Polarization dependent particle dynamics in simple traps

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ABSTRACT

Optical trapping has proved to be a valuable research tool in a wide range of fields including physics, chemistry, biological and materials science. The ability to precisely localize individual colloidal particles in a three-dimensional location has been highly useful for understanding soft matter phenomena and inter-particle interactions. It also holds great promise for nanoscale fabrication and ultra-sensitive sensing by enabling precise positioning of specific material building blocks. In this presentation we discuss our research on the effect of the polarization state of the incident laser on the trapping of nanoscale particles. The polarization of the incident light has a pronounced effect on particle behavior even for the simple case of two plasmonic silver nano-particles in a Gaussian trap,. When the incident light is linearly polarized, the particles form an optically induced dimer that is stably oriented along the direction of polarization. However, nanoparticle dimers and trimmers exhibit structural instabilities and novel dynamics when trapped with focused beams of circularly polarized light. The observed dynamics suggest electrodynamic and hydrodynamic coupling. We explore the electrodynamic phenomena experimentally and theoretically and discuss further examples of polarization controlled trapping.

Keywords: Optical trapping, plasmonics, polarization.

1. INTRODUCTION

Optical trapping of particles by lasers, as was first demonstrated by Ashkin et. al[1,2], has been used by scientists and engineers around the world to explore a wide range of physical phenomena ranging from molecular particle trapping[3], to statistical mechanics[4] and biophysics[5]. Thus, there exists a profound interest in expanding the reach of optical trapping by tweaking the characteristics of the particle (topology, material, surface ligands[6]), the trapping environment (chemical potential, viscosity[7]), potential landscape (usually achieved through phase and amplitude control as seen in holographic optical tweezers), and on the properties of the trapping laser (via wavelength, optical power and polarization[8]).

The polarization state of the trapping laser stands out as an intriguing but underexplored control knob for driving single particle behavior and inter-particle interactions. First, it allows fine tuning the particle interaction through the interplay between the potential landscape and the polarization[9]. Second, in the case of circular polarization, it introduces angular momentum (angular force) into the trapped system (see [10]). This allows application of torque on trapped systems, which allows experimental observation of particle spinning such as that reported in[11–14].

In this proceedings paper we discuss the effect of polarization on optical trapping and demonstrate its effect on a very basic trapping configuration - trapping of two spherical silver particles (with a diameter of 150 nm) in a simple Gaussian trap with varying polarization conditions. The reason for choosing these particles is that they have a high scattering cross-section at the trapping wavelength due to their strong plasmonic response at lower wavelengths, leading to strong interactions and facilitating observation through dark field microscopy.

Due to their strong scattering, trapped silver particles show strong inter-particle interactions even when they are beyond near field distances. When the distance between them is roughly one wavelength of the trapping laser in the medium they can be relatively stably positioned at what is known as the optical binding distance[9,15] from one another. The interaction potential can be as strong as $10\ k_bT$[15].

In section 2 of this paper we describe the optical trapping of two silver particles in a tight Gaussian trap when the polarization is linear and circular. We observe that when two particles are trapped in a circularly polarized Gaussian trap that they rotate around each other with a direction oriented with the handedness of the circular polarization.

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We find that the angular rotation velocity of the bound dimer is linearly dependent on the incident optical power. We also discuss the image analysis methods used to extract the data and analyze the results. In Section 3 we use finite-difference time domain (FDTD) software to model the system and understand the orbiting phenomenon and its handedness. Finally, in section 4 we discuss future work and conclude.

2. EXPERIMENTAL RESULTS

2.1 Experimental setup

The experimental setup and a dark field image of the optical beam are shown in Figure 1(a). A Ti:Sapphire laser tuned to a wavelength of 790 nm and emitting linearly polarized (LP) light was collimated and directed into a Nikon TI inverted optical microscope and focused with 60x IR corrected water immersion objective.

