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Radiation force exerted on nanometer size non-resonant Kerr particle by a tightly focused Gaussian beam

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Abstract

We calculate the radiation force that is exerted by a focused continuous-wave Gaussian beam of wavelength λ on a non-absorbing nonlinear particle of radius $a \ll 50\lambda/\pi$. The refractive index of the mechanically-rigid particle is proportional to the incident intensity according to the electro-optic Kerr effect. The force consists of two components representing the contributions of the electromagnetic field gradient and the light scattered by the Kerr particle. The focused intensity distribution is determined using expressions for the six electromagnetic components that are corrected to the fifth order in the numerical aperture (NA) of the focusing objective lens. We found that for particles with $a < \lambda/21.28$, the trapping force is dominated by the gradient force and the axial trapping force is symmetric about the geometrical focus. The two contributions are comparable with larger particles and the axial trapping force becomes asymmetric with its zero location displaced away from the focus and towards the beam propagation direction. We study the trapping force behavior versus incident beam power, NA, λ, and relative refractive index between the surrounding liquid and the particle. We also examine the confinement of a Kerr particle that exhibits Brownian motion in a focused beam. Numerical results show that the Kerr effect increases the trapping force strength and significantly improves the confinement of Brownian particles.

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1. Introduction

Single-beam optical tweezers were first reported with visible light (514 nm) in 1986 to capture and guide individual neutral particles of various sizes [1]. They were then employed to orient and manipulate irregularly-shaped microscopic objects such as viruses, cells, algae, organelles, and cytoplasmic filaments using an infrared light (1064 nm) beam [2]. The optical tweezer was later utilized in a number of exciting investigations in biomedical research such as chromosome manipulation [3], sperm guidance in all optical *in vitro* fertilization [4] and force measurements in molecular motors such single kinesin molecules [5] and nucleic acid motor enzymes [6].

Researchers have also been searching for ways to improve the performance of optical traps to achieve more efficient multidimensional manipulation of particles of various geometrical shapes and optical sizes [7,8]. Efforts in optical beam engineering were pursued to generate trapping beams with intensity distributions other than the diffraction-limited beam spot e.g. doughnut beam [9,10], helical beam [11], Bessel beam [12]. Multiple beam traps and other complex forms of optical landscapes were produced from a single primary beam using computer generated holograms [13–15] and programmable spatial light modulators [16,17].

Understanding the connection between the radiation force and the optical nonlinearity that is induced when

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a focused beam of sufficient intensity, interacts with a non-absorbing particle is an interesting subject that has only been barely investigated. One possible reason for the apparent lack of effort is the difficulty in finding a suitable strategy for computing the intensity-dependent refractive index of the particle. An investigation into the behavior of nonlinear particles in a strong radiation field is worth pursuing for its likely practical relevance – many proteins and organic molecules exhibit measurable nonlinear optical properties under suitable conditions [18–22].

Here, we calculate the behavior of the (time-averaged) radiation force $\langle \mathbf{F} \rangle$ that is exerted on a non-absorbing mechanically rigid Kerr particle by a focused continuous-wave TEM_{00} Gaussian beam of wavelength (in vacuum) λ when the size parameter $\gamma = 2\pi a/\lambda \ll 100$. The refractive index n_2 of a Kerr particle increases with the incident beam intensity. Radiation force analysis is performed as a function of particle position, beam power, numerical aperture (NA) of the focusing objective lens, λ, a, and relative index between the particle (n_2) and its surrounding medium (n_1). The radiation force characteristics are compared with that of a similarly sized linear particle under the same illumination conditions. We also investigate the confinement of a Kerr particle that exhibits Brownian motion due to random collisions with the liquid molecules and the Kerr particle. Brownian motion becomes significant for particles with $a \ll \lambda$.

To our knowledge, the characteristics of the radiation force on a Kerr particle have only been investigated in the geometrical optics regime ($\gamma \gg 100$) [23] and in the more challenging diffraction regime of $\gamma \approx 100$, where the Rytov approximation [24] was applied on the standard Lorenz–Mie scattering theory [25] to account for the nonlinear effects.

In our radiation force analysis, the incident focused beam polarizes the non-magnetic Kerr particle ($a \ll \lambda$). The electromagnetic (EM) field exerts a Lorentz force on each charge of the induced electric dipole. We derive an expression for $\langle \mathbf{F} \rangle$ in terms of the intensity distribution and the particle polarizability $\alpha = \alpha(n_1, n_2)$. The trapping force $\langle \mathbf{F} \rangle$ consists of two components – one that accounts for the contribution of the field gradient and the other from the light that is scattered by the particle. The two-component approach for computing the trapping force was previously used on (linear) dielectric particles in arbitrary electromagnetic fields [26]. For better accuracy especially when dealing with high NA (>0.5) focusing lenses, the intensity distribution in the focal volume of the beam is calculated using fifth-order corrected expressions for the six EM field components (three each for the electric and magnetic fields) that were first derived by Barton and Alexander [27].

