**Final scientific/technical report for “A study of plasmonic
enhanced transmission effects in nano-optics,”
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1. Executive summary of goals and accomplishments

This project involved a numerical study of the behavior of surface plasmons in nano-systems, focusing on the interaction between plasmons, light, and nano-scale structures such as nano-scale metallic wires and quantum wires/dots.

The primary results of the project included: a) the demonstration of the use of surface plasmons to modify the spatial coherence of a light wave, b) the demonstration of a feasible plasmonic superresolved readout system, and c) the demonstration of a “Plasmonic Zeno effect”, in which the attenuation of a light wave in metal is suppressed by breaking up the metal into a collection of structured layers. The integration of quantum wire/dot effects with the plasmonic simulations proved to be harder than expected, in large part due to the lack of accurate and simple quantum dot models.

The plasmonic coherence effects, in which the spatial coherence of light can be increased or decreased by the presence of plasmons, was proposed and demonstrated for the first time under this project. This result suggests that a “coherence converting” optical element can be constructed which can modify the state of coherence of light; initial simulations demonstrated the feasibility of this idea.

The superresolved readout system research represents one of the first direct applications of so-called enhanced transmission. The study clearly highlights that plasmons can improve readout system resolution and signal-to-noise, but also can hinder system performance through undesirable plasmonic interference effects. The results found lay the groundwork for more detailed future investigations.

The “Plasmonic Zeno effect” demonstrates that the structure of a multi-layer metal surface plays a significant role in the skin depth of the material when plasmons are involved. By breaking a bulk metal into multiple layers with roughness or other surface features, the skin depth can be dramatically reduced. This is of direct significance to the two previous applications, plasmon coherence and superresolved readout, both of which require a significant transmission through the metal in order to be useful.

In addition, studies of coherence effects in multi-hole arrays led to two general studies on the spatial coherence of multi-pinhole Young-type interferometers. These results highlight surprising complexity the very old and traditional understanding of Young’s experiment.

The general goals of the project were achieved, namely the study of the physical behavior of surface plasmon waves (what are plasmons capable of?) and the practical application of such waves (how can plasmonics improve nano-optical applications?). The one area that was not covered is the implementation of explicit quantum effects into the models, such as quantum dot structures. The detailed studies of spatial coherence effects in plasmonic systems, however, lays the groundwork to incorporate quantum statistical effects in future work.

2. Year 1 Summary (Sept 2006 – May 2007)

The first year of research focused on further development of the Green's tensor technique used for the numerical simulation of plasmonic effects and the application of this technique to solving some physical and practical problems.

Investigations involving plasmon/quantum dot interactions will inevitably involve optical fields of varying states of coherence. In anticipation of this, we extended our Green's tensor technique to allow for partially coherent fields. With this modified technique, we studied the effect of surface plasmons on the state of coherence of an illuminating field; the results were published in *Physical Review Letters* (publication 1). In this work, it was demonstrated that surface plasmon interactions in a traditional Young's double slit experiment can increase or decrease the spatial coherence of the field illuminating the apertures; a typical result is shown in Fig. 1. This work was presented by the PI at the 88th Eastern Forum of Science and Technology, in Shanghai, China, January 2007.

Figure 1. The enhancement/suppression of spatial coherence in a plasmonic Young's double slit experiment, as a function of the slit separation d . The degree of coherence μ_{12} of the transmitted light can be larger or smaller than the degree of coherence $\mu_{12}^{(inc)}$ of the incident light.

The work on plasmons and coherence effects in sub-wavelength apertures led to another study of unusual spatial coherence effects on transmission of an optical field through a multiple-pinhole screen. This work was published in *Optics Communications* (publication 3).

3. Year 2 Summary (May 2007 – May 2008)

The second year of research involved further investigations of coherence effects in plasmonic systems. An interesting application of the ability of surface plasmons to

modify the state of coherence is the development of global ‘coherence converting’ devices which could change the overall spatial coherence of a wavefield. As the spatial coherence influences the directionality, polarization, and interference-causing capability of a wavefield, such a device has many potential uses.

One significant question in scaling the Young’s double-slit experiment to an array of subwavelength holes is the influence of multiple interactions between holes. It is not unreasonable to suspect that the ‘coherence converting’ effect could be destroyed by various holes acting as a ‘barrier’ to surface waves. We studied a system of intermediate complexity, a triple-slit interferometer, to assess how well surface plasmons couple across a hole/barrier. It was found that the additional hole modifies the overall spatial coherence of the system, but can actually enhance or suppress the spatial coherence more than the double slit configuration. These results were published in *Plasmonics* (publication 4).

Other studies of plasmonic interactions on the nano-scale involved the investigation of the use of surface plasmons in a near-field optical readout system. We had demonstrated previously that multiple strategies and geometries could be employed to effectively harness plasmons to increase readout contrast and resolution. While previous studies focused on reflection geometries (in which the field reflected off of the optical disk is measured), a new study focused on transmission geometries (in which the field transmitted through a thin optical disk is measured). Preliminary results relating to this work were discussed at the OSA Annual Meeting in Rochester, NY by the student supported by this grant, Choon How Gan. The results were published in *Applied Physics Letters* (publication 2). Similar to the reflection geometry, a number of readout strategies were proposed and investigated, and have the potential for subwavelength readout as well as a signal strength greater than that which can be achieved in non-plasmonic systems. Some typical field distributions are shown in Fig. 2, which show the additional light throughput gained by using “plasmon pits” on the illuminated side of the readout system to help “funnel” light into the readout aperture.

