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Dependence on surface profile in grating-assisted coupling of light to surface plasmon-polaritons

Armando Giannattasio *, Ian R. Hooper, William L. Barnes

School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom

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Abstract

Grating coupling of light to surface plasmon-polaritons (SPPs) supported by a thin metal film depends on the detailed geometry of the grating used to couple the incident light to the SPP modes. Here we show experimental and theoretical evidence that, in the case of square gratings having the same pitch and depth, the maximum coupling of light to the SPPs is achieved when the ratio between the groove width and the pitch of the grating is equal to 1/2. A straightforward explanation involving a Fourier analysis of the different grating profiles is given and compared with the experimental results.

1. Introduction

Surface plasmon-polaritons (SPPs) are electromagnetic waves that are bound to a metal/dielectric interface through an interaction with surface charges and therefore exhibit a two-dimensional nature [1]. In exploiting SPPs to make photonic components the issue of coupling light into and out-of SPP modes is an important concern. Here the coupling between light and SPPs was investigated in the case of grating-assisted. Although the efficiency of light-SPP coupling (in and out) via miniature gratings and its dependence on the grating depth has been extensively investigated in the past [2–5], the use of novel fabrication techniques such as focussed-ion-beam (FIB) milling or electron-beam lithography allows one to study how such coupling depends on the geometry of the grating profile. Although some experimental data are available from particular applications such as Raman scattering [6], this dependence is not fully understood. The study reported here aimed to establish the best grating profile to produce the highest light-SPP coupling efficiency in the case of simple square gratings of the same pitch and depth. Different gratings were fabricated by ion-milling a periodic set of grooves on a silver surface, each grating having a different groove width, but the same pitch (same Bragg vector) and same groove depth. The grating-assisted coupling of light to SPPs was then investigated as a function of the groove-to-pitch ratio, γ, which is here defined as the groove width divided by the grating pitch.

2. Experiment

The gratings used in this work were based on a (50 ± 1) nm thin silver film thermally evaporated onto a flat silica substrate ($25 \times 25 \times 1$ mm). Three different gratings were then fabricated on the resulting metallic surface. Each grating consisted of equally spaced grooves etched into the metal/air interface using a focused ion-beam milling system (FEI Nova 600) with spatial resolution of <5 nm. The three gratings had a square profile, the same pitch (400 nm) and a depth $d = (10 \pm 5)$ nm. The error in the measurement of the grating depth is more an indication of the variation in the metallic structure owing to the presence of grains in the silver film. The gratings were all fabricated using exactly the same FIB parameters. The groove size was different

* Corresponding author. Tel.: +44 1392 264135/2091; fax: +44 1392 264111.

E-mail addresses: a.giannattasio@ex.ac.uk, armando.giannattasio@materials.ox.ac.uk (A. Giannattasio), w.l.barnes@ex.ac.uk (W.L. Barnes).

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in each structure: the three gratings had groove widths of approximately (a) 100 nm, (b) 200 nm and (c) 300 nm, which provided a groove-to-pitch ratio, γ, of 1/4, 1/2 and 3/4, respectively. A schematic of the gratings and a SEM micrograph of one of the structures are shown in Fig. 1. Each grating covered an area of 95×95 μm and they were spaced from each other by at least 5 mm. The sample was index-matched to a silica prism and the silver/air SPP mode was excited by using p-polarized light ($\lambda = 543$ nm) to illuminate each grating separately. In turn the SPP modes were coupled to light via prism coupling, light that was directed to a photo-detector (Fig. 2, inset). The grating grooves were normal to the plane of incidence (a configuration often known as the classical mount).

