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The integrated lensing effect and its application in single cell refractive index measurement in a dual-fiber optical trap

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ABSTRACT

We have fully investigated the integrated lensing effect that the beam suffers in a dual-fiber optical trap. A modified model for coupling of a beam to the opposing fiber has been built in consideration of the integrated lensing effect. We discussed the effect of z-axial position, radius and refractive index of the trapped sphere on the coupling efficiency using the modified coupling coefficient model. The measured and calculated coupling efficiency as a function of z-axial position have the same tendency in the allowable error. Comparison among above simulation and experiment has made clear that the magnitude relation between the smallest spot size and the mode field radius decide whether the spot size matching or wavefront phase matching dominate the coupling coefficient. What's more, we point out that the dependence of relative coupling coefficient on the refractive index has knee point. That is an obstacle to the application of single live cell refractive index measurement method based on lensing effect. Nevertheless, this method is absorbing and promising because there is a linear range for the known experimental parameters in an optical trap, and it needs no additional accessory.

1. Introduction

Since firstly demonstrated by Arthur Ashkin, optical manipulation has provided many important applications in the fields of biology, fundamental physics and engineering [1]. Especially, dual-beam optical trap has become increasingly popular in the recent decade due to its distinctive and abundant functions [2–7]. Recently a kind of dual-beam optical trap used for trapping and deforming biological cells, called optical stretcher, has quickly mushroomed into a research hotspot [7–10].

The optical stretcher proposed by Guck et al. has been proved to be a very powerful tool for the study of cell mechanics [7]. Several studies already demonstrated that cell mechanical properties measured by optical stretcher can allow us to distinguish healthy, tumorigenic and metastatic cells, as well as to reveal the effects of drug treatments on the mechanical response of the cell [8–10]. The accurate mechanical properties determination usually relies on knowledge about the refractive index of cell and laser radiation power in optical stretcher [8,10]. In addition, the refractive index of single cell is also conceived as the most important information for dual-fiber optical trap to correlate with other cell biophysical parameters and to study certain cell metabolic activities [11]. Several methods for single live cell refractometry have been developed based on different measurement techniques [12–15].

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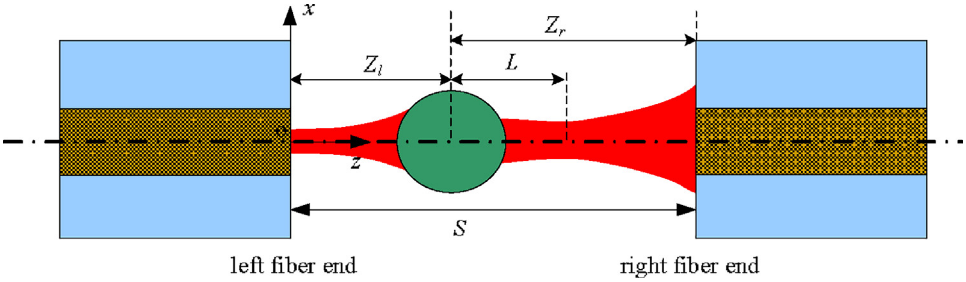

Fig. 1. The process of light propagation in a dual-fiber optical trap. The spacing between two fiber ends $S = Z_l + Z_r$.

Grosser et al present a new live cell refractometry measurement approach based on the lensing effect of trapped particles in an optical trap [16]. It is very simple and needs no additional accessory. They investigated the lensing effect that the trapped spheres act on the beams, and then discussed the effect of size and refractive index of the trapped sphere on the coupling signal of a beam to the opposing fiber. However, researches on the lensing effect and its application in single cell refractive index measurement in dual-fiber optical trap are highly limited.

In this work, we further investigate the influence mechanism of axial position of the integrated spherical lens on the coupling efficiency, which is a vital factor not focused on in [16]. Then change rules of coupling efficiency with the axial position, radius and refractive index of the integrated spherical lens are fully summarized. We point out that the dependence of the relative coupling coefficient on the refractive index has knee point, which is even affected by axial position and radius of trapped sphere. That is the limit of the application of forementioned single live cell refractive index measurement method. We demonstrate that for the constant axial position, radius of the trapped sphere in an optical trap, there is a given linear measurement range, which can be adjusted through changing the position of the integrated spherical lens.

2. Coupling coefficient model in dual-fiber optical trap

As Steffen Grosser stated [16], the propagation of a beam from one fiber to the opposite fiber in the dual-fiber optical trap will undergo several different progresses, including free Gaussian beam propagation, thermal lens effect resulting from laser absorption, focusing effect and gravitational displacement of trapped spheres. Here we treat thermal lens effect and focusing effect as an integrated spherical lensing effect, whose equivalent radius is r_s, as shown in Fig. 1. In this case, the ray transfer matrix of equivalent lens can be written as

$$M_s = \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \tag{1}$$

where f is the focal distance of integrated spherical lens

$$f = n_1/(n_2\text{-}n_1) \times r_s/2 \tag{2}$$

n_1, n_2 represent the refractive index of medium and microsphere respectively. Moreover, the matrices for propagation in the mediums on the left and right of the sphere are expressed by

$$M_l = \begin{bmatrix} 1 & Z_l \\ 0 & 1 \end{bmatrix}, M_r = \begin{bmatrix} 1 & Z_r \\ 0 & 1 \end{bmatrix} \tag{3}$$

where Z_l is the distance between the left fiber end and the left of the sphere, and Z_r is the distance between the right fiber end and the right of the sphere.

The energy distributions of the laser beam leaving the left fiber and right fiber are both assumed to Gaussian distributions U(0). Let their wavelength be λ, the mode field radius ω_0 calculated by the Marcuse Formula [17]

$$\frac{\omega_0}{a} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \tag{4}$$

where a stands for the radius of the core of the fiber, and V stands for the fiber's normalized frequency. One starts with $q(0) = i\pi\omega_0{}^2/\lambda$, the beam parameter $q(Z)$ of the beam in the position Z after passing from the trapped sphere can be modeled up by applying $M(S) = M_r \times M_s \times M_l$ using the transformation law of q parameters

$$q(z) = \frac{M(1,1)q(0) + M(1,2)}{M(2,1)q(0) + M(2,2)} \tag{5}$$