Transmission of light through thin silver films via surface plasmon-polaritons

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Abstract: We report results of measurements and calculations that help to clarify the role of surface plasmon-polariton modes in the transmission of light through thin continuous films of silver. Our experimental data show that there is an optimum silver film thickness for which transmission is maximal. We offer an explanation of this phenomenon in terms of competition between increasing absorption in the metal and increasing optical field-enhancement due to surface plasmon-polariton excitation as the metal film thickness is increased. We find no need to invoke the regeneration of evanescent waves as has recently been suggested.

OCIS codes: (240.6680) Surface plasmons; (260.3910) Optics of metals; (240.0310) Thin films.

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1. Introduction

The interaction of light with metallic nanostructures provides a rich arena for exploration that continues to yield new surprises. In studying the properties of left-handed materials, Pendry recently proposed that something as simple as a thin silver film might act as a super-lens [1], an idea that caused quite a stir [2, 3, 4]. The prospect of making a super-lens is an exciting one, not least because of the possibilities it might offer in such areas as photolithography. The role of evanescent waves in the super-lens concept is vital – the usual resolution limit arises from the failure of standard image-forming optical systems to collect these waves. Fang *et al.* [5, 6] have looked specifically at the role of evanescent waves in the transmission of light through a silver film and the relationship of these waves to the surface plasmon-polariton (SPP) modes such films support. It is natural to consider SPP modes in such circumstances since they are modes that have fields that decay evanescently away from the metal/dielectric interface that supports them [7] and are well established as a means of transporting optical energy across thin metal films [8-16]. Intriguingly Fang *et al.* [5] found that there is an optimal thickness of approximately 50 nm for the transmission of visible light mediated by SPP modes through a silver film. They explained their results in terms of the regeneration of evanescent waves (see Fig. 2(b) of Ref. [5]). The need to invoke such a phenomenon seems rather surprising given the extensive body of existing knowledge on the optical properties of thin metal films. Here we provide new experimental evidence that is more quantitative in nature and which, together with numerical modelling, allows us to offer an alternative explanation of the underlying physics. This explanation is based on a competition between field-enhancement due to the SPP and absorption in the metal, an explanation that fits more naturally with other SPP based phenomena.

2. Experiment

The SPP mode associated with the silver/air interface of a thin silver film supported by a glass substrate is non-radiative in air but may, provided the metal film is thin enough, decay to produce light in the glass substrate (in this work we will not consider the SPP mode associated with the silver/glass interface). In our experiments we excited the silver/air SPP mode of a thin silver film using grating coupling (rather than roughness coupling used by Fang *et al.* [5, 6]) and examined how the intensity of the light produced in the glass by the decay of these SPPs varied with silver film thickness. A schematic of the experimental set up is shown in Fig. 1. The samples comprised a thin silver film supported on a silica prism that possessed a grating like surface profile; fabrication details can be found elsewhere [13], the grating had a pitch $p = 380 \pm 1$ nm and an amplitude $a = 6.7 \pm 0.2$ nm. By sweeping the angle of incidence the condition for light (p-polarized, HeNe, $\lambda = 543.5$ nm) to couple to SPPs can be met; in particular, at the silver/air interface, SPP excitation occurs when the polar angle of incidence θ is such that,

$$k_0 \sin\theta \pm mk_g = \pm k_{SPP} \qquad (1)$$

where k_0 is the wavevector of the incident light (in air), k_{SPP} is the wave vector associated with the SPP mode, k_g is the Bragg vector of the grating and the integer m is the order of the

scattering process. The grating grooves were normal to the plane of incidence. Once excited by the incident light, SPPs can in turn be scattered by the grating and thus converted back into light which can then propagate in either the air or the silica prism, according to,

$$\pm k_{SPP} \pm mk_g = \pm nk_0 \sin\alpha \qquad (2)$$

where n is the refractive index of the medium (air or silica) through which the diffracted order propagates and α is the angle between the diffracted beam and the normal to the surface.

The light scattered back into the air interferes with the specularly reflected light and owing to the phase mismatch between the two, this interference is destructive, power is lost from the reflected beam and is instead transferred to the SPP mode. Monitoring the intensity of the specularly reflected beam allowed us to determine the fraction of incident power coupled into the SPP mode. We also measured the power radiated into the prism in the transmitted diffracted orders; through comparison with the power coupled into the SPP mode we were able to assess the efficiency with which light is transported across the silver film.

