Optical trapping and optical Manipulation

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Abstract: First introduced in 1986[1], optical tweezers (single-beam gradient force) has become an important tool in modern science, especially in the fields of biology, physical chemistry and soft condensed matter physics. Also, the experimental demonstration of Kaptiza-Dirac effect[2] tells the story of Deflection of electrons by high-intensity laser light, which provided a new possible method for optical manipulation. The optical trapping process can be realized by transmitting the through a highly multimoded fiber via wavefront shaping using spatial phase modulator (SLM)[3].

1. Introduction

The more than 20 years' development of optical tweezers has made itself a crucial part to the fields of cell biology and biophysics by manipulating particles in the micron-size regime without damaging them. The reason why optical tweezers are very useful is small particle manipulating without any damaging with infrared light can be realized using optical trapping technique [4]. Also, the possibility of applying controlled force fields on simultaneously trapped micro-particles has allowed to directly probe interactions and mechanical properties of colloids, macromolecules and living cells. The principle under optical trapping is transfer of momentum between the high-intensity beam and the object that the beam passes through. As shown in Figure 1, by applying that beam, the object particle can be trapped or moved to the center of the beam, usually the waist the Gaussian beam for the light comes from a laser.

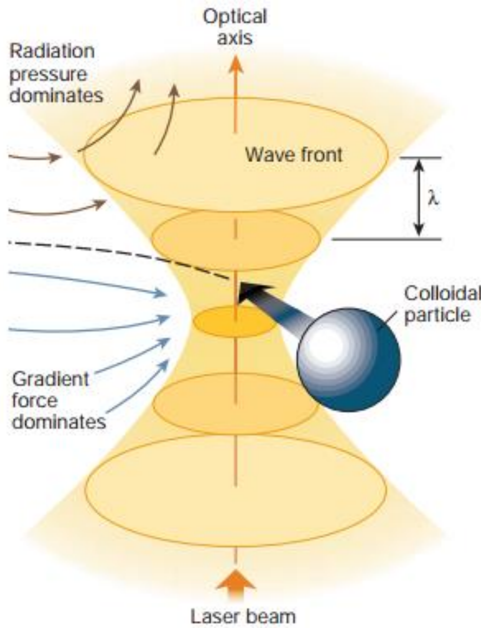

FIG. 1. Optical tweezers use a strongly focused beam of light to trap objects. Intensity gradients in the converging beam draw small object, such as a colloidal particle toward the focus, whereas the radiation pressure of the beam tends to blow them down the optical axis. Under conditions where the gradient force dominates, a particle can be trapped, in three dimensions, near the focal point [5].

The Kapitza-Dirac effect is another kind of light-matter effect. In which, the effect is analogous to the diffraction of light by a grating while it reversed the role of light and matter [2]. That is, the electrons are deflected by a high-intensity laser in this case and the diffraction can be detected, which gives a possibility of manipulating the particle in even smaller scale.

A real application of optical trapping and probing is to using a multimode fiber transmitting the hologram image via SLM. In this case, through discovering the light propagator of the fiber, the dynamic array of focused spots at the fiber output can be propagated. Therefore, a way that produces multiple light spots for optical tweezers without mechanical deformation of the optical system has been found [3].

2. Optical trapping basic

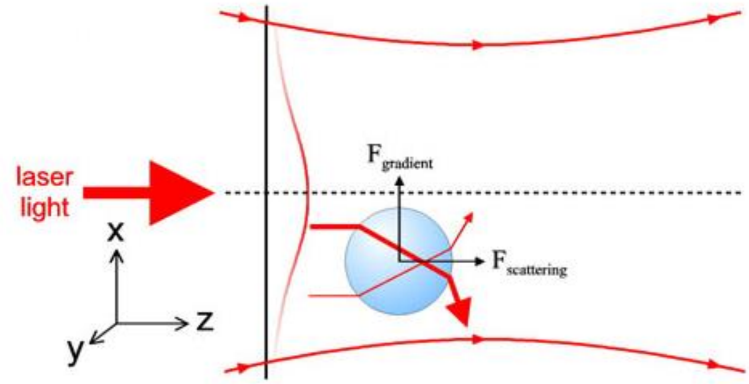

FIG.2. Optical Tweezers principles [6].

