COLD Activity Report - Year 2022

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1 Microwave sensitive Superconducting Quantum Network

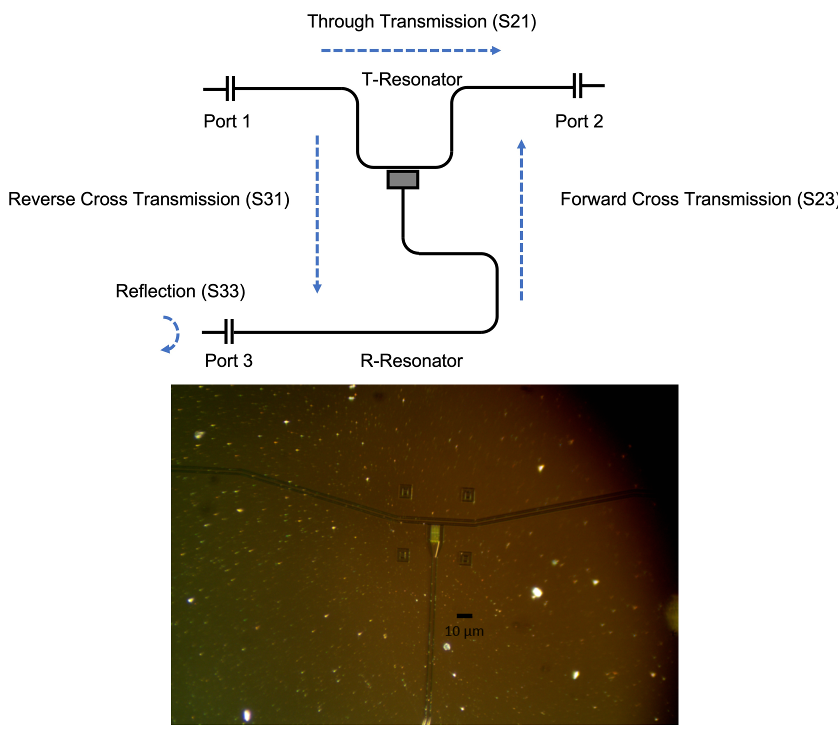


Figure 1: *Left: Scheme of the T-type device composed of two resonators* T *and* R *coupled by a SQN (gray box). Right: microscope picture of the SQN circuit.*

Due to the large quantum-fluctuations at few GHz frequency, linear amplifiers are not suited to reach the sensitivity to axions predicted by the DFSZ model, and new counters sensitive to single microwave-photons with low dark-counts must be used. In particular, a Superconducting Quantum Network (SQN) could be used to enhance the detection sensitivity to single microwave-photons. Recently, a device, arranged in a transistor-like geometry as in Fig. 1, was tested at LNF within the Supergalax project: an SQN working as a coupling element between two perpendicular resonators such that the transmission properties of the device are modified by the presence of few microwave photons. The advantage of using a SQN over a single qubit is that of a predicted scaling of the signal-to-noise ratio as N instead of $\sqrt{N}$, where N is the number of qubits in the network.

The device was tested at LNF in a Leiden Cryogenics CF-CS110-1000 dilution refrigerator at a temperature of 15 mK. The third-harmonic absorption-peak of the R-resonator at 7.74 GHz was considered. The VNA output-power was set to -40 dBm, corresponding to about -100 dBm at the device, and the through transmission (S21) was measured. At the same time, a single tone of frequency 7.743 GHz was sent to the R-resonator with the Rohde&Schwarz SMA100B connected to the Port 3, and the output power of the generator varied from -40 to -20 dBm (Fig. 2). By increasing the power sent to Port 3 a variation of the resonant-drop frequency in the through transmission-spectrum (S21) was clearly observed, confirming the feasibility of the device, but further optimization and engineering is needed to reach the single photon sensitivity.

