Light structuring photonic hook via temperature mediated effects

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ABSTRACT

Optical methods have been studied and used extensively for diagnostics and treatment of bio-tissues and cells. Yet, the quality of these methods is still biased by low optical contrast, background noise and heating. Therefore, the ability to track an object's location in cells and tissues is lacking. Here, we report on a method of optically moving gold nanoparticles in a temperature-mediated manner via a structured light - photonic hook. Since continuous wave (CW) generated photonic hooks are extremely weak in low-contrast media, we amplify the optical forces by using pulsed illumination. Our system consists of a micro-cylinder illuminated by an incident Gaussian pulse, and a mask controlling the asymmetry of the incident light. We show that the generated optical forces are around fifteen orders of magnitude larger than by illuminating with a continuous wave of equivalent average power. The photonic hook is applied to a gold nanoparticle embedded in liquid. By investigating the thermo-optical properties of metallic nanoparticles, we present the displacement of the gold nanoparticle, as a result of the momentum exchange. The displacement and changes in polarizability of the gold nanoparticle are examined.

Keywords: nanophotonics, subwavelength focusing, optical forces, photonic hook, nanojet.

1. INTRODUCTION

The trapping and manipulation of particles by optical tools (Ashkin's optical tweezers) have been widely used in biological research and implemented in medicine[1]. Yet, nanoscale objects cannot be manipulated by such tools due to the diffraction limit of light. Thus, achieving manipulation on the nanoscale requires auxiliary structures that generate tightly confined electric fields. Near-field methods of plasmonic tweezers and photonic crystal resonators overcome the diffraction limitation[2], yet excessive heating is damaging for the biological environment or atoms[3]. Photonic nano-jets (PNJ) are high intensity, narrow, light beams generated by dielectric structures that are subjected to illumination by a plane wave[4]. PNJs are a practical way to overcome the diffraction limit and enable focusing in a low contrast environment. When a PNJ is applied to a metallic nanoparticle, the optical forces acting on the nanoparticle result from the momentum exchange[5]. When the symmetry is broken, the generated structured light becomes curved, which is known as a photonic hook (PH). PH-based optical manipulation was previously explored under CW and pulsed illumination for an asymmetric auxiliary structure[6]. Yet, the construction of such a structure requires complicated fabrication processes. Here, we report on the generation of a structure light PH via a simple system; a dielectric micro-cylinder and a mask partially blocking the incident light, thus introducing asymmetry to the system. The optical forces are amplified by using pulsed illumination, which is used as a way to overcome the excessive production of heat. We study the temperature-mediated generated PH in a step-index medium, as a way of enhancing the resolution[7], and its' application as a tool for nanoparticle manipulation.

2. METHODS

Pulsed illumination simulation:

The electric and magnetic fields generated by the plane wave incident on the cylinder are simulated using Lumerical FDTD. The scattered field formalism was used with the source offset by 300 fs in order to input the full Gaussian signal into the system, while pulse length was 100 fs. The simulation is bounded by perfectly matched layers on all sides. We used a mesh size of 0.01 µm and a monitor with a minimum sampling rate per cycle of 10. The resulting dataset was then input in Matlab, where the field derivatives were obtained using the central difference method. The incident wavelength was 500 nm, cylinder and mask refractive index 1.4, cylinder diameter was 2 µm. Using the pulsed beam, the incident field amplitude was tuned from 1 V/m to 15 MV/m, corresponding to laser fluence…

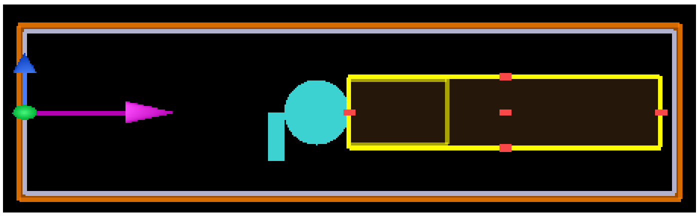

Figure 1. The studied model was simulated by Lumerical FDTD.

Super-resolution simulation:

The cylinder structure and mask simulations for the investigation of super-resolution in a step-index medium were simulated using Finite Element Method (FEM) software Comsol Multiphysics. Perfectly matched layers (PML) bound the simulation space from all sides, as well as a perfect electric conductor. Free tetrahedral mesh with maximum element size λ/7 for the cylinder, λ/3 for the surrounding media. The cylinder diameter was 10 µm.

