COLD Activity Report- year 2024

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1 QubIT

1.1 Al transmon characterization

Quantum computing is currently one of the most compelling fields of research. Its key advantage over classical computing lies in the qubit, the quantum counterpart of the conventional binary bit. Among the various qubit implementations, superconducting qubits based on Josephson junctions (JJs) stand out as the most promising, as they can be fabricated on substrates similar to those used in silicon electronics, offering excellent scalability. JJs are highly versatile superconducting devices with applications ranging from microwave photon detection to parametric amplification and entangled photon emission. In collaboration with our partners (IFN-CNR, Uviversity of Milano Bicocca, LNL), we designed fabricated and tested the first 3D qubit developed in Italy. We studied a transmon qubit coupled dispersively to a 3D resonant cavity [1]. This device was tested at

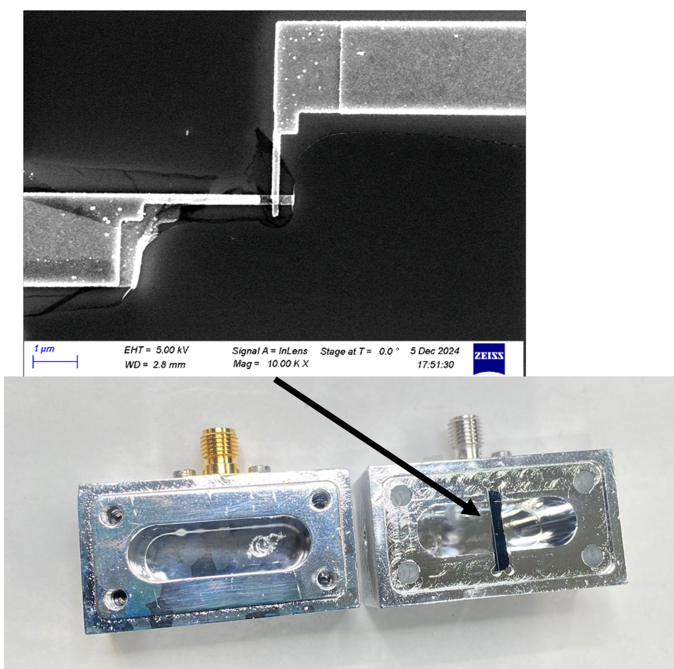

Figure 1: Picture of the qubit inside the 3D cavity and Scanning electron microscopy of the Al transmon. The image is magnified 10000x.

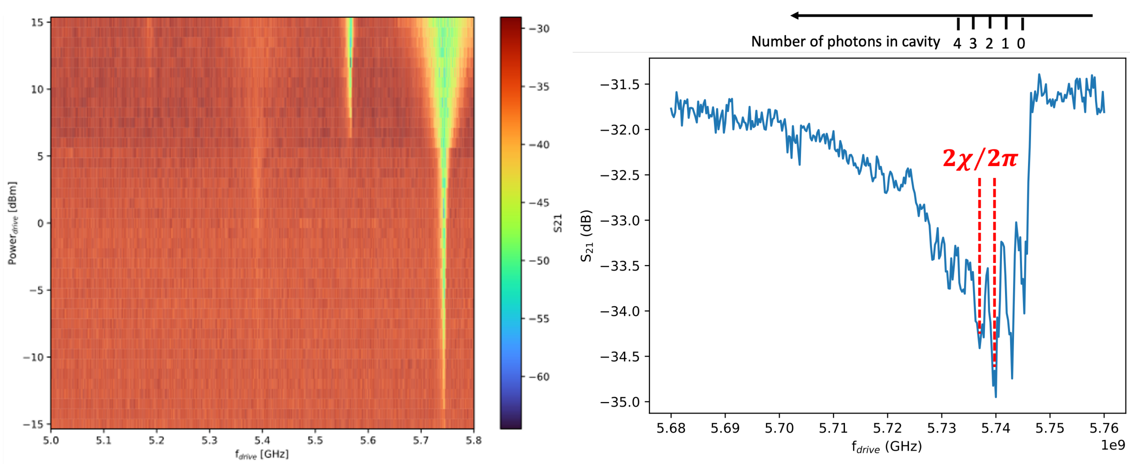

Figure 2: Left: two tone spectroscopy where we acquired the dressed cavity transmission as a function of the power and the frequency of the drive tone. Different absorption peaks are clearly observable from which we estimate the anharmonicity $\alpha/2\pi = 353$ MHz. *Right:*Qubit spectroscopy of individually resolved photon numbers inside the cavity $P_{probe} = -122$ dBm). Each peak is separated by $2\chi/2\pi = -2.4$ MHz.

