A MIXED PERTURBATIVE-NONPERTURBATIVE TREATMENT FOR STRONG LIGHT-MATTER INTERACTIONS

Carlos José Sánchez Martínez, Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049, Madrid, Spain
C/ Francisco Tomás y Valiente, 7, E-28049, Madrid, Spain
T: +34 669537364, carlosj.sanchez@uam.es
Johannes Feist, Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049, Madrid, Spain
Francisco José García Vidal, Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049, Madrid, Spain; and Institute of High Performance Computing (IHCP), Singapore 138632

The placement of a quantum emitter in close proximity to nanophotonic structures results in promising enhanced light-matter interactions. The description of such interactions is a nontrivial problem since these nanostructures support a complex electromagnetic (EM) environment where all the light degrees of freedom must be taken into account [1]. Recently, a novel approach [2] has addressed this scenario, achieving a few-mode quantization of arbitrary EM environments. It exploits the quantity encoding the full information about the emitter-environment interaction: the spectral density. This framework replaces the original environment by a model involving only a small number of lossy interacting discrete modes and providing a closed expression for its spectral density. A fitting procedure of this model spectral density to the original one then determines the parameters characterizing the discrete modes. The main downside of this approach is that, depending on the complexity of the EM environment, the number of modes involved can still be larger than ideally wished to ensure low computational cost.

In the present work [3], we tackle this issue by leveraging the underlying physics of the light-matter interaction. We split the spectral density into two contributions in order to effectively separate the part of the EM environment strongly coupled to the emitter from that one which is weakly coupled to it (see Figure 1). The strongly coupled part, which induces non-Markovian dynamics, is treated nonperturbatively using the fitting procedure described above [2], but now restricted to the region encompassing the emitter transition frequencies. The residual part is instead treated perturbatively under the assumption of Markovianity, such that its effect is reduced to an energy shift on the emitter energy levels [4], which does not induce any additional numerical cost. We demonstrate that our model allows the description of the emitter dynamics through a Lindblad-like master equation in any coupling regime. Finally, we illustrate its validity through numerical calculations of the excited state population of a two-level emitter in the problem of spontaneous emission. We test three different setups supporting strong light-matter interactions: the first one is a simple model consisting of a sum of Lorentzian resonances, the second one is a realistic hybrid metallodielectric nanostructure, and the third one is a single-mode setup corresponding to a two-level emitter under ultrastrong coupling to a single physical mode.

This work offers a practical model for progressing in both the experimental and theoretical research line investigating light-matter interactions in complex nanostructures.

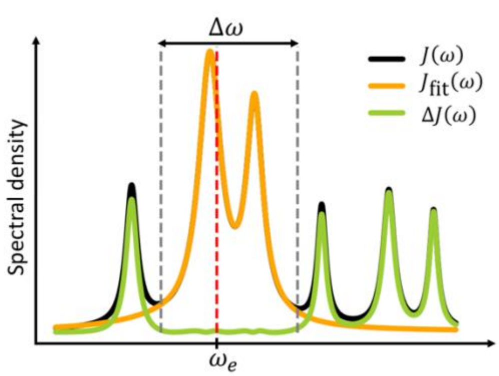

Figure 1 – Splitting of the spectral density, $J(\omega)$, as $J(\omega) = J_{fit}(\omega)+\Delta J(\omega)$. The region close to the emitter transition frequency ω_e, of width $\Delta\omega$, is fully described by $J_{fit}(\omega)$, accounting for all strong-coupling effects. The region detuned from the emitter level is described perturbatively by the residual spectral density $\Delta J(\omega)$.

[1] J. Feist et al., Nanophotonics, **10**, 477-489 (2021)
[2] I. Medina et al., Phys. Rev. Lett., **126**, 093601 (2021)
[3] Carlos J. Sánchez Martínez et al, arXiv:2312.15324 (2023)
[4] S. Y. Buhmann, Dispersion Forces I: Macroscopic Quantum Electrodynamics and Ground-State Casimir, Casimir-Polder and van der Waals Forces, 1 ed., Springer Berlin Heidelberg (2012)