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Generation of surface plasmons at single subwavelength slits: from slit to ridge plasmon

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Abstract. Understanding how surface plasmons can be launched by single subwavelength structures is crucial for the development of surface plasmon-based devices within highly integrated photonic circuits. In this paper, we study the coupling efficiency of light to surface plasmons for single slits milled in a thin metal film by analyzing the far-field optical images recorded in the Fourier plane of a leakage microscopy setup. A simple model based on a Fano-type interference allows us to give a clear physical interpretation of the plasmonic generation efficiency with an optimum value separating two regimes depending on the size of the system. This is an issue of practical interest in the context of plasmonic features with size close to or smaller than optical diffraction limit.

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1. Introduction

The field of plasmonics is based on exploiting surface plasmon polaritons (SPPs) which result from the coupling between light and collective electronic excitations in conducting materials. Since these modes are not constrained by the optical diffraction limit, they allow the construction of miniature optical elements and potentially complete photonic circuits [1]–[5]. For this latter purpose, optical components, such as waveguides, switches, Bragg mirrors, couplers and others, need to be integrated to steer and control SPP beams [6]–[8]. To launch SPPs from incoming light to feed the circuit, efficient couplers are required.

Different systems which overcome the inherent momentum mismatch can be used to couple light to SPPs. Launching SPPs at the level of a flat metal–dielectric interface via a prism is a technique well known for its efficiency but which does not offer much control over the localization and the SPP beam shape. This is a problem in the context of supplying a highly integrated circuit. Local scatterers, such as particles or holes, have been used: they play the role of a precisely localized SPP source. One of the most basic scatterers is a single hole milled in a metal film. Due to its symmetry, a typical two-dimensional (2D) dipolar SPP emission pattern is observed, with its axis being oriented along the polarization direction of the illumination. The SPP beam emerging from a single hole is thus highly diverging [9]. Holes have to be arranged in arrays if one wants to obtain a well collimated or even a converging SPP beam [10]–[13]. An alternative solution to hole arrays is the single slit source. Its extended shape imposes a directionality on the SPP beam, the divergence of which can be tuned by changing the illumination conditions [14]. A slit is thus an interesting structure, as it combines the compactness of a single defect with the directionality of an array launcher. In this paper, we focus on analyzing the slit efficiency for converting light into SPPs.

The SPP generation by light at the level of a single slit has already been investigated with a near-field scanning microscope for slit widths ranging from subwavelength dimensions to a few microns [15]. However, in analogy with what occurs for antennas, when the dimension of such a system is varied, one expects to see two different regimes depending on whether the slit width is smaller or larger than half the illumination wavelength. In other words, a relevant question is whether the SPP launching mechanism is determined by the shape of the slit acting as a whole or by the ridges of the slit acting individually. To answer this question, we need here only to consider slits widths smaller than the illumination wavelength. Additionally, this range of slit widths is of practical use in the context of a highly integrated circuit. In this paper, measurements are made in the far field using a leakage radiation microscope which allows a precise mapping in the Fourier plane of the transmission pattern of the slit and the excited SPPs. This method is similar to the one already used to characterize the coupling efficiency of single subwavelength holes [9].

2. Experiments

The source slits were prepared with a FEI Dual Beam Strata 235 focused ion beam in 60 nm thick gold films sputtered on BK7 glass substrates. The slit length was fixed at 20 µm, and the width was varied from 70 nm to 1 µm (see figure 1). The illumination was done by focusing at normal incidence a laser beam (wavelength 785 nm) with a microscope objective (20×, numerical aperture (NA) 0.40). This produces a spot with a full width at half maximum (FWHM) of 1 µm on the sample incident on the air–metal interface of the slit source, a condition

fairly compatible with the assumption of uniform illumination for the considered set of slit widths. The incident polarization was chosen perpendicular to the slit axis. As the glass substrate has an optical index $n_g$ higher than air and the metal film is thin enough for the SPPs to leak through it, the SPPs propagating at the upper interface can couple to freely propagating light into the substrate at a given angle $\theta_{LR}$ such that $n_g \sin(\theta_{LR}) = \text{Re}(k_{SPP})$ where $k_{SPP}$ is the SPP complex wavevector, defined by the standard dispersion relation $k_{SPP} = \frac{2\pi}{\lambda_0} \sqrt{\frac{(\varepsilon_m \varepsilon_d)}{(\varepsilon_m + \varepsilon_d)}}$ on a smooth metal–dielectric interface with respective dielectric functions $\varepsilon_m$ and $\varepsilon_d$ [16]. We point out that this dispersion relation, defined for a semi-infinite metal film, is actually not modified for a 60 nm thick film [6].

