A preliminary study of Traveling-wave Josephson parametric amplifiers (TWJPA)

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DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

HIPPOCRATICA CIVITAS STUDIUM SALERNI

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Outline

- Low noise microwave detection
- Principle of operation of JTWPA
- The DARTWARS project
- Samples description
- Experimental setup
- Preliminary results
- Conclusions and outlook

Superconducting quantum computing and several fundamental physics experimental demand quantum limited and wide bandwidth cryogenic amplifiers in the microwave frequency range

Cryogenic semiconductor based amplifiers can achieve a minimum noise temperature of 2 - 5 K*
Superconducting amplifiers, being almost non dissipative, can be a good alternatives

JPA

Josephson parametric amplifier

Large gain
Quantum limited noise

Narrow bandwidth (~100 MHz): One JPA per cavity or few qubit per read out per line

KITWPA

TL based on nonlinear kinetic inductance of SC

Wide BW (4-5 GHz)
Quantum limited noise

TL lengths in the order of one meter are required

JTWPA

TL based on nonlinear inductance of Josephson junctions

Wide BW (4-5 GHz)
Quantum limited noise
Shorter length devices

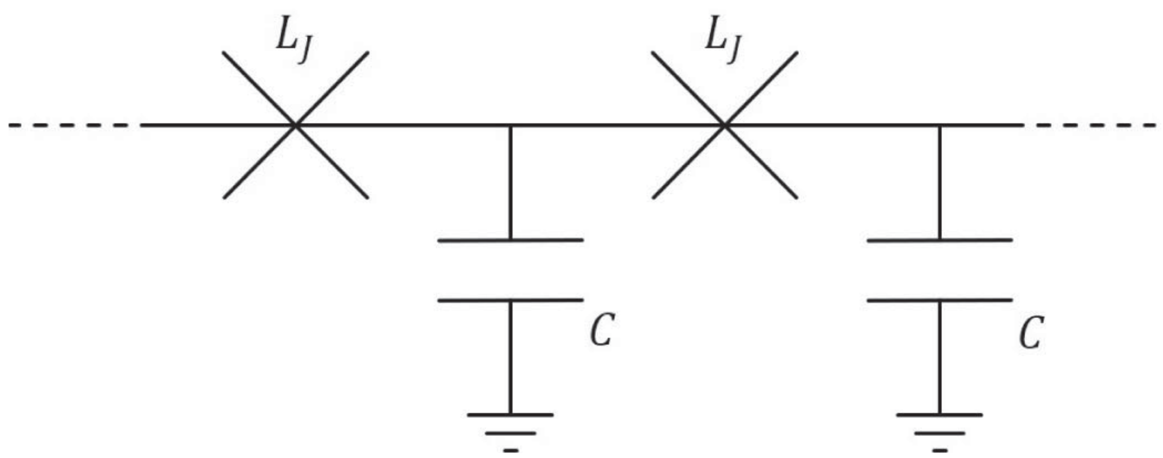
Design and fabrication more complex

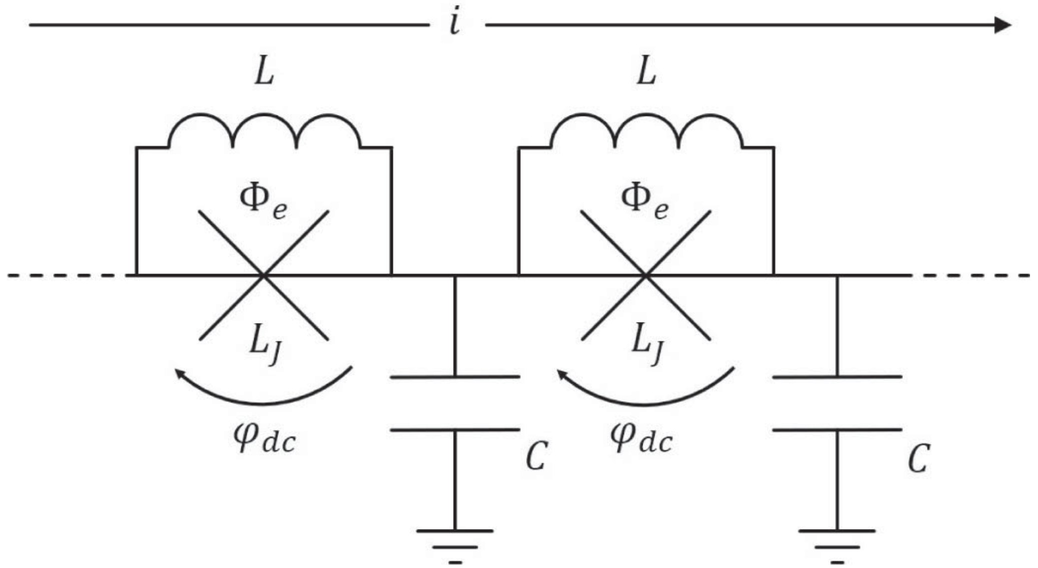
J. Aumentado, *IEEE MICROWAVE magazine* 1527-3342 (2020)

*J.Schleeh et al., *Solid-State Electron*. **91**, 74–77 (2014)

Josephson Traveling Wave Parametric Amplifiers (JTWPA)

Josephson Traveling Wave Parametric Amplifiers (**JTWPA**) has an architecture of a discrete microwave transmission line made of periodically repeated sections, including either single Josephson junctions or superconducting quantum-interference devices (SQUIDs)

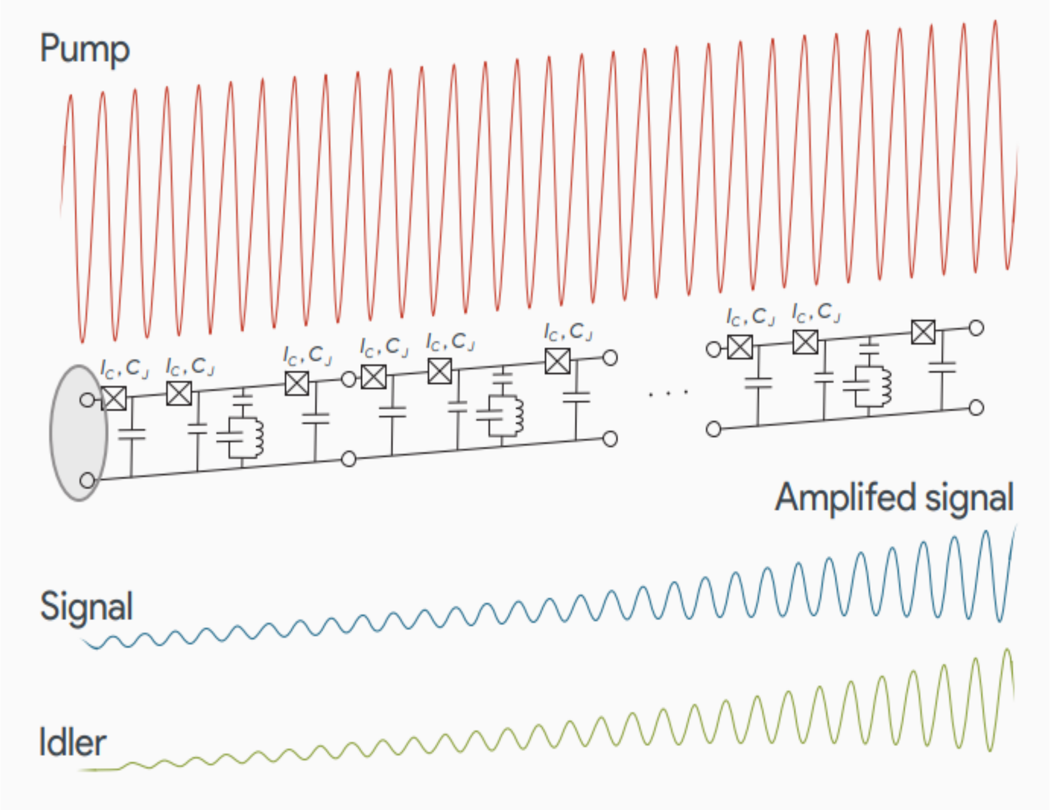




JTWPA employ the nonlinear dependence of the Josephson inductance L_J on current I(t), enabling time variation of $L_J(I(t))$ following a pump signal at frequency ω_p

Josephson Traveling Wave Parametric Amplifiers (JTWPA)

JTWPA transfers power from a strong microwave tone (**PUMP**) to a weak one (**SIGNAL**)



A large pump tone modulates this inductance, coupling the pump (ω_p) to a signal (ω_s) and idler (ω_i) tone via frequency mixing.

