Interaction of a plasmonic nanoparticle array and dipole emitters

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Abstract

Metal nanoparticle arrays have shown potential in creating feedback for lasing devices when immersed in organic dyes.[5] Nanoscale distributed feedback (DFB) lasers have the potential to be used in photonic circuits and optical communications.[1] An advantage to using metallic nanoparticles as a grating structure is their ability to interact with electromagnetic waves. Localized surface plasmons formed on the nanoparticle offer facile, continuous or structural modification, methods to tune the lasing emission. The motivation of this project is to investigate the effect of plasmonic induced coupling of electromagnetic waves from the stimulated emission of the organic dye to the nanoparticle array and to the surface diffraction mode of the grating. In this sense the nanoparticle array offers a second advantage as an optical antenna. Various plasmonic metal arrays were generated using soft interference lithography techniques. The gold nanoparticle array has a relatively narrow linewidth when pumped with increasing energies. Also the gold nanoparticle array demonstrates a linear relationship characteristic of lasing that begins at roughly 60uJ, the lasing threshold.

Array Fabrication

Nanohole arrays were prepared using a combination of soft interference (phase shifting) lithography and PEEL (phase-shifting photolithography, etching, electron-beam deposition and lift off], techniques created by the Odom Group of Northwestern. Soft interference lithography uses poly(dimethylsiloxane) (PDMS) stamps, created from a master mask that can be repeatedly adhered to photoresist surfaces and easily removed after UV exposure. The remaining surfaces have remarkable throughput.[6]

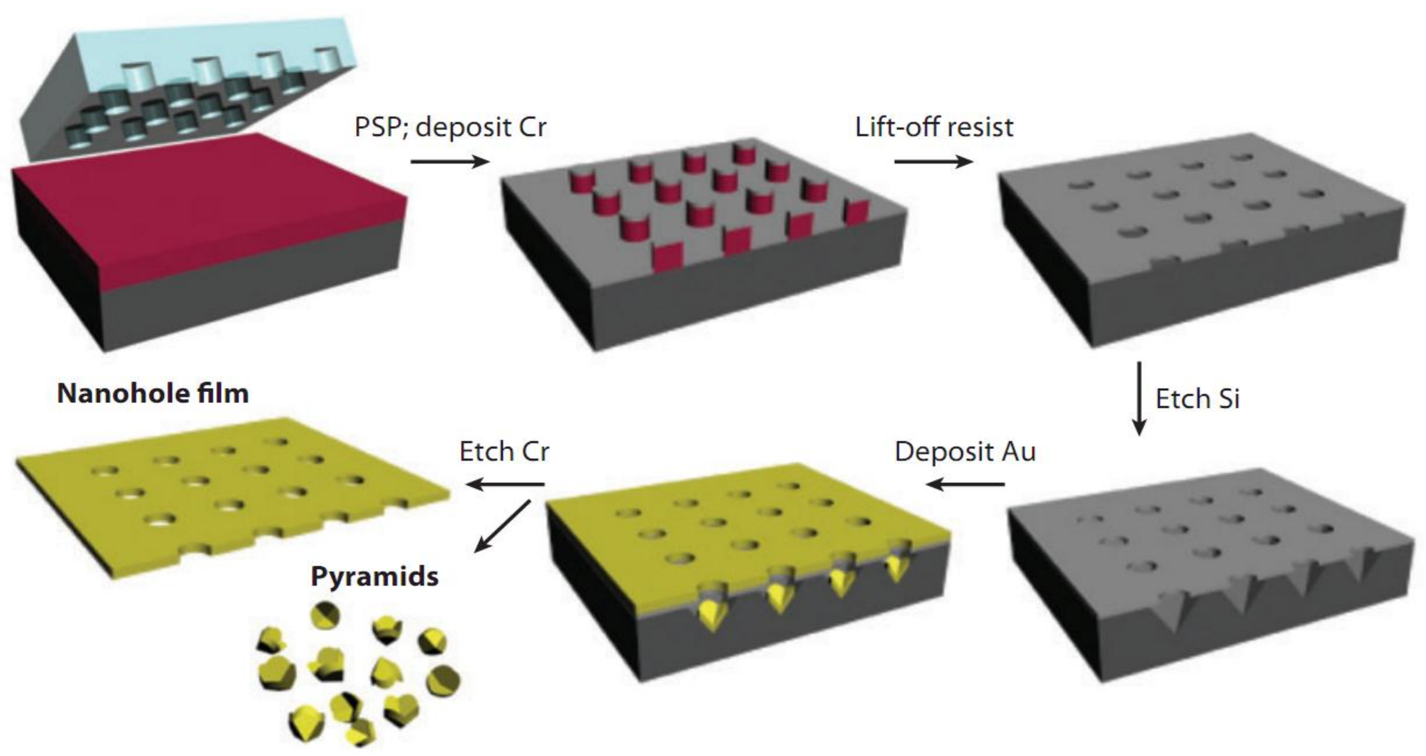

Figure 1: PEEL procedure to transfer patterns in a photoresist to functional materials