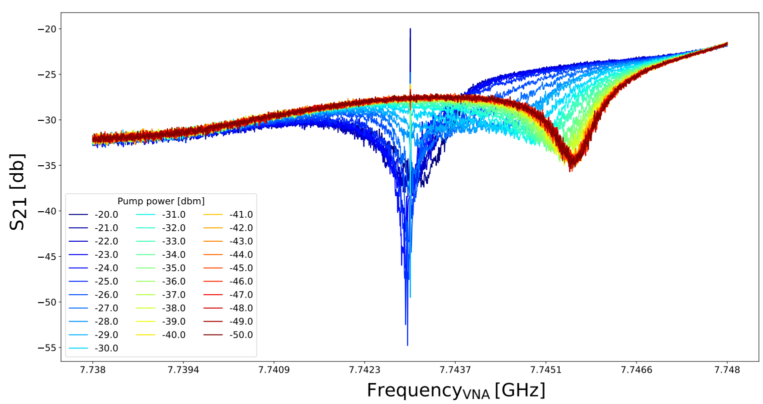


Figure 2: *Two-tone spectra measurements at frequency 7.74 GHz. First-tone through-transmission (S21) vs VNA-frequency dependencies recorded at different powers of the second-tone signal of frequency of 7.743 GHz applied to the Port 3.*

2 Josephson Parametric Amplifier

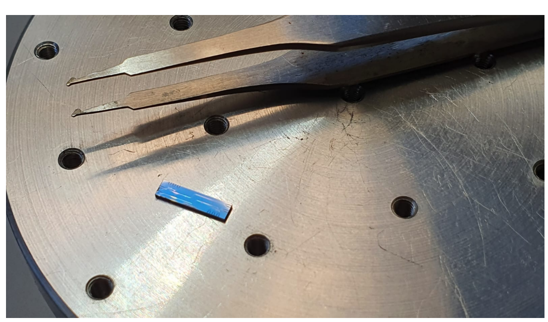


Figure 3: *Flux JPA fabricated at FBK*

Within the Qub-IT project of INFN CSN5 we designed a parametric amplifier known as *Flux-JPA*. It consists of a $\lambda/4$ resonator terminated by a DC-SQUID and coupled to the signal transmission line through a small capacitor. When an RF excitation is sent to the DC-SQUID at twice the resonance frequency (line 1 in Fig. 4), a signal entering through the capacitor (line 2 in Fig. 4) is amplified. JPAs add the minimum noise allowed by quantum mechanics to the amplified signal. In particular when the pump signal has exactly twice the signal frequency it is said to operate in degenerate mode. In this limit, the added noise is zero and the amplified signal has a noise corresponding to vacuum fluctuation $\hbar\omega/2$.

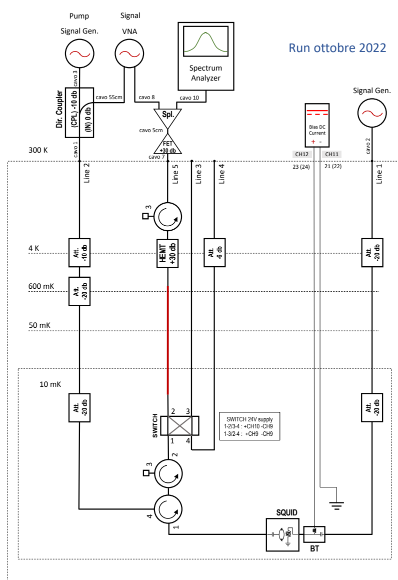


Figure 4: *Cryostat RF setup for the characterization of the Flux-JPA.*

Flux-JPAs were fabricated at FBK in aluminum on a silicon substrate (Fig. 3) and tested at Trento and LNF. The RF setup of the LNF dilution refrigerator is shown in Fig. 4. First, auxiliary RF lines were used to calibrate the system and determine the noise temperature and the total gain. Then, the resonator absorption peak position was measured with a VNA for different values of the DC flux-bias. The DC flux changes the inductance of the SQUID modulating the resonator frequency (Fig. 5).

