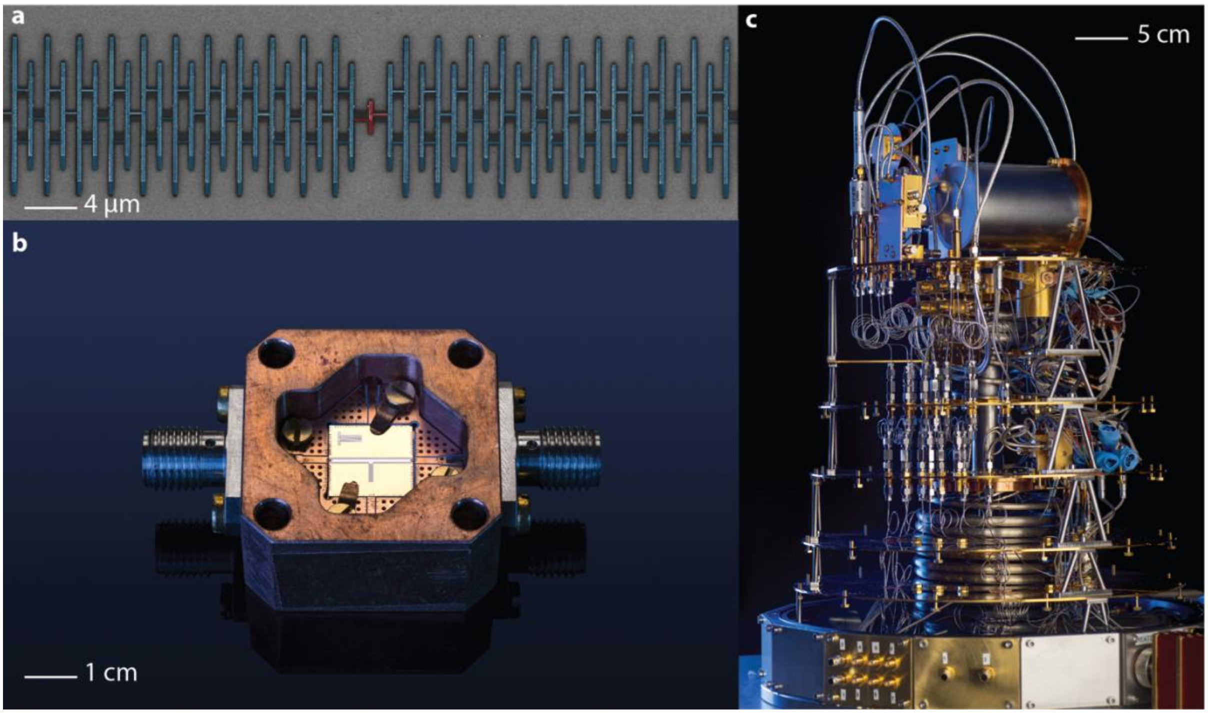
NÉEL INSTITUTE Grenoble

Topic for Master 2 internship – Academic year 2023-2024

Microwave quantum optics with superconducting meta-materials

General Scope: During the last decade, it has been demonstrated that superconducting Josephson circuits behave as quantum bits and are very well suited to realize advanced quantum mechanical experiments. These circuits appear as artificial atoms whose properties are defined by their electronic characteristics (capacitance, inductance and tunnel barrier).
Moreover, given their mesoscopic size, these quantum bits couple very strongly to electromagnetic radiations in the microwave range. Thus, it is now possible to perform quantum optics experiments using microwave photons and to unravel light-matter interactions using circuits. This field is dubbed circuit-QED (Quantum Electro-Dynamics).



a. *SEM image of a superconducting meta-material mixing small (red) and large (blue) Josephson junctions. This sample is fabricated in our clean-room using state-of-the-art e-beam lithography. The shape and quantum properties of this meta-material can then be tailored at will.* **b.** *These samples are enclosed in copper housings to ensure proper thermalization down 20mK, while enabling electrical measurements of their quantum properties.* **c.** *Dilution refrigerator and its various cables and shields. It is used to cooldown the samples at 20mK. We then reach the regime* $\boldsymbol{h\omega} \gg \boldsymbol{k_B T}$*, where quantum optical effects become prominent.*

During the last 5 years, our team has acquired a lot of experience in the fabrication of Josephson junction chains (Fig. a) forming a transmission line for microwave signals. In such chains, the propagation of microwave photons shows non-linear behavior due to the Kerr effect, a photon-photon interaction naturally arising from the Josephson junction physics. An example of device leveraging such interaction is the Josephson Travelling-Wave Parametric Amplifier, used for broadband quantum limited amplification of the readout signals of quantum bits [1,2,3,4]. In such devices, the Kerr effect allows for wave-mixing giving rise to an amplification process. In addition, the lines are impedance-matched to 50Ω, the standard impedance of the microwave environment which makes them behave as travelling-wave devices (as opposed to resonant structures). However, these chains are up to now mainly made of Josephson junctions close to their linear regime, where the Kerr interaction is a very small perturbation and does not impact too much the propagation of microwave signals. Yet, as the junctions' size is decreased, the Kerr interaction is increased, yielding stronger interactions between photons possibly up to the single-photon inelastic scattering. We propose to explore the new physics that can take place in

50Ω matched lines made of highly non-linear Josephson junctions. In this regime, strong interactions between microwave photons over a broad band of frequencies are expected to appear, and the applications of the study of such system ranges from the broadband photo-detection of single microwave photons, to single-microwave photons sources.

[1] Fabrication and characterization of aluminum SQUID transmission lines, L Planat, et al., *Phys. Rev. Applied* 12 (6), 064017 (2019).
[2] A photonic crystal Josephson traveling wave parametric amplifier, L. Planat., et al., *Phys. Rev. X* **10**, 021021 (2020).
[3] Fast high fidelity quantum non-demolition qubit readout via a non-perturbative cross-Kerr coupling, R. Dassonneville, et al., *Phys. Rev. X* 10, 011045 (2020).
[4] Kerr reversal in Josephson meta-material and traveling wave parametric amplification, A. Ranadive, et al., *Nat. Commun.* 13,1737 (2022).

Research topic and facilities available: Our team has a strong experience in nanofabrication, microwave electronics and cryogenic equipment. First, the student will be in charge of carrying out experiments on a non-linear 50Ω matched transmission line to try to observe the generation of quantum states of lights when the device is excited with a classical coherent microwave signal. This experiment will be performed at very low temperature (20mK), using one of the four fully equipped dilution refrigerators of the team. She/He will then explore the theoretical modeling of such an effect in a dilute media made of Josephson junctions. The devices are fabricated in the clean room of the Neel Institute (Nanofab). If the candidate is interested in learning these fabrication techniques, she/he can be associated to this part of the project.

Possible collaboration and networking: Our team is part of several national and international networks. For this specific project we are collaborating closely with Prof. K. Murch at Washington University in Saint-Louis, Missouri, USA, Prof. I. Carusotto at Trento University, Trento, Italy. This line of research is carried out in close collaboration with start-up Silent Waves.

Possible extension as a PhD: yes

Required skills: Master 2 or Engineering degree. We are seeking motivated students who want to take part to a state-of-the-art experiment and put some efforts in the theoretical understanding of quantum effects in non-linear transmission lines made of Josephson junctions.

Starting date: Flexible

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