The physics of optical patch antennas

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Abstract

In the last ten years, optical patch antennas have emerged as a platform allowing for a complete control of light – from huge Purcell enhancement to wavefront control. We review here the rich physics of these antennas, ranging from plasmonic slowdown of light to the impact of nonlocality on the optical response and show that a “gap-plasmon optics” can be established, bringing a full and thorough understanding of such structures.

1. Plasmonic effects and optical patch antennas

In the past ten years, there has been a growing interest for optical patch antennas. Chemically synthesized nanoparticles can actually be used to form optical patch antennas when deposited on a metallic film[1]. Such self-assembled resonators have proven to be the tiniest optical cavities which can be realized[2], and the extreme miniaturization associated with plasmonic effects allows for an unprecedented control of the Purcell effect[3] for instance.

Optical patch antennas share a large number of properties with more classical patch antennas. They constitute resonant cavities, so that the formalism which is used to describe classical patch antennas can be applied to optical patch antennas[4]. The first and main difference between the two are plasmonics effects - the fact that the mode propagating under the patch in the case of an optical antenna is a gap-plasmon, a mode with a very high effective index because it propagates in the metal where the Poynting flux is negative[5]. Presenting such a high effective index leads to a dramatci reduction in the size of the patch, so that a $\lambda/10$ large resonator is able to support a resonance.

Such a miniturization has very important consequences. First, the Purcell effect should obvisouly be much stronger in such cavities, as has been several times proven. Then the ratio of the absorption cross-section over the geometrical cross-section reaches very high values, typically of the order of 30 – meaning only 3% of the surface needs to be covered with resonators to absorb 100% of the incoming light. Furthermore, the large cross-section, for the fundamental resonance, does almost not depend on the angle of incidence. This is very peculiar, and an interferometric model of the cavity, which is excited on both sides, allows to understand this point[6].

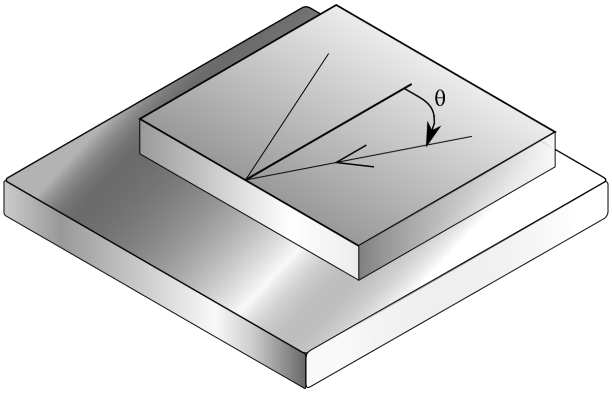

Figure 1: The incidence angle θ of the gap-plasmon propagating between the patch and the metallic film.

The large effective index of the gap-plasmons has finally a very important consequence: the resonators are so sensitive that they require an advanced description of the optical response of metals, able to take into account the fact that electrons repulse each other. Otherwise, experimental results can not be explained numerically[7, 8, 9, 10].

2. Total reflection of gap-plasmons

In order to completely understand what happens under an optical patch, we used a modal method[11] to retrieve the reflection coefficient of the gap-plasmon when the incidence angle (shown Fig. 1) is increased.

The modulus of the reflection coefficient is shown Fig. 2 and clearly shows that above a critical angle, there is a phenomenon which can be compared to total internal reflection - except for the losses. The angle θ_c for which such a response occurs is given by

$$\sin\theta_c = \frac{n_{sp}}{n_{gp}} \tag{1}$$

where n_{sp} is the effective index of the surface plasmon propagating along the metallic film, and n_{gp} is the effective index of the gap-plasmon. This shows that a gap-plasmon optics can be established – it is even possible to predict phenomenon like the Goos-Hnchen shift of the gap-plasmon total reflection.

This allows to understand the last properties of such patch antennas, like the fact that their emission can depend on the polarization for instance and how precisely their cross-section may vary with the distance between the patch

