An introduction to the optical tweezer engineering essay

Engineering

History

Arthur Ashkin invented optical trapping, or the process by which atoms are trapped by laser light, at Bell Labs [1]. He found that radiation pressure -- the ability of light to exert pressure to move small objects -- could be harnessed to constrain atoms [2]. By his work, he demonstrated that optical forces could levitate and manipulate dielectric particles (dimensions of the order of 10-6 m) in both water and air medium [3], and he developed a stable, 3-dimensional optical trap by the use of counter propagating laser beams [4]. His most valued research work led to the development of the single-beam optical trap, or " optical tweezers" [5]. Ashkin et al used optical trapping in different experiments from cooling and trapping of neutral atoms to micromanaging live bacteria and viruses [6]. Today, optical traps continue to be used in various fields of biological and physical sciences. We can now apply optical forces (of the order of 10-12 N) to micron-sized particles while simultaneously monitoring their position precisely (by 10-9 meter scale) [7] which can be used in various research field for example to study the molecular motors at the single-molecule level [8].

Principle of an Optical Tweezer

The simplest optical trap can be formed by focusing a laser beam using an objective lens having high numerical aperture on a dielectric particle which is put near the focus of the objective lens. The dielectric piece will experience a three-dimensional restoring force towards the focus due to the transfer of momentum from the incident photons [5].(b)Fig. 1 shows the gradient force. In the figure 1(a) we impinged the dielectric particle with parallel beams and it’s shows the scattering force on the particle whereas in figure 1(b) we focused the laser beam using a high NA objective and it’s shows the importance of focusing the laser which results in restoring gradient force on the particle [9]. The optical force experienced by the dielectric particle can be projected into two components: (1) a scattering force and (2) a gradient force. This method is just a traditional and convenient way of discussing the effect of the optical force on the dielectric particle [5], [9]. Incident laser beam impinges on the dielectric particle from one direction, and the incident photons get scatter in different directions, while absorption of some part of the incident light also takes place. As a result of scattering and absorption there is a momentum transfer to the dielectric particle from the incident light. In case of an isotropic scatter, the resulting forces cancel each other in all the directions except the forward direction hence the scattering component of the force will push the particle in the forward direction i. e. the direction of the incident light propagation [5]. The absorption and reflection of incident light by the trapped particle results in the scattering component of the optical force [5], [7]. FDi FDoFRi FRoFigure 2 shows the optical forces acting on the spherical dielectric particle. The i and o in the superscript represents the input and output of the beam and the D and R in the subscript represents the force due to reflection (or scattering) and Deflection (or refraction) of the photons [4]. An electric dipole will experience a force in the direction of the electric field gradient when placed in an inhomogeneous electric field. In an optical trap, fluctuating dipoles are induced by the electric field of the laser in the dielectric particle, and these dipoles experience a gradient trapping force due to their interaction with the inhomogeneous electric field of the laser beam at the focus. Hence, the gradient force is directly dependent on both the optical intensity gradient at the focus of the objective and the polarizability of the dielectric particle [7]. The momentum carried by the incident light changes when it gets refracted by the spherical dielectric particle. The change in incident light momentum imparts an equal and opposite momentum change to the spherical particle according to the Newton’s third law of motion. The force on the spherical particle can be calculated as the rate of change in momentum. Here we can consider two cases, let’s consider m can be defined as the ration of the refractive index of the particle to the refractive index of its surrounding. When m> 1, the incident light will get refracted inwardly which will result in the optical force in the direction of the intensity gradient and in the case when m <1, the force is in the opposite direction of the intensity gradient. The extremal rays contribute to the axial gradient component of the optical force, whereas the central rays are mainly responsible for the scattering component [5], [7]. To create a stable three dimensional optical trap, the resultant optical force should pull the dielectric particle towards the focal reason i. e. the axial gradient component of the force must exceed the scattering component of the force. To increase the gradient force we have to have a steep intensity gradient near the focus of a laser. So for stable trapping we need a very steep gradient in the light, which can be produced by focusing the trapping laser beam using an objective of high numerical aperture. Because of this balance between the two components of the force, the equilibrium position is located a little beyond the focal point of the objective (as shown in the Fig 1). In one of his seminal papers, Askhin derived an expression of the optical force on a dielectric spherical particle in the case of Mie Scattering [17]where n is the refractive index of the medium, P is the average power of the laser, c is the speed of light in vacuum and Q known as the " trapping efficiency", is a dimensionless quantity dependent on several quantities. Another case would be when the radius of the trapped spherical dielectric particle is much smaller in comparison to the wavelength of the trapping laser, (i. e., a <<λ). In such cases we can apply the conditions for Raleigh scattering and we can consider the particle as a point dipole and calculate the force acting on it. [5]The gradient force in case of Raleigh scattering will be [20]where E is the optical electric field, I is the intensity of the trapping laser and α is the polarizibilty which can be given byα = (n2 -1 / n2 +2) a3where n and a are the refractive index and the radius of the trapped spherical particle respectively. The most typical case arises when the dimensions of the trapped dielectric particle are in a close range to the wavelength of the laser used for trapping (i. e. a ~ λ), in such cases neither Mie scattering nor Raleigh scattering approximations are valid. Nussenzveig and co-workers have derived analytical expressions for force acting on particle on any arbitrary size using exact partial-wave expansion [18], [19].