Biasing the resonator frequency to about 7.4 GHz and operating the JPA in degenerate mode we observe 15.5 dB of amplification and measured a noise of about 130 ± 60 mK compatible with $h\nu/2k_B = 178$ mK at this frequency. Gain amplitude and bandwith are compatible with our simulations. Furthermore, by varying the phase difference between pump and signal we observed the expected modulation for a phase sensitive amplifier.

Due to spurious modes on the chip, the JPA was however amplifying in few sweet spots and work is underway to improve the circuit design and fabrication.

3 Superconducting Resonant Cavities

The development of superconducting resonant cavities able to operate in a multi Tesla magnetic field is an important task of the R&D for axion Haloscopes. Within the QUAX project we already

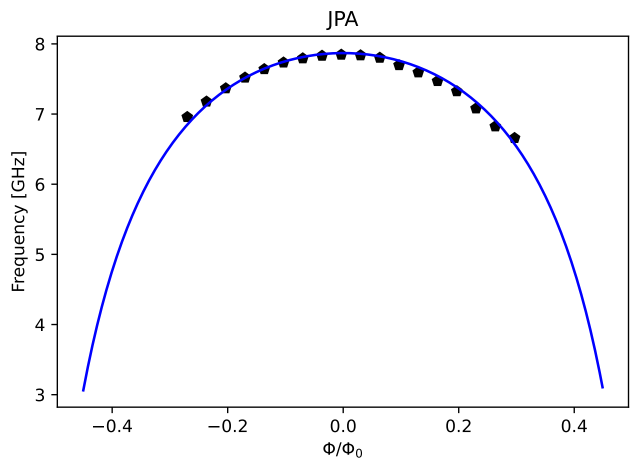


Figure 5: *JPA resonance frequency as a function of the flux bias.*

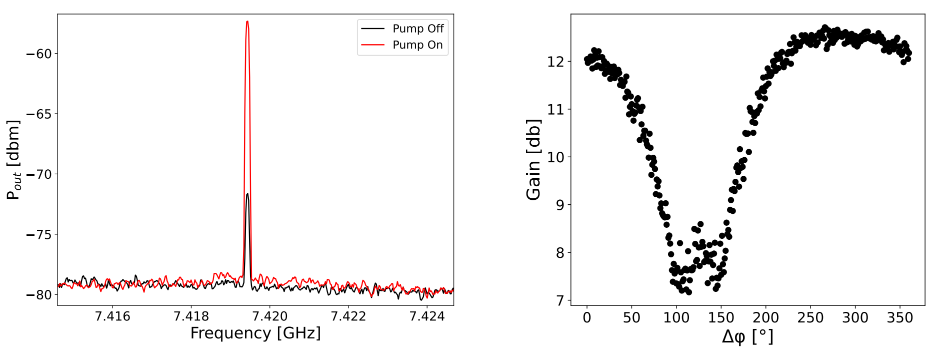


Figure 6: *Left: Signal reflected on the Flux-JPA observed at the Spectrum Analyzer when the pump is on (Red) and off (Black). Right: gain as a function of the phase difference between signal and pump.*

operated a 9 GHz copper cavity sputtered with NbTi inside the LNL haloscope providing the first QUAX limit on the $g_{a\gamma\gamma}$ coupling **??**. This R&D is ongoing now within the SAMARA and SQMS projects. The LNL group deposited a new NbTi film on a 9 GHz resonant cavity tested here at LNF, on a 7 GHz tested at LNL and on a 4 GHz cavity to be tested at FNAL.

We first analyzed the film with multi-harmonics technique. The results (Fig. 7) show a single phase and a good quality (Tc) of the superconducting film.

