Experimental and Theoretical Investigation of an Optical Levitation Using Dual-Beam from Optical Fibers Inserted at an Angle

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Abstract. Optical forces exerted on a sphere were experimentally and theoretically investigated in order to corroborate the three-dimensional optical trapping of a micro object by the laser beams from plural optical fiber ends, which were inserted into a sample cell at an angle. There was only one stable point of equilibrium located below the beam-crossing point and greatly enhanced stability could be obtained.

1. Introduction
Optical trapping is a technique that is used to capture, translate, and manipulate microscopic particles, such as dielectric microspheres and cells. Ashkin and co-workers demonstrated optical trap using a single beam, which is called a single-beam gradient trap or optical tweezers. In the single-beam gradient force trap, the beam is strongly focused to a diffraction-limited spot by a high-numerical-aperture objective. In this trapping system, the relation of refractive index between the micro object and surrounding medium is critical factor for trapping. Wright et al. developed an analytical method that accurately described the forces exerted on a dielectric microsphere (refractive index n₂) in liquid (n₁) and showed that when the relative index (n₂/n₁) was larger than 1.2, for example, an optical trap by the conventional trapping system was not created at all because of the reflection of light, which gives rise to a scattering force.

We have already developed a single-beam optical fiber trapping system[1][2], which was very economical and simple to operate, and verified that two-dimensional optical trapping and manipulation of a micro object were easily achieved by a single laser beam from an optical fiber end inserted at an angle to a sample cell. However we could not levitate a micro object against the gravity. Therefore, we tried to levitate a micro object by the laser beams emerging from plural optical fibers, and verified that a micro object laid at the bottom of the sample cell could be levitated and transferred to another sample cell[3].

In this paper, we experimentally and theoretically analyzed the optical forces exerted on a microsphere by the laser beams from optical fiber ends and verified that inserting the optical fibers at an angle played an important role for a strong three-dimensional optical trapping.

2. Dual-beam fiber-optic trap
We have already proposed a novel dual-beam trapping system and demonstrated a strong three dimensional optical trapping using plural optical fibers which were inserted at an angle to a sample cell[3]. Figure 1 shows the experimental setup used for our experiments. The fiber trap was formed using a temperature stabilized, 1480nm, cw diode laser (ANRITSU SD3F403D), pigtailed with single-mode fiber. The output of laser light was coupled into optical fibers, which had optical connectors at these fiber ends. Lensed optical fibers were used as trapping fibers. The fiber end had a hemispherical microlens with \(~5 \mu m\) radius of curvature for focusing the laser beam emerging from the optical fiber end. In this case, the focused spot size at the beam waist was \(\sim 3 \mu m\) in ethanol solution, which was measured using an IR camera.

These trapping fibers were attached to xyz manipulators and were inserted into a sample cell at an angle. A microscope with a liquid-immersion microscope objective was used to observe the trapped object and the trapping behavior was recorded on a VTR with a CCD camera. This proposed optical fiber trapping method has following merits: (i) optical trapping system using optical fibers is simple and inexpensive. (ii) trapping point is easily noticeable, because the fiber end points out the focal point.

![Experimental setup](image)

Figure 1: Experimental setup.

First, we try to levitate a micro object against gravity by the laser beams emerging from plural optical fibers. A biological cell(Yeast cell) dispersed in water was used as a sample object. Figure 2 shows the levitation of a biological cell using two optical fibers. The yeast cell indicated by arrow was captured and held in the laser beams emitted from two trapping fibers. The image of the trapped biological cell, which is removed from bottom of the sample chamber, is in focus, but the images of the other biological cells are out of focus because these biological cells stay at the bottom of the sample chamber. The levitated biological cell could be moved in 3-D space by moving the two optical fibers.
3. Numerical results and discussion
Next we investigated the relationship between the laser beam axis and optically levitated sphere to corroborate the optical levitation of a micro object by the laser beams from plural optical fiber ends.

The typical side view image of the relationship between the laser beam axis and optically levitated sphere is shown in Fig.3. Figure 3 can be obtained by measuring the vertical distance between the optical fiber end and the center of the optically levitated sphere as a function of the horizontal distance $D_{fH}$ between each optical fiber end. The center of the sphere is located at distance from the cross-position of the laser beams from optical fibers as shown in Fig. 3. In this case optical forces act on the sphere in the only vertical direction because the optical forces of horizontal direction are cancelled out. Calculation results indicate that the optical forces balance below the beam-crossing point. Furthermore, we could verify that a restoring force was produced that pulled or pushed the bead to the equilibrium position on the vertical axis. It was possible to vary the equilibrium position along the vertical axis by controlling the horizontal distance between each optical fiber.

In this section we calculate, using a formulation based on the ray optics approximation analysis, the optical forces on a spherical for corroborating the strong three-dimensional optical trapping by the laser beams from optical fiber ends. We calculated the optical forces acting on a sphere, as a function of the position of the particle in the x-y plane shown in Fig. 3. For calculation, it was assumed that the fiber ends were inserted into a sample cell at an angle of 35 degrees and a 5 $\mu$ m diameter acrylic
particle \( n_2 = 1.4 \) was suspended in ethanol \( n_1 = 1.36 \). In addition only laser beams with Gaussian intensity profiles were considered.

Figure 4: Calculated results of optical efficiency and direction of the optical forces acting on a sphere.
The total forces act on a sphere in the direction of the equilibrium position, which is on the vertical axis. These results indicate that a micro object can be captured and held at a stable point on the vertical axis, where the force of gravity and buoyancy, the total axial forces in the downward direction and the total transverse forces in the upward direction precisely balance as shown in Fig. 3. In an optical trap, a general observation is that the maximum value of the axial efficiency is smaller than that of the transverse efficiency by at least an order of magnitude. However, our proposed fiber-optic traps use the strong gradient transverse forces to trap a particle; therefore, they stabilize the particles much more firmly than do counterpropagating two-beam traps.

4. Conclusions
In this paper, we demonstrated a strong three-dimensional optical trapping using plural optical fibers which were inserted into a sample cell at an angle. There was only one stable point of equilibrium located below the beam-crossing point and greatly enhanced stability as compared with the corresponding counterpropagating dual-beam traps could be obtained. It was possible to vary the equilibrium position of an optically levitated object along the vertical axis by controlling the horizontal distance between each optical fiber end. Furthermore, we could experimentally verify that the manipulation characteristics of optically trapped object depended on the horizontal distance and fiber insertion angle, and employing microlenses in a dual-beam trap enhanced that trapping stability and increased the trapping volume. From these experimental results, we verified that our proposed manipulation technique was useful for the manipulation of microorganisms and biological cells.

References
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