

# Manipulation and arrangement of biological and dielectric particles by a lensed fiber probe

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**Abstract:** An optical trapping system with a single-mode lensed fiber probe inserted at an angle is built; this system is simpler and more flexible than conventional optical tweezers. Two lasers, with 632.8- and 1550-nm wavelengths, are employed to trap and manipulate yeast cells and polystyrene microspheres. Nine yeast cells are manipulated to form a letter "T." Finally, the manipulation performed with various inclination angles, particle materials, laser wavelengths, and laser powers is analyzed experimentally.

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**OCIS codes:** (140.7010) Trapping; (140.3510) Lasers, fiber; (170.4520) Optical confinement and manipulation

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## 1. Introduction

Since Ashkin *et al.* first proposed the optical trapping of dielectric particles by a single-beam gradient force optical trap in 1986 [1], this method has been developed as optical tweezers technology in the fields of biology, physics, and chemistry [2]. In especially biology, the

optical tweezers method has been applied in research on cells, viruses, bacteria and even DNA molecules.

Optical tweezers are applied with difficulty in turbid biological media, since it is hard to attain the tightly focused laser beam that is necessary for optical trapping. In addition, multiple optical tweezers systems based on microscopes are very complex. To solve these problems, optical fibers were introduced to carry the laser beam to the trapped object. A couple of cleaved or lensed fiber probes were placed in opposite positions to achieve stable three-dimensional (3-D) optical trapping of small dielectric spheres [3–5], and two pairs of fiber probes positioned in a cross formation were employed [6] to improve the stability and the versatility of trapping. With various shapes and orientations of the fiber probe, a single lensed fiber probe inserted into the sample chamber at an angle was used to trap and manipulate a microparticle on a surface [7, 8], and two lensed fiber probes inserted at an angle were used to rotate and levitate a particle in three dimensions [9, 10]. Recently a single fiber probe with an annular light distribution near the tip was used for 3-D trapping by the balance between the electrostatic force of attraction toward the tip and the light scattering force pushing the particle away from the tip [11]; the microbubble which is formed at the fiber end under the effect of a high power laser was used to trap and mix particles [12].

In the papers cited above the two-dimensional (2-D) arrangement of particles was not reported, and the trapping lasers used near-infrared but not visible light. In the present paper a trapping system with a single lensed fiber probe inserted at an angle is built, and two lasers with 632.8 and 1550-nm wavelengths are employed to trap and manipulate yeast cells and polystyrene microspheres. Nine yeast cells are manipulated to form a letter “T,” and some manipulations are analyzed experimentally.

## 2. Principle and setup

The optical force on a particle can be divided into two components. One, in the axial direction of the light, denoted  $F_{ax}$ , pushes the particle in the propagation direction when the spot size at the beam waist is larger than some value (for example 0.7  $\mu\text{m}$  in Ref. [13]). The second, in the transverse direction, denoted  $F_{tr}$ , pulls the particle back to the optical axis. In our experimental system the same result is seen: the spot size at the beam waist is approximately several micrometers ( $\sim 3 \mu\text{m}$ ), and  $F_{ax}$  pushes the particle away from the fiber probe. Figure 1 illustrates the optical forces acting on a particle [8]. In the equilibrium position, the horizontal force  $F_x$  acting on the particle

$$F_x = F_{ax} \cos \theta - F_{tr} \sin \theta \quad (1)$$

is equal to zero, where  $\theta$  is the inclination angle of the probe. In the vertical ( $z$ ) direction the vertical components of  $F_{ax}$  and  $F_{tr}$ , the gravity, the buoyancy, and the pressure of the sample chamber bottom are in equilibrium. If the particle deviates from the equilibrium position in the  $+x$  direction, less laser radiation reaching the particle decreases  $F_{ax}$ , and a greater excursion from the axis increases  $F_{tr}$ , so  $F_x$  decreases to become negative and pushes the particle toward the equilibrium position. In contrast, if the particle deviates in the  $-x$  direction,  $F_{ax}$  increases and  $F_{tr}$  increases, so  $F_x$  increases to become positive and also pushes the particle toward the equilibrium position. Therefore this equilibrium position is stable, and the particle can be trapped at the stable equilibrium position.

