Plasmon amplification by strong coupling in a layered structure

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[a]Université de Montpellier 2, Laboratoire Charles Coulomb
Unité Mixte de Recherche du Centre National de la Recherche Scientifique 5221
34095 Montpellier, France;

ABSTRACT

A layered waveguide supported hybrid modes between a surface plasmon and a confined guided mode is studied. The condition for the strong coupling regime are described. The Green function is obtained and decomposed along the continuous and discrete spectrum.

Keywords: plasmonics, PT-symmetry, spacers, strong coupling, planar waveguides, integrated optics

1. HYBRIDIZATION OF THE MODES

In this work we consider a layered structure such as that depicted in fig.1. The high index planar waveguide

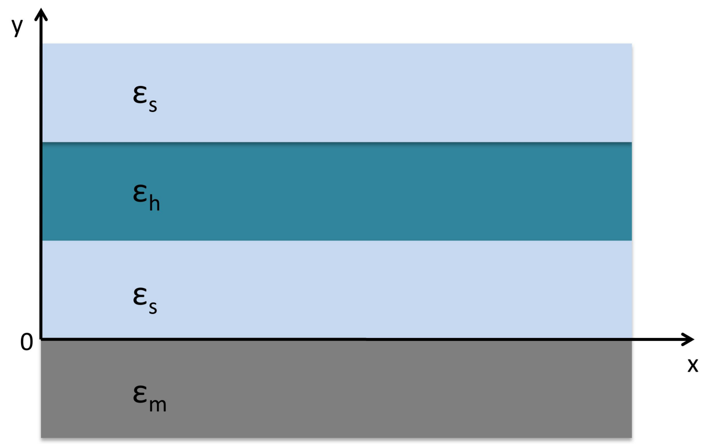

Figure 1. A layered structure supporting confined modes.

can support guided modes with dispersion curves given in fig. 2 (its width is taken to be 500nm). The layer of metal can support guided surface plasmon, whose dispersion curves are given in fig. 3 (its width is taken to be 100nm). When both layers are near each other the modes hybridize, resulting in the anti-crossing of the dispersion curves as shown in fig. 4.

The hybridization depends upon the coupling between the dielectric waveguide and the slab of metal. Let h denote this distance. When h is larger than the extinction length of the guided mode and the surface plasmon, no coupling can occur, this happens here for $h > 400nm$ and for the frequencies lying in the visible to infrared region. This situation is depicted in fig. 4. In fig. 5, the value of h is 100nm and the regime is that of the strong coupling[1,2] with an overlap of the evanescent part of the modes, leading to an anti crossing of the dispersion curves. Note however that for larger propagation constant the coupling can remain weak. Finally for $h = 30nm$ one enters the regime of ultra strong coupling where the dispersion curves of the waveguide and that of the plasmon cannot be tell apart. There are only hybrid modes that can be classified along their spatial repartition only (fig. 6).

Further author information: (Send correspondence to D. Felbacq)
D. Felbacq: E-mail: Didier.Felbacq@univ-montp2.fr

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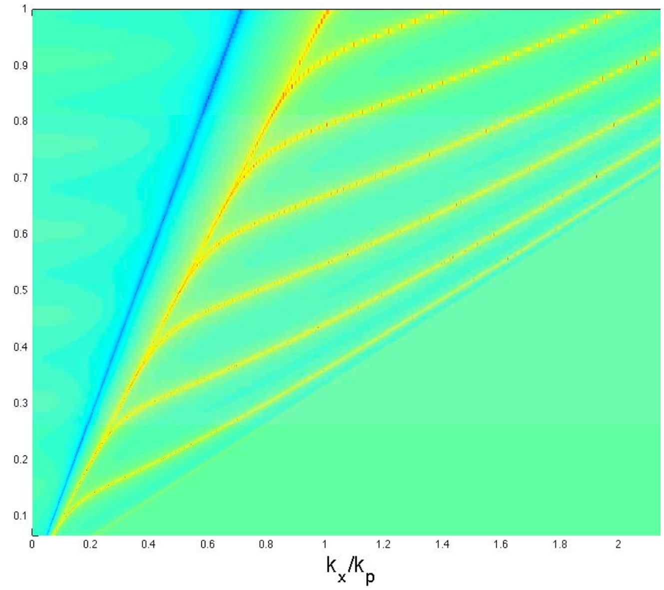

Figure 2. Dispersion curve for the dielectric slab.

