Tailoring quantum emission through Purcell effect engineering using plasmon-polaritons

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Abstract

Manipulating quantum emission processes is fundamental to enable quantum communication and photonic quantum computation. For the information to be properly transmitted via quantum emitters, decreasing the average spontaneous emission time is important to increase the channel bandwidth. This article will investigate the engineering of the Purcell effect using attributes of plasmon-polaritons in a graphene interface and comparing results for metal interfaces. In the end, potencial trajectories for future research are cast in perspective.

Keywords: Quantum Emission, Purcell Effect, Plasmon-Polaritons, Photonics, Quantum Communication.

1 Introduction

Quantum emitters are at the heart of quantum communication (Jacob et al. (2012)), helping in fields like cybersecurity with quantum keys (Lo, Curty e Tamaki (2014)) for quantum cryptography applications. These rely on the enhanced functioning of single photon emissions, for propagation of information, here the quantum emitters are necessary (Novotny e Hecht (2012)). Other fields such as remote sensing, DNA sequencing, etc. (Fan et al. (2011)) also need the quantum emitters to work flawlessly and as fast as possible.

A way of increasing the decay rate of single photon fonts is through the Purcell effect, for example, through the coupling of the quantum emitter with plasmon-polaritons, that are located in the interface between a dielectric and a metal. These modes, hybrids of electromagnetic field and plasmon matter also happen in 2D materials, such as graphene (single layer sheet of carbon atoms) or black phosphorus (anisotropic semiconductor)(Neto et al. (2009), Xia et al. (2019)).

In this paper we introduce the results for the decay rate of photons for a quantum emitter, designed as a electric dipole, at a estipulated distance from a interface. For this work, the differences between a metal surface and a graphene(with plasmon-polaritons) is shown, resulting in a difference of up to 5 orders of magnitude for the coupled graphene layer.

2 Materials and methods

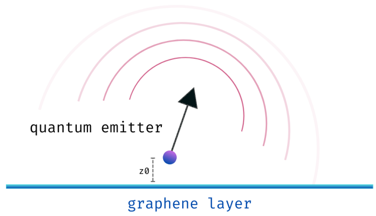

Figure 1 – Representation of the quantum emitter near a graphene layer.

We depict the quantum emitter as seen in Fig. (1), considering the electric dipole μ perpendicular to the interface, $\mu = (0, 0, \mu_z)$. In the presence of metal and graphene, the reflected evanescent field will change the spontaneous rate of emission, described by Eq. 1.

For quantum emitters, we can treat them as electric dipoles (Novotny e Hecht (2012)), with the characteristics determined by the dipole momentum $\mu = (\mu_x, \mu_y, \mu_z)$. By using dyadic Green's function and their polarization decomposition, is possible to determine the Purcell factor ($\frac{P}{P0}$),given in Eq. 1, for a dipole distant of z_0 to the interface:

$$\frac{P}{P_0} = 1 + \frac{3(\mu_z^2)}{2|\boldsymbol{\mu}|^2} \int_0^\infty ds \text{Re}\left(\frac{s^3}{s_z} r^p e^{2ik_1 z_0 s_z}\right) + \frac{3(\mu_x^2 + \mu_y^2)}{4|\boldsymbol{\mu}|^2} \int_0^\infty ds\, \text{Re}\left(\frac{s}{s_z}(r^s - r^p s_z^2) e^{2ik_1 z_0 s_z}\right), \quad (1)$$

with $s_z = \sqrt{1 - s^2}$, the Fresnel reflection coefficients (r^s and r^p) given for s and p polarization and k_1 the wave number in the dipole's region.

3 Results and Discussion

Now, for Fig. 2 and 3 the Purcell Effect ($P/P0$) is shown as a function of the quantum emitter frequency, and the varying lines are for different distances to the interface z_0. Based on these figures it is possible to see

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that the Purcell factor decays as the distance/frequency increases and has a maximum value whose frequency depends on the distance z_0. Comparing the metal interface values to the graphene, the Purcell factor for graphene has values considerably larger than those of the metal, showing the plasmon-polaritons effect.

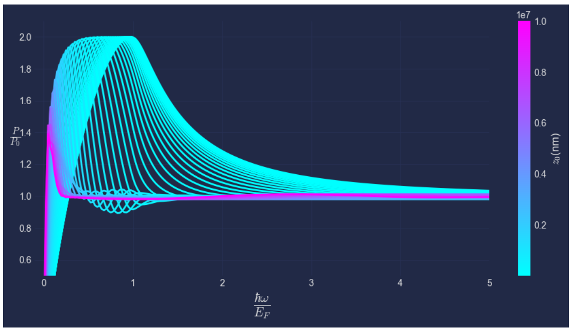

Figure 2 – Purcell factor, P/P_0, as a function of ω for different distances z_0 to the metal interface. Note the order of magnitude of P/P0 values related to the graphene.

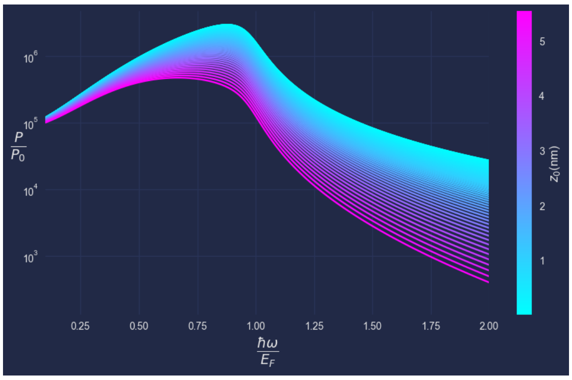

Figure 3 – Purcell factor, P/P_0, as a fucntion of quantum emitter frequency (ω) for different distances (z_0) to the graphene interface (logscale in y axis). Note the spike of emission near $\hbar\omega \approx E_f$.

To further study the behavior of the Purcell factor we shown in Fig. (4) the relation between the distance to interface($z0$) and the maximum value of P/P_0.

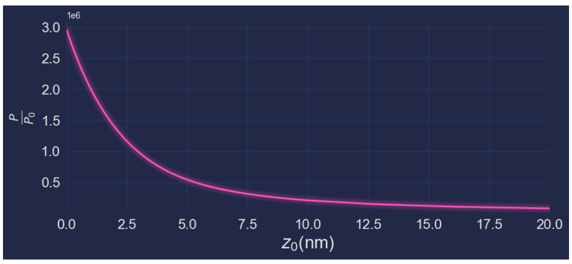

Figure 4 – Maximum Purcell factor for each distance to the graphene layer.

The difference between both interfaces Purcell effect is due to the plasmon-polaritons modes supported by the graphene layer. This results in the coupling of the quantum emitter with the interface, increasing drastically the decay rate, that keeps to higher in all range of frequencies and distances.

4 Conclusion and further perspectives

In this paper, the increasing of photon emission rate in coupled quantum emitters, through the Purcell effect, with graphene plasmon polaritons and normal metal interface were explored. As of the results, it was shown that the graphene interface increases significantly the Purcell factor of the quantum emitter, by up to 5 orders of magnitude largen than the metal interface.

These results provide us with the perspective of integrating 2D materials, such as graphene with plasmonic structures, for improvement of the Purcell effect efficiency. These effects can be used to improve single photon fonts, that are fundamental for quantum communication, and other emerging fields like cybersecurity.

As for future works, the coupling of quantum emmiters with anisotropic surfaces, such as black phosphorus, or more complicated structures, as photonic crystals, will be investigated.

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