Single-beam optical fiber trap

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Abstract. We have already developed a single-laser beam optical fiber trapping system. A biological cell dispersed in water solution could be easily trapped by a single laser beam emerging from an optical fiber, and the optically trapped micro-object could be freely transferred in 2-D plain synchronized to the trapping fiber. Separation/coupling of an individual cell from the cell groups was easily achieved using plural optical fibers. In this paper, fiber optic trap was experimentally and theoretically analyzed for corroborating the single laser beam fiber optic trap.

1. Introduction
Ashkin et al. proposed the optical trapping of dielectric particles by a single-beam gradient force trap for the first time[1]. This laser beam trapping method is considered to be useful for manipulation of biological object because of non-invasive technology. 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 for various dielectric particles. Its operation principle is based upon the electromagnetic momentum preservation. In recent years, a great deal of experimental and theoretical work has been done on the various types of laser beam trapping to manipulate micro-organisms. In these technologies, laser beams are focused by an objective lens and trapped objects are transferred by moving the focal point for these trapping systems. There are following some weak points: (i) laser beam manipulation and scanning systems are much complicated and expensive. (ii) degree of freedom from restriction of motion is small.

In this paper, we reported an optical fiber trapping system[2][3] and verified that optical trapping and manipulation of a micro object were easily achieved by a weakly focused single laser beam emerging from an optical fiber. The forces exerted by the trap were sufficient to move a micro object without physical contact. As compared with other embodiments, this implementation is most economical, much simpler to operate, and requires relatively low optical power to capture an object.

2. Optical Trapping Apparatus
Figure 1 shows the apparatus used for the optical trapping of biological cells. A YAG laser at 1.06 μm and a semiconductor laser module at 1.48 μm, which has a SMF(Single-Mode Fiber) pig-tailed connector, are used for experiments. 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 an xyz manipulator and the fiber is introduced into a sample cell at an angle of 35 degrees. The trapping fiber can be freely moved in the sample cell by controlling the xyz manipulator. For focusing the laser beam emitted from the trapping fiber end, the fiber end is polished to a tapered spherical end. 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. This optical fiber trapping method has following merits: (i) optical trapping systems using optical fibers are simple and inexpensive. (ii) trapped objects can be moved easily and freely, synchronized to the trapping fiber. (iii) optical sources can be changed easily using optical connectors. (iv) the trapping point is easily noticeable, because the tapered spherical end fiber points out the focal point.

In biology, an optical trap provides a new and novel tool for the manipulation of microorganisms and cells. Yeast cells dispersed in water solution were used as the sample biological objects and a YAG laser at 1.06μm was used as the light source. The lengths of the major axis and of the minor axis of the elliptically shaped yeast cell were ~9μm and 4μm, respectively. The minimum optical power for trapping a yeast cell was ~0.7mW. Under the trapped status, we could freely move the trapped yeast cell to the forward and backward or right and left directions synchronized to the trapping fiber. Next, we investigated the optical damage for cells. Figure 2 illustrates the reproduction of a yeast cell trapped by a focused infrared(IR) laser beam emitted from trapping fiber. For this experiment, a YAG laser was used as the light source. The emitted power from trapping fiber was ~5 mW. The first photograph(a) was taken after 10 minutes from the start of optical trapping and the second photograph(b), taken after 60 minutes, showed the reproduction of a yeast cell by budding. Reproduction of a biological cell in IR trap at ~10 mW was also observed. The reproduction of the biological cell clearly demonstrates that optically trapped biological cell is not damaged by the focused IR beam emitted from trapping fiber. But damage to a yeast cell was seen after a few minutes using a visible laser beam. With a visible light catastrophic damage due to absorption of biological cell occurred with only a few milliwatts of power. These experimental results indicate that IR laser must be used as a laser source for trapping a biological cell using optical fiber.
Figure 2: Reproduction of a yeast cell trapped by a focused infrared laser beam emitted from trapping fiber. The emitted optical power is $\sim 5$ mW.

