'Photonic hook' nanoparticle manipulator generated under pulsed illumination

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Abstract

The photonic hook - curved photonic nanojets generated by asymmetric dielectric structures - has been previously explored as a method for manipulating nanoparticles in a curved trajectory. However, under continuous wave illumination, these are extremely weak. We report in the work a way to amplify the optical forces generated by a photonic hook, using pulsed illumination. We also study the temperature effects and their contribution to the probe particle's polarizability.

1. Introduction

Asymmetric photonic nanojets, referred to as the photonic hook, generate a curved field at the shadow side, which has been studied as a method for specialized optical manipulation[1]. However, the generated force has a very small magnitude, and this makes it unsuitable for realistic manipulation. While increasing the input field in order to increase the force is possible, this also increases heating, which is potentially destructive to the system.

The photonic hook has also been experimentally shown for continuous wave (CW) illumination[2], and its potential for generating curved fields, and subsequently, manipulation of nanoparticles along curved paths, without large optical set-ups has garnered attention from the scientific community[3]. In this work, we aim to study the optical forces generated by a photonic hook generated by a asymmetric cuboid, as illustrated in Fig. (1), with a pulsed input field.

2. Optical Forces

In order to simplify the calculations for optical forces, we will assume that the particle is much smaller than the input wavelength, so that we can approximate the particle as an electric dipole. The force now becomes[4]

$$\mathbf{F} = (\mathbf{p} \cdot \nabla)\mathbf{E} + \dot{\mathbf{p}} \times \mathbf{B} \tag{1}$$

where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, respectively, and $\mathbf{p}$ is the electric dipole moment.

In the CW case, we can take the time average of Eq. (1) such that the force can be separated into two terms:

$$\langle \mathbf{F} \rangle = \frac{\alpha'}{4} \nabla E_0^2 + \frac{\alpha''}{2} E_0^2 \nabla \phi \tag{2}$$

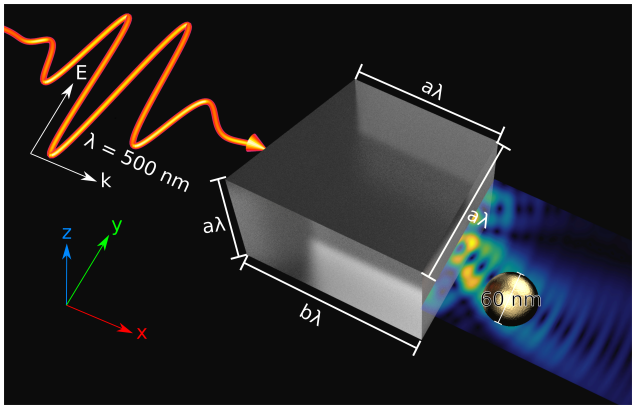

Figure 1: The dielectric cuboid, with refractive index of $n = 1.4$, embedded in air and irradiated by a pulsed input field. The size parameters a and b used in this study are 3 and 4, respectively.

where the dipole moment is $\mathbf{p} = \alpha \mathbf{E}$, the polarizability is given by $\alpha = \alpha' + i\alpha''$, and ϕ is the phase of the field. The terms of Eq. (2) are identified as the gradient and scattering forces. The former traps (or repels, depending on the polarizabiltity) the particle in locations of high field intensity gradient, and the latter moves the particle without any restrictions. The polarizability for a spherical particle with radius R in the Rayleigh approximation can be written as

$$\alpha = 4\pi R^3 \varepsilon_0 \frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d}. \tag{3}$$

Since we want to maximize the scattering force, we select the value of the wavelength λ such that α'' is maximized. The maximum imaginary polarizability can be found at $\lambda_{inc} = 500$ nm, in the vicinity of Au interband transition.

We can calculate the acceleration $\mathbf{a}$ using Newton's second law, and from this, we can estimate the velocity and the distance traveled by the gold nanoparticle during a single cycle of the electric field. Under CW illumination, the distance traveled by the particle is very small. However, we can use pulsed illumination to increase the distance traveled by the nanoparticle.

3. Pulsed Beam Input

To account for the interaction of the incident laser light with the metallic nanoparticle, the extended two- tempearture model (eTTM) is used. Solving the energy density evolution of non-thermal electrons given a Gaussian temporal pulse profile, we can calculate the electronic and lattice temperature dynamics. In order to calculate the temperature-dependent permittivity model[5], we also need to consider the interband and intraband contributions to the dielectric function of Au. From there, we get the polarizability from Eq. (3), as shown in Fig. (2).

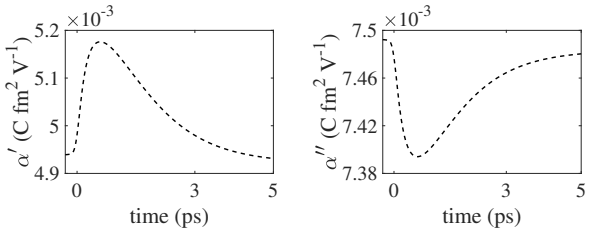

Figure 2: Dynamics of the (left) real and (right) imaginary parts of α as a result of uniform excitation at $\lambda = 500$ nm. The pump pulse duration is 0.1 ps and the absorbed electric field is 15 MV/m.

We use the pulsed beam as pre-defined in Lumerical FDTD, with pulse duration of 100 fs and the time delay set arbitrarily to 300 fs. Using the pulsed input, we can change the incident field amplitude from 1 V/m to 15 MV/m. As it interacts with the dielectric cuboid, the time-dependent electric and magnetic fields generated by the photonic hook is obtained, which we use in Eq. (1) to obtain the optical force. The resulting acceleration and force for both the CW and pulsed input cases are compared in Fig. (3).

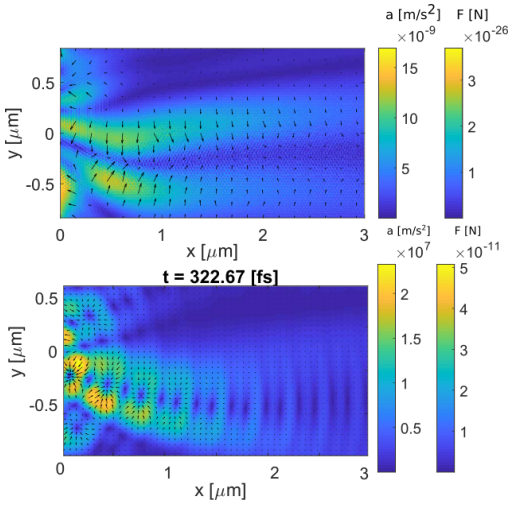

Figure 3: Acceleration and forces acting on a 30 nm spherical nanoparticle due to (top) CW illumination and (bottom) puled illumination at t=322 fs, both with wavelength 500 nm. The colormap and arrow field indicate the magnitude and direction of the optical force.

4. Conclusions

This work reports on an amplification of optical forces generated by a photonic hook on a spherical nanoparticle. We analyzed the influence of a Gaussian pulse with an amplitude much higher compared to the CW case, and we also studied the temperature effects arising from the higher amplitude. The magnitude of the optical force on the pulsed photonic hook incident on the nanoparticle is greater compared to the force and velocity of the same nanoparticle under CW illumination.

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