Proposition de stage/thèse
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Interactions atomes-photons avec un guide d'onde à modes lents à dispersion contrôlée : propriétés collectives et applications à la waveguide QED

Le sujet de ce stage se situe à l'intersection entre la Nanophotonique et l'Optique quantique. Il s'inscrit dans le cadre d'une collaboration entre le Laboratoire Lumière, Matière et Interfaces (LuMIn) de l'ENS Paris-Saclay et le Laboratoire Charles Fabry de l'Institut d'Optique financée par un projet ANR.

Mots-clés : Nanophotonique, Optique quantique, Waveguide QED, Cristaux Photoniques

The quantum technologies roadmap is marked by several milestones. Among them, the realization of strong interactions between single photons has been a driving force for a large community over the past decades. Since photons propagating in vacuum do not interact, photon-photon interactions can only be mediated by matter. Therefore, achieving strong light-matter interactions at the single photon level is a long-standing goal of both fundamental and technological importance, and various approaches have been explored to reach it. The most well-known is probably cavity quantum electrodynamics (QED), which consists in placing an "atom" (atom, quantum dot, super-conducting qubit…) in a high-finesse cavity. The interaction is increased because the photon bounces between the cavity mirrors, thereby "seeing" many times the atom. The field of cavity QED has been (and still is) very successful, providing major advances in quantum optics. Nevertheless, using a cavity to enhance light-matter interactions also presents some drawbacks, especially a narrow bandwidth and the difficulty to couple photons in and out of the cavity with high efficiency.

Because of these limitations, many recent works have studied **cavity-free systems, based on single-pass configurations**. In this context, **the atom-photon interaction can be increased by using sub-wavelength waveguides** that confine the electromagnetic field to deeply subwavelengths scales in the transverse directions. This is the emerging field of **waveguide QED**, where different platforms coexist. The main ones are superconducting qubits coupled to transmission lines at microwave frequencies, quantum dots in nanophotonic structures, and cold atoms trapped along a nanofiber.

Each platform has its own advantages and drawbacks, which can be grasped with two figures of merit. First, the coupling strength between atoms and guided photons is of major importance. It can be quantified with the β factor ($\beta \in [0,1]$), which represents the fraction of the decay rate that is funneled into the guided mode. Said in a different way, β quantifies the extinction of a propagating photon by a single atom. The second figure of merit that is important to compare waveguide QED platforms is the number of atoms N that can be coupled together to the waveguide. In a nutshell, systems based on superconducting qubits or quantum dots benefit from strong coupling strengths $\beta \geq 0.9$ but small N's of a few units while atoms trapped along a nanofiber offer much larger N's but small coupling strengths $\beta \sim 0.01$. **Currently, no system can provide both a large number of atoms $N \geq 100$ and a high coupling strength $\beta \geq 0.9$**, see Figure 1.

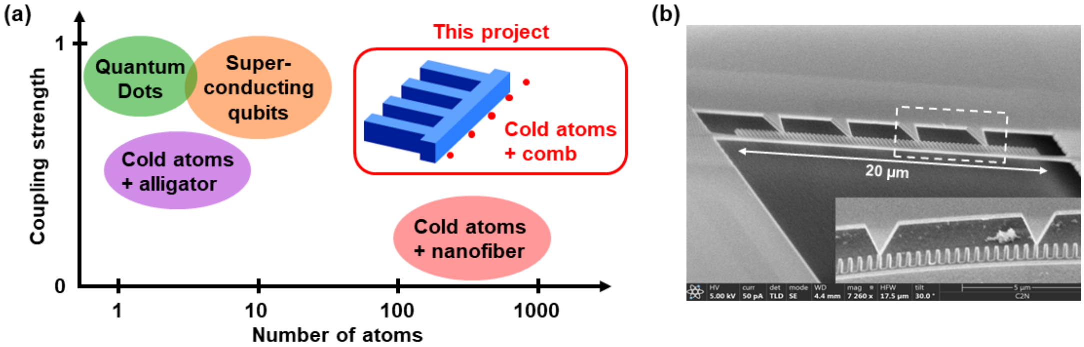

Figure 1. (a) Positioning of the project with respect to the state-of-the-art. We aim at reaching the high β – high N regime by using cold atoms trapped along an asymmetric comb waveguide supporting a slow mode. (b) SEM picture of a suspended comb waveguide fabricated at Centre de Nanosciences et de Nanotechnologies (C2N).

Among the different waveguide QED platforms, the ones that use real atoms instead of artificial atoms are well-suited to work with many emitters. Since the atom – photon interaction is inversely proportional to the group velocity of the guided mode, it is possible to **increase the interaction by using photonic-crystal waveguides that support slow modes** [Cha18]. Up to now, two main geometries supporting slow light have been investigated: the alligator waveguide (theory and experiments) and the hybrid-clad waveguide (theory) [Gob15,Zan16]. However, a stable trapping of atoms close to a photonic-crystal waveguide supporting a slow mode has not been demonstrated so far and that is why the number N of interacting atoms is limited to a few units ($N < 3$).

Recently, we have designed an innovative waveguide geometry, the asymmetric comb waveguide [Fay22]. Thanks to a well-designed transverse symmetry breaking, the asymmetric comb mitigates the weaknesses of existing structures and opens new perspectives. This new waveguide geometry (see a SEM picture of a fabricated sample in Figure 1) should allow to reach experimentally the high β – high N regime in order to realize quantum operations on propagating photons. **Moreover, this interaction regime is largely unexplored in waveguide QED. In this regime, the impact of the waveguide dispersion $\omega(k)$ on the collective properties of the atomic ensemble is still unknown.** The slow mode of the asymmetric comb waveguide follows a quartic dispersion $\omega \propto k^4$ [Fay22], whereas photonic-crystal waveguides often exhibit a quadratic dispersion near a band edge, $\omega \propto k^2$.

The usual theory in waveguide QED simplifies the problem by linearizing the dispersion relation around the atomic frequency because the bandwidth of the atomic transition is much smaller than the bandwidth over which the group velocity varies. However, N interacting atoms give rise to subradiant and superradiant states whose largest decay rate is proportional to N. Therefore, the linear assumption necessarily breaks down for large N's. **Now that the high β – high N regime is within reach of the experiment, it is of major importance to unravel the impact of the dispersion on the collective properties of an ensemble of atoms.**

The objective of the internship is to explore the role of the waveguide dispersion in the building of the collective properties of an ensemble of atoms coupled to a slow-light photonic-crystal waveguide. We are facing a totally blank page that we propose to start filling.

The study will rely on **theory (classical and quantum electrodynamics, nanophotonics) and numerical calculations**. It is part of a collaborative ANR research project that gathers Laboratoire Lumière, Matière et Interfaces (Lumin), Laboratoire Charles Fabry (LCF), Laboratoire Kastler Brossel (Julien Laurat and Alban Urvoy), Centre de Nanosciences et de Nanotechnologies (Kamel Bencheikh and Ariel Levenson), and Institut Pascal (Antoine Moreau). **It is preferable that the internship be followed by a PhD thesis. The PhD will be funded by the ANR project.**

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