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Optical Tweezers for Trapping Sub-micron Sized Particles

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Abstract
Optical Tweezers are the widely accepted and applied tools in many fields of sciences, working on the concept of radiation pressure. Many types of optical tweezer system have been introduced till date and is still in process of development. Due to the ability to trap and manipulate the particles as well as living cells and organisms of sizes ranging from few microns to few nanometers without any structural damage to it leads to a wide range of applications of OTs. In this paper we will be discussing different methods/systems of optical tweezers developed for different applications over the years. This will give us the insight of working process and manipulations technique of conventional optical tweezer (COT) as well as recent developments of it.

Keywords: Optical tweezer, radiation pressure, nanoparticle manipulation, conventional optical tweezer

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1. Introduction

Arthur Ashkin, famously known as the father of optical tweezer, was the first to come up with the idea of trapping particle using the light pressure in 1970 [1], after noticing a force pulling particle towards the beam axis (high intensity region) in the laser beam, and showed particle trapped in 2D and 3D trap. First 3D trap was made by two counter-propagating beams [2] with their respective focus points, where particle is trapped at the equilibrium point between the beam focuses. Then he used a tightly focused single gradient beam and trapped and levitated a Mie dielectric particle which was a 10-micron glass sphere [3]. He then called this setup as optical tweezer as it was similar to a manual tweezer. Optical tweezer is a device/setup which can trap and manipulate small particles/ molecules or living organisms or cells ranging from few microns to few tenths of nanometers by only using the light force without any significance damage to their bodies. The particle is trapped due to the presence of two main forces, i.e., scattering force and gradient force [4]. Scattering force is generated due to the momentum change during the process of scattering of incident photons after passing through the body of particle which eventually pushes the particle away from the source in the direction of the beam. Whereas, gradient force is generated because of the intensity gradient of a Gaussian beam which forces the particle to move towards the high intensity region or the beam waist. The particle can only be trapped if the gradient force overpowers the scattering force of the beam. In conventional tweezers it is achieved by tightly focusing the laser beam using high numerical aperture objective lens.

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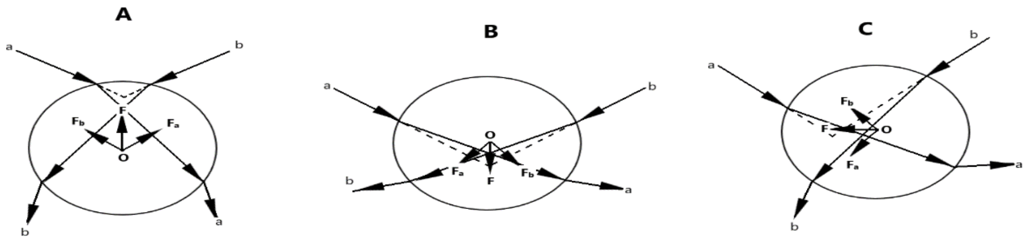

Figure 1: Mie particle trapped in single beam gradient trap. multiple refractions of rays a and b for the axial and transverse displacement from the beam focus f generates radiation pressure forces F_a and F_b. Net force F works as the restoring force for the particle pushing it towards the beam focus f [5].

1. Development of optical tweezers

1.1. First optical tweezer trap and optical levitation trap

Using the radiation pressure of light, he levitated the particle in the air by balancing the downward gravitational force of earth by the upward scattering force, whereas, the transverse displacement of the particle was confined by the gradient force of the beam making a levitation trap. In around 1983, Ashkin trapped a particle using a single gradient beam. To make gradient force greater than the scattering force he tightly focused the beam using a high numerical aperture objective lens[6].

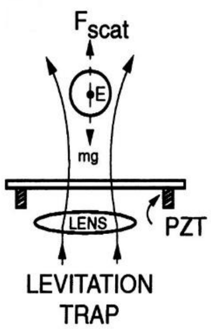

Figure 2: Schematic of Optical Levitation trap [2]

1.2. Magneto – Optic Trap setup (MOT)

MOT setup can slow down the particle and cool them to the temperature of few millikelvins. Since it traps a good number of atoms of the order of $10^6 – 10^8$ atoms at the center of the trap hence creating sea of trapped atoms called optical molasses[7].

