

# Enhanced transmission in near-field imaging of layered plasmonic structures

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**Abstract:** Near-field imaging of an engineered double layer structure in transmission mode has shown enhancement of light intensity through the structure. An array created by an optically thick double layer structure of a total thickness of 165 nm containing twin 50 nm Au layers was imaged using a near-field scanning optical microscope in illumination mode. The resulting transmission image shows an increased local transmission at the position of each particle in the array. This viewable enhancement is due to a nanoantenna effect that is created by a resonant plasmon oscillation between the two layers.

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OCIS codes: (260.5740) Resonance.

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## 1. Introduction

Optical transmission through a sub wavelength aperture can be greatly increased through the presence of surface plasmon resonances. It is widely known that surface plasmon resonances are

due to the collective oscillation of electrons along a metal surface in resonance with incident light. Such plasmon resonances along interfaces with sub wavelength apertures will lead to extraordinary optical transmission of incident light through an aperture [1]. It has since been shown that this enhancement of transmission, in thick structures, is due to photon tunneling through the sub wavelength diameter apertures [2].

The significant increase in transmission provided via surface plasmon resonance is welcome in the near-field optical microscopy community. With near-field scanning optical microscopy (NSOM), convention dictates that smaller apertures provide better resolution. As aperture diameter decreases, so does the amount of light exiting the aperture. It has since been shown that surface plasmon resonances can be used to increase the transmission through an NSOM aperture [3, 4].

Optical properties of small novel metallic structures are strongly influenced by the presence of local surface plasmons. These plasmons are strongly influenced by the size and shape of the particle along with its environment. Controlling these specifics affords direct control over certain plasmon properties as well as the creation of multiple excitation wavelengths [5]. Gaps between two resonant particles provide an area for buildup of electromagnetic energy in what commonly known as a nanoantenna effect. If these gap modes are resonant with a driving optical field, significant enhancement of the local electric field is expected. This enhancement influences and creates many interesting properties of such metallic structures [6, 7]. Such interactions can be used in novel geometries to confine light and guide light on a sub wavelength scale [8, 9].

We report enhanced optical transmission that has been observed in near-field imaging of a layered plasmonic structure. An array of a total thickness of 165 nm containing twin 50 nm Au layers was imaged using an NSOM to provide local illumination. The resulting transmission image shows an increased local transmission at the position of each particle in the array. This viewable enhancement is due to a nanoantenna effect that is created by a resonant plasmon oscillation between the two layers. The nanoantenna effect enables increased transmission through the illuminating aperture and transmission of light through the sample.

The area of each particle was  $\sim 5$  times that of the effective aperture area. Previous results have only explored resonances of particles smaller than the aperture diameter. The obtained near-field response shows an interference pattern acting between the plasmon resonances of the structure and the field exiting the NSOM aperture. Such an interference has previously been shown for much smaller particles [10, 11, 12].

## 2. The Experiment

Light-wave intensity enhancement in transmission imaging has been observed from gold mesoscopic scaled arrays. The sample used is a double layer array containing disks shaped like a kidney bean. The system was imaged using near-field illumination with collection of light below the sample. The observed transmission is due to a nanoantenna effect caused by the excitation of plasmon resonances between the two layers and the increase in intensity is provided by increased light delivery through the NSOM aperture.

Near-field scanning optical microscopy techniques were used to determine the near-field response of engineered arrays of metal particles. The arrays were defined using electron beam lithography techniques and then established using electron beam evaporation of various levels and appropriate liftoff techniques. The arrays are fabricated on ITO coated glass slides. Before applying the photo-resist for electron beam writing, the ITO coated glass slides were cleaned and baked at 160°C for 30 minutes. Next, a double-layer PMMA photo-resist was coated onto the ITO glass. A JEOL 6400 SEM equipped with a nanometer pattern generator system (NPGS) from JC Nabity Lithography Systems was used for electron beam writing. An

accelerating voltage of 35 kV was used for writing, while the writing dosage and spacing distance were optimized for use with the NPGS. After the photo-resist was developed, the desired z structure of metals and silicon dioxide were deposited in a vacuum using electron beam evaporation techniques. A liftoff process was then performed and the desired arrays were obtained. The arrays created for study in this article are  $50\ \mu\text{m} \times 50\ \mu\text{m}$  in the x-y plane. Creating such a layered array allows for the ultimate control of distance between neighboring particles (in the z direction). This provides a significant advantage for placing particles in a layered environment, as vertical spacing can be controlled much more precisely than lateral spacing.

