Experimental Observation of Optical Trapping Using Optical Fiber

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Abstract

Optical trapping method using optical fiber (Optical Fiber Trapping Method) was proposed. Optical trapping of a dielectric particle and a biological cell was successfully demonstrated. The experimental results showed that a trapped micro object was moved easily and freely synchronized to the trapping fiber.

Key Words: Optical fiber, Single laser beam optical trapping

I. Introduction

A.Ashkin et al proposed the optical trapping of dielectric particles by a single-beam gradient force trap for the first time[1]. Since then, this method was developed as an optical tweezers technology for various biological objects, such as viruses, bacteria and yeast cells as well as various dielectric particles.

Recently, K.Sasaki et al developed the laser scanning trapping method[2] which utilized the substantial net surrounding force, then, not only transparent particles, but also metal particles could be trapped and transferred. However, since laser beams are focused by objective lenses and trapped objects are transferred by moving the focal point for these trapping system, there are following some weak points.

1) Laser beam manipulation and scanning system are much complicated and expensive.
2) Freedom degree from the restriction of motion is small.

In this report, optical trapping method using optical fiber[3][4] was proposed. The method has capabilities to solve above mentioned problems. This optical fiber trapping method has many following merits.

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1) Optical trapping systems using optical fiber are simple and inexpensive.
2) Trapped objects can be moved freely.
3) Optical sources can be changed easily using optical connectors.
4) Trapping point is easily noticeable, because a fiber end points out the focal point.

These merits are verified by following experiments.

Ⅱ. Optical trapping apparatus

Fig.1 shows the apparatus used for optical trapping of a dielectric particle and a biological cell. The laser sources are YAG laser at 1.06 μm and a semiconductor laser at 1.48 μm. The output of laser light is coupled into an optical fiber which has an optical connector at the fiber end. The trapping fiber is attached to a xyz manipulator and the laser light is introduced through the optical connector. The trapping fiber end is polished to a tapered spherical end whose radius R_f is 2 μm, 4 μm and 6 μm, respectively. A microscope with a liquid-immersion microscope objective is used to observe the trapped objects and the trapping behavior is recorded on a VTR with a CCD camera.

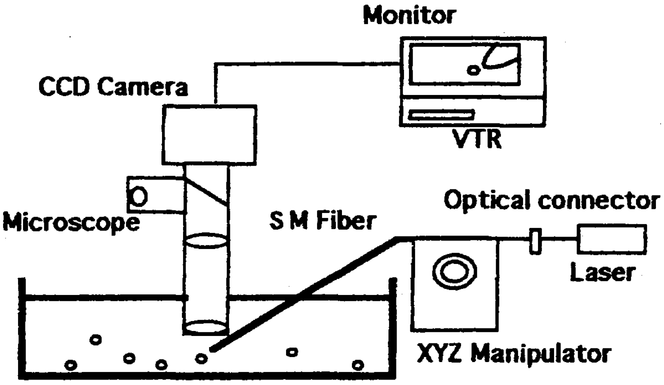

Fig.1 Experimental setup used for the optical trapping.

Ⅲ. Results and discussion

Polystyrene particles dispersed in *ethanol*(refractive index n=1.36) and yeast cells dispersed in water(n=1.33) were used as the sample microscopic objects for the trapping experiments. The light source used for trapping a 10 μm diameter polystyrene particle(n=1.59) was a semiconductor laser.

Fig.2(a) and (b) is a photograph of a trapped polystyrene particle. Without optical power, the polystyrene particles dispersed in *ethanol* were drifted from the top to bottom of this photograph with the Brownian motion as shown in Fig.2(b). Under the condition of trapping, we can freely move the trapped polystyrene particle to the forward and backward or right and left directions synchronized to the trapping fiber. The minimum optical power for trapping a polystyrene particle was about 1.3 mW for R_f = 2 μm SMF(Single-Mode Fiber), about 2.0 mW for R_f = 4 μm SMF and about 2.5 mW for R_f = 6 μm SMF, respectively. When we changed the light source of a semiconductor laser to YAG laser, the trapping characteristics was not so different from that of semiconductor laser. The minimum optical power of YAG laser to trap a micro-sphere was a little smaller than that of the semiconductor laser.