The relation between the frequencies depend on the type of nonlinearity and can be:

$$\omega_S + \omega_i = 2\omega_p \qquad \text{4WM}$$

$$\omega_S + \omega_i = \omega_p \qquad \text{3WM}$$

JTWPA in principle provide a larger bandwidth with respect to JPA and possibly allow a higher gain and dynamic range

The DARTWARS Collaboration

Detector Array Readout with Traveling Wave AmplifieRS

Development of wideband superconducting amplifiers with noise at the quantum limit and the implementation of a quantum-limited read-out in different types of superconducting detectors and qubit

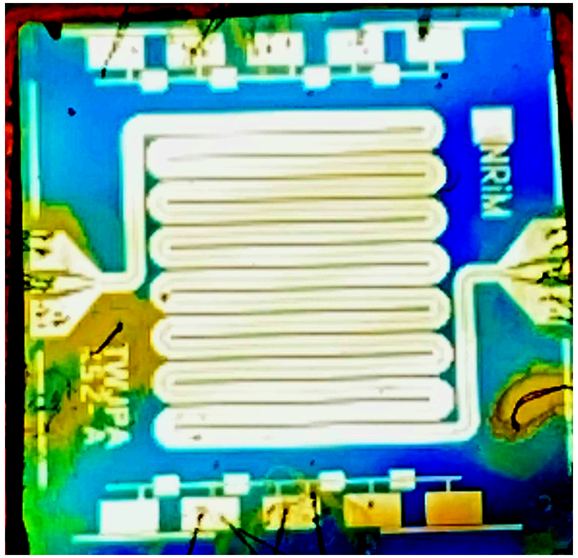
Involved Institutions

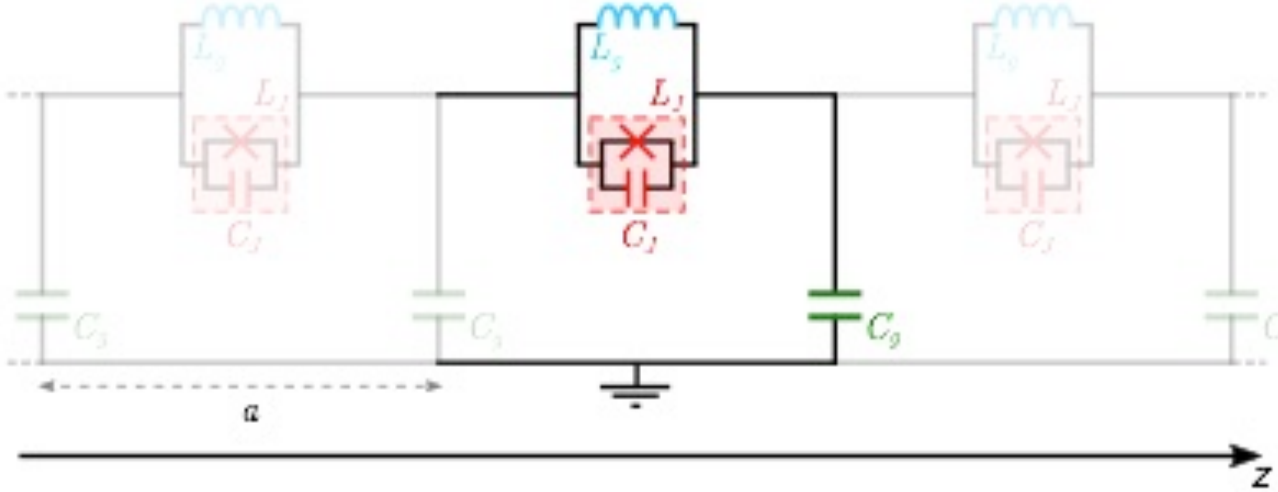
University of Salerno, Department of Physics, Fisciano, Salerno, Italy
INFN - Napoli, Salerno group, Fisciano, Salerno, Italy
University of Milano Bicocca, Department of Physics, Milan, Italy
INFN - Milano Bicocca, Milan, Italy
University of Salento, Department of Physics, Lecce, Italy
INFN Sezione di Lecce, Lecce, Italy
INO-CNR BEC Center, Povo, Trento, Italy
University of Trento, Department of Physics, Povo, Trento, Italy
INFN - Trento Institute for Fundamental Physics and Applications, Povo, Trento, Italy
Fondazione Bruno Kessler, Povo, Trento, Italy
INFN - Laboratori Nazionali di Frascati, Frascati, Rome, Italy
INRiM - Istituto Nazionale di Ricerca Metrologica, Turin, Italy
IFN-CNR, Povo, Trento, Italy
Polytechnic University of Turin, Turin, Italy
University of Sannio, Department of Science and Technology, Benevento
University of Sannio, Department of Engineering, Benevento, Italy
INFN - Torino, Turin, Italy

INFN Istituto Nazionale di Fisica Nucleare

JTWPA: initial design

- **JTWPA** is a two-port superconducting device consisting in a coplanar waveguide in which is embedded a repetition of hundreds of elementary cells
- One unit cell consists of RF-Superconducting Quantum Interference Device (RF-SQUID) coupled to ground through C_g.
- Each RF-SQUID consists in a superconducting loop containing a geometrical inductor L_g and Josephson junction (JJ) characterized by an intrinsic inductance L_J, an intrinsic capacitance C_J and an intrinsic resistance R_j (assumed very large at the operating temperature and therefore neglected).





JTWPA: samples description

Design and production by the Istituto Nazionale di Ricerca Metrologica (INRiM, Turin, Italy)

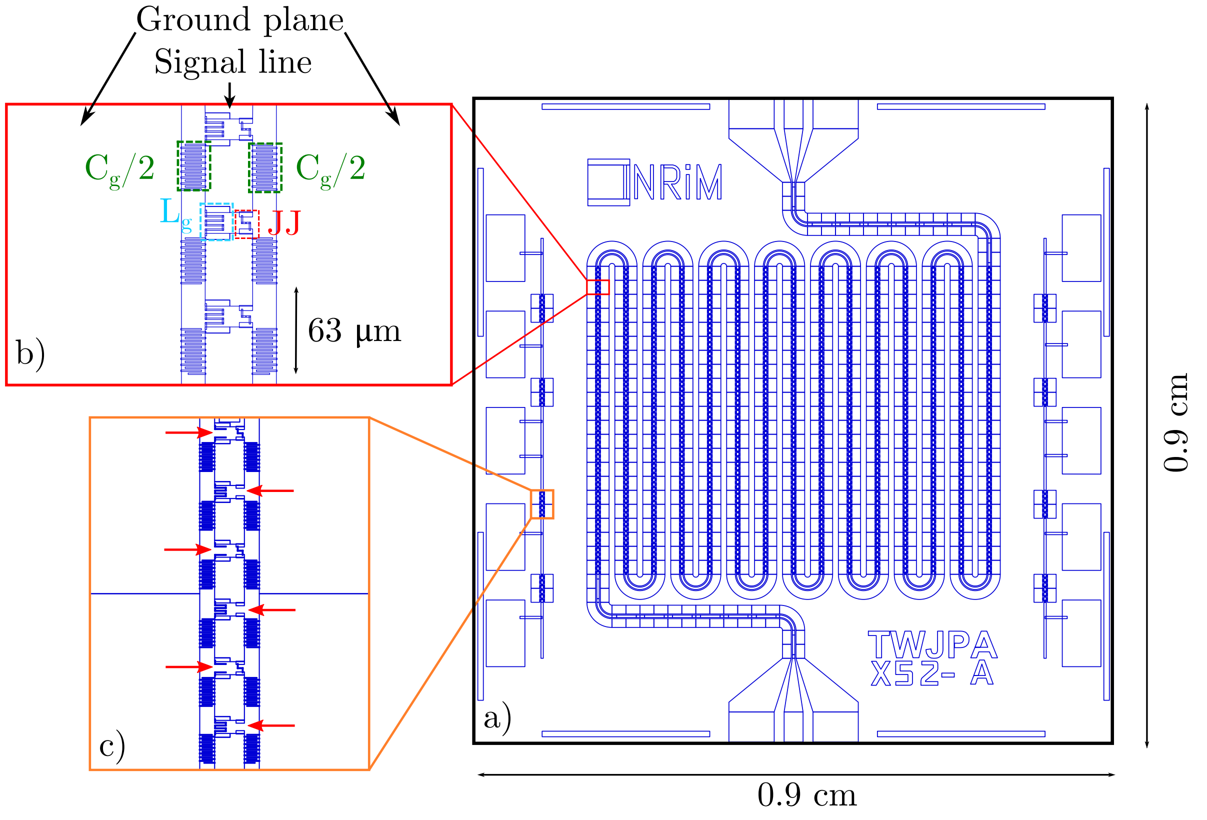
Repetition of N = 990 elementary cells
Cell size a = 63 µm,
Total length l = a · N ≈ 6.25 cm

