Analysis of quantum dynamics of an emitter near metal-dielectric interface

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1 Methodology

Using the Green function formalism developed in Part 1 of the Project using a Python code, the emitter's spectral response and dynamics are analyzed here. The geometry is a three-layer planar system: vacuum–metal–vacuum. The metallic slab is modeled by the Drude model with the dielectric function given by:

$$\varepsilon(\omega) = \varepsilon_b - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

and the parameters $\varepsilon_b = 9.5$, $\omega_p = 9.06$ eV, and $\gamma = 0.071$ eV. The emitter is placed in the upper vacuum region at a distance d from the metal surface, where the slab thickness is fixed at $t = 20\,\text{nm}$.

The spectral density $J(\omega)$ is calculated using the imaginary part of the Green function evaluated at the emitter's position, normalized to the free-space spontaneous emission rate γ_0 which is defined as $\gamma_0 = \frac{2}{3}\frac{\omega^3}{c^3}$. $J(\omega)$ is computed over a wide range of ω as follows

$$J(\omega) \propto \frac{\text{Im}\, G_{xx}(\mathbf{r}, \mathbf{r}; \omega)}{\gamma_0}.$$

The distance is normalized to the wavelength d/λ_0 and varied for three different position: $0.05\lambda_0$, $0.1\lambda_0$, and $1.0\lambda_0$, where $\lambda_0 = c/\omega_0$ and $\omega_0 = 2.0\,\text{eV}$.

2 Results and Discussion

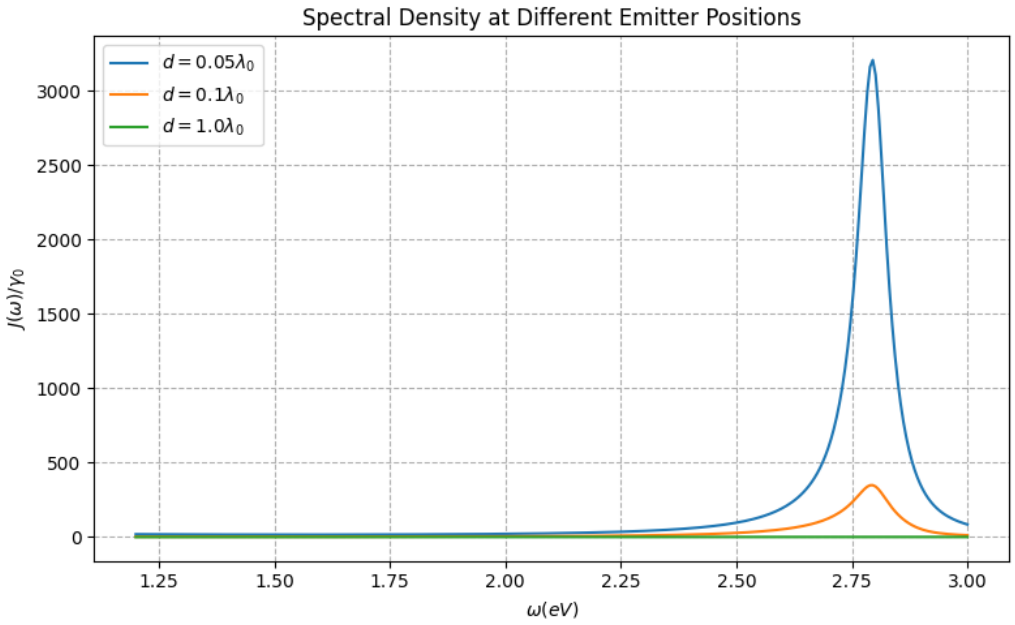

Figure 1: Spectral density $J(\omega)/\gamma_0$ computed at three different positions of the emitter d normalized to the emitter wavelength.

Figure 1 shows the normalized spectral density $J(\omega)/\gamma_0$ for different emitter–metal positions. When the distance is short (i.e., $d = 0.05\lambda_0$), the spectral density exhibits a sharp peak at a frequency slightly above 2.75 eV, which is above the emitter frequency $\omega_0 = 2.0$. The larger the distance between the emitter and the interface, the peak becomes weaker and broader as the spectral density flattens out at $d = 1.0\lambda_0$, where the density shows minimal frequency dependence.

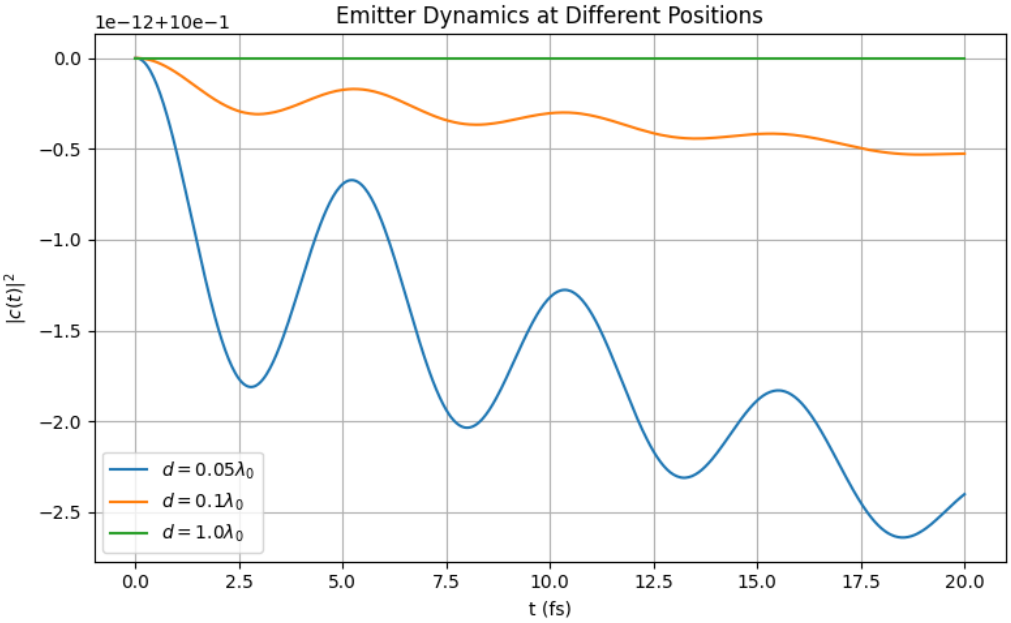

Figure 2: Time evolution of the excited state population $|c(t)|^2$ for a single emitter initially excited at three different distances from the surface d.

Assuming the emitter is intitially in the excited state, the dynamics are computed as shown in Figure 2, which is the time evolution of the excited state population $|c(t)|^2$ for the emitter at three different positions d. The dynamics are calculated by numerically solving the integro-differential equation.

The results as presented in Figure 2 show clear dependence on the position. For small distances (i.e. $0.05\lambda_0$), the decay is faster and non-exponential and shows oscillations. At larger distances (i.e. $0.1\lambda_0$), the decay slows and the oscillatory features flatten until it reaches d= $1.0\lambda_0$, where the decay is not significant within the time range.

These results can be explained as follows: When the emitter is placed close to the surface, it interacts strongly with surface-bound modes, such as surface plasmons, which makes the spectral density peaks and leads to faster and oscillatory decay dynamics. When the emitter is moved away from the interface, the influence of these modes vanishes, the spectral density becomes flatter and less peaky, and the population decay becomes slower and smoother. At large distances, the emitter behaves nearly as it would in a homogeneous dielectric environment.