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Engineering Notes

Transmission Spectrum of Asymmetric Nanostructures for Plasmonic Space Propulsion

Jaykob N. Maser,* Ling Li,† Huixu Deng,‡ Xiaodong Yang,§ and Joshua L. Rovey¶
Missouri University of Science and Technology, Rolla, Missouri 65409

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Nomenclature

f = location of expected edge
g = gap between nanostructures within a nanounit
l = nanostructure height
n = number of data points
w = nanostructure width
y = location of experimental edge
λ = wavelength of light

I. Introduction

NANOSATELLITES are defined as spacecraft with a mass of 1–50 kg. The demand for and use of these and other small satellites is widespread and is projected to continue to increase according to the 2015 SpaceWorks report on the nano/microsatellite market [1]. The SpaceWorks report also makes note that most nano/microsatellites are launched in large clusters and that certain companies such as SpaceX and OneWeb plan to use large constellations of small satellites for communications purposes. Satellites within sizeable constellations will need the ability to maneuver and orient themselves precisely in relation to the other satellites of the cluster. Coupling these requirements with the constraints of mass and volume demand the use of novel propulsion systems that are optimized for use on smallsats (a nano/micro type satellite defined in the SpaceWorks report). This propulsion system must also be adaptable for satellites that continue to decrease in size.

Plasmonics is a subfield of optics that addresses the nanoscale interactions of light and metallic nanostructures. If a beam of light is allowed to strike the surface of a metal, then the oscillating electric field component of the light will cause the electrons in the metal to oscillate. A group of oscillating electrons is known as a plasmon. If the metal is restricted in dimensions to the nanoscale regime, the plasmons are able to resonate with the incident light, which creates a strong electromagnetic field about the location of the nanostructure. This 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 control of nanoparticles in the vicinity of a plasmon interaction is well known as "plasmon nano-optical tweezers" [2]. This technique demonstrates optical particle trapping coupled with the plasmon interaction to trap nanoparticles beyond the diffraction limit.

Previous research [3] extended this idea of plasmonic nanoparticle manipulation from trapping to acceleration and was specifically aimed at propulsion for smallsats. This work developed a thruster design that made use of the plasmonic force concept. Results predicted that, with plasmonic force propulsion, the relative position (distance) and angular orientation (degrees) between two spacecraft was able to be controlled to a resolution that was one to two orders of magnitude smaller than state of the art. Results for a conceptual design of a plasmonic thruster that had 35 layers, 86 array columns, a multistage length of 5 mm, a 5-cm-diam light focusing lens, and used 100 nm polystyrene nanoparticles expelled at a rate of 1×10^6 per second would have a thrust of 250 nN, a specific impulse of 10 s, and a minimum impulse bit of 50 $\mathrm{pN \cdot s}$. The thruster mass and volume were estimated at 100 g and 50 cm^3, respectively [3]. Previous numerical simulations have shown that asymmetric nanostructures can resonate strongly within the visible spectrum, but this has never been demonstrated in experiments until now. Here, we report the first time these types of nanostructures have been manufactured and optically characterized. We report on the first experiment that demonstrates this resonance, with a nanostructure designed to resonate at $\lambda = 770$ nm, for use as a plasmonic space propulsion thruster.

II. Manufacturing Nanostructures

In the particle trapping experiments of the plasmon nano-optical tweezers, symmetric nanostructures are employed [4] 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 setup was developed by Shalin and Sukhov in 2012 [5] for the one-dimensional acceleration and ejection of nanoparticles out of the V grooves in a nanocannon fashion. They proposed that ejection of nanoparticles from the V grooves would occur due to the gradient force of the E field in the grooves and a negative real part of the polarizability of the nanoparticles.

Our asymmetric nanostructures are grouped by twos into a nanounit (Fig. 1), where the designed dimensions are $w = 100$ nm, $l = 400$ nm, and $g = 30$ nm. The geometrical dimensions were chosen such that, based on previous research, the nanounit would resonate strongly within the solar spectrum, specifically at a wavelength of 770 nm [3].

The nanounit described previously was replicated to form a repeating array in a gold film, approximately 24 nm thick, deposited on a glass substrate. The focused ion beam (FIB) on the FEI Helios Nanolab 600 Dualbeam scanning electron microscope (SEM)/FIB was used to mill the negative area of the pattern and leave behind the freestanding nanostructures. A high accelerating voltage (30 kV) was combined with a low beam current (9.7 pA) to mill the pattern. A large array of 50×50 nanounits was constructed by sequentially milling sets of 10×10 arrays (Fig. 1) adjacent to each other. Fabrication of a large array of 50×50 nanounits was necessary so that the physical dimensions of the entire array (~24.8 μm by ~24.0 μm) would be comparable to the optical beam that was used to experimentally determine the resonant wavelength of the array.

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*Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, 160 Toomey Hall. Student Member AIAA.

