# An optical fiber probe based on multi-optical well particle capture*

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In this paper, a new method of constructing single-fiber optical tweezers is proposed, which can achieve multi-optical well non-contact capture on the same optical fiber, so as to reduce the difficulty of making single-fiber optical tweezers and enhance the operation function of single-fiber optical tweezers. We use the 650 nm laser source to excite high purity $LP_{11}$ mode in 980 nm single-mode fiber, which can achieve the multi-optical trap capture effect around the fiber port after simple micro-staggered core fusion treatment for common single-core fiber. Optical fiber ports are fabricated using thermal method to construct special tip structures. Simulation and experimental results show the feasibility of the structure. The excitation and utilization of multi-mode beams in single fiber constitute a new development of single fiber optical trap, enrich the function of single fiber optical tweezers, and make more practical applications in biomedical research possible.

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Non-contact and non-destructive optical manipulation, which uses focused laser beams to capture, manipulate and arrange biological particles, has strong applications in biotechnology, DNA nanotechnology and microfluidics, and may even have a significant impact on future medicine[1]. Optical traps were first proposed by ASHKIN et al in 1986 and were first demonstrated in the biological sciences in the late 1980s[2]. Since then, optical capture has been applied to many different research areas throughout the 1990s, such as atomic physics[3], micromachining[4], chemistry[5], biomedicine[6] and microelectro mechanical systems[7]. As a low-cost and convenient tool, optical fiber is increasingly used in optical traps[8].

Normally, the light emitted from the fiber tip will diverge, while a stable optical trap can only be achieved by balancing the gradient and scattering force of two relative optical fibers. Therefore, the formation of a traditional single optical trap requires multiple optical fibers[9]. Based on the development of fiber end micromachining technology, the three-dimensional optical force generated by forming the fiber tip into a special conical shape captures biological particles, which marks the emergence of single fiber optical tweezers[10]. Based on ordinary single-fiber optical tweezers, it is more convenient for research and control, and power transmission[11] and distribution are easier than control[12]. Therefore, many structures have been rapidly developed, such as narrow parabolic tapered tip fiber optical tweezers[13,14], optical fiber tweezers based on reflection, axial cone-tipped fiber optical tweezers[15], high-index fiber optical tweezers[16], double-core fiber optical tweezers[17], four-core fiber optical tweezers[12]. In addition, due to the development of micromanipulation field[18], more and more requirements are put forward on the function of optical fiber optical tweezers. How to integrate multiple functions on the same fiber to improve efficiency and obtain multi-optical well optical tweezers by mode multiplexing has become an essential research topic. In recent years, there have been a lot of articles about how to use the non-corresponding wavelength of the transmission fiber to excite other low order modes and how to realize multi-function optical tweezers by mode reuse. In 2014, CHEN et al[19] utilized the inherent four-lobe intensity distribution and high coherence focusing of $LP_{21}$ mode beam in optical fiber to form an "optical chuck", which allowed the capture and reorganization of biological particles in clusters, as well as the translation and rotation of particles. However, the 650 nm light source is directly coupled into the G.652.D single-mode fiber, which may have a large power loss. In the same year, ZHANG et al[20] stimulated $LP_{11}$ mode beam by stitching 980 nm fiber and common single-mode fiber offset 2 μm, and modulated the $LP_{11}$ mode beam with mode selector and tension and distortion on the fiber, achieving experimental results of controllable deflection and directional manipulation of yeast cells. It makes full use of the low-order $LP_{11}$ mode beam in the fiber and

