Efficient coupling of surface plasmon polaritons to radiation using a bi-grating

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A nanostructured surface in the form of a bi-grating is shown to efficiently couple surface plasmon polaritons to free-space radiation in the visible part of the spectrum. Coupling was achieved for all propagation directions of the surface mode and the efficiency found to be independent of the propagation direction, taking a mean value of 60% for the structure examined. The consequences of the findings for emissive devices that make use of surface plasmons are discussed. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1414294]

Surface plasmon polaritons (SPPs) are electromagnetic waves that are guided by a metal–dielectric interface and are of increasing fundamental and technological interest.[1–3] In particular, our ability to fabricate structures on the subwavelength scale is opening up new opportunities in controlling SPPs.[4–6] SPPs are often regarded as a problem owing to their nonradiative nature. Absorption in the metal indicates that energy coupled to SPPs is usually lost in the form of heat, thus quenching optical emission[7,8] and detracting from performance in devices such as light emitting diodes (LEDs).[9] However, one can now envisage engineering metallic surfaces with new optical properties that arise from the interaction between SPPs and wavelength scale surface texture. Recently a similar approach to extract waveguide modes was explored theoretically[10] and successfully applied to organic LEDs.[11] Here we explore the coupling of SPP modes to radiation by focusing on measurements of the coupling efficiency.

Moreland *et al.*[12] showed that a SPP propagating normal to the grooves of a single grating could be coupled to radiation with an efficiency of up to 80%. However, in general in a device such as a LED, SPP modes will be generated that propagate in all in-plane directions. We recently addressed the question of how the coupling efficiency depends on the angle between the SPP propagation direction and the grating vector.[13] For SPP modes propagating on a singly corrugated surface not all SPP propagation directions can couple to radiation; we found that approximately half of all propagation directions can couple to radiation. Significantly, for those directions that can couple to radiation we found the efficiency to be independent of propagation angle, taking a value of between 53% and 73%. Could a two dimensionally corrugated surface do the same for all in-plane propagation directions? To answer this question we have measured the efficiency with which a bi-grating may couple SPP modes to radiation.

The measurements reported here were obtained using previously described techniques.[12,13] The SPP mode was excited using laser light and the Kretschmann prism coupling technique, shown schematically in Fig. 1. Once excited the SPPs are scattered by the corrugation to produce a propagating transmitted diffracted order. By determining the ratio of the power in the scattered order to that lost from the incident beam, the coupling efficiency of SPPs to radiation was determined. Prism coupling ensures that the SPP propagates in the plane of incidence, thus affording easy control over the SPP propagation direction.

The corrugated surface was obtained by exposing a photoresist coated silica substrate to an interference pattern produced by laser interferometry.[14] The surface profile was transferred to the silica substrate by reactive ion etching and then covered with a 63±1 nm thick layer of silver. Littrow angle measurements established the pitch (λ_g) of both corrugations to be 399±1 nm, atomic force microscopy data indicated both profiles could be well approximated by a sinusoidal function of amplitude 17.5±2.5 nm.

The corrugated sample was optically contacted to a silica prism using index matching fluid, thus allowing rotation (ϕ) of the substrate with respect to the prism and hence plane of incidence. The polar angle (θ) of the incident beam (543.5 nm HeNe laser, *p* polarized) was varied and the power emerging in the different diffracted orders then measured. We label reflected and transmitted orders as *R* and *T*, and use a double subscript to indicate the order of diffraction in the *x* and *y* directions respectively (Fig. 2). A superscript indicates

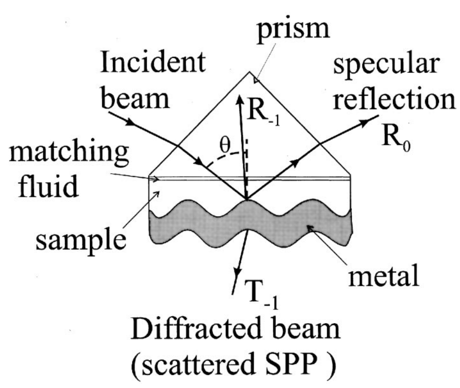

FIG. 1. Schematic of the prism-coupling configuration used. A laser beam is incident via a silica prism onto the corrugated metal film and excites a SPP on the air–metal interface. Also shown are the scattered diffracted orders, T_{-1} and R_{-1} and the specular reflection, R_0.