Figure 2. Field intensity distribution with and without light-side plasmon pits. Plots on the left column and right column for Ag and Si data layers, respectively.

It is to be noted that the work on spatial coherence and plasmons was highlighted in the year-end review of *Optics and Photonics News* as part of their “Optics in 2007” special issue (publication 5).

4. Year 3 Summary & no-cost extension (June 2008 – August 2010)

In the final year and the no-cost extension period, it was decided to focus on classical plasmonic effects, as the quantum effects had proven much more difficult to implement than first thought. Furthermore, the classical plasmonic effects showed the most promise.

A study was undertaken of the transmission of light through structured metal films. Though light typically is absorbed on propagation through metal with a skin depth on the order of tens of nanometers, earlier research had suggested that plasmonic metal layers with structured surfaces could have a much larger skin depth than comparable bulk layers, in what we loosely refer to as a “plasmonic Zeno effect”. This was demonstrated via simulation, and the results were published in *Optics Express* (publication 6), and the results were presented at Frontiers in Optics 2009. This result suggests that plasmonic transmission can be further enhanced, even through very thick metal films, by an appropriate structuring of the metal; an illustrative result is shown in Fig. 3.

Figure 3. Field distribution plots depicting the impedance to exponential decay of the fields with a multi-layered structure as opposed to a single metal slab with equivalent thickness and volume for number of layers $n=3$ and 5 . Extraordinary optical transmission for the multi-layered structures is clearly observable from the values of the associated optical transmission T .

The no-cost extension allowed this result to be completed and two others to be prepared for publication. The previous work on spatial coherence and plasmons suggested

strongly that plasmons could influence the global state of coherence of a light wave, raising the possibility of creating optical elements that can modify the spatial coherence of light. Considering the coherence of light influences many of its propagation characteristics (directionality, interference effects, spectrum, polarization), such a device could be extremely useful.

We considered the effect of a plasmonic hole array on a partially coherent illuminating field in a transmission geometry. The system was simulated using a straightforward Foldy-Lax scattering model that takes into account the multiple scattering of plasmons between holes. It was shown that an array of holes can in fact significantly increase the spatial coherence of the illuminating wavefield; a decrease in coherence seems less feasible as the number of holes increases. An example of the visibility of the transmitted field, as a function of hole separation, is shown in Fig. 4. The results are being submitted to *Plasmonics* (publication 7), and were presented at the Frontiers in Optics 2010 meeting.

Figure 4. The visibility of interference fringes (a measure of spatial coherence) for a 4x4 and 5x5 hole array, as a function of hole separation d . The dashed line indicates the degree of coherence of the illuminating field. Plots show results for two possible values of the light-plasmon coupling constant, β .

Two undergraduates were supported during the summer of the no-cost extension. One of these students extended the work of publication 3 to more general configurations of holes and coherence, and this paper is being prepared for submission (publication 8).

5. Publications

1. C.H. Gan, G. Gbur and T.D. Visser, "Surface plasmons modulate the spatial coherence in Young's interference experiment," *Phys. Rev. Lett.* **98** (2007), 043908.
2. C.H. Gan and G. Gbur, "Strategies for employing surface plasmons in a near field transmission optical readout system," *Appl. Phys. Lett.* **91** (2007), 131109.

3. C.H. Gan and G. Gbur, "Phase and coherence singularities generated by the interference of partially coherent fields," *Opt. Commun.* **280** (2007), 249.
4. C.H. Gan and G. Gbur, "Spatial coherence conversion with surface plasmons using a three-slit interferometer," *Plasmonics* **3** (2008), 111.
5. C.H. Gan, G. Gbur and T.D. Visser, "A New Role for Surface Plasmons," *Optics and Photonics News*, December 2007, 36.
6. C.H. Gan and G. Gbur, "Extraordinary optical transmission through multi-layered systems of corrugated metallic thin films," *Opt. Exp.* **17** (2009), 20553.
7. C.H. Gan, Y. Gu, G. Gbur and T.D. Visser, "Modulation of the spatial coherence of light with a subwavelength plasmonic hole array," to be submitted to *Plasmonics*.
8. C. Rosenbury and G. Gbur, "Phase singularities, correlation singularities, and conditions for complete destructive interference," in preparation.

6. Presentations

1. C.H. Gan and G. Gbur, "Strategies for employing surface plasmons in near-field optical readout systems," OSA Frontiers in Optics 2006.
2. G. Gbur, "Surface plasmon effects in nano-optics," The 88th Eastern Forum of Science and Technology, Shanghai, China, January 2007.
3. G. Gbur, "Getting more with less: surface plasmons in nano-optics," seminar at Mississippi State University, 2007.
4. C.H. Gan, G. Gbur and T.D. Visser, "Surface plasmons in Young's experiment modulate the spatial coherence of light," OSA Frontiers in Optics 2007.
5. C.H. Gan and G. Gbur, "Phase and Coherence Singularities Generated by the Interference of Partially Coherent Fields," OSA Frontiers in Optics 2008.
6. G. Gbur, "Plasmonic effects in statistical optics," seminar in Department of Mathematics, UNC Charlotte, September 2009.
7. C.H. Gan and G. Gbur, "Extraordinary Optical Transmission (EOT) through Multi-Layered Systems of Corrugated Metallic Thin Films," OSA Frontiers in Optics 2009.
8. G. Gbur, Y. Gu, C.H. Gan and T.D. Visser, "Coherence-converting plasmonic hole arrays," OSA Frontiers in Optics 2010.