The array imaged consists of a kidney bean like structure that measures  $\sim 0.22\ \mu\text{m} \times 0.42\ \mu\text{m}$ . There is a center to center spacing of  $\sim 1\ \mu\text{m}$ . SEM topography of this array is shown in Fig.1(a) and a single structure is shown in Fig.1(b). The z structure of this array (see Fig.1(c)) consists of a double layer of gold. On a glass slide coated with ITO, there is a 5 nm layer of titanium, a 50 nm layer of gold, a 5 nm layer of titanium, a 50 nm layer of silicon dioxide, a 5 nm layer of titanium and then another 50 nm layer of gold to complete the double layer structure. The silicon dioxide is used as a dielectric spacer between the two gold layers, while the thin titanium layers help with structural adhesion.

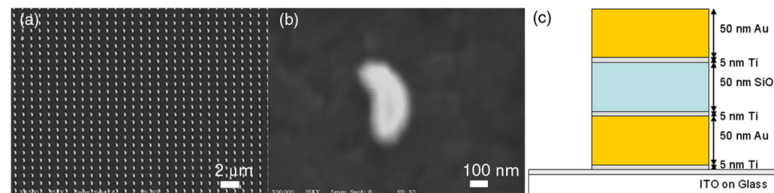


Fig. 1. Construction of double layer gold sample. (a) SEM topography of array; (b) SEM topography of a single dot; (c) Z-layer cross section

This double layer was designed in our research group to provide ideal conditions for plasmon resonance and electromagnetic interactions between the layers. Such interactions will provide capabilities for surface enhanced Raman scattering (SERS), and guiding light. Studying the local optical properties of such samples is an important early step for full characterization.

This sample was imaged using an NSOM. Our system is called the MultiView 2000 and was purchased commercially from Nanonics Imaging Ltd. Local excitation was provided by an  $\sim 150\ \text{nm}$  diameter aperture pulled from multi-mode fiber with chromium and gold metallic coating. The pulled fiber was bent a significant distance from the aperture to allow attachment to a tuning fork. The tuning fork was modulated normal to the surface to provide a topographic AFM channel along with feedback to control the separation between the tip and the sample. Laser light, at 532 nm, was coupled into the opposite end of the fiber. Transmitted light was collected in the far-field using a 50x objective lens with 0.45 NA. Photons were counted with an avalanche photo diode. The sample is raster scanned while the tip is kept stationary in the x,y plane. Please see Fig.2 for a diagram of this setup.

Images obtained from the AFM and NSOM channels can be found in Fig. 3. Figure 3(a) shows the topography of the sample obtained from the AFM channel while Fig. 3(b) shows the corresponding transmission NSOM image. In both figures, the position of the dots corresponds with the high intensity on the scale bar.

It is interesting to note that the middle of the scan region is missing three dots. This is due to fabrication error. When looking at this void, it is apparent that light is transmitted through the sample where there is no structure. In comparison to this void area, the positions of each structure show an increase in NSOM intensity. Between adjacent dots, the intensity of the NSOM signal is close to baseline.

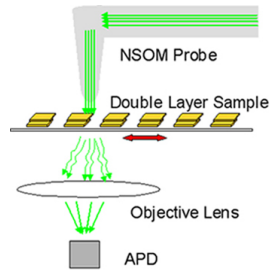


Fig. 2. Illustration of experimental techniques. The double layer sample is illuminated, with 532 nm light, through a 150 nm diameter aperture pulled from fiber optics. Incident light on the sample scatters everywhere. Light is collected using classical optics below the sample. An APD is used to count photons.

When looking at the NSOM image, there appear to be three different areas with different NSOM intensities. The positions of the dots exhibit a high NSOM intensity, the areas between the dots exhibit the lowest NSOM intensity and the area of the missing dots exhibits an NSOM intensity in between these two. A normalized cross section analysis is presented in Fig.3(c). The maximum intensity is taken to be unity while zero intensity is the baseline. The peaks of the NSOM intensity range from 0.88 to 1.0. The nulls between the structures range from 0.15 to 0.28. The void area in the middle ranges from 0.54 to 0.61. The position of the structures show an average enhancement of  $\sim 1.6$  over the void area.

