Theory of absorption-induced transparency

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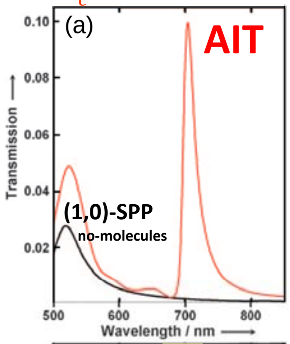
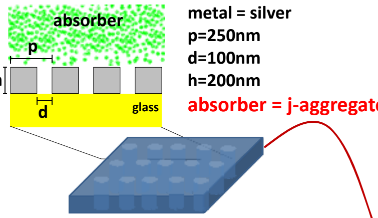
1.- Introduction

Recent experiments [Hutchison, O'Carroll, Schwartz, Genet, and Ebbesen, Angew. Chem. Int. Ed. 50, 2085 (2011)] have demonstrated that optical transmission through an array of subwavelength holes in a metal film can be enhanced by the intentional presence of dyes in the system. As the transmission maximum occurs spectrally close to the absorption resonances of the dyes, this phenomenon was christened "absorption induced transparency". Here, a theoretical study on absorption induced transparency is presented. The results show that the appearance of transmission maxima requires that the absorbent fills the holes and that it occurs also for single holes. Furthermore, it is shown that the transmission process is nonresonant, being composed by a sequential passage of the electromagnetic field through the hole. Finally, the physical origin of the phenomenon is demonstrated to be nonplasmonic, which implies that absorption induced transparency should also occur at the infrared or terahertz frequency regimes.

2.- Absorption-induced transparency : *Experiments*

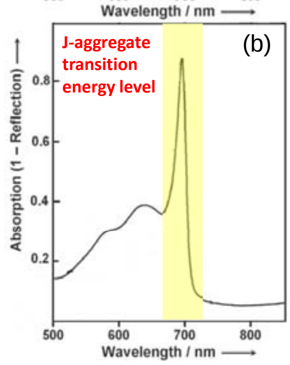
$\lambda_c \approx 400nm$

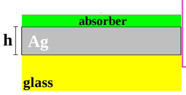




metal = silver
p=250nm
d=100nm
h=200nm
absorber = j-aggregate

Initially the main mechanism pointed to:
i) dipole-induced dipole interaction between molecules and localized SPPs, within the thin layer of j-aggregate formed on top of the system.
..and superimposed…
ii) cutoff function modification.
iii) Fresnel's coefficient modification.



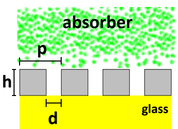


* absorber layer = 30nm

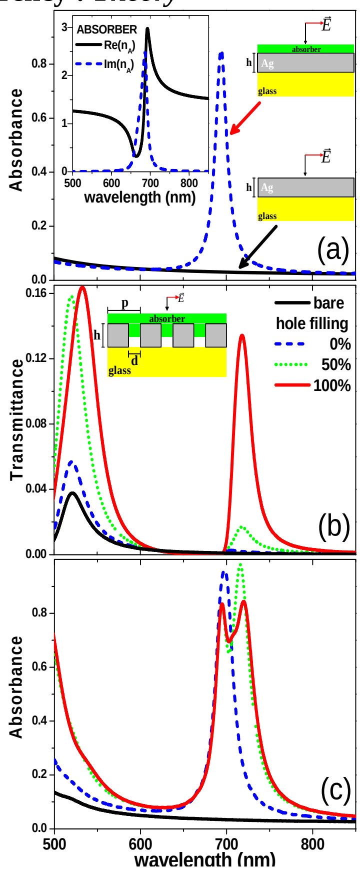
(a) Absorption induced transparency (AIT) , roughly speaking, is an extraordinary optical transmission (EOT) peak seen in the transmission spectrum of a holey metal film when a molecular dye is deposited on top of it **[1]**. As the AIT peak spectral location appears unexpectedly close to one of the absorption energies of the molecules **(b)**, transmission can only be possible through a strong modification of the propagation constant of holes, $\mathbf{k_z}$, as we have recently demonstrated **[2]**.

Experimental figures from Ref. [1]

3.- Absorption-induced transparency : *Theory*



metal = silver
p=250nm
d=140nm
h=200nm
absorber = j-aggregate

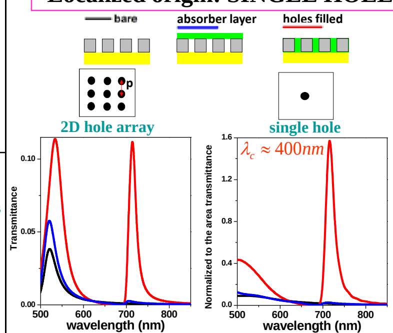


(a) Absorption spectra for an optically thick silver film calculated with the Finite-Difference Time-Domain (FDTD) method. The system is illuminated at normal incidence from the top interface. Two configurations are considered: (i) the silver film is coated with an absorbing overlayer (**blue** line), with the refractive index represented in the inset (Lorentz function), and (ii) no overlayer is present (**black** line).

