract: Optical trapping, also known as optical tweezers, is a powerful technique that uses highly focused laser beams to manipulate mesoscopic particles with high precision. Based on the transfer of momentum from photons to matter, optical traps can exert pico- to nano-newton forces to firmly hold and move dielectric particles, biological cells, or even individual molecules without physical contact. Here, we have demonstrated the trapping of single polystyrene particle using single beam gradient trap and the stiffness at which the trap is created were extensively studied by varying the laser power.

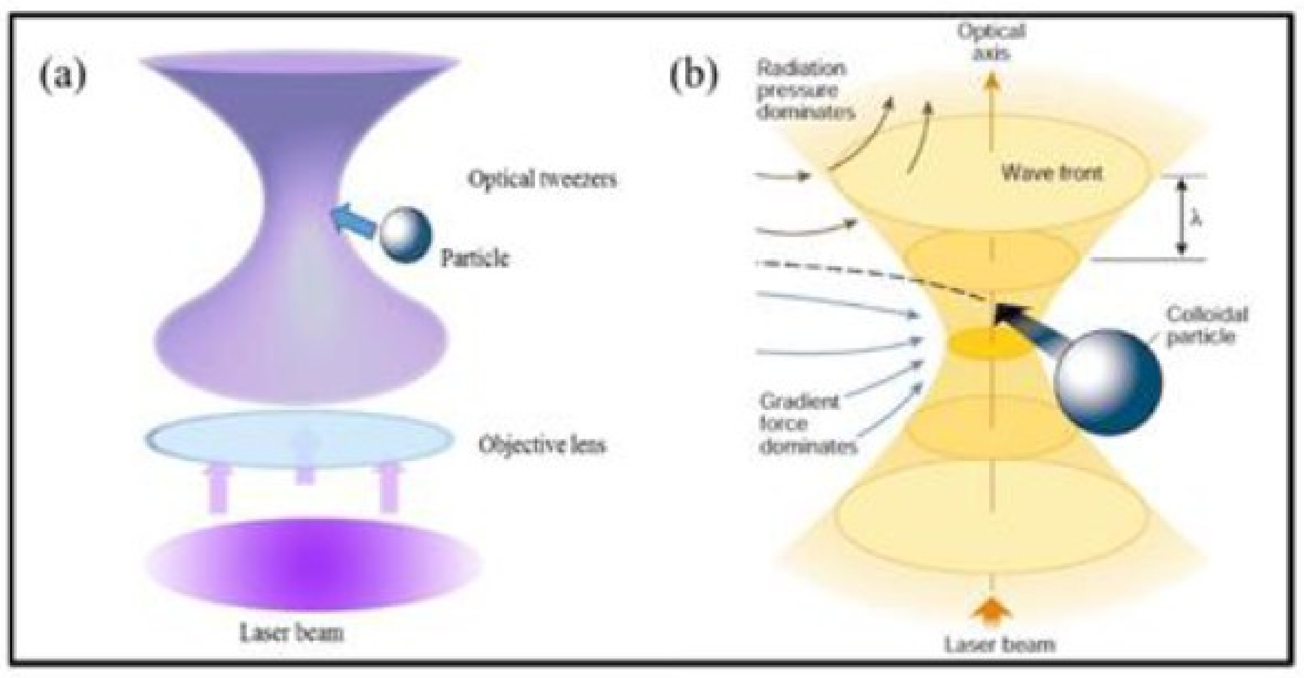
1. INTRODUCTION

The foundation for optical trapping was laid in the early 20th century when physicists like James Clerk Maxwell and Peter Lebedev theorized and demonstrated that light can exert pressure on objects. And with the invention of laser in 1960, which is a tightly focused coherent beam made it possible to trap the particle effectively. In the 1970s, Arthur Ashkin at Bell Labs developed practical methods [1, 2] for utilizing this radiation pressure to trap microscopic particles. Initially he developed a dual-beam optical trap, using two counter-propagating laser beams. This configuration provided opposing scattering forces that cancelled each other out, while the gradient forces (arising from the refractive index mismatch between the particle and surrounding medium) pulled the particle toward the region of highest intensity—typically, the center point between the two beams. A major breakthrough came when Ashkin discovered that a single highly focused laser beam could also act as a stable optical trap [4]. In this setup, known as a single-beam gradient trap, a strongly converging laser beam (focused by a high numerical aperture objective lens) creates an intense electric field gradient near the focal point. The gradient force pulls dielectric particles toward the beam focus, while the scattering force pushes them along the beam direction. When the gradient force dominates, the particle becomes stably trapped in all three dimensions. And this technique became a versatile tool in physics which had its application in various fields.

2. PRINCIPLES OF OPTICAL TRAPPING

Optical trapping relies on the radiation pressure exerted by light to manipulate small particles. This technique, often implemented using optical tweezers, involves a highly focused laser beam that creates a trap capable of holding and moving microscopic objects.

- **Scattering Force:** This force pushes particles in the direction of the light beam due to photon momentum transfer.
- **Gradient Force:** Arising from the intensity gradient of the laser beam, this force pulls particles towards the region of highest light intensity, typically the center of the beam.