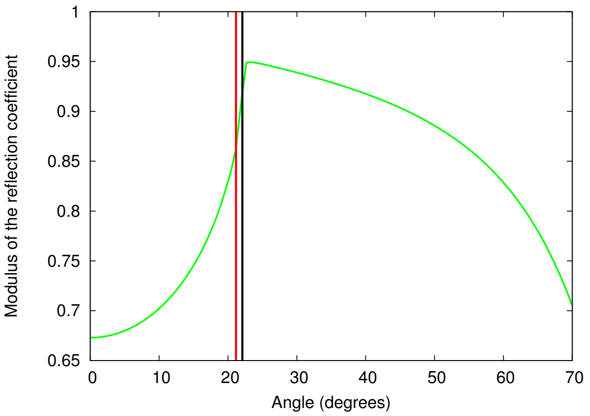

Figure 2: Modulus of the reflection coefficient of the gap-plasmon for a distance of 10 nm between the metallic film and the patch. The two vertical lines show the critical angle predicted when taking the index of air as the outside impedance (left) and the effective index of the surface plasmon (right). Definitely, the right impedance to consider is the

and the metallic film: the increase in the effective index of the gap-plasmon leads to an increase of the reflection coefficient. The patch thus forms a better cavity, which explains the increase in the cross-section. When the gap is below 5 nm however, the reflection coefficient is so high that coupling the cavity becomes difficult.

We underline in conclusion that the mechanisms which are explained here are actually not limited to such patch antennas and to the optical domain. It turns out that doped semi-conductors, in the close IR, present exactly the same kind of behaviour[12], including the sensitivity to spatial dispersion[13].

2.1. References

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References

[1] A. Moreau, C. Ciracì, J. J. Mock, R. T. Hill, Q. Wang, B. J. Wiley, A. Chilkoti, and D. R. Smith, “Controlled-reflectance surfaces with film-coupled colloidal nanoantennas,” *Nature*, vol. 492, no. 7427, pp. 86–89, 2012.

[2] J. J. Baumberg, J. Aizpurua, M. H. Mikkelsen, and D. R. Smith, “Extreme nanophotonics from ultrathin metallic gaps,” *Nature materials*, vol. 18, no. 7, pp. 668–678, 2019.

[3] G. M. Akselrod, C. Argyropoulos, T. B. Hoang, C. Ciracì, C. Fang, J. Huang, D. R. Smith, and M. H. Mikkelsen, “Probing the mechanisms of large purcell enhancement in plasmonic nanoantennas,” *Nature Photonics*, vol. 8, no. 11, p. 835, 2014.

[4] C. Ciracı, J. B. Lassiter, A. Moreau, and D. R. Smith, “Quasi-analytic study of scattering from optical plasmonic patch antennas,” *Journal of Applied Physics*, vol. 114, p. 163108, 2013.

[5] R. Ajib, A. Pitelet, R. Pollès, E. Centeno, Z. Ajaltouni, and A. Moreau, “The energy point of view in plasmonics,” *JOSA B*, vol. 36, no. 4, pp. 1150–1154, 2019.

[6] C. Lemaître, E. Centeno, and A. Moreau, “Interferometric control of the absorption in optical patch antennas,” *Scientific Reports*, vol. 7, p. 2941, 2017.

[7] A. Moreau, C. Ciracì, and D. R. Smith, “Impact of nonlocal response on metallodielectric multilayers and optical patch antennas,” *Physical Review B*, vol. 87, no. 4, p. 045401, 2013.

[8] A. Pitelet, E. Mallet, R. Ajib, C. Lemaître, E. Centeno, and A. Moreau, “Plasmonic enhancement of spatial dispersion effects in prism coupler experiments,” *Physical Review B*, vol. 98, no. 12, p. 125418, 2018.

[9] C. A. Reynaud, D. Duché, J. Le Rouzo, A. Nasser, L. Nony, F. Pourcin, O. Margeat, J. Ackermann, G. Berginc, C. A. Nijhuis *et al.*, “Enhancing reproducibility and nonlocal effects in film-coupled nanoantennas,” *Advanced Optical Materials*, vol. 6, no. 23, p. 1801177, 2018.

[10] A. Pitelet, N. Schmitt, D. Loukrezis, C. Scheid, H. De Gersem, C. Ciracì, E. Centeno, and A. Moreau, “Influence of spatial dispersion on surface plasmons, nanoparticles, and grating couplers,” *JOSA B*, vol. 36, no. 11, pp. 2989–2999, 2019.

[11] G. Granet, “Reformulation of the lamellar grating problem through the concept of adaptive spatial resolution,” *JOSA A*, vol. 16, no. 10, pp. 2510–2516, 1999.

[12] F. Omeis, R. Smaali, F. Gonzalez-Posada, L. Cerutti, T. Taliercio, and E. Centeno, “Metal-insulator-metal antennas in the far-infrared range based on highly doped inassb,” *Applied Physics Letters*, vol. 111, no. 12, p. 121108, 2017.

[13] J. R. Maack, N. A. Mortensen, and M. Wubs, “Size-dependent nonlocal effects in plasmonic semiconductor particles,” *EPL (Europhysics Letters)*, vol. 119, no. 1, p. 17003, 2017.