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Brief Basic of OPTICAL TWEEZERS

Imagine being able to pick up and move a single cell without physically touching it. Sound like science fiction? By leveraging special properties of laser beams, optical tweezers can do just that. Optical tweezers are noninvasive tools that use a laser beam, or beams, to generate piconewton forces powerful enough to manipulate microscopic matter. This ability is of increasing interest in an array of disparate subject areas that include studies of biological cells and molecular motors, micromachines, microfluidics, colloid physics, and properties of light beams.

Optical tweezers were first demonstrated by researchers at Bell Labs (Murray Hill, NJ) in 1986 by Arthus Ashkin [2]. The basic principles can be explained in terms of **Newton's laws**. **Because light carries a momentum, changing the direction of the light means that there must be a force associated with that change** (see Figure 2 and 3). So if we take a laser and shine it through a small particle, the light will be refracted as it moves through the particle. The force involved in this change of direction acts on the particle such that the particle moves toward the most intense part of the laser beam. A laser beam has a Gaussian profile, so the most intense part of the beam lies at the center of the beam axis. The force, therefore, confines the particle to the beam axis, and as the focus of the beam is the most intense part of the beam along the beam propagation direction, it draws the particle toward the focus. The particle becomes trapped in three dimensions. To create large enough forces to achieve this 3-D trapping effect, we do not need very much power (typically a minimum of a few milliwatts). We do, however, need high-intensity gradients, and so we focus the beam down to a spot only a few microns in diameter. Trapping particles in this way enables a wide variety of studies. It is possible to measure the elastic properties of DNA by grabbing hold of beads attached to the ends of the molecules and stretching them. Similarly, he force-producing properties of molecular motors, such as kinesin, may be studied with optical tweezers, as can the unfolding of proteins. Particles are easier to probe if they are trapped. Optical tweezers can be combined with Raman spectroscopy, two-photon spectroscopy, and confocal microscopy, among other tools. By combining optical tweezers with other laser beams, researchers can perform microsurgery on particles. For instance, they can grab chromosomes and then cut them into small pieces for further analysis using an IR (1064 nm) trapping beam and a green (532 nm) cutting laser, known as optical scissors. This is possible because most biological matter does not absorb strongly in the IR spectral region but does at green wavelengths.

Theory of Optical micromanipulation

Even though the laser beam modes that are used in micromanipulation varies in both phase and amplitude, much of the theoretical analysis of optical micromanipulation in the transverse plane is still based on how linear momentum of light is transferred to microparticles. Ashkin [2] proposed two different optical micromanipulation regimes based on the microparticle size (diameter) with respect to the wavelength of the laser used for the optical trap.

In atmospheric science, it is well-known that particle in air scatters light respective to their size. When light scatters in the Rayleigh regime, the scattering particles size is much smaller than the wavelength of the light, thus results in an angular separation of colors that is responsible for the reddish color of sunset and the blue of the sky (selective scattering). When light scatters in the Mie Regime, the particles causing that scattering are larger in size than the wavelengths of light, such as pollen, dust, smoke, water droplets. Mie scattering is responsible for the white appearance of the clouds. Following that same fashion, Ashkin proposed that optical micromanipulation can be analysis by two separate methods namely, Ray Optics approach for Mie Particles (diameter of particle $d > \lambda$ wavelength of light) and Electric Dipole approximation for Rayleigh particles (diameter of particle $d < \lambda$ wavelength of light) as seen in Figure.3.1.

Within the Ray Optics analysis, rays tracing of the refraction and reflection process through the microsphere is sufficient to analyze the optical trapping. Figure 2 shows a simple ray tracing diagram of a light ray through the refractive sphere.

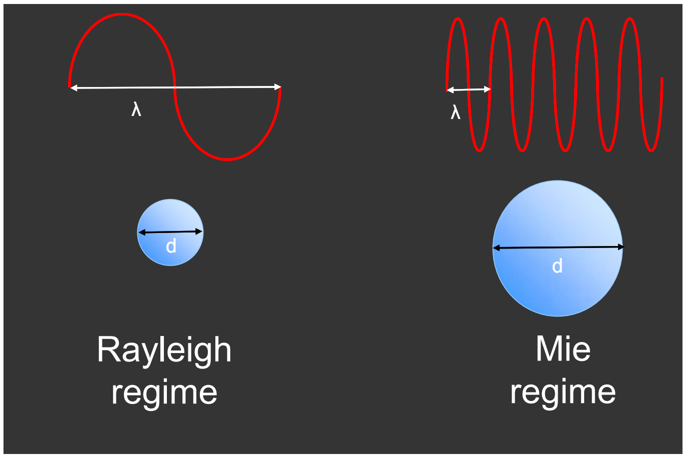


Figure1 – wavelength of light vs the particles diameter that determine the region of analysis