Essential Elements of Optical Tweezer

The basic constituents of an optical tweezer are a trapping laser, microscope, a high NA objective, and some way for position detection. For any additional feature other then trapping and manipulating trapped particles, additional elements would be required.

Trapping Laser

For a stable optical trapping the basic feature needed in the trapping laser that it should deliver a single mode output with minimal power fluctuations and pointing stability. Generally for a single mode output Gaussian TEM00 mode laser beams are used which closely satisfy all the requirements. In case if laser beam is not pointing stable it will lead to undesired displacements of the focused beam hence resulting in the movement in the optical trap position. Another case when we face the unwanted power fluctuations, the fluctuations will hamper the stiffness of the laser. To remove the pointing instability we can couple the laser with an optical fiber but this will result in amplitude fluctuations and will add noise to the outcome. Output power of the laser is also a major criterion in the selection of the laser since it determines the optical trap stiffness and the optical force applied on the trapped particle which we have already seen in the force terms. Also in case when we are trapping biological substrate wavelength of the laser become a selection rule because selection of certain wavelength laser might lead to damaging the biological specimen.

Microscope

Generally traditional light microscopes are used to build optical traps with some modifications. A dichoric mirror is put just before the microscope on the laser beam path to reflect the trapping laser beam into the optical path of the microscope simultaneously it transmits the light of the lamp which is used to illuminate the microscope. Inverted microscopes are also used for optical trapping since they have a fixed stage and the motion of the objective; make the stable coupling of the trapping light easier.

Objective

Objective lens is used to focus the laser beam which directly results in the optical trapping of the nano-sized particles. The basic features of the objective which directly affects the efficiency of the optical trap are the numerical aperture and the transmittance of the objective. Other important features are the medium in which objective is immersed and the working distance of the objective which also define the limits on the depth up to which the particle can be trapped.

Position Detection

Precise position detection of the trapped particle is the most important step in the quantitative optical trapping, since a well-calibrated system is required for pico-scale measurements of optical forces and nano-scale measurements of the displacement of the trapped particle. Currently precise position and force calibration is only possible for spherical objects. The position detection methods discussed below were initially used to track microscopic silica or polystyrene beads. Video based position detectionIn this method we use a video camera to detect the position of the trapped particle. We calibrate the video picture using a distance standard to calculate the size covered by a single pixel. The position of the trapped object can be determined by processing the signal captured by the camera using a pre-defined algorithm with sub pixel accuracy. There are some restrictions associated with this method, which is due to limit over the rate of video acquisition. The rate of video acquisition can be improved with the use of high speed video cameras which on the other hand can be limited by computer or system speed to which the video is sent by the camera or the memory capacity of the computer or of the recording device can also restrict the use of high speed video cameras. Even if we able to overcome this computer related problems, high-speed video recording will be restricted by the number of photons recorded because high speed video acquisition will result in shorter exposures which will require much more illumination in comparison to the normal rate exposures to generate a good quality video. Imaging Position DetectorIn this method we directly image the trapped particle onto a quadrant photodiode (QPD). Then we add the diode quadrants pair wise, and differential signals are calculated from the pairs for both x and y dimensions [9]. Laser Based Position DetectionThis method uses a single laser beam for both trapping and position detection. To use the same laser for both the purposes we put another dichroic mirror on the microscope‘ s condenser side which is used for the coupling of the laser scattered by the dielectric particle. d. Axial Position DetectionThe three position detection methods discussed above can only measure the horizontal displacement of trapped particle within the specimen plane. If we have to determine the axial position of the trapped particle we can do it by measuring the intensity of scattered laser beam on an overfilled photodiode. In this approach we measure the axial position dependent intensity which is generated due the far-field interaction between the scattered and unscatterred laser light. The axial position detection is measured using a detector and it is found to be inversely proportional to the numerical aperture of the detector.

