Low-contrast photonic hook manipulator for cellular differentiation

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Abstract

By illuminating an asymmetric cuboid, the photonic hook is generated, a specialized curved photonic jet. In this work, we numerically explored the optical forces generated by the photonic hook's field, and found that the cuboid system can move large objects along a curved trajectory. We considered the interaction of this cuboid in the presence of a backing substrate, as our system is simple enough to be embedded in a 'lab-on-a-chip' platform, and possible applications for cellular differentiation.

1. Introduction

It is known that electromagnetic radiation can produce mechanical action on particles[1]. Through the use of auxiliary structures, it is possible to generate specialized fields, and these fields allow more varied kinds of optical manipulation beyond trapping. On the other hand, it is also known that dielectric microparticles (usually spheres) with a certain refractive index generate a photonic nanojet - a highly-localized, subwavelength, low-divergence beam - while being illuminated. This can be used for optical manipulation, with applications toward high-resolution microscopy, biology, etc.

In this work, we use the photonic hook[2] - a curved photonic nanojet - as a structured field formed by an asymmetric dielectric particle for generating optical forces to move large objects along curved trajectories. This photonic hook field combines the construction simplicity of the photonic nanojet, as well as the curvature produced by Airy and other self-accelerating beams. We note that other curved beams, such as the Airy beam, require the use of complicated and expensive optical elements that make these beams unsuitable for particular applications, such as embedding the system shown in Fig. 1, to generate the beams. Here we show that our photonic hook system can be used for manipulation of large objects with low-contrast between the probe and the background. This manipulation can be implemented for a variety of applications such as cellular differentiation in a lab-on-a-chip platform.

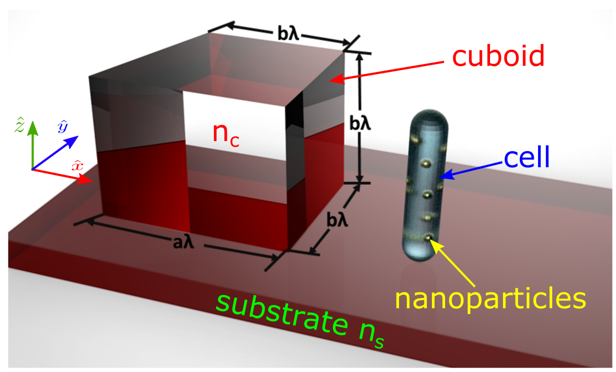

Figure 1: Illustration of the cuboid-substrate system. The E-field is polarized along the y axis, propagating along x.

2. Optical Forces

Mathematically, the forces acting on an arbitrary object can be obtained through the integration of the Maxwell stress tensor over a surface around the object[1]. Despite its accuracy, this process is computationally consuming. For the case of Rayleigh particles (where the particle size is much smaller compared to the incident wavelength), we can simplify the process and approximate the forces by assuming that the object is an electric dipole. In this case, the force in the electric dipole approximation becomes[1]

$$\langle F_i \rangle = \frac{1}{2}\mathrm{Re}\left(\alpha \mathbf{E} \cdot \frac{\partial \mathbf{E}^*}{\partial x_i}\right), \tag{1}$$

where x_i indicates the spatial coordinate, α indicates the particle's complex polarizability, and $\mathbf{E}$ is the incident electric field.

Using the equation Eq. (1), we investigate the forces produced by the photonic hook system: we consider the cuboid geometry shown in Fig. (1). To simplify the calculations, we initially neglect the substrate contribution to the fields, while the cuboid parameters are considered as $a = 4$ and $b = 3$. The cuboid is considered as made of glass ($n_c = 1.46$, in the optical frequencies), illuminated by

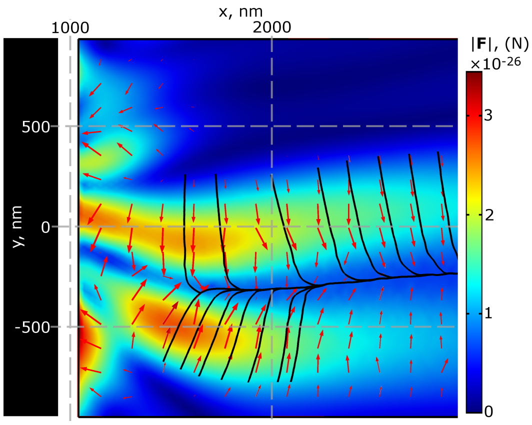

Figure 2: Force magnitude (colormap) and direction (arrow field, streamlines) of the cuboid obtained using the dipolar approximation method.

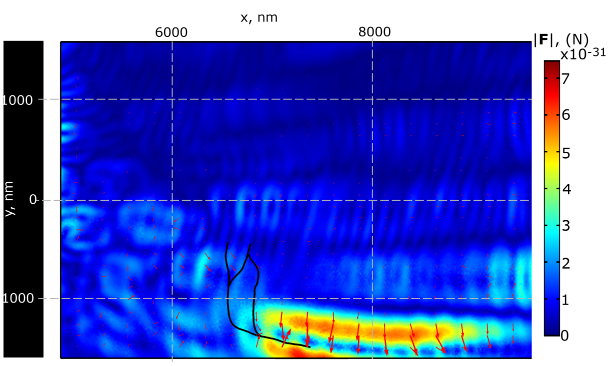

Figure 3: Force magnitude (colormap) and direction (arrow field, streamlines) of the cuboid placed atop a substrate.

a plane wave with wavelength of $625\,nm$, with propagation and polarization along the x and y axes, respectively. The entire system is embedded in air; the probe particle in this case is a gold sphere with radius of $0.03\,\mu m$ and complex dielectric permittivity $\epsilon = -11.208 + 1.3184i$. The calculation result of the forces are shown in Fig. (2). Fig. (2) shows that the trajectory produced by the photonic hook is curved. A related work[3] has shown that the forces acting on a dipolar probe particle are nearly identical with the forces obtained by integrating the Maxwell stress tensor.

3. Substrate contribution to the effect

A factor to consider in the system presented in the previous section is that the background of the cuboid is air. In a realistic system, the cuboid would need to be in contact with another larger substrate. However, this substrate generates its own scattered field, which interferes with the photonic hook field. Our approach to reduce this interference would be to add, for example, a index-matching liquid background to the whole system, as shown in Fig. (3). For this figure, the incident wavelength remains the same, however, the cuboid parameters are changed to $a = 7$ and $b = 5$, the cuboid material was changed from fused silica to zirconia of $n_c = 2.15$. In addition, the backing substrate has refractive index $n_s = 1.52$ (corresponding to borosilicate), and the index-matched background has $n = 1.47$ (glycerol). We emphasize that viscous forces were not considered in the force calculations.

4. Cellular Differentiation

One possible method of using this system in in-vitro application would be using it to guide the cells in a curved trajectory, in order to differentiate between them. However, the equation of the forces in Eq. (1), has a dependence on the polarizability α, which can be expressed as

$$\alpha = 4\pi r^3 \frac{\epsilon_p - \epsilon_a}{\epsilon_p + 2\epsilon_a} \tag{2}$$

and we note that the force becomes dependent on the permittivity contrast between the probe particle and the environment. If we were to consider guiding the cells without any modification, the force acting on these cells would be nearly negligible, as the index contrast is low. To address this challenge, we introduce gold nanoparticles using cellular uptake to serve as 'handles' to provide the needed material contrast.

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