Optical transmission through hole arrays in optically thin metal films

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Abstract

We present a theoretical study on the extraordinary optical transmission through square hole arrays in a metal film, focusing on the dependence on the metal thickness. More precisely, we will study the crossover from the (now canonical) optically thick films to the case of optically thin films. We show that, as the thickness of the metal film decreases the extraordinary optical transmission peak redshifts, due to the coupling of light with the short-range surface plasmons. Remarkably, the ratio between the maximum and minimum values of the transmittance is high even for metal thicknesses as small as one skin depth.

1. Introduction

Since the discovery of extraordinary optical transmission (EOT) [1], i.e., resonances in the transmission of light through subwavelength holes drilled in a metal film, numerous works have explored different parameter configurations of two-dimensional hole arrays (2DHAs) [2]. In the original EOT configuration the metal film is opaque. In this case, the EOT process involves surface modes at each side of the film that couple through the holes [3]. On the other hand, continuous metal films (thin enough to be translucent), also present transmission resonances when periodically corrugated. In this configuration, resonant spectral features are related to the surface plasmon polaritons (SPPs) of the thin film [4, 5]: the short-range SPPs (SRs), and the long-range SPPs (LRs).

The transmission through 2DHA for films with thicknesses of a few skin depths has been studied in the terahertz regime [6, 7]. The spectral position of EOT peaks was found to be mainly determined by the lattice parameter. In this presentation we will extend the study on EOT in thin films to the optical regime.

2. EOT thorough 2DHA in thin films

We consider square lattices of square holes; the period, P, is chosen to be 400 nm (to obtain EOT in the visible). The metal is gold (with a frequency dependent dielectric constant, ε_M taken from [8]). The film is immersed in a medium with dielectric constant $\varepsilon = 2.25$. This is so because thin films

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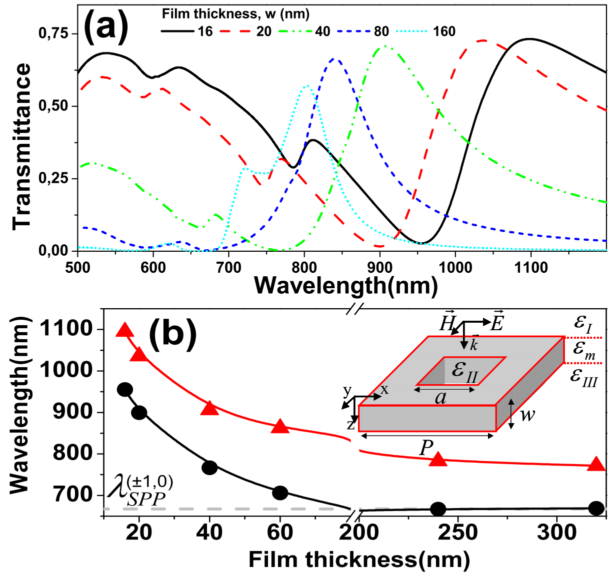

Fig. 1: Panel (a): Zero-order transmittance through 2DHAs in gold, as a function of the film thickness w (P=400 and a=160 nm). The dielectric constant is $\varepsilon = 2.25$ everywhere in the non-metallic regions. Panel (b): Spectral position as a function of w for both the EOT maximum (triangular symbols) and the EOT minimum (circular symbols). The horizontal dashed line renders $\lambda_{SPP}^{(\pm1,0)}$

should lie on a glass substrate for mechanical stability and the presence of an index-matching liquid facilitates the interpretation of results [9]. The inset to Fig. 1(b) presents a schematic of the structure. Calculations where performed with the FDTD method with the particular implementation for metals described in [10]. Figure 1(a) shows the calculated zero-order transmittance spectra through 2DHAs with different thicknesses, revealing the presence of resonances that redshift as the metal thickness decrease. At optically thick films (with thicknesses of several skin depths, i.e. larger than around 100nm) the resonance is slightly redshifted with respect to the Rayleigh wavelength ($\lambda_R = \sqrt{\varepsilon_3}P = 600$nm). However, for film thicknesses of the order of the skin depth, both maximum and minimum transmittance redshifts by even hundreds of nanometers while, notably, keeping high peak visibility.

In order to understand these results we have computed the band structure for EM modes bounded to the metal film. A flat unperforated optically thick metal layer supports an SPP on each surface. When the film thickness is reduced, these two modes interact and are substantially coupled whenever the film thickness is smaller than $2-3$ skin depths. In this case, the dispersion relations of film modes can greatly differ from that of the SPP. We denote by $\vec{q}_{mode}(\lambda)$ the in-plane wave vector of these film modes (the label *mode* can be either SPP, LR, or SR). The periodic corrugation of the metal film allows light to couple to these otherwise bounded modes. If the corrugation is small the coupling occurs at the condition

$$\left(k_x^{in} + \frac{2n\pi}{P}\right)^2 + \left(k_y^{in} + \frac{2m\pi}{P}\right)^2 = q_{mode}^2(\lambda) \qquad (1)$$

where $\vec{k}_{in} = (k_x^{in}, k_y^{in})$ is the in-plane momentum of the incident field and n and m are integers.

