Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | NQSTI National Quantum Science and Technology Institute

Missione 4 Istruzione e Ricerca

PNRR Partenariato Esteso

NATIONAL QUANTUM SCIENCE AND TECHNOLOGY INSTITUTE "NQSTI"

Spoke 6 Quantum Integration

A6.3.3 Superconducting quantum networks

A6.3.3.1 Mikhail Lisitskiy SPIN CNR

A6.3.3.2 Berardo Ruggiero ISASI CNR

Superconducting Qubit Networks with highly entangled quantum phases appearing

Mikhail Lisitskiy

SPIN- CNR Institute of Superconductors, Innovative Materials and Devices,

mikhail.lisitskiy@spin.cnr.it

Co-authors of the presentation:

Carmela Bonavolontà[2], Berardo Ruggiero[2] , Alessandro D'Elia[3], Daniele di Giocchino[3], Claudio Gatti[3], Carlo Ligi[3], Fabio Chiarello[4,3], Giorgio Brida[5], Emanuele Enrico[5], Luca Fasolo[5], Luca Oberto[5], Mikhail Fistul[6], Gregor Oelsner[7], Eugeni Ill'chev[7], Patrick Navez[8], Alexandre Zagoskin[8], Francesco Romeo[9] and Paolo Silvestrini[10,2]

1. SPIN CNR ,Via Campi Flegrei 34, I- 80078, Pozzuoli (Naples), Italy
2. ISASI CNR ,Via Campi Flegrei 34, I- 80078, Pozzuoli (Naples), Italy
3. LNF INFN , Via Enrico Fermi 54, I- 00044 , Frascati (Rome), Italy
4. IFN CNR , Via Fosso del Cavaliere 100, I- 00133 , Rome, Italy
5. INRiM, Strada delle Cacce 91, I-10135 , Turin Italy
6. Ruhr University Bochum, Universitätsstraße 150, D-44801, Germany
7. Leibniz Institute of Photonic Technology, Albert-Einstein-Straße 9, D-07745 Jena, Germany
8. Loughborough University, LE11 3TU, Loughborough, United Kingdom
9. Università degli Studi di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, I- 84084 Fisciano (Salerno), Italy
10. Università degli Studi della Campania "L. Vanvitelli", Dipartimento di Matematica e Fisica, Viale Lincoln 5, I- 81100 Caserta, Italy

Contents

1. Progress on demonstration of quantum networks of qubits with highly entangled quantum phases appearing

1.1. Superconducting quantum network (SQN) and physical conditions necessitating to observe collective (synchronized) quantum states

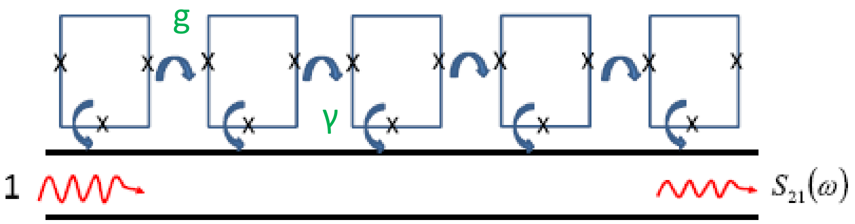


Figure 1. The schematic of an experimental setup allowing one to observe the coherent quantum-mechanical oscillations in the SQM. The SQM based on an array of flux qubits (3-Josephson junction SQUID) is shown. The array of qubits is coupled to the transmission line. The inductive coupling between adjacent qubits, K, is taken into account. The amplitude of transmitted electromagnetic wave is $|S_{21}|$.

g is the strength of mutual (inductive or capacitive) coupling between adjacent qubits leading to the Ising (short-range) type of interaction;
γ is the coupling strength between a single qubit and a resonator

Two types of interactions can be realized in the SQNs: the nearest-neighbor interaction that is due to direct inductive or capacitive electromagnetic interaction between adjacent qubits and/or the long-range electromagnetic interaction arising due to consequent emission, propagation and absorbtion of *virtual photons* in the low-dissipative resonator coupled to the network.

Fistul, M. V. Quantum synchronization in disordered superconducting metamaterials. Sci. Rep. 7, 43657; doi: 10.1038/srep43657 (2017).

Formulation of a generic quantum-mechanical model of disordered interacting SQNs coupled to a low-dissipative resonator and transmission line was carried out.