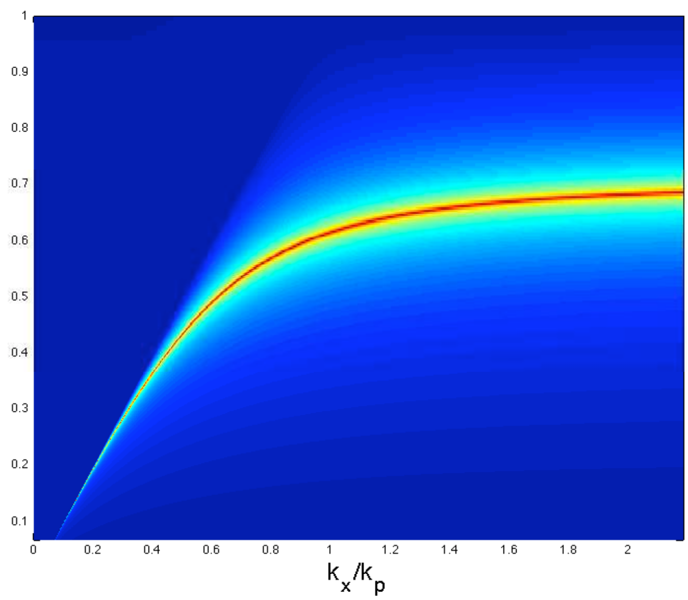

Figure 3. Dispersion curve for the metal layer.

2. THE GREEN FUNCTION

In view of describing the emission of a source embedded in the waveguide,[3,4] with give here a short derivation of the Green function of the system. To do so, we solve the Helmholtz equation:

$$\nabla \cdot (\varepsilon^{-1} \nabla G) + k_0^2 G = \delta_{x_0} \otimes \delta_{y_0} \tag{1}$$

upon performing a Fourier transform in the x direction, we obtain:

$$G(x - x_0, y, y_0) = \int g(y, y_0; \gamma) e^{i\gamma(x - x_0)} d\gamma \tag{2}$$

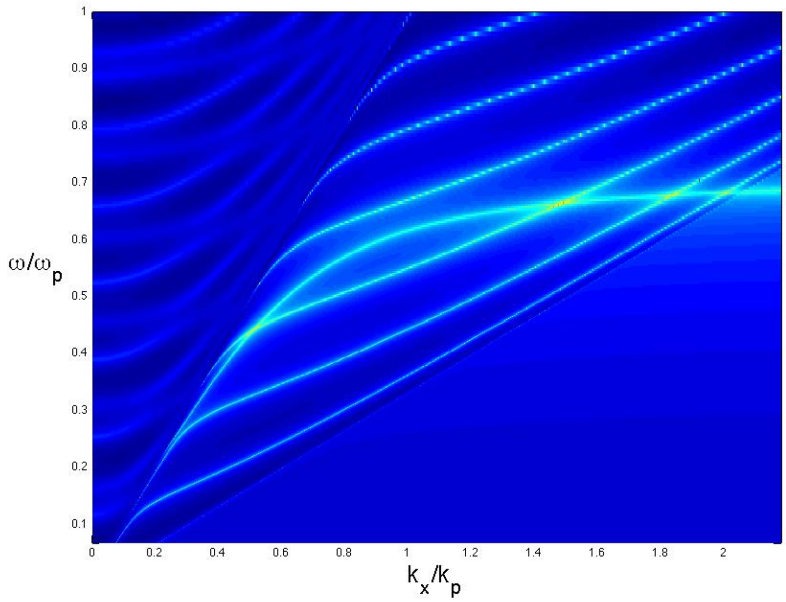

Figure 4. Dispersion curves for the hybrid structure.