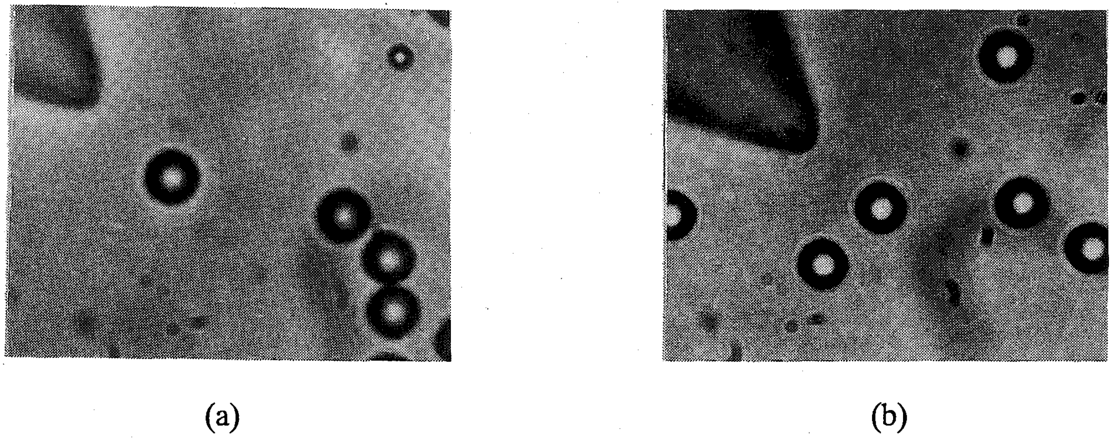
(a) (b)

Fig.2 Photograph of a polystyrene particle trapped near the focal point.

Fig.3(a) and (b) is a photograph of a trapped yeast cell. Under the condition of trapping, we can freely move the trapped yeast cell to the forward and backward or right and left directions synchronized to the trapping fiber as shown in Fig.3(b).

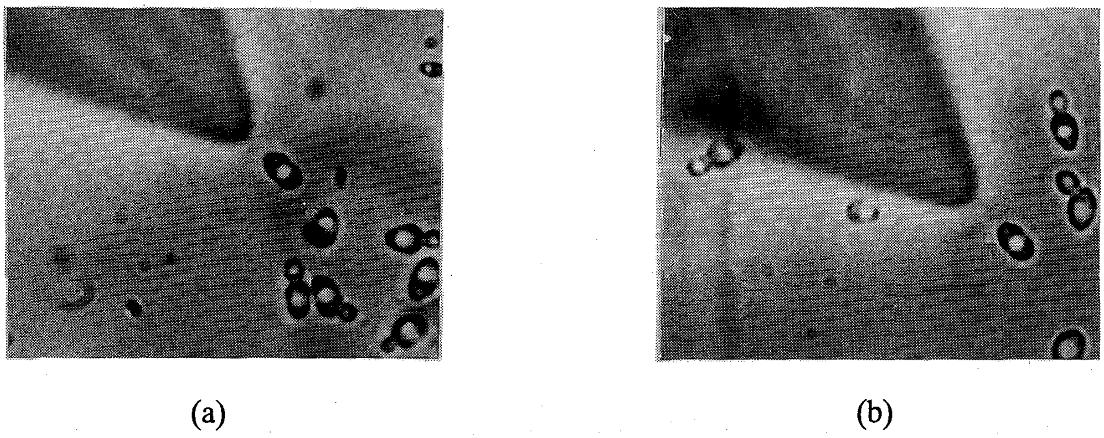
(a) (b)

Fig.3 Photograph of a yeast cell trapped near the focal point.

For this experiment, YAG laser was used as the light source and the radius of the spherical end was 2 μm. The length of the major axis and the minor axis of the elliptically shaped yeast cell was about 9 μm and 4 μm, respectively. The experimental result showed that the yeast cell was trapped at about 20 μm from the fiber end and the major axis of yeast cell and the optical axis direction of the laser beam were coincident with each other. The minimum optical power was about 0.7 mW for $R_f = 2$ μm SMF, about 1.0 mW for $R_f = 4$ μm SMF and about 1.5 mW for $R_f = 6$ μm SMF, respectively.

These experimental results are easily understood considering a radius of a fiber spherical end, beam waist position from a fiber end and spot size at the beam waist. Fig.4 shows the schematic diagram of micro-spheres trapped by a focused beam emitted from a tapered spherical end.

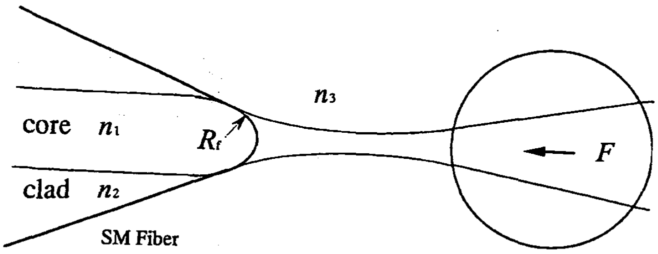

Fig.4 Schematic diagram of micro-spheres trapped by a focused beam emitted from a tapered spherical end.