†Postdoctoral Fellow, Department of Mechanical and Aerospace Engineering, 227 Toomey Hall.

‡Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, 227 Toomey Hall.

§Assistant Professor of Mechanical Engineering, 227 Toomey Hall.

¶Associate Professor of Aerospace Engineering, 292D Toomey Hall. Associate Fellow AIAA.

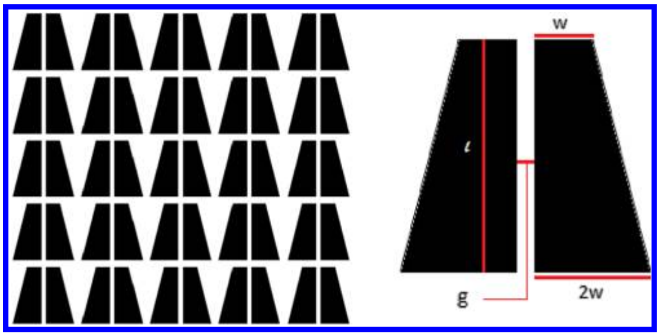

Fig. 1 Geometry of a nanounit comprised of two trapezoidal nanostructures.

A good-quality SEM image, or FIB pattern, is one in which the features are distinguishable and the image/pattern is in focus and not washed out, which is caused by having a poorly focused FIB. Fabricated nanostructures are compared to the theoretically desired pattern to determine the array that has the least amount of error between the template and the manufactured sample. Images of each array are taken using the scanning electron microscope on the aforementioned FEI system, as well as the Hitachi S4700 SEM. Due to the glass substrate, heavy charging occurs throughout the array after milling takes place; therefore, steps are taken to reduce charging. A large negative bias voltage (−150 V) is placed on the Everhart–Thornley detector so that only backscattered electrons, which have the energy of the beam, are detected. Since backscattered electrons have such high energy, the observed charging effects of the sample are minimal, if not inconsequential. Obtaining images of an array allows each nanostructure to be measured and the roughness, which is a measure of the variation of each data point along an edge from its expected value, to be calculated. The approximate edge of each nanostructure is determined by finding the greatest change in pixel value of the image at the location of the nanostructure edge within the image. Then, the dimensions of the nanostructures are determined by using the approximate edges that are found. The error, or roughness, along each edge of the nanostructures is determined by calculating the distance between the approximate edge and where the edge should be by using Eq. (1): the mean absolute error (MAE). A set of operating conditions that produces the highest accuracy nanostructures is then chosen by minimizing the roughness of the edges of the nanostructures. The resolution, or quality of focus, of the ion beam when undergoing fabrication is, by far, the predominant factor in increasing the quality of the fabricated arrays. The array that is used for optical characterization, seen in Fig. 2, has an estimated mean absolute error of ∼18%:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |f_i - y_i| \tag{1}$$

III. Characterization of Nanostructure Optical Transmission

An incoherent, Halogen, white-light source was focused onto the array to mimic solar light and a Horiba spectrometer with a charge-coupled device detector was used to measure the intensity of light transmitted through the array. The light source was turned on and focused through a Nikon microscope to illuminate the sample. The spectrometer was then used to scan through the wavelengths produced by the source to measure the transmission of the source light.

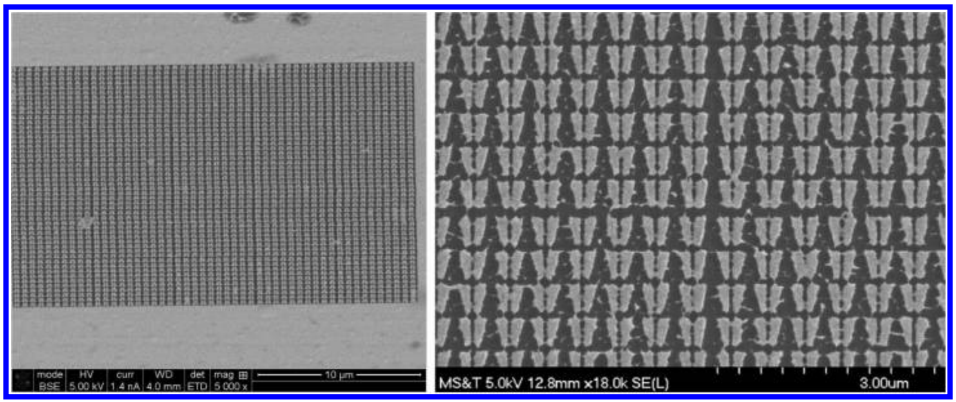

Fig. 2 Full image and zoomed-in subsection of the 50 × 50 nanounit array used for optical characterization.

