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Enhanced transmission of slit arrays in an extremely thin metallic film

A. Moreau, C. Lafarge, N. Laurent, K. Edée and G. Granet

June 6, 2006

Abstract

We explore the behaviour of slit arrays for very low thicknesses and found that they could constitute very interesting filters. Two mechanisms are responsible for the enhanced transmission depending on the thickness : first, cavity resonances, for a surprisingly low thickness and a resonance whose nature still has to be understood for extremely small thicknesses.

Since the discovery of Ebbesen that subwavelength hole arrays could transmit light,[1] much has been understood concerning the behaviour of such structures. Resonances of the structure are responsible for the extraordinary transmission. Two types of resonances are usually involved : surface resonances (plasmons) for bidimensional hole arrays[3, 4] and cavity resonances, for slit arrays[2, 5, 6, 7] and coaxial hole arrays[9, 10].

This paper deals with the case of subwavelength slit arrays, which have attracted much attention[2, 6] and are quite well understood[3, 7]. The enhanced transmission is explained for these structures by cavity resonances : the propagative mode inside the slits is excited and each slit behaves like a cavity because the mode is reflected on the upper and on the lower side. The transmission is then very well approximated by a one-mode model[5, 7].

Our purpose is to study the behaviour of such structures for very small thicknesses. Since the resonances involved in the transmission are cavity resonances, other authors do not expect such resonances to occur below a given depth of the slits[2, 3, 7], and no resonance of the structure is of course expected when the one-mode approach is not valid any more. The lower limit for a *perfect* validity of the one-mode approach is thought to be around one third of the wavelength[7].

We have found that cavity resonances occur for surprisingly low thicknesses and that the one-mode approach can be considered as relevant in this case. In addition, we have found that another type of resonance may occur for extremely thin structures when many evanescent Bloch waves have to be taken into account.

The geometrical parameters of the structure are its thickness h , its period d and the width of the slits, a . The structure is represented figure 1. The metal considered here is silver. The optical constants of silver are taken from [11].

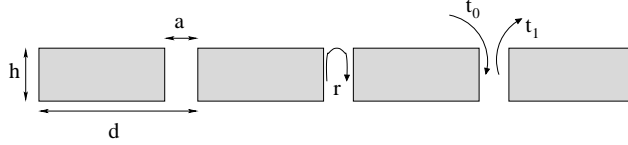


Figure 1: Geometric parameters of the slits array.

Let us recall the one-mode approach of the transmission of the slits array. Each slit can be considered as a waveguide. For a slit width smaller than the wavelength, there is only one propagative mode in the slit. In consequence, there always exists a propagative Bloch mode in an array of slits. This mode corresponds to the excitation of the guided mode in each slit. The assumption that only the propagative Bloch mode is responsible for the extraordinary transmission leads to a classical Fabry-Pérot formula for the zero-order transmittance of the whole structure [2, 7]:

$$T = \left| \frac{t_0 t_1 e^{-i\beta h}}{1 - r^2 e^{-2i\beta h}} \right|^2 \quad (1)$$

where h is the depth of the structure, and $\beta = \frac{2\pi}{\lambda_g}$ is the propagation constant of the guided mode and λ_g its effective wavelength (which is close to the real wavelength). The coefficient t_0 is the transmission coefficient between the incident wave and the propagative Bloch mode, while t_1 is the transmission coefficient between the propagative mode and the plane wave (see figure 1). When there are no losses $t_0 = t_1$ due to reciprocity. Here, t_0 and t_1 slightly differ from each other. Finally, r is the reflection coefficient of the guided mode inside the slits. The propagation constant and all these coefficients are computed using a Rigorous Coupled Wave Analysis[12, 13].

A cavity resonance occurs when the denominator of (1) is close to zero. This is the case when two conditions are fulfilled. First the modulus of r must not be null, and as close to 1 as possible, which is fulfilled as soon as $\lambda > d$. Second, if we denote ϕ the phase of r , the resonance condition can be written

$$\phi(\lambda) - \beta h = m \pi \quad (2)$$

where m is an integer. When the reflexion coefficient is real, the condition (2) cannot be fulfilled if h is smaller than $\frac{\lambda_g}{2}$. But it can be fulfilled for very low h if either the phase is close to zero but positive with $m = 0$ (we will label the associated resonance 0^+), or if it is close to $-\pi$ but greater than $-\pi$ with $m = -1$ (the resonance being labelled π^+).