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plays a great role in enriching the function of fiber optical tweezers. However, excessive external mechanical equipment may cause certain damage to the fiber itself and increase the complexity of the device. Moreover, when it captures two yeast cells, it has a double-body structure particle. In 2020, KUANG et al[21] proposed a single-beam intra-cavity optical tweezer where nonlinear coupling laser operated with the motion of trapped particles. The effects of numerical aperture, pump power, particle radius and refractive index on the optical confinement efficiency are studied, and the equilibrium position of optical tweezers in a single beam cavity is discussed. In the same year, LIU et al[22] proposed a fiber-based Bessel optical trap, which incident a beam of 980 nm into the designed integrated fiber structure to obtain a Bessel beam. By using high refractive index glass microspheres glued to the tip of the multi-mode fiber, the Bessel beam was converged along the axis to produce a bright focal spot and a dark cage. High index particles and low index particles are trapped in bright spot and dark cage respectively. It enriches the optical tweezers function, but axial optical trap, and the use of special optical fiber increases the production cost. In 2021, FOOLADI et al[23] proposed a novel plasma conical dual-core fiber optical tweezer for nanoparticle trapping. The main objective is to improve the optical gradient force of the proposed aperture. Its equipment process is more complex. ZHANG et al[24] used 980 nm light source to excite $LP_{11}$ and $LP_{01}$ modes in spliced-core fiber, and captured two particles in the axial direction simultaneously based on mode reuse technology. After analyzing the light field emitted by $LP_{11}$, it should be able to give play to its greater advantages and improve the utilization rate of the fiber. In addition, some of them use mode multiplexing to adjust the axial capture position, but most of them use the 980 nm light source to manipulate biological cells, while the multi-optical trap capture of particles based on 650 nm light source needs to be explored.

In this paper, a new attempt is made to fuse the common communication fiber with the typical working wavelength of 980 nm optical fiber with 0.2 μm offset, and use 650 nm light source to excite the $LP_{11}$ mode. Experimental results show that the optical tweezers can be used as a novel single-fiber optical tweezer structure to generate $LP_{11}$ mode light, and the capture point exists in the vertical axial plane, and the incident light field mode can be changed to the axial capture point only by fine-tuning the incident end of the laser source, which can achieve stable non-contact capture of particles. The whole system does not introduce other mechanical devices, reducing mechanical damage to optical fibers, making the structure more simple, lower requirements for the external environment. In addition, a simulation model is established by finite element analysis to demonstrate the feasibility of the structure of the single fiber optical tweezers.

The experimental device is shown in Fig.1. We use the 650 nm laser light source with power adjustment range of 1—30 mW. Firstly, a G.652.D single-mode fiber (core diameter of 9 μm) is connected at the outlet of the light source, and then it is splicted with a typical single-mode fiber with a working wavelength of 980 nm (core diameter of 4.7 μm). The mode excitation of 650 nm laser source in typical 980 nm single-mode fiber is realized by split-core docking. The 980 nm fiber was used for particle capture. The fiber probe port is fixed and manipulated by an optical five-dimensional micromanipulator, one end is connected to the laser light source, and the port is immersed in a microsphere suspension. Finally, the data collected by charge coupled device (CCD) is connected to a personal computer to observe and record the experimental images in real time.

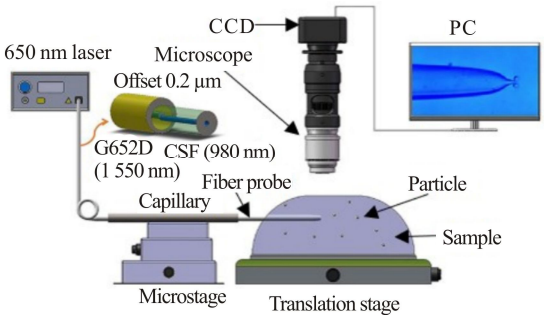


**Fig.1 Experimental structure of the $LP_{11}$ mode beam single fiber tweezers**

The single-mode fiber transmits only the fundamental mode at the corresponding operating wavelength, but when it transmits other light sources at other wavelengths, other low-order and high-order mode beams will be excited accordingly. The number of propagation modes in the fiber depends on the normalized frequency parameter $V$ of the transmitted light wave in the fiber. When $V<2.405$, only $LP_{01}$ mode beam can propagate. When $2.405\leq V\leq 3.832$, the next higher-order mode $LP_{11}$ will be generated and propagated. Eq.(1) can be used to calculate the mode of the laser source in the single mode fiber when the 650 nm laser sources are connected respectively.

$$V=\frac{2\pi\alpha}{\lambda}\sqrt{n_1^2-n_2^2}. \tag{1}$$

The normalized frequency parameter $V$ is determined by the core radius $a$, the laser wavelength $\lambda$, the core refractive index $n_1$ and the cladding refractive index $n_2$. Therefore, according to the above calculation, the wavelength of the light source is 650 nm, the diameter of the fiber core is 4.7 μm, and the refractive index of the fiber core and cladding is 1.464 22 and 1.456 76 respectively, so that $2.405\leq V=3.352\leq 3.832$ can be obtained, that is, in addition to $LP_{01}$ mode beam, $LP_{11}$ mode beam can also exist in the designed fiber probe. Fig.2(b) shows the far-field contour distribution image of $LP_{11}$ mode beam when the optical fiber port is cut off.