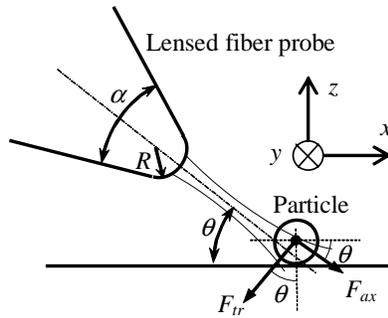


Fig.1. Optical forces acting on a particle

The complete experimental system with a He-Ne laser is shown as Fig. 2(a). The 632.8-nm laser beam emitted from a He-Ne laser passes through a variable attenuator and a beam expander and then is coupled into a single-mode optical fiber, with the fiber coupler consisting of a microscope objective and a fiber adjuster. The other end of the fiber, namely the lensed fiber probe, adheres to a syringe needle attached to a multidimensional micro-manipulator. The fiber probe is inserted into a sample chamber moved by a 3-D nanostage, which includes three piezoelectric tubes controlled by a computer and is fixed on a microscope stage. The particles in liquid and the manipulation process are observed by an inverted microscope (Leica DM IRE2) with a CCD camera. A filter in front of the CCD is used to block the scattering laser. If the wavelength is changed to 1550 nm, a semiconductor laser and a SMF-28 fiber (Corning Corporation) are connected directly by a FC-PC connector, as shown in Fig. 2(b).

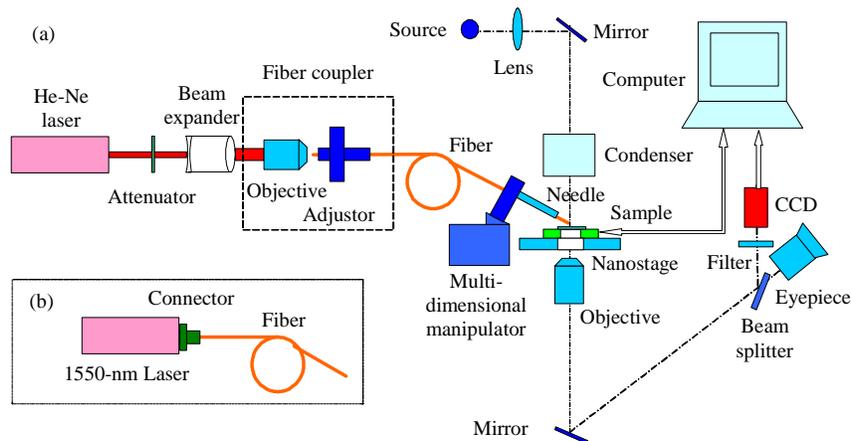


Fig.2. Experimental setup. (a) He-Ne laser is employed. (b) 1550-nm laser is employed.

### 3. Experiments and discussion

In our experiments, first the trapping and manipulation of a 5- $\mu\text{m}$ -diameter yeast cell in water are carried out. A He-Ne laser and a 632.8-nm single-mode lensed fiber with 55° cone angle ( $\alpha$ ) and 5.9  $\mu\text{m}$  lens radius ( $R$ ) are employed. The output power from the fiber probe is 1.5 mW, and the inclination angle  $\theta$  is 50°. After the yeast (A, Fig. 3) on the chamber bottom is successfully trapped, the nanostage moves the sample chamber in sequence in the  $-y \rightarrow +y \rightarrow -x \rightarrow +x \rightarrow -z \rightarrow +z$  directions, as shown in Figs. 3(a)–3(g), and the displacements are  $\sim 50 \mu\text{m}$  in the  $y$  direction and  $\sim 40 \mu\text{m}$  in the  $x$  and  $z$  directions. Then the micromanipulator moves

the fiber probe in sequence in the  $+y \rightarrow -y \rightarrow +x \rightarrow -x$  directions, as shown in Figs. 3(g)–3(k), and the displacements are  $\sim 40 \mu\text{m}$  in both the  $x$  and the  $y$  directions. During the entire process yeast A is trapped and manipulated by the probe, and untrapped yeast B moves with the chamber bottom. While the chamber moves along the  $-z$  direction as shown in Figs. 3(e)–3(f), trapped yeast A also moves down with the chamber bottom but is still trapped near the optical axis of the probe, so that the CCD image shows that yeast A and B both are out of focus and that yeast A is pushed away from the probe. In contrast, while the chamber moves along  $+z$  direction as shown in Figs. 3(f)–3(g), yeasts A and B both come back into focus and yeast A is pulled toward the probe. This experiment shows the ability of our system to trap and manipulate particles by moving the chamber and the probe.

