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Optical transmission through subwavelength metallic gratings

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We present measurements of enhanced resonant transmission of infrared radiation through subwavelength metallic gratings made of rectangular grooves. This is achieved either by exciting a resonant waveguide mode in the cavities, or when the field is large enough above the groove, which is particulary satisfied close to surface plasmon excitation conditions at the air/metal interface. Moreover, we show that a model with plasmons on the incident side only explains this result very well.

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The transmission of infrared radiation through metal films is governed by their highly negative dielectric constant which leads to a skin depth of only a few nanometers, independent of the wavelength. Consequently, metal films are almost opaque, the electromagnetic waves in the film are evanescent, and the transmission through the film is only possible by tunneling. Under some conditions, transmission can be enhanced by resonant tunneling. This is the case, for instance, if two metallic films are separated by a distance corresponding to a Fabry-Perot cavity. Another type of resonant tunneling transmission occurs when surface plasmons exist at both surfaces of the thin film at the frequency of the impinging wave. In this case, an attenuated total reflection (ATR) configuration or a corrugated surface is necessary in order to provide the momentum to excite the surface plasmons. Experimental evidence for enhanced transmission through a flat thin film by surface plasmons resonance was provided by Dragila *et al.*,[1] using ATR configuration.

Recently, the origin of the high transmission through holes of lateral dimensions smaller than the incident wavelength, observed on opaque metallic films,[2] has been the subject of important debate.[3–5] It is generally admitted that this enhanced transmission is related to resonances which can localize a tremendous amount of electromagnetic energy in holes or slits with dimensions much smaller than the wavelength, an effect very interesting in many respects. A key point actively discussed so far is the role played by surface plasmons on the enhanced transmission. In spite of active investigations of this topic, a well-established response to these questions is still missing. Recently, through the consideration of air/metal/air interfaces with slits geometry, Porto *et al.*[3] proposed that two separate mechanisms were important: either the excitation of a *cavity resonant mode*, or *resonant coupling between plasmons on both sides*. These latter modes, which also occur for two dimensional gratings with holes, were called "molecular plasmons" by Moreno *et al.*[4] This mechanism was extended to uncoupled surface plasmons when the difference of dielectric constant between medium (I) and (III) (see Fig. 1) is high.[3]

The results presented in this report are based on measurements and calculations performed on the particular device shown in Fig. 1(b), to check the possible mechanisms. The samples were prepared by standard electron-beam lithography: a 1-μm-thick SiO_2 layer was thermally grown on a Si substrate and covered by an electronegative resist. The surface was illuminated by an electron beam realizing straight parallel lines of nominal width $w=0.9$ μm separated by a periodic distance $d=1.75$ μm. The irradiated resist and the SiO_2 beneath it were etched away by SF_6 reactive ion etching down to the Si interface, producing the rectangular profile of height 1 μm, as shown in Fig. 1(a). The obtained structured surface was then metallized by evaporating a gold layer 60 nm thick (thicker than the skin depth of light). The bottom of the grooves was preserved from gold coverage by a self-shading effect: the evaporation was done by tilting the sample successively through an angle $\pm\alpha$ whose value was roughly $\alpha=\arctan(w/h)$. The final height of the groove is given by the height of the gold coating along the vertical walls, here $h=0.96$ μm. The transmission was measured for p-polarized light (magnetic field perpendicular to the plane of incidence) impinging the sample with an angle of $\theta=0$.