In addition, the structure of the optical tweezers is simple to design and manufacture. It is basically impossible to have only $LP_{11}$ mode in the optical fiber in the experiment, so we can only concentrate the energy of the light wave in the fiber on the $LP_{11}$ mode as much as possible in the experiment. In this paper, staggered core fusion technology is adopted in the experiment. Due to the difference in the diameter of two single-mode optical fiber cores, the ideal energy ratio of high purity $LP_{11}$ mode can be obtained with extremely small eccentricity or even no deviation, thus reducing the power loss. This technology is realized by fine-tuning the position of optical fiber after automatic alignment of the optical fiber welding machine. In this way, the incident angle of the light wave exiting from the G.652.D standard single-mode fiber and entering the 980 nm single-mode fiber is larger, and the more energy entering the cladding, the higher the energy of the $LP_{11}$ mode may be excited. Therefore, we cut the stripped G.652.D and 980 nm single-mode fiber and put it into the welding machine, and set the biased 0.2 μm fusion splicing. Using the fine-tuning function of the welding machine to fine-tune the position of the optical fiber, the energy of the fundamental mode transmitted in the optical fiber is relatively low, and the energy of the $LP_{11}$ mode is dominant. The ratio between $LP_{11}$ mode and $LP_{11}$ mode is controlled by adjusting the degree of core error. Finally, cover the spliced optical fiber with the fiber fusion heat shrinkable tube to the interface and then place it in the fusion machine for heating and fixing to prevent the splicing from bending and breaking easily.

The fiber probes were fabricated from commercial single-mode optical fibers using a flame heating technique. First, a fiber stripper was used to remove the buffer and polymer jacket to give a bare fiber with a length of 4 cm. The naked fiber was then sheathed with a glass capillary (inner diameter is ~0.9 mm, wall thickness is ~0.1 mm, length is ~120 mm) to protect it from breakage and warping. The non-fused end of 980 nm fiber was used as the capture end, and stainless steel capillary coating was adopted to avoid the influence of fiber probe bending on the stability of subsequent capture and manipulation. The bare fiber outside the capillary was then heated for 45 s using the outer flame of an alcohol lamp to reach its melting point. The fiber was then drawn along the optical axis at a rate of 2.5 mm/s. When the fiber is stretched, it is thinned to within 10 μm, and the speed is accelerated to about 30 mm/s until it breaks. The surface tension of the melted fiber forms a tapered tip at the end. This method is simple and low cost to fabricate fiber tip. The formed fiber probe port is shown in Fig.2(a). Considering the particularity of $LP_{11}$ mode light field, the direction of the outgoing light field extends symmetrically from the central axis to both sides, so the particles should be captured on both sides of the port. The tip angle has a significant effect on the focus of the light output from the fiber tip. The position of the focus on the beam axis can be adjusted by changing the tip angle, so as to realize the non-contact capture of particles. Compared with other shapes, the effect of this tip shape is more obvious and easier to observe. In addition, since 650 nm red laser light source was used in the experiment, a narrowband filter was added below the CCD, so the overall picture showed light blue, as shown in Fig.3.

