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Photonic nanojets in optical tweezers

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A B S T R A C T

Photonic nanojets have been brought into attention ten years ago for potential application in ultramicroscopy, because of its sub-wavelength resolution that can enhance detection and interaction with matter. For these novel applications under development, the optical trapping of a sphere acts as an ideal framework to employ photonic nanojets. In the present study, we generated nanojets by using a highly focused incident beam, in contrast to traditional plane waves. The method inherits the advantage of optical trapping, especially for intracellular applications, with the microsphere in equilibrium on the beam propagation axis and positioned arbitrarily in space. Moreover, owing to optical scattering forces, when the sphere is in equilibrium, its center shifts with respect to the focal point of the incident beam. However, when the system is in stable equilibrium with a configuration involving optical tweezers, photonic nanojets cannot be formed. To overcome this issue, we employed double optical tweezers in an unorthodox configuration involving two collinear and co-propagating beams, the precise positioning of which would turn on/off the photonic nanojets, thereby improving the applicability of photonic nanojets.

1. Introduction

A photonic nanojet (PNJ) is a narrow (subwavelength) and elongated region with high intensity located at the shadow-side surface of an illuminated loss-less dielectric microcylinder or microsphere [1,2]. In the present study, we focus on PNJs generated by a dielectric microsphere acting as a focusing lens, which results in the build up of spherically aberrated rays in the focal region. This build up of rays in the spatially localized high-energy-density region constitute the external caustic [3,4]. Therefore, PNJs are not a new phenomenon, but they have attracted renewed interest because of recent technological advances allowing the exploitation of this high-energy-density region. Nonetheless, contrary to a possible understanding via geometrical optics or catastrophe theory, we aim to obtain an exact solution of Maxwell's equations by employing the generalized Lorenz–Mie theory (GLMT) [5], as in the study by Devilez et al. [6]. Such focusing of light using a microsphere has also been investigated by Kofler et al. [7] using the uniform caustic asymptotic method, to obtain analytical expressions for the intensity by matching the geometrical-optic solutions with Bessoid integrals. However, for optical trapping applications, the scattering object is a microsphere of size comparable to the illuminating wavelength and consequently outside the regime of geometrical optics.

Optical trapping results from the change in linear momentum of a beam scattered by a microsphere, producing a resultant restoring force. The most common setup for laser trapping is of optical tweezers [8,9]. PNJs and optical tweezers (OT) have attracted attention because, in combination, they can be highly useful in applications including nanoscale processing [10–15], high-resolution microscopy [3,16–19], and enhanced inelastic spectroscopy, such as Raman scattering [20–23], coherent anti-Stokes Raman scattering [24,25] and fluorescence [26,27], or elastic enhancement through backscattering from

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nanoparticles [28]. A recent study that aimed to position PNJs in a controlled manner involved a microsphere attached to a movable micropipette [29] and magnetically controlled Janus spheres [30]. In addition, an optically trapped non-spherical dielectric particle in a Bessel beam was employed to generate PNJs from another pulsed laser for direct laser writing [31]. The disadvantage of this approach is in the engineering of particular non-spherical particles, each exhibiting a characteristic PNJ. Other studies on optical forces and PNJs are related to the radiation pressure effect produced by a PNJ on nearby nanoparticles [32–34]. In contrast, the scope of this study is different; we investigate the PNJs generated from an optically trapped microsphere in terms of the incoming beam, trading the complexity of structuring special shaped particles for the ease of manipulating the trapping beam.

It is widely known that the main features of PNJs are waists smaller than the diffraction limit and propagation over several wavelengths without significant diffraction. These features lead to the potential application of PNJs for developing spectroscopic methods with high spatial resolution and high detection sensitivity through backscattering enhancement. Therefore, the characteristics of a nanojet have been described with a few parameters: the location of the intensity maximum, the distance from this maximum to the sphere surface (radial shift), the distance from the intensity peak to the point where the intensity decays to e^{-2} times the initial intensity in the direction of the beam (decay length), and the PNJ width, which is e^{-2} waist of the jet [35]. The behavior of PNJs for a given wavelength is as follows: the PNJ waist widening is proportional to the relative refractive index, and the PNJ lengthening is due to the increasing sphere size. This transverse confinement (PNJ waist) has been approximated as a Gaussian, while a part of the longitudinal confinement (decay length) is approximated as a Lorentzian profile [36]. In the present work, it is shown that a Bessoidal-type surface best describes the shape of light confined by these PNJs originating from the interference between the scattered field and the incident beam [6] and therefore the extinction component of the Poynting vector.