Exchange of virtual photons results in a strong exchange interaction between well-separated qubits and a system is described by Hamiltonian

$$\hat{H}_{\mathrm{SQA-res}} = \sum_{i=1}^{N}\left[\frac{\Delta_i}{2}\hat{\sigma}_i^x + \frac{\epsilon_i}{2}\hat{\sigma}_i^z\right] + \hat{U}_{\mathrm{int}}\{\hat{\vec{\sigma}}_1, \ldots \hat{\vec{\sigma}}_N\} + \hbar\omega_0 \hat{a}^\dagger \hat{a} + \gamma \sum_{i=1}^{N} \hat{\sigma}_i (\hat{a}^\dagger + \hat{a}),$$

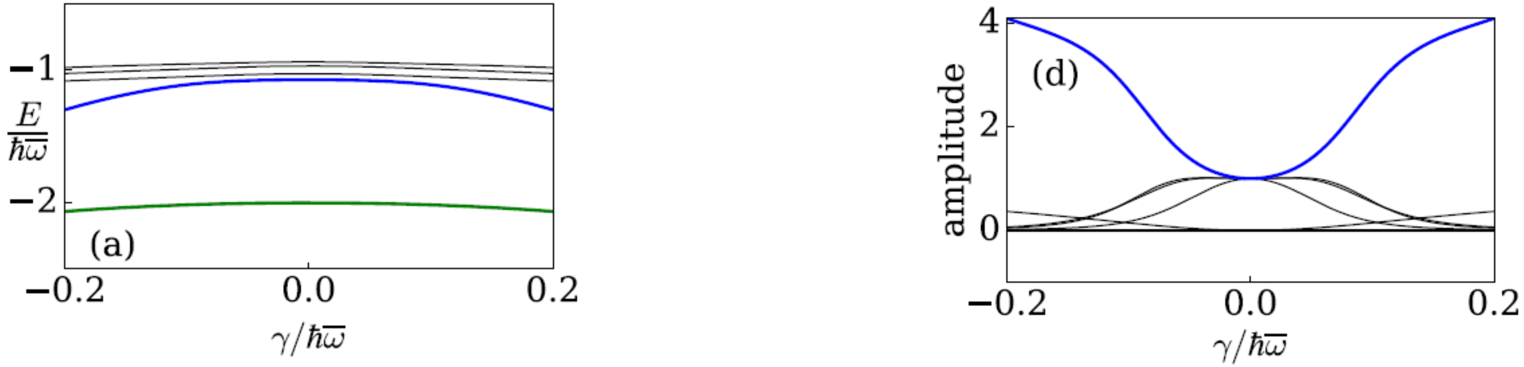
Temporal quantum correlation function

$$C(t) =< \Psi_{in} | \left[\sum_i \hat{\sigma}_i^z(t)\right]\left[\sum_i \hat{\sigma}_i^z(0)\right] | \Psi_{in} >$$

Transmission coefficient S_{21} calculation

$$\Delta S_{21}(\omega) \sim C(\omega) = \lim_{t_0\to\infty} \frac{1}{t_0}\int_0^{t_0} dt e^{i\omega t}\, \mathrm{Im}\, C(t)$$

M. V. Fistul, O. Neyenhuys, A.B.Bocaz, M. Lisitskiy and I.M.Eremin, "Quantum dynamics of disordered arrays of interact-ing superconducting qubits: Signatures of quantum collective states" Phys. Rev. B, vol. 105 , 2022, Art. No. 104516.



The dependence of low-lying energy levels (a) and the amplitudes of resonances (b) on the coupling strength γ for the disordered SQNs composed of four qubits and four photon states for C_0 *(ω)* (no photons in resonator). The dominant resonances correspond to the transitions between energy levels indicated by green and blue lines. The disorder strength is fixed as σ = 0.1.

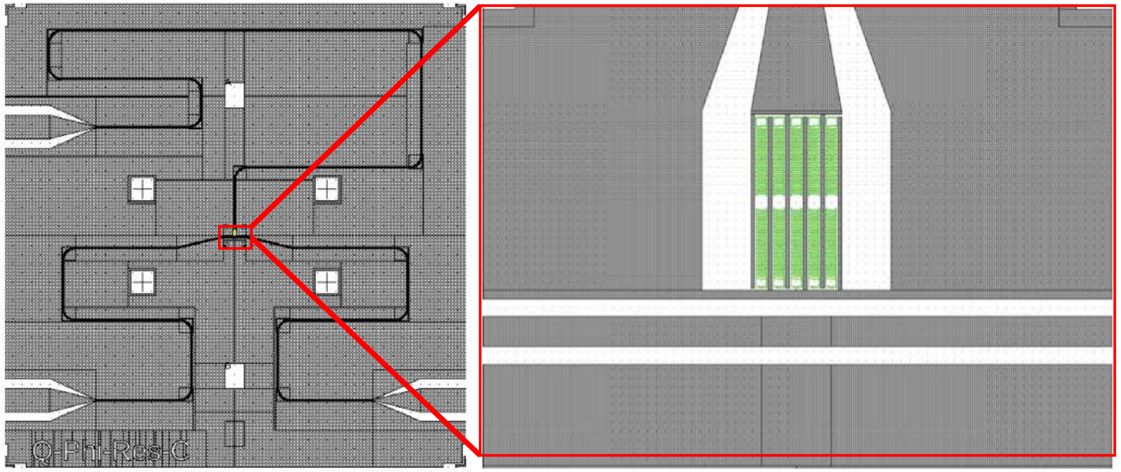
An amplitude of the dominant resonance drastically increases as the interaction between qubits overcomes the disorder in qubit frequencies , and the collective state is formed.