A positive photoresist layer is spin coated onto a silicon (110) wafer with an intermediate primer layer. The wafer is exposed to UV radiation (Shipley 1805) through a master mask and washed in a developer solution of .1M NaOH. Altering the amount of time the exposed photoresist is developed will vary the diameter of the nanoscale posts on the silicon substrate. Development times of four to twelve seconds in increments of 2 were used to modify the diameter of the nanohole array. The varied diameter hole arrays were used as a mask to deposit 100nm gold nanoparticle arrays.

Reactive ion etching with a composition of CF_4 & O_2 (ratio of 25:3) at 13.3torr removes residual photoresist. 8.5nm of chromium is electron beam deposited onto the wafer normal to the surface. The remaining photoresist is lifted off and the wafer is reactive ion etched. Gold is electron beam deposited normal to the surface of the wafer. Both nanoparticle and nanohole arrays are developed. The samples are placed into a chromium etchant solution and subsequently placed in water. The samples are air dried and again placed into water at an angle to cause the gold film to float. The nanoparticle array deposited into the Si pits was not used in this experiment.

The optical properties of these devices will be tested via angle resolved optical transmission maps and dispersion diagrams and dark spectroscopy. During the lithography process the samples were studied under the SEM to ensure high quality production.

Device Fabrication

The adhering polymer-dye mix is made from a 1:4 ratio of PMMA and IR-40 in a PDMEA solvent at a concentration of .01M dye. The second mix is a 1:4 ratio of PAA and IR-140 in ethanol at a concentration of .01M dye. The PMMA mix is spin coated onto a glass disk and its thickness was measured by ellipsometry to be roughly 160nm.

Gold Hole Array Mask

Previously the gold nanoparticle array produced from the phase shifting lithography technique was used as the nanoparticle array within the device by performing a template stripping technique. However, this technique limited the variation of other metal depositions due to the poor curing adhesion to the polymer substrate. Thus this technique has been replaced by depositing metals through a gold hole array mask to produce a nanoparticle array. The gold hole array masks are floated onto the polymer-dye substrate. 100nm gold, silver, copper and chromium nanoparticles were electron beam deposited through the nanohole arrays. The gold film is then removed using scotch tape. A 700nm layer of PAA and IR-140 mix was spin coated onto the device.