The condition for light to couple to SPPs was met by sweeping the angle of incidence: at the silver/air interface, SPP excitation occurred when the polar angle of incidence θ was such that

$$\pm k_0 \sin\theta \pm m k_{\mathrm{g}} = \pm k_{\mathrm{SPP}} \qquad (1)$$

where k_0 is the magnitude of the wave vector of the incident light (in air), k_{SPP} is the magnitude of the wave vector associated with the SPP mode, k_{g} is the magnitude of the Bragg vector of the grating and the integer m is the order of the scattering process. Once excited by the incident light, SPPs at the metal-air interface can be converted back into light which propagates in the silica prism, a process often referred as "leakage radiation" and its intensity is an indicator of the light-SPP coupling efficiency [7]. The equation governing this reverse coupling process is very similar to Eq. (1), but in this case k_0 and θ refer to light transmitted through the prism rather than incident light [9] (i.e., here θ refers to the angle of the T_{-1} diffracted order in the prism). By monitoring the intensity of the power radiated into the prism in what is in effect the transmitted diffracted order ($m = -1$), it was possible to quantify the efficiency of light coupling to SPPs and re-emitted through the silica prism via this SPP-assisted process. The intensity of the light transmitted into the first diffracted order (T_{-1}) was measured for each of the three gratings and the results were then compared, discussed and modelled.

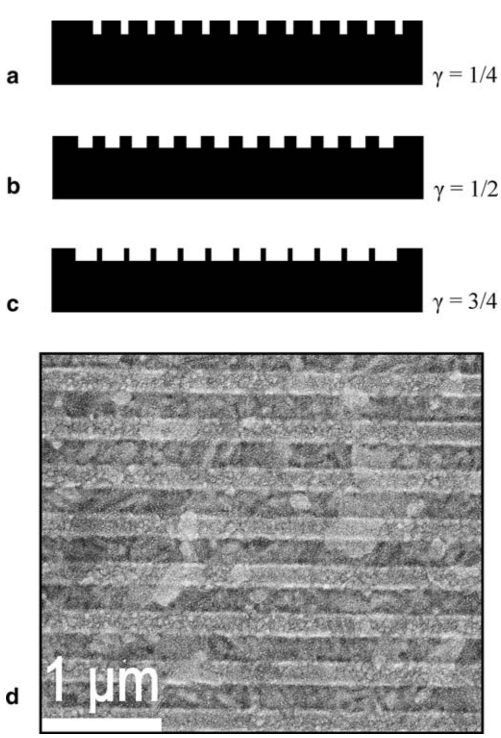

Fig. 1. Schematic of the three grating profiles. The pitch of the gratings was 400 nm and groove width was approximately: (a) 100 nm; (b) 200 nm; and (c) 300 nm. A SEM image of one of the gratings is shown in (d). The depth of the gratings was ~10 nm.

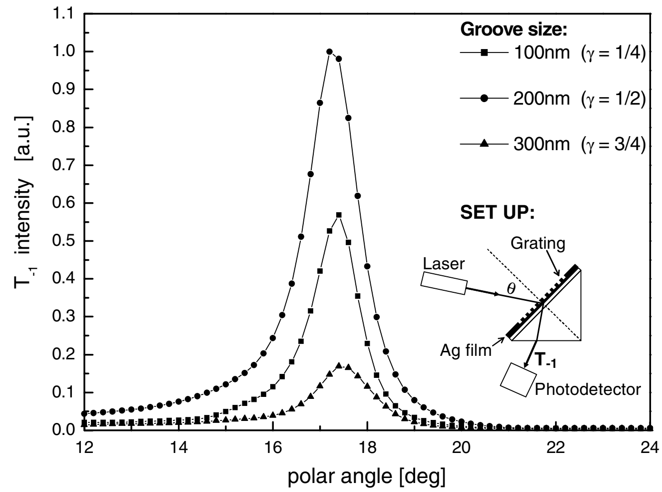

Fig. 2. A schematic of the experimental setup is shown in the inset. Intensity data collected using this geometry for different groove-to-space ratios are plotted in the graph. A maximum in transmitted diffracted intensity is reached when $\gamma = 1/2$.