LNF in a Leiden Cryogenics CF-CS110-1000 dilution refrigerator on the 10 mK plate. The qubit was fabricated at IFN-CNR while the superconducting resonant cavity was built at LNL. We investigated the transmon-cavity system using spectroscopic techniques [2]. We determined the qubit frequency to be 5.74 GHz. We also estimated the qubit cavity coupling $g_{01}/2\pi = 90$ MHz (simulated value $g_{01}/2\pi$= 92 MHz), the anharmonicity $\alpha/2\pi$=353 MHz, the dispersive coupling $\chi/2\pi$=1.2 MHz. The measured quantity are in excellent agreement with the simulated values. These characterizations demonstrate the ability of our group to follow all the steps of the production process of a qubit: design, fabrication and characterization.

2 Characterization of a 2D qubits device coupled to a quantum bus

We studied two transmon qubits connected via a quantum bus. These devices are well-suited for leveraging the Quantum Non-Demolition (QND) technique to develop a photon counter based on superconducting qubits for fundamental physics applications. Following the design proposed last year [3], developed within the QubIT project and in particular with Milano Bicocca and Università di Firenze, the device was fabricated at NIST (Boulder, Colorado). It consists of two Xmon qubits: one featuring a single Josephson junction (JJ) positioned at the top-right and another incorporating a DC-SQUID located at the bottom-left. Both qubits are capacitively coupled to a $\lambda/4$ resonator, while the tunable qubit is also capacitively connected to a drive line. An optical image of the device is presented in3.

We tested this 2 qubit system measuring resonator spectroscopy as reported in figure 4. There are clear evidence non linear frequency shift as a function of the readout power due to the self Kerr effect. We also tested the frequency tunability of the qubit. In figure 4 right is reported the dressed resonator frequency as a function of the bias supplied to the feed line (i.e. the frequency of the qubit). The plot shows signatures of avoided crossing when the qubit and the resonator have the same characteristic frequency. From these measurements we managed to extract the coupling $g_{01}/2\pi$= 77 MHz which is in good agreement with respect to the simulated value of 68 MHz.

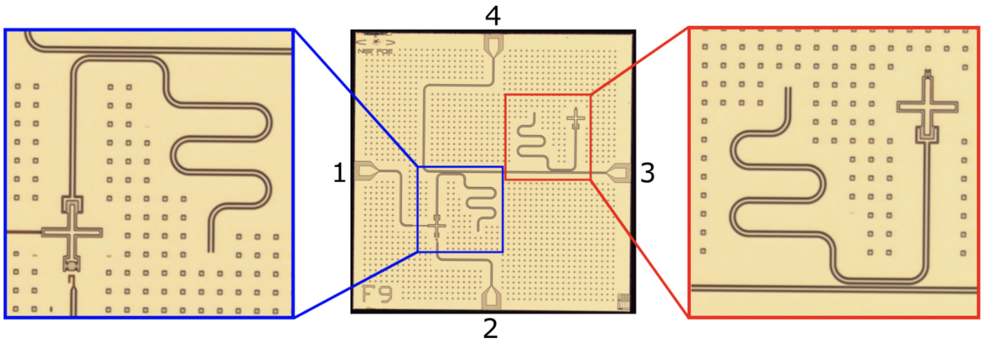

Figure 3: Optical image of the 2 qubit device. On the left we reported a zoom of the tunable frequency qubit, on the right of the fixed frequency qubit.