M. V. Fistul, O. Neyenhuys, A.B.Bocaz, M. Lisitskiy and I.M.Eremin, ”Quantum dynamics of disordered arrays of interact-ing superconducting qubits: Signatures of quantum collective states” Phys. Rev. B, vol. 105 , 2022, Art. No. 104516.

1.2. Experiment on SQN with 10 capacitively shunted flux qubits

1.2.1. Designs of SQN detectors

T-type three terminal SQN device with 10 C.shunted flux qubits



Left: Chip layout of the T-type three terminal device. Two resonators at same frequency are coupled by an array of 10 capacitor shunted flux qubits. Right: Magnified part of the layout with the 10 C-shunted flux qubits with three Josephson junctions.

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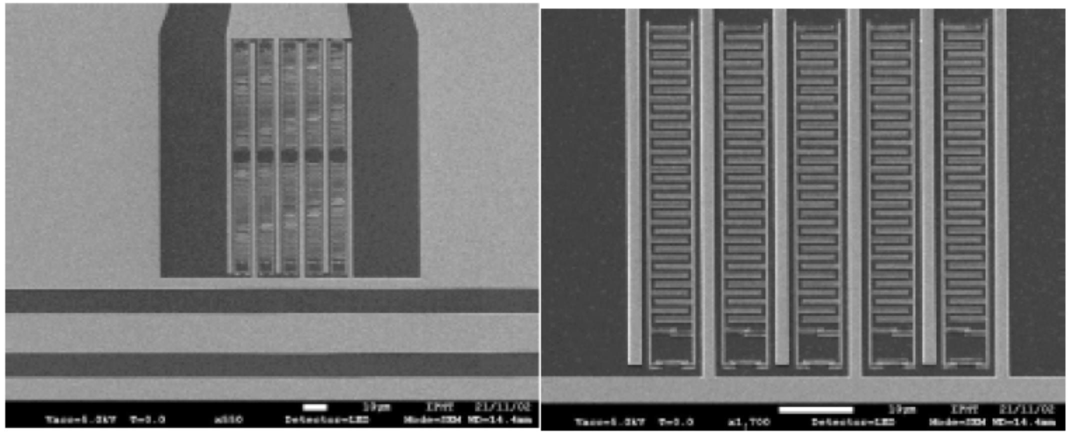
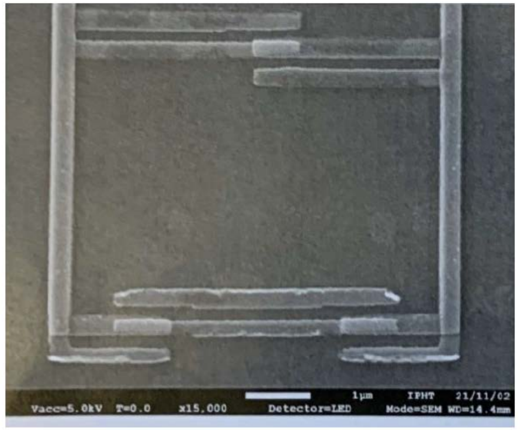
1.2.2. Fabrication of three-terminal SQN device

The Leibniz Institute of Photonic Technology (Leibniz IPHT), Jena Germany

The 22 mm long resonators are fabricated by depositing a 200 nm thick Nb film on a silicon substrate that is structured by the RIE. **The flux qubits are made of Al Josephson-junctions fabricated by two angle shadow evaporation technique.** Every flux qubit of the SQN consists of a 6x4.5 μm^2 loop with three Josephson junctions. Two junctions are designed to have identical size of 0.2x0.87 μm^2 while the third is scaled by a factor $\alpha < 1$. For qubits of the SQN measured here, the factor $\alpha = 0.8$.



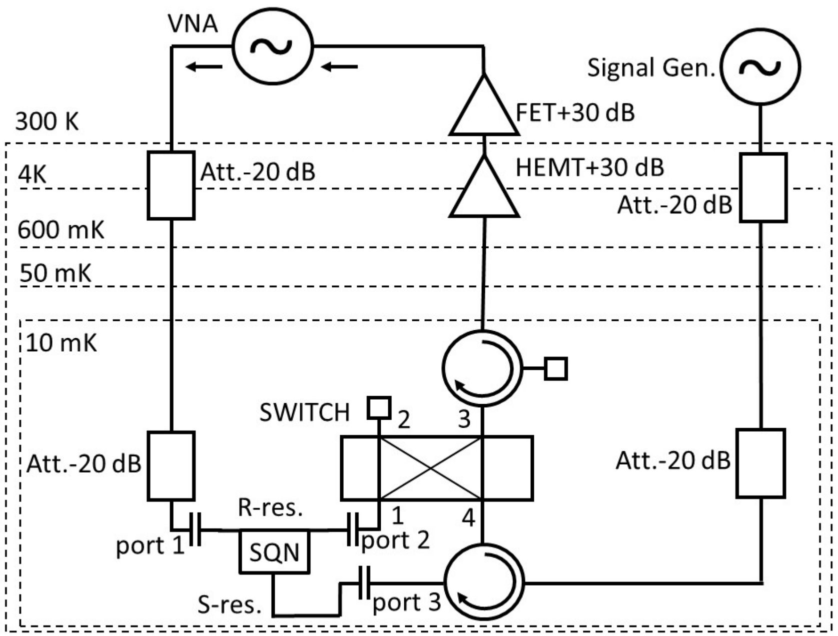
SEM picture of three-terminal device with 10 C-shunted flux qubits



