Dielectrophoretic Nanoparticle Propellant Injection with Plasmonic Acceleration

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***Abstract* — We describe the concept of a dielectrophoretic propellant injector and its inclusion in a plasmonic-based, small-satellite propulsion system. Thrust is achieved by applying a plasmon generated non-uniform electromagnetic field, and corresponding dielectrophoretic force, to net-neutral nanoparticles.**

Keywords—plasmonics, satellite, propulsion

I. Introduction

The surface electrons in a metal oscillate when optical radiation strikes the surface of a metal. A group of oscillating electrons is known as a plasmon. When the metal is reduced in dimensions to the nanoscale regime, the plasmon oscillation length becomes comparable to the nanostructure length-scale, and the plasmons are able to resonate with the incident radiation. This resonance creates an intense, localized electromagnetic field distributed about the region of the nanostructure. The electromagnetic field can be tuned by changing the size and shape of the metallic nanostructures and used to control the motion of particles within the vicinity of the nanostructure. The nanoparticle manipulation and acceleration enabled by the enhanced plasmonic forces is well-known and often referred to as "optical tweezers." [1] These plasmon-generated forces have been demonstrated to optically trap particles beyond the diffraction limit.

Our research extends this idea of plasmonic nanoparticle manipulation from trapping to acceleration and is specifically aimed at propulsion for smallsats. Our work focuses on harnessing the nanoscale light-metal interaction for net-neutral nanoparticle acceleration.

II. Plasmon Force Propulsion Concept

A. Geometry and Thruster Scheme

In the particle trapping experiments of the "plasmon nano-optical tweezers," symmetric nanostructures are employed [2] because they create symmetric trapping volumes, or potential wells. Therefore, in order to create an asymmetric potential and strong particle acceleration, asymmetric nanostructures are investigated. An asymmetric, V-groove type structure was developed by Shalin and Sukhov in 2012 [3] for the one dimensional acceleration and ejection of nanoparticles out of the V-grooves in a nanocannon fashion. They propose that ejection of nanoparticles from the V-grooves will occur due to the gradient force of the *E*-field in the grooves and a negative real part of the polarizability of the nanoparticles. They estimated particle velocities on the order of 1 m/s with optical excitation between 300 – 400 nm. [4] Our asymmetric nanostructures are grouped by two's into a nano-unit as shown in Figure 1 (a). They resonate with a small, tunable range of incident light that is polarized perpendicularly to their nanoparticle acceleration axis, along the width of the nano-unit. We have found that the asymmetric, trapezoidal nanostructures resonate strongly within the visible spectrum at a wavelength of λ = 770 nm when dimensions are $w = 110\ nm$, $l = 400\ nm$, and $g = 30\ nm$. [5]

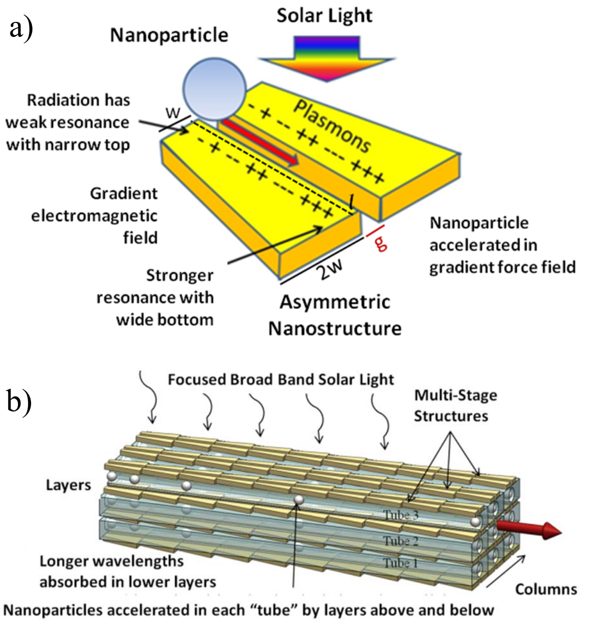

Figure 1: Plasmon Force Propulsion Concept

A schematic of the relevant plasmonic physics and how it might be employed for propulsion is shown in Figure 1 (b). Sunlight is directly focused onto subwavelength metallic nanostructures through a lens (not shown). The resonant interaction and coupling of the light with the nanostructures excite surface plasmon polaritons that generate a strong gradient optical force field. Nanoparticles (e.g., glass beads) are accelerated by the gradient force field and are expelled. Because the optical force field is coupled to the nanostructure through the strong light-matter interaction with surface plasmon polaritons, thrust is generated through momentum exchange with the expelled particles.