The laser beam was focused onto a sample cell containing 150nm diameter silver nanoparticles coated with a ligand layer of Polyvinylpyrrolidone (PVP) immersed in de-ionized water at a ratio of 1:200.The beam was positioned so that its focus would be slightly below the top cover slip and had a measured FWHM of ~500nm (see figure 1(b-c)). By positioning a quarter waveplate beneath the objective we were able to control the polarization state of the incident light and investigate various nanoparticle dynamics in the ensuing trapping. The particles were illuminated using a dark field condenser and their motion was captured using an Andor Neo camera. Due to the high rotational velocity of the particles in the circularly polarized case (see Figure 2(a)), we viewed only a small region of interest on the camera chip (roughly 50 x 50 pixels), allowing us to capture the motion with an exposure time of 0.1ms at a frame rate of 2004 frames per second.

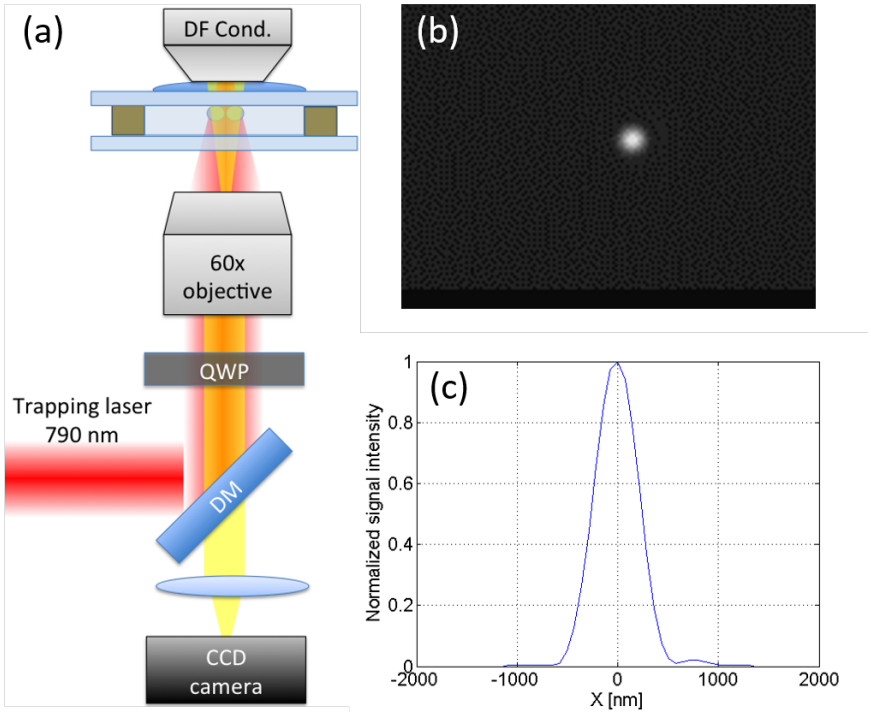


Figure 1. (a) Diagram of experimental setup (DF condenser – dark field condenser, QWP – quarter wave plate, DM dichroic mirror). (b) CCD photo of scattered Gaussian beam used for described optical trapping experiments. (c) Normalized cross section of Gaussian beam shown in (b). FWHM of trap was measured as approximately 500 nm. The image was captured with a Andor Neo camera after a 1.5x magnifier, leading to an effective size of 72 nm per pixel.

The positions of the particles in each frame of a movie were determined by tracking and linked into a trajectory table *{x(t),y(t)}* using the algorithm described in[16], resulting in a table of (x,y) positions of the particles in each frame. From this table we can readily calculate the value at frame *n* of the Cartesian interparticle distance d_n, and the interparticle

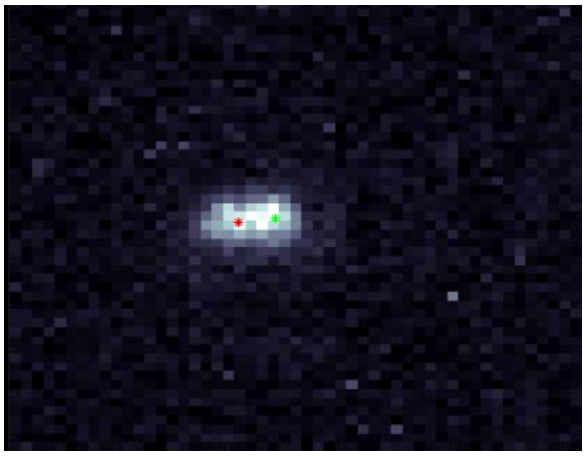
angle θ_n. The angular velocity of the orbiting particles, ω, is defined as the difference in the interparticle angle between two sequential frames, so for frame n we define $\omega_n=\theta_{n+1}-\theta_n$.