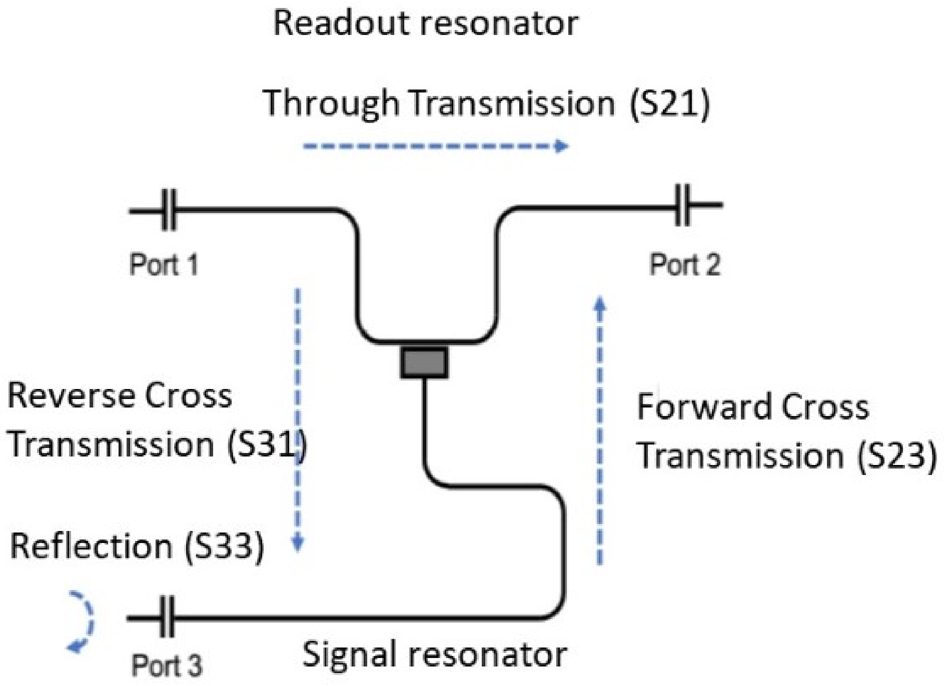
SEM- image of a fabricated flux qubit

1.2.3. Electrical part of experimental set-up

Measurements of fabricated T-type SQN were carried out at the Laboratori Nazionali di Frascati (LNF) (Italy) in a Leiden Cryogenics CF-CS110-1000 dilution refrigerator at temperature of 15 mK.