3. Results

At the excitation wavelength used in the experiment (543 nm), the data in Fig. 2 confirm the validity of Eq. (1), which is fulfilled for $m = -1$ when the polar angle θ is approximately 17.4°. Interestingly, the data in Fig. 2 also show that in the case of square gratings having the same pitch (400 nm) and depth (~10 nm), the best coupling condition is achieved when the groove-to-pitch ratio γ of the grating is equal to 1/2. Moreover, the difference in transmitted intensity, and thus in coupling efficiency, between the three different grating profiles is large: when compared to the T_{-1} peak intensity for $\gamma = 1/2$ (100%), the same normalized peak measured in the other two geometries falls to 57% for $\gamma = 1/4$ and to 17% for $\gamma = 3/4$. These significant differences confirm the key role played by the grating profile and in particular by the parameter γ, since the three gratings were practically identical in all other respects. The different coupling angles exhibited by the three gratings arise because of the way the different surface profiles modify the dispersion of the SPP.

4. Discussion and modelling

The profile of a periodic corrugation, such as that used in this work, can be expressed in terms of a Fourier expansion as:

$$S(x) = C_0 + \sum_{n=1}^{\infty} C_n \sin\left(\frac{2\pi n x}{p} + \varphi_n\right) \quad (2)$$

where C_n is the amplitude of the nth sinusoidal component (C_0 is a constant), p is the pitch of the corrugation and φ_n is a suitable phase. If the series is truncated at $n = 1$, then the profile function simply becomes (given $C_0 = 0$)

$$S(x) = h \sin(2\pi n x/p) \quad (3)$$

where $h = C_1$ is now the amplitude of the grating. In this case, using the first-order approximation ($h \ll p$ and $h \ll \lambda$), the p-polarized intensity emitted into the first diffraction order can be written as [1]

$$T_{-1} = (I_{-1}/I_0) \propto \omega^2 |t^p(\theta)|^2 h^2 \quad (4)$$

where ω is the frequency of the incident radiation and $t^p(\theta)$ is amplitude transmission coefficient of the metal film. Thus, at a fixed wavelength, it is expected that T_{-1} will increase with the square of the grating amplitude. Although the sinusoidal grating represents the shallow profile gratings used in the experiment reported here only poorly, it is however reasonable to assume that in the general case, the intensity of light diffracted by the grating will be dominated to first order by the first term ($n = 1$) of the series in Eq. (2). In fact, for a square profile such as those studied here, the first Fourier term will always exhibit the largest amplitude, C_1, and thus will dominate the expression for the transmitted diffracted order when a general profile function given by Eq. (2) is considered:

$$T_{-1} \propto \omega^2 \sum_n \left|t_n^p(\theta)\right|^2 C_n^2 \quad (5)$$

The three profiles of the square gratings used in this work were approximated by a suitable Fourier series. To a first approximation, the first Fourier component ($n = 1$) was calculated for the three different gratings having different values of γ and the resulting profiles are compared in Fig. 3a for the case of square gratings with a depth of 10 nm. From Fig. 3a it is clear that the amplitude of the first Fourier term associated with the grating having $\gamma = 1/2$ is approximately 40% larger than the harmonic amplitude in the other two structures with different groove-to-pitch ratio. In this case, according to Eq. (5), the transmitted diffracted order T_{-1} should be largest when $\gamma = 1/2$. To show this, T_{-1} was calculated for each of the (first order approximated) grating profiles shown in Fig. 3a using a well known model based on the Chandezon technique [9,10].

The dielectric function for silver at the excitation wavelength was taken as $\varepsilon_{Ag} = -11.68 + 0.48i$ in the simulation [8]. Results of the calculation are shown in Fig. 3b; these are in excellent agreement with the discussion above, as