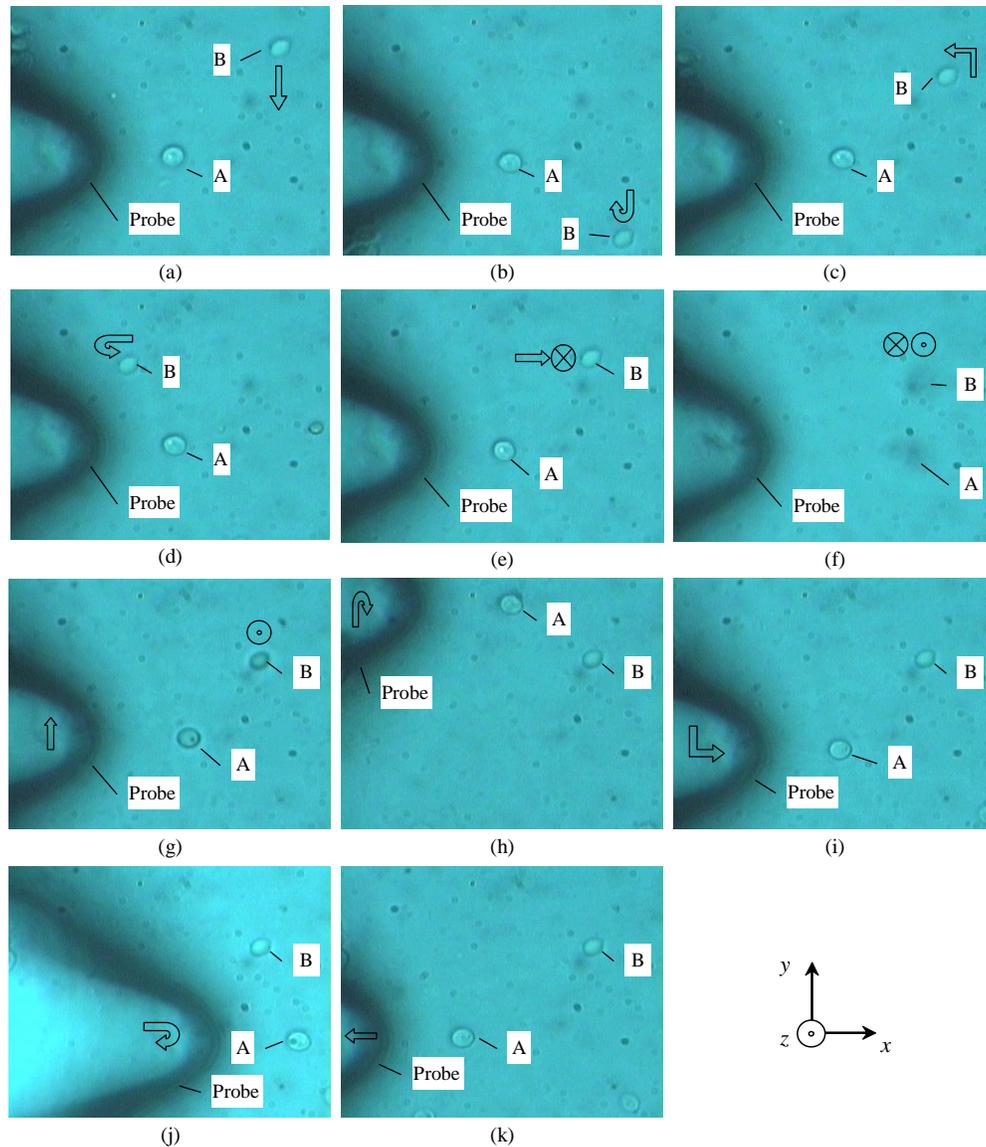


Fig.3. Yeast cell A is always trapped by the probe, and untrapped yeast B moves with the chamber bottom. (a)–(g): The nanostage moves the sample chamber in sequence in directions  $-y \rightarrow +y \rightarrow -x \rightarrow +x \rightarrow -z \rightarrow +z$ . (g)–(k): Then the micromanipulator moves the fiber probe in sequence in directions  $+y \rightarrow -y \rightarrow +x \rightarrow -x$  (observed with a  $100\times$  objective).

Then, under the same experimental parameters, nine yeast cells are manipulated in sequence to form a letter “T” on the chamber bottom, as shown in Fig. 4. Owing to disturbance of the probe and the water, yeast cells that have been manipulated migrate a little from the target location while other cells are being manipulated. Thus we have to manipulate them again to correct their location. Figure 4 shows the corrected location of the nine cells. Since the additional technology such as chemical solution method [14] is not employed, the temporal stability of the pattern is not very good owing to the disturbance of the probe and the water, and it is hard to locate the particles at the exact position. However the pattern is near stable when the fiber probe doesn’t move. On the whole, this experiment shows the ability of our system to arrange particles.

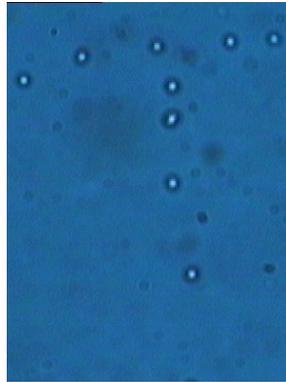


Fig.4. Nine yeast cells form a letter “T” (observed with a 40× objective).

Next the performance of the single lensed fiber trapping system during manipulation is analyzed experimentally.