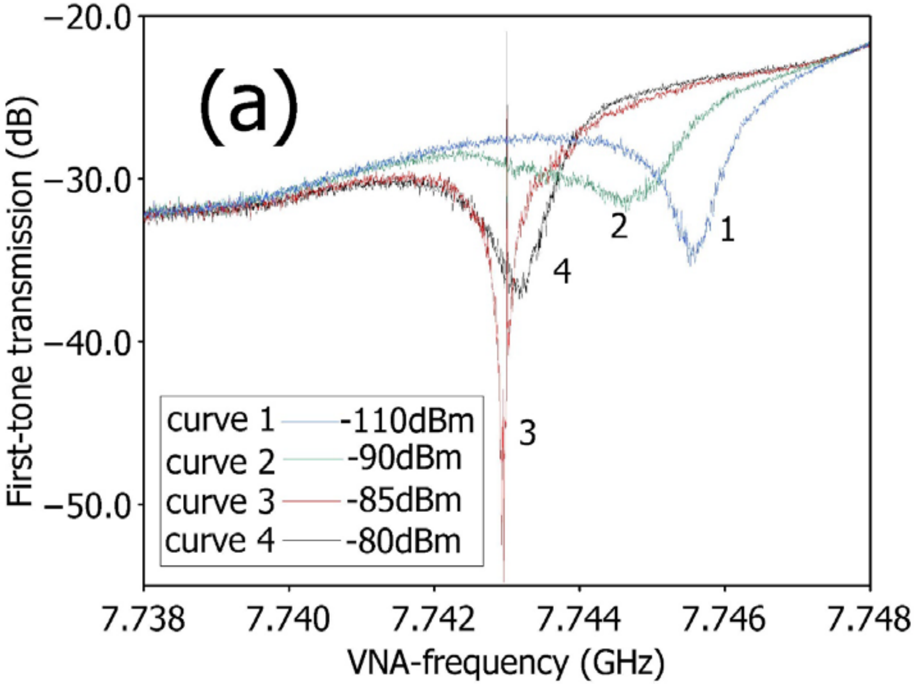


Experimental set-up for microwave measurements

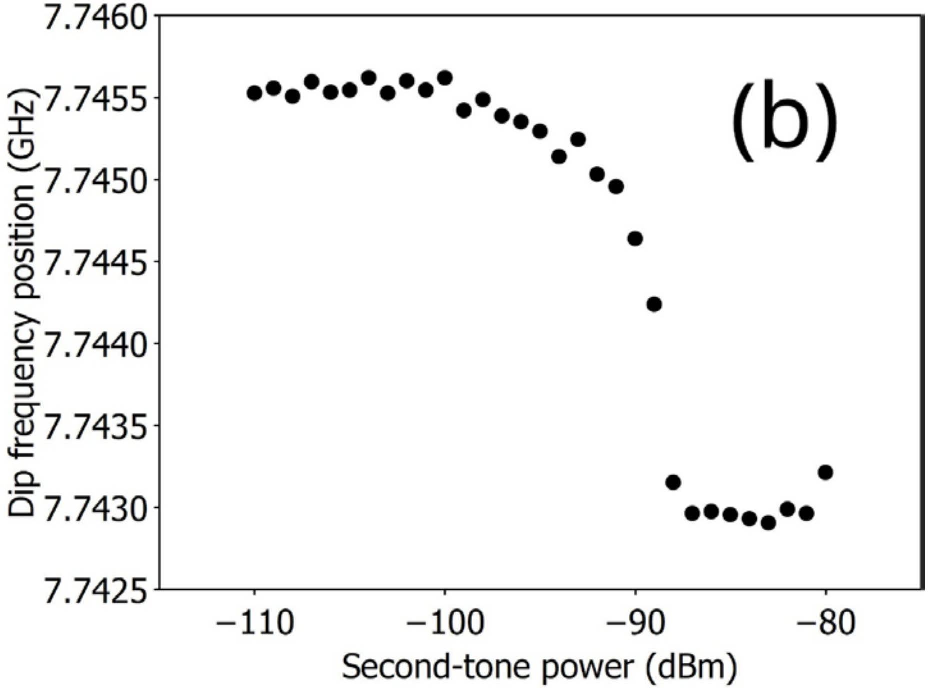


Cabling of T-type three terminal device

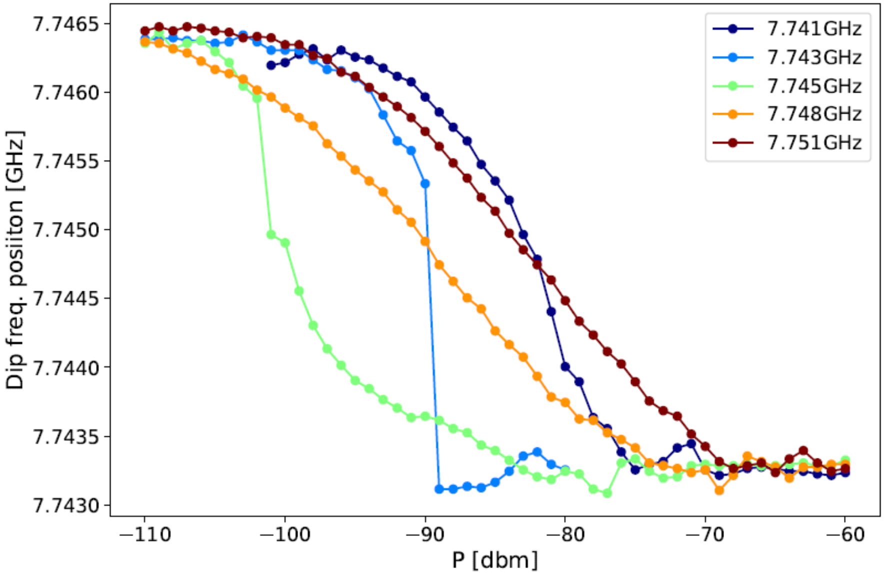
1.2.4. Measurement of two-tone spectra of the three-port SQN -device