Figure 2 shows a typical internal reflection coefficient r for a period $d = 600 \text{ nm}$ and a slit width $a = 100 \text{ nm}$. In order to understand the behaviour of the structure, we will perform an analysis using the zeros and the poles[7] of the different coefficients in equation (1).

At $\lambda \simeq 568 \text{ nm}$ an almost real zero of r can be seen. For this wavelength the transmission does not depend on the depth h of the slits. At $\lambda \simeq 618 \text{ nm}$ there is a pole of r . Of course, this pole is rather far from the real axis because the modulus of r must remain smaller than one. It can be seen that the phase goes from $-\pi$ to a

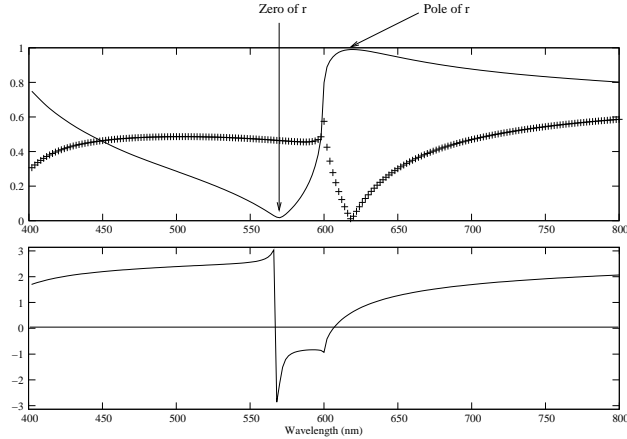


Figure 2: Modulus (top, solid line) and phase (bottom) of the internal reflexion coefficient r for $d = 600 \text{ nm}$ and $a = 100 \text{ nm}$. The modulus of $t_0 t_1$ is shown (crosses) too.

finite and positive value between the zero and the pole of the reflexion coefficient. It is null for $\lambda \simeq 608 \text{ nm}$. *Considering the phase only*, both 0^+ and π^+ resonances may thus occur between the zero and the pole for very low values of h .

Let us consider the case of the 0^+ resonance. The modulus of r is close to 1 for $\lambda > d$ because of the presence of the pole. This means that the denominator of (1) can be very close to zero. Since the transmission given by (1) must remain finite, the product $t_0 t_1$ presents a zero at exactly the same wavelength[6, 7]. This wavelength corresponds to the surface plasmon excitation condition

$$\lambda = d \operatorname{Re} \left(\sqrt{\frac{\epsilon(\lambda)}{1 + \epsilon(\lambda)}} \right), \quad (3)$$

where ϵ is the permittivity of silver. For $d = 600 \text{ nm}$ we find that the wavelength at which the surface resonance is excited is $\lambda_p = 618 \text{ nm}$. In the case of the slits array, the surface resonance can be seen as two counter-propagative surface plasmons which interfere destructively above the slits. That is why this mode is not sensitive to the presence of the slits and why the position of the zero of $t_0 t_1$ does not depend on the width of the slits[7]. Finally, because of the presence of this zero, the 0^+ resonance cannot occur for a very small thickness.

An optimization using a genetic algorithm has been performed in order to see if this structure can be considered as a good monochromatic filter at $\lambda = 600 \text{ nm}$. The objective function which is minimized is simply $|1 - T(600)| + T(400) + T(750)$. The thickness is limited to 150 nm in order to have only one resonance and thus a monochromatic filter. In order to have no π^+ resonance, we imposed $a > 70 \text{ nm}$. The zero order transmittance spectrum of the obtained structure ($d = 505 \text{ nm}$, $a = 115 \text{ nm}$, $h = 125 \text{ nm}$) is shown figure 3. Even if the resonance provides a very intense transmission, the slits are so wide that the propagative mode is easily excited. Finally, the transmission is quite high at any wavelength (except near the plasmon resonance). The one-mode approach is perfectly valid for these conditions.

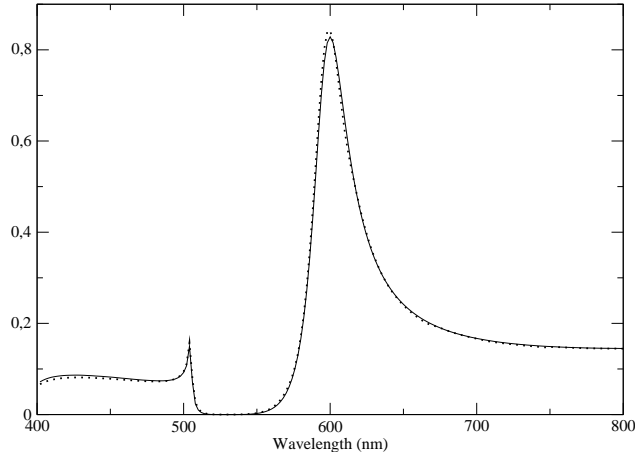


Figure 3: Zero-th order transmission of a structure with $d = 505 \text{ nm}$, $a = 115 \text{ nm}$ and $h = 125 \text{ nm}$ (solid line). The comparison is made with the prediction of the one-mode model, which is found to be very accurate. The peak at 505 nm is a peak of $t_0 t_1$ that can be found when $\lambda = d$.