Dynamic Position Control

To manipulate and move objects relative to the surface of the trapping chamber we need precise calibrated lateral motion of the optical trap in the specimen plane. More significantly, if we want to vary the force on a trapped object in real time we would need dynamic computer control over the position and stiffness of the optical trap. Additionally, if the position of the optical trap is scanned at a rate faster than the Brownian relaxation time of a trapped object, multiple traps can be created by time sharing a single laser beam. Following are few beam-steering methods: Scanning MirrorsThese are traditional galvanometer scanning mirrors incorporated with feedback to improve stability and precision. The comparatively slow temporal response limits their usefulness for fast-scanning applications, but their low insertion loss and large deflection angles make them a low-cost option for slow-scanning and feedback applications. With recent development in feedback-stabilized piezoelectric (PZ) systems; of PZ scanning mirrors have been introduced which have slightly better resolution and linearity than galvanometers. Acousto- Optic DeflectorsAn acousto-optic deflector (AOD) consists of a transparent crystal inside which an optical diffraction grating is generated by the density changes associated with an acoustic traveling wave of ultrasound. The diffraction efficiency is proportional to depth of the grating, and therefore to the amplitude of the acoustic wave that produced it. AODs are thereby able to control both the trap position (through deflection) and stiffness (through light level). A pair of AODs can be combined in an orthogonal configuration to provide both x and y deflections of the optical trap. Electro-Optic DeflectorsAn electro-optic deflector (EOD) consists of a crystal in which the refractive index can be changed through the application of an external electric field. Despite low insertion loss and straightforward alignment, due to high cost and a limited deflection range, EODs have not been widely employed in optical trapping systems.

Pulse Optical Tweezer

The application of pico-Newton forces upon mesoscopic particles by optical fields has resulted in many advance research across all of the sciences. The most important feature of optical trapping is that it allows the contact-free manipulation of microparticles by light. The calibratable nature of such optical traps has enabled ultra-precise measurements of the dynamics of macromolecules [9]. The most important elements of a very basic optical tweezers system are the high numerical aperture objective lens which is used to obtain a tightly focused beamand second, the trapping laser [9]. The choice of laser wavelength is critical for minimizing damage to the trapped particle: especially when we are trapping biological material. Thus the most widely used laser sources have typically been continuous-wave (CW) near-infrared lasers [6]. However, recently there has been an increase in use of pulsed and broadband lasers instead of, or in addition, to Continuous-Wave sources [10]. The use of pulsed lasers instead of continuous-wave lasers offers the ability to observe nonlinear effects or perform spectroscopy in combination with optical trapping. The another advantage of using pulsed lasers is that it offer extremely high peak powers even at lower average powers, and therefore allow access to multiphoton processes that would otherwise require very high average powers. These effects become ground breaking for ultrashort pulsed lasers, typically employing lasers in the femtosecond region of 100fs or less in pulse duration [11][12]. The high peak power offered by the pulsed lasers is the most important feature of it. It has been used in separating stuck particles from surfaces. This phenomenon was theoretically modeled in a paper by Deng et al [14], who calculated that the peak gradient force during a laser pulse was enough to overcome the binding interaction between a particle and a glass surface. Similarly a microsecond pulsed laser was used by Ambardekar et al to separate adsorbed 2μm polystyrene beads and yeast cells from their substrates [15], which they attributed to the high peak gradient force of their pulsed laser. In his research Ambardekar has shown that the continuous wave laser offer a pico-newton optical force which is sufficient to confine the suspended particles in liquid but not to levitate and manipulate the particles that are stuck on the glass surface owing to the strong binding force. However the large peak gradient force (of the order of nano-Newton) produced by pulsed laser allows the binding interaction between the stuck particle and the glass surface to be broken such that the levitated particle can be captured and manipulated by the continuous wave laser [15].