Experimentally speaking, the angle at which the leakage radiation is emitted in the substrate has a typical value of $43^\circ$, slightly higher than the critical angle of a glass/air interface. We used an oil immersion objective (100×, NA 1.3) to be able to collect this signal and to prevent total internal reflection of the leakage radiation on the free interface of the glass substrate. To image the wavevector distribution of the transmitted light and retrieve the SPP coupling efficiency, we recorded the intensity profile in the Fourier plane of the collection objective. The illumination and collection setup is schematically shown in figure 2(a).

3. Observations

A typical measurement of the intensity in the Fourier plane is shown in figure 2(b). The bright circular lines close to the edge are due to the SPP resonance and their radius equals $\text{Re}(k_{SPP})$. The remaining signal of the Fourier plane is a convolution between a disc, which stands for the Fourier transform of the Airy spot of the excitation, and a sinc function, the Fourier transform of the rectangular aperture.

In figure 3, we show the angular SPP intensity profile along the bright ring. This is a direct measure of the angular divergence of the SPP beam on the metal film. Note that this is limited by the NA of the illumination objective. This is in agreement with previous observations [14, 17] and can be easily understood in real space: the divergence of the SPP beam depends on the portion of the slit that casts the incident field, or in other words on the size of the illumination spot which is linked to the NA of a given objective. The smaller the illuminated portion is, the...
Figure 2. (a) Sketch of how both the directly transmitted light and the leakage radiation are collected by the microscopy setup and their interference in the Fourier plane. (b) A typical optical image of the intensity pattern that is seen in this Fourier plane.

Figure 3. Comparison of the angular cross-cuts of the SPP intensity profile taken with two different illumination objectives. The orange and brown curves were obtained with respectively a 0.40 NA and a 0.55 NA objective corresponding to angular acceptances of 23.6° and 33.4°. For comparison, the dashed curve represents the intensity profile of a typical \( \cos^2 \) dipolar emission pattern.

closer the emission pattern is to the typical \( \cos^2 \) behavior of a point dipole. On the contrary, a low NA objective illuminates an extended portion of the slit. The interferences between SPPs excited all along the illuminated portion of the slit result in the decrease of the divergence of the SPP emission [13].

To study the influence of the slit width on the intensity of the SPP resonance, we recorded the intensity in the Fourier plane with the same illumination conditions for all widths and performed radial cross-cuts along the direction perpendicular to the slit as shown in figure 4. Importantly, our data reveal a non monotonic evolution of the SPP resonance intensity with respect to the slit widths. This can be associated with a modulation of the SPP coupling efficiency. In order to quantify this efficiency, it is also necessary to account for the contribution of the directly transmitted light through the slit since it will interfere with the SPP signal in the far field. Indeed, if the SPP contribution were to be the only one, its radial distribution in the Fourier plane would follow a Lorentzian profile centered on $\text{Re}(k_{\text{SPP}})$ with a FWHM of $2\text{Im}(k_{\text{SPP}})$. On the contrary, the data of figure 4(b) clearly show asymmetric profiles rather than Lorentzian ones. For all widths $w$, the SPP resonance maxima are located at the same wavevector $\text{Re}(k_{\text{SPP}})$ with a dip just below $\text{Re}(k_{\text{SPP}})$. This can be understood from a Fano-type interference in the far field between the direct transmission of light through the aperture and the leakage radiation from the launched SPPs.

Using a simple model we are able to reproduce the intensity distribution of the Fourier plane displayed in figure 4 by considering the interference between these two contributions. The amplitude of the electric field transmitted through the leakage microscope can be described as:

$$E_{\text{total}} = E_{\text{light}} + E_{\text{LR}},$$

Figure 4. (a) Intensity patterns recorded in the Fourier plane for different slit widths, and (b) cross-cuts along the direction perpendicular to the slit. Illumination conditions and the exposure time are the same for all measurements.
Figure 5. Calculated intensity pattern in the Fourier plane for a 100 nm wide slit (a) is the radial cross-cut, fitted on experimental data and (b) the fully calculated image. The difference, in the central region, between the experiment and our model comes from our assumption concerning diffraction at the slit. This has no consequence for our analysis of the SPP excitation, since our theoretical approach separates the two contributions.