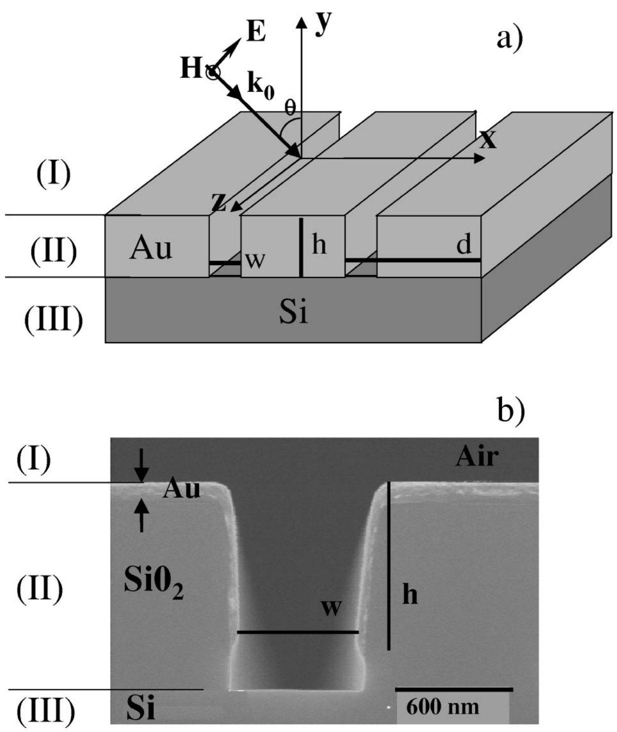

FIG. 1. In (a) geometrical configuration and parameters used with $d=1.75$ μm, $w=0.61$ μm and $h=0.96$ μm; (b) SEM picture of the gratings studied showing one cavity.

As the skin depth is smaller than the gold coating, our sample is equivalent to those depicted in Fig. 1(a), *without the Si/metal interface on the bottom*. Thus modes related to this interface, namely surface plasmons, cannot exist in our case. Consequently, this eliminates *de facto* the transmission mechanism described above, i.e., surface plasmons on both sides coupled through the slit. Therefore, to gather more insight on the physics of the problem, we have performed calculations based on the well-known *exact* modal expansion, originally developed by Sheng.[6] We used the surface impedance approximation, which is an approximate version of Sheng's method and has been fully described by Wirgin *et al.*[7] in the case of reflectivity of metallic gratings. This approximation is used for the horizontal interfaces, while the vertical walls in the slits are supposed to be perfectly metallic. With this approximation, the electromagnetic problem can be solved without taking into account the waves in the metal, and the field has to be determined only in the air and the silicium. The geometry and notations are sketched in Fig. 1(a). For commodity, we used a geometry different from the experimental, since we take a metal/Si interface at $y=-h$ in our calculations symmetrical to the air/metal interface at $y=0$. We show later that our model describes perfectly the experimental data, provided that we "remove" from our calculations the effects due to the excitation of the metal/Si interface plasmons to come back to the experimental geometry.

The z-component of the magnetic field, which is the only relevant one in our geometry, is a Bloch wave and can be expanded in Fourier series in two regions of space: region (I) for $y\geqslant 0$ and region (III) for $y\leqslant -h$. For the region (II) inside the slits $(-h\leqslant y\leqslant 0)$, we use a modal expansion.[6,7] Thus the field is expressed in the three regions as:

$$H_z^{(I)}(x,y)=e^{ik_0(\gamma_0 x-\beta_0 y)}+\sum_{n=-\infty}^{+\infty} R_n e^{ik_0(\gamma_n x+\beta_n y)},$$

$$H^{(II)}{}_z(x,y)=\sum_{n=0}^{+\infty}\cos\left[\frac{n\pi}{w}\left(x+\frac{w}{2}\right)\right](A_n e^{i\mu_n y}+B_n e^{-i\mu_n y}),$$

$$H_z^{(III)}(x,y)=\sum_{n=-\infty}^{+\infty} T_n e^{ik_0(\gamma_n x-n_3\beta_{n,t}(y+h))}. \qquad (1)$$

$\mu_n^2=k_0^2-(n\pi/w)^2$. In (I) and (III) $\gamma_n=\sin\theta+n\lambda/d$, $k_0=2\pi/\lambda$, $\beta_n^2=1-\gamma_n^2$, and $\beta_{n,t}^2=1-(\gamma_n/n_3)^2$ ($n_3^2=\epsilon_3$ is the dielectric constant of Si). $\{R_n,T_n\}$ are, respectively, the reflected and transmitted wave amplitudes, while $\{A_n,B_n\}$ are the amplitude waves in the slits. The analytic expression of all these complex coefficients is obtained from the four impedance boundary conditions at the two boundaries given by the following expressions.[7] For $x\in[-d/2,+d/2]$, one has:

$$\left(\frac{\partial H_z^{(I)}}{\partial y}+ik_0(Z/Z_1)H_z^{(I)}\right)_{y=0^+}=\left(\frac{\partial H_z^{(II)}}{\partial y}+ik_0(Z/Z_1)H_z^{(II)}\right)_{y=0^-},$$

$$\left(\frac{\partial H_z^{(II)}}{\partial y}+in_3k_0(Z/Z_3)H_z^{(II)}\right)_{y=-h^+}=\left(\frac{\partial H_z^{(III)}}{\partial y}+in_3k_0(Z/Z_3)H_z^{(III)}\right)_{y=-h^-}, \qquad (2)$$

and for $x\in[-w/2,+w/2]$, one gets:

$$H_z^{(I)}(x,0^+)=H_z^{(II)}(x,0^-)\quad\text{and}$$

$$H_z^{(II)}(x,-h^+)=H_z^{(III)}(x,-h^-). \qquad (3)$$

In Eq. (2), Z, Z_1, and Z_3 are the surface impedances of metal, air, and silicium, respectively, which are given by $Z_i=\sqrt{\mu_0\mu_i/\epsilon_0\epsilon_i}$ for the media $i=1,3$, with magnetic permitivity $\mu_i=1$ and dielectric constant ϵ_i ($\epsilon_1=1$ and $\epsilon_3=11.70$). The values of the complex dielectric constant $\epsilon(\lambda)$ of gold are taken from Ref. 10.

We have first restrained the modal expansion to the first term $n=0$. Using this assumption, one gets all the coefficients necessary to determine the field in any point of space:

$$A_0=\frac{[2\beta_0S_0/(\beta_0+Z/Z_1)][1-D_3^+]}{[1-D_1^+][1-D_3^+]-e^{-2ik_0h}[1+D_1^-][1+D_3^-]}$$

$$B_0=\frac{[-2\beta_0S_0/(\beta_0+Z/Z_1)]e^{-2ik_0h}[1+D_3^-]}{[1-D_1^+][1-D_3^+]-e^{-2ik_0h}[1+D_1^-][1+D_3^-]}, \qquad (4)$$

with,

$$D_1^{\pm}=(1\pm Z/Z_1)\Gamma\sum_{n=-\infty}^{+\infty}[S_n^2/(\beta_n+Z/Z_1)]$$

$$D_3^{\pm}=(1\pm Z/Z_1)\Gamma\sqrt{\varepsilon_3}\sum_{n=-\infty}^{+\infty}[S_n^2/(\beta_{n,t}+Z/Z_3)].$$

$\Gamma=w/d$ and $S_n=\mathrm{sinc}(\gamma_nk_0w/2)$. Using these formulas, we obtain the reflection and transmission coefficients of any order:

$$R_m=\left(\frac{\beta_0-Z/Z_1}{\beta_0+Z/Z_1}\right)\delta_{m,0}+\frac{\Gamma}{\beta_m+Z/Z_1}S_m\times[A_0(1+Z/Z_1)-B_0(1-Z/Z_1)], \qquad (5)$$

$$T_m=n_3\frac{\Gamma}{\beta_{m,t}+Z/Z_3}S_me^{ik_0h}\times[-A_0e^{-ik_0h}(1-Z/Z_1)+B_0e^{ik_0h}(1+Z/Z_1)]. \qquad (6)$$

The measured zero-order transmitted field is drawn in Fig. 2. It was performed in dried air at room temperature with a FTS-60A Bio Rad spectrometer with a beam divergence of two degrees and a spectral resolution of 4 cm^{-1}. The spectra were normalized to the transmittance of the empty 5-mm-diameter hole of the sample holder. It is well known that these kinds of gratings excited by p-polarized light become