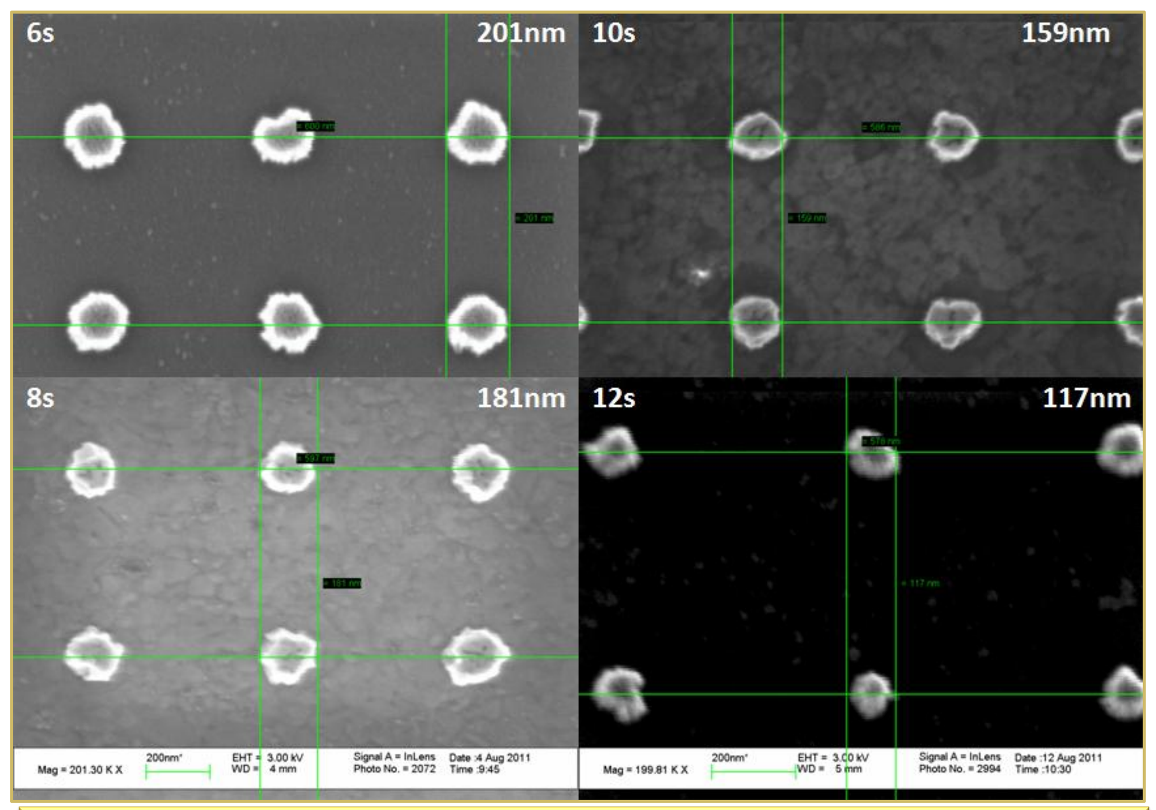

Figure 2:Nanoparticle arrays at varying developing time

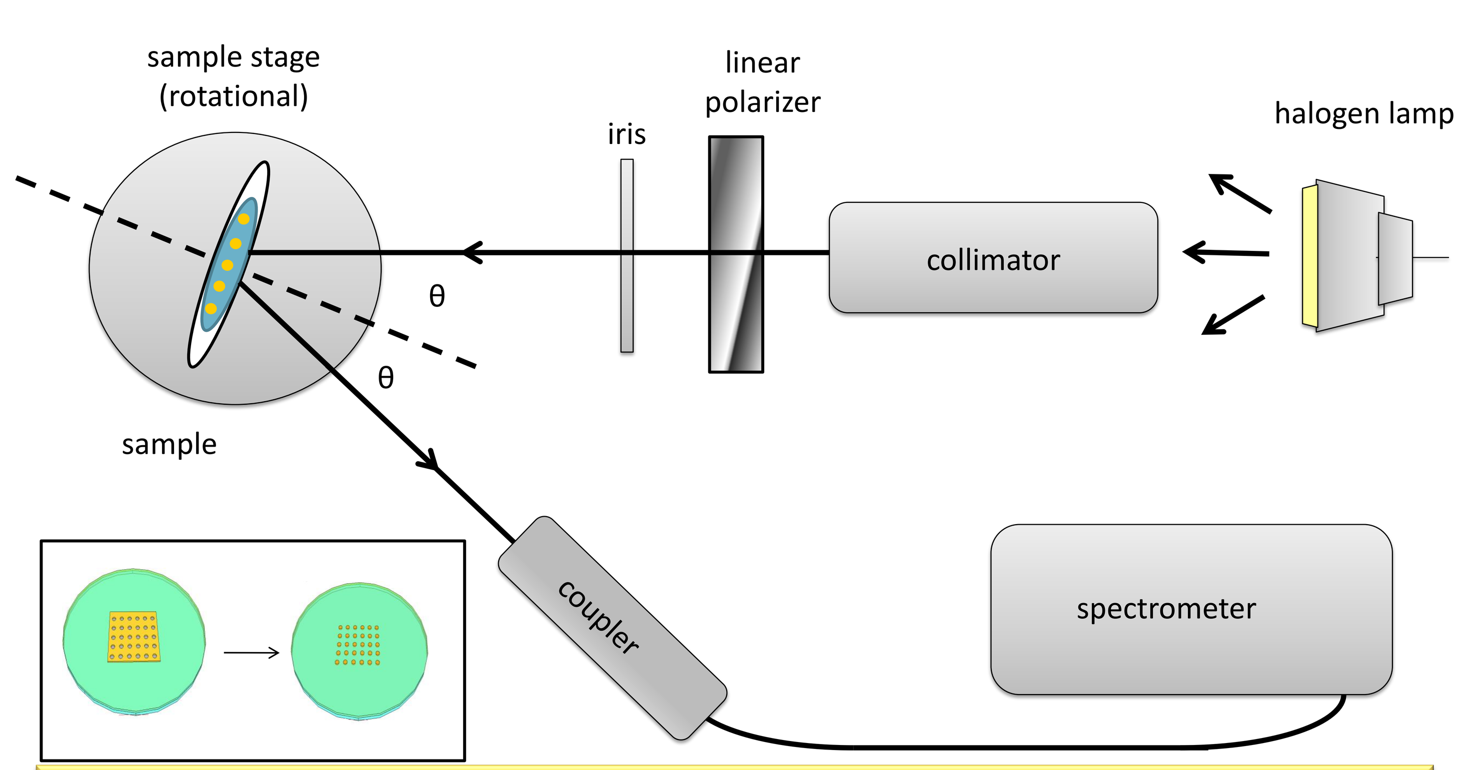

Figure 3:Schematic of the rotational stage. Inset: Nanoparticle array transfer process