To make this device as compact as possible the coplanar waveguide is folded in 15 segments

L_g has been engineered in the form of a bi-dimensional meander inductor

Ground capacitance C_g has been divided in two interdigitate capacitors $C_g/2$

An array of 8 preliminary characterization units (PCU) is present on both sides of the chip

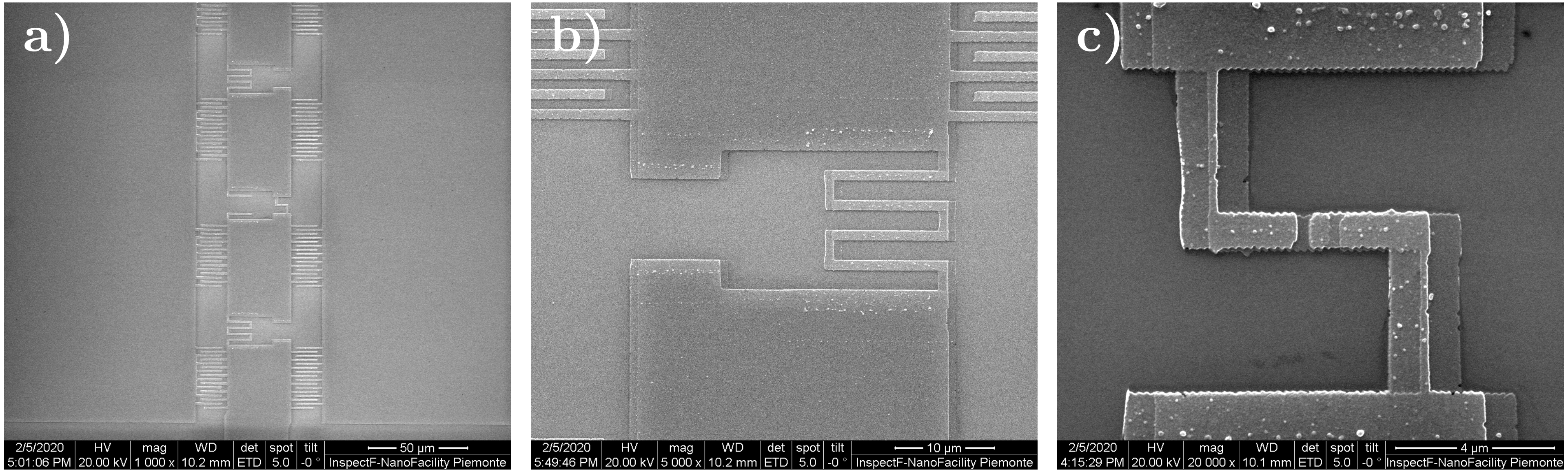


JTWPA: sample fabrication process

Substrate: p-doped, 100 oriented, Si/SiO2(300nm)

The geometry is defined by a single-step Electron Beam Lithography (EBL) process.

JJs: Al(30 nm)/Al-Ox/Al(80 nm) deposited by a ultra-low pressure electron beam evaporator, equipped with a tiltable sample holder that ensure the possibility to create exploiting the Niemeyer-Dolan technique.



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JTWPA: sample properties

The nominal values of the individual components of the circuit are:

- ✓ Critical current of Josephson junctions: I_C = 2 µA
- ✓ Josephson junction capacity: C = 200 fF
- ✓ Inductance of the Josephson junction at the working point: L_J = 258.5 pH
- ✓ Geometric inductance: L_g = 120 pH
- ✓ Plasma frequency: ν_p = 38 GHz
- ✓ Resonator quality factor: Q = 100

Cryogenic setup

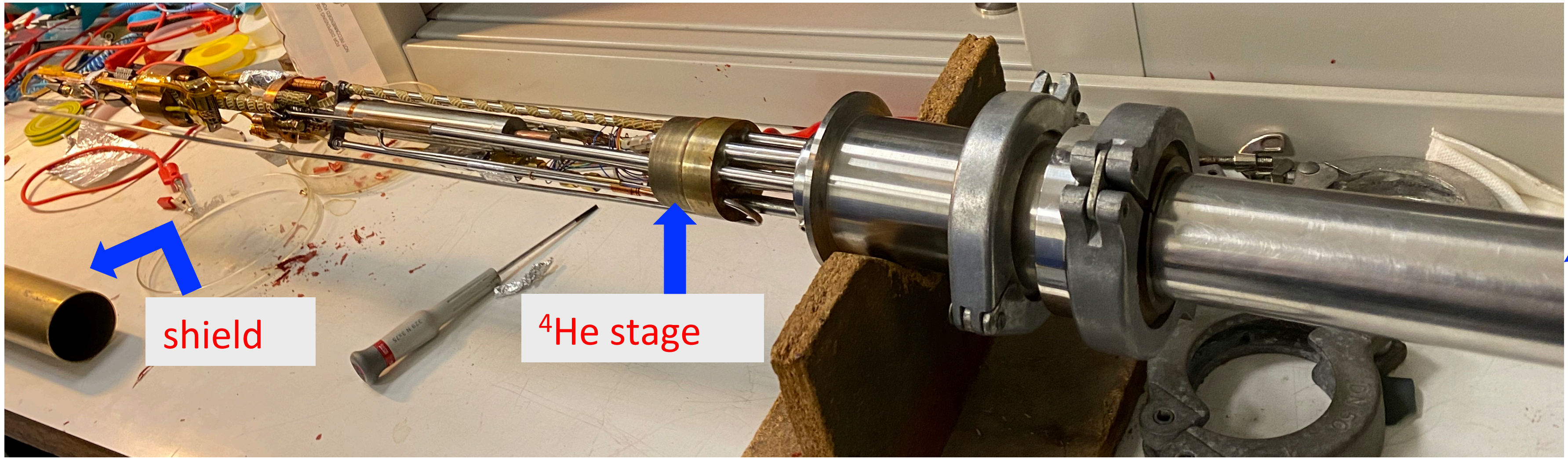
Oxford Heliox VL ^{3}He cryostat

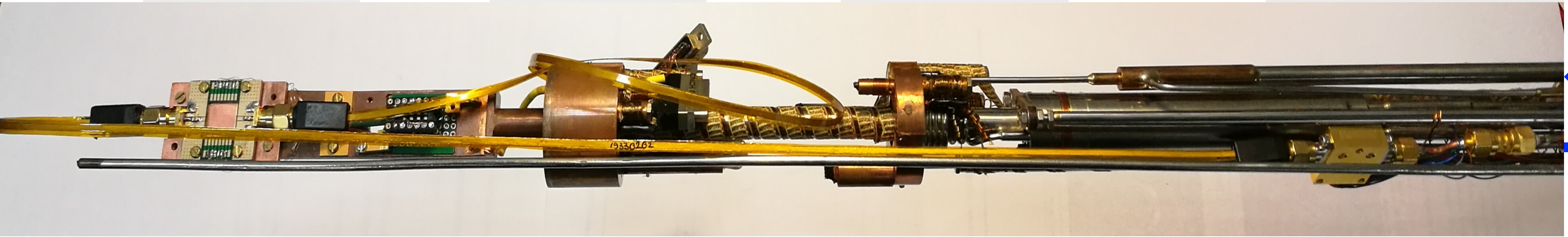
Base T = 245mK Cooling Power = 40 μW at T < 290 mK