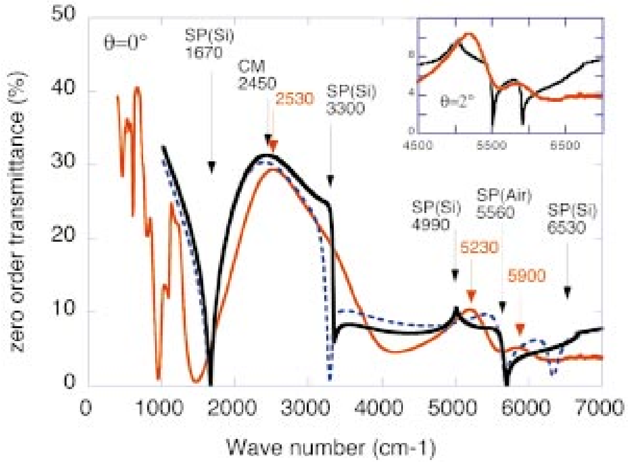

FIG. 2. (Color) Measured (red bold line) and calculated zero-order transmittance: blue dotted line using the one mode (n=0) in region (II), black bold line using four modes. The parameters used are those of Fig. 1, and the incident angle is $\theta=0$ (normal incidence). The black arrows indicate the theoretical excitations of silicium/metal surface plasmons interface with SP(Si) symbols and Air/metal surface plasmons with SP(Air). The symbol CM corresponds to the cavity mode. The three red arrows indicate the location of experimental enhanced transmission. In the inset, the black line is the calculated curve obtained for an angle $\theta=2$ degrees (see text).

transparent when the wave number goes to zero.[9] At small wave numbers, the experimental curve also exhibits the SiO_2 and Si phonons (below 1400 cm^{-1}), which are not taken into account in the model. However, it also appears clearly that resonant transmission peaks occur for particular frequencies at 2530 and 5230 cm^{-1} and 5900 cm^{-1} (red arrows in Fig. 2), exactly as was observed for the two-dimensional (2D) cases studied by Ebbesen *et al.*[2]

The calculated spectrum $t_0=T_0T_0^*/n_3$, corrected for multiple incoherent scattering in the silicon substrate, is also reported in Fig. 2 for two cases : with the unimodal approximation [from Eq. (6)], and the numerical results using four modes (which is enough for numerical convergency). The analytical expressions are reported in Ref. 8, but the results obtained are qualitatively identical. However some quantitative changes can be seen, especially at shorter wavelengths. This is due to the fact that the one mode approximation induces some artificial ‘‘rigidity’’ of the field in Si (which is constant on a scale of w at $y=-h$ with this approximation). While the nature of the excitations remain qualitatively unchanged if one uses one or four modes, the fine structure of the field in the Si, the locations of the excitations, and the aspect of the transmittance can be quantitatively slightly changed.

There are three types of excitations in the theoretical spectra (black arrows in Fig. 2). The minima of the modulus of β_m+Z/Z_1 in Eq. (5) lead to surface plasmons excitations[12] at the air/metal interface [symbols SP(Air) in Fig. 2], while the minima of $\beta_{m,t}+Z/Z_3$ in Eq. (6) lead to surface plasmons excitations at the Si/metal interface [symbols SP(Si)]. Both are essentially uncoupled owing to the

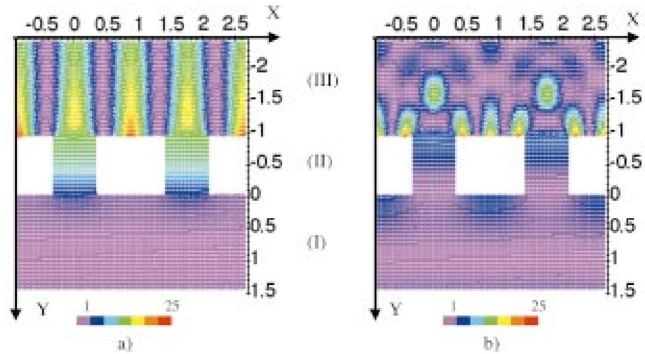

FIG. 3. (Color) Graph of the field's intensity using four modes (see text); (a) at 1670 cm^{-1}. The scale for the x and y axes is in μm. The scale in colors of the field intensity is in units of the incident intensity normalized to unity; (b) at 3300 cm^{-1}. In both cases, the surface plasmon at the Si/metal interface is recognized by the nodes along the x-direction.

difference in dielectric constants.[3] Moreover, since our device does not have a Si/metal interface, the corresponding surface plasmons cannot be experimentally observed. This is why we have some strong differences between the experience and the theory at these excitation frequencies, i.e., 1670 cm^{-1} (deep extinction of the zero-order transmission), 3300 cm^{-1}, 4990 cm^{-1}, and 6530 cm^{-1}. The field maps for two of these excitations are reproduced in Fig. 3.