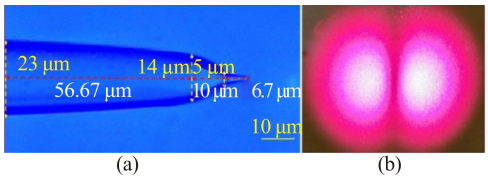


**Fig.2 (a) Image of tapered tip of optical fiber; (b) Far-field contour distribution of $LP_{11}$ mode**

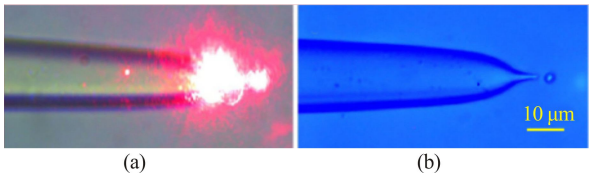


**Fig.3 (a) Optical fiber diagram without filter; (b) Optical fiber diagram when adding filter**

The reason why optical tweezers can capture particles in their light field lies in that the light field can produce two forces on the particles in it, which are respectively the light gradient force caused by the gradient distribution of the light field and the light scattering force caused by the radiation pressure due to the propagation of light. The effect of gradient force on particles comes from the force exerted by the electric dipole moment in the medium ball in the uneven electromagnetic field. It is proportional to the gradient of light intensity and points to the maximum intensity of the light field. Its effect is to move the particles towards the point of maximum optical power density. The effect of scattering force on particles is caused by the momentum exchange between light and photon in the scattering process, the particle changes the photon momentum, and the particle itself is affected by the reaction force of the momentum change. The direction of the scattering force is along the direction of the light, and the effect is to move the particles along the direction of the light beam. Therefore, when the particle moves near the focusing position of the optical fiber tip, the gradient force and scattering force reach an equilibrium state, which means that the particle is stably bound to the three-dimensional optical potential well.

According to the principle of action, the beam propagation of optical fiber probe is simulated by using COMSOL Multiphysics software, and the light field diagram of $LP_{11}$ mode is given. As shown in Fig.4(a) and Fig.4(d), we simulate the light field of $LP_{01}$ and $LP_{11}$ respectively. The biggest difference between the outgoing light field of $LP_{11}$ mode and that of the base mode is that the main energy is not concentrated near the optical

axis, but collects in the position toward the center, and separate focusing positions are formed on both sides after the exit, corresponding to effective light traps for capturing particles. Since the outgoing light field of single fiber optical tweezers is close to gaussian beam, there is always a stable gradient force pointing towards the optical axis perpendicular to the optical axis. It is shown that the optical tweezers with $LP_{11}$ mode beam can form two or more capture points on the plane perpendicular to the optical axis in addition to the axial direction. Fig.4(b) and Fig.4(e) show the particle capture experiment pictures corresponding to the model.

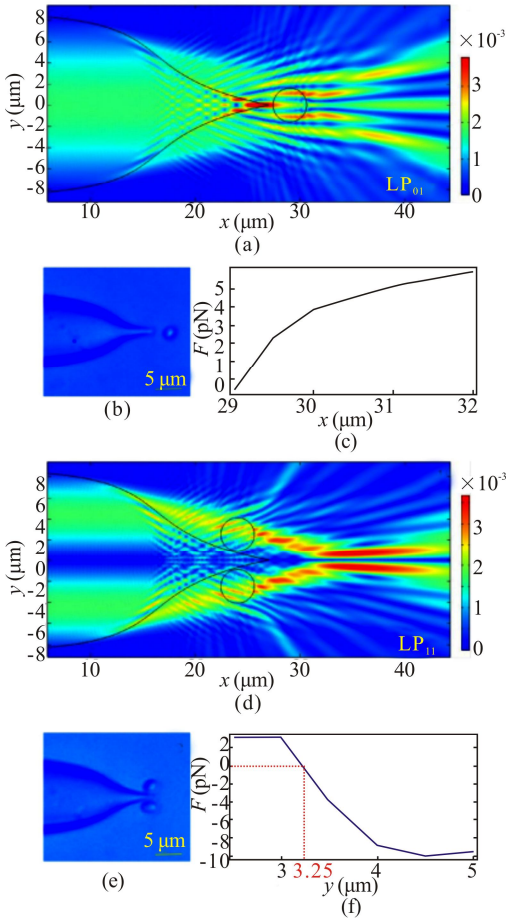


**Fig.4 (a) and (d) are the simulation diagrams of light field distributions of $LP_{01}$ mode and $LP_{11}$ mode; (b) and (e) are the capture diagrams of particles corresponding to $LP_{01}$ mode and $LP_{11}$ mode respectively; (c) Force analysis of particles in axial direction *x* under $LP_{01}$ mode; (f) Force analysis of particles in radial direction *y* under $LP_{11}$ mode**