Hold time = several hours Recycle time = 1h

OK for testing Al based junctions

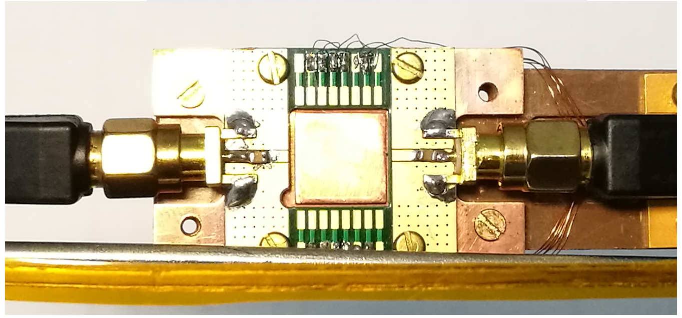
Needed adaptations for MW signals

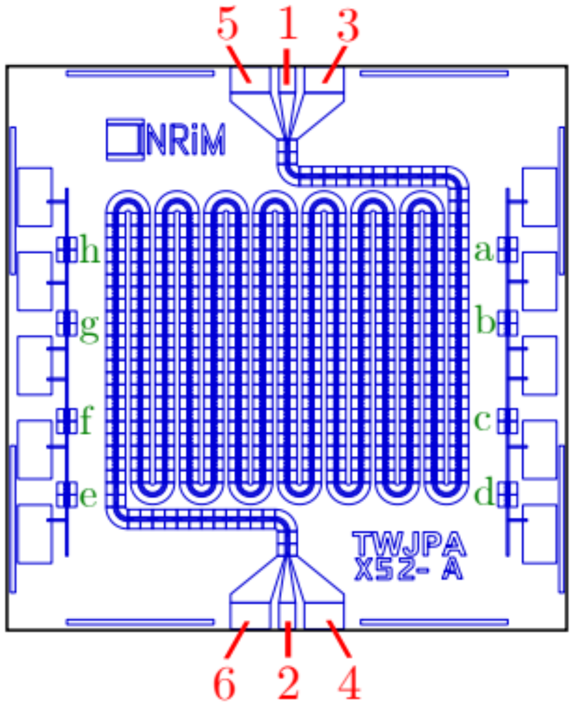




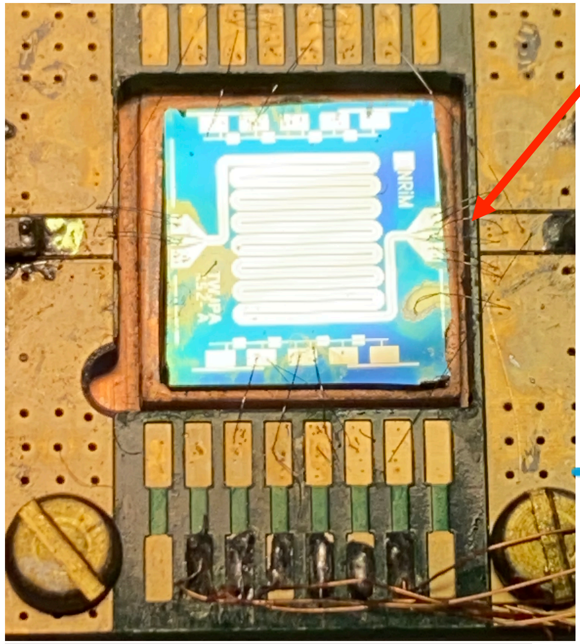
DC Setup

Sample holder





TWJPA X52-A



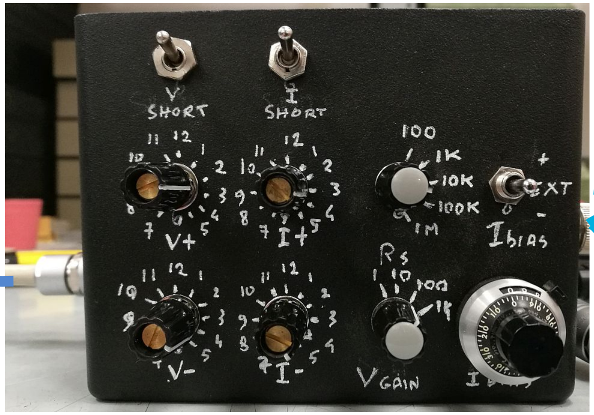
Ultrasonic bonding

RF in

RF out

DC bias and test lines

Filtering and grounding box



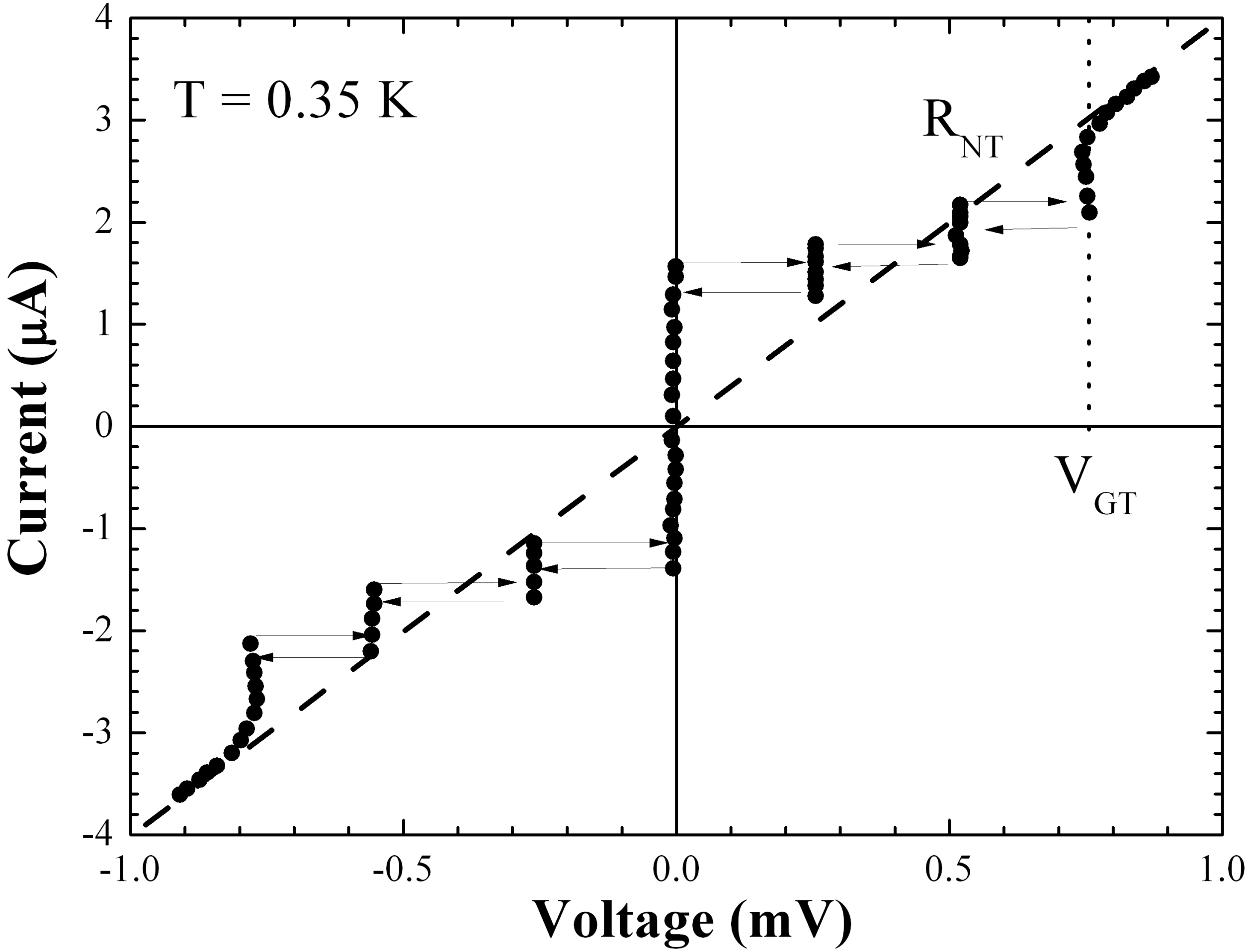
Low Noise DC readout

PC

DAC/ ADC

3 Junction array

X52-A c Sample



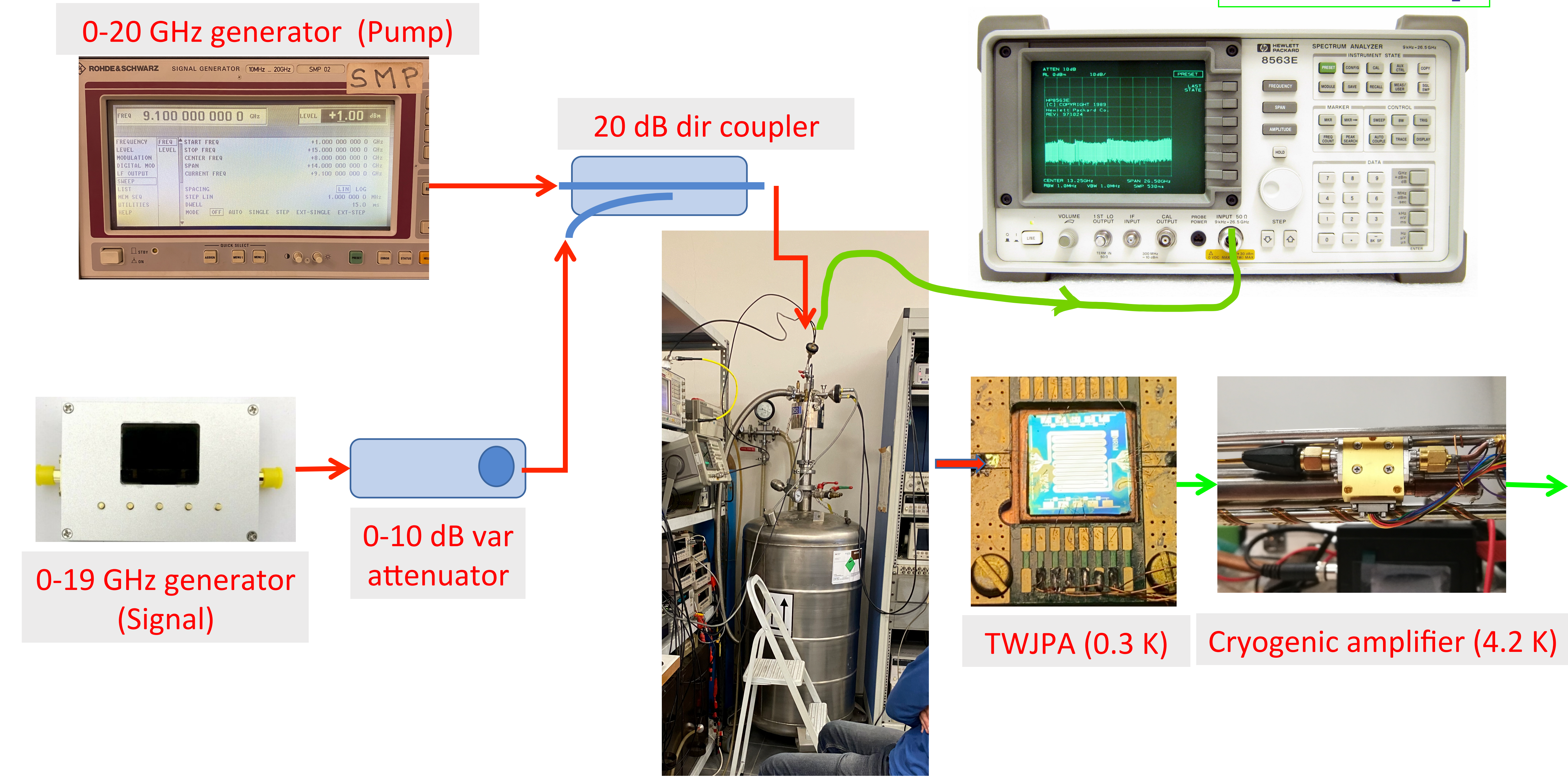
- ✧ T = 0.350 K
- ✧ I_c = 1.6 μA, 1.9 μA and 2.3 μA
- ✧ R_n = 237 Ω → 79 Ω/junction

The measurements of other test junction in the same chip give open or short circuits, due to damaged JJs. The damage of the JJs is most probably due to ESD during the chip mounting procedure (bonding, chip and sample holder handling).

