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“Nanophotonics and Optical Control of Single Nanoparticles”

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Chapter 1: Introduction

In recent years, manipulation of micro-sized and nano-sized particles is in the lime light of the world technology. Optical tweezers are one of the techniques, which use a highly focused beam to control and hold those microscopic particles. Because of this unique ability, this method is recently being used as a tool for micro-assembly.

1.1: A Brief History of Optical Tweezers

Johannes Kepler (1571-1630), a German astronomer, is distinguished as the establisher of the Kepler's laws. Besides studying astrophysics, Kepler did lots of fundamental works in the area of optics. Among his optical studies, discovery of the radiation pressure (light pressure) is very remarkable. He noticed that comet's tail always points away from the sun, because of the sun's radiation pressure. For this reason Kepler conjectured whether light can apply pressures or forces to an object. 200 years later, the existence of the light pressure was demonstrated by a British physicist, James Maxwell (1831-1879), using his theory of electromagnetism. In 1910, a Russian Physicist, P. N. Lebedev (1866-1912) measured the light pressure on his experiment. Since then, Albert Einstein (1879-1955) confirmed that photons possess its own momentum, by his light quantum theory. Soon, Arthur Compton, an American physicist (1892-1962), showed the existence of the light momentum on his experimental work. But from that time on, the researching on the radiation pressure hadn't been actively conducted until Arthur Ashkin appears, a half century later.

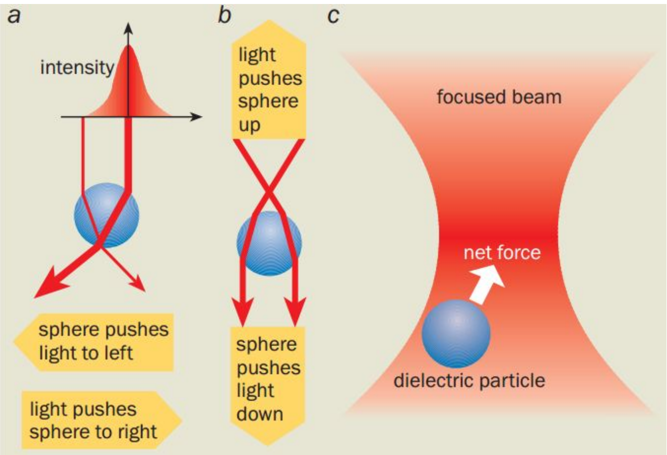
Arthur Ashkin is an American scientist, worked AT&T Bell Labs in the United States. In 1970, Ashkin and his collegues proved that light can grab and release nanometer particles by its momentum, using the light quantum theory. They called this detection as "radiation pressure-gravity traps" (optical levitation). Optical levitation is when laser light is incident from bottom to upside of a particle there must appears a force called "Scattering force". And if we make this scattering force parallel to the gravity, we can capture the particle in axis. In addition to working with this method, Ashkin developed various ways of trapping microscopic particles. He demonstrated the ability of the levitation of airborne droplets (Ashkin & Dziedzic 1975), confinement in vacuum (Ashkin & Dzidzic 1976), precision trapping via feedback (Ashkin & Dziedzic 1977), and confining particles in dual beam radiation pressure traps (Ashkin & Dziedzic 1985). However, these methods contained some problems in the ability of applications. For example, controlling more microscopic particles was very limited in optical levitation. In 1986, Ashkin proved that he could trap 10nm diameter dielectric particles only using gradient force. He named this method as "Single-beam gradient force trap" (Optical Tweezers). In terms of this easy and useful method, optical tweezers have been more developed. Now we can trap not only one particle, but multi-particles. Also we can understand easier the three-dimensional position of detection. Nowadays, Optical tweezers are used in cell biology, colloidal physics, and micro-machine, where needs controls of microscopic particles.

Chapter 2: Theoretical Foundation

Optical Tweezers are originally called the "Single Beam Gradient Force Trap". These are scientific instruments, which can hold and manipulate nanometer and micrometer sized dielectric particles by a highly focused laser beam, exerting very small forces. To trap the small particles, there are some conditions. For example, photon's momentum should be changed. Also the refractive index of the particle should be greater than the surrounding medium. Then the particle will be attracted to the center of the beam. But if the particle is smaller than the surrounding medium, then the particle will be repelled from the beam. In this chapter we will study the optical trapping force and how the optical trap works.

