Transmission Resonances on Metallic Gratings with Very Narrow Slits

J. A. Porto,[1,*] F. J. García-Vidal,[2] and J. B. Pendry[1]
[1]*Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom*
[2]*Departamento de Física Teórica de la Materia Condensada, Facultad de Ciencias (C-V), Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
(Received 14 April 1999)

Transmission metallic gratings with very narrow and deep enough slits can exhibit transmission resonances for wavelengths larger than the period of the grating. By using a transfer matrix formalism and a quasianalytical model based on a modal expansion, we show that there are two possible ways of transferring light from the upper surface to the lower one: by the excitation of coupled surface plasmon polaritons on both surfaces of the metallic grating or by the coupling of incident plane waves with waveguide resonances located in the slits. Both mechanisms can lead to almost perfect transmittance for those particular resonances.

PACS numbers: 78.66.Bz, 42.79.Dj, 71.36.+c, 73.20.Mf

For decades, it has been thought that subwavelength apertures have a very low transmission efficiency of light [1]. However, very recently, several experiments have shown that, if holes are structured forming a 2D periodic array in a metallic film, extraordinary optical transmission can be obtained at wavelengths up to 10 times larger than the diameter of the holes [2]. It has already been proposed that this effect could be exploited in different important technological areas such as photolithography or near field microscopy, or even to extract light from light emitting diodes [3]. Although experiments suggest that the excitation of surface plasmon polaritons (SPPs) in the metallic interfaces of the film plays a crucial role in this effect, a detailed understanding of the physical mechanism behind the enhanced transmission has not been reported yet.

In this Letter we propose a simpler alternative structure in which similar extraordinary optical transmission effects can also been found and hence used for practical purposes: transmission metallic gratings with very narrow slits. We will show how, for particular wavelengths, incident light can excite surface electromagnetic modes of the gratings that are able to reemit the absorbed light in the forward direction with almost 100% efficiency. Moreover, a detailed study of these transmission resonances will provide physical insight into the mechanism of the extraordinary transmission in 2D hole arrays.

Reflection metallic gratings have been analyzed for many years, mainly in connection with the study of SPPs and/or localized electromagnetic modes of the grooves [4–9]. With regard to transmission gratings, there have been some theoretical works in the past few years [10,11]. However, transmission gratings with very narrow slits remain unstudied, except for a very recent calculation of the optical transmission properties of a silver grating having the same geometrical parameters of the 2D hole arrays of Ref. [2] and with a special geometry for the slits [12]. The scope of this Letter is, however, different: we do not pretend to fit the experiments on 2D hole arrays because this is a different geometry. Instead, we are interested in analyzing the coupling between the SPPs of the two metallic interfaces of the grating as a possible mechanism to enhance optical transmission through perforated metallic films. We also study, for the first time, the transmission properties of waveguide modes excited in very narrow slits that are periodically structured.

On top of Fig. 1 we show a schematic view of the structures under study with the definition of the different parameters: the period of the grating (d), the width (a), and height (h) of the slits. The substrate is characterized by a dielectric constant, ϵ. Advances in material technology have allowed the production of transmission gratings with well-controlled profiles [13]. In this Letter we consider metal gratings made of gold and we use a fixed value for the grating period ($d = 3.5\ \mu$m). We will only show the results for $a = 0.5\ \mu$m, although the dependence of the transmission resonances on a is also addressed. The thickness of the metallic grating (h) will be varied between 0 and 4 μm. We believe this range of geometrical values can be reached using present day technology, as reflection gratings with similar parameters have already been prepared [9]. Nevertheless, it should be pointed out that the effects discussed in this Letter do appear for any other range provided a is very small in comparison to d and the frequency of the incident light is well below the plasma frequency of the metal. The dielectric function of gold is described using the tables reported in Ref. [14].