$$\mathbf{F}_{\mathbf{scatt}} = \frac{I_o}{c}\frac{128\pi^5 R^6}{3\,\lambda_o^4}\left(\frac{m^2-1}{m^2+2}\right)^2 n_m$$

$$\mathbf{F}_{\mathbf{grad}} = -\frac{n_m^3 R^3}{2}\left(\frac{m^2-1}{m^2+1}\right)^2 \nabla E^2$$

$$F_{gradient} > F_{scattering}$$

Our present work is mainly divided into three parts. (i) Preparation of dilute polystyrene sample for optical trapping. (ii) Study of the experimental setup and trapping the particles. (iii) Processing the image and extracting the coordinates from the processed video that are used to determine trap stiffness.

3. SAMPLE PREPARATION

A dilute suspension of polystyrene microspheres is prepared by diluting it with water. This dilution ensures that the particles are well separated and can be individually trapped. To create the sample chamber, a clean glass microscope slide is used as the base, and a thin spacer is placed on it to create a shallow cavity. A small drop (around 5–10 μL) of the diluted solution is then added to the center of the slide, and a clean cover slip is gently placed over the drop, ensuring no air bubbles are trapped. The spacer prevents the cover slip from pressing directly on the sample.

4. EXPERIMENTAL PROCEDURE

For trapping, a continuous-wave infrared laser (commonly 1064 nm) is used, chosen for its low absorption by polystyrene and water. The laser beam is expanded using beam expanders and directed through a high numerical aperture (NA > 1.2) oil-immersion objective lens, which focuses the beam tightly into the sample chamber mounted on a microscope stage. The expanded beam ensures optimal focusing and a strong gradient force at the focal point. With the help of steering mirrors the focused spot can be moved in x-y plane. As the laser is focused slightly above the glass surface into the solution, Brownian motion causes individual particles to drift into the focal region, where they become trapped if the optical gradient force overcomes scattering forces. Temperature of the system also plays a major role in trapping as it directly affects the random motion of the particles. A camera attached to the microscope allows real-time visualization and recording of the trapped particle which can be then processed using image processing software. This setup enables the non-contact manipulation and precise control of microscopic particles using only a laser.

5. RESULTS AND DISCUSSIONS

5.1. Potential curve

After successfully trapping the particle, the next step involves analyzing its motion to extract physical parameters of the optical trap. A video of the trapped polystyrene bead is recorded using a microscope-mounted camera. This video is then processed using image analysis software to extract the two-dimensional (x, y) coordinates of the particle over time (fig.1).