2.1: Principles of Optical Trapping Particles

Moving particles with light is possible. If we exert a laser beam to the very small particle, the light will be reflected or refracted from the surface of the particle. The momentum of photon, refracted to the particle, will be changed and by the law of the conservation of the momentum, the force of the variation of momentum will be exerted to the small particle. This force is called the *Optical Trapping Force*. This optical trapping force can be divided in two forces. These are the *Scattering Force* and the *Gradient Force*". The scattering force is when the force pushes the particle in the same direction of the light propagation direction. In contrast with this, the gradient force is when the force pulls in the opposite or perpendicular direction of the light propagation direction. These two forces vary depending on the value of the numerical aperture of the objective lens. If we transmit a highly focused laser beam with a high value of the numerical aperture of the objective lens, then the gradient force will be greater than the scattering force, and the particles will experience an attraction to the direction of high light intensity. Therefore we can put the small particles into the narrowest point of the focused beam.



(a) If the particle is to the left, say, of the center of the beam, it will refract more light from the right to the left, rather than vice versa. The net effect is to transfer momentum to the beam in this direction, so, by Newton's third law, the particle will experience an equal and opposite force – back towards the center of the beam. In this example the particle is a dielectric sphere

(b) Similarly, if the beam is tightly focused it is possible for the particle to experience a force that pushes back towards the laser beam.

(c) We can also consider an energetic argument: when a polarizable particle is placed in an electric field, the net field is reduced. The energy of the system will be a minimum when the particle moves to wherever the field is highest – which is at the focus. Therefore, potential wells are created by local maxima in the fields.

How optical tweezers work (2.1)

Optical tweezers: the next generation, Kishan Dholakia, 2002,

2.2: Conditions of Optical Trapping Particles

Optical trapping also can be described in conditions of the size of particles. There are three conditions for which the force on a sphere can be calculated. If the size of the trapped particle sphere r is bigger than wavelength of the incident light λ $(r \gg \lambda)$, this condition can be described in the *Ray Optics Regime*, because we can neglect the effect of wavelength. But if the size of the trapped particle is smaller than wavelength of the incident light, $(r \ll \lambda)$, in this case, we have to think about the wavelength effect, so the "electromagnetic Regime" (Also called Rayleigh Regime) is suitable to trap the small particles. And If the size of sphere and the wavelength are much the same $(r \approx \lambda)$, we can use the "Mie regime". For example if the wavelength is 834nm, and the size of particle is $r \gg 10\mu m$, we use the ray optics model, and if the size is $r \ll 1\mu m$, we use the electromagnetic model.

2.3: The optical trapping Force, acting on the small particles

2.3.1: The Electromagnetic Regime ($r \ll \lambda$)

The Scattering Force

The Scattering force causes by the light pressure. The incident light impinges on the particle from one direction, but it can be scattered in variety of directions. And some of the incident light can be absorbed. Therefore there is a net momentum transfer to the particle from the incident photons. And the net force is calculated by the direction of the photon flux from the incident light.

$$F_{scatt} = \frac{I_0 \sigma n_m}{c}, \qquad (2.1)$$

$$\sigma = \frac{128\pi^5 a^6}{3\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2 \qquad (2.2)$$

Where,

I_0 *- The intensity of the incident light*

σ *- The scattering cross section of the sphere*

n_m *- The index of refraction of the medium*

c – The speed of light in vacuum

m - The ratio of the index of refraction of the particle to the index of the medium

λ *– The wavelength of the trapping laser*

The Gradient Force

In the conditions for the electromagnetic regime, a trapped particle can be treated as a point induced dipole in an electromagnetic field. The force applied on a single charge in an electromagnetic field is known as the Lorentz force. For this condition, the gradient force causes by this Lorentz force.

