Optics Communications 354 (2015) 34–39

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Calculating the torque of the optical vortex tweezer to the ellipsoidal micro-particles

Lie Zhu [a], Zhongyi Guo [a,b,*], Qiang Xu [a], Jingran Zhang [a], Anjun Zhang [a], Wei Wang [b], Yi Liu [b], Yan li [b], Xinshun Wang [b], Shiliang Qu [b]

[a] School of Computer and Information, Hefei University of Technology, Hefei 230009, China
[b] Department of Optoelectronics Science, Harbin Institute of Technology at Weihai, Weihai 264209, China

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
18 May 2015
Accepted 21 May 2015
Available online 28 May 2015

Keywords:
Orbital angular momentum (OAM)
Ellipsoidal micro-particles
Scattering phase function (SPF)

ABSTRACT

In this paper, we have accurately computed the torque of the optical vortex tweezers to the ellipsoidal micro-particles with the method of finite-difference time-domain (FDTD). The transferred orbital angular momentum (OAM) from the vortex beam to the micro-particles can be obtained based on the scattering phase function (SPF) of the micro-particles. We have verified that the calculated SPF of a spherical particle by FDTD agrees well with that by Mie theory, which indicates that the SPF of micro-particles with any shapes can be calculated by FDTD accurately. In addition, with the method of FDTD, we have obtained the SPFs of the different-shape ellipsoidal micro-particles with same volume, including prolate ellipsoids and oblate ellipsoids. Meanwhile, the transferred OAM between the light and the ellipsoidal micro-particles have been deduced analytically by the relative formulas. And the rotating angular velocities of the trapped ellipsoidal micro-particles have been investigated and discussed in detail based on the obtained corresponding SPFs.

1. Introduction

The single-beam gradient trap which was named as optical tweezers, was firstly proposed and investigated by Ashkin in 1986 [1]. Because of their superior characteristics, optical tweezers can be used to trap and manipulate the micro-particles (with size of ranging from nanometers to microns) without any contacts and damages. Therefore, in recent years, optical tweezers have been widely applied in physics [2], biology [3,4], nanotechnology [5] and so on. With the developments of the investigation, optical vortex beam (LG beams) as the light sources was also introduced into optical tweezers systems, which was called the vortex tweezers [6]. The vortex tweezers can offer a new type of the manipulating method to the trapped micro-particles because of the unique characteristics, presented “spiral wavefront” [7,8], in which the trapped micro-particles can rotate in the beams because the orbital angular momentum (OAM) can be transferred from beams to the trapped particles [6].

There are some groups who focus their research on the manipulating forces and the optical torques from the tweezers to the trapped particles, but most of theoretical researches just focus on the micrometer-sized spherical particles commonly [9,10]. However, the overwhelming majority of particulates are non-spherical in nature. Thus it is more reasonable and meaningful to investigate the interactions on the irregular micro-particles theoretically, such as prolate spheroids and oblate spheroids. Recently, the scattering phase functions (SPFs) of the scattering particles have been verified that can be obtained by finite-difference time-domain (FDTD) accurately [11,12]. It means that we can obtain the SPFs of the irregular particles numerically by the FDTD, which is very important to calculate the manipulating forces and the optical torques.

In this paper, we have mainly investigated the computation of the optical torque which is generated by optical vortex tweezers to the trapped particles. Firstly, with the method of the Mie theory, we will verify the effectiveness of generating the SPFs of the scattering particles by FDTD method. Then, we can obtain the SPFs of the scattering ellipsoidal particles with different ellipticities (the ratio of long axis and short axis) in the range 1–10. Besides, we innovatively calculate the total transferred OAM from the vortex beam to the trapped micro-particle according to the obtained SPFs. Moreover, the relationship between the rotating angular velocity (RAV) of the ellipsoid particles and the power of the incident vortex laser is investigated fully, and the different shaped ellipsoidal particles, including a prolate ellipsoid and oblate ellipsoid are considered and discussed for comparisons.

* Corresponding author at: School of Computer and Information, Hefei University of Technology, Hefei 230009, China.
E-mail address: guozhongyi@hfut.edu.cn (Z. Guo).

http://dx.doi.org/10.1016/j.optcom.2015.05.062
0030-4018/

2. Validation of the FDTD technique

Mie scattering theory is derived from the strict mathematical solution of Maxwell's equations for the isotropy spherical particles [13]. Assuming that the incident light is natural light, the SPF of spherical micro-particle can be written as

$$P = \frac{|S_1(\theta)|^2 + |S_2(\theta)|^2}{\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2)} \quad (1)$$

where S_1 and S_2 are the amplitude function, a_n and b_n are Mie coefficients, θ is the scattering angle and n is the ordinal number. Fig. 1(a) shows that the direction of the incident beam with the wavelength of 0.532 μm is along the z-axis and then the light is incident on a micro-particle with the relative refractive index of m=1.311 and the radius of $r = 0.504$ μm. Firstly, we will try to calculate the SPF of the spherical particles with the method of the FDTD which is formulated by replacing temporal and spatial derivatives in Maxwell's equations with their finite-difference correspondences [14], and then we will verify the accuracy of the SPF of spherical particles with the method of FDTD by comparing with that by Mie theory. In FDTD simulations, a grid size of $\Delta s = \lambda/20$ is used. Fig. 1(b) depicts the scattered electric field of spherical particles in every scattering direction based on the FDTD simulation method. Then, the far field of the scattered light in every scattering angle θ can be deduced by the electric field E and the magnetic field Hon the surface of the sphere, which is shown as follows:

$$E_{far}(\theta) = \frac{ik}{4\pi}\vec{n} \times \oint \{\vec{n}' \times E - \vec{n} \times (\vec{n}' \times H)\}\exp(-ik\vec{n}\cdot r')d^2r' \quad (2)$$

where $\vec{n}$ is the unit vector pointing from the origin to the far-field, $\vec{n}'$ is the unit vector which is perpendicular to the surface S of the spherical particle, r' is the radius of the surface, and k is the wave number. The simulation result is shown in Fig. 1 (c).

According to the definition, the SPF is the ratio of scattered energy in a given unit solid angle to the average in all directions [15]. In order to compute more accurately, the scattered energy is expressed by the square of the far field instead of near electric field. So the SPF of any directions can be computed by

$$P(\theta) = \frac{|E_{far}(\theta)|^2}{\overline{|E_{far}|^2}} = \frac{|E_{far}(\theta)|^2}{\frac{1}{4\pi}\iint_S |E_{far}(\theta)|^2 dS} \quad (3)$$

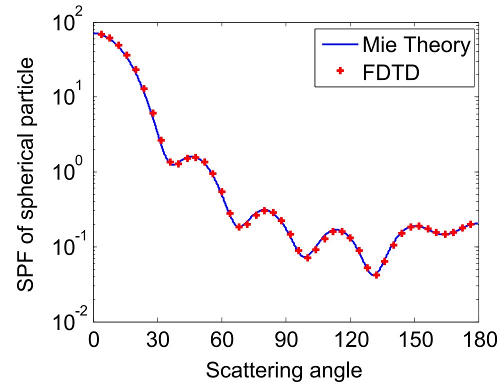

Fig. 2. Comparison of the SPFs of a spherical particle obtained by Mie theory and the FDTD respectively.

Fig. 2 shows the SPF ($P(\theta)$) of a spherical micro-particle with the radius of $r = 0.504$ μm calculated by the Mie theory and the FDTD method, respectively. It is easy to find that the variances of the results calculated by two ways are very small. Numerical results show that it will be more accurate while using a smaller cell size. Since we have verified that the FDTD can be used to calculate the SPF of non-spherical particle, it is easy to get the SPF of ellipsoidal micro-particles including the prolate spheroid and oblate spheroid.

3. Theoretical model for angular momentum transfer

If we select a vortex beam as the incident light, the reflection, deflection and absorption will be occurred in the interacting

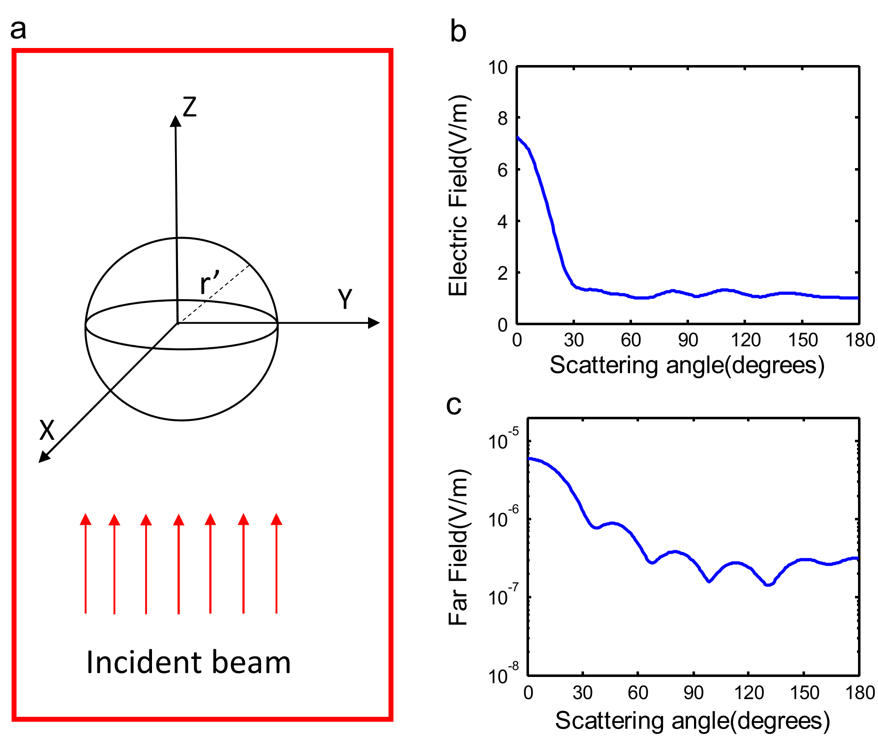

Fig. 1. Incident beam propagates through the spherical particle for the size parameter $ka = 5$ (a); near electric field of every direction of this spherical particle after been scattering (b); far field of every direction of this spherical particle after been scattering (c).