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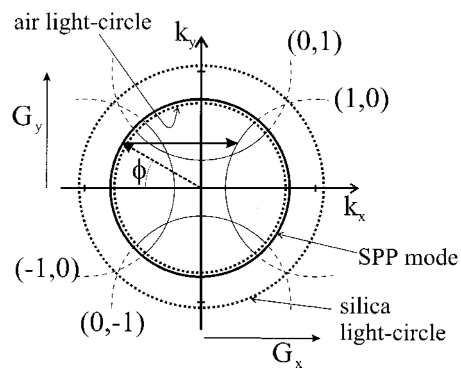

FIG. 2. In-plane wave vector diagram of the bi-grating, pitch λ_g=400 nm for incident radiation of λ_0=543.5 nm. The dotted circles are the silica and air light circles, respectively. The bold circle is the SPP mode. SPP modes scattered by a grating vector are represented by arcs. Arcs labeled $(\pm 1,0)$ are scattered by the corrugation whose grating vector lies in the x direction, those labeled $(0,\pm 1)$ by the corrugation with grating vector in the y direction. Where these arcs lie inside the air light circle the scattered SPP modes may couple to radiation, in these regions the arcs are shown as full lines.

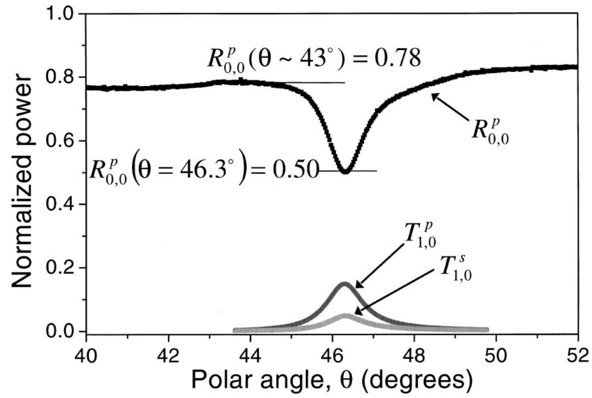

FIG. 3. Power in the specular reflected beam, R_0^p, and the polarized components of transmitted diffracted order, T_{-1}^P and T_{-1}^S, as functions of the polar angle for ϕ=30°. The power is scaled such that the incident beam has unit intensity.

the polarization selected at the detector; no superscript indicates that no selection was made.

The direction of propagation of the diffracted orders can be evaluated using the wave vector diagram shown in Fig. 2. The grating vectors of the two corrugations, G_x and G_y lie in the x and y directions and have magnitude $2\pi/\lambda_g$. The large dotted circle represents the maximum in-plane wave vector a photon can have when incident from the silica prism (index n_s), the silica light circle; it has radius $n_s k_0$ where k_0 is the free space wave vector of the incident beam. Similarly, the smaller dotted circle represents the air light circle, radius k_0. For the amplitude of the corrugation used the textured nature of the surface does not significantly perturb the dispersion of the SPP mode from that of a planar surface. The SPP circle is shown as a full line of radius $\sim 1.03 k_0$.[15]

The four off-center arcs represent the first order scattered SPP mode, indicated by $\{n,m\}$ where $n(m)$ is the order of $x(y)$-direction grating scattering. These scattered SPPs are shown as full lines when they lie within the air light circle, the region of wave vector space in which they may couple to free space radiation. The incident beam excites the SPP mode propagating at angle ϕ with respect to the x axis, represented by the dotted arrow. The solid arrow represents scattering by the grating G_x. Consider how the SPP mode may be scattered to radiation as the azimuth is increased from zero. For $0<\phi<41°$ the SPP may only couple to radiation via G_x. For $41°<\phi<49°$ the SPP may couple to radiation via both G_x and $-G_y$, and for $49°<\phi<90°$ only $-G_y$ allows the mode to be scattered to radiation. As the system has fourfold rotational symmetry this behavior is repeated in all four quadrants, hence SPPs propagating in any in-plane direction may couple to radiation via first-order scattering. Having established that all SPP modes may be coupled to radiation, we now examine the efficiency of this process.