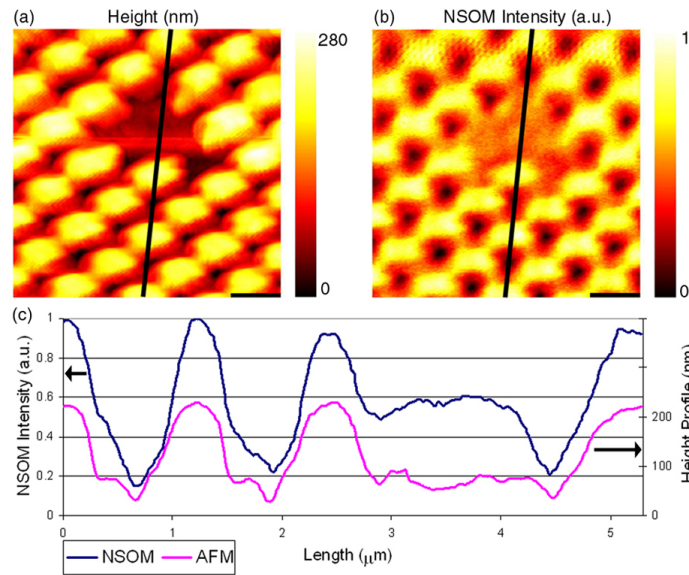


Fig. 3. Scanning results. The line drawn through (a) and (b) represents the cross section presented; (a)AFM channel, in nm; (b)NSOM channel, in arbitrary units; (c)A representative cross section of the AFM and NSOM channels is presented.

Two complimentary particles close together provide an ideal geometry for the plasmon induced nanoantenna effect. The transmission of light through the double layer structure is due to a nanoantenna effect produced by the plasmon resonances of the upper and the lower particle. Energy is concentrated between the two particles and what can be considered as a gap mode

excitation. Such resonance in the gap can be thought of as an optical LC circuit, where the gap provides the effect of optical capacitance and the metal particles provide optical inductance [7]. For coupling between the two particles, the local illumination induces a z-direction resonance in the system, which is mediated by the x-y geometry of the particle.

This observation is very interesting. The metal thickness of each gold layer, at 50 nm, is greater than the optical skin depth of gold ( $\sim 30$  nm). The light wave intensity through the structure is greater than the intensity of light through the void because the double layer structure induces surface plasmons in the aperture for increased optical transmission through the aperture. When this thickness is structured into a double layer sandwiching a 50 nm dielectric, illumination output of the system is increased over no structure at all.

Overall, the NSOM image presents a superposition of the light exiting the aperture and the induced nanoantenna effect of the double layer. This leads to the observation of destructive (nulls) and constructive (peaks) interference.

An array of rods with the exact same z structure as the beans was imaged immediately after the beans using the same aperture with the same experimental procedure. In the x-y plane, these rods showed a width of  $\sim 0.34 \mu\text{m}$ , a length of  $\sim 1.25 \mu\text{m}$  and horizontal period of  $\sim 1.04 \mu\text{m}$ . The NSOM image of these rods did not show a nanoantenna effect. The position of the rods showed a low NSOM intensity and between the rods showed a higher NSOM intensity. The NSOM intensity between the rods was similar in magnitude to the void area in previous result, while the positions of the rods showed an intensity  $\sim 3.5$  times less than that of the higher intensity. Changing the x-y geometry of the double layer structure significantly adjusts the optical response of the system. Changing from a smaller bean structure to a larger rod structure results in the nanoantenna resonance being replaced by a stark shadow effect. The resonant conditions of the bean structure do not exist for the rod structure.

As a comparison to the double layer sandwich structure, near-field transmission imaging was performed on a similar single layer gold structure. This sample contains an array of mesoscopic sized disks. These were fabricated following the same procedures as the double layer structure except for the evaporation of the different z layers. The z structure is 128 nm of Au on top of 5 nm of Ti, all on an ITO coated glass slide. Each disk is  $\sim 260$  nm in diameter and there is a periodicity of  $\sim 880$  nm between each disk. The SEM topography is found in Fig.4(a) and the z structure in Fig.4(b). Empty dot positions were specifically fabricated into the sample for reference purposes in such a large array.