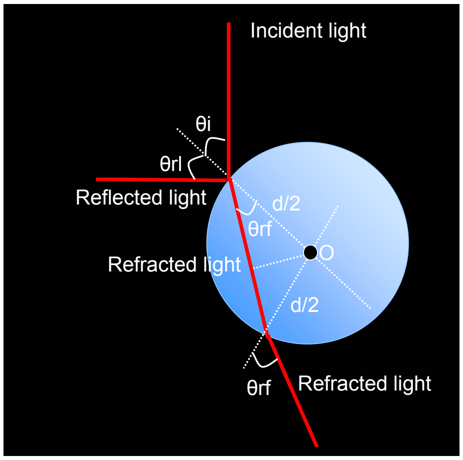


Figure 2 – single ray light tracing for a highly refractive sphere

From Figure 2, a simple ray optics equation is developed based on geometrical optics. The ray tracing in Figure 2 indicates a directional change of linear momentum with respect to time. Hence, this rate of change of momentum of light rays, by Newton's 2nd Law of motion (photon as particles), will result in a physical force. Similarly, there will be a reaction force from the sphere acting on the light rays.

The linear momentum of light from a laser beam of wavelength λ can be expressed as

$$p = \frac{E}{c} \qquad (1)$$

where p is the momentum of light, E is the energy of light and c is the speed of light. Since the speed of light at a wavelength λ is expressed as

$$c = \lambda . f \qquad (2)$$

where c is the speed of light, λ is the wavelength, f is the frequency of light.

Whilst the energy of light E is given as

$$E = hf \qquad (3)$$

where E is the energy of light, h is the Planck's constant, f is the frequency of light. The momentum of a single photon is expressed

$$p = \frac{E}{c} = \frac{hf}{\lambda f} = \frac{h}{\lambda} \qquad (4)$$

where p is the momentum of light, h is the Planck's constant, f is the frequency of light and λ is the wavelength. From equation 5, a crude interpretation would be that a region of higher intensity of light will possess more N photons and thus higher momentum and force due to the change of momentum, F.

$$F = \frac{\sum_{i}^{N} \Delta p_i}{\Delta t} \qquad (5)$$

Hence a simple two light ray diagram can be used to explain the optical forces by a refractive microsphere, high refractive index than the surrounding medium that encounters a laser beam of Gaussian irradiance function beam. By using simple ray and force vector diagram, shown in Figure 3, I show that the microsphere will experience two different optical forces F_a and F_b due to the Gaussian intensity profile (different of input and output momentum with respect to the sphere). F_a being the region of higher intensity than F_b creates an imbalance of the momentum transfer. The net forces from the imbalance action and reaction forces pulls the sphere towards the region of highest intensity region of the Gaussian beam. The resultant force is termed as the gradient force. However, due to the strong on-axis scattering forces from the scattering light rays, the sphere is propelled axially along the beam's propagation direction. Even thought the gradient forces pull the particles into the highest intensity region of the beam, the trap is not a three dimensional one.

Using the conservation of momentum, the total force acting onto the sphere will be the summation of all the force acting onto it. The scattering force, gradient force and their total force can be simplified into the following equations [1]

$$\begin{aligned} F_{scattering} &= \frac{n_m P}{c}\left(1 + R\cos(2\theta) - \frac{T^2\left[\cos(2\theta - 2r) + R\cos 2\theta\right]}{1 + R^2 + 2R\cos 2r}\right) \\ &= \frac{n_m P}{c} Q_{scattering} \end{aligned} \tag{6}$$

$$\begin{aligned} F_{gradient} &= \frac{n_m P}{c}\left(R\sin(2\theta) - \frac{T^2\left[\cos(2\theta - 2r) + R\cos 2\theta\right]}{1 + R^2 + 2R\cos 2r}\right) \\ &= \frac{n_m P}{c} Q_{gradient} \end{aligned} \tag{7}$$

$$F_{total} = \frac{Q n_m P}{c} \tag{8}$$

where P is the power of the incident light and rat hitting a dielectric sphere, r are the angles of incidence and refraction, R and T are the Fesnel reflection and transmission coefficients, Q, $Q_{gradient}$ and $Q_{scattering}$ is the dimensionless efficiency, n_m is the index of refraction of the suspending medium and c is the speed of light.