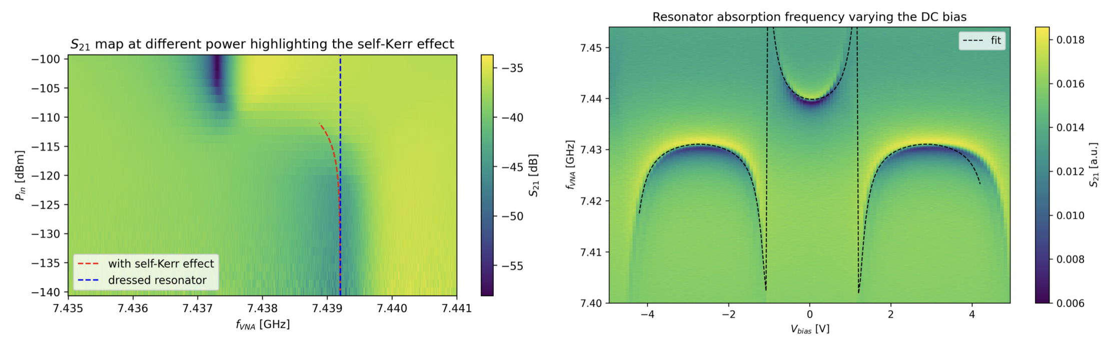

Figure 4: Left: Resonator spectroscopy as a function of the readout power. Right: frequency of the resonator-qubit dressed system as a function of the voltage bias (i.e. the frequency of the qubit). An avoided crossing is observed when the resonator and the qubit have the same resonance frequency.

3 Superconducting resonant cavity

Within the QUAX experiment, we seek to detect axions using a haloscope, which is composed of a resonant cavity placed within a strong magnetic field. However, this field typically degrades the quality factor, thereby limiting the haloscope's detection capabilities. To mitigate this issue, we are conducting R&D aimed at utilizing alternative superconductors with a high critical field (H_{c2}) for constructing resonant cavities. This R&D effort is currently underway as part of the SAMARA and SQMS projects. We have designed and manufactured a ten-faced cavity using OFHC copper. Our plan involves adhering YBCO tapes to the inner walls of the cavity. YBCO is a high-T_c superconductor capable of withstanding extremely strong magnetic fields. Over the next year, we will proceed with attaching the YBCO tapes inside the cavity and evaluating its quality factor under varying applied magnetic fields.

4 RESILIENCE

RESILIENCE is a a young researcher project founded by the CSN5 of INFN. Its purpose is to use $NbSe_2$ to fabricate JJ. $NbSe_2$ is a van der Waals (vdW) material that can withstand a magnetic

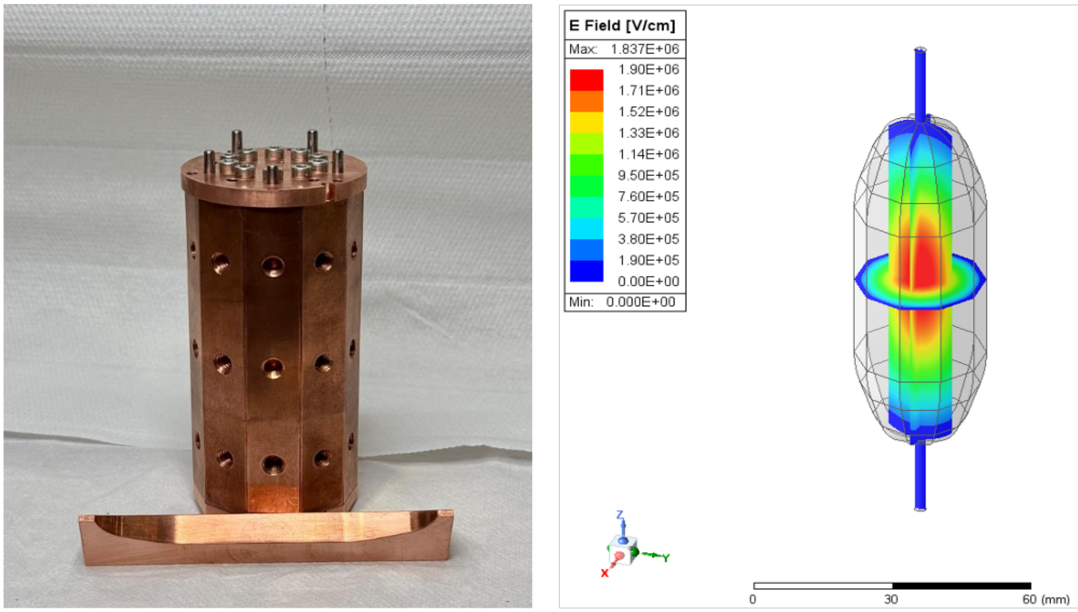

Figure 5: *Left)*:10 faces OFHC Cu cavity. *Right)*: ANSYS simulation of the TM 101 mode f =8.489 GHz.

