MOCA - Integrated Microwave-to-Optical Conversion by Atoms on a superconducting chip

Simon Bernon[1], Natascia De Leo[2], Peter Domokos[3], David Petrosyan[4] and Jozsef Fortagh[5](coordinator)

(1)Laboratoire de photonique numérique et nanosciences (IOGS/CNRS/UB - FRANCE) , (2) Istituto Nazionale di Ricerca Metrologica (ITALY), (3) Wigner Research Centre for Physics (HUNGARY), (4) Foundation for Research and Technology-Hellas (GREECE), (5) University of Tübingen (GERMANY)

FUNDING AGENCIES

AGENCE NATIONALE DE LA RECHERCHE ANR

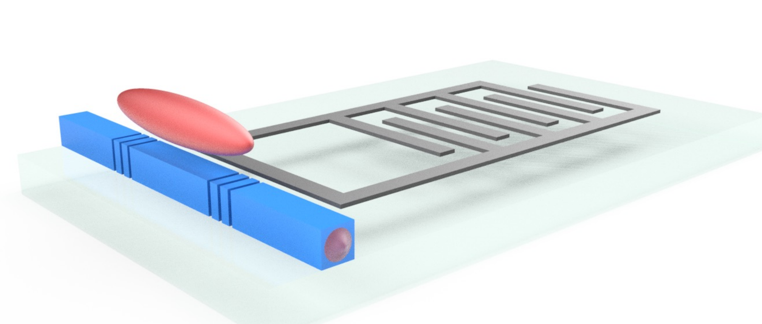
MUR

NEMZETI KUTATÁSI, FEJLESZTÉSI ÉS INNOVÁCIÓS HIVATAL

DFG Deutsche Forschungsgemeinschaft

Own funding : FORTH INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

Motivation



In the recent years, circuits of **superconducting (SC) qubits** have shown extraordinary abilities for performing **fast and high-fidelity** quantum logic operations which made them move from fundamental research to the R&D units of companies. This technology is yet still **limited by short coherence times** precluding long-term storage of quantum information, and the **difficulty to transport microwave (MW)** photons that prevents long distance coupling of quantum registers. While **cold gases of alkali atoms** have a smaller processing speed than SC qubits, they can well **perform these two tasks**. Their incorporation into a SC hybrid device has excellent perspectives but represents an experimental challenge. ***This project aims at the coherent conversion of MW to optical signals on an integrated atom chip compatible with SC quantum processors and optical communication networks.*** Such hardware components will form the basis for long-distance quantum communication between SC quantum (sub)processors – nodes of a quantum network – mediated by optical photons.

Transporting and coupling atoms to the near field

Main contributor : **LP2N**

LP2N will develop, on a room temperature atom chip, the experimental methods to optically transport atoms to the near field of nano-optical devices and to characterize the optical coupling.

In the framework of this project LP2N will develop and tests solutions to **transport and trap ultra-cold gaz in the near field of plane and nano-structured surfaces.** The solutions will be developed in a **room temperature** environment while optimizing their functioning for further integration in a low temperature (4K) apparatus in UT. Ahead of the SC chip integration, LP2N will develop efficient integrated IN/OUT coupling method of photons to the quantum gaz via **evanescent optical waveguides** or sub-wavelength ordered arrays.

Reference : Zang. *et al*, Phys. Rev. Applied **5** 024003 (2016) / Bellouvet *et al*, Phys. Rev. A **98** 023429 (2018)

MW and optical waveguides

Main contributor : **INRiM**

INRIM will initially develop in a few iterations a **room temperature atom chip.** The design will include both a gold coplanar MW transmission line and an Si3N4 nano-waveguide cavity integrated in the 10 µm gap of the MW line, aiming to reach propagation losses below 1dB/cm [1]. The design will also include a gold surface required for the atom transport. The couplers design will be optimized to achieve injection coupling efficiency above 70% [2].