Careful examination of Figure 1 (b) reveals a major benefit of plasmonic propulsion: little to no electric or spacecraft power required. Solar energy is directly converted into propulsive thrust, additional solar cells, batteries, or other energy storage is not required. This has distinct advantages for the mass and power budget of a spacecraft, especially nanosats where mass and power are already severely limited. However, unlike other direct energy conversion propulsion technologies, plasmonic propulsion is not due to photon pressure, but rather the strong gradient optical force field generated by surface plasmon polaritons excited in the designed metallic nanostructures by the strongly resonant light-matter interaction.

B. *Fabrication and Computational Modeling*

A periodic array of asymmetric nano-units is shown in Figure 2 (a). The array was milled into a Au film 24 nm thick that was deposited on a glass substrate by using a focused ion beam. A high accelerating voltage (30 kV) was combined with a low beam current (9.7 pA) to mill the pattern.

The optical characterization was performed using an incoherent, Halogen, horizontally polarized, white-light source focused onto the array through a microscope to mimic solar light. Additionally, a Horiba spectrometer with a CCD detector was used to measure the intensity of light transmitted through the array. The spectrometer was used to scan through the wavelengths produced by the source to measure the transmission of the source light through the fabricated array.

We also developed a three-dimensional, full-wave simulation of the array using the finite element simulation software COMSOL Multiphysics (v. 5.0). Figure 2 (b) shows the numerical simulation and experimental results of the optical characterization of the array, normalized to the intensity of the unobstructed beam. The shaded grey region indicates the measurement error associated with the data points (the black, solid line) of the experimental characterization.

Figure 2 (b) shows a difference between resonance wavelengths of the experimental characterization, 750.0 ± 0.2 nm, and the numerical simulation, 770 ± 10 nm, to be 2.6 %. It also shows that the transmittance of the experimental sample is 7.7 times greater than the numerical simulation at the respective resonance wavelengths.

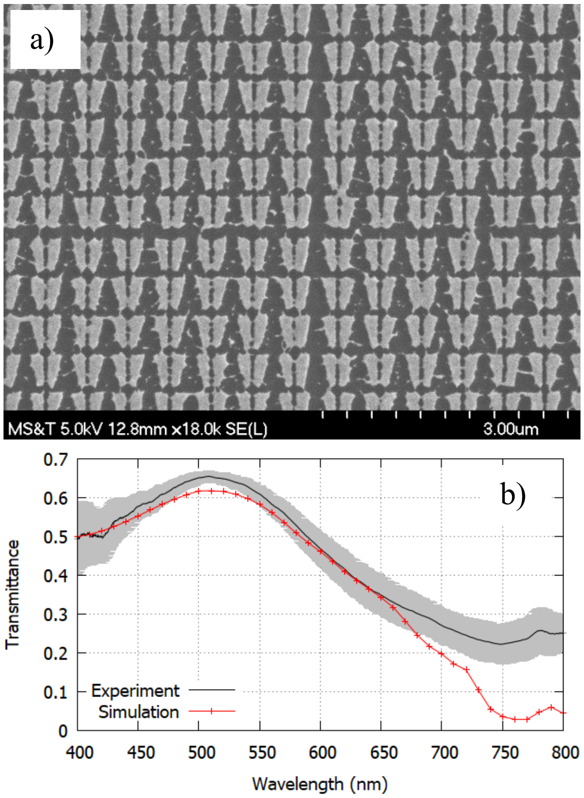

Figure 2: (a) Subsection of the nano-unit array used for optical characterization. (b) Comparison of experimental and numerical simulation results of the optical characterization.

The differences in resonance wavelength and transmittance magnitudes are due to the dispersion in dimensions of the fabricated nano-units because the surface plasmon resonance is size dependent [6, 7]. Variations in shape between nano-units in an array cause the resonance location of each nano-unit to shift in relation to each other. We see that the overall shape of the transmittance spectra of the numerical simulation and the experimental characterization agree over the entire spectrum, even off-resonance.

