Development of far field and near field optical trapping

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Optical trapping is an increasingly important technique for manipulating and probing matter ranging from nanometers to millimeters. In this paper, the theories of optical trapping to date are reviewed briefly. The typical conventional far field trapping design is introduced. A 5-μm yeast cell is trapped and manipulated with a 1.25 numerical aperture (NA) oil-immersion, 100× magnification objective by a 780 nm trapping beam at 16 mW in our experiment. Furthermore, the development of near-field optical trapping associated with evanescent wave is also discussed. Several proposed near-field trapping schemes, respectively using laser-illuminated metal tip, metal-coated fiber probe in the scanning near-field optical microscopy (SNOM) and focused evanescent wave, are also described.

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Optical trapping technique utilizes the forces of laser radiation pressure to trap small particles. Arthur Ashkin at Bell labs in the US pioneered the field of laser-based optical trapping in the early 1970s. The most important breakthrough of optical trapping was accomplished in 1986, when Ashkin *et al.* using a single tightly focused laser beam successfully trapped a dielectric particle in three dimensions, which is referred as single-beam gradient force optical trap or optical tweezers[1]. Owing to the ability to trap and manipulate small particles with nanometer precision and to measure forces between particles with piconewton accuracy, optical trapping technique has been developed and applied extensively in biological[2] and physical fields[3].

Optical trapping is essentially based on conservation of momentum of light. Whenever light is reflected, refracted or scattered by a particle, the light momentum is changed, which results in a corresponding force on the particle. The force exerted on the particle is equal to the momentum transferred per unit time, which is on the order of piconewtons. The theoretical description of optical forces depends on the comparison between the particle radius a and the laser wavelength λ.

In Mie regime, where the particle size is much larger than the wavelength of light ($a>>\lambda$), the ray optics computing method is applied to describe the optical forces exerted on the particle. Optical force is usually decomposed into two components: scattering force and gradient force. The scattering force always acts along the direction of light propagation. Considering the refraction index of the particle is larger than that of the surrounding medium, the gradient force points in direction of increasing intensity. The two components balance around beam focus where the particle is stable trapped. The scattering and gradient forces are[4]:

$$F_{\rm scatt} = n_{\rm m}P/c\left\{1 + R\cos 2\theta - \frac{T^2\left[\cos(2\theta-2\theta') + R\cos 2\theta\right]}{1+R^2+2R\cos 2\theta}\right\}, \quad (1)$$

$$F_{\rm grad} = n_{\rm m}P/c\left\{R\sin 2\theta - \frac{T^2\left[\sin(2\theta-2\theta') + R\sin 2\theta\right]}{1+R^2+2R\cos 2\theta'}\right\}, \quad (2)$$

where n_m, P, c, θ and θ' are refractive index of the surrounding medium, incident laser power, speed of light, angle of incidence and angle of refraction, respectively. R and T are the Fresnel coefficients of reflection and refraction.

In Rayleigh regime, where the particle size is much smaller than the wavelength of light ($a<<\lambda$), Rayleigh approximation can be applied to describe the behavior of the particle in the electromagnetic wave. The particle is treated as an induced dipole in an optical field. Optical forces exerted on the particle can be divided into those originating from scattering of the light and those originating from an intensity gradient. The scattering force is due to absorption and reradiation of light by the dipole, which is proportional to the optical intensity and points toward the propagation direction of incident laser light. The gradient force arises from the Lorentz force acting on the induced dipole, which is proportional to the intensity gradient and points in the direction of the intensity gradient. For a particle of radius a, the scattering and gradient forces are[5]:

$$F_{\rm scatt} = \frac{I_0 n_m}{c}\frac{128\pi^5 a^6}{3\lambda^4}\left[\frac{m^2-1}{m^2+2}\right]^2 \quad (3)$$

$$F_{\rm grad} = \frac{2\pi a^3}{c}\left[\frac{m^2-1}{m^2+2}\right]\nabla I_0 \quad (4)$$

where I_0 is the intensity of the incident light, m is the radio of the index of refraction of particle to the index of the surrounding medium, and λ is the wavelength of trapping laser.