In parallel, INRIM will fabricate a **SC MW coplanar-waveguide cavity** (6,8 GHz, Q~104-105 at T=4K) and wire components (Z-shaped wire) for magnetic trapping of Rubidium atoms. The SC chip and MW cavity will be fabricated with Niobium thin film technology on polished sapphire chip surfaces. Finally, **INRIM will integrate on the SC chip an optical waveguide cavity in the gap of coplanar MW cavity.**

Reference :

[1] F. Ferrarese Lupi J. Lightwave Technol. 30, 169-174 (2012)

[2] Hong, J. *et al* Sci Rep 9, 12988 (2019).

Free space benchmark

Main contributor : **WIGNER**

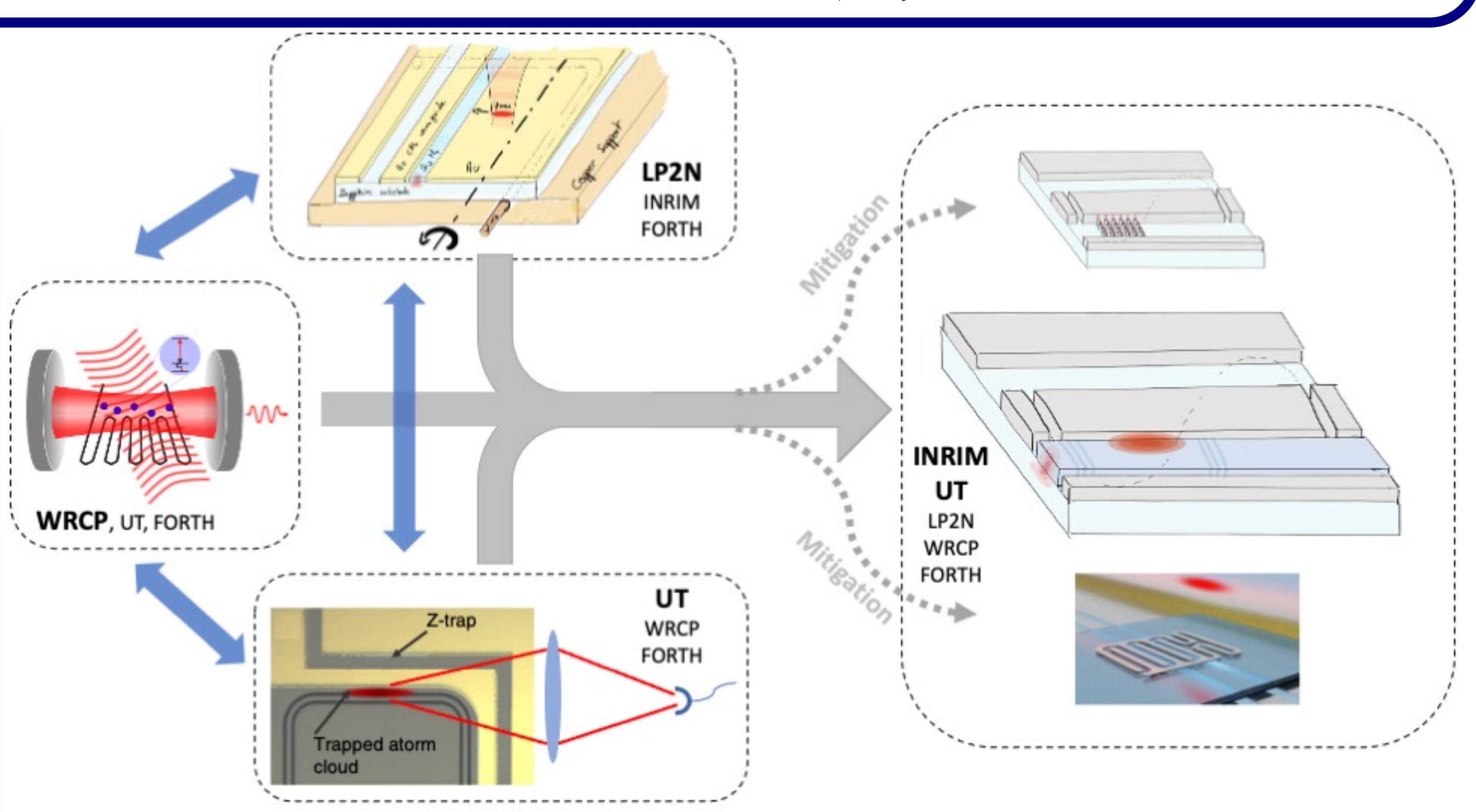
The Wigner center has a running optical cavity QED setup in which cold ^{87}Rb atoms are deterministically loaded from a magneto-optical trap into a **high-finesse Fabry-Pérot resonator** (finesse F=4000) of length 1.5cm. With up to 10^4 atoms in a single mode, the strong collective coupling regime is achieved. This intra-vacuum optical cavity QED system with an ensemble of cold atoms will be upgraded to hold a near-field MW antenna that allows realising coherent MW-optical wave mixing at low intensities. In this project, the transitions between the hyperfine F=1 and F=2 states will be driven by a classical MW source. Besides demonstrating various MW-optical photon conversion schemes, this setup will serve as a **benchmark for the physical concept by implementing artificially undesired external perturbations present in the vicinity of an atom chip.**

