Surface-plasmon-enhanced transmission through metallic gratings

U. Schröter and D. Heitmann
Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Jungiusstraße 11, 20355 Hamburg, Germany

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In a recent paper Ebbesen *et al.* [Nature **391**, 667 (1998)] reported on extraordinary optical transmission through hole arrays in metallic films. They suggested an enhancement of the transmission by surface plasmons. Using the Chandezon method, we have performed numerical calculations for the transmission through silver gratings with very small slits. Our results agree qualitatively with Ebbesen's measurements. By evaluating the near field in the media above and below the metal we can verify that the astonishingly high transmission maxima indeed correspond to the excitation of surface plasmons on either side of the metal.
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I. INTRODUCTION

In a recent paper Ebbesen *et al.*[1,2] report on optical transmission experiments on arrays of subwavelength cylindrical holes in metallic films. They found extraordinary high transmission efficiencies compared to standard aperture theory. The positions of the transmission maxima in wavelength and angle of incidence as well as the fact that Ge films with hole arrays show no enhanced transmission suggest that the transmission enhancement is due to the coupling of light with surface plasmons.

We have performed far and near field calculations for arrays of narrow slits and can confirm the high transmission efficiencies. In particular, our near field calculations give us detailed insight into the enhancement effect. This is actually beyond the paper of Ebbesen *et al.*[1] and may be of quite general interest since there is currently great interest in the optical properties of microstructures.[3–6] Although there is already a long tradition in the investigation of structured metallic systems,[7–11] this field of research has attracted recent interest. There are two principle aspects under which the interaction of a microstructure with light is studied: On the one hand, in media with a periodicity in the order of the light wavelength energy gaps open up in the dispersion relation for the propagation of light. On the other hand, microstructures such as apertures smaller than the wavelength of light may lead to a localization of electromagnetic fields, overcoming the diffraction limit of conventional optics. These two phenomena offer the possibility of controlling the optical properties of structured materials with the aim of application in novel photonic devices.[12]

We have calculated the zeroth order transmission through slit arrays by combining the Chandezon method[13,14] with a point matching method.[15] We consider slit arrays instead of arrays of cylindrical holes to keep the model two dimensional. The Chandezon method was originally designed for modulation gratings and has already been used to study the dispersion of surface plasmons on gratings.[14,16,17] Despite the somewhat different structure we model, our results for the zeroth order transmission efficiencies are in good qualitative agreement with Ebbesen's experimental findings.[1] The Chandezon method has the advantage that it also allows us to evaluate the near field.[16] Although slit arrays are the extreme case of modulation gratings, for the wavelengths and angles of incidence corresponding to the transmission maxima we find the enhanced field strength of the surface plasmon on either side of the grating.

II. FAR FIELD SPECTRA

The combination of the Chandezon method with the point matching method allows us to model the electrodynamic response of the grating profile shown in the inset of Fig. 1. In all the following calculations the thickness of the silver film is $h=200$ nm and the grating period is $d=900$ nm. The flat part of the grating wires is 77% of the period, but the actual slit, where the metal thickness is equal to zero, is only 3% of the period. As dielectric constants, $\epsilon=1$ for air, $\epsilon=2$ for glass, and an experimentally determined fit function $\epsilon(\lambda)$ for silver have been used (λ denotes the wavelength of the radiation). The incident plane wave is *p* polarized for the results shown in this paper. The same calculations with an *s*-polarized incident wave lead to structureless, nearly flat spectra with no peaks of enhanced transmission.

In analogy to Ebbesen's[1] Fig. 1, our Fig. 1 shows transmission spectra at normal incidence for illumination of the grating from the substrate and from the air side. In both spectra there are pronounced peaks at $\lambda=1325$ and $\lambda=963$ nm. In analogy to Ebbesen's Figs. 3 and 4, we plot

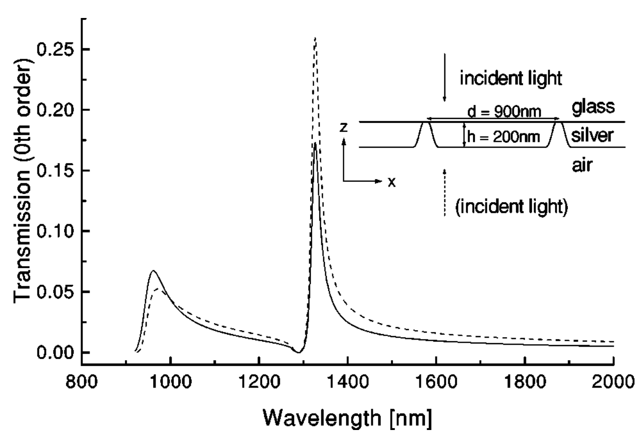

FIG. 1. Zero-order transmission spectra of a slit array for normal incidence ($\theta=0°$). Solid line: incident light from substrate side, dashed line: incident light from air side. The inset shows the shape and dimensions of the slit array.