field of up to 30 T. A JJ made of $NbSe_2$ would inherit its magnetic field resiliency and could be used as a single-photon counter. Thus, fabricating JJ made of $NbSe_2$ would be extremely beneficial for experiments like QUAX, where a high magnetic field is coupled with the need for single-photon counting. To fabricate $NbSe_2$ JJ, we mechanically exfoliate $NbSe_2$ flakes using the standard approach proposed in [4]. We assembled a $NbSe_2$/ $NbSe_2$ omojunction on the contacts of two cirular Al pads (figure 6) to replicate a transmon geometry and placed it inside an Al 3D cavity. To our knowledge, this is the first time a quantum device based on $NbSe_2$ JJ has been been fabricated and characterized. Increasing the readout power the transmission of our device shows

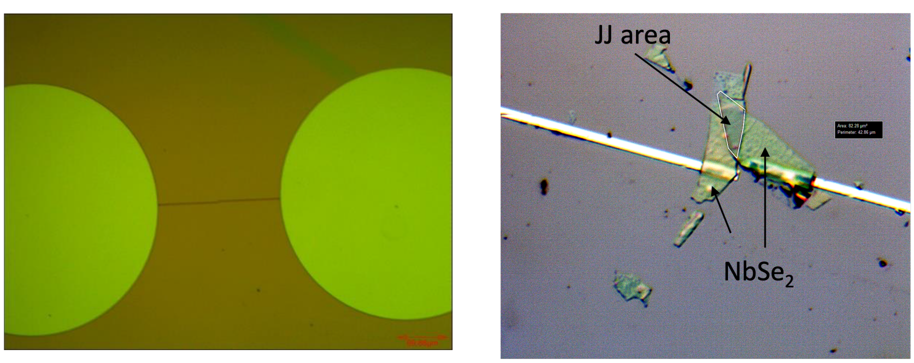

Figure 6: *Left)*:optical image of the circular Al pads .*Right)*: Optical image of the $NbSe_2$ JJ we used as a qubit.

a discontinuous shape typical of Duffing oscillators (7). The onset from a symmetrical Lorentzian shape to a step-like resonance is around -124 dBm. The deeply non linear nature also manifests in hysteretical behavior depending if the readout frequency is swept ascending or descending as reported in figure 7 right. The dressed cavity-Duffing oscillator hamiltonian is [5]:

$$H = (\omega_r + \frac{K}{2} - (\frac{g^2}{\Delta} - K)\sigma_z)a^\dagger a + \frac{K}{2}\sigma_z(a^\dagger a)^2 \quad (1)$$

Where, a ($a^\dagger$) is the annihilation (creation) operator, $\Delta = \omega_q - \omega_r$ is the detuning between the qubit and the bare cavity, g is the coupling strength, σ_z is the Pauli matrix, $K = \frac{2g^4}{\Delta^3}$ is the Kerr term.