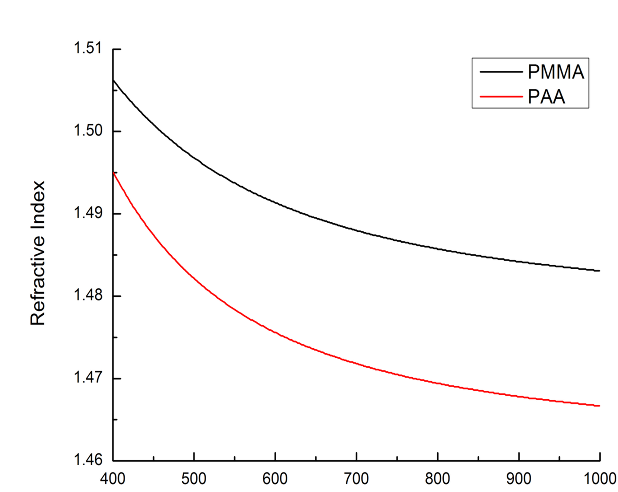

Figure 4:Refractive indices of polymer layers

Results

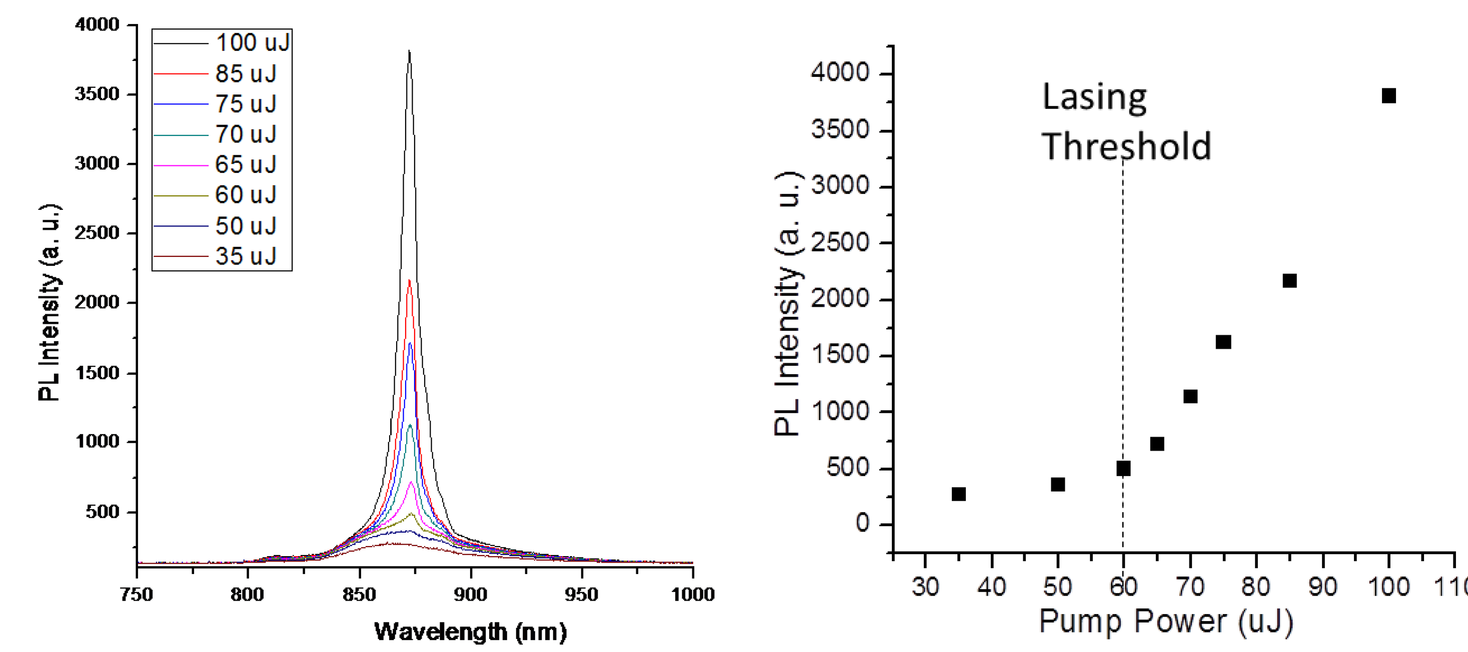

Figure 5a: Narrowing linewidth with increasing pump energy; 5b: lasing linear correlation

Defining characteristics of lasing modes from dipole emitters include i.) a narrow emission linewidth ii.) the intensity of the emitted light from the device will linearly increase, after the lasing threshold, as pump energy is increased.[1] The gold nanoparticle array has a relatively narrow linewidth when pumped with higher energies as seen in figure 2a. In figure 2b, the gold nanoparticle array demonstrates the linear relationship characteristic of lasing that begins at roughly 60uJ, the lasing threshold. These are promising results that the device is attaining of stimulated emission.

Data similar to the graphs shown in figure 2 will be produced for varied metal nanoparticle arrays in the future. However, we currently can acknowledge that each metal deposited is showing its own characteristic plasmonic effects as seen in figure 6 from isolated spectroscopy