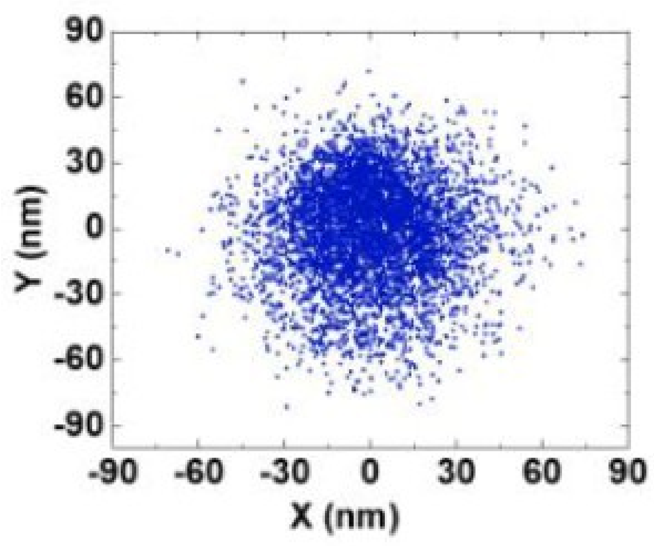


Figure 1. The scatter plot of extracted coordinates after processing the video.

For simplicity, typically only one coordinate (either x or y) is analyzed further. The extracted positional data is binned to create a histogram that represents how often the particle occupies each spatial position. According to the Maxwell-Boltzmann distribution, the probability $P(x)$ of finding the particle at a particular position x is related to the optical potential $U(x)$ by the relation

$$P(x) \propto e^{-\frac{U(x)}{k_B T}}$$

Where, k_B is Boltzmann's constant and T is the absolute temperature. By taking the natural logarithm of the normalized histogram, the potential energy profile $U(x)$ can be obtained

$$U(x) = -k_B T ln P(x)$$

This potential curve reflects the shape and depth of the optical trap. The procedure is repeated for different laser powers, allowing the study of how trap stiffness and potential depth vary with laser intensity which can be seen in Figure 2. This analysis helps quantify the strength of the optical trap and provides insight into the particle's confinement under different experimental conditions.