Figure 1 shows the angular dependent intensities associated with the zero-order reflected beam (R_0), the zero-order transmitted beam (T_0), and the first-order transmitted beam (T_{-1}). For the data shown the silver film had a thickness of 38 nm and the drop in the reflectivity R_0 at $\theta{\sim}22.2°$ indicates that power is coupled into the SPP mode. Similar data were acquired for silver films of different thickness ranging from 25 to 85 nm.
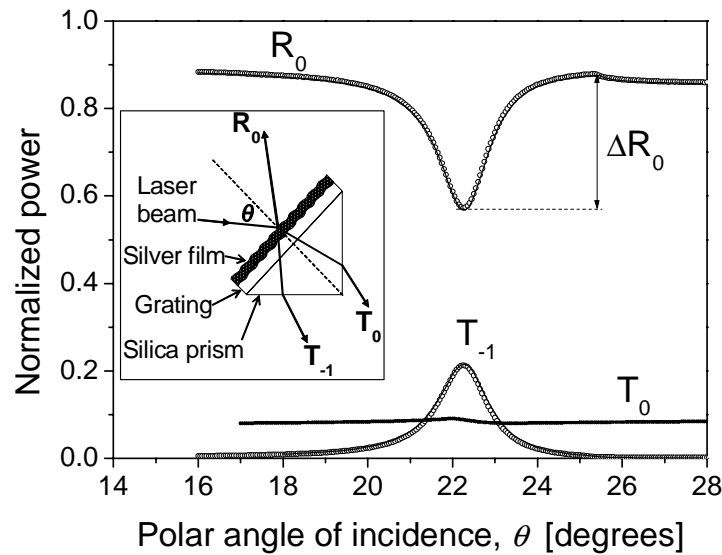

Fig. 1. Geometry of the experiment (inset) and the intensity of the diffracted orders measured for a silver film with thickness d=38 nm. The silver coated grating was produced on a planar substrate that was subsequently optically contacted onto the prism. The solid lines represent the simulation carried out using the following fitting parameters: grating amplitude a= 6.7nm, pitch p = 380nm, ε_{Ag} = -11.15+0.45i. The grating was assumed to be sinusoidal having a profile of the form $y(x) = a_0 \sin(2\pi x/p)$.

The power coupled into the SPP mode was deduced from the reflectivity data as being the difference between the reflectivity measured at the critical angle ($\theta{\sim}25.3°$) and that recorded at the reflectivity minimum, indicated by ΔR_0 in Fig. 1. The fraction of power attributed to

the radiation of light by the SPP mode into the prism was in turn deduced from the peak value of T_{-1}. The power associated with the zero-order transmitted beam, T_0, was also measured so as to account for power lost via this channel. By fitting numerically simulated data for the intensities R_0 and T_{-1} (solid lines in Fig. 1) to the experimental data using a model based on the Chandezon technique [17], the silver film thickness d and dielectric function ε_{Ag} were obtained together with the amplitude and pitch of the grating [18].

3. Discussion

The data presented in Fig. 2 show how the fraction of power associated with the different beams vary with silver film thickness, the lines indicate the predicted power of these beams calculated using the Chandezon model and are in good agreement with the experimental data. There are three features that we need to explain. First, the power associated with the zero-order transmission T_0 at the SPP coupling angle was found to fall with increasing silver film thickness. Second, the power coupled into the SPP mode, ΔR_0, was found to increase with increasing silver film thickness. Third, the power associated with the T_{-1} diffracted order exhibited a peak for a film thickness of approximately 50 nm, in agreement with the observation of Fang et al. [5].
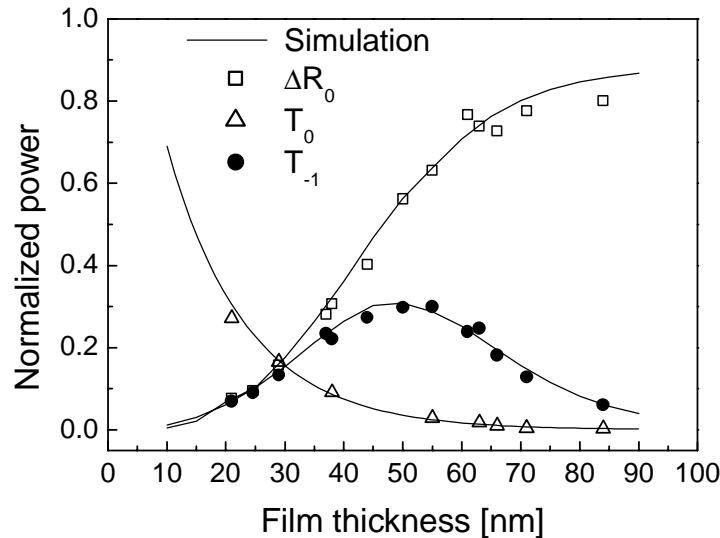

Fig. 2. Experimental data showing the power associated with the different diffracted orders ΔR_0, T_0 and T_{-1} as a function of silver film thickness. Data are shown as points, modelling as thin lines. The dielectric function for silver was taken as ε_{Ag} = -11.68+0.48i, the mean value obtained from fitting the reflectivity data.