We denote by $\lambda_{SPP}^{(n,m)}$ the wavelength that holds Eq. (1) at normal incidence for given values of n and m. Figure 1(b) shows the spectral positions of both minimum and maximum of the EOT peak appearing at the largest wavelengths. We find that when the film is thick enough the EOT minimum very approximately coincides with $\lambda_{SPP}^{(\pm1,0)}$ [11]. In contrast, both maximum and minimum redshift as the film thickness reaches the optically thin regime. To analyze whether the EOT phenomenon through optically thin 2DHAs has its origin in the excitation of an EM mode bounded to the film, we focus on the case with $w = 20$nm and study the dependence with hole size. Figure 2 renders the spectral positions of both maximum and minimum of peak appearing at largest frequencies. It also shows the the wavelengths $\lambda_{SR}^{(\pm1,0)}$ of the short-range SPP *of the holey film* (denoted by $\widetilde{\lambda}_{SR}$ and extracted from the band structure of electromagnetic modes see [12]), as well as the value obtained from the SR of the flat surface through Eq. (1). This last value gives the limit for the resonant wavelength as the hole size vanishes.

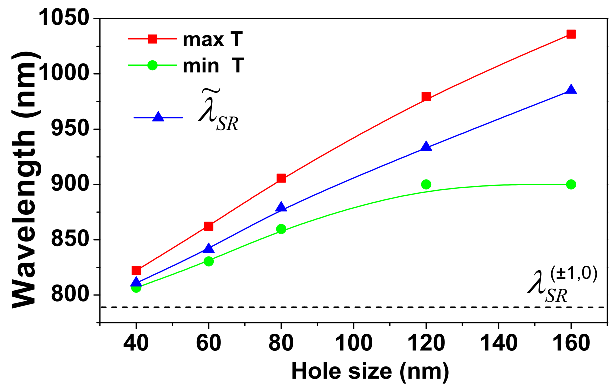

Fig. 2: EOT maxima (square symbols), minima (circular symbols), and wavelength for excitation of the SRSPP of the holey film (triangular symbols) as a function of the hole size.

4. Conclusion

We have shown that the EOT peak can be tuned to longer wavelengths (by even hundreds of nanometers) by decreasing the film thickness without strongly affecting either transmission intensity or peak visibility (which is still large at $w \approx 20$ nm). We have demonstrated that short range surface plasmons are responsible for the EOT phenomenon in optically thin metallic 2DHAs.

References

[1] T. W. Ebbesen et. al., Extraordinary optical transmission through sub-wavelenght hole arrays, *Nature* vol. 391, p. 667, 1998.
[2] F. J. Garcia-Vidal et al., Light passing through subwavelength apertures, *Rev. Mod. Phys.* vol. 82, p. 729, 2010.
[3] L. Martin-Moreno et. al., Theory of extraordinary optical transmission through subwavelength hole arrays, *Phys. Rev. Lett.* vol. 86, p. 1114, 2001.
[4] I. R. Hooper and J. R. Sambles, Coupled surface plasmon polaritons on thin metal slabs corrugated on both surfaces, *Phys. Rev. B* vol. 70, p. 045421, 2004.
[5] D. Gerard et al., Analysis of the Bloch mode spectra of surface polaritonic crystals in the weak and strong coupling regimes: grating-enhanced transmission at oblique incidence and suppression of SPP radiative losses, *Opt. Express* vol. 12, p. 3652, 2004.
[6] A. K. Azad and W. L. Zhang, Resonant terahertz transmission in subwavelength metallic hole arrays of sub-skin-depth thickness, *Opt. Lett.* vol. 30, p. 2945, 2005.
[7] X. Shou, A. Agrawal and A. Nahata, Role of metal film thickness on the enhanced transmission properties of a periodic array of subwavelength apertures, *Opt. Express* vol. 13, p. 9834, 2005.
[8] E. D. Palik, *Handbook of Optical Constants of Solids*, Academic Press, 1985.
[9] A. Krishnan et. al., Evanescently coupled resonance in surface plasmon enhanced transmission, *Opt. Comm.* vol. 200, p. 1, 2001.
[10] S. G. Rodrigo, F. J. Garcia-Vidal and L. Martin-Moreno, Influence of material properties on extraordinary optical transmission through hole arrays, *Phys. Rev. B* vol. 77, p. 075401, 2008.
[11] Q. Cao and P. Lalanne, Negative role of surface plasmons in the transmission of metallic gratings with very narrow slits, *Phys. Rev. Lett.* vol. 88, p. 574031, 2002.
[12] S. G. Rodrigo et al., Extraordinary optical transmission through hole arrays in optically thin metal films, *Opt. Lett.* vol. 34, p. 4, 2009.

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