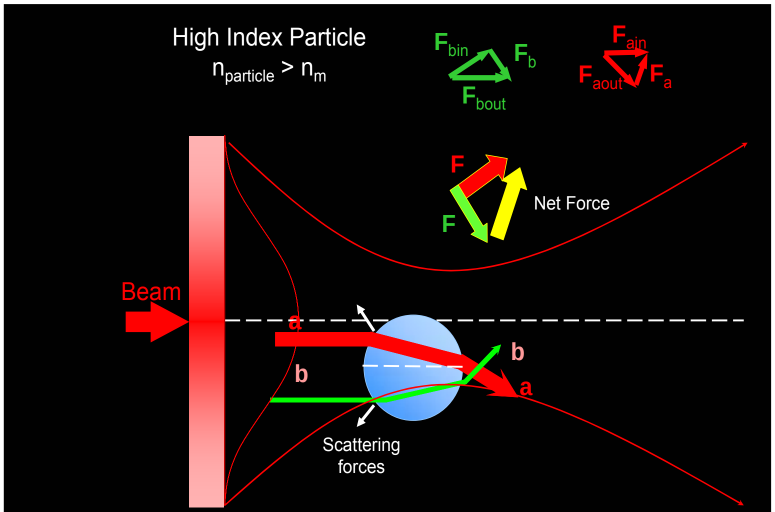
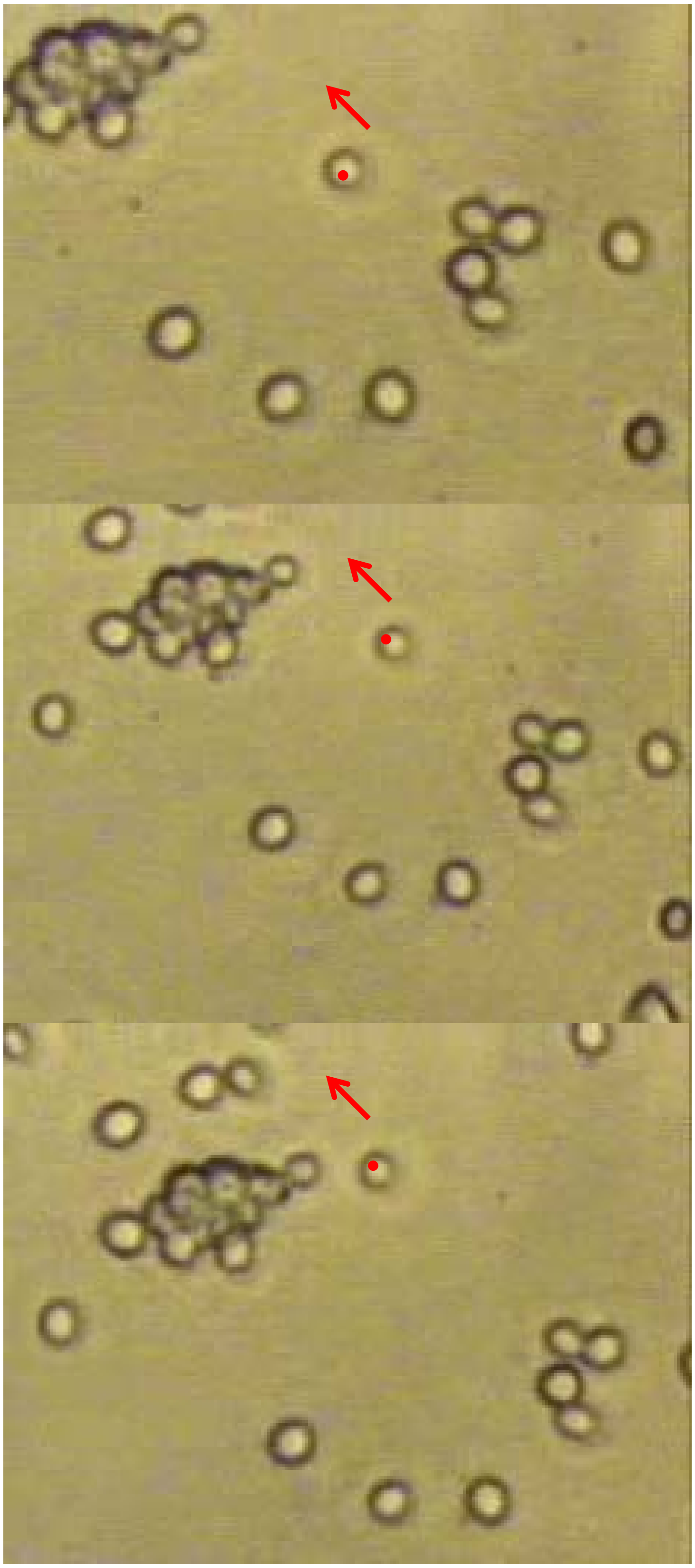
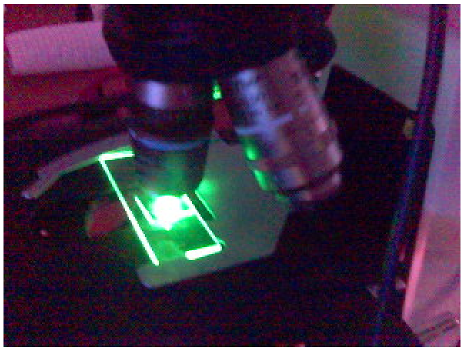


Figure.3 – Ray tracing for a highly refractive sphere in a Gaussian beam





On the left is A single trapped yeast cell being manipulated by a two dimensional optical trap formed by a 532nm laser beam focused through **(see above**) ELWD Nikon CFI60 microscope objective with NA=0.6, 50X