The modeling of PNJs originating from plane-wave incidence involves only four parameters: the refractive indices of the particle and its surroundings, wavelength of the incident wave, and radius of the sphere. However, with an incident focused beam, which is required for an optical trap, the complexity of the modeling increases with additional parameters: the numerical aperture and location of the waist with respect to the scatterer. The positioning of the incident focused beam with respect to the scatterer is very important, and we demonstrate that it is responsible for switching the PNJs on and off for an optically trapped microsphere.

2. Theoretical model of photonic nanojets

Any Maxwellian beam can be expressed by its electromagnetic field in terms of partial waves. We start with the general expression for the electromagnetic fields of interest: the incident and scattered fields. Later, we simplify this to a two-dimensional problem, which is useful for a 2D plot and subsequently for a 1D profile such as the longitudinal intensity of the PNJ.

2.1. Generalized Lorenz–Mie theory

The basic idea of GLMT is that a beam, which is expressed by a solution to Maxwell's equations (i.e., Maxwellian beam), can be written as an infinite series of spherical functions and spherical harmonics, each multiplied by a coefficient called a beam shape coefficient (BSC). These BSCs completely describe the incident, internal, and scattered electromagnetic fields in terms of partial-waves series. The correct determination of these radially independent BSCs allows for the precise determination of the observed electromagnetic phenomena [5].

The present notation follows that of previous works [37–39], expressing the electromagnetic fields in terms of spherical vector wave functions even though the original formulation of GLMT was in the framework of the Bromwich scalar functions [40,41]. The microsphere scatterer has a radius a and real refractive index n, and the incident beam is directed towards the positive z-axis of the rectangular coordinate system. The incident wave has a time dependence $\exp(-i\omega t)$ (omitted for clarity), wavelength λ, and wave number $k=2\pi/\lambda$. The scatterer and the surrounding medium are homogeneous, isotropic, and nonmagnetic. The incident and scattered electromagnetic fields can be written as follows:

$$\mathbf{E}_{inc}=E_0\sum_{p=1}^{\infty}\sum_{q=-p}^{p}G_{pq}^{TM}\mathbf{N}_{pq}(\mathbf{r})+G_{pq}^{TE}\mathbf{M}_{pq}(\mathbf{r}), \tag{1}$$

$$\mathbf{H}_{inc}=H_0\sum_{p=1}^{\infty}\sum_{q=-p}^{p}G_{pq}^{TM}\mathbf{M}_{pq}(\mathbf{r})-G_{pq}^{TE}\mathbf{N}_{pq}(\mathbf{r}), \tag{2}$$

$$\mathbf{E}_{sca}=E_0\sum_{p=1}^{\infty}\sum_{q=-p}^{p}a_{pq}\mathbf{N}_{pq}(\mathbf{r})+b_{pq}\mathbf{M}_{pq}(\mathbf{r}), \tag{3}$$

$$\mathbf{H}_{sca}=H_0\sum_{p=1}^{\infty}\sum_{q=-p}^{p}a_{pq}\mathbf{M}_{pq}(\mathbf{r})-b_{pq}\mathbf{N}_{pq}(\mathbf{r}), \tag{4}$$

where the terms involving the spherical functions and vectorial spherical harmonics can be abbreviated as

$$\mathbf{N}_{pq}(\mathbf{r})=\frac{i}{k}\nabla\times\mathbf{M}_{pq}(\mathbf{r}), \tag{5}$$

$$\mathbf{M}_{pq}(\mathbf{r})=z_{pq}(kr)\mathbf{X}_{pq}(\theta,\phi), \tag{6}$$

where $z_{pq}(kr)$ denotes spherical Bessel or spherical Hankel functions, depending on whether it expresses the incident or scattered field, respectively. The vectorial spherical harmonics are defined as $\mathbf{X}_{pq}(\mathbf{r})=\mathbf{L}Y_{lm}(\mathbf{r})/\sqrt{l(l+1)}$, where $Y_{lm}(\mathbf{r})$ denotes the scalar spherical harmonics and $\mathbf{L}=-i\mathbf{r}\times d/d\mathbf{r}$ is the angular momentum operator in direct space. The scattering partial-wave coefficients a_{pq} and b_{pq} are related to the Mie scattering coefficients by