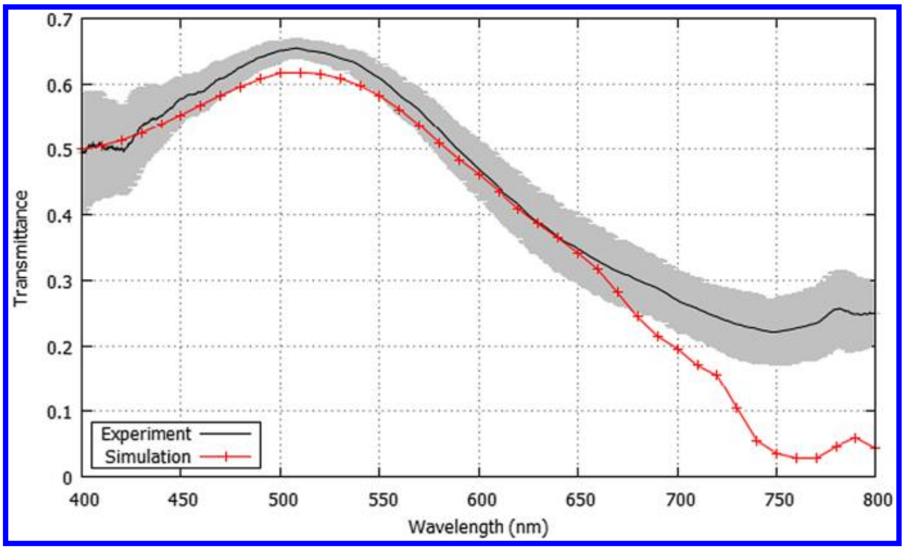

Fig. 3 Comparison of experimental and numerical simulation results of the optical transmission of nanostructures.

Figure 3 shows the numerical simulation and experimental results of the optical characterization of the array, normalized to the intensity of the unobstructed beam. The shaded gray region indicates the measurement error associated with the data points (the black line) of the experimental characterization. To understand the transmittance measurement, the finite element simulation software COMSOL Multiphysics (version 5.0) was employed to run a three-dimensional full-wave simulation of one unit cell consisting of one nanounit structure. This is the same simulation procedure used in previous research [3]. The simulation domain size is set to be one period (500 nm; previous simulations had a periodicity of 800 nm) in the direction of the structure plane, with the thickness of the glass substrate and the air superstrate as 1.0 and 1.5 μm, respectively. Floquet periodic boundary conditions are applied on the four boundaries perpendicular to the structure plane considering the periodic distribution of the nanounit structures on that plane. The top and bottom capping layers are set as perfect matched layers (PMLs). A pair of ports and scattering boundary conditions are activated on the two PML surfaces adjacent to the simulation domain and the two outmost PML surfaces, respectively. One of the ports serves as the plane wave light source, and the other measures the transmitted electromagnetic wave. The PML and scattering boundary condition ensure no backscattering from the two capping layers. The top width w. and thickness of the asymmetric structure are adjusted to be 110 and 24 nm, respectively.

Figure 3 shows the difference between resonance locations of the experimental characterization (750.0 ± 0.2 nm for horizontally polarized light) and the numerical simulation (770 ± 10 nm) to be 2.6%. The difference in resonance location is likely due to the error in nanostructure dimensions between the modeled nanounit and the experimentally fabricated nanounit because the surface plasmon resonance is size dependent [6,7]. Further analysis of Fig. 3 shows that the transmittance of the experimental sample is 7.7 times greater than the computed model at the respective resonance locations. This means that less energy is absorbed by the nanounits at the resonance location than predicted by the simulation, which is likely due to the small variations in shape between nanounits within a single array. Reference [7] shows that a change in nanostructure shape from a triangle with a side length of 83 nm to approximately the same size pentagon or sphere causes the peak plasmon resonance wavelength to shift by 110 and 150 nm, respectively. Therefore, variations in shape between nanounits cause the resonance location for each nanounit to shift in relation to each other. This means that, at the desired resonance location, there are fewer nanounits within the array that are absorbing the incident light, which allows a higher percentage of the incident light to transmit through the array at the desired resonance location [6,7]. This implies that, as the uniformity of the nanounits increases, the resonance of the array at a single location will also increase. If fabrication resolution using a FIB is inhibited by sample features such as the glass substrate, then alternate forms of fabrication, such as deep ultraviolet photolithography, may need to be investigated. Finally, we see that the transmittance spectra of the numerical simulation and the experimental characterization agree in shape over the entire spectrum, even offresonance, in spite of the large difference in transmittance.

IV. Conclusions

The first fabrication and optical characterization of asymmetric nanostructures for plasmonic space propulsion was achieved. The resonant wavelengths between experimental results and numerical simulations were in agreement with an error of 2.6%. This accomplishment improved the feasibility of using a micropropulsion device that operates solely off of visible solar irradiation. Further research may need to be conducted in order to determine the practical usability of a plasmonic space propulsion device in terms of force generation and energy transfer.

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