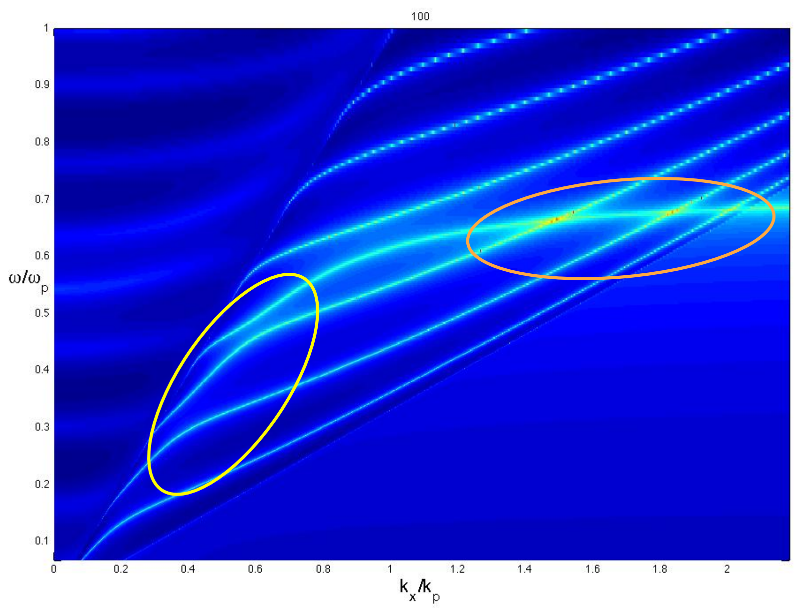

Figure 5. Hybridization in the strong coupling regime. The yellow ellipsis corresponds to a region of strong overlap whereas the orange one corresponds to a weak coupling.

From translational invariance, we may take $x_0 = 0$. The Fourier transform $g(y, y_0; \gamma)$ satisfies:

$$\frac{d}{dy}(\varepsilon^{-1}\frac{d}{dy}g) + (k_0^2 - \frac{\gamma^2}{\varepsilon})g = \delta_{y_0} \tag{3}$$

It can be expressed as a linear combination of the modes described in fig. 7 and 8.

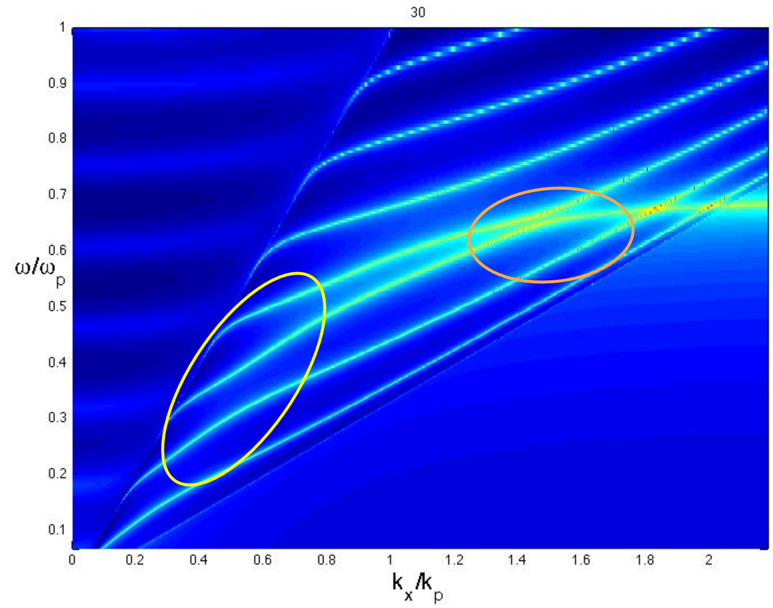

Figure 6. Hybridization in the ultrastrong coupling regime. There is a strong anti crossing for both the yellow and orange ellipsis. The region of larger propagation constants still exhibit a weak coupling.