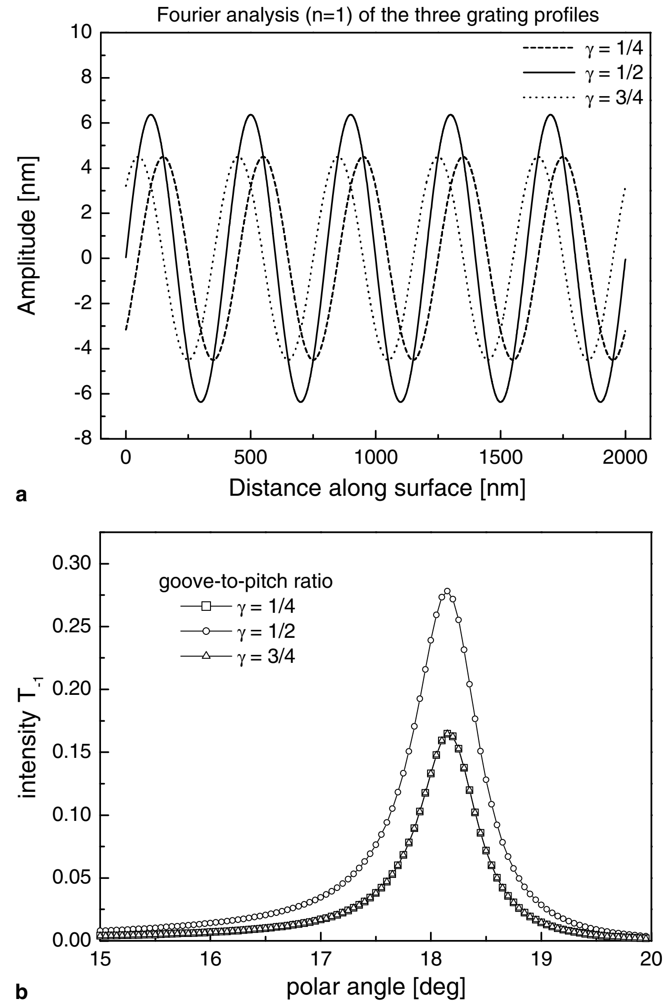

Fig. 3. (a) Fourier analysis: first order approximation ($n = 1$) of the three square grating profiles in the case of a grating depth equal to 15 nm. (b) Calculated intensity of light transmitted through the prism via SPP-coupling in the structures shown in (a) (data for $\gamma = 1/4$ and $\gamma = 3/4$ are superposed). Even in this simple case, maximal transmission occurs when $\gamma = 1/2$.

the intensity of T_{-1} is higher for the grating with the larger amplitude of the first Fourier term of the expansion, that is when $\gamma = 1/2$ (Fig. 3a). However, this first approximation of the square profiles does not account for the differences found experimentally between the gratings with γ equal to 1/4 and 3/4 respectively; in Fig. 3b these structures appear to have the same peak intensity, whereas the experimental data shown in Fig. 2 show them to be markedly different.

To investigate the effect of the other higher harmonics on the diffracted intensity, $n = 21$ Fourier components were used to describe the square grating profiles with sufficient accuracy (as shown in Fig. 4, for example, in the case of a grating with depth equal to 15 nm). Fig. 5 contains the results of the calculation carried out using the profiles shown in Fig. 4 and for a number of different values of the grating depth. The experimental data of Fig. 2 are consistent with the simulation shown in Fig. 5 for a grating

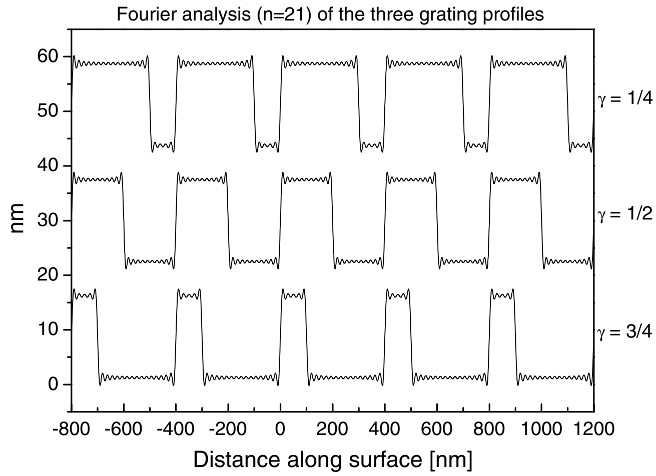

Fig. 4. Approximation of the square profiles of the gratings (depth = 15 nm) using a Fourier series with 21 terms. These and other similar profile functions were used in the simulation the results of which are reported in Fig. 5.

