Photon tunneling via surface plasmon coupling

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The measurement of a photonic signal via plasmon-plasmon coupling in curved thin metal films is presented. In domains of subwavelength dimension, we calculate the resonant dispersion relations by modeling the curved thin film as a single sheeted hyperboloid of revolution. We show that several such surface modes are accessible optically at frequencies below the plasma frequency of the metal. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1793351]

Resonant optical and electronic interactions[1] sustained by material boundaries at subwavelength scales are the basis for the operation of many photonic devices. Such mechanisms, and their mutual coupling, are continuously being employed in the investigation and design of sensing,[2–6] probing,[7] and imaging,[8,9] techniques. In particular, optical excitation of surface plasmons[10,11] and their characterizations continues to be an attractive topic in fields, such as scanning probe microscopy (SPM).[12–16] For example, the probe tip of an atomic force microscope can be gold coated in order to locally enhance the Raman signal during spectroscopy.[17] However, the dynamics of collective electronic behavior in the involved metallic or dielectric particulates,[18–20] voids,[21,22] and thin films[15,16] can be greatly modified by geometric effects, in particular, as the dimensions of the system are reduced. Regularly patterned surfaces such as metal gratings,[23,24] or randomly distributed inhomogeneities such as surface roughness,[25] can be mentioned in this regard.

In this letter, we present a theoretical and experimental investigation of the coupling of optically excited surface plasmons on a planar gold thin film to the modes of a curved gold thin film. We predict several resonance modes in the visible for this configuration and demonstrate their experimental observation. The experimental arrangement is shown in Fig. 1. The planar film of thickness 45 nm was vacuum evaporated onto a quartz prism substrate (Kretschmann configuration),[26] and the curved film of thickness 35 nm was evaporated onto a pulled quartz multimode optical fiber. The coated fiber shown in Fig. 2 was then held vertically above the planar film using a precision kinetic stage driven by a piezoelectric tube. The cleaved and polished end of the fiber was focused onto a photomultiplier tube (PMT). The output of the PMT was partially engaged in a feedback loop to control the distance between the tip of the fiber coating and the substrate coating (gap region). The examined (p-polarized) visible wavelengths $\lambda=632.8$, 543.5, and 441.6 nm were provided by two 5 mW HeNe lasers and a 30 mW HeCd laser. In our model, the metal films are characterized by a complex, frequency dependent, local dielectric function $\epsilon(\omega)$. For numerical evaluation of the surface plasmon resonance values of our metal-coated dielectric probe tip above a metal-coated dielectric substrate (see Fig. 1), we use a dielectric function obtained from interpolation in experimental bulk data.[27] To model systems composed of coated or uncoated probe tips facing planar metal-dielectric multilayer systems, and as suggested by SEM images of a metal-coated probe tip such as those shown in Fig. 2, we have invoked the infinite hyperboloidal surfaces of the prolate spheroidal coordinate system. The coating boundary is confocal with the tip surface.