C. *Thruster Predictions*

Using the COMSOL model of the nano-unit array, we developed an estimate of the force produced by a single nano-unit due to the optical-plasmonic interaction. Figure 3 shows the force profile on a glass nanoparticle as a function of position for a single nano-unit in the array. Examination of this figure shows that the force profile extends a great distance beyond the length (400 nm) of the nano-unit.

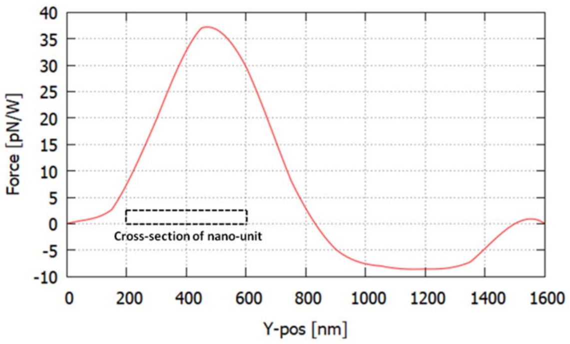

Figure 3: The calculated optical force profile of the nano-unit resonating near a wavelength of 800 nm.

Force profiles like Figure 3 are coupled with a nanostructured array and thruster model to predict propulsion performance. Our original results for a conceptual design of a plasmonic accelerator that has 35 layers, 86 array columns, multi-stage length of 5 mm, a 5-cm-diameter light focusing lens, and uses 100 nm polystyrene nanoparticles expelled at a rate of 1×10^6 per sec would have a thrust of 250 nN, specific impulse of 10 sec, and minimum impulse bit of 50 pN-s. The thruster mass and volume are estimated at 100 g and 50 cm^3, respectively. [8] A major assumption we made for these preliminary results was the rate at which the nanoparticles are expelled, namely, $f = 1 \times 10^6$ per sec. We are now developing higher fidelity model predictions of the projected performance of the thruster by incorporating a nanoparticle injection model based on dielectrophoresis.

Dielectrophoresis occurs when a net-neutral particle is placed in a non-uniform electric field. The electric field polarizes the particle and the polarized particle then feels a force due to the gradient in the magnitude of the field. The direction of the force depends on the difference between the permittivity of the particle and that of the medium surrounding the particle. The DEP force is utilized in a variety of research fields but most commonly in microfluidics and biomedical applications [9]. Its effectiveness in these areas is due, in part, to its ability to separate particles according to their polarizability and/or size. We desire to make use of its ability to precisely control the motion/flow of a concentration of net-neutral nanoparticles.

III. Dielectrophoretic Injector

A. Theory of Dielectrophoresis

Research has shown that dielectrophoresis can be used to continuously pump particle-laden microfluidic flows through virtual (wall-less) channels using microstructured electrodes in a variety of configurations [10]. Research has also shown that dielectrophoresis can filter particles from a stream of gas; expanding the usability of the DEP mechanism [11]. Further progress in this field has demonstrated that particulate matter can be separated by use of dielectrophoresis in a vacuum environment, known as vacuum dielectrophoresis [12]. Vacuum dielectrophoresis eliminates certain interactions due to the particles moving in a medium/fluid, making the DEP force the only interaction with the particles in the plane perpendicular to the force of gravity. If these experiments were further ushered into the coupled microgravity-vacuum regime then even the force of gravity could be neglected and the dominant motion would be due to the DEP force (assuming adhesive/cohesive interactions such as van der Waals forces are negligible and no Coulomb force acts between the particles).

The DEP motion depends on the dielectric properties of the particles and the surrounding medium. Specifically, it depends on the effective polarization of the suspended particles. If the polarizability of a net-neutral nanoparticle is greater than the polarizability of the surrounding medium, then the nanoparticle will be pushed toward the stronger region of the electric field (pDEP) and vice-versa (nDEP) if the medium has higher polarizability. Equations (1) and (2) define the DEP force acting on a particle.

$$\vec{F}_{DEP} = 2\pi R^3 \varepsilon_m k \nabla\left(\left|\vec{E}\right|\right)^2 \tag{1}$$

$$k = \frac{\epsilon_p - \epsilon_m}{\epsilon_p + 2\epsilon_m} \tag{2}$$

R is the radius of the particle. ε_m is the permittivity of the surrounding medium in which the particles are suspended. k is the Clausius-Mossotti factor, defined in Equation (2), that relates the permittivity of the particle and medium and is positive when the particle permittivity is greater than the medium permittivity. $\vec{E}$ is the electric field. From these equations we see that the DEP force is proportional to the cube of the radius of the suspended particles as well as the gradient of the magnitude of the electric field.

