Journal of Quantitative Spectroscopy & Radiative Transfer 146 (2014) 81–99

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Inhomogeneous and anisotropic particles in optical traps: Physical behaviour and applications

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ARTICLE INFO

Article history:
Received 12 November 2013
Received in revised form
18 March 2014
Accepted 19 April 2014
Available online 26 April 2014

Keywords:
Optical tweezers
Optical scattering
Optical forces and torques
Micro-rheology
Force sensing
Plasmonic nanoparticles

ABSTRACT

Beyond the ubiquitous colloidal sphere, optical tweezers are capable of trapping myriad exotic particles with wildly varying geometries and compositions. This simple fact opens up numerous opportunities for micro-manipulation, directed assembly and characterization of novel nanostructures. Furthermore, the mechanical properties of optical tweezers are transformed by their contents. For example, traps capable of measuring, or applying, femto-Newton scale forces with nanometric spatial resolution can be designed. Analogous, if not superior, angular sensitivity can be achieved, enabling the creation of exquisitely sensitive torque wrenches. These capacities, and others, lead to a multitude of novel applications in the meso- and nanosciences. In this article we review experimental and theoretical work on the relationship between particle geometry, composition and trap properties. A range of associated metrological techniques are discussed.

1. Introduction

Over the past two decades optical tweezers have become an indispensable tool in the meso-sciences. In a typical experiment, optical gradient forces are used to hold a colloidal sphere in the high intensity region surrounding the focal point of a tightly focused Gaussian beam. Since, in this case, the optical force field is locally harmonic and conservative, the equipartition theorem allows the elastic energy of the trap to be equated with the allowed thermal energy, $\frac{1}{2}k\langle x^2\rangle = \frac{1}{2}k_BT$ (see [1], for example). Accurate measurements of the position of the sphere, and its variance, can therefore be used to find k, the trap *stiffness*, and can subsequently be used to measure small, pN scale forces. The applications with, perhaps, the greatest significance arise in biology, where the technique can be used to probe the mechanics of vital biological processes. Numerous reviews of optical tweezers technology and applications exist in the literature. Grier has provided an excellent, general account of optical tweezers, including holographic optical tweezers [2]; more recent developments are summarized by Bowman and Padgett [1]. Neumann and Block concentrate on instrumentation [3]. Applications of these techniques to biological systems are reviewed elsewhere [4–6]. In [7], the use of spatial light modulators to holographically shape optical fields, and thereby the force fields they generate, is discussed and the special case of optical vortices is treated by Padgett and Bowman [8]. This latter approach indicates a growing theme in optical micro-manipulation; progress in micro-mechanical measurement requires the generation of novel force fields. Whilst substantial effort has been devoted to shaping optical fields to this end, the conjugate approach, of shaping particles to produce desirable forms of behaviour, is less well established. This point was recently made elsewhere [9]. In fact, this strategy has been pursued by various research groups, for perhaps a decade, but the work has yet to be identified with an underlying theme. It is the purpose of this review to do just that: to collect and unite the progress made in this area, to draw relevant conclusions and to anticipate future avenues to explore.

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http://dx.doi.org/10.1016/j.jqsrt.2014.04.012
0022-4073/

2. Theoretical underpinning

2.1. Variety of optical forces

In the following section we examine the various sources and forms of force that can be applied by time harmonic optical fields, to discrete particles. Before proceeding it should be noted that none of the material presented below is completely free of controversy. Where appropriate, references are given that express varying opinions or document issues under debate. It is hoped that the main perspective given below can be used to qualitatively understand the physical effects documented in the remainder of the paper.

2.1.1. Small particle approximation

Most, but not all, optical trapping experiments make use of particles with typical dimensions on the order of a micron. However, insight into the nature of optical forces can be acquired by considering the case of particles that are much smaller than the incident wavelength. In this approximation, objects are treated in the quasi-static limit and can be represented by point polarizabilities [10]. Initial attempts at describing optical traps in this regime expressed forces in terms of scattering cross sections augmented by a term proportional to the intensity gradient [11,12]. More recent work makes use of equations that make no assumptions about the local structure of the incident field.