where $E_{\text{light}}$ is the direct transmission of light through the aperture, and $E_{\text{LR}}$ accounts for the leakage radiation originating from the SPPs. $E_{\text{light}}$ is obtained from the incident field $E_{\text{in}}$, taken as a plane wave with a Gaussian amplitude profile that corresponds to the experimental size of the laser spot incident on the sample, multiplied by the aperture function $\tau_{\text{slit}}$ which is equal to 1 over the slit (augmented by the penetration depth of the field into the slit ridges) and to a complex value over the metal, calculated from the tabulated experimental value of $\varepsilon_m$ [18]. For each slit width, the associated transmission amplitude is fitted from the experimental data with a free parameter $\alpha$. $E_{\text{LR}}$ is deduced from the SPP field, $E_{\text{SPP}}$, propagating at the air/metal interface and multiplied by the leakage transmission factor $\tau_{\text{LR}}$, calculated from the SPP relation dispersion [17]. For a 60 nm thick gold film illuminated at 785 nm, we find $\tau_{\text{LR}} = 0.076641 \exp(i1.05052)$. $E_{\text{SPP}}$ is evaluated from a scattering model based on a Huygens–Fresnel principle, as described in [13]. Here, we take into account an additional phase difference $\exp(-ik_{\text{SPP}}w/2)$ due to the change of position of the ridges with respect to the center of the slit. The dependence of $E_{\text{SPP}}$ on the field $E_{\text{in}}$ is fitted for each width from the experimental data with a free parameter $\beta$. The global field $E_{\text{total}}$ cast by the leakage microscopy setup is defined as the coherent sum of both indirect and direct contributions (equation (1)), and the intensity measured in the Fourier plane $I_{\text{Fourier}}$ is eventually given by:

\[
I_{\text{Fourier}} = |\text{TF} (E_{\text{light}} + E_{\text{LR}})|^2 = |\text{TF} (\alpha \tau_{\text{slit}} E_{\text{in}} + \beta \tau_{\text{LR}} E_{\text{SPP}} \exp(-ik_{\text{SPP}}w/2))|^2.
\] (2)

While more realistic models have been provided recently [19, 20] for describing the scattering dynamics at the level of a subwavelength slit, our simple approach appears well adapted in this context for reproducing optical images given by leakage microscopy. Indeed, changing the values of $\alpha$ and $\beta$ make it possible to balance the interfering contributions, in other words to play on the visibility of the SPP resonance with respect to the light diffracted by the aperture. Figure 5 displays a comparison between an experimental image of the Fourier space of a single...
Figure 6. (a) Intensity of the SPP resonance and (b) coupling efficiency $\eta = \beta/\alpha$ of light to SPPs as a function of the slit width. The dashed curve on (b) is the power spectrum density calculated at $\Re(k_{\text{SPP}})$ as a function of the slit width and normalized to the maximum of $\eta$.

slit and the results given by equation (2). As stressed above, if the SPP contribution were the only one, the linewidth of the Lorentzian profile of the leakage radiation would be given by the imaginary part of the dispersion relation, consistently with [6, 18]. Due to the interference between the direct light and the SPPs, we obtain a much narrower and asymmetric profile, which is well reproduced by the model. The rather good agreement between equation (2) and the experiment allows us to extract for each slit the value of the coupling efficiency $\eta$ that is given by the ratio $\beta/\alpha$.

In figure 6(a), we plot the different intensities associated with the SPP resonances as a function of the slit width with an optimum value around half the 785 nm illumination wavelength. In figure 6(b), we compare $\eta$ with the calculated power spectrum density for each slit width (taking into account the illumination properties) at a wavevector equal to $\Re(k_{\text{SPP}})$. Two different regimes can be identified in this figure. For values of the slit width smaller than half the illumination wavelength, $\eta$ follows closely that of the power spectrum. In contrast, for larger widths, the coupling efficiency of light to SPPs deviates significantly and tends toward a constant value as can be seen in figure 6(b). For these wide slits, the coupling efficiency is actually that of an isolated ridge which becomes constant as the width increases.

This finding appears to be quite different from the experimental results reported in [15]. This might be due to the illumination and collection conditions of those near-field experiments. The SPP launching efficiency has also been estimated theoretically [20] but for slits much deeper which involve Fabry–Perot type resonances and plane–wave illumination, so comparison is difficult. Nevertheless, maximum efficiency is reported for slits much narrower than the wavelength in agreement with our results. It is remarkable to note in figure 4(b) that for slit
widths smaller than half the wavelength, the SPP resonance intensity remains much higher than the background signal due to the optical diffraction of the aperture (around 5 times higher for a 70 nm wide slit, for example). Moreover, due to this small width, the first zero of the associated diffraction pattern is rejected far away in the Fourier plane, totally out of the collection angle of any classical optical system operating in the far field.

4. Conclusion

We have implemented a leakage microscope to characterize the SPP launching from single subwavelength slits. This has allowed us to retrieve from the recorded images quantitative information related to the divergence of launched SPP beams and the efficiency of the coupling process of light to SPPs. At the level of a single slit source, two different coupling regimes can be identified depending on the slit width. Beside the fundamental aspect, these findings should be helpful for the design and optimization of compact single plasmonic sources.

Acknowledgments

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