We have analyzed the electromagnetic properties of these gratings by means of a transfer matrix formalism [15]. Within this formalism it is possible to calculate transmission and reflection coefficients for an incoming plane wave. Subsequently, the transmittance and reflectance of the grating as well as real-space electromagnetic fields can be calculated. Figure 1 shows zero-order transmittance for p-polarized normal incident radiation on metallic gratings in vacuum as a function of the wavelength of the incoming

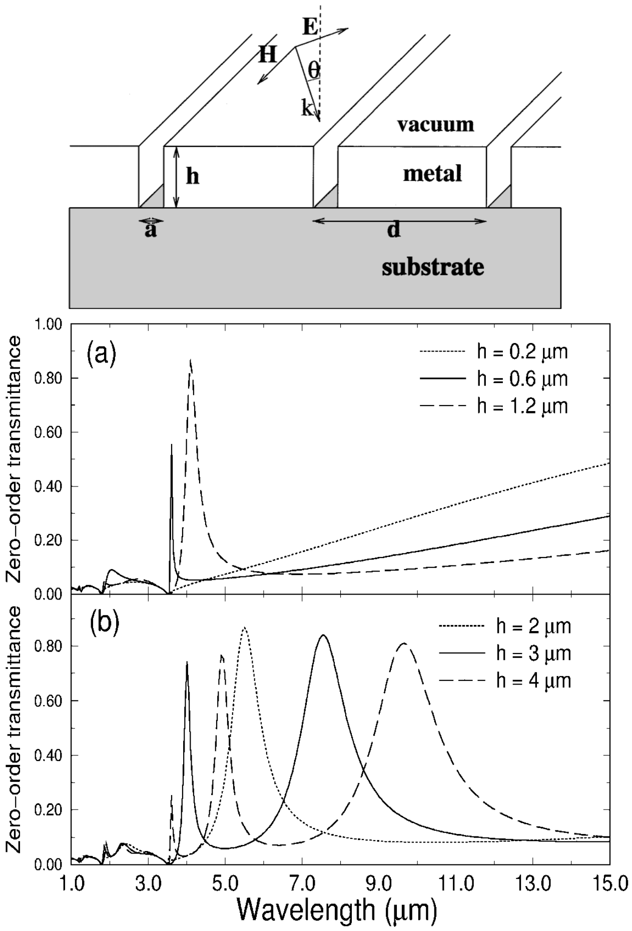

FIG. 1. Top: Schematic view of the lamellar transmission metallic gratings studied in this paper (see text). Zero-order transmittance for a normal incident plane wave calculated by means of the transfer matrix formalism for lamellar metal gratings in vacuum ($d = 3.5$ μm, $a = 0.5$ μm) for different values of the grating height (h), ranging from 0.2 to 4.0 μm.

plane wave. The grating height (h) is varied in these calculations from 0.2 to 4 μm. As can be seen in Fig. 1a, for deep enough gratings ($h \geq 0.6$ μm) a remarkable transmission peak appears for a wavelength slightly larger than the grating period (in this case, 3.5 μm). This transmission peak moves to larger wavelengths as the grating height increases, whereas its linewidth is broadened. And, as illustrated in Fig. 1b, subsequent peaks emerge for deeper gratings.

In order to analyze the physical origin of these transmission resonances, we have also developed an approximated modal method. We incorporate two main simplifications to the exact modal method reported in [16]. First, as the frequency regime we are interested in is below the plasma frequency of the metal, surface-impedance boundary conditions [10] are imposed on the metallic boundaries, except on the vertical walls of the slits which are treated as perfect metal surfaces. Second, we consider only the fundamental eigenmode in the modal expansion of the electric and magnetic fields inside the slits, which is justified in the limit where the wavelength of light is much larger than the width of the slits. Within this single-mode approximation, the two field amplitudes inside the slits (the one associated with the $e^{ik_0 z}$ wave and the other with the $e^{-ik_0 z}$ wave) are proportional to $1/D$, where the denominator D is given by

$$D = [1 - (1 + \eta)\phi][1 - (1 + \eta)\psi]e^{ik_0 h} - [1 + (1 - \eta)\phi][1 + (1 - \eta)\psi]e^{-ik_0 h}, \quad (1)$$