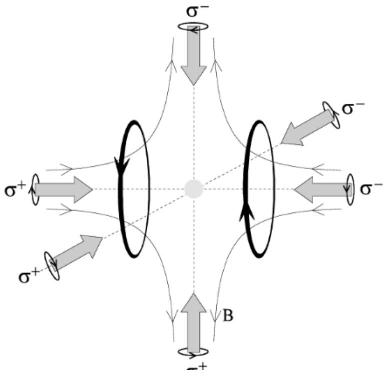

Figure 3: Schematic of magneto-optic trap MOT trapping rubidium atoms [8]

Six counter – propagating laser beams in all the three directions, i.e., ±X ±Y and ±Z reducing the degrees of freedom of atoms along with two magnetic field coils providing inhomogeneous magnetic field to the trap to accomplish spatial localization of the atoms and also keeps the laser beams properly polarised. For atoms to able to use the kinetic energy of their linear movement the frequency of the light is kept slightly below to the resonance frequency[8]. Recently, the Bayesian optimization approach has been introduced which is used in determining the maximum capture velocity of a molecular MOT[9].

1.3. Holographic Optical Tweezers (HOT)

A single collimated beam trap is converted into multiple beam traps using holograms by splitting the single beam into multiple beams using computer-generated diffractive optical element (DOE). A sequence of holograms designed by computer is then dynamically reconfigures the resulting trap patterns projected by a liquid crystal spatial light modulator (SLM)[10][11][12].

1.4. Fiber Optical Tweezers (FOT)

Demonstration of first fiber optical trap was done in 1993 using infrared diode laser with fiber pigtails. This trap was able to increase the density of trapped atoms. It enabled the measurements of elasticity and absorption of the trapped particle since here the trap was decoupled from the microscope resulting in greater allowance of viewing and manipulating the sample[13]. Later, modifications were done in the making of the fiber for the FOTs. Single tapered[14] and double tapered[15] fibers were applied in the original setups. Different methods to get the desired and suitable fibers were introduced which consequently enhanced the area of application.

1.5. Plasmonic Optical Tweezers (POT)

Plasmonic optical tweezers also known as surface plasmons based optical tweezers was introduced around 2008[16]. For the stable trapping with the forces and to asses the properties of surface plasmons photonic force microscopy was used. In this, radiation force is enhanced using the properties of surface plasmons which enables the trapping in the deep of samples[17]. The photothermal effects of the conventional optical traps have also been reduced in these traps. POT works on the principle of nano-optics and low power[18].

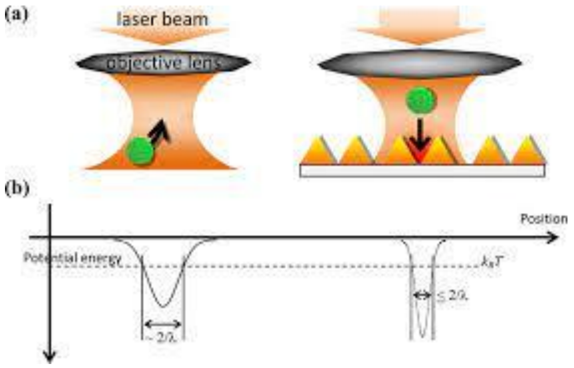

Figure 4: Schematic illustration of conventional optical tweezer and plasmonic optical tweezer [17]

1.6. Optical Tweezer – Raman Spectroscopy (OT-RS)

Integrated optical tweezer – Raman spectroscopy (OT-RS) is introduced in 2018[19]. Here, optical tweezer is combined with Raman spectroscopy and used for microscopic imaging and single particle study. 2 counter-propagating hollow beams were used and could able to stably levitate wide particles of wide range properties, such as, transparent or absorbing materials, organic (polymers, bioaerosols, etc.) or inorganic constituents (carbon, silica, glass, etc.), and spherical or irregularly shaped morphologies. Raman spectra deduce the chemical compositions and crystalline state etc., whereas physical properties of particles are revealed by the imaging. OT-RS provide new approach to characterize and monitor the physical and chemical properties for single micrometer sized object optically trapped in air**.**