The fall off in the zero-order transmission is primarily a consequence of absorption by the metal. In addition there is a small contribution due to light that is grating coupled into the SPP and then grating coupled back out into the T_0 beam. This can be seen in Fig. 1 as the slight modulation in T_0 as the angle is swept through the SPP coupling condition; slight on account of the conformal nature of the top and bottom profiles of the silver grating [19, 20].

To understand the increase in power coupled to the SPP as the silver film thickness increases we need to consider the effect of damping. Optimum coupling into the SPP is achieved when the rates of radiative damping and non-radiative damping are equal [21, 22].

For very thin silver films radiative damping dominates and coupling is thus not optimal; ΔR_0 is therefore small. As the thickness of the silver film rises the non-radiative damping will increase and radiative damping to diffracted orders in the prism half-space will be closed off; ΔR_0 therefore increases.

Finally we come to the key observation, that the power associated with T_{-1} beam exhibits a peak for a silver film thickness of approximately 50 nm. To understand this observation we need to consider the field enhancement associated with the SPP mode, something that is dictated by the total damping of the SPP mode. For our choice of grating amplitude the total damping falls as the film thickness increases, the increase in internal damping apparently being more than offset by the reduction in radiation damping due to the prism half-space. This fall in damping can be seen by calculating the field-enhancement factor at the silver/air interface [23], the field enhancement with respect to the incident field rises with increasing silver thickness, Fig. 3. The strength of the T_{-1} transmitted beam is proportional to the amplitude of the field associated with the silver/air SPP at the silver/glass interface. As the film thickness rises absorption in the silver acts to reduce this amplitude but better field-enhancement of the SPP mode acts to increase it. The competition between these two mechanisms results in the observed peak.
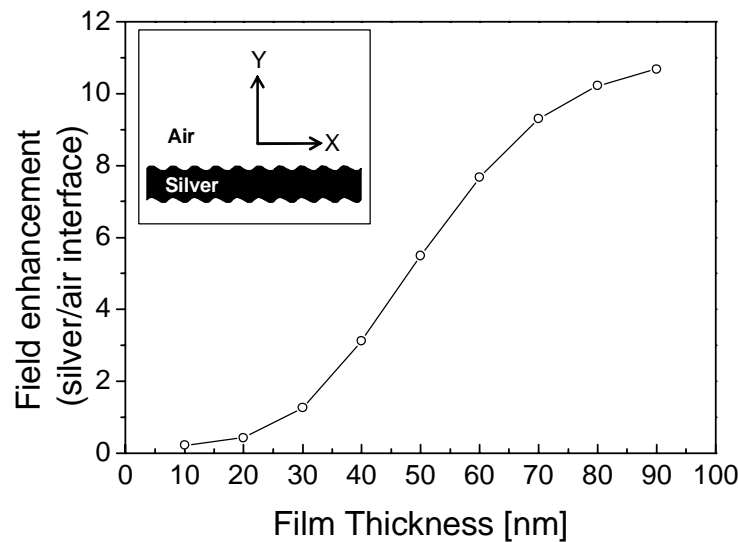

Fig. 3. Calculated field-enhancement factor for the electric field E_y as a function of silver film thickness. The behaviour of the field shown in this graph is very similar to that of ΔR_0 in Fig. 2.

A similar optimum silver film thickness is found for Kretschmann-Raether prism coupling to SPPs [21]. Light that is incident from the prism side of the metal film couples to the SPP at the silver/air interface. At the optimum silver thickness for coupling (~50 nm) the reflectivity is almost zero. Competition between absorption and field-enhancement of the SPP mode as the thickness of the silver varies leads to an optimum thickness at which the amplitude of the specularly reflected light and light that is coupled into the SPP mode and then re-radiated back into the prism are equal; since they are also out of phase cancellation gives rise to the reflectivity minimum [21, 22]. Thus the SPP mediated transmission of light through a metal film and the prism coupling to SPPs involve similar physics, competition between damping limited field-enhancement and absorption.

4. Conclusions

By bringing together experimental results and numerical modelling we have confirmed that an optimum silver film thickness exists for SPP mediated transmission of light through a thin silver film. Perhaps more importantly we find that the existence of an optimum film thickness is a consequence of two competing mechanisms, field-enhancement and absorption. We find no need to invoke the regeneration of evanescent waves proposed by Fang *et al.* [5]. In conclusion, we hope that these new results will clarify the role of evanescent waves in SPP related transmission phenomena. The competition between field-enhancement and absorption is a fascinating one relevant not just to the SPP modes of metal films but also to the localized surface plasmon resonances of metallic nanoparticles [24, 25].

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