Figure 2 is the physics of how the single beam trapping works in detail. It is, specifically, explained by the transfer of momentum from the photons of the beam to the particle being trapped or manipulated. Because of the difference of the refractive indices between the object particle and the environment, the light will be refracted and reflected, and such change of direction will cause the change of the momentum of the photons. Based on conservation of momentum, the particle must have an equal but opposite momentum change and hence forms a force acting on the object. In general, a higher index of refraction than that of the surrounding medium is needed for a good trapping [4].

Typically, the incoming light source is a laser source with a Gaussian intensity profile. That means the intensity of the beam center is usually higher than the edge of the beam. When the bead is interacted with the light beam, the light rays are bent due to the refraction and reflection. The sum of the forces from all such bent rays comprises two components: the scattering force ***Fs*** and the gradient force ***Fg***, and the total force is ***F = Fs + Fg*** [6].

The scattering force points into the direction of the incident light, z-axis in figure 2. The gradient force, arising from the gradient of the Gaussian intensity profile, points in the x-y plane toward the beam center. The gradient force works as the restoring force that pulls the bead into the beam center. The difference scattering forces caused by reflected beam and refracted beam also forms a restoring force in z direction. By having these two recover forces in two directions, the particle can be trapped stably in the beam center.

3. Kpaitza-Dirac effect

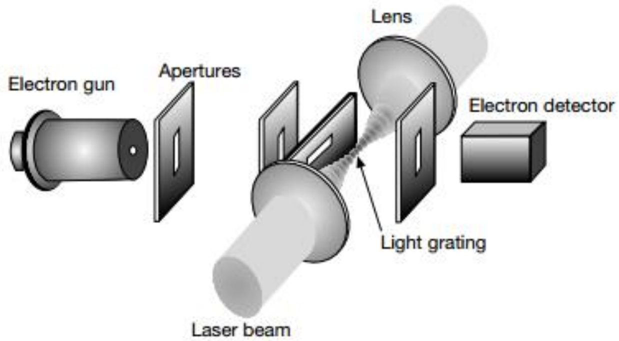

FIG. 3. Schematic or the apparatus. Electrons are collimated by four molybdenum slits and diffract from a standing wave of light formed by two counter-propagating laser beams. The electrons muct be described by a quantum mechanical wave while the standing light wave acts as a grating [2].

The Kapitza-Dirac effect here is observed by the free electrons diffraction from a standing light wave. Figure 3 shows the setup of the measurement system. In the experiment, an electron beam cross two counter-propagating laser beams which form the standing wave light grating. Sufficient high energy is needed so the pulsed lasers are utilized here. The third slit is used to cut the height of the electron beam to the laser beam waist size and the fourth slit is used to scan the electron beam profile [2].

The mode distance is $55\mu\text{m} = {2\lambda_{dB}}/{\lambda_{opt}}$, where λ_{dB} is the de Broglie wavelength of the electrons and λ_{opt} is the wavelength of the laser source. The left plot of figure 4 shows the experiment result of the diffraction pattern. The diffraction orders are clearly resolved and fall at their expected positions ($n \times 55\mu m, n = 0, \pm 1, \pm 2, \cdots$). The heights of the diffraction peaks can be found out by numerically solve the Schrodinger equation.

The observation of the Kapitza-Dirac effect opens the door to some new experiments. Since the diffracted electron beams are completely coherent, it can be used to realize a coherent beam splitter. Also, by doing that, it suggest a new way to manipulate the electron beams.

Besides using the Kapitza-Dirac effect as a tool, it is also proofed in the experiment that atoms moving through a standing light wave represents an example of classical and quantum chaos. Future study of the interaction of free electrons with laser light might be extended from quantum mechanics to including spin, chaotic behavior and relativistic mechanics.

