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Coupling of Light to Plasmonic Modes on Metal Surfaces through the Local Density of States

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Abstract. We study the behaviour of the coupling between a radiating source and a metallic interface, for several geometric and physical configurations. To do this we study the LDOS for the configurations under study and perform analysis for the possible implications of the response of the media to the source.

Keywords: Nanooptics, density of states, plasmonics, quantum optics, purcell enhacement.

1 Introduction

The β-factor is a figure of merit in nano-optics. It describes electromagnetic field enhancement properties to plasmonics modes, such as the NV-color center nanodiamond as emitters with plasmonic nanostructures [3, 5]. Surface polariton plasmons (SPPs) are electromagnetic waves that travel along with a metal–dielectric or metal–air interface, guiding light efficiently in nanoscale elements [5].

They play an essential role in nanophotonics by near-field enhancement and short wavelength. When the separation falls below 20 nm, the classical theory deteriorates progressively due to its neglect of quantum effects. Remarkably, there is an enhancement near material interfaces [8] . The NV color centers in diamonds are of great interest in fields such as quantum information processing. Their use in these applications involves optimizing the lifetime and emission properties of the centers.

However, now, we understand that the interaction between an emitter and its electromagnetic environment by changing this environment can thus modify spontaneous emission. The spontaneous emission decay rate is calculated through the local density of states (LDOS), $\rho(\mathbf{x}, \omega)$, i.e., $\Gamma \sim \rho(\mathbf{x}, \omega)$ [9]. Thus, the modification of the decay rate of an emitter into a plasmonic mode is calculated with the help of the β-factor, which is defined as $\beta = \Gamma/\Gamma_0$.

1.1 The Electromagnetic Field Equations

The behaviour of the electromagnetic fields is ruled by the well-known Maxwell equations:

$$\nabla \cdot \mathbf{D} = \rho, \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{2}$$

$$\nabla \times \mathbf{E} = i\omega \mathbf{B}, \tag{3}$$

$$\nabla \times \mathbf{H} = \mathbf{J} - i\omega \mathbf{D}. \tag{4}$$

Along with the respective boundary conditions. Each physical configuration has its own solution. In particular, for the electric field we have the solution:

$$\mathbf{E} = 4\pi \, i \, \omega \, \mu \int \mathbf{G}_0 \cdot \mathbf{J} d^3\mathbf{x}', \tag{5}$$

where the function $\mathbf{G}_0$ satisfies the equation:

$$\nabla \times \nabla \times \mathbf{G}_0 - \omega^2 \, \mu \, \epsilon \, \mathbf{G}_0 = 4\pi \delta(\mathbf{x} - \mathbf{x}')\mathbf{I}, \tag{6}$$

where $\mathbf{G}_0$ is the Green's dyadic and $\mathbf{I}$ is the unit dyadic. We can resolve this equation, i.e. represent it in terms of some basis.

1.2 The Local Density of States (LDOS)

The local density of states is defined as the number of states with energy between k and $k + dk$, in terms of the modes of the electromagnetic field its is proportional to $\sum_n |\psi_{k_n}(\mathbf{x})|^2$. We can prove there is a relation between the imaginary part of the Green's function and the density of states as follow:

$$\rho(\mathbf{x}) = \frac{2\omega}{\pi c^2} \Im \operatorname{Tr} \mathbf{G}_0(\mathbf{x}, \mathbf{x}). \tag{7}$$

The contribution to the density of states from electric and magnetic terms is given by [2]:

$$\rho(\mathbf{x}, \omega) = \frac{1}{2} \left[\rho_E(\mathbf{x}, \omega) + \rho_M(\mathbf{x}, \omega) \right], \tag{8}$$

where the indices E, M stand for the electric and magnetic contribution respectively. Thus, the evident task to perform is the calculation of the Green's function for the appropriate configuration.

1.3 The Coupling to Different Surfaces

The presence of materials, metals dielectrics and different kind of non transparent nature for light to the optical wavelengths are of importance, because depending of the specific nature of them the electromagnetic properties of the quantum emitter or classical radiating dipole will be modified and is our task here to show how this happen.

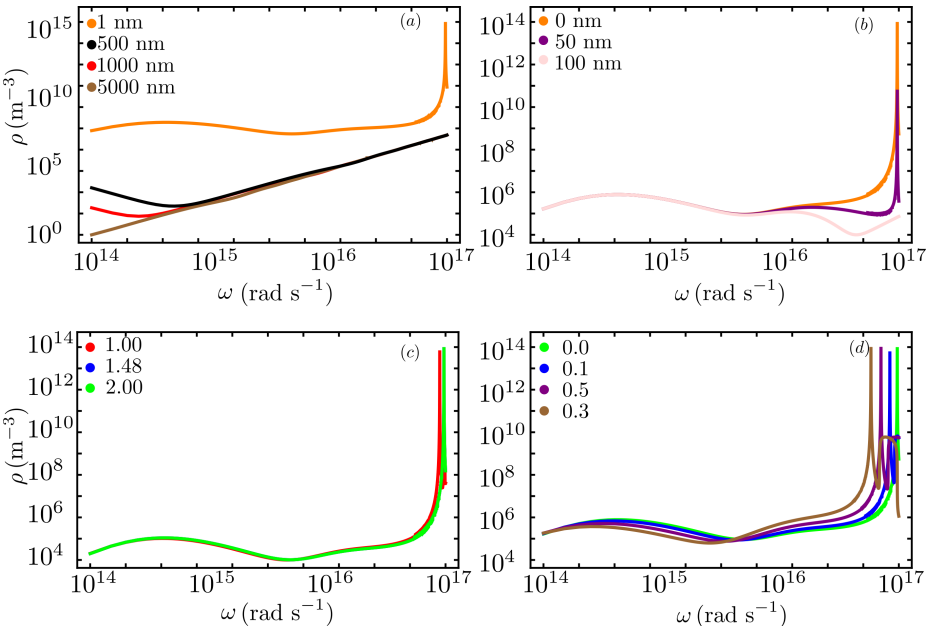

Fig. 1. The figure shows the local density of states for several configurations, for the parameters involved in the coupling of electromagnetic waves to a metallic surface: (a) an emitter at different distances z above the surface, (b) in the roughness of the surface, expressed in terms of the parameter σ, (c) in function of the refraction index n of the neighbor dielectric, (d) as a function of the packed fraction f.