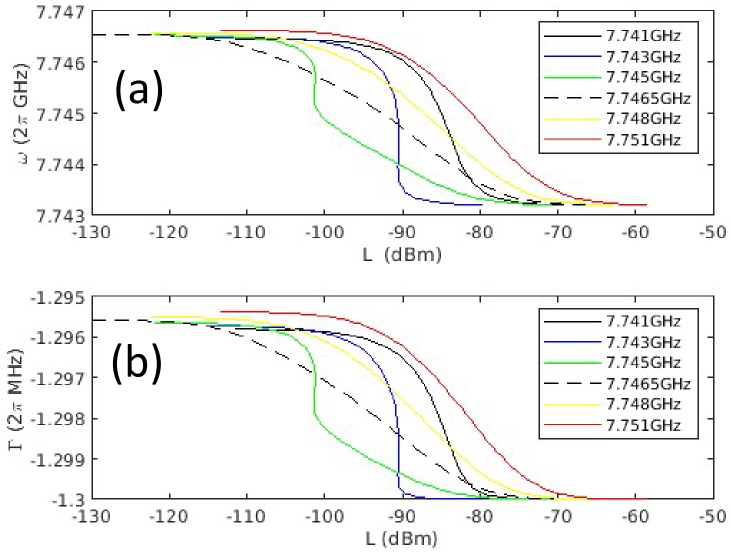
First-tone through-transmission (S_{21}) vs VNA-frequency dependencies recorded at different powers of the second-tone signal of frequency of 7.443 GHz applied to the Port 3. T=15 mK .



Dependence of the frequency position of the resonant drop reported in (a) as a function of the power of the second-tone signal.



We observed the sensibility of the frequency position of the resonant drop both to the power of pump signal and to pump signal frequency.



Theoretically predicted values of frequency shift (a) and linewidth (b) versus the input power in dBm

Experimental results are in a good agreement with the model based on a non-linear multiphoton interaction between pump microwave signal and a qubit system of the SQN where the frequency shift is the sum of the multiphoton AC Stark shift values of each qubit. (P. Navez et al, in preparation). This agreement permits to attribute the absorption peak to the collective quantum state stimulated by the second tone microwave signal.

Contents

1. Progress on demonstration of quantum networks of qubits with highly entangled quantum phases appearing (description 6.3.3.1. of activity 6.3.3. Superconducting quantum networks – Mikhail Lisitskiy – CNR-SPIN))

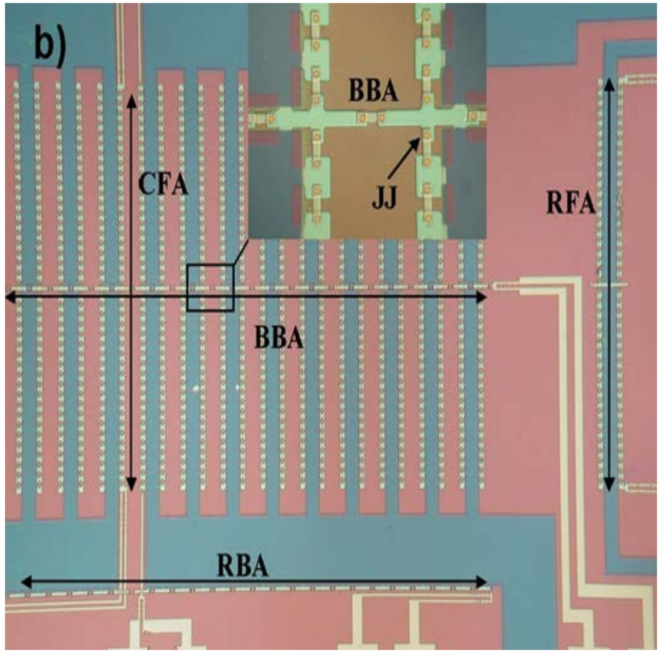
2 Progress on demonstration of superconducting quantum networks topologies composed of interacting Josephson junctions in 2D lattices (description 6.3.3.2. of activity 6.3.3. Superconducting quantum networks – Berardo Ruggiero - CNR-ISASI).

3. Conclusions and works in future

2. Progress on demonstration of superconducting quantum networks topologies composed of interacting Josephson junctions in 2D lattices .

2.1 Previous experimental studies of topologies of superconducting Josephson 2D lattice

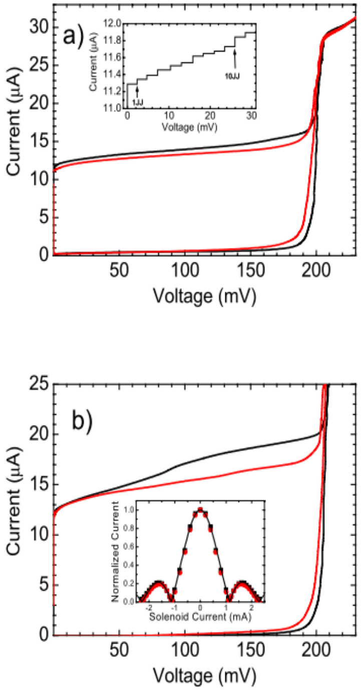
@ T= 1.2 K



Josephson Junction COMB Array

BBA (black)
RBA (red)