In order to verify the rationality of the experiment, this paper simulates the forces on the particles at different capture positions, as shown in Fig.4(c) and Fig.4(f). In the figure, *x*-axis represents the distance from the optical fiber port, and *y*-axis represents the optical force *F* on the particles, where *F* is the combined force of gradient force and scattering force. Fig.4(c) shows the force analysis of the particle on axial *x* in $LP_{01}$ mode. It can be seen from Fig.4(c) that the particle is subjected to a negative optical resultant force at the position of $x$=29 μm, which attracts the particle to the optical fiber port. Fig.4(f) shows the force analysis of particles on radial *y* in $LP_{11}$ mode. It can be seen from Fig.4(f) that the optical force on particles on radial *y* decreases gradually. At $y$=3.25 μm, the optical force *F* is 0, which is manifested as that the particles receive a thrust first, and at $y$=3.25 μm, the thrust is converted into tension. Thus the particles are trapped at $y$=3.25 μm. Simulation conditions are as follows: the wavelength of the light source is 650 nm, the core diameter is 4.7 μm, the refractive indexes of core and cladding are 1.464 22 and 1.456 76, respectively. The refractive index of glass (water) is 1.33.

In the experiment, the slide and cover slide were placed and fixed on a three-dimensional precision table to calibrate the fiber tip. A square chamber about 2 cm long and 1—2 mm high was formed between the cover glass and the slide glass with the help of blue gel to weaken the Brownian motion of particles in the solution and the evaporative force of the solution in the air. Use a needle tubing to extract part of the solution and gently push it into the chamber until the solution fills the chamber. Then, the tip of the tapered fiber covered with capillary was fixed on a five-dimensional platform and adjusted to the same height as the solution. After that, the fiber was extended into the solution from one side for particle capture. In this experiment, 3—8 μm chlorella was used, which has strong regeneration ability and simple sample solution preparation.

It is found in the experiment that there is no obvious difference between the fundamental mode and $LP_{11}$ mode when the conical single fiber optical tweezers capture a single particle. When capturing multiple particles, single fiber optical tweezers using fundamental mode can only obtain multiple particles arranged along the optical axis. The single optical tweezers based on $LP_{11}$ mode show its unique side. Because it is difficult to remove all fundamental modes in the optical fiber, the single-fiber optical tweezers not only have the fundamental mode capture characteristics, but also have the $LP_{11}$ mode capture characteristics. Specifically, the particles can be captured on both sides of the optical fiber port, and the axial capture effect can be achieved by adjusting the incident end of the light source to change the incident angle or bending the optical fiber to change the mode power ratio. Fig.5 shows axially captured particles. As shown in Fig.6, there are two capture positions in the vertical axial plane.

When the light source is connected, the output power of the optical fiber is 5.58 mW. Particles with a diameter of 3—5 μm are attached to both sides of the optical fiber port. By manipulating the optical fiber probe, the captured particles can be controlled in $+x$, $-x$, $-y$, $+y$ directions. To observe the movement of the optical fiber, use the fixed white spot inside the yellow circle as a reference (The white point is the microlens defect mold

point). In Fig.5, the optical fiber is manipulated to move from $t$=0 s (Fig.5(a)), and moves to $+x$ direction when $t$=10 s, with distances of 21 μm (Fig.5(b)). When $t$=20 s and 25 s, it moves in the $-x$ direction with a distance of 30 μm (Fig.5(c)) and 56 μm (Fig.5(d)). At $t$=35 s, we go back to the starting position. When $t$=47 s, it moves in the $+y$ direction with a distance of 30 μm (Fig.5(e)). When $t$=60 s, it moves in the $-y$ direction with a distance of 32 μm (Fig.5(f)).