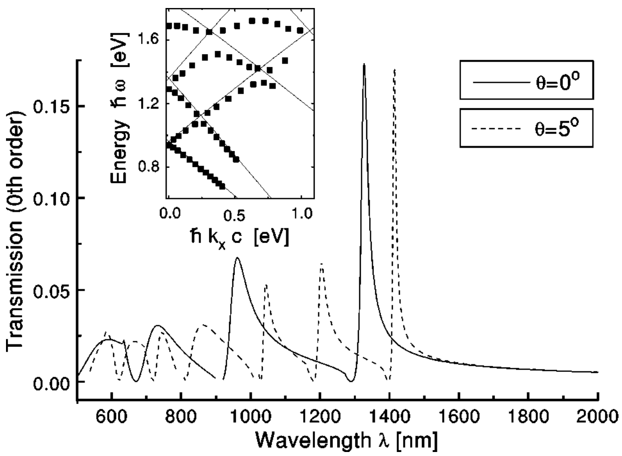

FIG. 2. Zero-order transmission spectra for $\theta = 0^o$ and $\theta = 5^o$ for incident light from the substrate side. (Inset) Squares: Dispersion of the transmission peaks for angles up to $\theta = 25^o$ plotted against the wave vector $k_x = (\omega/c) * \sin\theta$. Lines: Dispersion relation for surface plasmons on flat metal-air and metal-glass surfaces backfolded into the first Brillouin zone.

spectra for different angles of incidence and the dispersion of the peak positions in our Fig. 2. The transmission maxima are easily associated with surface plasmons. We recognize the steeper branches of the silver-air-plasmon beginning at 1.30 eV as well as the flatter branches of the silver-glass-plasmon beginning at 0.94 and 1.70 eV; these branches arise from backfolding of the plasmon dispersion of a flat silver surface by $n = 1$ or $n = 2$ reciprocal lattice vectors. The grating coupler accounts for the shift $\hbar k_x = n * 2\pi\hbar/900$ nm in the lateral momentum. Anticrossing is observed at $\hbar k_x c = 0.7$ eV, $\hbar\omega = 1.4$ eV, and $\hbar k_x c = 0.3$ eV, $\hbar\omega = 1.6$ eV, indicating the photonic bandgap effect of the periodic array.[8,9,18] At $\hbar k_x c = 0.3$ eV, $\hbar\omega = 1.6$ eV the coupling even occurs between modes on different sides of the grating.[2] The lines in the inset are the dispersion relations for surface plasmons on flat metal-air and metal-glass surfaces backfolded into the first Brillouin zone. They do not differ much from the light lines in the energy region shown. For the lower branches the transmission peaks follow the dispersion for surface plasmons on flat surfaces, whereas the higher branches become significantly flatter for our high amplitude grating.

The transmission is of the order of 10% for the two peaks in Fig. 1. If we normalize this to the width of the slits, which is about 3% of the period, we get an enhancement of the transmission of roughly 3. Ebbesen *et al.*[1] get transmission enhancements of about 2 from the spectrum in their Fig. 1. But as the walls of our slits are assumed to be not absolutely vertical, the ''effective'' slit width is likely to be a little greater than 3% of the period.

The two transmission spectra in Fig. 1 for illumination of the grating from different sides are very similar, but they are not identical. Ebbesen *et al.*[1,2] got exactly identical spectra regardless of whether their sample was illuminated from the glass or the air side. It is astonishing that this holds true for antidot arrays, but it need not generally be the case. As for a grating besides the incident beam and the zeroth order transmission beam there are diffraction orders, measuring the zeroth order transmission for illumination from different sides of the sample is not equivalent to simply reversing the light path. For each of the two peaks in Fig. 1 the situation is different for the two curves insofar as the plasmon is on the illumination side of the grating for one curve and on the transmission side for the other. The peak at $\lambda \approx 963$ nm (silver-air-plasmon) is slightly shifted in the wavelength when the direction of the illumination is changed. This could be due to the fact that there is only the zeroth transmission order in air for illumination from the glass side whereas for illumination from the air side there already exist the two first diffraction orders in glass. We have performed transmission experiments on periodically modulated silver films and obtained transmission spectra that are not absolutely identical for both directions of the light.

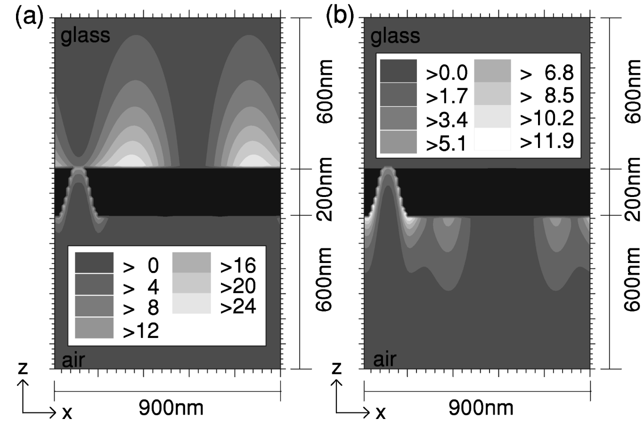

FIG. 3. Normalized near field intensities along one grating period in glass and air for normal incidence ($\theta = 0^o$) from glass side. (a) $\lambda = 1325$ nm (silver-glass-plasmon). (b) $\lambda = 963$ nm (silver-air-plasmon).