B. Dielectrophoretic Injector Design

The DEP force can be used to inject nanoparticle propellant into the plasmonic accelerator. We investigate here a wedge-shaped trapezoidal prism, whose 2-D cross section is a simple non-parallel plate capacitor. This geometry creates a steady, non-uniform electric field when supplied with a DC voltage and the electric field can be easily solved analytically in 2-dimensions.

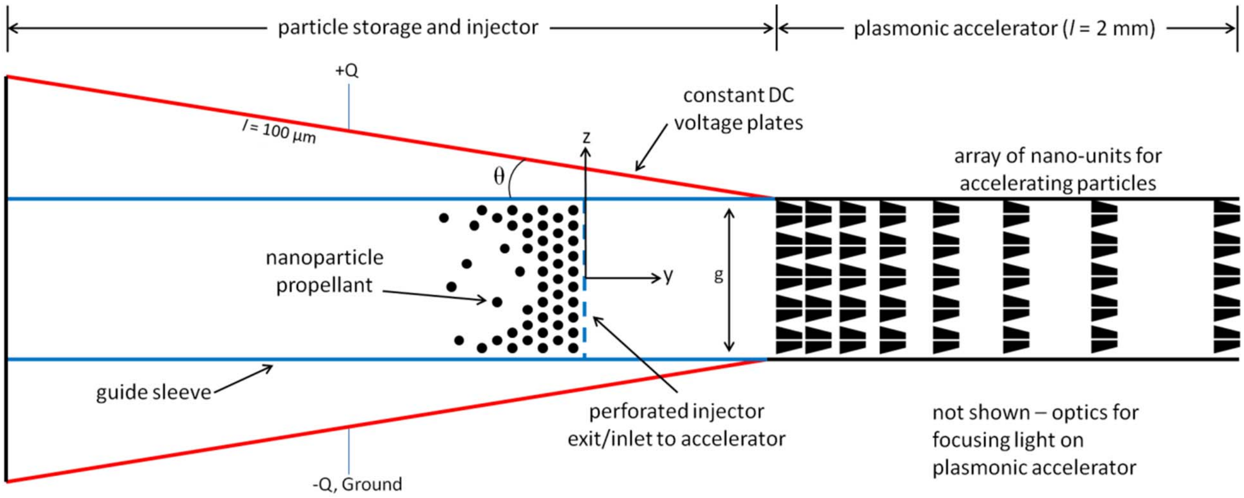

Figure 4: Geometry of trapezoidal prism propellant injector

The non-parallel plate capacitor cross-section is shown in Figure 4, where the red lines show the silhouette of the injector, and the design is such that the particles will start in the injector (injector doubles as a storage tank) and exit into the accelerator on the right. The upper and lower surfaces of the injector (red lines in the image) are electrically separated and a potential difference is maintained across them in order to produce the desired electric field. A dielectric, rectangular guide-sleeve is inserted along the axis of the injector between the charged surfaces (solid blue lines) with height equal to the opening of the injector exit. The dielectric guide sleeve keeps the particles away from the conducting walls where our simulations show they can become trapped. All calculations are performed with the assumption that the setup is in a vacuum such that there is no influence from ambient air.

IV. Conclusion

We have developed a thruster design that makes use of the plasmonic force concept. Results predict that with plasmonic force propulsion the relative position (distance) and angular orientation (degrees) between two spacecraft is able to be controlled to a resolution that is 1-2 orders of magnitude smaller than current state-of-the-art. [8] Also, our numerical simulations show that asymmetric nanostructures can resonate strongly within the visible spectrum such that sunlight in low Earth orbit can be used to operate a propulsion system designed on plasmonic mechanisms. [5, 8, 13] Our current research focuses on developing a high-fidelity model of the coupling characteristics between the DEP propellant injector and plasmonic accelerator.

V. References

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