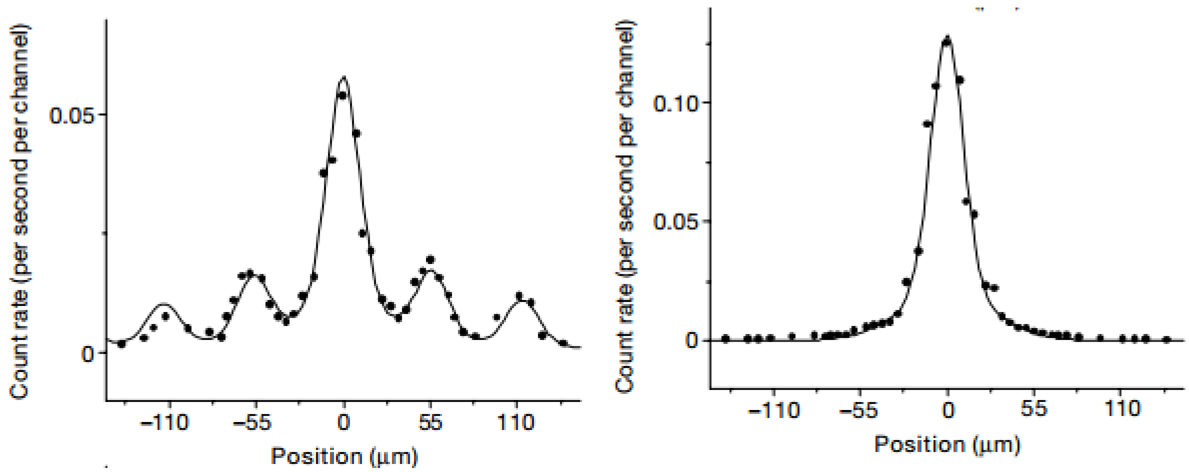

FIG. 4. Experimental data. The electron detection rate is presented as a function of dector position. The data (black points) agree reasonably well with a numerical solution of the Schrodinger equation and clearly show diffraction peaks, which is the signature of the Kapitza-Dirac effect. The right figure shows the electron beam profile with the laser beams turned off [2].

4. An application of optical tweezers

In this section, after understanding the physics about how the single beam trapping works, the view of the paper will be turned to a potential realization of optical tweezers by focusing and imaging through a multimode fiber using SLM. The basic idea here is to treat the multimode fiber as a highly-scattering material and using wavefront shaping technique to produce light-intensity pattern at the output. In this case, the light propagation system is a linear system and the characterization of such system is found by measuring the fiber propagator [3].

4.1 fiber propagator measurement

Figure 5 shows the light propagating in the whole optical system. We only consider the forward propagation first. SLM, fiber input and fiber output planes are all divided to multiple pixels and hence the propagator matrix can be used to describe the propagation of the optical field.

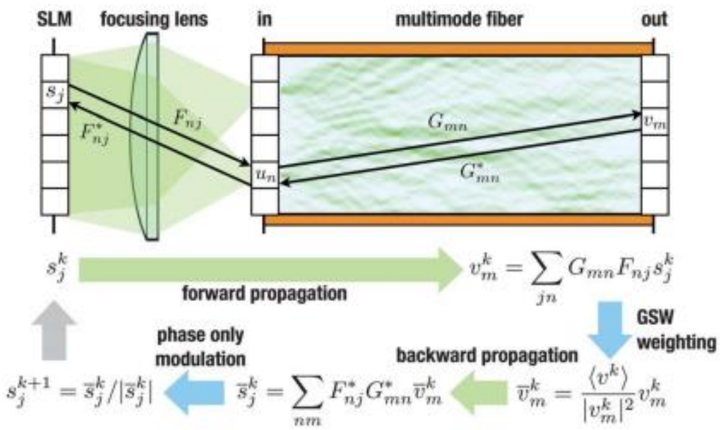

FIG. 5. Schematization of light propagation in the optical system. The iteration of the light propagates forward and backward is used to get even distributed spots [3].

From SLM to fiber input, the propagation process is $u_n = \sum_j F_{nj} s_j$, where u_n is the field in nth pixel at the fiber input and s_j is jth pixel on the SLM. Since both the SLM and fiber input are on the Fourier planes of the lenses system, the propagation matrix F can be directly found by Fourier transform $F_{nj} = \frac{1}{J}\exp\left[-i\frac{2\pi}{\lambda f}\left(x_j x_n + y_j y_n\right)\right]$, where f is the effective focal length of the optical system and J is the total number of SLM pixels. From fiber input to output, the propagation is described by $v_m = \sum_n G_{mn} u_n$, where v_m is the field of mth pixel at the fiber output and G is the fiber propagator that needs to be measured by the experiment.

First consider the amplitude measurement, by setting SLM $s_j = F^*_{nj}$ the unit input will be realized at the fiber input and hence the amplitude can be directly measured by $|v_m|^2 = |G_{mn}|^2$. As for the phase measurement, a more complicated algorithm (random mask algorithm) must be used. The result is directly given here, more details can be found in references [3]. The reference phase of G_{mn} is $\theta_{mq} = \theta_{m0} + \arctan\left[\frac{4I_m^{\pi/2} - |G_{mq}|^2 - |G_{m0}|^2}{4I_m^0 - |G_{mq}|^2 - |G_{m0}|^2}\right]$. The truly measured propagator is $\overline{G} = DG$ where D is an unknown diagonal unitary matrix describes the reference phase with $D_{mm} = \exp[-i\theta_{m0}]$. Combined the propagation from SLM to fiber input, the full forward propagation matrix is $K = \overline{G}F$.