III. NEAR FIELD DISTRIBUTION

With our method we now have the possibility to investigate in detail the origin of the transmission enhancement. In Fig. 3 we plot the near fields in glass and air corresponding to the two transmission maxima of Fig. 1 for $\theta = 0^o$. The intensities have been normalized to the intensity of the incoming plane wave. Indeed, in Figs. 3(a) and 3(b) we find strong field enhancements on the glass and on the air side of the metal, respectively, indicating the excitation of surface plasmons. In both cases the highest field strengths on the air side are obtained at the edges of the holes, but surprisingly the field strength is quite low inside the holes. This holds true for transmission maxima at any angle of incidence and of any order, and it is in contrast to Ebbesen's[1,2] suggestion that there is a microcavity effect and strong scattering in the holes. Nevertheless, the light is transferred through the holes as indicated by the field enhancements at the edges and the much lower field strengths at the metal-air interface towards the middle of the grating wires. Even in the case of the silver-air-plasmon, where the surface plasmon is not on the illumination side, but on the transmission side of the grating, the field strength at the metal-air-interface decreases considerably in the middle of the grating wires. And after all, the 200 nm metal film is too thick for direct transmission or surface plasmon excitation in an attenuated total reflection configuration[10,11,19] anyway.

In Fig. 4 we plot the intensity of the electric field on the air side up to a distance of 3 μm from the grating to study

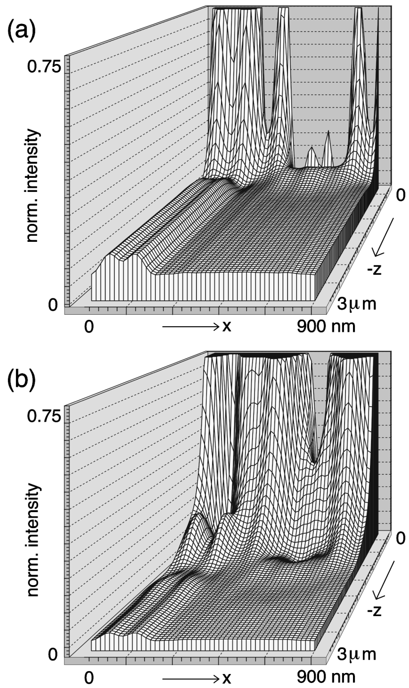

FIG. 4. Normalized near field intensities for normal incidence from the glass side as in Fig. 3, plotted for 3 μm on the air side. (a) λ = 1325 nm (silver-glass-plasmon). (b) λ = 963 nm (silver-air-plasmon).

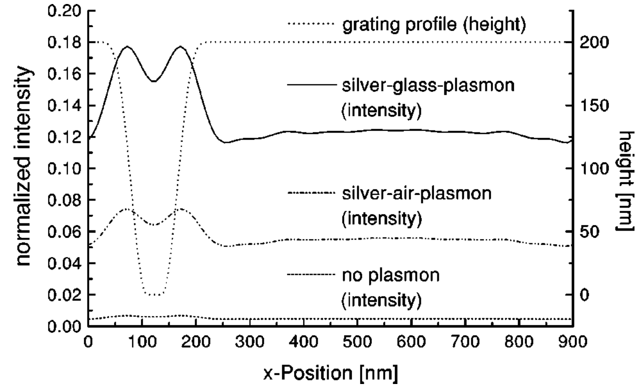

FIG. 5. Normalized field intensities (left vertical axis) along one grating period at 3 μm to the air side of the grating. Solid line: λ = 1325 nm (silver-glass-plasmon). Dashed-dotted line: λ = 963 nm (silver-air-plasmon). Dashed line: λ = 1240 nm (no plasmon). Dotted line: grating profile (right vertical axis).

the transition from the near to the far field. The intensity scale has been cut at 0.75 to show the small scale structures further away from the metal-air-interface. Cross sections of the transmitted fields are plotted in Fig. 5. For the wavelengths corresponding to the transmission peaks of Fig. 1, the far field has two characteristic features: a double maximum at the position of the hole edges and a clearly enhanced value over the rest of the grating period. The field strength is much lower for a wavelength at which there is very little transmission. Of course, the grating is needed to couple the surface plasmons with purely inplane momentum to light of the zeroth diffraction order. As transmission mechanism, however, the near field plots suggest that the surface plasmons ''creep up'' the walls of the holes[4] and round the corners rather than scattering in the holes.

IV. CONCLUSIONS

We have presented numerical calculations for the optical transmission through metallic slit gratings, and we found the same extraordinary transmission through very small holes which Ebbesen *et al.*[1,2] observed for two-dimensional hole arrays in metal films. Evaluation of the near field clearly shows that the light is coupled via surface plasmons.

ACKNOWLEDGMENTS

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