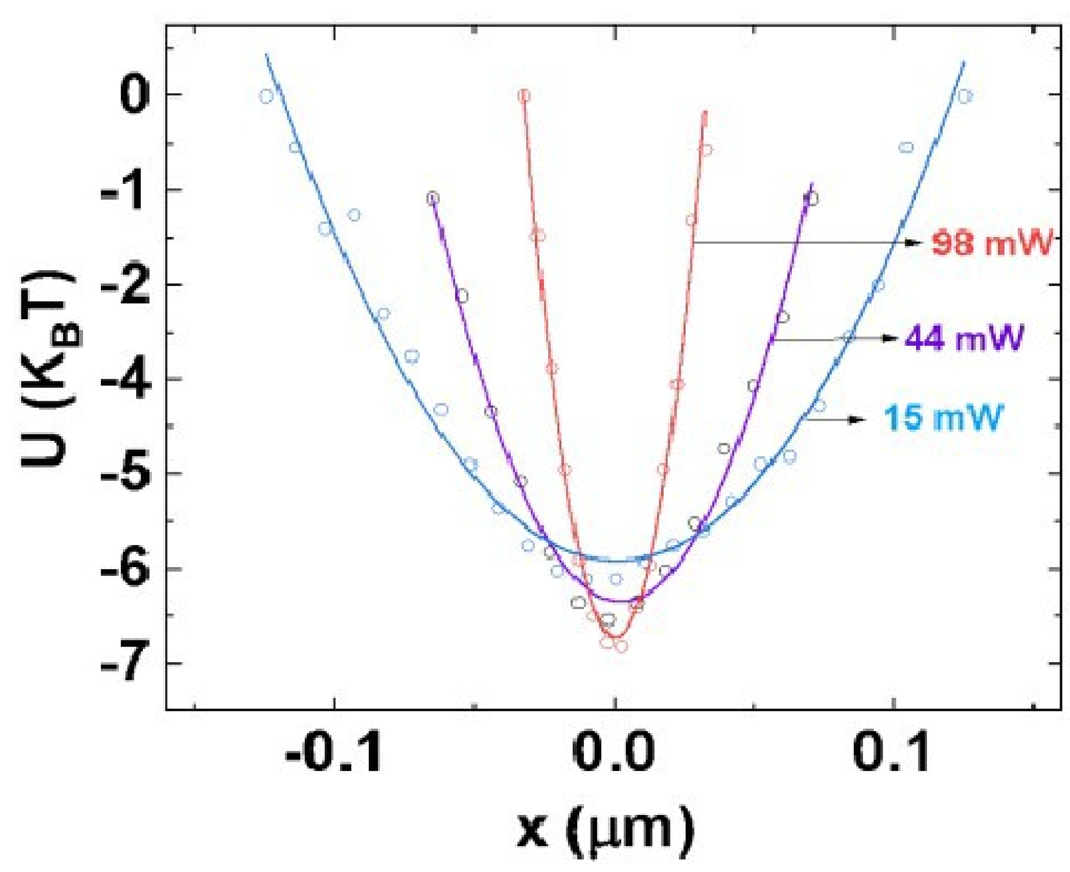


Figure 2. The variation in optical potential with respect to the laser power.

5.2 Factors affecting stiffness constant

The stiffness constant of an optical trap, which determines how tightly a particle is confined within the trap, is influenced by several key factors. One major factor is the numerical aperture (NA) of the objective lens; a higher NA enables tighter focusing of the laser beam, resulting in a steeper intensity gradient and thus a stronger trapping force. The refractive index of the particle also plays a critical role—when the refractive index of the particle is significantly higher than that of the surrounding medium, the gradient force becomes more effective, leading to increased trap stiffness. Additionally, the size of the particle affects the stiffness; larger particles generally interact more strongly with the light field, experiencing greater optical forces, although this relationship holds only up to a certain size before other effects like scattering dominate. Lastly, the laser power directly influences the stiffness, as higher power increases the intensity of the light at the focus, strengthening the gradient force and thereby enhancing the particle's confinement within the trap.