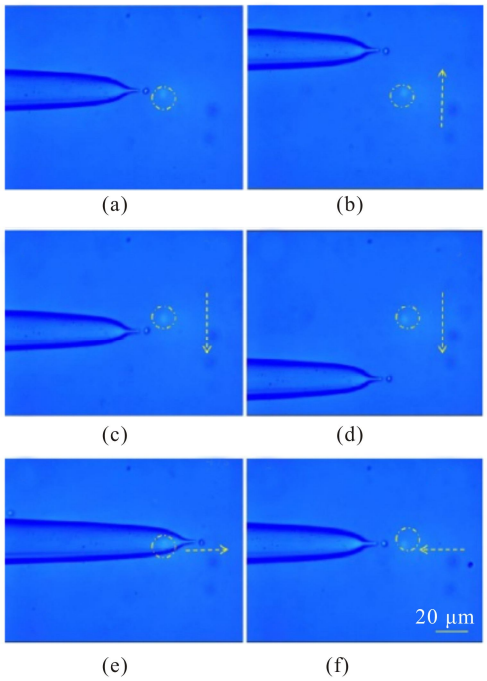


**Fig.5 Optical fiber movement process (axially captured particles): (a) $t$=0 s; (b) $t$=10 s in $+x$ direction; (c) $t$=20 s in $-x$ direction; (d) $t$=25 s in $-x$ direction; (e) $t$=47 s in $+y$ direction; (f) $t$=60 s in $-y$ direction**

In Fig.6, optical fiber movement is manipulated from $t$=0 s (Fig.6(a)), and moves toward $+x$ direction at $t$=7 s and 10 s, with distances of 10 μm (Fig.6(b)) and 15.5 μm (Fig.6(c)) respectively. When $t$=20 s, it moves in the $-x$ direction with a distance of 20.5 μm (Fig.6(d)). When $t$=45 s, it starts to move in the $y$-axis direction, and when $t$=54 s, it moves in the $+y$ direction with a distance of 30 μm (Fig.6(e)). When $t$=70 s, it moved to the $-y$ direction with a distance of 23.3 μm (Fig.6(f)). With the increase of the travel distance and speed of the fiber probe, the travel distance and speed of the captured particles can be further increased. Under the condition that the particles do not fall, the maximum velocity of the particles depends on the notch capability of the fiber probe, which increases with the increase of laser power. In addition, the controlled release of particles can be achieved when the laser is turned off. This indicates that the dynamic operation is caused by a fiber optic probe.

In conclusion, we have successfully demonstrated a single-fiber optical tweezer with a novel structure and

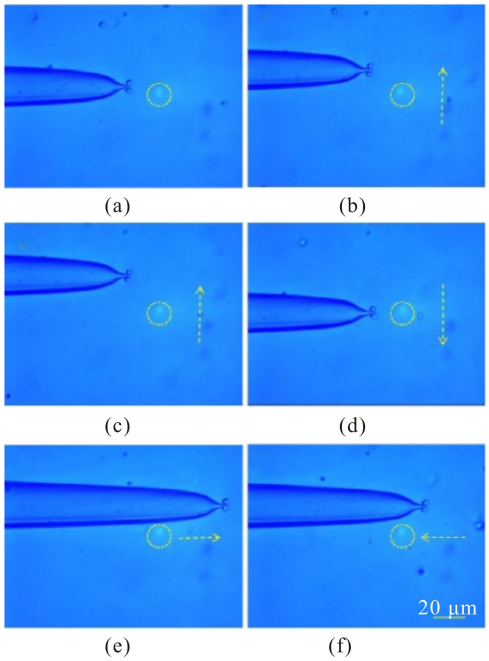


**Fig.6 Optical fiber movement process (vertically captured particles): (a) $t$=0 s; (b) $t$=7 s in $+x$ direction; (c) $t$=10 s in $+x$ direction; (d) $t$=20 s in $-x$ direction; (e) $t$=54 s in $+y$ direction; (f) $t$=70 s in $-y$ direction**

$LP_{11}$ mode beam as a powerful tool that can capture one or more particles, laying the foundation for the subsequent multi-particle directional rotation and other multi-dimensional manipulation. The single-fiber optical tweezers use $LP_{11}$ mode light beam guided by common single-core fiber, which can form two or more separate optical traps around the tip of the vertical optical axis. It will guide the further control and utilization of various modes of light transmitted in optical fiber in the future. The feasibility of this method is verified by theoretical simulation and calculation. This technique can be extended to biochemical analysis and operation. Because such single-fiber optical tweezers can be easily integrated with other micro-optical device platforms, the proposed configuration can find potential applications in lab-on-a-chip devices and also opens the possibility for more practical applications in biomedical research.

## Statements and Declarations

The authors declare that there are no conflicts of in-terest related to this article.

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