For particles in between Mie and Rayleigh regimes, the particle size is comparable with the wavelength ($a\sim\lambda$). The generalized Lorenz-Mie theory (GLMT) is considered to be the most promising candidate to calculate optical forces in this range so far. In GLMT, the Cartesian coordinate center is located at the beam waist center, where z is the axial direction of beam propagation and x is the polarization direction of the electric field. The center of the particle is located at position $\vec{r}$=(x,y,z), and $\hat{x},\hat{y},\hat{z}$ are the unit vectors in the x, y, z direction, respectively. The radiation force is written in terms of three cross-sections according to[6]

$$\vec{F}(\vec{r}) = \left(\frac{n_m}{c}\right)\frac{2P}{\pi\omega_0^2}\left[\hat{x}C_{pr,x}(\vec{r}) + \hat{y}C_{pr,y}(\vec{r}) + \hat{z}C_{pr,z}(\vec{r})\right], \quad (5)$$

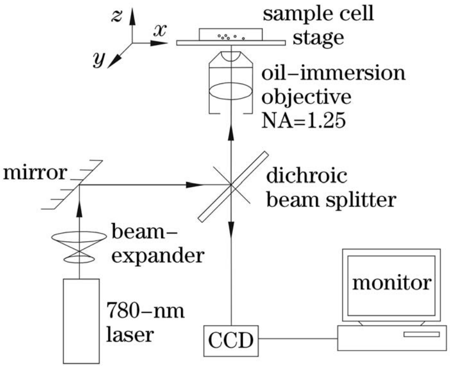

Fig. 1. Experimental setup used for far field optical trapping.

where ω_0 is the radius of beam waist, $C_{pr,x}$, $C_{pr,y}$, $C_{pr,z}$ are the cross sections with complex expressions[7]. Without any assumption, GLMT is the most general and complete expression of the above three approaches, and shows great promise for predicting radiation forces in all size regimes.

Conventional far field optical trapping experiment design is usually modified from a common inverted optical microscope. Figure 1 shows the apparatus used for optical trapping of yeast cells in our experiment. The laser beam is first expanded by a beam expander, and then reflected by a mirror and a dichroic beam splitter. In order to achieve the minimum spot size of the focus, the real pupil of the objective is entirely illuminated by expanded laser beam. By translating the stage, the samples in the sample cell can be trapped and manipulated in the focal plane. A microscope with a liquid-immersion microscope objective is used to observe the trapped objects and the trapping procedure is recorded on a monitor with a charge coupled device (CCD) camera.

In our experiment, a yeast cell with diameter of 5 μm is trapped with a 1.25 NA oil-immersion, 100× magnification objective. The laser source is a semiconductor laser at 780 nm. The trapping power is 16 mW. Figure 2 is the photographs of the trapping procedure. The trapped yeast in the sample cell is at the central position of the pictures. The arrows are used to indicate the moving direction of the trapped yeast cell. Figures 2(a)–(c) show the moving direction along the y-axis, whereas Figs. 2(d)–(f) along the x-axis.

In far field optical trapping, an oil immersion objective with a high NA is generally used to generate a highly focused trapping beam, and hence a gradient force toward the focus. Owing to the limitation of the far field, the spot size of the focused laser beam can hardly be down to $\lambda/2$, which hinders the precision of far field optical trapping. The trapping volume of the far field is diffraction limited. On the other hand, near-field optical trapping is proposed for overcoming the optical diffraction limit and reducing the trapping volume. The fact that the strength of near-field evanescent wave decays exponentially with the distance may produce a gradient force and significantly reduce the trapping volume. Kawata *et al* first studied the interaction between micro-particles and near-field evanescent wave and implemented the near-field optical driving. Small particles have been moved in the evanescent fields produced under total internal reflection condition (TIR)[8,9]. As for near-field optical trapping, three trapping methods based on the use of evanescent wave have been proposed so far.

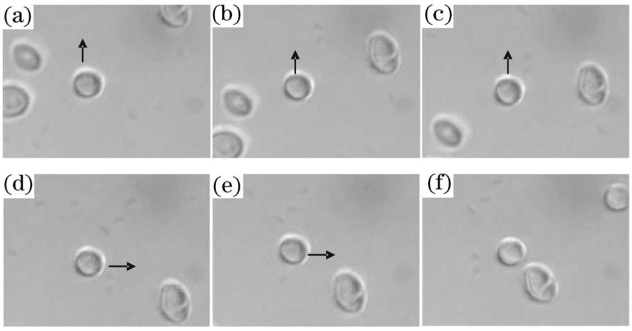

Fig. 2. A 5-μm yeast cell was trapped and manipulated using semiconductor laser beam.

