QUANTUM EMITTER INTERACTING WITH A DISPERSIVE DIELECTRIC OBJECT: A MODEL BASED ON THE MODIFIED LANGEVIN NOISE FORMALISM

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Harnessing the interaction between electromagnetic fields and matter is of growing importance across diverse areas of physics, from condensed matter physics to quantum optics and information [1]. In particular, light-matter interaction in the strong coupling regime enables the precise manipulation of the physical properties of hybrid systems and the preparation of nonclassical states of light. Engineered coupling with electromagnetic resonators in Circuit quantum electrodynamics (circuit QED) platforms can profoundly alter the radiative properties of quantum emitters, regulate photochemical reaction rates, and prove as a useful tool to simulate collective phenomena in quantum materials. Moreover, thermal effects can play a significant role in determining steady-state properties in these quantum systems. The electromagnetic environments in these systems are open, dispersive, and absorbing, characteristics that pose challenges to field quantization. Macroscopic quantum electrodynamics (e.g. [2]) offers a powerful phenomenological framework for quantizing the electromagnetic field in such complex systems, enabling a consistent description of light–matter interaction.

In Ref. [5-6], we modelled the interaction of a quantum emitter with a finite-size dispersive dielectric object in an unbounded space within the framework of macroscopic quantum electrodynamics [2], using the modified Langevin noise formalism [2], without any restrictions on the emitter level structure or dipole operator. The quantized electromagnetic field consists of two contributions: the medium-assisted field, which accounts for the electromagnetic field generated by the noise polarization currents of the dielectric, and the scattering-assisted field, which takes into account the electromagnetic field incoming from infinity and scattered by the dielectric. We show that the emitter couples with two distinct bosonic baths: a medium-assisted bath and a scattering-assisted bath, each characterized by its spectral density. Therefore, for initial thermal states of the reservoirs having different temperatures, the common approach based on the dyadic Green function of the dielectric object cannot be employed. In Ref. [5], we identified the conditions under which the electromagnetic environment composed of these two baths can be effectively replaced by a single bosonic bath, so that the reduced dynamics of the quantum emitter remain unchanged. In particular, when the initial states of the medium- and scattering-assisted baths are thermal states with the same temperature, we find that a single bosonic bath with a spectral density equal to the sum of the medium-assisted and scattering-assisted spectral densities is equivalent to the original environment.

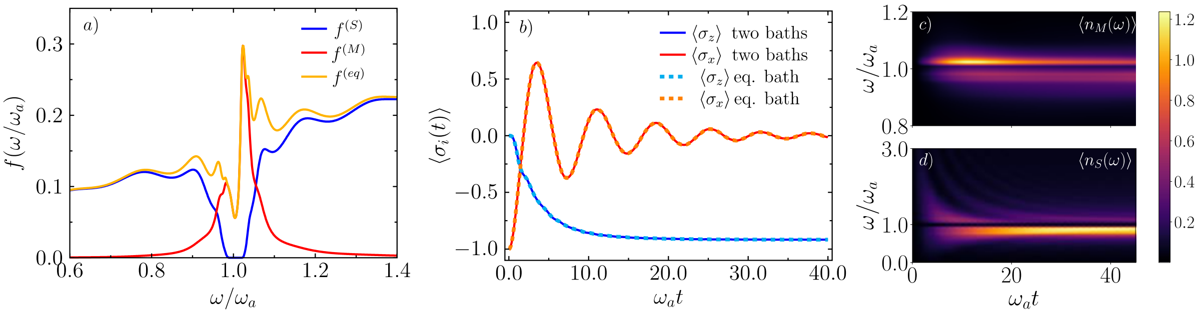

Figure 1: (a) Normalized spectral density of the scattering (S), medium (M), and equivalent (eq) baths plotted against ω/ωa. (b) Expectation values of $\hat{\sigma}_x$ and $\hat{\sigma}_z$ plotted versus time. Case i) Solid lines: the emitter couples to the medium and scattering baths, prepared at t = 0 in their vacuum states. Case ii) Dashed lines: the emitter couples to a single equivalent bath with spectral density $J_{eq} = J_S + J_M$, which at t = 0 is in its vacuum state. (c) Expectation values of the occupation numbers of the medium bath modes $n_\omega^{(M)}$ (c) and of the scattering bath modes $n_\omega^{(S)}$ (d) plotted versus mode frequency and time.

In Ref. [6], we studied the interaction of a quantum emitter with these two reservoirs introducing a temperature-dependent effective spectral density of the electromagnetic environment, focusing on the case of a homogeneous dielectric sphere. We derive analytical expressions for the medium-assisted, scattering-assisted, and effective spectral densities in this setting. We then study the dynamics of the quantum emitter for initial thermal states of the two reservoirs, adopting a non-perturbative approach.

References

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