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Influence of the dielectric substrate on the field emitted by a subwavelength slit in a metal film

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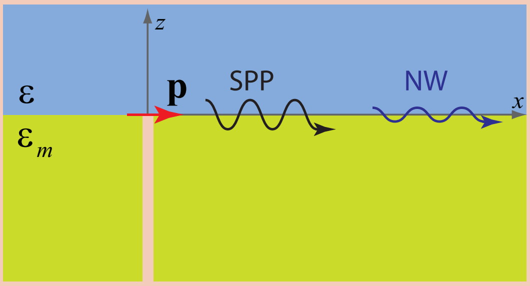
The field emitted by a localized source in the metal surface bounding to a half-media with arbitrary dielectric permittivity is studied. The far field at the surface is composed of both the surface plasmon polariton and the algebraically decaying Norton wave contributions. The crossover distance at which the Norton wave overtakes the surface plasmon, depends upon the refractive index of the bounding media. Substrates with high dielectric permittivity bring the crossover substantially closer to the source.



The field emitted by a subwavelength slit. Far away from the source the field presents contributions from both the surface plasmon and the Norton wave.

Localized excitation of surface waves at metal surfaces has been a subject of intense research over several decades [1, 2]. One of the configurations most extensively used for studying the radiation pattern and interference effects is the excitation by a p-polarized plane wave through a subwavelength slit, placed in an optically thick metal film. Recently, it has been found that the field emerging from a slit, apart from a complex short distance behavior [3–6], shows two far-field regions: an intermediate one, where surface plasmon polaritons (SPPs) dominate and a long-distance one, dominated by Norton waves (NWs) [5–8].

On a lossy metal surface, the SPP suffers an exponential decay along its propagation $\propto e^{-x/L_{SPP}}$, where L_{SPP} is the SPP propagation length. At the distance from the slit X_c, the SPP is overtaken by a weak, but slowly decaying NW. As an example, in the optical spectral region the transition takes place at the typical distance $X_c \simeq 6L_{SPP}$ for Al–vacuum and $X_c \simeq 9L_{SPP}$ for Au–vacuum interface. Taking into account that the typical value for L_{SPP} is of order of 50 μm for both metals, X_c reaches distances of the order of 300 μm for Al, and 500 μm for Au. From the experimental point of view, apart from the difficulties related to a wide dynamical range, for such long spacing the imperfections of real experimental samples can destroy the field behavior that corresponds to the plane ideal metallic surface. To reduce X_c the dielectric substrate can be helpful.

In this Letter we will concentrate on the intermediate and long-distance regimes in order to study the influence of a dielectric substrate with an arbitrary ε on the transition region between SPPs and NWs. We will show that the crossover distance can be brought substantially closer to the source and a slight gain in the field amplitude can be achieved at the crossover point.

Let us consider a plane p-polarized monochromatic wave, impinging onto a thick metal film bounding to a dielectric half-space with a subwavelength slit (see abstract figure). The field radiated by the slit into the substrate can be found, from the analysis of the Lippmann–Schwinger integral equation [8], with the help of the asymptotic steepest-descent method [9]. The subwavelength slit can be approximated by a dipole with moment $\boldsymbol{p}$, pointing along the x-axis and proportional to the integral of the x-component of the electric field across the slit, $\boldsymbol{p} = \left[i\lambda\sqrt{\varepsilon_{\mathrm{m}} - \varepsilon}/(2\pi) \right] \boldsymbol{e}_x \times \int_{\text{slit}} \mathrm{d}x\, E_x(x)$, where $\boldsymbol{e}_x$ is the unitary vector along the x-axis. Then the calculation of the field simplifies to finding the asymptotic of the Green's function (see e.g. [2]). In this paper we omit the derivations; instead we use the expressions reported in [8] for the magnetic field at the metal–vacuum interface ($z = 0$) and the relation

$$H_y\,[x, \lambda, \varepsilon, \varepsilon_{\mathrm{m}}(\lambda)] = H_y\,[x, \lambda/\sqrt{\varepsilon}, \varepsilon = 1, \varepsilon_{\mathrm{m}}(\lambda)/\varepsilon]\,.$$

The asymptotic of the field is composed of three components: SPP contribution (coming from the pole of the density of states), algebraically-decaying NW contribution $\propto 1/x^{3/2}$ (coming from the kink on the density of states at the light cone) and a term coming from the interaction between the pole and kink. Starting from the distance of several wavelengths from the source, the interaction term decays much rapidly than both SPP and NW, so that the first two contributions define the far-field behavior. However, the SPP term, which dominates at the intermediate region (from several λ to several L_{SPP}), is present only on the condition of $\mathrm{Re}\,(\varepsilon + \varepsilon_{\mathrm{m}}) < 0$ [1, 2]. When this inequality is not fulfilled, the pole does not have a physical meaning and, therefore, does not contribute to the field.