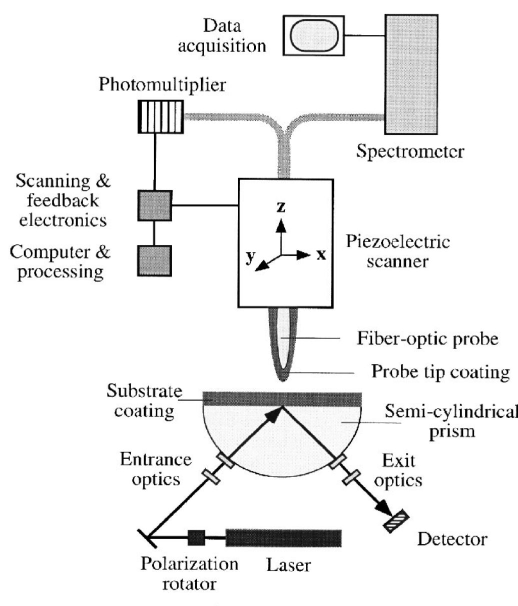

FIG. 1. Schematic representation of a metal-coated optical fiber scanning probe near a thin metal foil incorporated in a scanning probe microscope arrangement. The laser beam steered into a plano-convex cylindrical lens is reflected from the planar metal foil. Upon excitation of surface plasmons in the planar foil, the intensity of the reflected photons will suffer a minimum. The field associated with surface plasmons couples to a surface mode of the probe tip coating. Electrons undergoing collective oscillations in the tip coating decay to light, whereupon a photonic signal is generated in the optical fiber probe and detected in a detector.

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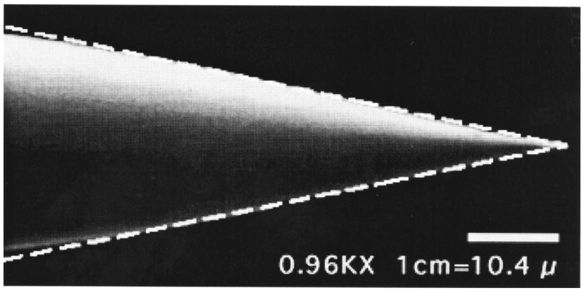

FIG. 2. SEM image of a gold-coated dielectric probe tip. A hyperboloid (the dashed curved) has been fitted to this image to display its boundary. The curvature of the tip and the fitted curve can be seen by further zooming into the nanometer-sized apex region.

The distance between the apex of the coating hyperboloid and the planar metal film below it, will depend on the curvature of the probe coating. We present, within the local response theory, the exact results of the calculation of the nonretarded dispersion relations for the system. Figure 3 displays the calculated modes as a function of the scaled surface-plasmon momentum q. Excluding the virtual modes for the dispersion relation of the coupled system, there are four branches $\omega_i^m(q), i=1-4$ describing the possible retarded modes of resonance. Optical access to these modes, in the arrangement shown in Fig. 1, is governed by the common solutions to the system composed of the light dispersion equation and these modes, and access in the visible requires further that the solutions be within the visible frequency band. This restricts the number of accessible modes for a particular wavelength and propagation angle of the incident laser beam and the selected film thicknesses. The plasmon decay at the inner interface between the dielectric probe and its metal coating constitutes the origin of the observed signal. In Fig. 3, the lowest frequency (ω_1^m) and highest frequency (ω_4^m) modes belong to the thin Cartesian film (symmetric and antisymmetric modes, respectively), whereas ω_3^m and ω_2^m correspond to the (in charge distribution) symmetric and antisymmetric modes of the two surfaces of the curved metal

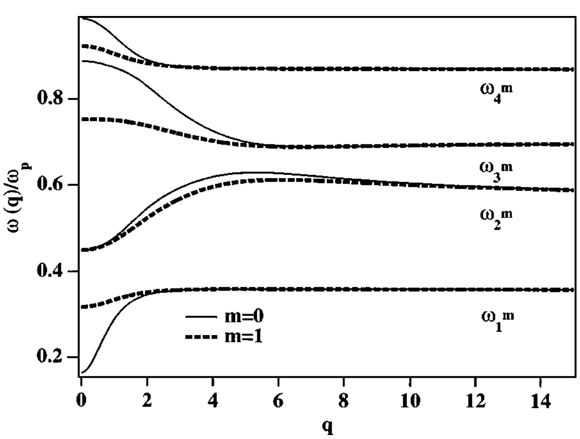

FIG. 3. Nonretarded surface-plasmon resonance values for the azimuthal modes $m=0,1$, assuming an undamped Drude metal, for substrate thickness $d=45$ nm, with tip and coating boundaries set to opening angles $\theta_t=0.45$ and $\theta_c=0.93$, respectively. The modes have been normalized using the bulk-plasmon frequency $\omega_p=5.7\times10^{15}$. The abscissa is the scaled surface plasmaon momentum. The effect of the inclusion of retardation can be shown[28] in the cartesian limit of the curved films (i.e., as the probe and its confocal metal coating become increasingly wider) to be restricted to the small momentum region, and will pull the modes below the light dispersion in vacuum.