with $k_0 = 2\pi/\lambda$, $\eta = \epsilon_{\mathrm{metal}}^{-1/2}$, and ψ given by the following sum:

$$\psi = \frac{a}{d}\,\epsilon \sum_{m=-\infty}^{\infty} \frac{[\mathrm{sinc}(\frac{k_0 \gamma_m a}{2})]^2}{(\epsilon - \gamma_m^2)^{1/2} + \epsilon\eta}, \quad (2)$$

where ϵ is the dielectric constant of the substrate, $\mathrm{sinc}(\xi) \equiv \sin(\xi)/\xi$, and $\gamma_m = \sin\theta + m\frac{\lambda}{d}$ is associated with the mth diffraction order. The quantity ϕ is also given by Eq. (2) but with $\epsilon = 1$. It can be shown that zero-order transmittance is just inversely proportional to $|D|^2$ and hence transmission spectrum of the grating is completely governed by the behavior of the denominator D. Moreover, we have found that there is a close correspondence between the maxima of zero-order transmittance and spectral positions of the zeros of the imaginary part of D, $\Im(D)$. This result allows us to analyze the nature of the electromagnetic modes responsible for the transmission resonances shown in Fig. 1 just by studying the zeros of $\Im(D)$ as given by Eq. (1). Also, by varying the angle of incidence θ we can calculate the photonic band structure, $\omega(k_x)$, of these surface excitations. In Fig. 2a we show the photonic band structure for a grating in vacuum ($\epsilon = 1$) and $h = 0.6$ μm (black dots) and, for comparison, the energetic positions of the SPP excitation for a nearly flat metal surface (gray dots). Note that, due to the range of photon energies we are analyzing, these SPP frequencies almost coincide with the energetic positions of the Rayleigh anomalies [4]. As can be seen in the inset of Fig. 2a, a very narrow band gap between the first and second bands appears in the spectrum. The lower branch at $k_x = 0$ is associated with the transmission peak at λ close to d in Fig. 1a. Its close proximity to the energy of SPP bands suggests that this transmissive mode is associated with the excitation of an electromagnetic mode with a SPP character in each surface (top and bottom) of the grating. From now on, we name this kind of resonances as *coupled SPPs.* As h is increased, new bands, as we will show later are associated with waveguide modes of the slits, appear in the spectrum. This can be seen in Fig. 2b which shows that for $h = 3$ μm a flat band is present at $\omega = 0.17$ eV. This localized mode is responsible for the transmission peak located at $\lambda = 7.5$ μm (see Fig. 1b). The other transmission resonance obtained for $h = 3$ μm at $\lambda \approx 4$ μm corresponds to the lower branch of the first band gap. Therefore we conclude that transmission resonances appearing in Fig. 1 are due mainly to the excitation of two types of electromagnetic modes: coupled SPPs for $\lambda \approx d$