However, due to the small size of the particles, and the small inter-particle distance between them, which was usually of the order of 3-4 pixels (corresponding to 200~300 nm), the tracking algorithm introduced errors, due to the overlap at the images (photon distributions) of each particle). Fixing this distortion was done by adapting the algorithm to better suit our tracking and inter-frame linking requirements. This was done by introducing two adjustments to the linking method. First, the tracking was done with a Gaussian filter using the smallest possible window (equivalent to a radius of one pixel). Using a window of this size introduces a systematic narrowing in the subpixel accuracy when using Gaussian center fitting, so we applied a correction algorithm to adapt to this systematic noise and reduce the resulting analysis errors. Second, taking into account the nature of the rotational motion, we often saw skipping of the particle identification between frames – that is particle 1 in frame n was linked to particle 2 in frame $n+1$ because the Cartesian distance between their positions is smaller than the distance to particle 1 in frame $n+1$, leading to errors in the linking of particles across frames. To overcome this we developed a biased linking algorithm which linked the particles in subsequent frames by comparing the possible interparticle angles and choosing the identification that better suits the dynamics we observed.

2.2 Linearly polarized Gaussian trap

When the particles are placed in a narrow linearly polarized Gaussian trap, the gradient force holds them together in the near-field, where their interaction causes them to orient along the direction of the polarization, effectively creating an optically bound dimer. As the scattering between the particles aligns them as two head-to tail dipoles[9], the result is a stable system, where a motion of each particle due to Brownian motion is corrected and the particles are brought back to the equilibrium condition.

An image of such an optically bound dimer, as well as a link to a movie showing its motion in the trap is shown in Video 1. It is worth noting that the optical binding between the particles is contingent on the optical scattering between them. When the laser is turned off, the particles separate from one another and colloidal Brownian motion ensues.

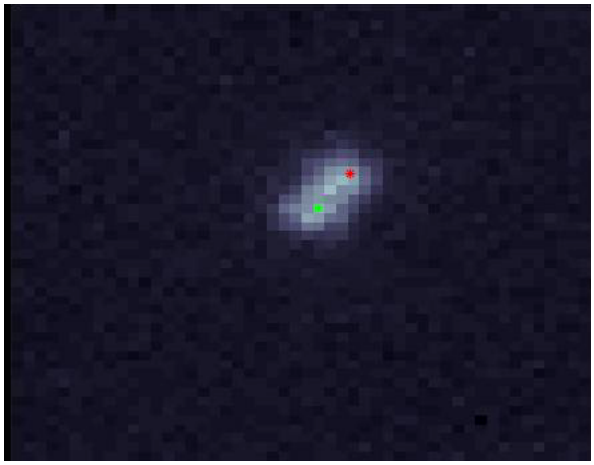


Video 1. Movie of two Ag particles (150nm diameter) trapped in a Gaussian trap that is linearly polarized along the horizontal direction. The strong transverse EM field gradient causes the formation of an optically bound dimer. The red and green dots are tracking markers attached in the post-processing to the particles. Incident optical power is 7mW measured before the dichroic mirror in the microscope, and the images are acquired at 2004 frames per second (FPS).

2.3 Circularly polarized Gaussian trap

In contrast to LP light, where we observe a single trapping state (a Gaussian distribution of interparticle separations), changing the incident polarization of the light to circularly polarized (CP) light alters this stability. Since CP is a linear combination of two LP light sources polarized along the x and y direction with a phase difference between them, trapping with CP light can be thought of as exciting two orthogonal dipoles, of equal strength in the trapped particles.

Under these conditions, the particles do not have a single equilibrium state (distribution of interparticle separations), and as a result of the scattering interaction between them, which will be explained more fully in section 3, they orbit.



Video 2. Movie of two Ag 150nm diameter particles trapped in a circularly polarized Gaussian trap with right-handed circular polarization, causing clockwise rotation of the particles as an optically bound dimer. The red and green dots are tracking markers attached in the post-processing to the particles. Incident optical power is 7mW just before the microscope objective, and measured at 2004 FPS.