2. Table for modifications and applications of different optical tweezers

S. no.	Types of OT	Year	Developer	Modifications	Applications
1.	First optical trap	1970 1983 2018	Arthur Ashkin Arthur Ashkin	First 2D and 3D optical trap using two counter-propagating laser beams Optical levitation trap First trap using a tightly focused single beam gradient laser beam Awarded by Nobel Prize for invention of optical tweezers and their application to biological systems.	Mechanical unfolding and refolding of RNA Disassembly of cellular clusters Magnetic resonance sensing with nano-diamonds Etc.
2.	Magneto-optic trap (MOT)	1975	Hansch and Schawlow	Proposed the idea of laser cooling through using six counter-propagating laser beams tuning them below the atomic resonance, using the	For Bose – Einstein condensation. Cooling the molecule below the

				concept of Doppler Shift.	temperature of doppler limit
		1985	W. Ertmer and others	Slowed the atoms to zero velocity by using same setup but frequency chirping the incident radiation using precise eletro-optic modulation techniques, creating first optical molasses.	
		1987	Steven Chu, Raab	Constructed first MOT setup using six counter-propagating laser beams along with a pair of two magnetic field coils to provide inhomogeneous magnetic field to the beams.	
		1997	S. Chu, C. C. Tannoudji, W. D. Phillips	Jointly awarded by Noble Prize for ‘development of methods for cool and trap atoms with laser light’.	
3.	Fiber optical tweezers (FOT)	1993	A. Constable, J. Kim and others	Demonstration of first fiber based optical tweezer using infrared diode laser with fiber pigtails, without any external optics.	Intracavity optical trapping Fabrication of nanomaterials. For particle manipulation and in – situ fiber probing Etc.
		2006	Z. Liu, C. Guo and others	Introduced single tapered fiber optical tweezer fabricated by heating and drawing technology.	
		2017	Z. L. Liu, Y. X. Liu and others	Introduced double-tapered fiber optical tweezers fabricated by the chemical etching called interfacial layer etching. Interfacial layer etching time control the second taper	

				angle (STA).	
4.	Holographic optical tweezers (HOT)	1997	E. Fallman, O. Axner	First stable and movable dual trap using single laser beam was introduced. Beam-splitters were used to split the single beam into two making dual beam traps.	Optical trapping of microparticles from frozen waves 3D trapping of individual Rydberg atoms
		2000	J. Liesener, M. Reicherter and others	Multiple laser traps were introduced using computer holograms. LCD was used to display the hologram which provided high flexibility for beam shaping. Spatial light modulator (SLM) was used to reduce efficiency loss from periodic electrode structure of LCD.	
		2003	W. J. Hossack, E. Theofanidou and others	Use of ferroelectric liquid crystal spatial light modulator was introduced instead of conventional SLM. Shown advantages in rapid reconfiguration of trap geometrics, control, high speed particle movement, tweezer array multiplexing etc.	
		2011	M. Padgett, R. D. Leonardo	The lab – on – chip demonstration was done.	
5.	Plasmonic optical Tweezers (POT)	2008	M. Righini, G. Volpe and others	First introduced as surface plasmons based optical tweezers. Used photonic force microscopy for stable trapping. Here, depth of	Nanomaterial characterization

		2019	D. G. Kotsifaki, S. N. Chormaic	trapping potential well is increased to reach the depth of trap. In this review letter, it was seen that POT works on lower power and nano-optics principles.	
6.	Optical tweezers – Raman Spectroscopy (OT-RS)	2019	Z. Gong, Y. L. Pan and others	Conventional OTs are combined with Raman spectroscopy for better study of physical and chemical properties of microscopic particles. It used two counter-propagating hollow beams and stably levitated particles of wide range of properties.	Study physical and chemical properties and behaviors of different molecules.

3. Conclusion

Here, we have now seen the different setups of optical tweezers with their respective applications. It is evident that optical tweezers are widely developed according the needs in different fields of science. It is seen that the focusing of the laser beam in optical tweezers is done on the basis of need of the depth and area of the trapping potential according to the application. Beam is tightly focused if a narrow trapping potential is needed, similarly, beam is lightly focused to get a wide area to trap particles and work. Development of tweezers has been done keeping these things in minds.

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