Let us now consider the π^+ resonance. For slits larger than 70 nm this resonance cannot occur because in the range where the phase is close to $-\pi$, r has a zero. But when the slits becomes smaller, the zero is heading towards the pole located at λ_p (see figure 4). It goes off the real axis, so that the minimum of $|r|$ is no longer zero. There is no major change in the behaviour of the phase : it is equal to $-\pi$ at the minimum of $|r|$. Some minor changes occur, though : the phase varies slower near the zero so that for very thin structures the condition on the phase (2) is verified somewhat further from the zero, in a range where the modulus of r is greater. Finally, a phase close to $-\pi$ can be found when $|r|$ is not too small if the width of the slits is small enough. A π^+ cavity resonance can thus be expected for narrow enough slits for extremely low thicknesses, as long as the one-mode assumption (on which this prediction relies) is still valid. Because the phase varies very rapidly near the zero of r , the transmission peak linked to the π^+ resonance is expected to be very narrow. As far as we know, this resonance has never been studied in previous works[2, 6, 5, 7] maybe because all authors expect enhanced transmission to occur for $\lambda > d$ and for wide enough slits[2]. Another reason is that previous works deal with lower frequencies at which the permittivity of silver is higher, so that the zero and the pole of r are much too close and the π^+ resonance cannot be excited.

When the thickness is large enough, both the 0^+ and the π^+ resonances can be seen on the same transmission spectrum (see figure 5). As expected, the one-mode model gives excellent results in this case.

We have performed the same optimization than for the 0^+ resonance, except that we have imposed $a < 70$ and a period d much closer to 600 nm . The obtained structure has a period of 600 nm , a slit width of $a = 45.5 \text{ nm}$ and a thickness of only 60.5 nm . The π^+ resonance is shown figure 6. It can be seen that the one-mode approach is correctly predicting the position, the width and the intensity of the enhanced transmission even

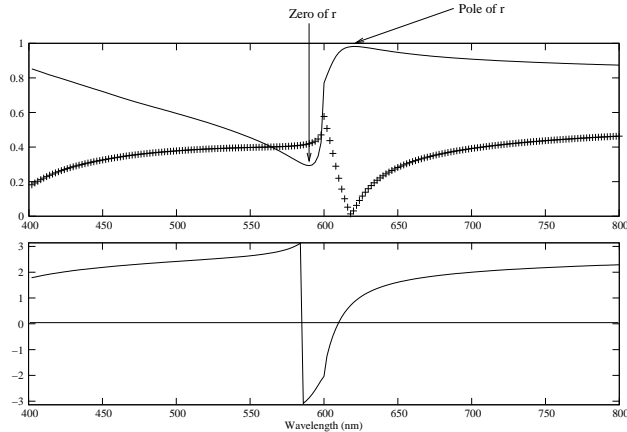


Figure 4: Modulus (top, solid line) and phase (bottom) of the internal reflexion coefficient r for $d = 600 \text{ nm}$ and $a = 45.5 \text{ nm}$. The modulus of $t_0 t_1$ is shown (crosses) too.

if this is not the case at other wavelengths. That is why we think that the peak in the transmission spectrum can be considered as a cavity resonance, but with a 60 nm thick only cavity - which is surprising.

Even if this resonance is clearly a cavity resonance, it is excited when the transmission coefficients t_0 and t_1 reach a peak, at exactly 600 nm . The fact that these two phenomenon coincide is due to the optimization : the best possible resonance is clearly found when the cavity resonance and the peak of $t_0 t_1$ occur at the same wavelength. When it is not the case, the transmission is of course not as high as in the previous case.

When the thickness becomes even smaller, the role of the evanescent waves cannot be neglected any more. They can be responsible for the transmission. Surprisingly, we found that at extremely low thicknesses an enhanced transmission is still observed for $\lambda = d$. It cannot be explained using the one-mode model (see figure 7). Since it occurs for a wavelength equal to the periodicity of the array it does not seem that it can be linked to the plasmon resonance. Until now, we have no explanation for this resonance.