This procedure has to be revised to eliminate the problem

V. Granata et al., submit to *IEEE Transactions on Applied Superconductivity (TAS)*

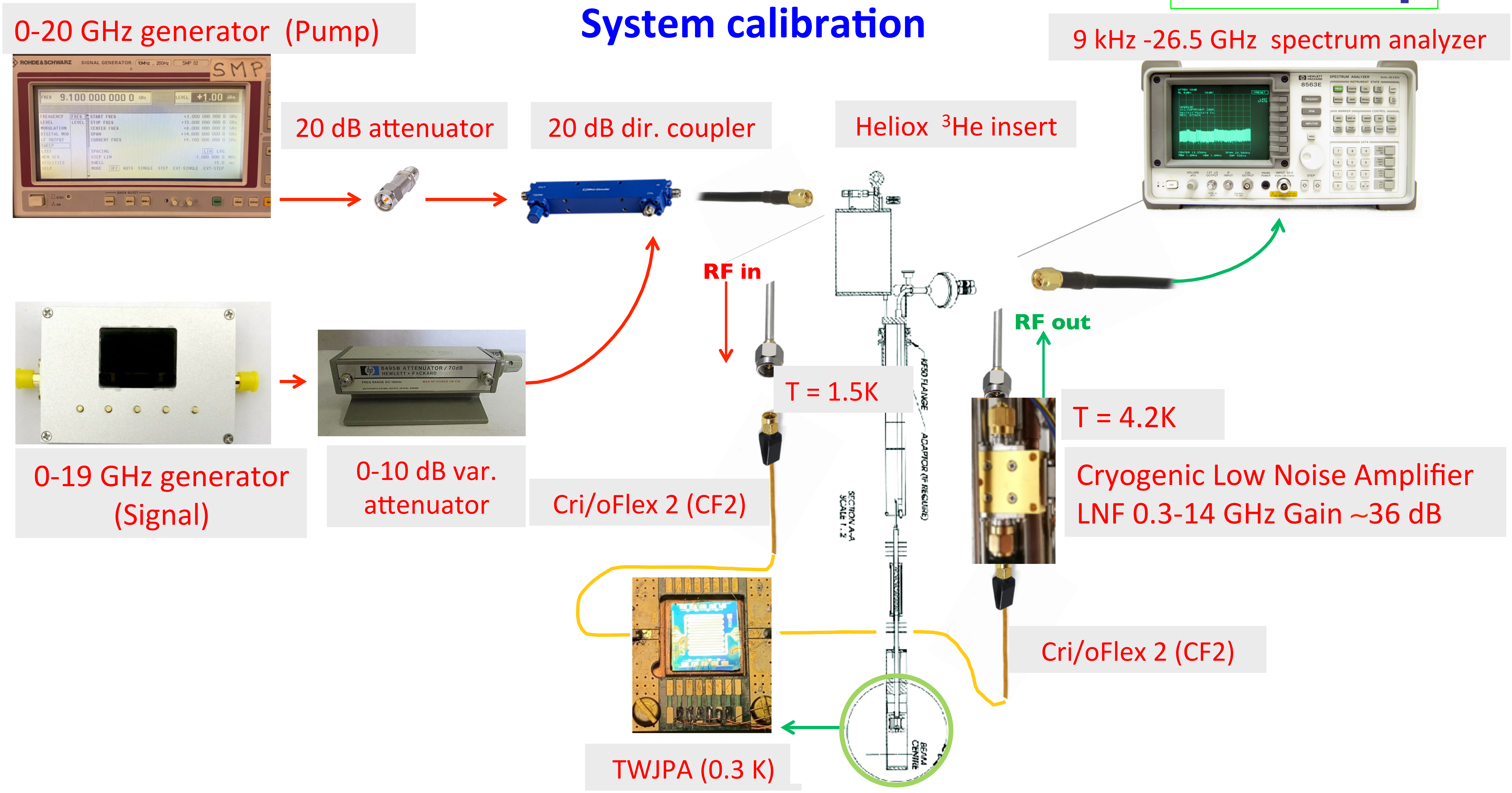
RF setup



0-20 GHz generator (Pump)
ROHDE&SCHWARZ
SIGNAL GENERATOR
SMP 02
SMP
20 dB dir coupler
HEWLETT PACKARD
SPECTRUM ANALYZER
8563E
0-19 GHz generator (Signal)
0-10 dB var attenuator
TWJPA (0.3 K)
Cryogenic amplifier (4.2 K)