4.2 Method of single and multiple spots focusing and experiment result

The single spot focusing can be realized by choosing the phase on SLM. That is, by taking the derivative of the output intensity at the wanted pixel and set the derivative to zero $\frac{\partial}{\partial\phi_j}|v_m|^2 = \frac{\partial}{\partial\phi_j}\left|\sum_j K_{mn}e^{i\phi_j}\right|^2 = 0$, the phase for single spot focusing can be found by $\phi_j = \arg[K_{mj}^*]$. Multiple spots focusing can be simply realized by take the complex superposition of single spot case $\phi_j = \arg[\sum_m K_{mj}^*]$. To get spots with evenly distributed intensity, the iteration shown in figure 5 is needed. The resolution of the spot can also be improved by fabricating a parabolic reflector on the fiber end, which increase the numerical aperture (NA) [7]. The experiment result is shown in figure 6 with single spot case, multiple spots case, evenly distributed multiple spots case and no modulation case (random pattern).

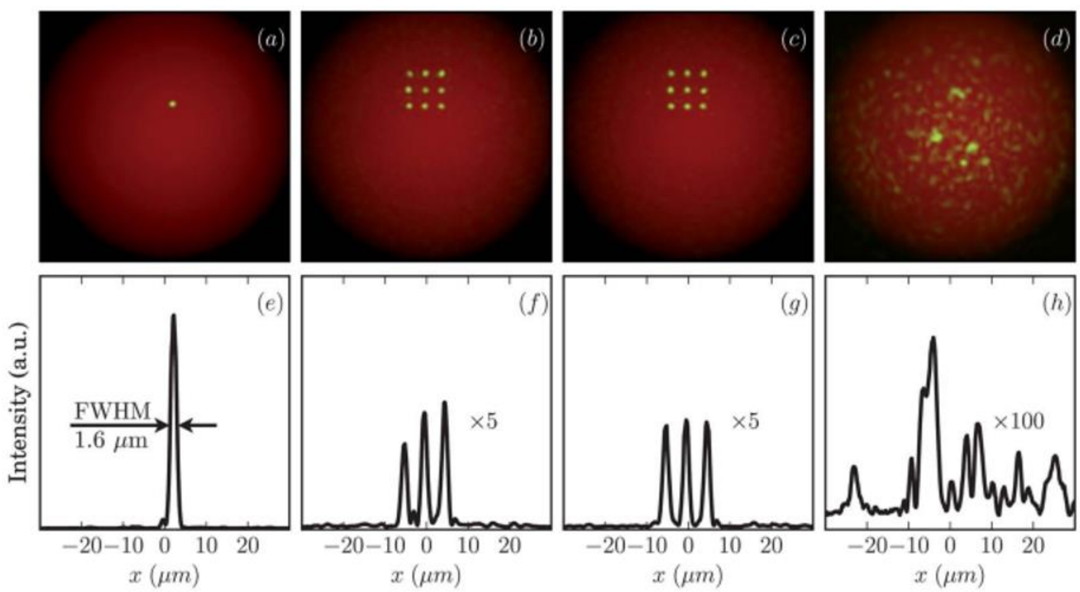

FIG. 6.Using an SLM modulating light at the input of a multimode fiber in such a way to obtain a single spot (**a,e**) or an array of 3x3 spots (**b,f**). Using an iterative algorithm for computer generated holograms results in a much more uniform intensity distribution (**c,g**). When no phase modulation is applied a random speckle pattern appears at the output (**d,h**) [3].

7. Conclusion

This paper first provides a brief review of the basic physics of optical tweezers. By applying a strong optical field to object particle in micro- or nano-scale, due to the momentum transfer

between the photons and the bead, the bead can be trapped at the center of the high intensity beam with two recover forces in two direction. Furthermore, a successful observation of the Kapitza-Dirac effect is also talked, offering a possible way to manipulate electron movement or atom movement. The last part is a method to apply optical tweezers for getting arbitrary trapping pattern, which is done by transmitting the holograms through a multimode fiber using SLM.

Reference

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