In a single-mode fiber, the guided mode can be approximated by a gaussian beam whose beam spot size is W_0. The spot size of the guided mode used for experiments is about 4 μm. Therefore, the beam waist position z_f and the beam spot size W_f are given as following equation[3]:

$$z_f = \left\{\left(\pi W_0^2/\lambda\right)^2 (n_1-n_3)/\left(R_f n_3\right)\right\} \Big/ \left\{1+\left(\pi W_0^2/\lambda\right)^2 (n_1-n_3)^2/\left(R_f n_3\right)^2\right\}, \tag{1}$$

$$W_f = W_0 \Big/ \sqrt{1+\left(\pi W_0^2/\lambda\right)^2 (n_1-n_3)^2/\left(R_f n_3\right)^2} \tag{2}$$

, where n_1, n_2 and n_3 are the refractive indices of a fiber core, fiber clad and immersion liquid, respectively, and λ is wavelength of incident laser beam.

Fig.5 shows the calculated waist position z_f and spot size W_f as a function of the radius of a spherical end.

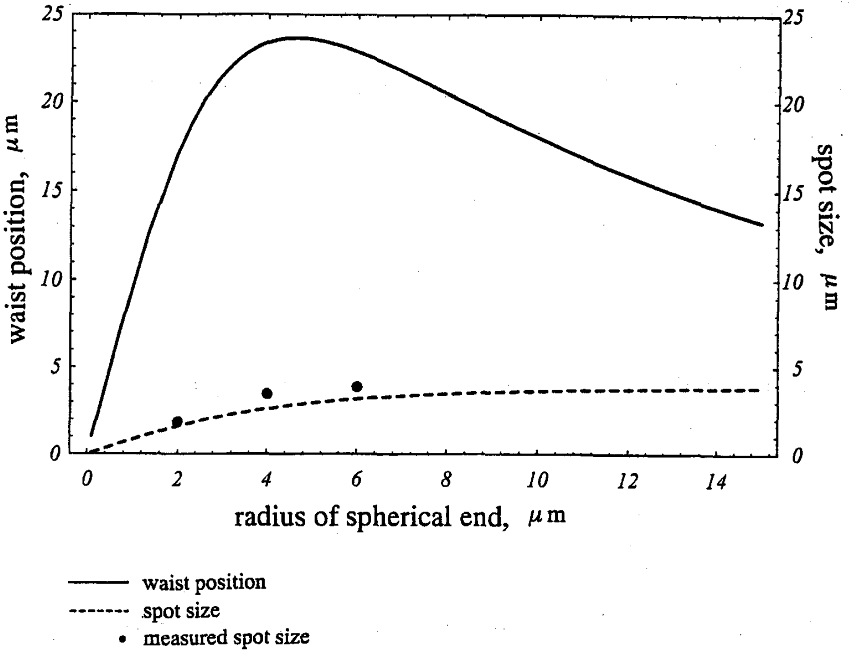

Fig.5 Calculated waist position from a fiber end and spot size at the beam waist as a function of a radius of spherical end.

The calculated result of waist position shows that the yeast cell in Fig.3 was trapped near the focal point of the tapered spherical end fiber, because the calculated focal point z_f are about 17 μm for R_f = 2 μm. And the calculated result of spot size shows that the beam spot size becomes small with decreasing the radius of a spherical end. This calculated result is well coincident with the measured result. Trapping force is due to the conservation of photon momentum carried by the incident laser light on the trapped microscopic objects. When the laser light beam is refracted at the surface of the microscopic object, the beam direction is changed and then a kinetic force is produced to conserve the light beam momentum. Generally, the produced trapping force is inversely proportional to the spot size w_f [5]. Therefore, when the trapping fiber(R_f = 2 μm) is chosen for trapping a microscopic object, the trapping force is larger than that of different trapping fiber whose R_f is 4 μm or 6 μm. These results well explain the trapping characteristics of polystyrene particle and yeast cell using different trapping optical fiber.

Ⅳ. Conclusion

In this report, a single laser beam optical trapping using optical fiber was successfully demonstrated. The experimental results showed that a microscopic object was trapped near the focal point of the trapping fiber and the minimum optical power for moving a yeast cell easily and freely was about 0.7 mW for $R_f = 2\ \mu\mathrm{m}$ SMF.

It was verified that optical fiber trapping method was useful for the manipulation of microorganisms and cells.

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