Reference :

T. W. Clark, Phys. Rev. A 105, 063712 (2022)

A. Dombi, New J. Phys. 23 083036 (2021)

H. Ritsch, Rev. Mod. Phys. 85, 553–601 (2013)



On chip MW to optical conversion

Main contributor : **Tübingen Univerity**

UT will perform cold-atom experiments on **superconducting atom chips** at 4K temperature. The experimental platform involves a SC atom chip with a coplanar **MW waveguide resonator**, ultra-cold rubidium atoms trapped at ten micron distance to the chips surface, and **high aperture optical photon collection optics**. The experimental plan includes the proof of concept of MW to optical photon conversion on the SC atomchip, the extraction of MW photons from the SC cavity by atoms, the **cooling of the microwave cavity mode, and finally the operation of a fully integrated atomchip for MW to optical conversion.**

Reference :

M. Kaiser et al Phys. Rev. Research 4, 013207 (2022)

H. Hattermann et al Nature Communications 8, 2254 (2017)

Theory support

Main contributor : **FORTH**

FORTH will provide the theoretical support and guidance for the experiments on MW to optical conversion with cold, trapped atoms via coherent wave-mixing, phase-matched emission and steering of the optical radiation and its **optimal collection** by geometric and/or integrated optics on chip. In collaboration with all the partners, FORTH will develop follow-up theoretical concepts for **robust state transfer from SC qubits to atoms** and from the atomic ensemble memories to optical photons in nano-waveguide cavities.

Reference :

A. Kurko, EPJ Quantum Technology 8, 11 (2021)

D. Petrosyan *et al* New J. Phys. 21, 073033 (2019)

Consortium

The consortium combines the multi-disciplinary expertise required to effectively interface microwave and optical photons using cold atomic ensembles in dual microwave and optical waveguide cavities at cryogenic temperatures. The project will demonstrate experimental techniques for microwave to optical conversion that are integrable on chips. It will include fabrication of planar superconducting cavities as well as integrated optical waveguides and cavities. After separate evaluation and benchmarking of the optical and microwave components in dedicated cold atom experiments, there will be fabricated hybrid chips that combine both.

EBERHARD KARLS UNIVERSITÄT TÜBINGEN
- József Fortágh (Coordinator)
- Reinhold Kleiner

LP2N Laboratoire Photonique Numérique & Nanosciences
- Simon Bernon (Co-coordinator)

wigner
- Peter Domokos
- András Dombi

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
- Natascia De Leo
- Angelo Angelini
- Frederico Ferrarese Lupi
- Luca Boarino
- Matteo Fretto

FORTH INSTITUTE OF ELECTRONIC STRUCTURE AND LASER
- David Petrosyan
- Giorgos Vasilaks