Atomic Force Microscopy as a tool for the study and manipulation of surface plasmons *in situ*

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Surface plasmons (SP) are coherent electronic waves at an interface, often studied at dielectric-metal interfaces. Their properties have been the focus of intense scrutiny due to their potential application across a wide variety of fields, including the development of novel electro-optic devices and a variety of sensing techniques. The experimental realisation of such devices is heavily dependent on the ability to controllably manipulate the propagation of SPs on a metal-dielectric interface. Therefore, many groups are attempting to build optics for SPs that are analogous to conventional optics for free-space radiation.

Coupling between free-space radiation and SP modes is normally forbidden due to an inability to satisfy the phase matching condition that arises from the dispersion relations for SPs and free-space radiation. However, a variety of experimental methods exist to excite SP modes that do satisfy the phase matching condition. The most common is to use an evanescent-wave geometry, such as the Kretchmann total internal reflection geometry, where the evanescent-wave allows coupling between the radiation in the prism and the SP mode. It has also been known for many years that coupling between electronic waves and free-space radiation can occur through the medium of a micro- or nano-structured surface such a grating. Fano originally discovered this while studying anomalous diffraction effects in gratings with small periodicities and this idea was further developed by others[1]. This mechanism has the significant advantage of localizing the SP wave to the area where the nanostructure exists, which allows a more in-depth study of the SP modes.

Concurrently with the development of experimental methods for SP excitation, theoretical descriptions of nanostructure-plasmon interaction have been advanced by Sanchez-Gil and others[2,3]. These descriptions predict that given a plasmon excitation on a surface, simple nanostructures formed by changes in height on the surface should behave in an analogous fashion to conventional laser optics, but for the plasmon waves. This is explained in a qualitative fashion by a local change in the index of refraction in the neighbourhood of such nanostructures, giving rise to all of the corresponding equivalents of conventional optics, including lenses, mirrors, and diffraction gratings.

There is considerable excitement about the experimental realisation of such plasmonic optics. Two components are necessary in the development of such SP optics – the construction of nanostructures to interact with the SP wave and the interrogation of the SP wave to measure the effect of the interaction. A variety of experimental methods exist that address each of these components[4-6]. In the first case, Scanning Tunnelling Microscopy (STM) and laser-ablation direct-write techniques have shown some promise as far as creating nanostructures mid-experiment. Also, traditional lithographies such as electron-beam lithography work well, though such processes are expensive and do not allow the modification of a nano-structure during the experiment. As far as measuring the interaction, both far-field and near-field optical techniques exist, including fluorescent labelling of the SP path, and apertureless or apertured near-field probes.

We believe that the mature scanning probe techniques, in particular Atomic Force Microscopy (AFM) and STM, lend themselves well to the *in situ* study of plasmonic optics. Like STM, AFM has the ability to perform lithographic operations on metallic surfaces through a physical etching process. The AFM tip can also act as an apertureless near-field probe of surface optical properties, such as the propagation of SP waves. Finally, AFM is a technique that can easily be applied in ambient conditions. Hence, it is an excellent tool for the study of plasmon-nanostructure interactions for practical applications that would stability to environmental effects.

We present a novel experimental realisation of SP optics that relies on these properties of AFM. Creation of nanostructures *in situ* on a flat gold surface created by evaporative deposition is demonstrated using a physical etching process where the metallic surface is scratched off by the application of an AFM tip. As shown schematically in Figure 1, we have employed this technique to couple free-space laser radiation into a (SP) mode via a nanostructured grating. The plasmon excitation is allowed to propagate on the metallic surface and then is coupled back into free-space radiation using a second grating. Such a "proof-of-principle" experimental set-up will allow future creation of active optical elements in the path of the SP wave on the surface. Initial attempts to monitor the propagation of the SP wave using AFM as an *in situ* apertureless near-field probe are also discussed.

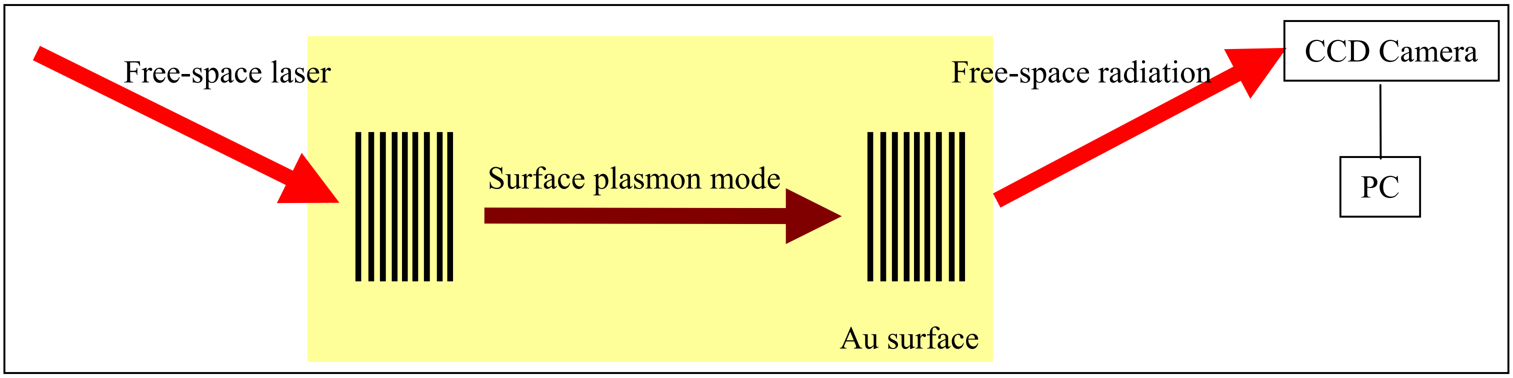

Figure 1: Schematic of SP excitation and detection apparatus

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