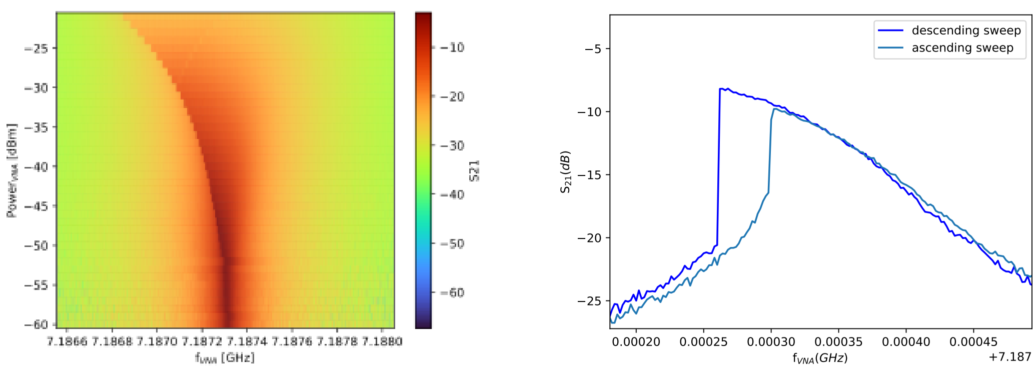

Figure 7: *Left:* Resonator spectroscopy as a function of the readout power. The dressed cavity frequency shows strong non linear behavior. *Right:* Transmission of the dressed cavity showing a step-like resonance and a clear hysteresis depending if the readout frequency sweeps from low to high values (ascending) or vice versa (descending).

We used two tone spectroscopy to investigate the absorption properties of the qubit (8). We found the vdW qubit frequency to be ν_q=12.64 GHz. The qubit absorption map show a continuous broadening and red shift as a function of the drive power. This suggest a small anharmonicity that we estimated through simulations and through low power measurements to be $\approx$ 10 MHz. Tracking the dressed cavity frequency as a function of the qubit frequency we managed to estimate the qubit cavity coupling $g/2\pi$=138 MHz, which is in good agreement with the simulated value of 200 MHz. We tested the coherence properties of our device performing Rabi oscillations measurements. We observed coherent quantum oscillations with Rabi frequency in the range 40-120 KHz for excitation powers (-17,-5) dBm. We managed to measure the relaxation time T_1=6.5$\pm$0.4 μs (figure 9). This is an extraordinary result that increases the coherence time of vdW materials based quantum devices of 2 orders of magnitude compared to other vdW materials devices [6]. In addition our device is very robust against thermal noise. We observed coherent oscillations in presence of an equivalent noise temperature of $\approx$ 3K. This is due to the high transition temperature of $NbSe_2$ (about 7 K) with respect to Al (T_c=1 K).

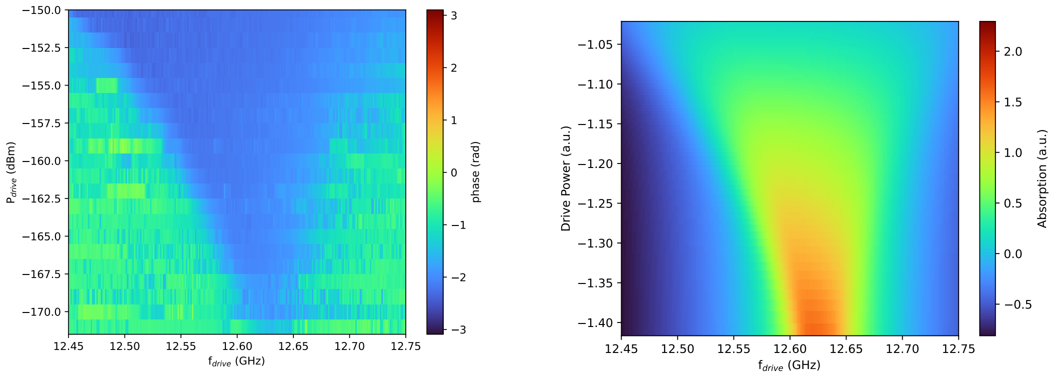

Figure 8: *Left:* Two tones spectroscopy of the VdW qubit. *Right:* simulated qubit absorption spectrum