As can be seen in Video 2, the introduction of the CP light causes the particles to orbit. Furthermore, we found that changing the CP direction from left handed to right-handed causes the rotation of the particle pair to switch from the clockwise (CW) to the counter-clockwise (CCW) direction. Furthermore, by varying the incident optical power we found a linear dependence of the angular velocity ω of the optically bound dimer. Both results are shown in Figure 2.

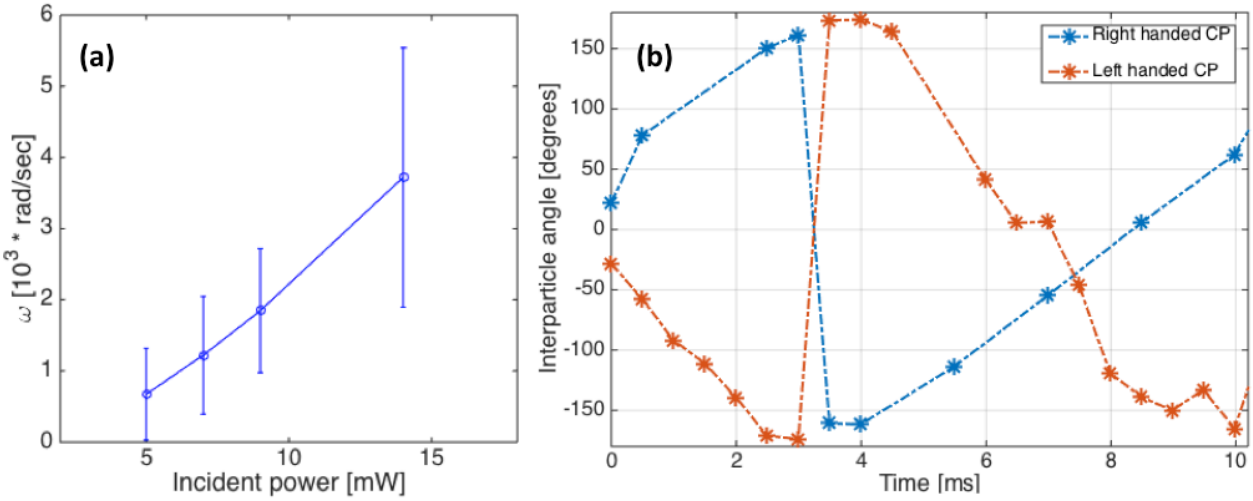


Figure 2. (a) Dependence of angular velocity of the bound dimer as a function of incident optical power. Error bars are the standard deviations of the measured results. (b) Measured interparticle angle resulting from frame-by-frame tracking of an optically induced dimer in different CP Gaussian traps. Skipped data points in the graph are a result of tracking errors (such as identifying a single particle in the frame). Data for both configurations were obtained with an incident power of 7mW, and by analyzing a 2004 FPS movie.

3. THEORETICAL MODELING

The system was modeled using Lumerical – a commercial grade FDTD software suite[17]. The particles were modeled as pure Ag spheres with a diameter of 150 nm immersed in water. The silver dielectric function was calculated using the Drude dielectic function given in the software. The particles in the simulations were separated by a distance of 50 nm

surface to surface to model their experimental distance when they are in the near field. The excitation was done using a pulsed source emitting light between 600 and 1000 nm, and with linear or circular polarization. The forces were determined by calculating the Maxwell stress tensor[18] in a bound box around each one of the particles when the incident radiation. Special attention was paid to the force in the *x* and *y* direction, and the results are shown in Figure 3 along with a diagram detailing the coordinate system.