data. This variation in plasmonic resonance may affect the lasing threshold or linewidth of the emission. These affects will demonstrate how well the nanoparticle array acts as an optical antenna in transducing local electric fields to propagating electromagnetic radiation in free space.

The refractive index of the two polymers were index coupled as shown by figure 4. The two polymers with close indexes minimized any interfacial reflection.

All periodic structures can maintain two dimensional block modes. In order to identify these block wave modes, we must know its dispersion relation. These dispersion energies and mode energies are dependent on the wave vector. Knowing the relationship between these variables, can provide us with the data to stitch plots of plasmonic or photonic energy versus the surface diffraction wave vector from angle dependent data. Therefore it is important this data is collected in the future.

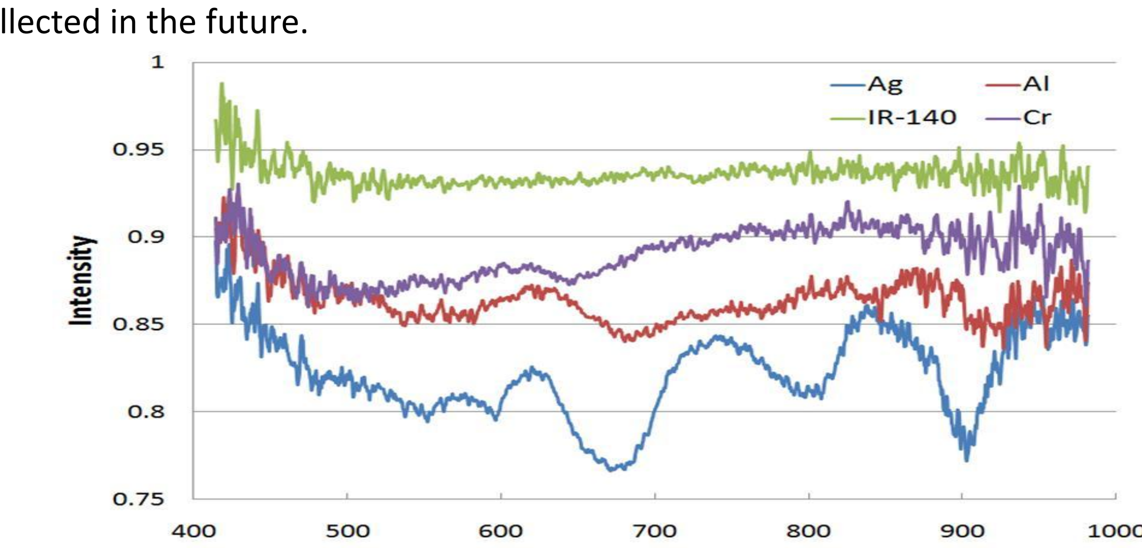

Figure6: Isolated spectroscopy data of varied metal nanoparticle array devices

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