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par

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Waveguide quantum electrodynamics in a plasmonic nanowire: Strong coupling regime, energy transfer and single photon transport

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Abstract

Quantum plasmonics represents a promising frontier at the intersection of quantum optics and nanophotonics, aiming to integrate quantum functionalities within nanoscale photonic circuits. By exploiting surface plasmon polaritons (SPPs) sustained by metallic nanostructures, one can achieve subwavelength confinement of electromagnetic fields and drastically enhance light–matter interaction. These properties are essential for the realization of efficient single-photon sources, quantum communication channels, and scalable on-chip quantum technologies. However, plasmonic systems are intrinsically lossy, and their quantum description demands rigorous formulations capable of incorporating dissipation, non-Markovian effects, and strong coupling regimes beyond the rotating wave approximation (RWA).

This thesis develops a comprehensive theoretical framework describing the interaction of quantum emitters with plasmonic nanowires. Starting from macroscopic quantum electrodynamics (QED), the dyadic Green's tensor of the nanowire is derived and decomposed into its radiative and evanescent components, allowing for a precise quantization of lossy plasmon modes. Effective Hamiltonians are then constructed to link this continuous description to standard waveguide QED formalisms. The approach is progressively extended from single-emitter to multi-emitter configurations, incorporating both Förster Resonance Energy Transfer (FRET) and laser-driven stimulated Raman adiabatic passage (STIRAP)-like dynamics.

The work reveals that the Fano modal decomposition of the Green tensor accurately captures the spectral response of emitter–nanowire systems and clarifies the emergence of dressed states in the strong-coupling regime. The numerical results demonstrate how the Purcell enhancement and dipole–dipole interactions determine population transfer and coherence preservation at nanometer scales. Comparison between RWA and no-RWA dynamics shows that counter-rotating terms play a decisive role in the near-field regime, accelerating population oscillations and modifying decay rates. Moreover, by introducing time-dependent laser coupling, it is shown that STIRAP-like schemes are proposed to achieve nearly complete and robust population transfer between spatially separated emitters. The model is then generalized to analyze single-photon transport in one-dimensional plasmonic nanowires, where modal quantization provides explicit expressions for reflection and transmission.

This research establishes a unified quantum optical description bridging Green's function methods, modal quantization, and effective Hamiltonian models for dissipative nanoplasmonic systems. It demonstrates that plasmon-mediated strong coupling enables coherent energy transfer and controllable photon transport at deeply subwavelength scales, providing a pathway toward the integration of quantum plasmonic circuits on photonic chips. Future research could extend this framework to include collective effects in multi-emitter arrays, explore chirped or structured light excitations for robust state transfer, and investigate hybrid plasmonic–dielectric architectures to mitigate losses while preserving the benefits of extreme field confinement.

Keywords: Quantum Plasmonics, Non-hermitian Hamiltonian, Green dyadics, Population Transfer driven by laser, Single photon transport, Rotating Wave Approximation, Markovian dynamics, Fano resonances.