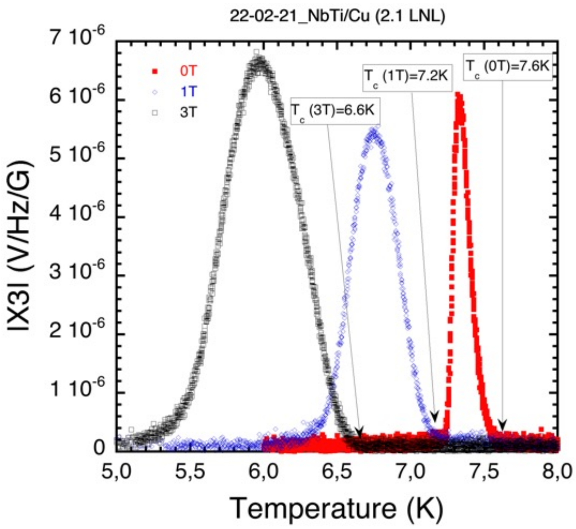


Figure 7: *Critical temperature of the NbTi film with multi-harmonics technique at three different fields.*

We then measured the 9 GHz cavity inside a LHe cryostat equiped with a 8T solenoid. The quality factor and frequency of the cavity were measured by means of a VNA for different values of the applied DC field. The results are shown in Fig. 8. The quality factor is clearly deteriorated by the presence of the DC field, but still above typical values of OFHC copper cavities at this frequency (about 100,000), but worst than in our previous publication.

Vortex losses in a type II superconductor are strongly frequency dependent. The LNL group obtained infact higher values with the cavity at 7 GHz. A new cavity resonating at 4 GHz was designed simulated and fabricated at LNF, and sent to LNL for chemical polishing and sputtering of NbTi. The final cavity, shown in figure 9, was sent to FNAL for the characterization.

4 Readout and Acquisition of signals from multiple cavities

One strategy to fasten the axion search of a haloscope is to collect the signal from multiple cavities. For this purpose, a low-loss di-(multi)plexer is an essential component to combine more microwave signals and route it to a broadband amplifier as the TWJPA, as expected in the QUAX and Dart Wars projects. A normal combiner has an insertion loss of 3dB nullifying the multiple cavity approach. We first designed a planar diplexer with loss reduced to 1 dB in 100 MHz bandwith at 6 GHz frequency. However, increasing the frequnecy above 8 GHz resulted in increased losses and we are now designing a waveguide (3D) multiplexer as the one discussed in [2]. Ansys simulation are ongoing to define the final design (Fig. 10).

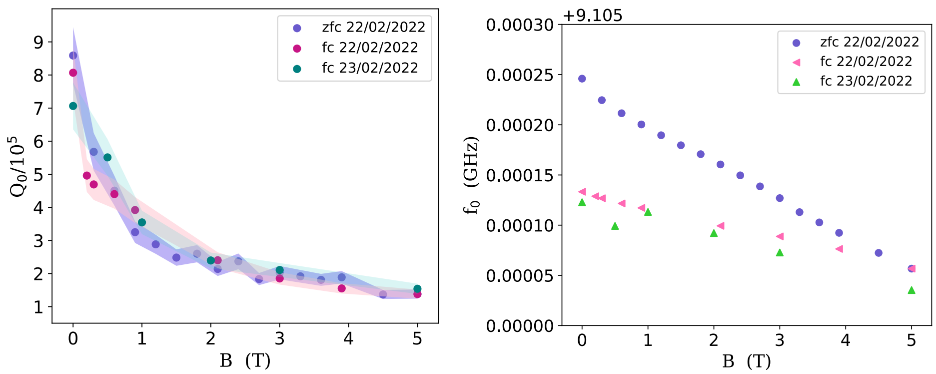


Figure 8: *Unloaded quality factor (Left) and frequency (Right) as a function of the applied DC field.*