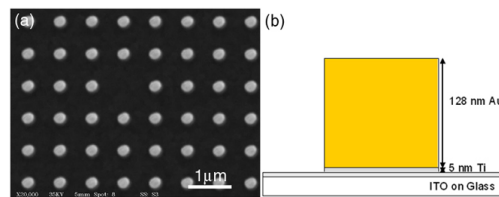


Fig. 4. Construction of single layer gold sample. (a)SEM topography of dots; (b)Z-layer cross section

Scanning of the single layer gold sample was performed with an aperture of size  $\sim 120$  nm, again coated with chromium and gold. Except for the different aperture and sample, the experimental setup was exactly as that for the double layer sample. The resultant imaging can be found in Fig. 5. The AFM channel is shown in part (a), the NSOM channel in part (b) and a cross section analysis in part (c). From the AFM channel, the position of the dots corresponds with the high intensity on the scale bar, while the NSOM channel shows dot positions corresponding to a low intensity.

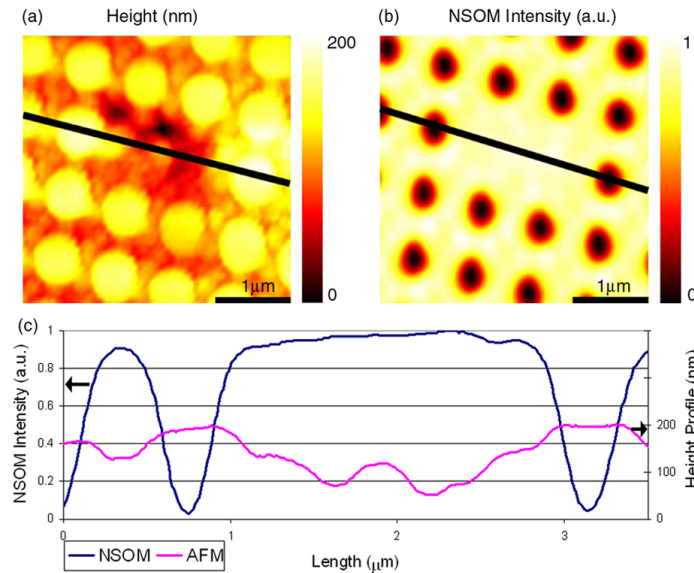


Fig. 5. Scanning results - single layer gold dots. The line drawn through (a) and (b) represents the cross section presented; (a)AFM channel, in nm; (b)NSOM channel, in arbitrary units; (c)A representative cross section of the AFM and NSOM channels is presented.

The NSOM image shows that the thick single layer dots are characterized in transmission NSOM with a distinct shadow effect. When the NSOM probe is not blocked by the dot structure, the NSOM intensity is very high, but when the probe position corresponds to a dot position, the NSOM intensity is very low. The intensity ratio between the shadow of the dots and the bright area between them is calculated to be  $\sim 25$ . In comparison to the double layer structure, there is no nanoantenna effect for transmission through the structure and there is no increased transmission through the NSOM aperture.

### 3. Conclusion

Near-field optical images of a double layer and a single layer structure have been presented. The engineered double layer kidney bean structure exhibits enhanced transmission through the sample structure while imaging of a larger double layer rod and a single layer dot structure shows a shadow effect from the structure.

The enhanced transmission of the double layer structure has two roots. The transmission through the double layer structure, which is significantly thicker than the skin depth, is enabled through a nanoantenna effect between the upper and lower levels. The upper and lower levels act like the two dipoles of an antenna. An environment that welcomes strong optical resonances in the gap between them is created. This allows the system to radiate and presents the transmission through an optically thick structure. The level of light is increased over the bare substrate as the double layer structure induces increased optical transmission through the NSOM aperture.

Observation of such transmission and enhancement is a crucial first step in full characterization of this effect created in our laboratory. Exploitation of this antenna effect due to particle plasmon resonance will include surface enhanced Raman scattering, confining and guiding light on the nanoscale, while the increased aperture transmission will result in improved capabilities of near-field optical microscopy.

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