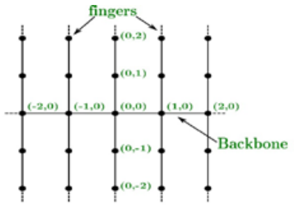
$$F = \frac{\langle I_{c,BBA}\rangle - \langle I_{c,RBA}\rangle}{\langle I_{c,RBA}\rangle} = 0.15$$



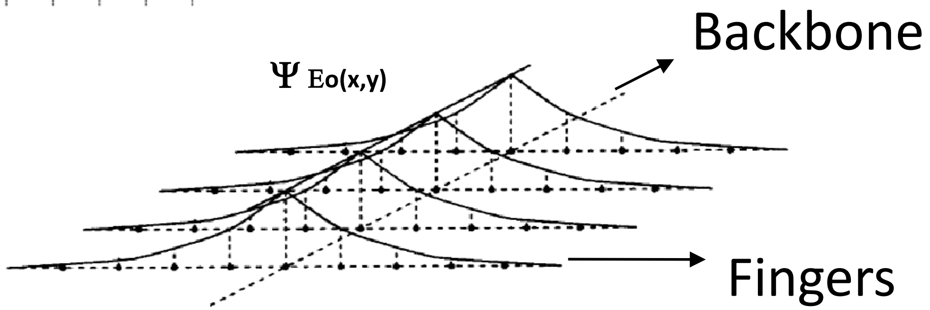
Collaboration with the Physics Department of University of Torvergata Roma and with the Department of Physics, Mathematics and Computer Sciences- University of Parma

Experiments on the Josephson junction Arrays which confirm the topological effect. I-V characteristic of BackBone Array (BBA) is comapred with the I-V characteristic of the Reference Backbone Array (RBA). The observed differences evidence new and surprising behavior of transport properties in superconducting Josephson arrays

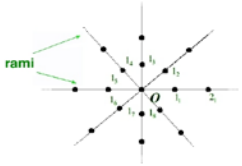
2.2. Theory of topologies of superconducting Josephson 2D lattice



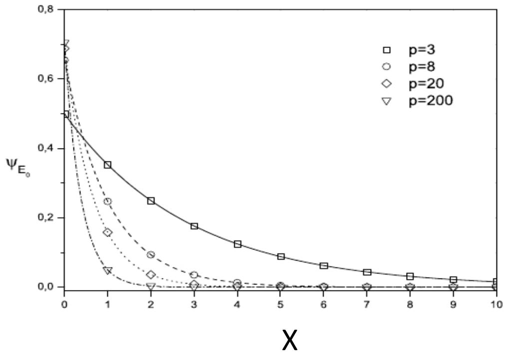
$$\psi_{E_0}^{comb}(x,y) = e^{-|y|/\xi_0}$$

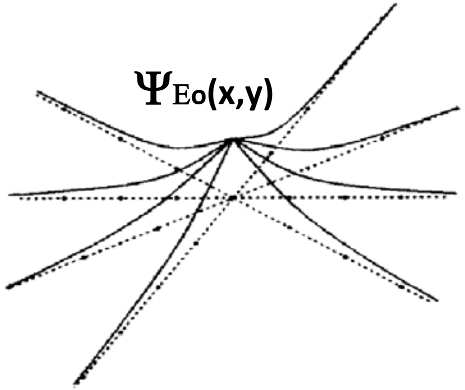


R. Burioni et al., EPL 52, 251 (2000)



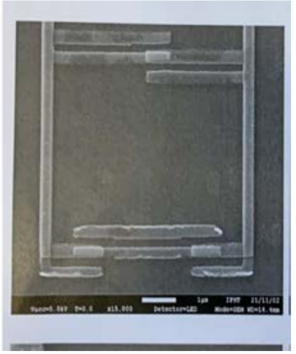
$$\psi_{E_0}^{star}(x,y) = \sqrt{\frac{p-2}{2p-2}}e^{-\frac{x}{\xi}} \qquad \xi = \frac{2}{\log(p-1)}$$

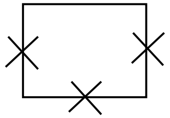




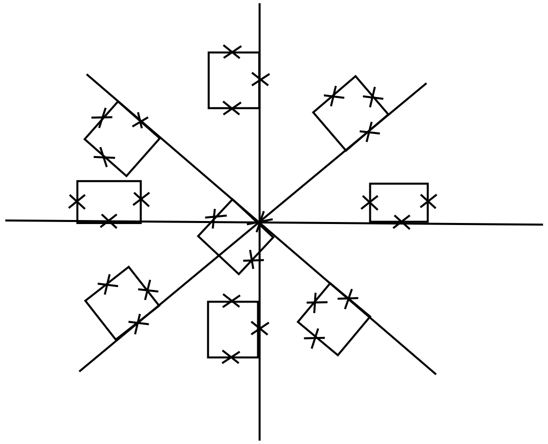
I. Brunelli et al., JPB 37, S275 (2004)

2.3. Development of topologies of superconducting Josephson 2D lattice toward new topologies of superconducting nano-qubit networks (SNQN)





Three Josephson junctions flux qubit with Josephon tunnel junction of 0.2 .x 0.87 µm² (left) and its circuit diagram (right)



Star configuration of the superconducting namo-qubit network

We are carrying out theoretical studies of new topologies of superconducting Josephson 2D lattices and their analysis in the view of search of quantum collective states taking into account Bose condensation phenomenon.