3. RESULTS AND DISCUSSION

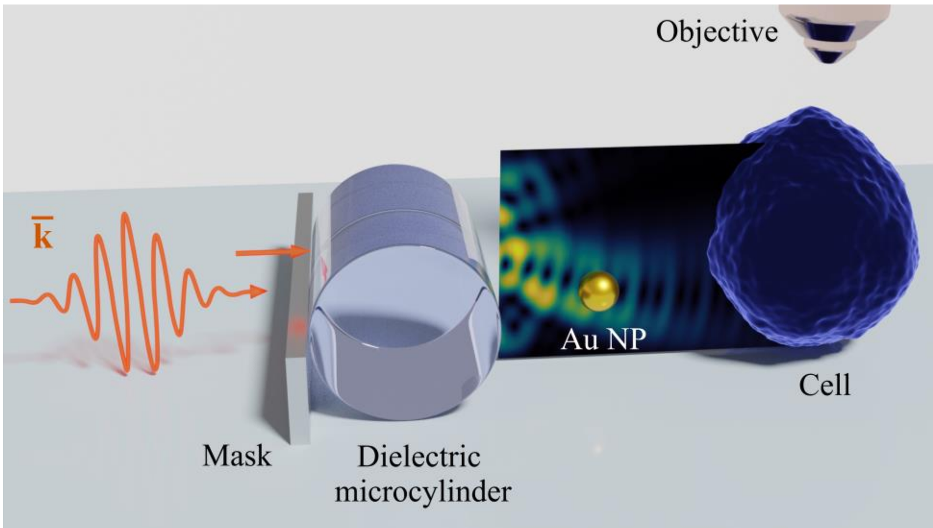

Figure 2. The dielectric cylinder and mask with refractive index n=1.4, irradiated by a pulsed Gaussian input field. The cylinder radius is 1 µm, the incident field wavelength is λ=500 nm. The generated PH would push the nanoparticle into a cell for biological research applications.

Figure 2 illustrates the studied system in which a pulsed beam illuminates a cylinder, while being partially blocked by a mask, therefore breaking the symmetry of the system. The photonic hook is generated at the output of the cylinder and is applied on a gold nanoparticle, due to its biocompatibility for in vivo manipulation[8], and its ability to carry cargo. The simulation was done under illumination at a wavelength of 500 nm, at the vicinity of the Au interband transition, due to the optimal force that can be obtained with the studied particle[6].
The forces exerted on the metallic nanoparticle are calculated by assuming the radius of the gold nanoparticle (taken as 30 nm) is much smaller than the incident wavelength, so that the particle can be approximated as an electric dipole. The force can be written as:

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

Where p is the dipole moment, E and B are the electric and magnetic fields, respectively. Taking the time average of Eqn (1), and by writing the dipole moment as p=αE, we obtain:

$$\langle F\rangle = \frac{\alpha'}{4}\nabla E_0^2 + \frac{\alpha''}{2}E_0^2\nabla\phi \qquad (2)$$

The polarizability of the gold nanoparticle is α=α'+iα", and ϕ is the phase. Assuming that the nanoparticle is spherical, the polarizability in the Rayleigh approximation can be written as the Clausius-Mosotti relation[6]:

$$\alpha = 4\pi R^3\varepsilon_0\frac{\varepsilon_p-\varepsilon_m}{\varepsilon_p+2\varepsilon_m} \qquad (3)$$

Where R is the radius of the nanoparticle, ε_p, ε_m and ε_0 are the dielectric constants of the nanoparticle, surrounding medium and free space.

To account for the temporal dynamics of the dielectric function of the gold nanoparticle, the temperature-dependent permittivity model is employed, taking into account the interband and intraband contributions to the dielectric function of Au as a function of temperature and time[9], in addition to the extended Two Temperature Model[6].

Figure 3 shows the electric and magnetic fields generated by the simulation. The force is calculated using equation (2).

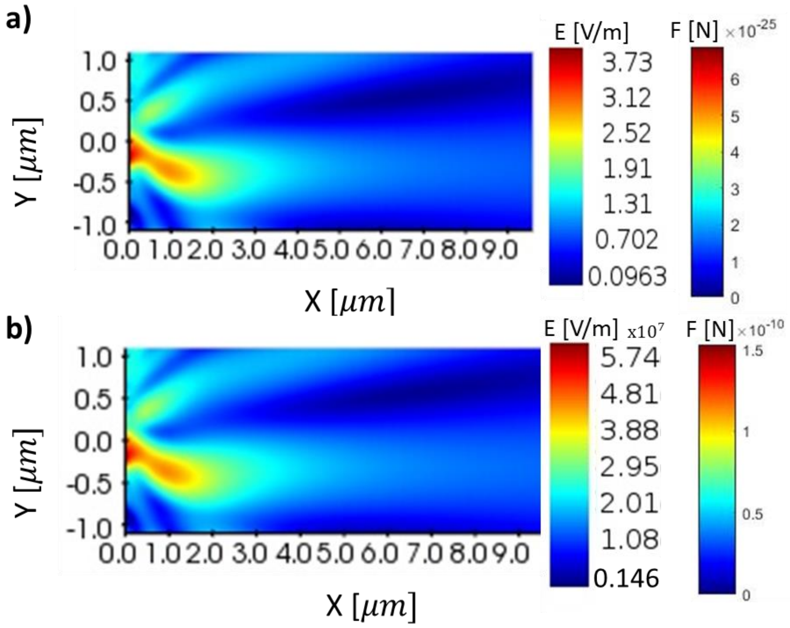

Figure 3 – Simulated electric field and calculated force acting on a gold nanoparticle due to a) CW illumination and b) pulsed illumination with a wavelength of 500nm.