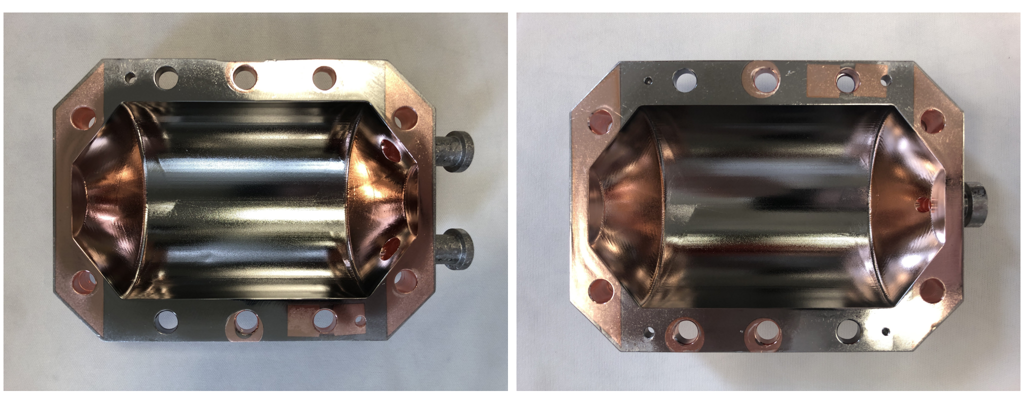


Figure 9: *4 GHz resonant cavity designed and fabricated at LNF and chemically polished and sputtered with NbTi at LNL. The cavity was sent to FNAL for test within the SQMS project*

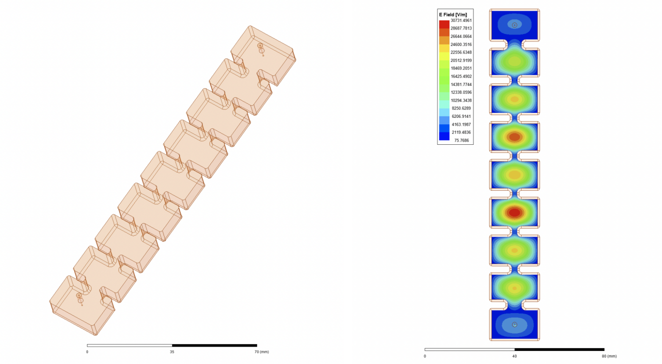
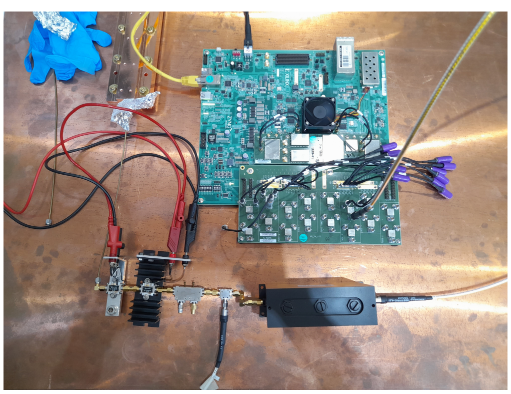


Figure 10: *Simulation of the waveguide band pass filter to be used in the multiplexer.*

We designed the acquisition system for 4 signals separated by about 100 MHz in frequency. The signal must be first amplified, downconverted and splitted and filtered before being digitized. We chose to use the ZCU208 Xilinx board to digitize and preprocess the signal. We tested a single channel system, composed of a resonant cavity with fundamental mode at 8.5 GHz, two FET amplifiers, a cirulator to avoid reflections, a mixer for down-conversion to 1 GHz and a 5MHz bandwith filter. The output of the filter was connected to the input of the ADC of the FPGA (Fig. 11 left panel). The signal was sampled inside the FPGA and numerically downconverted to base frequency and the FFT calculated and sent to an external PC for storage. The acquired spectrum is shown in the right panel of Fig. 11.