3. Conclusions

- Generic quantum-mechanical theory of disordered interacting SQNs coupled to a low-dissipative resonator was developed;

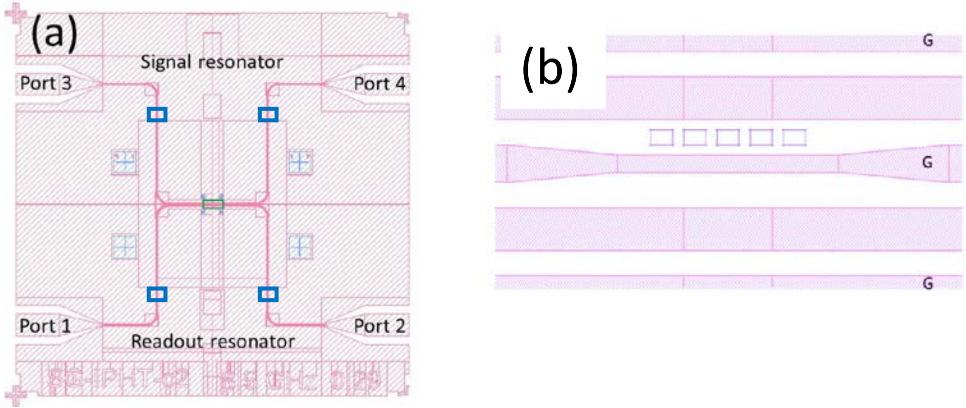
- Design of the layout of T –type three terminals SQN detectors containing 10 C-shunted flux qubits was developed and the samples were fabricated by Al-based two angle shadow evaporation technique;

-Two-tone spectral measurements of the T-type three terminals SQN with 10 C-shunted flux qubits were carried out at zero external magnetic field in LNF. Non-linear effects such as shift of the absorption peak both by power and by frequency of the pump second tone signal were observed. Good agreement between experiment and theoretical model permits to attribute this absorption peak to the collective quantum state stimulated by the second tone microwave signal.

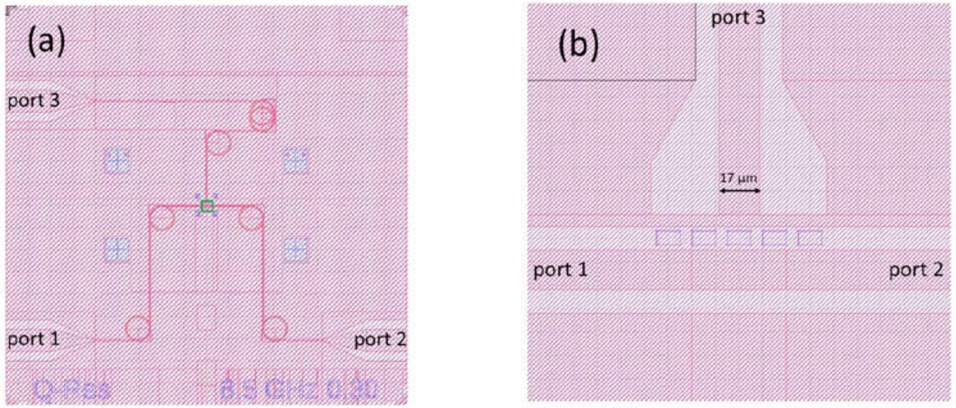
- Theoretical studies of new topologies of superconducting Josephson 2D lattices and their analysis in the view of search of quantum collective states taking into account Bose condensation phenomenon are in progress.

4 . Works in future

- Development of layouts of new configurations of SQN devices (M. Lisitskiy (MC), SPIN CNR, C. Bonavolontà (TD), B. Ruggiero (MC)) ISASI CNR).



(a) Layout of the two resonators four terminal SQN device. The chip dimension is 9 mm x 9 mm. (b) The zoomed central part of figure (a) outlined by green rectangle. Letter "G" indicates the ground layer of the microwave circuits.



(a) Layout of the two resonators three terminal SQN device. The chip dimension is 9 mm x 9 mm . (c) The zoomed central part of figure (a) outlined by green rectangle.

-Evaluation of nano - technology based on the EBL System of the CNR-ISASI for fabrication of superconducting nano-qubit networks with new topologies
M.Lisitskiy (MC), SPIN CNR E. Esposito (MC), V. Di Meo (TD) , C. Bonavolontà (TD), B.Ruggiero (MC) ISASI CNR

Thank you for your attention!