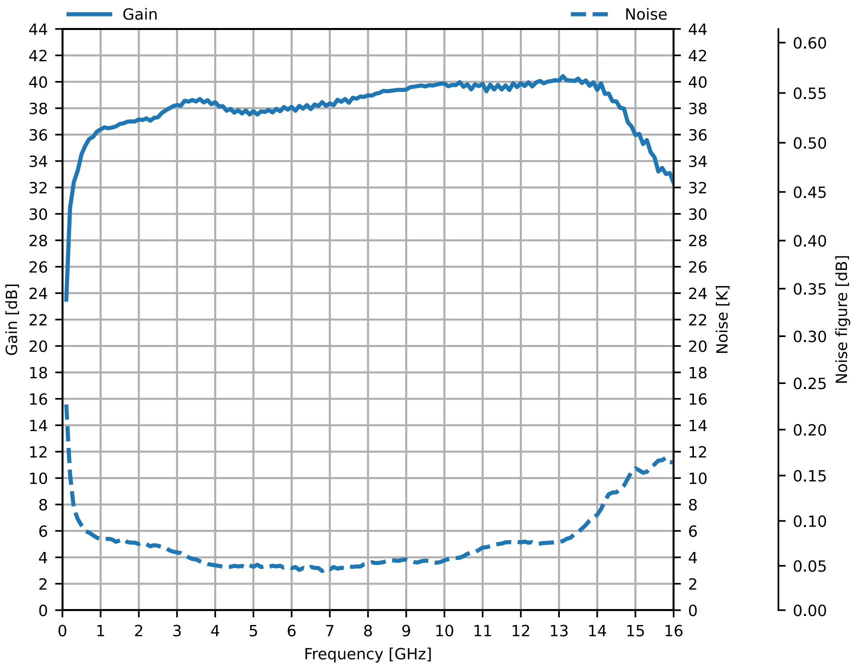
RF setup

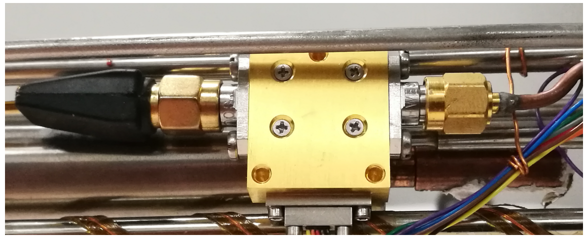
System calibration

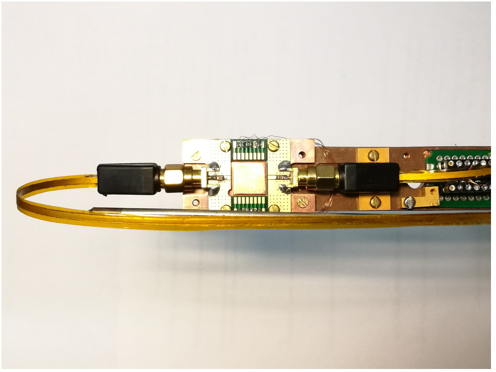


Setup Attenuation

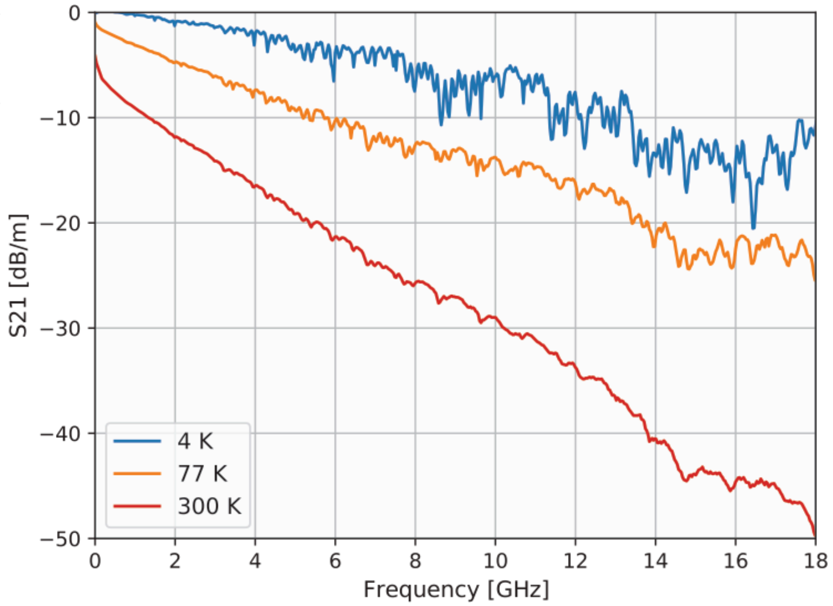
Cryogenic amplifiers
T = 4 K



