Journal of Quantitative Spectroscopy & Radiative Transfer 175 (2016) 46–53

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Spinning gold nanoparticles driven by circularly polarized light

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ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form
8 January 2016
Accepted 8 January 2016
Available online 2 February 2016

Keywords:
Circularly polarized light
Gold nanoparticle
Optical torque
Rotation
Surface plasmon resonance
Maxwell's stress tensor
Absorption
Scattering
Surface traction
Mie theory
MMP
Axis of revolution

ABSTRACT

This study theoretically examines a spinning gold nanoparticle (GNP) driven by circularly polarized (CP) plane waves. The wavelength-dependent optical torques which were exerted on three different shapes of GNPs (spherical, prolate and oblate spheroids) were analyzed by utilizing Mie theory for the former and the multiple multipole method for the latter two, respectively. Numerical results show that both the absorbed and scattered photons contribute to optical torques in most cases. For the case that the CP wave is incident along the long axis of an oblate spheroid or the short axis of a prolate one, the scattering effect in optical torque is more pronounced than the absorption one. This phenomenon is significant especially when the wavelength of the CP wave is close to the longitudinal surface plasmon resonance band of the GNP. In contrast, when the CP wave is incident along the axes of revolution of these shapes of GNPs, the ratio of optical torque to absorption power is directly proportional to the wavelength. Moreover, this ratio is independent of the size and even the aspect ratio of GNPs. This result suggests that only the absorbed photons contribute to optical torques, but not the scattered ones, due to the conservation of angular momentum for cases of rotational symmetry.

1. Introduction

Using optical forces and torques to trap, move, align and rotate microparticles and nanoparticles via optical tweezers techniques has become an important optical manipulation in the past decade [1–9]. As early as 1909, Poynting predicted the angular momentum of circularly polarized (CP) lights [10]. Beth discovered optical torques induced by a CP light irradiating a quartz plate [11]. The experiment can be explained by the transfer of angular momentum through the absorption of CP-light photon flows inducing the optical torque on the irradiated plate [12–16]. Optical torques, induced by a CP light on a spherical particle, has been studied analytically by using Mie theory [17,18]. Due to the collective motion of conductive electrons in gold nanoparticles (GNPs), the localized surface plasmon resonance (LSPR) enhances the polarizability of GNPs, particularly in the regime from visible-light to near infrared. Therefore, the light-matter interaction of GNPs is profound, compared to those of dielectric nanoparticles. As a result, the induced optical forces and torques exerted on GNP are significantly strong and

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http://dx.doi.org/10.1016/j.jqsrt.2016.01.012
0022-4073/

associated with severe heating [19–24]. A high-speed spinning spherical GNP induced by the illumination of a focused CP Gaussian beam has been demonstrated [25]. Additionally, a Laguerre-Gaussian beam (or called optical vortex) can also be used to constantly rotating spherical GNP due to the orbital angular momentum of photons [26]. Recently, the optical torque exerted on a GNP of thin-plate shapes (circular, rectangular, triangular or hexagonal) irradiated by a normal-incident CP light was analyzed theoretically by utilizing the finite difference time domain (FDTD) method; one of the important findings is that the scattering contribution resulting from the multipolar plasmon resonance of the symmetry-breaking nanostructure could be larger than the absorption one [27]. Various shapes of GNPs have been synthesized in the past decade, e.g. gold nanorods, bi-pyramids etc., in addition to spherical GNPs [28–30]. The behaviors of light-matter interaction of different-shaped GNPs are different due to their longitudinal surface plasmon resonance (LSPR). Optical trapping performances of gold decahedron, icosahedron, triangular and hexagonal prisms were studied [31]. Rotating a single silver nanowire by CP laser beam has been demonstrated experimentally [32,33]. Recently, optical torque that is exerted on a gold or silver nanorod induced by CP or linearly polarized light has been analyzed theoretically utilizing the multiple multipole (MMP) method [34–36].

This paper theoretically investigated and compared the wavelength-dependent optical torques, which are induced by a CP light, continuously driving GNPs (of spherical, and prolate or oblate spheroidal shapes) to rotate. Mie theory and MMP method were used to study optical torques exerted on a spherical GNP [16], and on a prolate/oblate spheroidal GNP [34,35], respectively. Optical forces and torques can be obtained by integrating Maxwell's stress tensor over the surface of GNP. The absorption and scattering powers of GNP were analyzed. In addition, the roles of absorption and scattering playing on the mechanical responses of GNP due to CP light incident along principal axes of GNP were investigated. Steady-state rotation (spinning) of a spherical GNP was also discussed, which was due to the optical torque provided by CP light balancing with the viscous torque from the dragging of the surrounding medium. The simulations for gold prolate and oblate spheroids can be applied to predict the light-matter interactions of the gold bi-pyramids and gold decahedrons, respectively. Through the optical manipulation, a rotating GNP may have promise in the applications of nanofluidics [37].