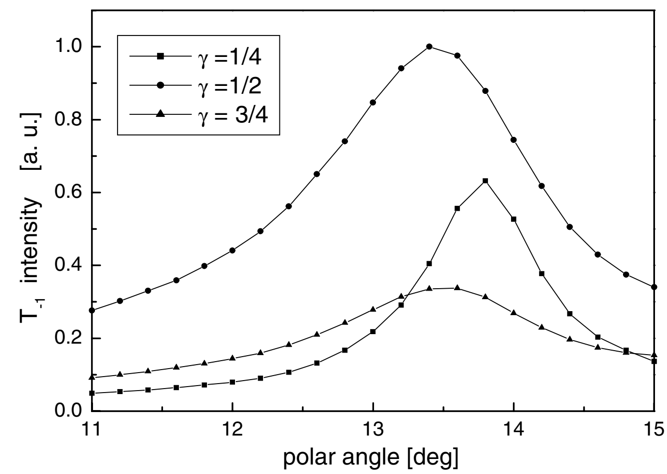

Fig. 6. Experimental data similar to those in Fig. 2. In this case the grating pitch was 425 nm (SPP excitation occurs at $\theta = 13.4°$) and the grating depth was ∼20 nm. A relative shift is visible for the peaks associated with the gratings having $\gamma = 1/4$ and $\gamma = 3/4$.

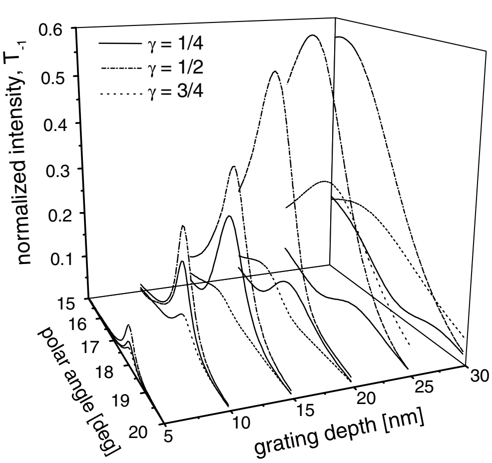

Fig. 5. Intensity data (T_{-1}) calculated for the three different groove-to-space ratios as a function of grating depth. Experimental data in Fig. 2 (for which grating depth was approximately 10 nm) are in good agreement with these theoretical predictions.

depth of approximately 10 nm, which was the case of the experiment described here. Moreover, the simulation in Fig. 5 confirms that the effect of the groove-to-pitch ratio on light coupling into SPPs is considerable and the influence of γ on the coupling efficiency is at least as important as that of the grating depth, d.

The calculation in Fig. 5 shows that if the grating depth is increased, then there is an angle shift in the peak intensity; this is particularly visible in the case of gratings with $\gamma = 1/4$ and $\gamma = 3/4$ where the shift in angle has opposite directions. We used a square grating with slightly larger pitch (425 nm) and a depth equal to approximately 20 nm (deeper than that used earlier in this work) to repeat the experiment in Fig. 2 and measure the angle at which the different T_{-1} peaks are positioned. These new data are reported in Fig. 6 and show a relative shift in angle between the peaks associated to the structures with $\gamma = 1/4$ and $\gamma = 3/4$. This shift is not as marked as expected from the modelling, probably due to the presence of silver grains which caused the groove bed to have a pronounced roughness. However, the data in Fig. 6 at least confirm that the optimal coupling occurs when $\gamma = 1/2$.

One may wonder as to the role played by the higher harmonic components in the grating profile since these higher order components have too high an associated wave vector to allow them to couple light to the SPP mode – only the fundamental can do this. The reason these components matter is that they do act to modify the dispersion of the SPP mode. In the extreme case such components can act to backscatter SPP modes, leading to the formation of SPP stop-bands and even SPP band-gaps [11].

In conclusion, the two grating parameters, γ and d, should be carefully considered in order to maximize the light-SPP coupling in periodically corrugated metallic structures. In the case of square gratings of a given depth d (<30 nm), the data presented in this paper, experimental and calculated, indicate that the coupling strength is always maximal when the groove-to-pitch ratio is equal to 1/2. The explanation, involving a Fourier analysis of the grating profile, is associated with the amplitude of the first Fourier harmonic, which dominates in the expression (5) for the transmitted intensity T_{-1}, and which is largest when $\gamma = 1/2$.

Acknowledgement

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