$$\vec{p}(\vec{r}, t) = \alpha \vec{E}(\vec{r}, t) \qquad (2.3)$$

Where, α *-The polarizability*

$\vec{E}(\vec{r},t)$ *– The electromagnetic field vector of the incident light.*

$$\vec{F}(\vec{r},\ t)= [\vec{p}(\vec{r},\ t)\nabla]\ \vec{E}(\vec{r},\ t) \tag{2.4}$$

$$\nabla\vec{E}^2=2(\vec{E}\nabla)\ \vec{E}+2\vec{E}\times(\nabla\times\vec{E}) \tag{2.5}$$

Then, the Maxwell's equation will be,

$$\nabla\times\vec{E}=0 \tag{2.6}$$

From (2.4),

$$\vec{F}(\vec{r},\ t)=\frac{1}{2}\ \alpha\nabla\vec{E}(\vec{r},t)^2 \tag{2.7}$$

The Gradient force is in connection with the time which the particle experiences and we can get the equation,

$$<\vec{E}(\vec{r},t)^2>_T=\frac{1}{2}\left|\vec{E}(\vec{r})\right|^2 \tag{2.8}$$

$$\vec{F}(\vec{r})=<\vec{F}(\vec{r},t)^2>_T=\frac{1}{2}\ \alpha\nabla<\vec{E}(\vec{r},t)^2>_T=\frac{1}{4}\alpha\nabla\left|\vec{E}(\vec{r})\right|^2 \tag{2.9}$$

We can describe the intensity of light by the (2.5) equation,

$$I(\vec{r})=\frac{n_m\epsilon_0 c}{2}\left|\vec{E}(\vec{r})\right|^2 \tag{2.10}$$

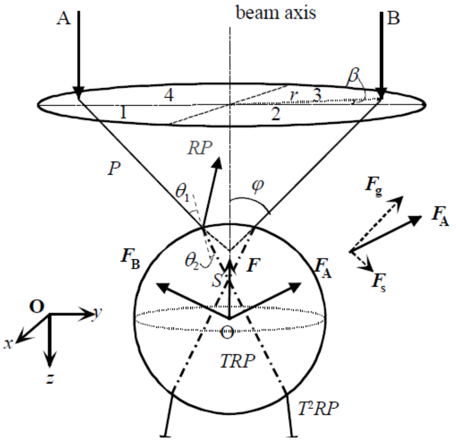
Where, n_m *– The refractive index*
ϵ_0 *– The Permittivity*
c *– The speed of light*

Finally, we can describe the gradient force as,

$$\vec{F}(\vec{r})=\frac{1}{2n_m\epsilon_0 c}\ \alpha\nabla I(\vec{r}) \tag{2.11}$$

2.3.2: The Ray optical Regime ($\mathbf{r} \gg \boldsymbol{\lambda}$)

We can use the “Ray Optics Regime” when the size of the trapped particle sphere “r” is bigger than wavelength of the incident light “λ” ($r \gg \lambda$). In this case we can neglect the effect of wavelength and we have to look at this case in the area of geometrical optics.



Principles of Optical trapping (2.2), Roman Spectroscopic Analysis of micro-particle by using Optical Tweezers, Wonhoe Koo, Seoul, 2005

When a light beam is exerted to the particle, the light will be reflected or refracted from the surface of the particle by the Snell’s law. The momentum of photon, refracted to the particle, will be changed and by the law of the conservation of the momentum, the force of the variation of momentum will be exerted to the small particle. The picture 2.2 shows how we can trap a small particle in the ray optical regime. The optical trapping force can be divided in two forces. These are the “scattering force” and the “gradient force”.

The Scattering Force

In the ray optics regime, the scattering force equals,

$$F_{scatt}=\frac{n_m P}{\mathrm{c}}\left\{1+R\cos 2\alpha-\frac{T^2[\cos(2\alpha-2\beta)+R\cos 2\alpha]}{1+R^2+2R\cos 2\beta}\right\}=\frac{n_m P}{\mathrm{c}}Q_{scatt} \qquad (2.12)$$

The Gradient Force

The gradient force in the ray optics regime is,

$$F_{grad}=\frac{n_m P}{\mathrm{c}}\left\{R\sin 2\alpha-\frac{T^2[\sin(2\alpha-2\beta)+R\sin 2\alpha]}{1+R^2+2R\sin 2\beta}\right\}\frac{n_m P}{\mathrm{c}}Q_{grad} \qquad (2.13)$$

Where, n_m *– The refractive index*

P – The laser beam power

c – The speed of light

R – The reflexibility

T – The Transmissivity

Q – The efficiency

2.4: The Calculation of the Optical Forces

If we transmit a highly focused laser beam with a high value of the numerical aperture of the objective lens, then the gradient force will be greater than the scattering force, and the particles will experience an attraction to the direction of high light intensity. Therefore we can put the small particles into the narrowest point of the focused beam. And we can describe the optical forces to the particles.