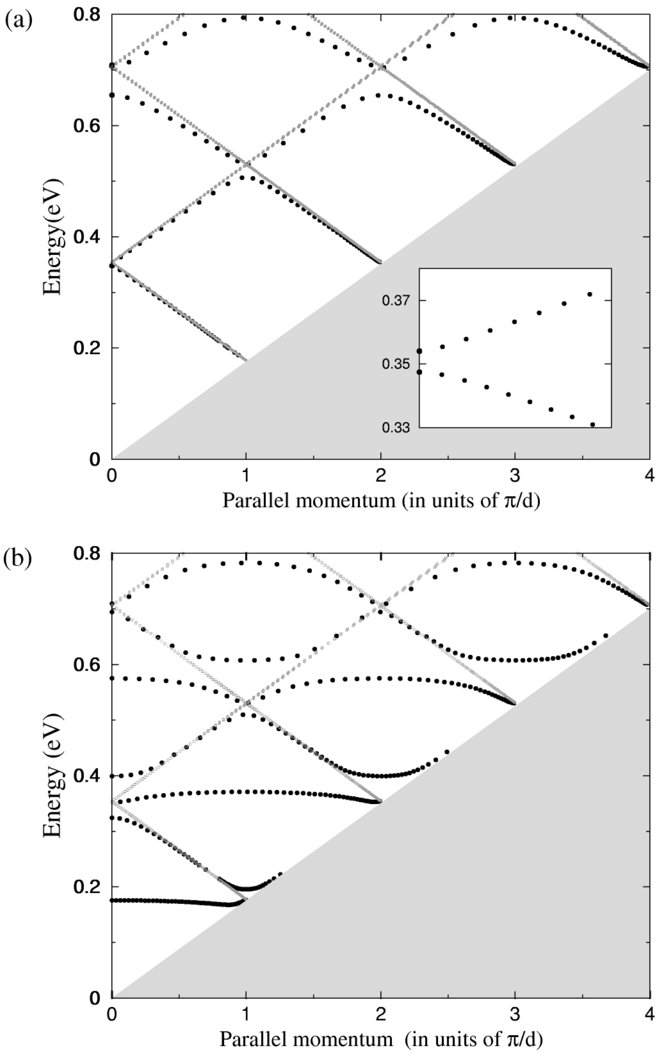

FIG. 2. Photonic band structure (black dots) of the surface plasmons responsible for the transmission resonances appearing at (a) $h = 0.6\ \mu$m and (b) $h = 3\ \mu$m. In the same figure we plot the energetic positions (gray dots) of SPPs in the limit $h \rightarrow 0$. These bands are calculated using the simplified modal method. In the inset of (a) we show a closed-up picture of the opening of the first band gap for this case.

and waveguide resonances for $\lambda \gg d$. Besides, a totally different dispersion relation for these two types of modes is clearly seen in Fig. 2. Then, transmittance associated with coupled SPPs will show a strong dependence on θ, whereas for waveguide resonances the transmission will be almost independent of θ.

Using the simplified modal method, we have also studied in detail the behavior of transmission resonances as a function of the width of the slits, a. The main results of our analysis are the following: for the case of transmission resonances linked to coupled SPPs a minimum value of a is needed in order to couple SPPs of each surface of the grating and hence to excite the corresponding transmissive mode. Above this threshold (whose value depends on the depth of the slits and, for $h = 0.6\ \mu$m, is about $0.2\ \mu$m), the resonance is extremely narrow and is broadened as a is increased. For example, for $h = 0.6\ \mu$m the linewidth increases from 10 nm for $a = 0.25\ \mu$m to 30 nm for $a = 0.5\ \mu$m. Narrowness of these transmission resonances could be used to filter electromagnetic radiation for wavelengths close to the period of the grating. Besides, even for extremely narrow slits, the transmissivity of the transmission resonances linked to waveguide modes could be close to 1. In this limit ($a \rightarrow 0$), the wavelength of the resonance tends to $2h$ (that corresponds to the first zero of $\sin k_0 h$) and its linewidth goes to zero. As in the case of coupled SPPs, the transmission resonances associated with waveguide modes are broadened as the width of the slits is increased.

Finally, two questions remain to be answered: How is light transmitted from one side of the metallic grating to the other one by these electromagnetic modes? What is the difference in the transmission process between the two mechanisms mentioned above? In order to answer these questions, we show in Fig. 3 detailed pictures of the **E** field for two cases, both with $a = 0.5\ \mu$m: (a) $h = 0.6\ \mu$m and $\lambda = 3.6\ \mu$m (which corresponds to coupled SPPs) and (b) $h = 3.0\ \mu$m and $\lambda = 7.5\ \mu$m (example of waveguide resonance). As can be seen in Fig. 3a, the normal incident plane wave is exciting first a SPP in the upper metal surface. Although metal thickness is much larger than the skin depth of gold, this SPP couples with the corresponding SPP mode of the lower metal surface through the slits of the grating. The SPP mode of the lower surface can then match to an outgoing propagating plane wave of the same frequency and momentum as the incident one, leading to a large transmittance. Because of the nature of this process, these transmission resonances are very sensitive to the presence of a substrate in the lower surface: when energies of the two SPPs involved do not coincide, the coupling between them is less effective. As a consequence, two nondegenerate transmissive modes (instead of only a degenerate one, as seen for $\epsilon = 1$) appear in the photonic spectrum. The decoupling process is accompanied by a reduction in the transmissivity of the modes, reduction that depends strongly on ϵ (less transmittance as ϵ increases) and the height of the slits.