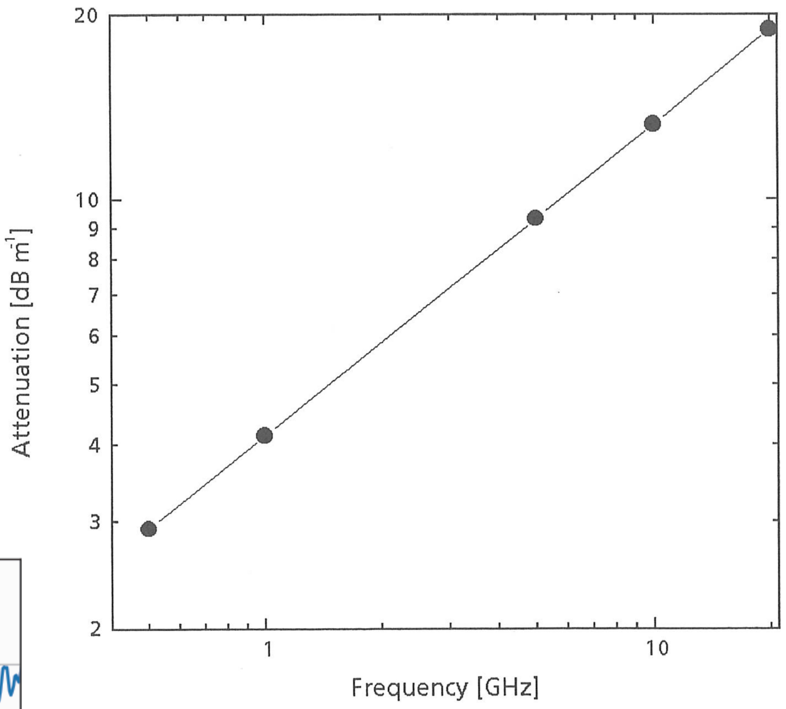




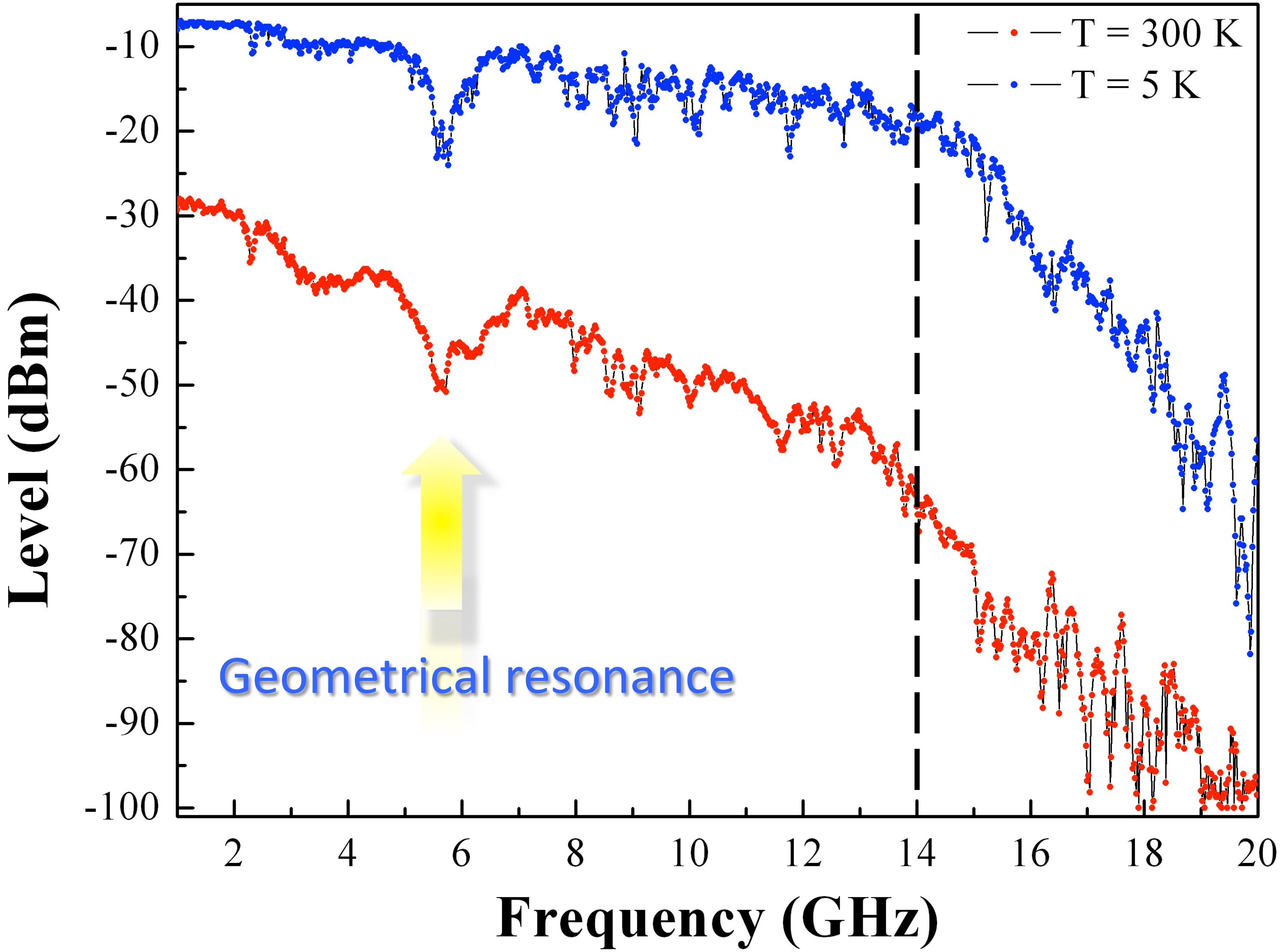
CrioFlex 2 (CF2) cabling



Heliox ^{3}He rf cable



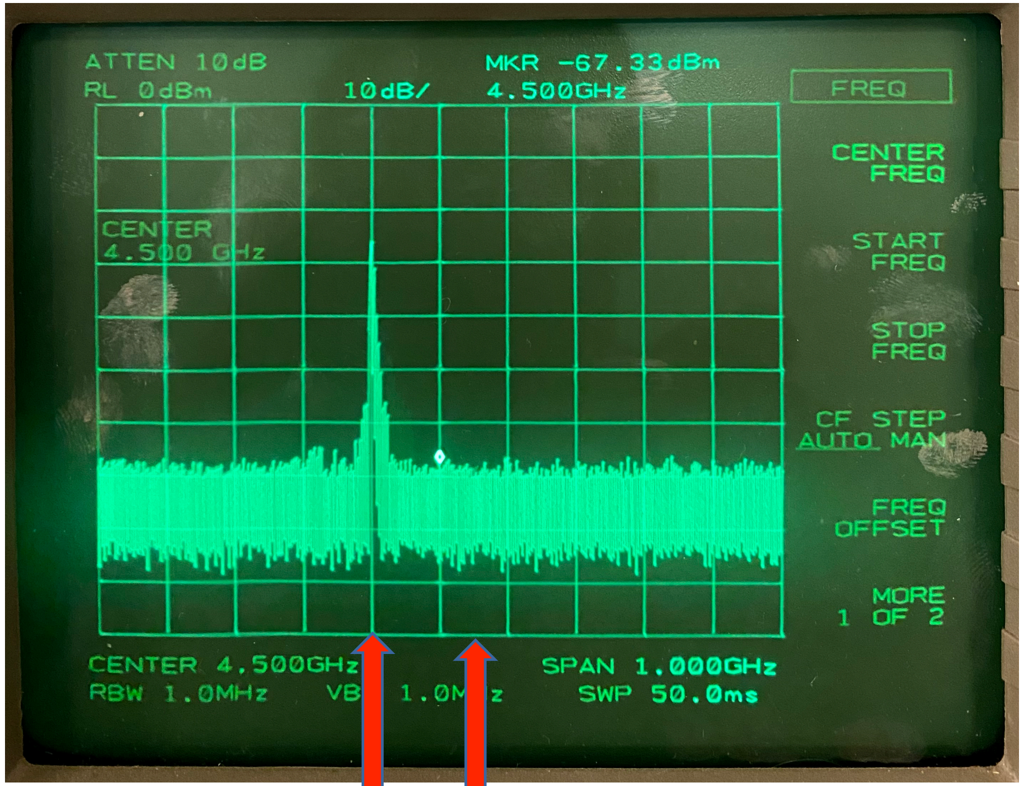
IN/OUT measurement of frequency response without sample



