

Nanophotonics for Quantum Information and Simulation (NanoQUIS)

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Period: 01/02/2015-31/12/2017

1. Introduction.

Quantum technologies have recently attracted the attention of many governments, e.g., with the European Flagship, and private companies such as Google, IBM, Microsoft, ... because of their potential to transform our economy and society. For example, the ability to simulate quantum systems beyond the classical capabilities, studied by the field of Quantum Simulation, may shed light into important technological problems such as high-Tc superconductivity or the design of efficient drugs by solving quantum chemistry problems. On the other hand, quantum systems also hold the promise of achieving more secure quantum networks to transmit information, mostly encoding information in light particles (photons) and boosting our precision measurements exploiting quantum metrology protocols.

There remain, however, many open challenges to exploit all the opportunities provided by quantum physics. In NanoQUIS we were concerned about three of them:

- 1) In order to make a faithful quantum simulation of a hamiltonian or perform a quantum gate for quantum computation, the coherence of the processes must overcome any other possible sources of decoherence such as thermal fluctuations, disorder, ... One alternative to beat that shortcoming consists of **increasing the energy scales** of the quantum gates, that will allow, e.g., to make more faithful quantum simulations, but also to scale them up to larger system sizes.
- 2) In order to solve relevant problems, such as Quantum Chemistry ones, it is required to obtain **long-range interactions** between quantum systems. However, in most of the current implementations such as cold atoms in optical lattices or circuit QED, the interactions are limited to nearest neighbour or short range ones.
- 3) The **generation of non-classical states** of light, e.g., with a **fixed photon number**, is instrumental to achieve better focusing of light beyond classical limits and obtain better precision in measurements. The larger the photon number, the better precision. However, the rate in generating them scales exponentially with the photon number, which limits their applicability.

The goal of the project was trying to exploit a new hybrid system, namely, cold atoms coupled to nanophotonics system to go beyond state of the art capabilities. Cold atoms are one of the best candidates to store quantum information due to their long coherence times and reproducibility as they have naturally all the same level structure. On the other hand, nanophotonics structures are the ones that are able to mold and

confine the flow of light at the nanometric scale (see Figs 1 and 2). In the beginning the main motivation was to obtain better figures of merit for atom-light coupling due to the reduced mode volume which lead to higher interaction strengths. However, it was soon realized how the low dimensionality of the light may give rise to novel exotic phenomena not present in other realizations. In NanoQUIS, we explore the capabilities of these systems from the more practical perspective to the more fundamental one.

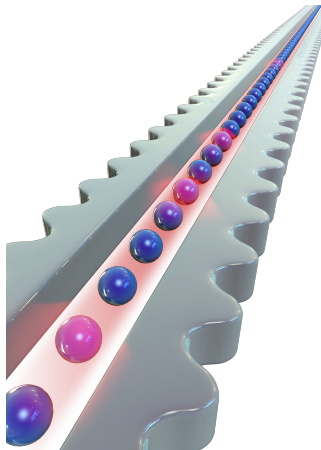


Fig. 1

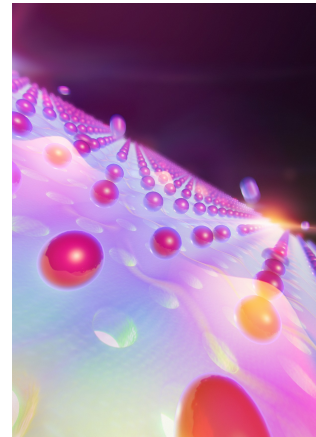


Fig.2

2. NanoQUIS results highlights

During the project we have obtained several relevant results exploiting atom-nanophotonics systems for Quantum Information and Simulation procedures.

A) Subwavelength optical lattices for large interaction strengths.

In *Nature Photonics* **9** (5), 320-325 (2015), we give a practical design for generating two-dimensional optical lattices for ultracold atoms by placing them close to 2d photonic crystals (see Fig. 2). Exploiting the subwavelength modulation of the refractive index, we show how to trap atoms at shorter distances of around 50 nm which have associated an increase of the energy scales in two orders of magnitude with respect to state of the art optical lattices.

B) Inducing long-range interactions between atoms.

In the same Ref. *Nature Photonics* **9** (5), 320-325 (2015), we also gave a feasible design on how to use the low dimensional photonic reservoir to mediate long-range interactions between the emitters. The periodic modulation of the refractive index induces the so-called photonic bandgaps in which light cannot propagate. If the frequencies of the atoms match those of the photonic bandgap, the decoherence

through the reservoir disappear, while still being able to induce coherent interactions between them. Moreover, we showed how this interaction can be long-range and with length scale which can be tuned at will optically.

In a follow-up work, published in *PNAS*, **113**, 34 E4946–E4955 (2016), we showed how to enlarge the toolbox of atom-nanophotonics by using magnetic field gradients and multifrequency lasers to engineer at will pairwise interactions and artificial gauge fields which opens the way of simulating topologically non-trivial models.

C) Efficient generation of non-classical states of light in waveguide QED

In Ref. *Physical Review Letters* **115** (16), 163603 (2015), *New Journal of Physics* **18** (4), 043041, *arXiv* 1603.01243, we show how to exploit the strong collective dissipation appearing in one-dimensional waveguide QED (see Fig. 1) to generate multiphoton states. The strong collective dissipation induces the appearance of both super and subradiant states which decay with an enhanced/suppressed decay rate into the waveguide. In these works we show how it was possible to move within the subradiant states to create entangled atomic superpositions which can afterwards be mapped to multiphoton states at will.

Exploiting the collective and strong interactions induced by nanophotonics, we predict the enhancement of fidelities and generation rates compared to state of the art proposals using parametric down converted photons

3. NanoQUIS results dissemination.

The project NanoQUIS has resulted in several peer-reviewed publications, including several high-impact ones such as *Nature Photonics*, *Proceedings of National Academy of Sciences* and *Physical Review X* and *Letters*. Moreover, the *Nature Photonics* publication was selected for the cover of the issue of May 2015.

Apart from the publications, the project results were presented in several international conferences and invited seminars among the most prestigious institutions of Europe and US, such as Niels Bohr Institute, Harvard University and Caltech among others, which has allowed the applicant to establish a strong collaboration with pioneering experimental groups in the field. In particular, 5 publications has been done in collaboration with the group lead by Prof. Kimble at Caltech.

Last, but not least, the project has help to boost the connection between the atomic physics and nanophotonic community by organizing a Summer School at DIPC in San Sebastian with the thematic of the project: “Nanotechnology meets Quantum Information” in the summer of 2016, and which will have a second edition in the summer of 2017.