We believe that electromagnetic modes of a nature similar to coupled SPPs in transmission gratings are responsible for the extraordinary optical transmission reported in 2D hole arrays [2]. There are several facts which support this belief. The positions of the transmission peaks in both structures (hole arrays and transmission gratings) are determined mainly by the periodicity of the system and refraction index of the substrate and are almost independent of the diameter of the holes or the slits' width and of the particular metal used. Besides, dispersion of the transmission peaks in 2D hole arrays as a function of incident angle [2] is quite similar to the one obtained for coupled SPPs in transmission gratings (see Fig. 2a). However, hole arrays and gratings are two different geometries and the correspondence between both systems must be established with certain caveats.

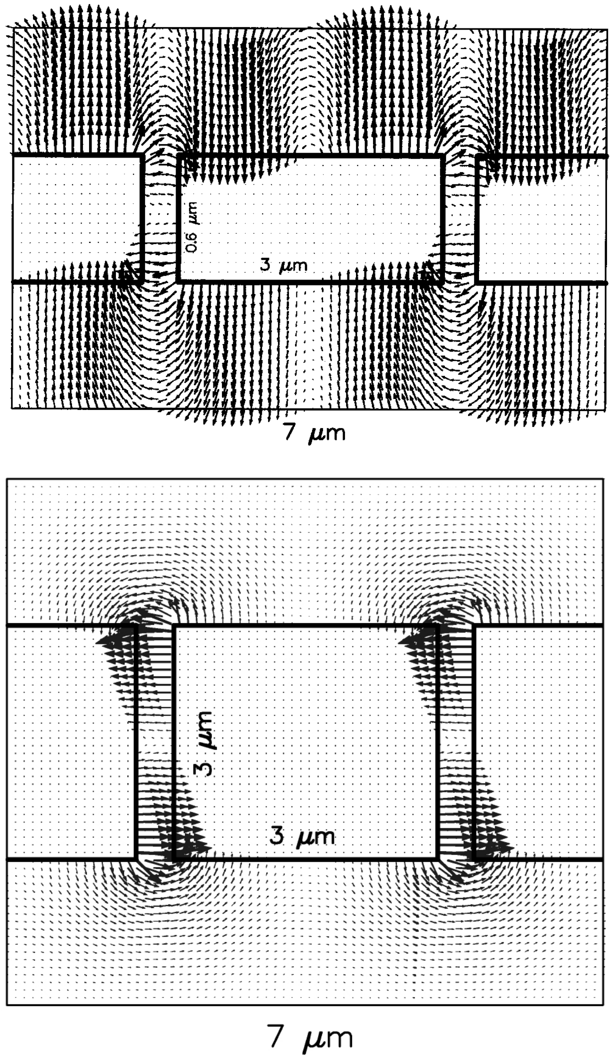

FIG. 3. Detailed pictures of the **E** field over two periods of transmission metal gratings ($d = 3.5$ μm, $a = 0.5$ μm) of thickness, (a) $h = 0.6$ μm and (b) $h = 3.0$ μm in vacuum. The wavelengths of the normal incident radiation are for (a) $\lambda = 3.6$ μm and (b) $\lambda = 7.5$ μm, which correspond to the different transmission peaks shown in Fig. 1. These **E** fields have been obtained with the transfer matrix formalism.