The magnitude of the forces acting on the gold nanoparticle generated by pulsed illumination is 15 times larger than the forces generated by CW illumination. Using Newton's second law of motion, the maximal acceleration of the particle under pulsed illumination is 7*10^7 m/s, while the acceleration under CW illumination is 3.15*10^-7 m/s^2. The acceleration is 14 times larger in the case of pulsed illumination.

In addition to nanoparticle manipulation, the system was investigated as a tool for in situ imaging[10]. A CW beam illuminated the micro-cylinder, generating a photonic jet, in three surrounding media: air, water and an air-water step-index. The FWHM, along with the focal distance (measured from the cylinder center) were measured for all three surrounding environments, as seen in figure 4. The calculated FWHM and focal distance are summarized in table 1.

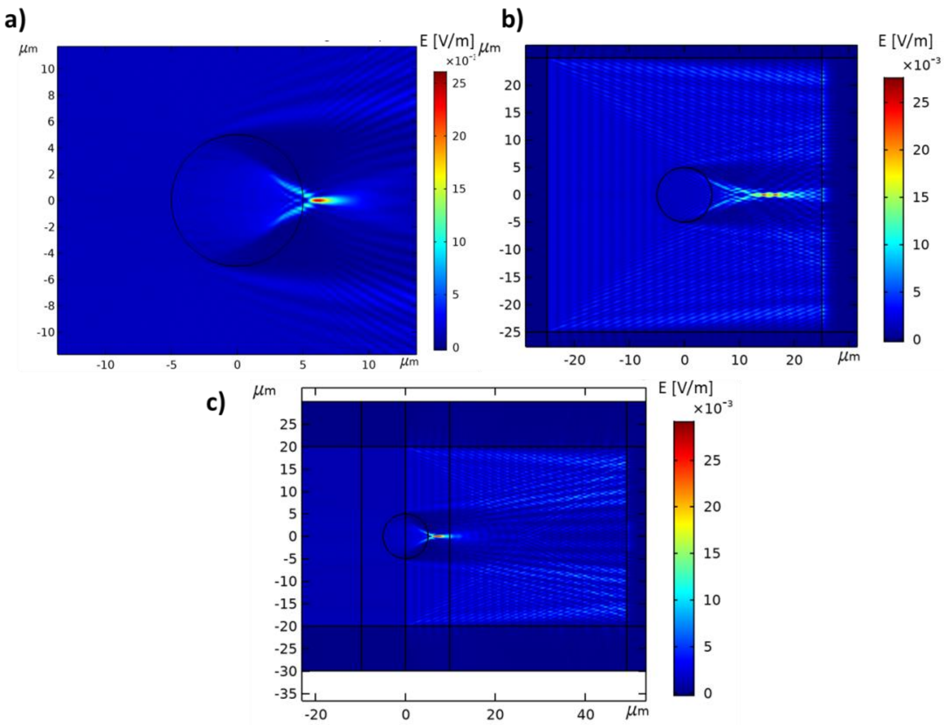

Figure 4 – simulated electric field for a 10 µm PDMS cylinder emerged in a) air, b) water and c) air-water step-index, where the CW beam illuminated the cylinder from the air direction.

Table 1. Measured FWHM, focal distance and maximal intensity of the photonic jet generated in air, water and air-water step-index medium.

Medium	**FWHM**	**Focal distance [µm]**	**Max intensity** $\left[{}^{W}/_{m^2}\right]$
Air	0.48λ	6.12	0.026
Water	0.68λ	16.41	0.027
Air-water interface	0.39λ	7.27	0.029

Considering the obtained FWHM results, it is clear that the generated photonic jet in a step-index medium of air-water goes below the diffraction limit and can therefore be used as a sub-diffraction limit imaging tool. The maximal intensity in all cases is similar, while the focal distance differs for the water medium due to increased scattering events.

4. CONCLUSION

We report on amplification of the optical forces generated by a photonic hook applied on a spherical gold nanoparticle via pulsed illumination mediated by temperature effects. The photonic hook is generated using a dielectric micro-cylinder and mask, which are simple to construct for experimental studies. The magnitude in force is increased 15 times when generated by pulsed illumination, in comparison to CW illumination with same average power. In addition, an in situ imaging concept is proposed together with particle manipulation. When the micro-cylinder is immersed in an air-water interface, resulting in a step in refractive index, the FWHM of the photonic jet is below the diffraction limit. Therefore, the system proposed is an efficient way to both manipulate and track nanoparticles.

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