In conclusion, we can say that the behaviour of slit arrays at very small thicknesses has been explored. Let us first underline that, although the surface plasmon resonance hinders the excitation of cavity modes, its existence is responsible for the unusual behaviour of the structure. The phase and the modulus of the internal reflexion coefficient for the Bloch mode, r , are indeed determined by the position of the pole and the zero linked to the plasmon resonance. And the exotic behaviour of the phase allows the excitation of cavity resonances for thicknesses as small as one tenth of the wavelength in vacuum. Using optimization techniques, we have found some structures could constitute very interesting filters.

For even thinner structures, the one-mode approach is not valid any more but an enhanced transmission is still observed when the wavelength is equal to the period. It cannot be explained using the one-mode approach, and it does not clearly correspond to a plasmon resonance. The exact nature of this resonance is still an open problem.

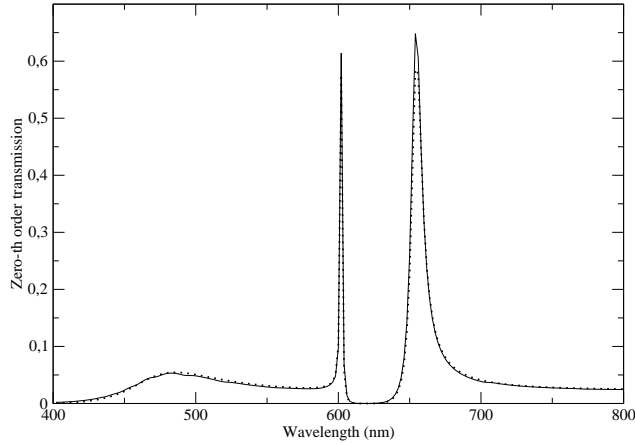


Figure 5: Zero order transmittance of a structure with $d = 600 \text{ nm}$, $a = 45.5 \text{ nm}$ and $h = 120 \text{ nm}$ (solid line). The comparison is made with the prediction of the one-mode model (dotted line).

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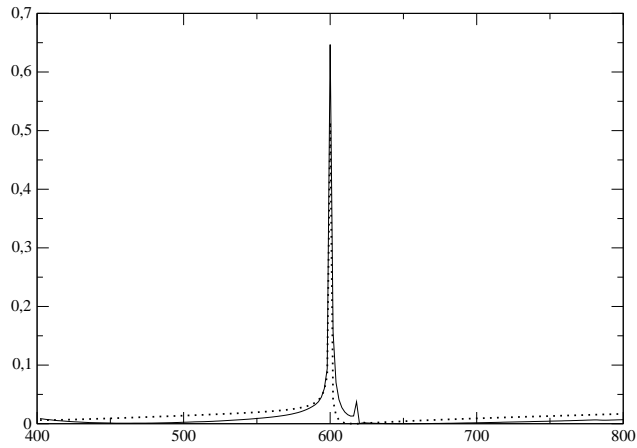


Figure 6: Zero order transmittance of a structure with $d = 600 \text{ nm}$, $a = 45.5 \text{ nm}$ and $h = 60.5 \text{ nm}$ (solid line). The comparison is made with the prediction of the one-mode model (dotted line).

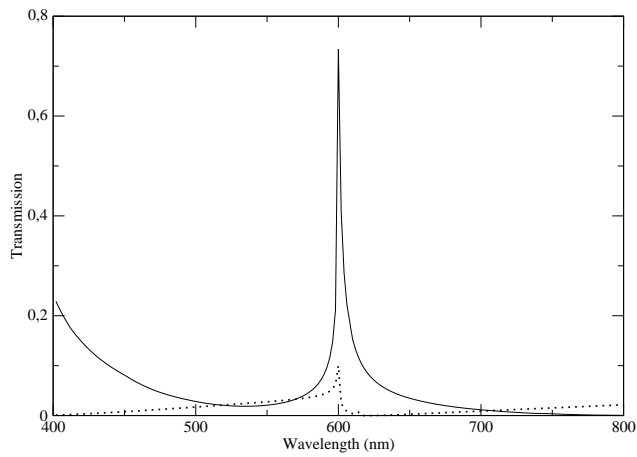


Figure 7: Zero-th order transmission of a structure with $d = 600 \text{ nm}$, $a = 51.4 \text{ nm}$ and $h = 33.9 \text{ nm}$ (solid line). The comparison is made with the prediction of the one-mode model (dotted line).