In the next section we derive an expression for the radiation force that is acting on the Kerr particle. Simulation results are presented and discussed in Sections 3 and 4, respectively.

2. Theoretical framework

2.1. Derivation of radiation force on non-absorbing Kerr particle

A linearly polarized Gaussian beam (TEM_{00} mode) of total beam power P and wavelength λ, propagates along the optical z-axis in a linear medium of refractive index n_1. The beam is focused by an objective lens unto the geometrical focal plane at $z = 0$ (see Fig. 1). The beam waist radius at $z = 0$ is $w_0 = \lambda/(2\mathrm{NA})$. We determine the intensity distribution of the focused beam using expressions for the six EM field components that are corrected to the fifth order in parameter $s = \lambda/(2\pi w_0) = \mathrm{NA}/\pi$ [27]. Focusing with a high NA objective produces a relatively high beam intensity at $z = 0$, which decreases rapidly with increasing $|z|$ values. On the other hand, low NA objectives produce a slowly varying intensity distribution from $z = 0$.

The refractive index of the Kerr particle is described by: $n_2(\mathbf{r}) = n_2^{(0)} + n_2^{(1)} I(\mathbf{r})$, where $n_2^{(0)}$ is the (constant) linear component of n_2, $n_2^{(1)}$ is the nonlinear component, $I(\mathbf{r})$ is the intensity of Gaussian beam at particle center position $\mathbf{r} = \mathbf{r}(x, y, z)$ from the geometrical focus at $\mathbf{r} = 0$ which also serves as the origin of the Cartesian coordinate system. Throughout this paper, we represent vector quantities in bold letters.

In the Rayleigh scattering regime, the particle behaves like a simple electric dipole with its positive ($+q$) and negative ($-q$) charges located at $\mathbf{r} = \mathbf{r}_+$ and $\mathbf{r} = \mathbf{r}_-$, respectively. The two charges are separated by a distance $|\delta\mathbf{r}| = |\mathbf{r}_+ - \mathbf{r}_-|$. The total radiation force $\mathbf{F}$ that is acting on the particle is:

$$\mathbf{F} = \mathbf{F}_{+q}(\mathbf{r}_+) + \mathbf{F}_{-q}(\mathbf{r}_-) \tag{1}$$

where $\mathbf{F}_{+q}(\mathbf{r}_+)$ and $\mathbf{F}_{-q}(\mathbf{r}_-)$ are the individual forces on $+q$ and $-q$, respectively.

The incident EM fields $\mathbf{E} = \mathbf{E}(\mathbf{r}, t)$ and $\mathbf{B} = \mathbf{B}(\mathbf{r}, t)$ are approximately uniform for both $+q$ and $-q$, when $a \ll w_0$. The constant field assumption allows us to calculate the charge separation $|\delta\mathbf{r}|$ as a first-order approximation in $\delta\mathbf{r}$ and to express the force $\mathbf{F}$ as:

$$\begin{aligned}\mathbf{F} &= (\boldsymbol{\mu} \cdot \nabla)\mathbf{E} + \frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t} \times \mathbf{B} + \frac{\mathrm{d}\mathbf{R}}{\mathrm{d}t} \times (\mu \cdot \nabla)\mathbf{B} \\ &= \mathbf{F}^{\mathrm{inhom}} + \mathbf{F}^{\mathrm{Lorentz}} + \mathbf{F}^{\mathrm{inhom}}_{\mathrm{moving}}\end{aligned} \tag{2}$$

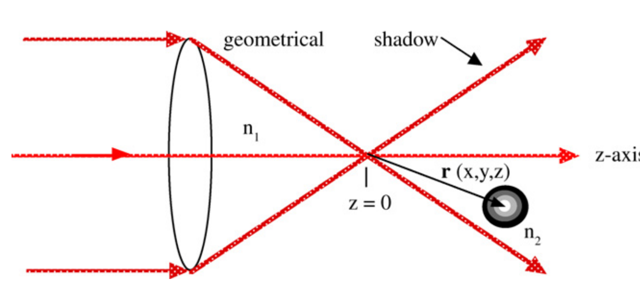

Fig. 1. Kerr particle of radius a and refractive index n_2 is located in the focal volume of a Gaussian beam of wavelength $\lambda \gg a$ and beam waist radius w_o. Beam propagates in a linear medium of index n_1. Particle center is located at $r(x, y, z)$ from the geometrical focus at $r(0, 0, 0)$.