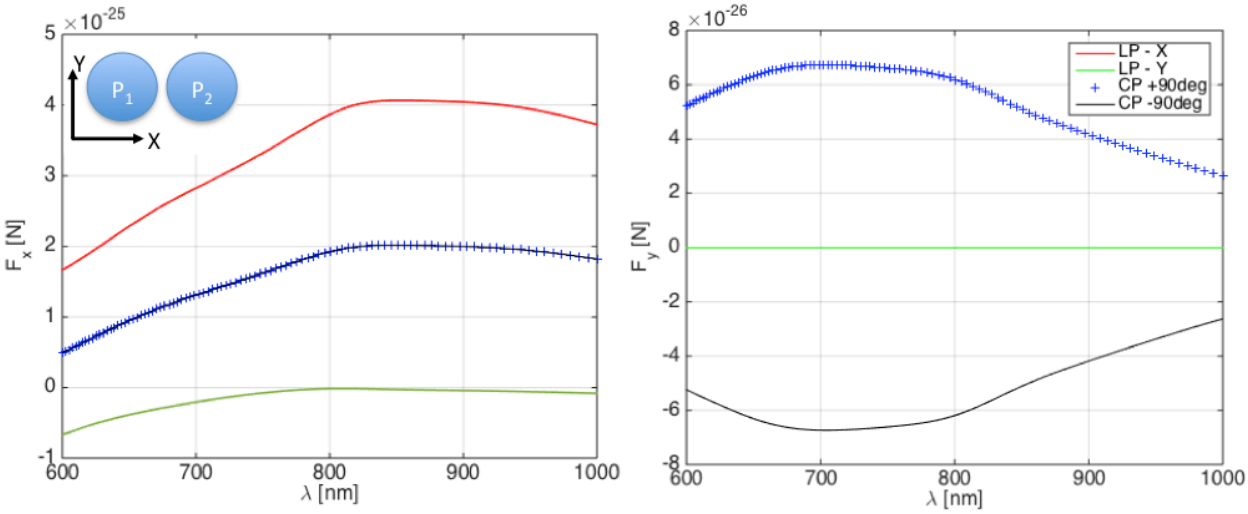


Figure 3 Polarization-dependent calculated forces on particle 1 in the bound dimer pair in the *x* (left) and *y* (right) directions. Forces were calculated in FDTD using the Maxwell stress tensor method. Inset in left plot shows particle orientation. LP -X or Y: linear polarization in the *x* and *y* directions, respectively, CP – RH or LH: Right of left handed circular polarization, respectively.

From Figure 3 we can better understand the forces acting on an individual particle in the dimer. Particle 1 (on the left side of the dimer) is attracted to its partner, and the force is maximal when the induced dipole is aligned head to tail, is when the light is LP in the *x* direction. The force is small but slightly negative for light polarized along the y direction, evidence of repulsion between the induced dipoles when they are aligned side by side. Finally, for CP light, the force is the sum of the two LP components resulting in a weak attractive force. The results for particle 2 are identical in magnitude but have opposite direction.

Analyzing the force in the *y* direction, we find that the force all but vanishes when the light is linearly polarized, regardless of orientation, but has a non-zero component when the light is circularly polarized. This non-zero component is reversed in direction for the second particle and as a result the two particles, seen as a dimer, experience an optical torque causing them to rotate. This torque explains the difference in rotation direction observed in Figure 2(b). Since the forces are linearly dependent on the power of the incident optical source, we can understand the linear dependence of ω on the incident optical power. The interaction between the particles depends on the scattering between them and changes with the interparticle distance, an observation which will be elaborated in the talk.

4. CONCLUSIONS AND FUTURE WORK

In this proceedings paper we reported on the experimental conditions necessary to optically induce a dimer consisting of two 150 nm diameter Ag particles. The formation of the dimer is due to near-field scattering interactions between the particles; once the light is turned off, the particles decouple, dissolving the dimer. When the trapping laser light is set to CP, the dimer starts to rotate in a direction corresponding the handedness of the incident light, and with a rotation speed linearly dependent on the incident optical power. Furthermore, we have also described numerical methods used to model and better understand this effect. Using FDTD calculations, were able to recreate experimental conditions and quantify them.

Controlled positioning and manipulation of nano-scale particles is of utmost importance any application that uses the benefits of plasmonics, such as holography[19], drug delivery[20] and ultra-sensitive biological sensing[21]. In this work we have shown that even in a relatively straightforward optical trap there is a wealth of physical effects to be understood

which can be applied towards better particle control. In future work we hope to expand on this project by including Langevin motion calculations[22], increasing the number of trapped particles and investigating polarization effects on more complex trapping systems.

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