First, the effect of the inclination angle  $\theta$  is discussed. The experiments show that the yeast can be trapped and manipulated in all directions at large inclination angles ( $\theta = 55^\circ, 50^\circ, 45^\circ, 40^\circ$ ) but that at small inclination angles ( $\theta = 35^\circ, 30^\circ$ ) the yeast can be trapped only while the chamber moves in the  $\pm y$  and  $-x$  directions and cannot be trapped while the chamber moves in the  $+x$  direction. From Eq. (1), when  $\theta$  decreases, if  $F_{ax}$  is assumed to be constant,  $F_{tr}$  must increase to maintain equilibrium ( $F_x = 0$ ), which entails that the offset of the yeast from the optical axis of the probe must increase. Since there must be a maximum  $F_{tr}$  and a threshold of transverse offset,  $F_{tr}$  is assumed to be maximum in equilibrium at small inclination angles ( $\theta = 35^\circ, 30^\circ$ ). If the yeast moves in the  $+x$  direction in the new equilibrium,  $F_{ax}$  decreases, but  $F_{tr}$  also decreases because the offset exceeds the threshold; therefore  $F_x$  may increase to become positive and cannot push the yeast toward the equilibrium position. Thus it can be seen that the inclination angle is a very important parameter in the lensed fiber trapping system and that it must be greater than a critical angle (which is  $\sim 35^\circ\text{--}40^\circ$  in this experiment) in order to trap the particle completely in all directions.

Second, the effect of the particle’s material is discussed. A polystyrene microsphere with a 5- $\mu\text{m}$  diameter is employed. The experiments show that the microsphere can be trapped and manipulated completely at the inclination angle  $\theta = 55^\circ$  but not at  $\theta = 45^\circ$ . This demonstrates that for different particle materials the critical angle is different,  $\sim 35^\circ\text{--}40^\circ$  for yeast cells and  $\sim 45^\circ\text{--}55^\circ$  for polystyrene microspheres in our experiments. This result is due to the difference in absorbance and reflectance of different materials, which causes a different ratio of  $F_{tr}$  to  $F_{ax}$ .

Third, the effect of the wavelength is discussed. A 1550-nm semiconductor laser and a SMF-28 lensed fiber with  $\alpha = 55^\circ$  and  $R = 10 \mu\text{m}$  are employed, as shown in Fig. 2(b). The output power from the fiber probe is 1.3 mW, and the inclination angle  $\theta$  is  $50^\circ$ . A yeast cell

with a 5- $\mu\text{m}$  diameter is trapped and manipulated in all directions. However, the trapping ability of the 1550-nm laser is much weaker than that of the 632.8-nm laser. A possible reason is that the spot size at the beam waist emerging from the 1550-nm fiber with 10.2- $\mu\text{m}$  core diameter is bigger than that from the 632.8-nm fiber with 3.2- $\mu\text{m}$  core diameter; hence the transverse force generated with a bigger spot size is less than that with a smaller spot size.

Finally, the effect of the laser power is discussed. A yeast cell with a 5- $\mu\text{m}$  diameter is trapped and manipulated by a fiber probe with 632.8-nm wavelength and 0.9-mW output power. The experiments show that the critical angle is also  $\sim 35^\circ$ – $40^\circ$  which is the same as that with 1.5-mW output power mentioned above. Due to the decrease of the output power, the maximum speed of moving the particle decreases. If the output power is too small, for example 0.1 mW, it is hard to trap and manipulate particle because the optical force is too small to overcome the disturbance of the water. Therefore, enough output power is necessary to trap particle, and it is easy to manipulate the particle with large output power, but the critical angle doesn't change.

#### **4. Summary and conclusion**

In summary, the ability of the single lensed fiber trapping system to manipulate and arrange the biological and dielectric particles in visible and infrared light is demonstrated experimentally. The performance with various inclination angles, particle materials, laser wavelengths, and laser powers is analyzed experimentally.

This lensed fiber trapping system has some merits in comparison with optical tweezers. (1) Particles in turbid biological media can be trapped. (2) The system is simple and inexpensive because the microscope is used only to image, not to trap. (3) The lensed fiber probe points to the focus and may be manipulated like the pipette of a microinjection system, so the system is visual and flexible for manipulating bioparticles. (4) The optical sources can be changed easily by using different optical coupling devices. (5) Multiple optical trapping may be performed easily by adding other independent trapping systems.

One of the potential applications, for example, is that the lensed fiber probe may be used with the microinjector of a normal biological micromanipulation system to achieve contactless and nondestructive manipulation and injection. The lensed fiber trapping system may also be applied for research in interaction and communication between cells, the characteristics of fine particles, microassembly, and other problems in biology, physics, chemistry, and micromechanics.

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