In the method first reported by Novotny, a metallic tip illuminated by a laser beam has been suggested for the trapping of nanometric particles in aqueous environments[10]. The evanescent field closed to the tip can be strongly enhanced by the surface plasmon effect under laser illumination, which may generate large field gradients producing a larger trapping force. The calculation shows that nanoparticles suspended in water could be trapped using a laser-illuminated gold tip. Chaumet *et al.* extended metallic tip trapping by using symmetric evanescent illumination under TIR[11]. A combination of evanescent illumination and light scattering at the apex of an apertureless near-field metal probe is used to shape the optical field into a three-dimensional optical trap. A glass sphere with radius of 10 nm on a flat dielectric surface is illuminated by evanescent wave, and the tungsten tip is used to trap it. Analysis result predicts that nanoparticles can be selectively captured and manipulated in vacuum or air above substrate.

Another proposed near-field trapping method involves the use of the evanescent field near a nanoaperture of a scanning near-field optical microcsopy (SNOM) tip. A metal-coated fiber probe with an aperture on the tip used for SNOM imaging is typically recommended for optical trapping. The optical near-field distribution of nanoaperture has been investigated[12]. The possibility of trapping of nanometric particles by the strong gradient generated by the evanescent field near the tip is theoretically discussed[13]. Analysis result shows that the near-field trapping by metal-coated fiber probe is theoretically possible. The main difficulty hindered this trapping method is the poor optical throughput of conventional SNOM fiber probe, typically less than 1×10^{-5} with diameter of aperture about 100 nm. The light power in the tip-sample region is rather low, typically on the order of nW, which is insufficient to generate a stable optical trap. Increasing input laser power helps to enhance the transmitted power from the fiber tip, but since laser power above a certain value may rupture the metal coating layer, the power that can be coupled into the fiber cannot exceed a few mW. According to the above consideration, the metal-coated fiber probe trapping is difficult to implement in practice.

Recently, a new near-field trapping method based on focused evanescent wave illumination is first demonstrated by Gu *et al.*[14,15]. The focused evanescent field is generated by the use of ring beam produced by a high NA objective that is centrally obstructed. By putting an opaque disk in the path of the beam, only the light rays satisfied TIR are allowed to pass through the focusing objective, thus a focused evanescent wave on the interface is generated to trap particles. The experimental scheme is shown in Fig. 3. In their experiment, the trapping efficiency along the transverse and axial directions is measured separately. Furthermore, the transverse evanescent field trapping can be achieved. A 2-μm polystyrene sphere suspended in water under focused wave illumination is trapped while the sample cell is translated. Further calculation shows that a polystyrene particle of up to 800 nm in radius can be lifted with 10 μW optical power.

In summary, we briefly reviewed optical trapping theories to date. As a demonstration of far field trapping, a 5-μm yeast cell is captured and manipulated with a 1.25 NA oil-immersion objective by 780 nm evanescent trapping beam at 16 mW in our experiment. Near-field optical trapping, owing to the nature that the strength of wave decays exponentially with the distance from the interface, may significantly reduce the trapping volume. Several proposed near-field trapping methods so far are described in this paper. Further development of near-field optical trapping may result in the trapping volume beyond the diffraction limitation.

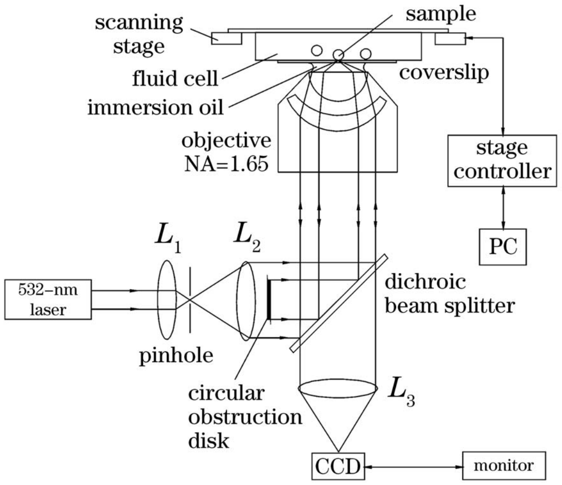

Fig. 3. A schematic diagram of near-field trapping system under focused evanescent wave illumination.

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