The general case of a dipole placed at a distance z near a semi infinite slab of material is given by [9]:

$$\rho(z,\omega) = \frac{\rho_0}{2}\left\{\int_0^1 \frac{\omega}{c}\frac{dk^2}{2k_{0z}}\left[2 + k^2\Re\left((r_s + r_p)e^{2ik_0 z}\right)\right] + \int_1^\infty \frac{dk^4}{4|k_0|}\Im\left(r_s + r_p\right)e^{-2k_0 z}\right\}, \quad (9)$$

where $k_{0z} = \sqrt{1-k^2}\omega/c$, r_s and r_p are the Fresnel coefficients for the polarization s and p defined as:

$$r_s = \frac{\sqrt{1-k^2} - \sqrt{\epsilon^p - k^2}}{\sqrt{1-k^2} + \sqrt{\epsilon^p - k^2}} e^{-2\left(\frac{2\pi\sigma}{\lambda}\right)^2}, \quad (10)$$

$$r_p = \frac{\epsilon^p\sqrt{1-k^2} - \sqrt{\epsilon^p - \frac{\epsilon^p}{\epsilon^s}k^2}}{\epsilon^p\sqrt{1-k^2} + \sqrt{\epsilon^p - \frac{\epsilon^p}{\epsilon^s}k^2}} e^{-2\left(\frac{2\pi\sigma}{\lambda}\right)^2}, \quad (11)$$

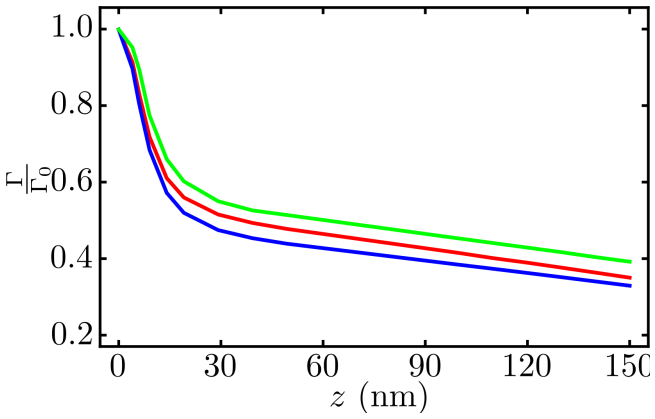

Fig. 2. The Purcell factor β as a function of the distance z over the interface air-material for perfect bulk metal (green), metamaterial $f = 0.1$ (red) and metal with roughness $\sigma = 10$ nm.

where $\epsilon^{s,p}$ are effective permitivity functions which are different for the different cases we are dealing with, and σ is the parameter characterizing the roughness of the surface, being $\sigma = 0$ the perfect surface.

Coupling to Perfect Metal Surfaces: As we know, the behavior of the light when it reaches a metal interface is described very well in terms of the dispersion relations of the Drude model $\epsilon(\omega)$. Which is introduced in the Fresnel coefficients by replacing $\epsilon^p = \epsilon^s = \epsilon(\omega)$ and $\sigma = 0$ in the expression Eq. (10).

Coupling to Non-Perfect Surfaces: In the case of nonuniform surfaces some changes in the Fresnel coefficients must be modified in order to have these effects into account [4, 6]. Here we use the dependence $\epsilon^p = \epsilon^s = \epsilon(\omega)$ and $\sigma \neq 0$.

Coupling to Metasurfaces: The vast majority of materials existing in nature has well-behaved properties,as we refer to their permeability and permitivity. If we can, by some mean, to put several small volumes, of the order of sub-wavelength, of a material inside another, and allow them to be distributed in any way inside the host, we can claim we have constructed metamaterial [1]. In this case we must replace in Eq. (10), the coefficients:

$$\epsilon^s = \epsilon(\omega)(1 - f) + f, \tag{12}$$

$$\epsilon^p = \epsilon(\omega)\frac{1 + f + \epsilon(\omega)(1 - f)}{1 - f + \epsilon(\omega)(1 + f)}. \tag{13}$$

Which depends on the packing fraction f, i.e. the volume fraction of material respect to the volume of the host. In Fig.1 we can se how the resonance in the LDOS for a metamaterial moves from right to left as the packed fraction f increases. This could be used to perform operations with multiple frequencies.

1.4 The Purcell Factor

The Purcell factor gives account for the decay rate enhancement or suppression for a nuclear magnetic dipole in the presence of different boundary conditions [7] and is defined by:

$$\beta = \frac{\Gamma}{\Gamma_0}. \tag{14}$$

Being the index 0 related to the decay rate in vacuum.

2 Conclusions

In summary, we use the concept of LDOS to extract the β-factor to evaluate the enhancement or suppression of the decay rate of an emitter into a plasmonic mode, and we investigate the LDOS variations versus the distance to interface at the resonance frequency condition.

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