The transmission process associated with waveguide modes is completely different from the one obtained for coupled SPPs. As shown in Fig. 3b, for these electromagnetic modes only the metal walls of the slits play an active role. Incident light induces current densities flowing parallel to the slits' walls, having different signs on the two opposite surfaces of the slits. Therefore, and different from coupled SPPs, the transmittance associated with these waveguide resonances is not very sensitive to the refraction index of the substrate. It is interesting to point out that experimental evidence of the excitation of similar waveguide modes in reflection gratings has been recently given [9]. In these systems, their excitation provokes a strong absorption of light, concentrated mainly in the grooves. Remarkably, in transmission gratings these localized modes are able to reemit the absorbed light in the forward direction with a very high efficiency.

In conclusion, we have shown how, for transmission metallic gratings with very narrow and deep enough slits, almost perfect transmission resonances appear for wavelengths larger than the period of the grating. Their properties are controlled mainly by just geometrical factors: spectral location of the transmission peaks can be selected with the period of the grating and the height of the slits, whereas their linewidths can be tuned by varying the width of the slits. These extraordinary transmission properties could have important applications: for example, they could be used to overcome present limitations in photolithography or to geometrically filter electromagnetic radiation with no diffractive effects. Moreover, if the grating is deep enough so that transmissive waveguide modes can be excited, a narrow band of wavelengths may be transmitted over the whole range of incident angles.

We are indebted to J. Sánchez-Dehesa and T. López-Ríos for many helpful discussions, and L. Martín-Moreno and J. J. Greffet for a critical reading of the manuscript. We also acknowledge partial financial support from the Acciones Integradas Program under Contract No. HB-1997-0032. J. A. P. also acknowledges financial support from the Ministerio de Educación y Cultura of Spain.

*Present address: Laboratoire EM2C, Ecole Centrale Paris, F-92295 Châtenay-Malabry Cedex, France.

[1] H. A. Bethe, Phys. Rev. **66**, 163 (1944).
[2] T. W. Ebbesen *et al.*, Nature (London) **391**, 667 (1998); H. F. Ghaemi *et al.*, Phys. Rev. B **58**, 6779 (1998); T. J. Kim *et al.*, Opt. Lett. **24**, 256 (1999).
[3] J. R. Sambles, Nature (London) **391**, 641 (1998); P. R. Villeneuve, Phys. World **11**, 28 (1998).
[4] H. Räther, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer-Verlag, Berlin, 1988).
[5] W. L. Barnes *et al.*, Phys. Rev. B **51**, 11 164 (1995); W. L. Barnes *et al.*, Phys. Rev. B **54**, 6227 (1996).
[6] F. J. García-Vidal and J. B. Pendry, Phys. Rev. Lett. **77**, 1163 (1996).
[7] A. A. Maradudin, A. V. Shchegrov, and T. A. Leskova, Opt. Commun. **135**, 352 (1997).
[8] M. B. Sobnack *et al.*, Phys. Rev. Lett. **80**, 5667 (1998).
[9] T. López-Rios *et al.*, Phys. Rev. Lett. **81**, 665 (1998).
[10] H. Lochbihler and R. A. Depine, Appl. Opt. **32**, 3459 (1993); H. Lochbihler, Phys. Rev. B **50**, 4795 (1994).
[11] J. J. Kuta *et al.*, J. Opt. Soc. Am. A **12**, 1118 (1995).
[12] U. Schröter and D. Heitmann, Phys. Rev. B **58**, 15 419 (1998).
[13] M. L. Schattenburg *et al.*, Opt. Eng. **30**, 1590 (1991).
[14] *Handbook of Optical Constants of Solids,* edited by E. D. Palik (Academic, Orlando, 1985).
[15] J. B. Pendry, J. Mod. Opt. **41**, 209 (1994); P. M. Bell *et al.*, Comput. Phys. Commun. **85**, 306 (1995).
[16] P. Sheng, R. S. Stepleman, and P. N. Sanda, Phys. Rev. B **26**, 2907 (1982).