HOLES FILLED for AIT

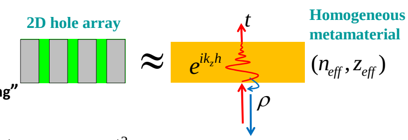
(b)-(c) Transmittance and absorbance calculated with FDTD for a square hole array of circular holes on a glass substrate for (i) no absorber present (**black** line) and (ii) in the presence of an absorbing overlayer and different degrees of hole filling: no filling (**blue** line), hole half filled (**red** line), and hole fully filled (**red** line).

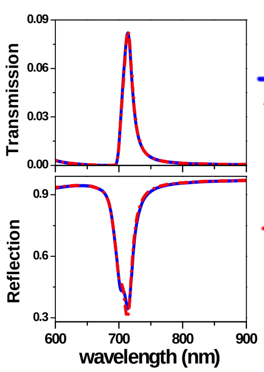
Localized origin: SINGLE HOLES



4.- Transmission process

h=200nm
p=250nm
d=140nm
"free standing"



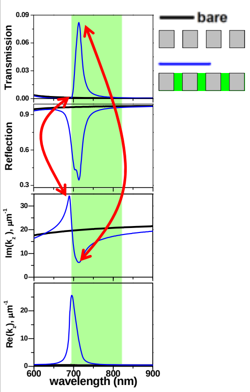


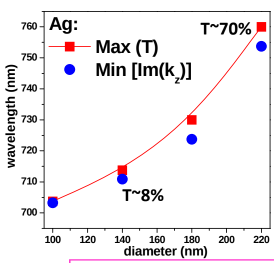
$$T_{full} = |t|^2 = \left| \frac{1-\rho^2}{1-\cancel{\rho^2 e^{ik_z h}}} \right|^2 e^{-2\mathrm{Im}(k_z)h}$$

$$R_{full} = |\rho|^2 \left| (1 - \cancel{e^{ik_z h}} t) \right|^2$$

$$T \approx \left| 1-\rho^2 \right|^2 e^{-2\mathrm{Im}(k_z)h}$$

$$R \approx |\rho|^2 \qquad \rho = \frac{1-z_{eff}}{1+z_{eff}} \;, \; z_{eff} = \mu_{eff}^{-1} \frac{k_z}{k_o}$$



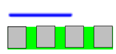


$Min(T) \sim Max[\mathrm{Im}(k_z)]$

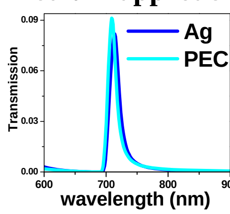
$Max(T) \sim Min[\mathrm{Im}(k_z)]$

Non-resonant transmission process, mainly controlled by the propagation constant of holes

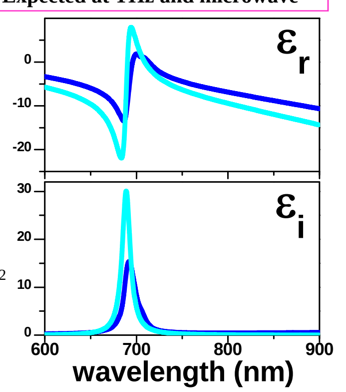
5.- Effective medium approach



h=200nm
p=250nm
d=140nm*
"free standing"



PEC →
- NO PLASMONS INVOLVED!
- Expected at THz and microwave



- Silver approximated as a Perfect Electric Conductor
- Effective medium approach (λ >> p > d) **[3,4]**

METAMATERIAL = LORENTZ + DRUDE

$$\varepsilon_{eff} = \left(\varepsilon_{host} - \frac{\Omega^2 \Delta\varepsilon}{\omega^2 - \Omega^2 + i\omega\Gamma} - \frac{\omega^2}{\omega_p^2} \right) S^{-2}$$

$$\mu_{eff} = S^2, S = cte$$

6.- References

[1] J. A. Hutchison, D. M. O'Carroll, T. Schwartz, C. Genet, and T.W. Ebbesen, "Absorption-induced transparency" Angew. Chem. Int. Ed. 50, 2085 (2011)
[2] S.G. Rodrigo, F. J. García-Vidal, and L. Martín-Moreno, "Theory of absorption-induced transparency" Phys. Rev. B 88, 155126 (2013)
[3] J. B. Pendry, L. Martín-Moreno, and F. J. García-Vidal, Science 305, 847 (2004)
[4] A. Mary, S.G. Rodrigo, L. Martín-Moreno, and F. J. García-Vidal , Phys. Rev. B 80, 165431 (2009)

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