Increasing ε of the bounding dielectric media, L_{SPP} can be substantially decreased. It decays with ε and has the following long-wavelength (large $|\varepsilon_{\mathrm{m}}| \gg \varepsilon$) form: $L_{\mathrm{SPP}} \propto \varepsilon^{-3/2}$. Figure 1 illustrates the spatial variation of $|H_y|$ for two values of ε. The chosen values of ε correspond approximately to glass and Ta_2O_5. The wavelength dependence $\varepsilon_{\mathrm{m}}(\lambda)$ is taken from [10]. Along with the total field, the amplitudes of the SPP and NW contributions are also shown. In the intermediate region of distances, starting from several wavelength up to X_{c}, the field follows the SPP behavior. In the vicinity close to $x = X_{\mathrm{c}}$, where the amplitude of the SPP and NW are comparable, some deviations from the monotonic dependence (in the form of maxima and minima) are observed due to the interference between NW and SPP contributions. Depending upon the wavelength and ε, the phase difference between SPP and NW can lead to destructive or constructive interference. In logarithmic scale, the

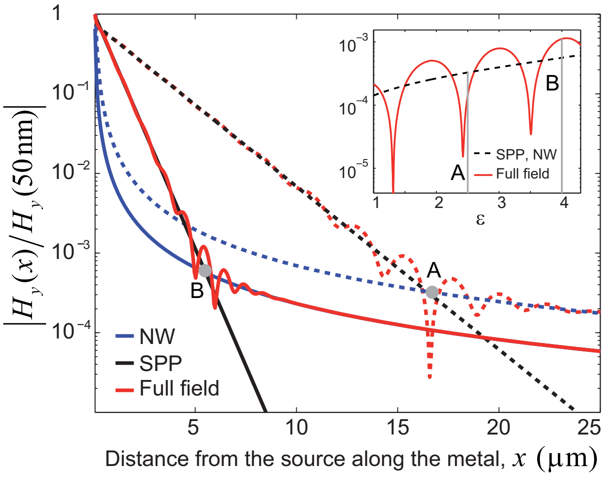


Figure 1 (online colour at: www.pss-rapid.com) The total magnetic field modulus $|H_y|$ together with the SPP and NW contributions as a function of the distance from the source x at the gold surface for $\lambda = 600$ nm. Discontinuous curves correspond to $\varepsilon = 2.5$, while the continuous ones correspond to $\varepsilon = 4$. For large distances, the full field curves are practically indistinguishable from the NW ones. The inset shows the dependence of $|H_y|$ upon ε at the crossover distance $x = X_{\mathrm{c}}$. The fields are normalized to total field value at $x = 50$ nm in order to compare with a representative value in the near field.

decrease of L_{SPP} changes the slope of the straight line corresponding to the SPP so that it crosses the curve representing the NW closer to the source (see Fig. 1). The amplitude of the NW also decreases, but the amplitude of the field at $x = X_{\mathrm{c}}$ is increased by a factor of order of 5 (however, still a large dynamical range would be needed to experimentally observe the NWs). The field amplitude taken at the crossover is shown in the inset of Fig. 1 as a function of ε. The analogous dependence for the SPP field at X_{c} and the NW (which, by definition, at X_{c} has equal amplitude) is present in the inset as well. As seen, the amplitude of the SPP (NW) at X_{c} increases in a monotonic way with ε, while the total field has a set of minima and maxima due to the interference between the SPP and NW. Nevertheless, in the minima the field does not reach zero, since the contribution from some residual rapidly-decaying components is still present.

In Fig. 2, the field $|H_y|$ is rendered as a function of both λ and x in the optical regime. In this figure, the interference appears in the form of spots along the line marking the crossover between the SPP and NW. The topologies for Au and Al cases are quite different. However, independently upon the type of the metal, the increase of ε brings the crossover line downwards along the distance axis for any wavelength.

In order to better illustrate the displacement of the spatial crossover, Fig. 3 shows X_{c} as a function of ε for both Al and Au surfaces. The range of ε considered covers a wide range of dielectrics and certain semiconductors. In the figure X_{c} is normalized to both the vacuum wavelength (bottom panel) and the L_{SPP} (top panel). These results show that