2. Theory

In this paper, the optical torques which are exerted on three different shapes of GNP (sphere, prolate and oblate spheroids) illuminated by a CP plane wave were studied. Spheroids have three principal axes, including an axis of revolution. Oblate spheroids and prolate spheroids are flattened and elongated, respectively, along the axes of revolution. The boundary surfaces of spheroids (assumed that axes of revolution are coincided with the z-axis, and the centers coincided with the origin of the coordinate system) can be expressed as

$$\left(\frac{x}{a}\right)^2+\left(\frac{y}{a}\right)^2+\left(\frac{z}{b}\right)^2=1, \tag{1}$$

where a and b denote the half lengths of the principal axes; $a=b$: spheres, $a<b$: prolate spheroids, and $a>b$: oblate spheroids. Mie theory was utilized to study the optical torque on a spherical GNP analytically. For the cases of prolate and oblate spheroids, MMP method was used to analyze the optical torque numerically. A CP plane wave can be treated as a superposition of two linearly polarized plane waves of the same frequency with mutually perpendicular electric fields and 90° phase difference. Let the CP plane wave propagate along the negative z-direction, the wave can be divided into two orthogonal components, and written as $\mathbf{E}^i=E_0(\mathbf{e}_1 \pm j\mathbf{e}_2)/\sqrt{2}$, where $\pm$ corresponds to the right-handed and left-handed CP waves, and $j=\sqrt{-1}$. Throughout this paper, the time harmonic factor $\exp(-j\omega t)$ has been omitted in Maxwell's equations, where ω is the angular frequency. The time-averaged Maxwell stress tensor $\mathbf{T}$ is expressed as

$$\mathbf{T}=\frac{1}{2}\mathrm{Re}\left\{\epsilon\mathbf{E}\overline{\mathbf{E}}+\mu\mathbf{H}\overline{\mathbf{H}}-\frac{1}{2}(\epsilon\mathbf{E}\cdot\mathbf{E}+\mu\mathbf{H}\cdot\overline{\mathbf{H}})\mathbf{I}\right\}, \tag{2}$$

where $\mathbf{I}$ is the unit tensor, and ε and μ are the permittivity and permeability of the surrounding medium, respectively. In Eq. (2), over-bar denotes a complex conjugate, and Re denotes the real part of a complex number. The total EM fields in the exterior region of GNP are the linear sums of the incident and scattered fields: $\mathbf{E}=\mathbf{E}^i+\mathbf{E}^s$ and $\mathbf{H}=\mathbf{H}^i+\mathbf{H}^s$, where the superscript "i" and "s" denote the incident and scattered parts, respectively. In terms of the Maxwell's stress tensor, the induced optical force $\mathbf{F}$ and torque $\mathbf{M}$ about the center of GNP generated by the EM field are expressed by the surface integrals,

$$\mathbf{F}=\int_S \mathbf{T}\cdot\mathbf{n}\,dS, \tag{3}$$

$$\mathbf{M}=\int_S \mathbf{r}\times\mathbf{T}\cdot\mathbf{n}\,dS, \tag{4}$$

where S is the surface of GNP, $\mathbf{n}$ is the unit outward normal vector, and $\mathbf{r}$ is the position vector of a generic point on S with respect to the center of GNP. In the following, the effective surface traction $(\mathbf{e}_r\times\mathbf{T}\cdot\mathbf{n})\cdot\mathbf{e}_k$ inducing optical torque will be analyzed where $\mathbf{e}_k$ is the propagating vector of the CP plane wave. The absorption (dissipation) power of GNP irradiated by a CP plane wave can be expressed as a surface integral of the Poynting vector,

$$P_a=-\frac{1}{2}\mathrm{Re}\left\{\int_S \mathbf{E}\times\overline{\mathbf{H}}\cdot\mathbf{n}\,dS\right\}, \tag{5}$$

The absorption (dissipation) power is associated with the plasmonic heating. The absorption efficiency of GNP is further defined as

$$Q_a=P_a/AS^i, \tag{6}$$

where $S^i=\left|\mathbf{E}^i\times\overline{\mathbf{H}}^i\right|/2$ is the fluence of a circularly polarized laser beam, and A is the cross-sectional area of the GNP. Throughout this paper, λ is the wavelength of the CP plane wave in vacuum. Since the problem is linear, optical forces, optical torques, absorption powers and scattering