Numerical Computations of the Optical Forces Acting on an Elliptically Shaped Object

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We theoretically analyzed the optical force acting on an elliptically shaped object in order to numerically obtain the magnitude of the applied torque and direction of rotation. An elliptically shaped object could be rotated and trapped on condition that the major axis of the object and the propagating direction of the laser beam were coincident with each other.

Keywords: optical fiber, numerical analysis, rotational manipulation, elliptically shaped object

1. Introduction

We have already developed an optical fiber trapping system and verified that optical trapping and manipulation of a micro object and a biological cell were easily achieved by a weakly focused single laser beam emerging from an optical fiber[1]. The forces exerted by the trap were sufficient to move a micro object. As compared with other embodiments[2][3], this implementation is most economical, much simpler to operate, and requires relatively low optical power to capture an object.

Recently rotational manipulation of a microscopic object and a biological cell was demonstrated. E. Higurashi et al. realized the directional rotation of an asymmetrically shaped object[4], but the rotational direction depended on the asymmetric shape of the object. On the other hand, we have already demonstrated a novel technique to manipulate biological cells using optical fibers[5]. In this experiment a YAG laser at 1.06μm was used as a light source, and lensed optical fibers used for experiments had hemispherical microlens with ~8μm radius of curvature for focusing the laser beam from the fiber ends. In this case, the focused spot size at the beam waist was ~4.5μm in ethanol solution, which was measured using an IR camera. An elliptically shaped yeast cell was rotated counterclockwise/clockwise and trapped near the focal point of the optical fiber on condition that the major axis of the yeast cell and the propagating direction of the laser beam emitted from the fiber end were coincident with each other. These experimental results indicated that directional rotation could be achieved by controlling the output optical power from each trapping fiber and the characteristics of rotational manipulation depended on the laser power emitted from the optical fiber end[5].

In this paper, we theoretically analyzed the optical force acting on an elliptically shaped object for corroborating the directional manipulation of an elliptically

shaped yeast cell.

2. Numerical Results and Discussion

It is true for all rays that the actual optical forces always act through the center G of mass of a sphere. This indicates that no radiation pressure torque occurs on a sphere. On the other hand, when the long/short axis of an elliptically shaped object is not coincident with the propagating direction of the laser beam, the optical force F tends to rotate the object about the center G, because the center G is not on the line of action of the force F . This rotational tendency is known as the moment of the force. The forces of radiation pressure arise from the momentum change of photons due to the refraction and reflection of light. Radiation pressure forces are exerted on the surfaces where light enters and exits the micro-object. In this section, we theoretically analyzed the optical force acting on an elliptically shaped object in order to numerically obtain the magnitude of the applied torque and direction of rotation. As shown in Fig.1, an elliptically shaped object with refractive index n_2 is suspended in a liquid whose index is n_1 . In Fig.1, l , m and θ are the length of the major axis of the elliptically shaped object, the minor axis of the object and the angle between the major axis and x axis, respectively. For all calculations, it was assumed that an object(refractive index $n_2=1.4$) was suspended in ethanol($n_1=1.36$) and the negative torque induced a spinning of the micro object in the clockwise direction. In addition, only laser beams with Gaussian intensity profiles were considered. Each reflectance and transmittance was calculated as the average of that corresponding to TE polarization and that corresponding to TM polarization, respectively. The total optical force F can be obtained by summing the force contributions from each ray over the surface of the object.

Fig.2 depicts the calculated torque efficiency as a

function of θ for laser beam spot size of $4.5\mu\text{m}$ when the relative index $n_{re}(=n_2/n_1)$ is equal to 1.03. For above calculation, l and m were defined as $7\mu\text{m}$ and $6\mu\text{m}$, respectively, and the parameter θ was varied from 0 to 180 degrees.

Fig.1 Elliptically shaped object. l , m and θ are the length of the major axis of the elliptically shaped object, the minor axis of the object and the angle between the major axis and x axis, respectively.

Fig.2 Calculated torque efficiency as a function of θ for laser beam spot size of $4.5\mu\text{m}$. The relative index n_2/n_1 is equal to 1.03.

When $0 < \theta < 90$, the torque has only negative values, which lead to clockwise rotation as shown in Fig.3(a); when $90 < \theta < 180$, the torque has only positive values, which induces the object to spin in the counterclockwise direction as shown in Fig.3(b). These calculation results are in excellent agreement with the experimental results, as was observed experimentally by Taguchi[5].

These results show that an elliptically shaped object is rotated and trapped on condition that the major axis of the object and the propagating direction of the laser beam are coincident with each other. Furthermore, we verified that the relative index n_{re} was a critical parameter for rotational manipulation. When the relative index n_{re} was equal to 0.96, the torque had only positive values in the range from 0 to 90 degrees, which led to counterclockwise rotation. This direction was opposite to that when the relative index n_{re} was greater than 1. From these results, it was found that an elliptically shaped object could be made to spin in one direction

when n_{re} was greater than one and in the opposite direction when n_{re} was less than one.

Fig.3 Rotation direction of an elliptically shaped object. (a)when $0 < \theta < 90$. (b)when $90 < \theta < 180$.

3. Conclusion

In this paper, a novel technique to manipulate a biological cell using plural optical fibers was discussed. The optical force acting on an elliptically shaped object was theoretically analyzed in order to numerically obtain the magnitude of the applied torque and direction of rotation. These results verified that an elliptically shaped biological cell could be rotated and trapped on condition that the major axis of the object coincided with the propagating direction of the laser beam, and the relative index n_{re} was a critical parameter for rotational manipulation.

(Manuscript received June 12, 2000)

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