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PhD thesis project: Engineering collective emission in waveguide quantum electrodynamics

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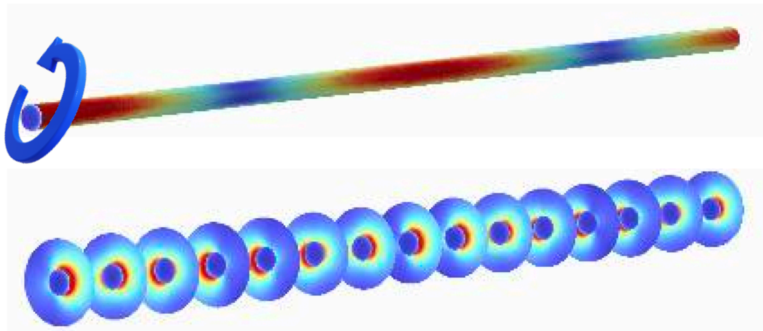
Introduction and context. Waveguide quantum electrodynamics (wQED) is a dynamic field at the intersection of quantum optics, quantum information science, and nanophotonics. It explores the interaction between quantum emitters (atoms, molecules, or artificial atoms like superconducting qubits) and electromagnetic fields confined in one-dimensional (1D) waveguides, including optical nanofibers and plasmonic nanowires. This platform enables fiber to chip quantum optical convergence and is a promising candidate for all-optical quantum computing devices. Recent advances have demonstrated the potential of wQED for implementing single photon optical transistors, two qubits-entanglement, long-range energy transfer or nanowire lasers [1].

a)



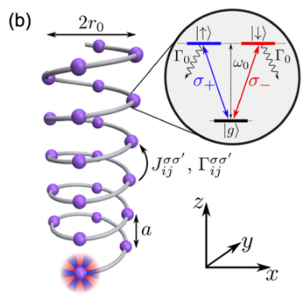


Fig. 1 : a) Chiral plasmon propagating along a gold nanowire. The mode profile follows a helical wave. b) Quantum model of chiral superradiance (see ref. [5]) along helical arrangement of quantum emitters.

Scientific objectives. This PhD project aims to harness the unique properties of wQED to generate and control non-classical states of light, with a focus on collective quantum phenomena. The project will build on a novel formalism—an effective Hamiltonian for quantum nano-optics—recently developed by our joint teams (ICQ and Photonics departments) and extended to wQED [2, 3]. The research will proceed in three main steps:

i) Optimization of Robust, Long-Range Energy Transfer

We will adapt established cavity QED (cQED) protocols to the wQED platform, leveraging our new formalism to define a scaling law between cQED in micro-optical cavities and wQED in nano-optical waveguides. Quantum control techniques will be employed to optimize energy transfer along the nanowire, ensuring robustness and efficiency.

ii) Superradiance in Waveguide-Coupled Quantum Emitters

Superradiance refers to a collective emission phenomenon where excited atoms in a subwavelength volume emit coherently. This phenomenum originates from spontaneous phase locking of the atomic dipoles through a same mode and is very similar to the building of cooperative emission in a laser amplifier. Superradiant emission promises applications in narrow-linewidth lasers and quantum memories. Superradiance will be investigated in the context of wQED. By coupling collective emission into the guided mode rather than free-space radiation, we aim to generate bright, coherent arrays of qubits along the waveguide.

iii) Engineering Chiral Collective Emission

Under specific excitation conditions, chiral plasmons propagate along the nanowire [4]. We will engineer the coupled system of quantum emitters and plasmonic nanowire to achieve chiral superradiant emission. This represents a new paradigm for controlling photon transport, offering unprecedented opportunities for directional and coherent light-matter interactions [5].

Methodology

The project is theoretical, combining analytical and numerical approaches to model the interaction between quantum emitters and guided modes. The effective Hamiltonian formalism will be central to describing collective effects and optimizing system parameters for targeted quantum states.

Expected Outcomes

- Development of robust protocols for long-range energy transfer in wQED.
- Generation of non-classical light states via superradiance in waveguide-coupled emitters.
- Demonstration of chiral collective emission, enabling new degrees of control for photon transport.

References

[1] *Interfacing single photons and single quantum dots with photonic nanostructures*. P. Lodahl, S. Mahmoodian, and S. Stobbe, Review of Modern Physics **87,** 347 (2015).

[2] *Collective strong coupling in a plasmonic nanocavity*, H. Varguet, A. Diaz-Valles, S. Guérin, H. Jauslin, G. Colas des Francs, Journal of Chemical Physics **154**, 084303 (2021).

[3] *Single photon transport in one dimensional plasmonic nanowire,* A. Díaz-Valles, B. Rousseaux, S. Guérin, H. Jauslin, A. Leray, and G. Colas des Francs, *in prep* (2026).

[4] *Chirality dependent photon transport and helical superradiance.* J. Peter, S. Ostermann, S. F. Yelin, Phys. Rev. Res. **6**, 023200 (2024).

[5] *Chiral Surface Plasmon Polaritons on Metallic Nanowires.* S. Zhang, H. Wei, K. Bao, U. Hakanson,N. Halas, P. Nordlander, H. Xu. Physical Review Letters **107**, 096801 (2011).

Type of project (theory / experiment): theoretical

Required knowledge: quantum optics, nanophotonics