Quantum emitter interacting with a dispersive dielectric object: a model based on the modified Langevin noise formalism

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Abstract: We model the interaction of a quantum emitter with a finite-size dispersive dielectric object in an unbounded space within the framework of macroscopic quantum electrodynamics using the modified Langevin noise formalism

In this work, we model the interaction of a quantum emitter with a finite-size dispersive dielectric object in an unbounded space within the framework of macroscopic quantum electrodynamics [1-2], using the modified Langevin noise formalism [3], 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 to two distinct bosonic baths: a medium-assisted bath and a scattering-assisted bath, each characterized by its own spectral density. We identify 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 electromagnetic environment.

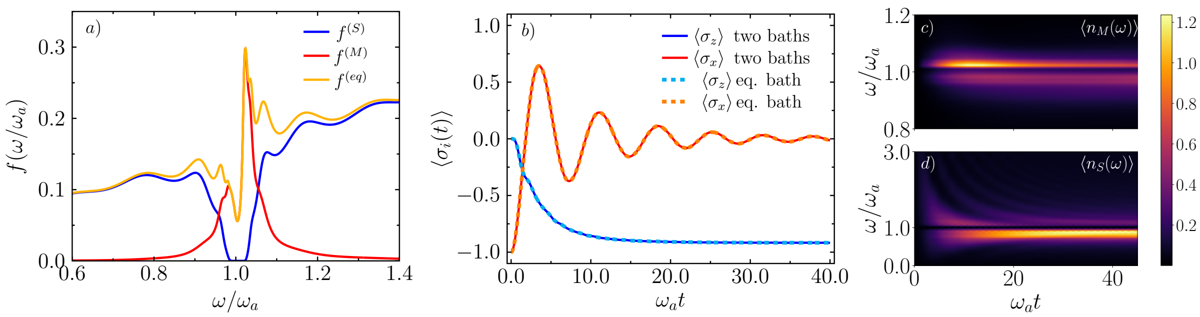

Fig. 1 (a) Normalized spectral density of the scattering (S), medium (M) and equivalent (eq) baths plotted against ω/ω_a. (b) Expectation values of $\hat{\sigma}_x$ and $\hat{\sigma}_z$ plotted versus time. Case i) Solid lines: the emitter couples to the medium and scattering baths, prepared at t=0 in their vacuum states. Case ii) Dashed lines: the emitter couples to a single equivalent bath with spectral density $\mathcal{J}_{eq} = \mathcal{J}_S + \mathcal{J}_M$, which at t=0 is in its vacuum state. Expectation values of the occupation numbers of the medium bath modes $\hat{n}_\omega^{(M)}$ (c) and of the scattering bath modes $\hat{n}_\omega^{(S)}$ (d), plotted versus mode frequency and time. The parameters are the same as in (b).

In Fig. 1, we present one-dimensional numerical simulations of a two-level quantum emitter in a lossy dielectric slab for medium and the assisted baths that are initially in the vacuum state. We performed simulations of the evolution of $\rho(t)$ considering the instances of an emitter coupled with: Case i) two different baths, each described by $\mathcal{J}_M(\omega)$ and $\mathcal{J}_S(\omega)$ (ω); Case ii) a single equivalent bath with $\mathcal{J}_{eq}(\omega)$. As expected, for the chosen initial states of the bath, the dynamics of the observables coincide in the two cases, indicating that the influence of the dielectric slab on the reduced dynamics of the emitter can be effectively simulated with a single, equivalent bath. When the baths are in non-equilibrium states, e.g., when the temperatures of wo baths are different, it is not possible to introduce an equivalent spectral density.

References

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