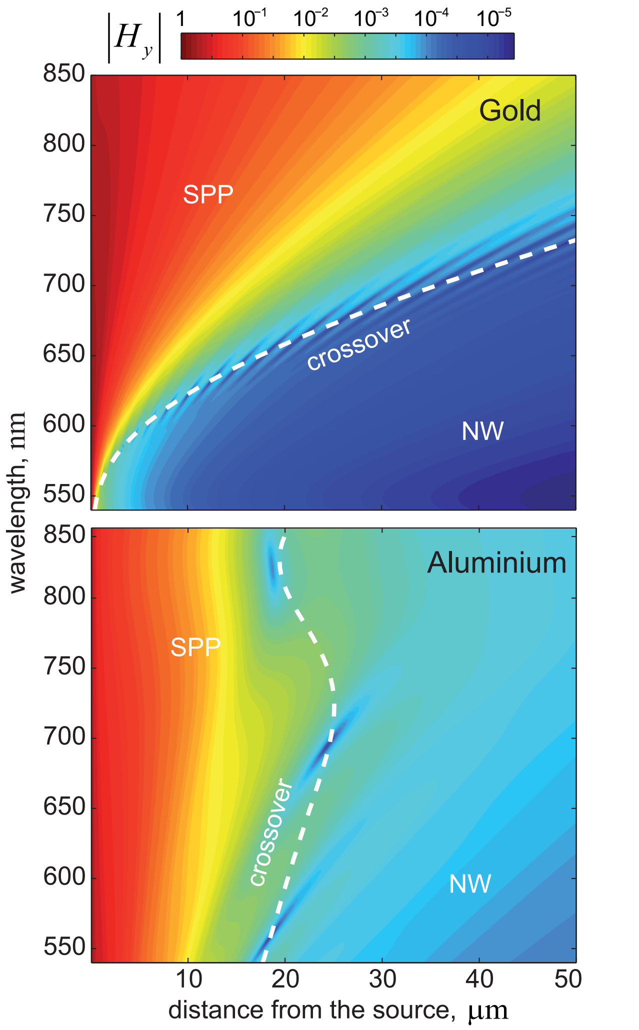


Figure 2 (online colour at: www.pss-rapid.com) The module of the magnetic field $|H_y|$ at the dielectric–metal interface as a function of both wavelength λ and distance x to the source. In the top panel the metal is gold while it is aluminium in the bottom panel. In both cases the dielectric has $\varepsilon = 4$. The field is normalized to its value at $x = 50$ nm. The crossover distance between SPP and NW is shown by a white discontinuous curve.

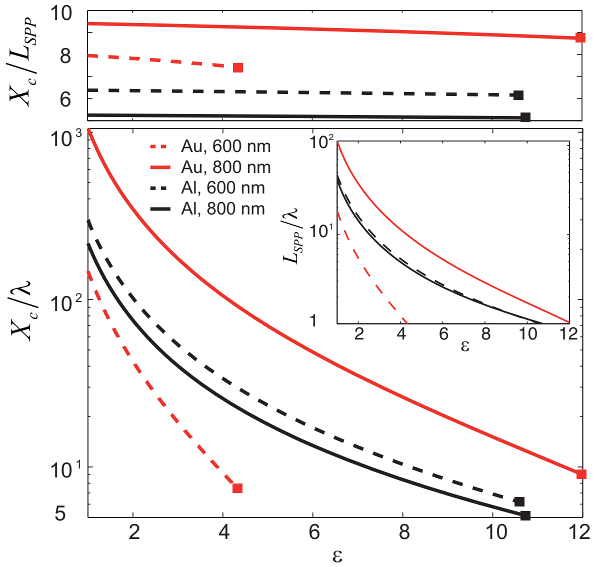


Figure 3 (online colour at: www.pss-rapid.com) Crossover distance X_c as a function of ε at two different wavelengths for both aluminium and gold interfaces. The squares on the curves correspond to the condition $L_{SPP} = \lambda$. The inset renders the dependence of L_{SPP} upon ε.

X_c/λ can be reduced by two orders of magnitude. Square symbols, marking the end of the curves, are located at the values of ε, for which L_{SPP} is equal to a wavelength. Figure 3 shows that X_c/L_{SPP} depends very weakly on ε, implying that the strong dependence of X_c/λ on ε is related to the strong decrease of L_{SPP} (as the inset of Fig. 3 shows). This is explained by the fact that the crossover distance is dominated by the decay of the SPP, which is faster than the NW decay, so as in a first approximation X_c scales linearly with L_{SPP}.

In conclusion, these results demonstrate the influence of the dielectric permittivity of the substrate on the transition region between the surface plasmon-polaritons and Norton waves in the optical region. When scaled to the SPP propagation length, the crossover distance remains practicably unchanged due to a weak decay of the Norton wave, but it reduces up to two orders of magnitude in absolute metric scale. The amplitude of the field at the crossover suffers an increase when the permittivity of the substrate grows. Both the reduction of the crossover distance and the increase of the field amplitude could be useful for experimental studies on the asymptotes of the fields emitted along metal surfaces by localized sources.

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