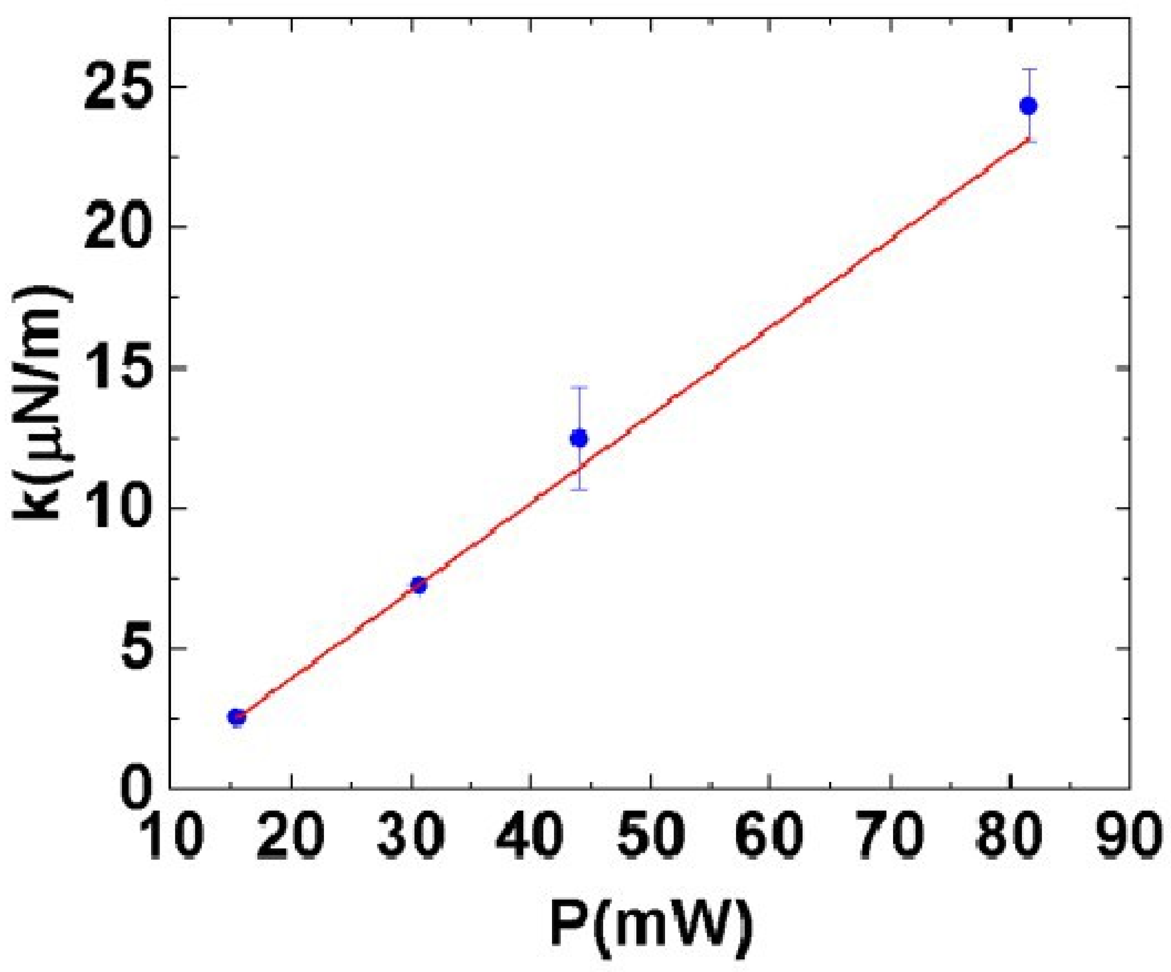


Figure 3. Linear relation of trap stiffness with respect to laser power.

5. CONCLUSIONS

This study demonstrates the principles and practical implementation of optical trapping using a single, tightly focused laser beam to confine polystyrene microspheres in a liquid medium. Through video analysis and application of the Maxwell–Boltzmann distribution, the optical potential was reconstructed, revealing how the particle's motion reflects the underlying trap landscape. As the laser power increases, the optical potential becomes steeper and deeper, leading to stronger confinement and a higher stiffness constant.

A plot of trap stiffness versus laser power (fig.3) shows a clear linear relationship, confirming that the stiffness of the trap scales proportionally with optical intensity. This controllable and quantifiable behavior makes optical trapping a precise and adaptable tool [3]. Its ability to apply well-defined, non-invasive forces at microscopic scales has enabled breakthrough applications across multiple disciplines—ranging from measuring biomechanical properties of cells and molecules to manipulating nanoparticles [5] and constructing soft matter systems. As a result, optical tweezers continue to be a cornerstone technique in experimental physics, biophysics, and nanotechnology.

REFERENCES

[1] A. Ashkin, "Acceleration and Trapping of Particles by Radiation Pressure," Phys. Rev. Lett., vol. 24, pp. 156–159, Jan. 1970

[2] A. Ashkin, "Optical trapping and manipulation of neutral particles using lasers," Proc. Natl. Acad. Sci. U.S.A., vol. 94, no. 10, pp. 4853–4860, May 1997.

[3] C. J. Bustamante, Y. R. Chemla, S. Liu, and M. D. Wang, "Optical tweezers in single-molecule biophysics," Nature Rev. Methods Primers, vol. 1, Art. no. 25, 2021.

[4] History of optical trapping and manipulation of small-neutral particle, atoms, and molecules. (2000, December 1). IEEE Journals & Magazine | IEEE Xplore.

[5] R. Wang, W. Li, Z. Xia, H. Deng, Y. Zhang, R. Fu, S. Zhang, T. G. Euser, L. Yuan, N. Song, Y. Jiang, and S. Xie, "Optical trapping of mesoscale particles and atoms in hollow-core optical fibers: principle and applications," Light: Sci. Appl., vol. 14, Art. no. 146, 2025.