3. Single-beam optical fiber trap
We have already experimentally investigated the optical force acting on a micro-sphere to corroborate the optical trapping by a weakly focused single laser beam from a lensed optical fiber[2][3]. These results indicate that the particle is trapped at the point where the $x$-directed (horizontal) optical forces are balanced as shown in Fig. 3. At this stable point, the total $z$-directed optical forces act on the sphere in the downward direction. Generally the force on a microsphere divides itself naturally into two components [2][3], which always act through the center of the sphere: one in the axial direction of the light, denoted by $F_{ax}$, and the other a transverse force, denoted by $F_{tr}$.

Furthermore, we calculated, using a formulation based on the ray optics approximation analysis, the optical forces on a micro-sphere for corroborating the optical trapping by the laser beams from optical fiber end. For calculation, it was assumed that 10 $\mu$ m diameter silica particle was suspended in ethanol. In addition only laser beams with Gaussian intensity profiles were considered. These results indicate that the transverse force $F_{tr}$ pulls the micro-sphere to the beam axis, but axial force $F_{ax}$ always acts on the sphere in the direction of beam away from the optical fiber end. Therefore a stable trap can be defined at the point where the $-x$-directed optical force $F_{trH}$ and $+x$-directed optical force $F_{axH}$, which correspond to the projection of $F_{tr}$ and $F_{ax}$ along the horizontal axis, are precisely balanced as shown in Fig. 3, and where restoring forces act to keep the sphere at the stable point.

Next, we investigated the influence of the vertical distance $Dz$ shown in Fig. 3 on trapping characteristics. In these experiments, a semiconductor laser module at 1.48 $\mu$m was used as a light
Lensed optical fiber used for experiments had a hemispherical microlens with 5µm radius of curvature for focusing the laser beam from the fiber end. Figure 4(a)-(c) show experimental results of 10µm diameter silica particle (refractive index 1.41) dispersed in ethanol. Figure 5 depicts the optical forces acting on a silica particle as a function of the offset distance from the point O that represents the position of x(horizontal) axis where the center of the sphere is on the beam axis. For above calculations, it was assumed that the fiber end was inserted into a sample cell at an angle of 35 degrees and the center of the sphere was coincident with the beam waist at the point O.

Figure 4: Experimental Results.

Figure 5: Calculated results of x-directed trapping force acting on a 10µm diameter silica sphere as a function of Dz.
From these experimental and theoretical results, we could verify that it was possible to vary the equilibrium position of a given bead to any point along the $X$ axis by varying the vertical distance $Dz$. Furthermore, we could verify that the stiffness of the produced restoring force to the stable point, which was on the $X$ axis, depended on the vertical distance $Dz$ as shown in Fig. 5. On the other hand, Figure 4(d)-(f) show experimental results of 10$\mu$m diameter polystyrene particle (refractive index 1.59) dispersed in ethanol. From these experimental results, we could verify that polystyrene particle could not be trapped when $Dz$ was higher than 39$\mu$m as shown in Fig. 4(f). Figure 6 depicts maximum of attracting force as a function of $Dz$, and indicates that polystyrene particle can not be trapped when $Dz$ is higher than 37.5$\mu$m, which is good agreement with experimental results. From these studies, we could reveal that vertical distance $Dz$ between the bottom of the sample cell and the optical fiber end is important parameter for fiber trapping.

![Figure 6: Calculated results of maximum of attracting force on a sphere as a function of Dz.](image)

4. Conclusions
In this paper, optical trapping and manipulation of biological cells using optical fibers were successfully demonstrated without physical contact. The biological object was trapped near the focal point of the trapping fiber and the minimum optical power for trapping a yeast cell was ~0.7mW. Optically trapped micro-object was freely transferred in 2-D plane synchronized to the trapping fiber. These experimental results verified that proposed optical tweezers technology using optical fibers was useful for the manipulation of microorganisms and biological cells.

References
[1] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm and S. Chu, Opt. Lett. 11 (1986) 288.
[2] K. Taguchi, H. Ueno, T. Hiramatsu and M. Ikeda, Electron Lett. 33 (1997) 413.
[3] K. Taguchi, K. Atsuta, T. Nakata and M. Ikeda, Optical and Quantum Electronics. 33 (2001) 99.