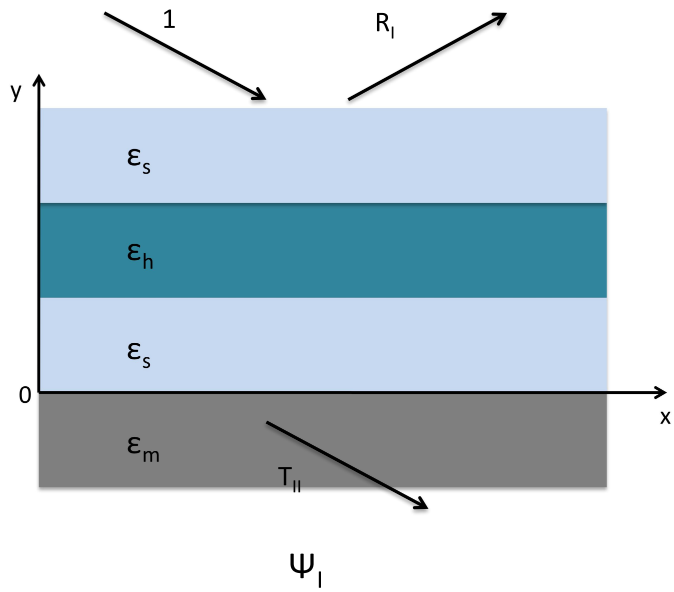

Figure 7. Scattering mode Ψ_I .

A direct calculation shows that the $g(y, y_0, \gamma)$ has the following expression:

$$g(y, y_0, \gamma) = \begin{cases} \frac{1}{W(\Psi_I, \Psi_{II})} \, \Psi_I(y) \, \Psi_{II}(y_0) \text{ if } y < y_0 \\ \frac{1}{W(\Psi_I, \Psi_{II})} \, \Psi_I(y_0) \, \Psi_{II}(y) \text{ if } y > y_0 \end{cases} \tag{4}$$

3. NUMERICAL RESULTS

We plot in fig. 9 and 10 the map of the field $|g|$ generated by a point source situated at the middle of the dielectric waveguide. It is the local density of states.[5,6] Physically a point source can be considered as a quantum emitter

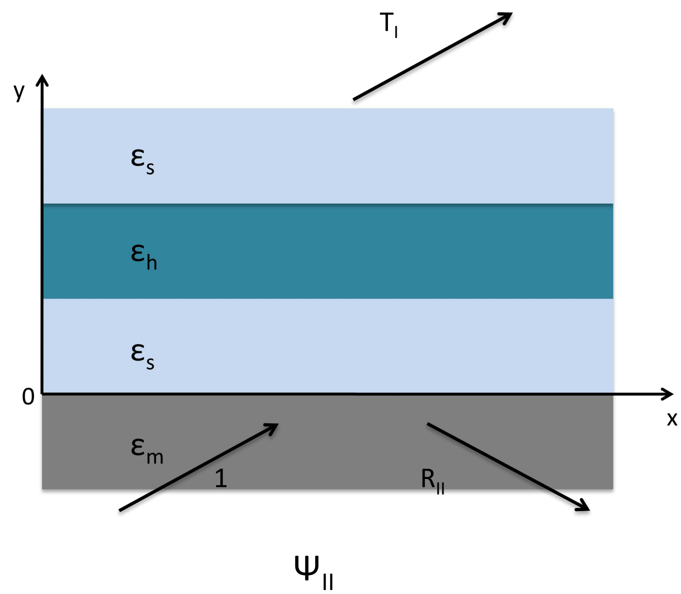

Figure 8. Scattering mode Ψ_{II} .