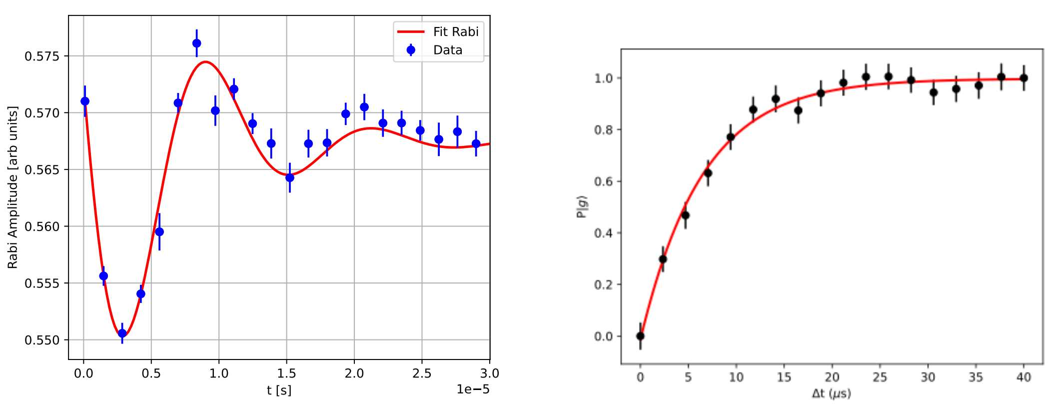

Figure 9: *Left:* Rabi oscillations of the VdW qubit. Spectrum acquired with drive frequency 12.611 GHz and power -167.7 dBm. *Right:* Measurements of the relaxation time T_1. From fitting procedure (red line) we estimate a $T_1 = 6.5 \pm 0.4\ \mu$s

5 List of Conference Talks by LNF Authors in Year 2023

Include a list of conference talks by LNF authors.

1. S. Tocci *Superconducting qubit in a 3D cavity* NQSTI I meeting, Jan. 2024

2. C. Gatti "I Qubit Superconduttivi," seminar at Physics Department of Bologna University, Bologna March 2024

3. C. Gatti "Superconducting Circuits," seminar at Politecnico di Torino, Torino 19 March 2024.

4. A.D'Elia *Toward magnetic field resistant microwave single photon detector based on van der Waals Josephson junctions* WOLTE 16, June 2024

5. A.D'Elia *Toward single microwave quantum sensing with NbSe2 Josephson junctions* SENSE, Sept. 2024

6 Acknowledgement

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7 Publications

1. E. Ferri et al. Development of KI-TWPAs for the DARTWARS project IEEE Transactions on Applied Superconductivity (2024)
2. L. Fasolo et al. Experimental characterization of RF-SQUIDs based Josephson Traveling Wave Parametric Amplifier exploiting Resonant Phase Matching scheme IEEE Transactions on Applied Superconductivity (2024)
3. C. Guarcello et al. Nonlinear Behavior of Josephson Traveling Wave Parametric Amplifiers IEEE Transactions on Applied Superconductivity (2024)
4. Moretti, R. et al. Design and simulation of a transmon qubit chip for Axion detection IEEE Transactions on Applied Superconductivity, 34, 3, (2024)
5. D'Elia, A. et al. Characterization of a Transmon Qubit in a 3D Cavity for Quantum Machine Learning and Photon Counting. Applied Sciences 14, 1478 (2024).
6. M. Faverzani et al, Broadband Parametric Amplification in DARTWARS, J. Low Temp Phys, (2024)
7. G. Marconato et al, NbTi Thin Film SRF Cavities for Dark Matter Search, IEEE Transactions on Applied Superconductivity, (2024)
8. A. Rettaroli et al, Novel two-qubit microwave photon detector for fundamental physics applications, NIMA, (2024)

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1. Koch, J. *et al.* Charge-insensitive qubit design derived from the Cooper pair box. *Physical Review A* **76,** 042319 (2007).
2. D'Elia, A. *et al.* Characterization of a Transmon Qubit in a 3D Cavity for Quantum Machine Learning and Photon Counting. *Applied Sciences* **14,** 1478 (2024).
3. Moretti, R. *et al.* Design and Simulation of a Transmon Qubit Chip for Axion Detection. *IEEE Transactions on Applied Superconductivity* (2024).
4. Castellanos-Gomez, A. *et al.* Deterministic transfer of two-dimensional materials by all-dry viscoelastic stamping. 2D Mater. *Lett* **1,** 1–8 (2014).
5. Mavrogordatos, T. K. *et al.* Simultaneous bistability of a qubit and resonator in circuit quantum electrodynamics. *Physical review letters* **118,** 040402 (2017).

6. Wang, J. I.-J. *et al.* Coherent control of a hybrid superconducting circuit made with graphene-based van der Waals heterostructures. *Nature nanotechnology* **14,** 120–125 (2019).