Opposite to this situation, the SP(Air) excitations are experimentally possible. Theoretically, one is observed at 5560 cm^{-1}, the field map of this being reproduced in Fig. 4(a). However, at normal incidence, this excitation corresponds to two (almost) degenerated air/metal surface plasmons. This degenerence is very sensitive to the angle of incidence. By taking into account the experimental beam divergence of two degrees, we are able to reproduce the experimental curve which corresponds to two nondegenerate surface plasmons at the air/metal interface (see inset of Fig. 2).

The third type of excitation is obtained when the minima of the modulus of the denominator in Eq. (4) is reached. It corresponds to a cavity mode.[3,11] One is observed at 2530 cm^{-1}, the field map being reported in Fig. 4(b). The amplification of the field in the grooves which is visible on

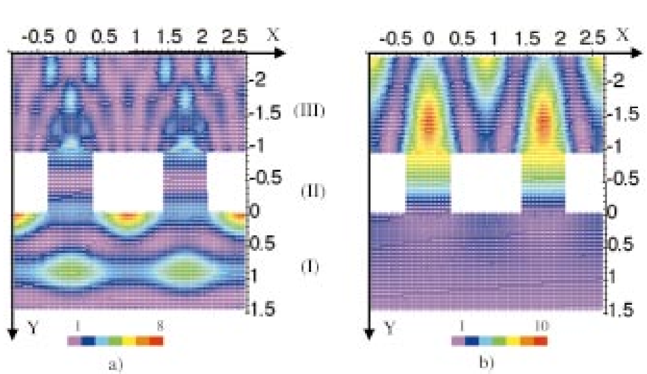

FIG. 4. (Color) Same as Fig. 3 at (a) 5560 cm^1 with plasmon excitation at the Air/metal interface, and (b) at 2450 cm^{-1} which corresponds to a cavity mode.

the figure is characteristic of this type of mode. Finally, we think that the experimental smooth shoulder on the right side of this peak is probably due to some inhomogeneities in the height of the metallization of the groove.

As was earlier noted by Hessel,[11] the slits in the grating behave as Fabry-Perot cavities which are *forced to resonate* under specific conditions, either when the frequency is close to the Fabry-Perot resonance (mode at 2530 cm^{-1}), or when a surface plasmons is excited (5560 cm^{-1}). In both cases, the field is amplified in the slit, and owing to its nonevanescent nature (mode $n=0$), this allows transmission to the region (III). This makes a strong difference between 1D systems and 2D squares or holes systems where only the plasmon coupling mechanism exists. The essential discrepancy comes effectively from the nature of the modes inside the cavities. While the field is given by $H_z^{(II)}$ in Eq. (1) for a p-polarized incident field, the expression of the same component for a 2D square cavity is given by:

$$H_z^{(II)}(x,y,z)=\sum_{m=0}^{+\infty}\sum_{p=1}^{+\infty}(A_{m,p}e^{i\mu_{m,p}y}+B_{m,p}e^{-i\mu_{m,p}y})\times\sin\left[\frac{p\pi}{w}\left(z+\frac{w}{2}\right)\right]\cos\left[\frac{m\pi}{w}\left(x+\frac{w}{2}\right)\right], \tag{7}$$

with $\mu_{m,p}^2=k_0^2-(m\pi/w)^2-(p\pi/w)^2$. It is clear that for a subwavelength size of the hole, the first mode $(m,p)=(0,1)$ is evanescent along y since $\mu_{0,1}$ is complex. No propagation in the cavity can occur and the only possible mechanism seems to be the *molecular mode*,[4] with tunneling of the evanescent light through the holes. This only occurs if the hole is not too deep, and the transmission should completely vanish for large h. The situation is clearly different from the present 1D slits for which the first cavity mode $n=0$ remains propagative. Hence, the transmission is allowed whatever the height of the slits, and whenever a field amplification above the slit is provoked (surface plasmon on one side, or cavity mode).

In this report, we have presented measurements of resonant transmission through metallic subwavelength slits. We have shown that transmission occurs by exciting either a cavity mode or a surface plasmon at the incident air/metal interface, inducing a propagative field in the slit leading to transmission.

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