Figure 3 shows the specular, p-polarized reflectivity, $R_{0,0}^p$, as a function of the polar angle θ for a fixed azimuthal angle ϕ=30°. At $\theta \sim 46.3°$ the reflectivity drops to a minimum; at this angle the in-plane wave vector of the incident beam and the SPP mode are equal, thus enabling the incident beam to excite the SPP mode. Figure 3 also shows the power of the outcoupled SPP radiation, both p and s polarized, via G_x scattering, $T_{1,0}^p$ and $T_{1,0}^s$. The power coupled out in this way is negligible unless the incident beam is at an angle appropriate for SPP excitation.

The power coupled from the incident laser beam to the SPP mode was evaluated from data shown in Fig. 3. In doing so one has to decide on a reference level. Two choices can be made. First, the fraction of power coupled to the SPP can be taken as the difference between the incident power and the power reflected at the specular reflectivity minimum, i.e., 50%. However, we also need to take account of the power coupled to the other scattered order, the $-G_x$ reflected beam, R_{-1} (see Fig. 1). This contribution was found to be largely independent of polar angle, taking a value of 9±3%. On this basis 41% of the incident power is coupled into the SPP. Second, examination of the specular reflectivity of Fig. 3 shows that the reflectivity at the critical edge ($\theta \sim 43°$) takes the value of 0.78. This implies 22% of the incident beam goes into losses not associated with the SPP resonance, of which 9±3% is coupled to the $-G_x$ reflected beam, as mentioned above. Adopting this second approach 28% of the incident power is coupled to the SPP. We thus have an upper estimate of the fraction of power coupled to the SPP mode

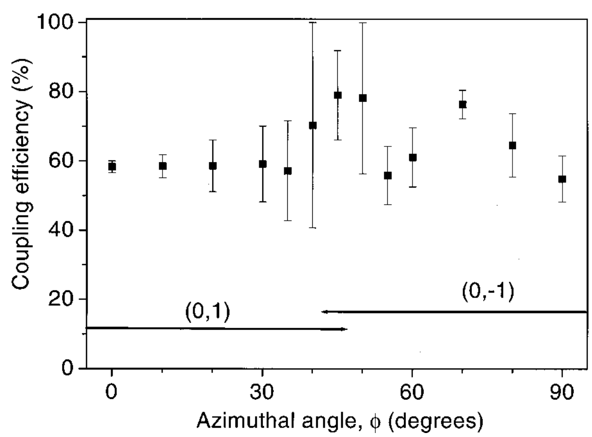

FIG. 4. Measured coupling efficiency of the SPP mode to radiation as a function of the azimuthal angle. The error bars represent the limits imposed by the two methods used in evaluating the power coupled from the incident beam to the SPP mode. The horizontal lines represent the azimuthal angles for which each of the scatters may couple to radiation.

and available for radiation into the air of 41%, and a lower estimate of 28%. The coupling efficiency is obtained by dividing the normalized power in the outcoupled beams by the two estimates given above for the power coupled into the SPP, yielding 49% and 70%, respectively, for this azimuthal angle.

Data for different azimuthal angles were obtained from which we determined the efficiency with which the SPP couples to radiation in the air half space. The results are shown in Fig. 4 where the error bars correspond to the range imposed by the two assumptions for the power coupled from the incident beam to the SPP mode discussed above. For the structure used here, the efficiency has an arithmetic mean over all propagation directions of 60%. We anticipate this may be improved by optimizing the surface profile of the bi-grating.[12]

In summary, our key finding is that the coupling of SPPs propagating in all in-plane directions to free-space radiation may be efficiently accomplished through the use of an appropriately nanostructured system, in this case a bi-grating. We have thus demonstrated that SPPs can be considered as a radiative channel rather than simply as a loss. This opens up many interesting possibilities, notably the extraction of light from thin-film optical sources containing metallic layers.[16,17]

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