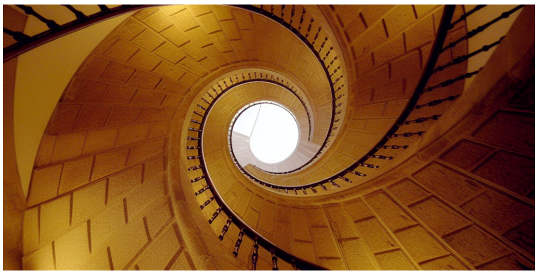

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Waveguide QED in the Dipole Gauge

Recent studies on the ultrastrong coupling of light and matter have pointed out the nuances of approximating the number of energy levels of the matter system. In cavity QED systems it was shown that directly applying the two-level approximation to a model describing the interaction with a momenta-like operator (as in the Coulomb gauge) could lead to gauge dependent observables [1,2]. Instead, a gauge invariant model can be obtained by first transforming into the dipole gauge and then applying the truncation [1,2].
In this work we extend this idea to the realm of waveguide QED platforms. We obtain a model in the dipole gauge for a cavity array waveguide coupled to an atom in one of its cavities. Unlike for the typical Coulomb gauge representation, the dipole gauge includes a coupling between the atom and the adjacent cavities. We show that this model has an accurate two-level approximation unlike for the one obtained in the Coulomb gauge.
The couplings to the adjacent cavities introduce modifications in the properties of the model such as the spectral density that strongly affect the dynamics in the USC regime. In particular we focus on two phenomena, the spontaneous emission and the scattering.
In order to properly characterize the spontaneous emission we study the emitted photons in a distant cavity, an observable given by a gauge invariant operator. Simulations of the truncated and full models in both gauges show that, while in the weak coupling regime all models are equal, the predictions obtained in the truncated Coulomb gauge within the USC regime differ from the ones in the dipole gauge and the full model simulations.
Another property of the system greatly affected by the truncation is the single photon transport through the waveguide. In the dipole gauge, as a consequence of the adjacent couplings, there is a Lamb-shift contribution that displaces the resonance condition for which the transmission vanishes in the USC regime.
References
[1] De Bernardis et al. Physical Review A 98 053819 (2018)
[2] Di Stefano et al. Nature Physics 15, 803-808 (2019)

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