In general, the optical force can be broken into three parts. The first is associated with the electric polarizability, the second with magnetic polarizability and the third arises from interference between the previous two [13–16]. In addition, polarizabilities that take into account the small, but finite, phase changes across the particle are used so as to comply with the optical theorem [17]. As will be seen, this modification is necessary to correctly represent optical scattering forces. At optical frequencies, most materials are non-magnetic, $\mu = 1$. The resulting force on a point electric polarizability is given by [18]

$$\langle \mathbf{F}(r_1) \rangle = \frac{1}{2}\Re\left(\sum_i p_i \nabla E_i^{\star}(r)|_{r=r_1} \right). \tag{1}$$

Here, $\mathbf{F}(r_1)$ is the force on the particle with coordinates r_1, $\mathbf{p}$ is the polarization, $\mathbf{p} = \alpha\mathbf{E}$ and α is the total, *dynamic* polarizability [17]. The dynamic polarizability for a small isotropic sphere is given below, in terms of the usual Claussius–Mossotti polarizability, α_0:

$$\alpha = \alpha_0 / \left[1 - \tfrac{2}{3} i k_0^3 \alpha_0 \right], \tag{2a}$$

$$\alpha_0 = a^3 \frac{\epsilon - 1}{\epsilon + 2}. \tag{2b}$$

For isotropic polarizabilities, this equation can be suggestively rewritten to reveal three distinct components to the optical force [19–21]:

$$\langle \mathbf{F} \rangle = \frac{1}{4}\Re(\alpha)\nabla|\mathbf{E}|^2 + \frac{C_{tot}}{c}\langle \mathbf{S} \rangle + C_{tot}c(\nabla \times \langle \mathbf{L}_s \rangle). \tag{3}$$

Here $\mathbf{E}$ is the electric field, $C_{tot} = k_0 \Im[\alpha]/\epsilon_0$ (with k_0 the wave-vector of the incident light), is the total cross section and $\mathbf{L}_s$ is the transverse electromagnetic spin density [22,19]. The first term, the *gradient force*, is derived from the gradient of the electric energy [16] and is proportional to the real part of the polarizability. The second two are scattering forces; the Poynting force, proportional to $\langle S \rangle$, and a term associated with inhomogeneities of the spin angular momentum of the field [22,21]. These latter terms depend on the imaginary part of the dynamic polarizability, α, which, even for non-absorbing particles, is non-zero (see Eq. (2a)). Self-evidently, the gradient force is conservative; the scattering forces, in general, are not (this latter point is vividly demonstrated by the optical vortices considered in [8,2]). In the case of an optical trap, particles can be confined when the gradient force is dominant. Under these conditions a mechanical equilibrium emerges down stream of the focal point, the off-set arising as a consequence of the scattering forces.

This expression can be simply extended to geometrically or optically anisotropic particles by replacing α in Eqs. (2a) and (2b), with an appropriate tensor [10]. Explicit derivation of the dynamic polarizability of spheroidal particles is provided in [23]. A decomposition analogous to that expressed by Eq. (3) can be written down for anisotropic point particles; equations similar to Eq. (3) operate in directions parallel to each of the Eigen vectors of the polarizability tensor, and α and σ are replaced by appropriate Eigen values. In this case, the gradient force itself becomes non-conservative at all points (since it is no longer the gradient of a scalar field), except those at which all first derivatives of the intensity vanish identically (i.e. at the focal point of a Gaussian beam).

Small anisotropic particles also experience optical torques [24]:

$$\langle \mathbf{\Gamma} \rangle = \frac{1}{2}\Re\left(\mathbf{p} \times (\alpha_0^{-1}\mathbf{p})^{\star}\right). \tag{4}$$

This equation contains a subtlety. A direct use of $\langle \mathbf{\Gamma} \rangle = \frac{1}{2}\Re(\mathbf{p} \times \mathbf{E}^{\star})$ with $\mathbf{p} = \alpha\mathbf{E}$ would imply that a non-absorbing, spherical particle could be made to spin in circularly polarized light ($\langle \mathbf{\Gamma} \rangle = \frac{1}{2}\Re(\mathbf{p} \times \mathbf{E}^{\star}) = \frac{i}{2}\Im(\alpha)\ (\mathbf{E} \times \mathbf{E}^{\star})$; $(\mathbf{E} \times \mathbf{E}^{\star})$ is either imaginary or zero, and $\Im(\alpha)$ is a non-zero scalar, for non-absorbing dielectric spheres, Eq. (2a)). As will be seen, this is not possible and the form of Eq. (4) carefully compensates for this. For anisotropic particles α_0 is a tensor [10]. Evidently, the torque will vanish when the polarization, $\mathbf{p}$, is parallel and in phase with the electric field, $\mathbf{E}$. Hence, if the incident field is linearly polarized it will align the particle. Alternatively, as can be easily verified, circularly polarized light will give rise to continuous rotation. These observations apply equally to optically and geometrically anisotropic particles, although the precise form of the Claussius–Mossotti polarizability tensor varies, and explicit forms of the dynamic polarizability require careful evaluation.

From the above considerations, we expect small particles to orient with respect to the local electric polarization and to migrate towards high intensity regions whilst simultaneously being propelled by scattering forces in the direction of the Poynting vector [25]. Because the particles discussed here are point-like, they do not sample field inhomogeneities above first order.