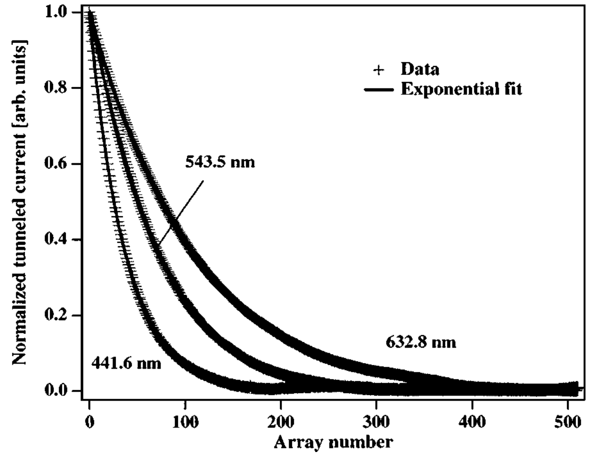

FIG. 4. Experimentally observed photon tunneling via plasmon coupling. Photon tunneling in the visible for a gold substrate coating thickness $d=45$ nm, and a gold probe tip coating thickness $d=35$ nm. Incidence angles for the three examined wavelengths $\lambda=632.8$, 543.5, and 441.6 nm were set to $\theta=47.0°$, 50.0°, and 55.0°. The x axis displays the relative proximity of the tip to the substrate coating surface; that is, $x(0)=z_l$ and $x(512)=z_l+1.0$ μm, where z_l is the unknown absolute distance to the surface.

film.[28] Several resonance frequencies of the probe-substrate coupled system are predicted at the experimentally practical wavelengths in the visible. Specifically, excitations at $\omega_{\rm inc}/\omega_p=0.522(\lambda=632.8$ nm) and $\omega_{\rm inc}/\omega_p=0.608$ ($\lambda=543.5$ nm) are predicted by ω_2^0/ω_p branch of the dispersion relations. Similarly, $\omega_{\rm inc}/\omega_p=0.748$ ($\lambda=441.6$ nm) is predicted by ω_2^1/ω_p.

To measure the coupling experimentally, we used an arrangement similar to that of the photon scanning tunneling microscope (PSTM).[29] In the conventional PSTM, a laser beam incident at an angle slightly above the critical angle for total internal reflection at the base of the semicylindrical prism gives rise to an exponentially decaying evanescent field above the prism. When the fiber-optic probe is placed within this field, photon tunneling occurs. In this work, the photon tunneling is a consequence of excitation of surface plasmons, and thus the plasmon field provides the tunneling photons via a coupling mechanism between the two metal coatings. The results are summarized in Fig. 4. The vertical axis in these spectra represents an explicit measure for the detected intensity. The shorter decay length for the shorter wavelength is clearly observed. Here we are concerned with the relative variation of the tunneled intensity and thus express the measured signals in arbitrary units. Thus, for an initial probe-substrate separation, the reading on the vertical axis is proportional to the amplitude of the tunneling signal. Decreasing this separation increases the tunneling signal. Despite a lack of a knowledge of the absolute probe-substrate separation, the spectra presented here verify that a signal established as a consequence of plasmon coupling can be detected with a high enough intensity that the relative gap size variations can be clearly recorded.

The tip-substrate arrangement demonstrates a convenient way to study several important aspects of plasmon excitation and coupling, and in combination with scanning, and feedback systems, provides a way for imaging. The results establish the feasibility of an exponential coupling capable of sensing surface topography. By monitoring an applied potential difference between the probe coating and the substrate coating during optical activation, our system can be mounted to a hybrid STM-PSTM configuration and is currently under investigation.

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