that be de-excited into different modes. Specifically, it can couple to hybrid (discrete) modes or in the continuum of scattering modes. A representation reads as follows:

$$G(x, y; y_0) = \sum_p c_p \psi_n(y)\psi_n(y_0)e^{i\gamma_n x} + \int_{C_I} c_I(\gamma)\psi_I(y)\psi_I(y_0)e^{i\gamma x}d\gamma + \int_{C_{II}} c_{II}(\gamma)\psi_{II}(y)\psi_{II}(y_0)e^{i\gamma x}d\gamma \qquad (5)$$

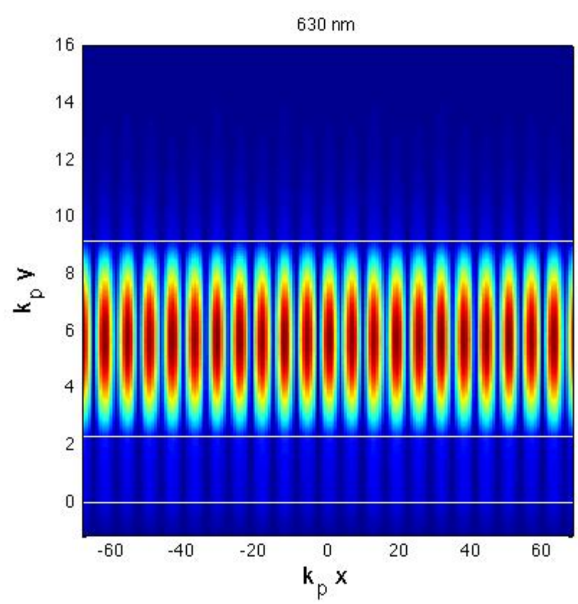

Figure 9. Local density of states for a source located in the middle of the dielectric waveguide. The wavelength is $\lambda = 630nm$ and the regime is that of strong coupling.

The coefficients c_p, c_I, c_{II} can serve to quantify the coupling into the different modes. More precisely, the part of the field projected on the guided modes is $\sum_p |c_p|^2$. In fig. 9 and 10, we have plotted the local density of states for two different wavelengths ($630nm$ and $1500nm$). It can be seen that, despite the fact that the regime is that of strong coupling, the hybrid mode is not necessarily coupled by a point source.[7–10] Rather, in fig. 9, it is clearly seen that it is mainly the confined part that is excited. However, in fig. 10 the hybrid mode is completely coupled and the surface plasmon is clearly excited.

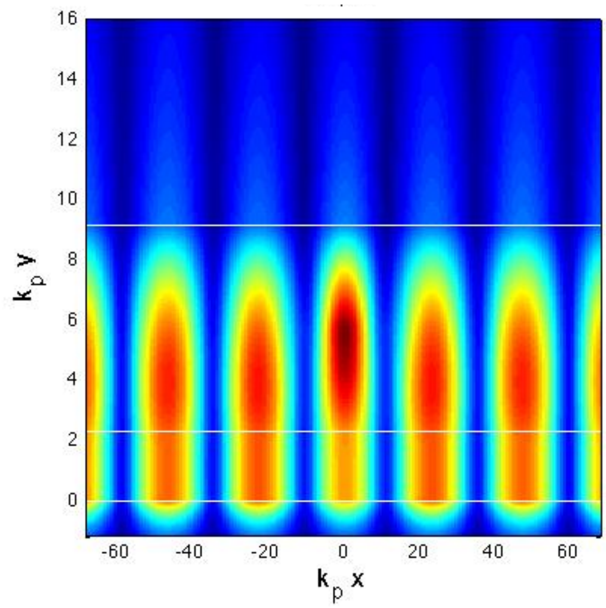

Figure 10. Local density of states for a source located in the middle of the dielectric waveguide. The wavelength is $\lambda = 1550nm$ and the regime is that of strong coupling.

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