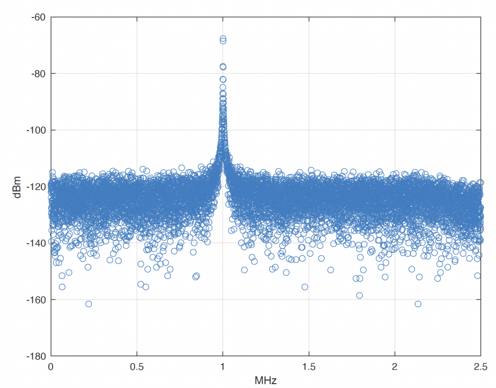


Figure 11: *Left: picture of the DAQ system. Right: example of acquired FFT spectrum.*

5 Talks

- A. Rettaroli, “Testing a Josephson junction as a photon detector with pulsed microwaves measurements,”cQED@Tn, Trento, 3-5 Ottobre 2022.

- A. Rettaroli, “”Ultra low noise readout with Travelling Wave Parametric Amplifiers: the DARTWARS projec,” 15th Pisa Meeting on Advanced Detectors, 22-26 Maggio 2022, La Biodola - Isola d’Elba.
- A. D’Elia, “Development of single-photon detector based on Josephson junction circuits for dark matter search,” WOLTE 15, Matera, 6-9 June 2022.
- A. D’Elia, “Toward single photon detector based on Josephson effect for dark matter search,” INFN workshop on future detectors IFD2022, 17-19 October 2022.
- C. Gatti “COLD the CryOgenic Laboratory for Detectors of LNF,” LNF Seminar January 2022.
- C. Gatti “COLD the CryOgenic Laboratory for Detectors of LNF,” QUANTUM MATERIALS FOR QUANTUM TECHNOLOGIES QMQT Workshop February 2022 LNF.
- C. Gatti “QUANTUM SENSING WITH SUPERCONDUCTING CIRCUITS AT LNF-INFN,” Thecnology Innovation Institute, Abu Dhabi 7 November 2022.

6 Publications

- A. D’Elia *et al.*,“Stepping Closer to Pulsed Single Microwave Photon Detectors for Axions Search,” IEEE Trans. Appl. Supercond. **33** (2023) no.1, 1500109
- V. Granata *et al.*,“Characterization of Traveling-Wave Josephson Parametric Amplifiers at T = 0.3 K,” IEEE Trans. Appl. Supercond. **33** (2023) no.1, 0500107
- C. Guarcello *et al.* “Modeling of Josephson Traveling Wave Parametric Amplifiers,” IEEE Trans. Appl. Supercond. **33** (2023) no.1, 0600207
- G. Filatrella *et al.* “Theoretical and Numerical Estimate of Signal-to-Noise Ratio in the Analysis of Josephson Junctions Lifetime for Photon Detection,” IEEE Trans. Appl. Supercond. **33** (2023) no.1, 0600105
- M. Borghesi *et al.* “Progress in the development of a KITWPA for the DARTWARS project,” Nucl. Instrum. Meth. A **1047** (2023), 167745
- A. Rettaroli *et al.*, “Ultra low noise readout with traveling wave parametric amplifiers: The DARTWARS project,” Nucl. Instrum. Meth. A **1046** (2023), 167679
- D. Labranca *et al.*, A. Giachero and A. Nucciotti, “First design of a superconducting qubit for the QUB-IT experiment,” Nucl. Instrum. Meth. A **1046** (2023)
- S. Pagano *et al.*, “Development of Quantum Limited Superconducting Amplifiers for Advanced Detection,” IEEE Trans. Appl. Supercond. **32** (2022) no.4, 1500405
- F. Chiarello *et al.*, “Investigation of Resonant Activation in a Josephson Junction for Axion Search With Microwave Single Photon Detection,” IEEE Trans. Appl. Supercond. **32** (2022) no.4, 1100305
- A. Giachero *et al.*, “Detector Array Readout with Traveling Wave Amplifiers,” J. Low Temp. Phys. **209** (2022) no.3-4, 658-666

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6. G. Filatrella, C. Barone, G. Carapella, C. Gatti, V. Granata, C. Guarcello, C. Mauro, A. S. P. Komnang, V. Pierro and A. Rettaroli, *et al.* IEEE Trans. Appl. Supercond. **33** (2023) no.1, 0600105 doi:10.1109/TASC.2022.3214500

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