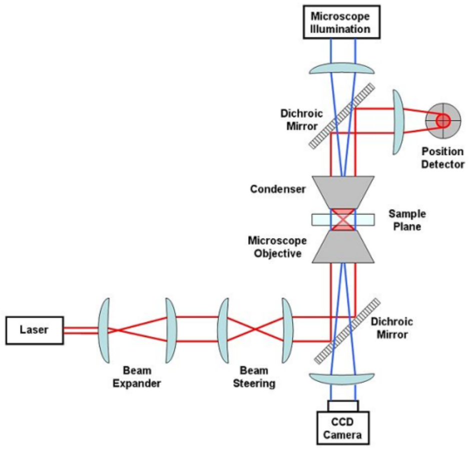
$$\mathrm{F} = F_{scatt} + F_{grad} = \frac{n_m P}{\mathrm{c}}(Q_{scatt} + Q_{grad}) = \frac{n_m P}{\mathrm{c}} Q \qquad (2.14)$$

And we can calculate the optical trapping efficiency as well,

$$\mathrm{Q} = \sqrt{{Q_{scatt}}^2 + {Q_{grad}}^2} \qquad (2.15)$$

Chapter 3: The Experimental Methods and Implementation

3.1: The Optical Tweezers Set up



A generic optical tweezers diagram with only the most basic components. (3.1)
The Optical Tweezers, Wikipedia

The most basic optical tweezers setup includes the following components: a laser, a beam expander, some optics used to steer the beam location in the sample plane, a microscopic object and condenser to create the trap in the sample plane, a position detector to measure beam displacements and a microscope illumination source coupled to a CCD camera.

3.2: The Experimental Method

The Laser beam first passes through a focusing lens to expand the beam filling the back lens of the microscope objective and to focus the beam to a point at the back focal length of the objective. From the focusing lens, the laser beam reflects to a dichroic mirror. The dichroic mirror is used to refect the beam into the objective. But the dichroic mirror reflects only in the specific wavelengths. When the laser beam passes through, it reachese to the sample and it focuses the beam to a point. Once the beam passes through the objective, it reaches the sample, where it focuses the beam to a point. By moving the objective toward or away from the sample slide, the position of the focal point can be placed anywhere within the sample solution. A backlight is used to illuminate the slide for viewing on the camera.

The camera is positioned behind the dichroic mirror. By adjusting the position of the camera different parts of the sample are viewed through the objective. The goal is to be able to focus on trapped beads. When collecting images of a trapped bead, a second dichroic mirror will filter the reflection of the laser beam off the trapped bead.

Chapter 4: Conclusion

Optical tweezers is one of the most effective methods of manipulating micron and sub-micron sized particles. Their use covers a number of research areas in biology, chemistry and physics and has found its greatest use in the growing field of biophysics.

In this paper we have learnt the principles of optical trapping particles. According to the theory, Moving particles with light was possible. If we exert a laser beam to the very small particle, the light will be reflected or refracted from the surface of the particle. The momentum of photon, refracted to the particle, will be changed and by the law of the conservation of the momentum, the force of the variation of momentum will be exerted to the small particle. The particle will be attracted to the center of the beam. But if the particle is smaller than the surrounding medium, then the particle will be repelled from the beam. There were some of the conditions of trapping particles. The two main conditions were that If the size of the trapped particle sphere r is bigger than wavelength of the incident light λ $(r \gg \lambda)$, this condition can be described in the "Ray Optics Regime" And if the size of the trapped particle is smaller than wavelength of the incident light, $(r \ll \lambda)$, in this case, we have to think about the wavelength effect, so the "Electromagnetic Regime".

Chapter 5: References

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