Input Power = -30 dBm

RF preliminary Results

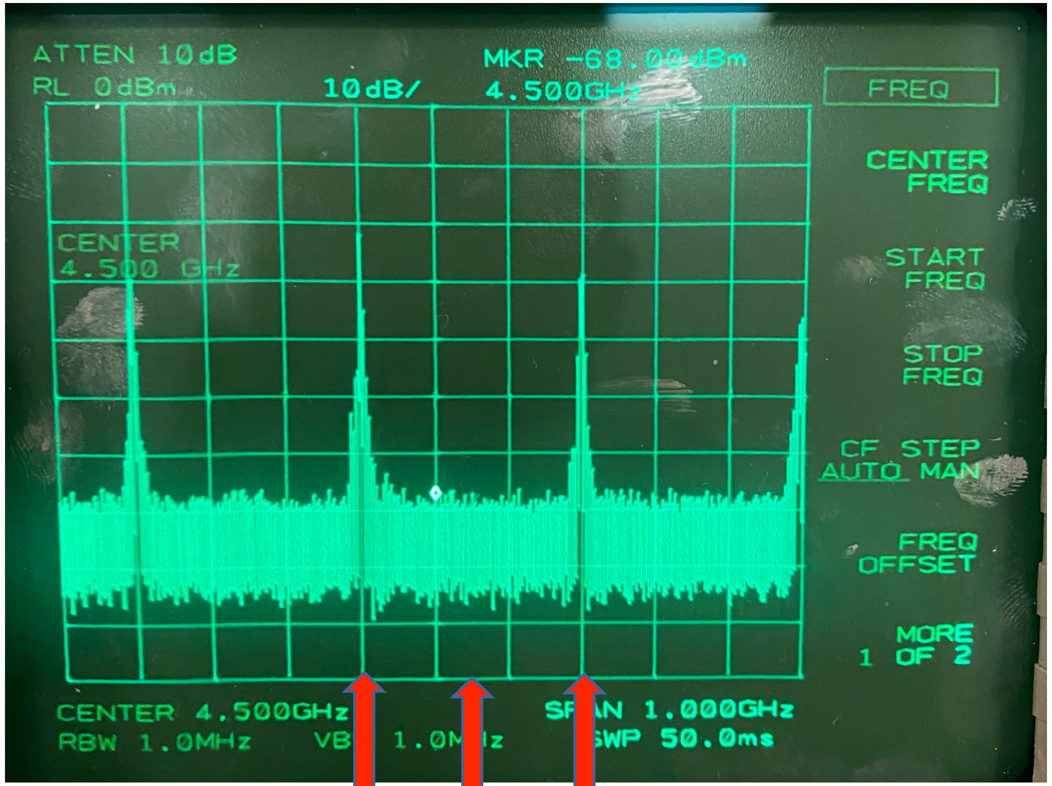
Fpump = 9.10 GHz RF OFF
Fsignal = 4.40 GHz



Fsignal Fpump/2

1 GHz

Fpump = 9.10 GHz RF ON
Fsignal = 4.40 GHz

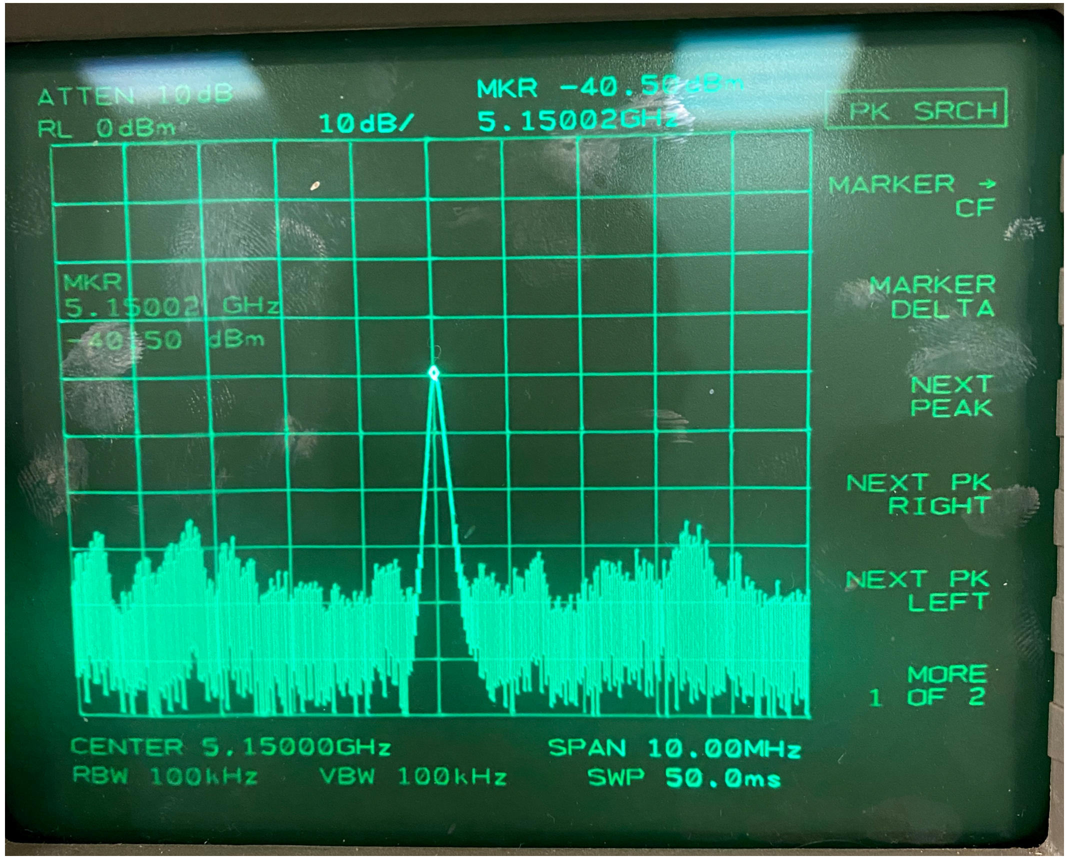


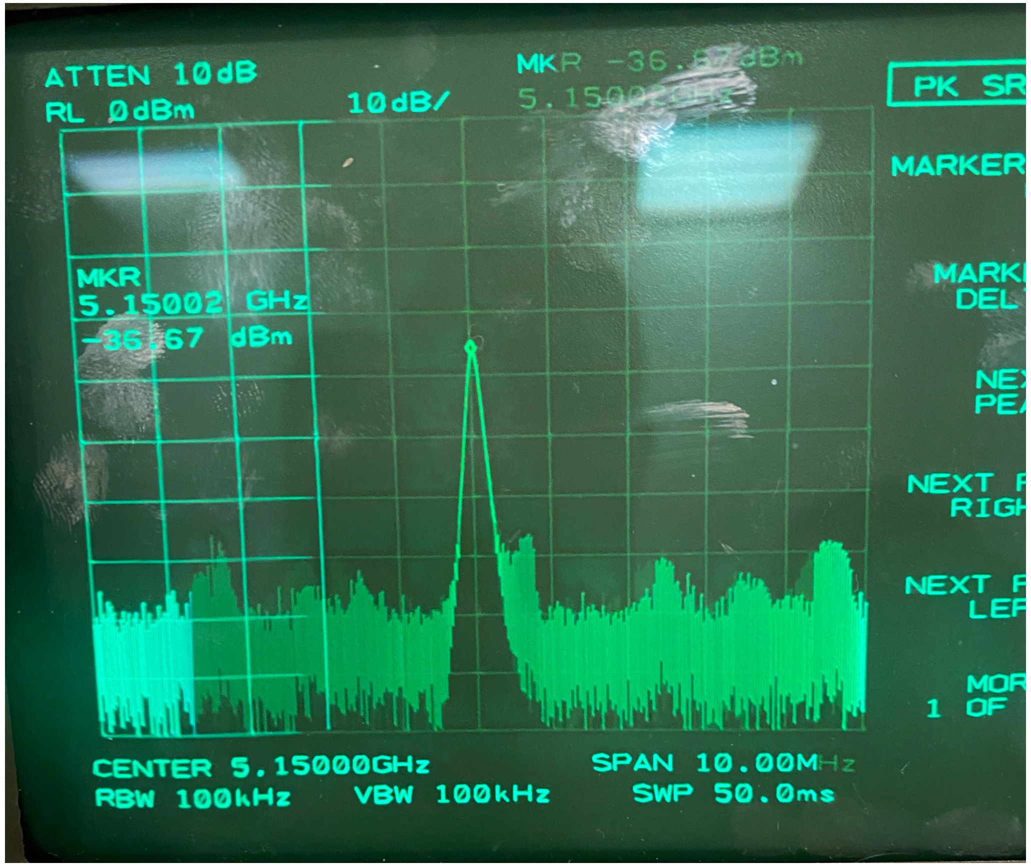
Fsignal Fidle
Fpump/2

RF preliminary Results

Fpump = 10.0 GHz RF OFF
Fsignal = 5.15 GHz
Asignal = -40 dBm

Fpump = 10.0 GHz RF ON
Fsignal = 5.15 GHz
Asignal = -36.7 dBm ≈ + 3 dB





1 MHz

RF preliminary Results

The same effect is visible at $T > T_c(Al)$

→ It is not due to the JTWPA

Effect due to a direct coupling between the cables in / out of the device and cryogenic amplifier

cable connectors have been shielded

JTWPA: samples description – 2nd generation

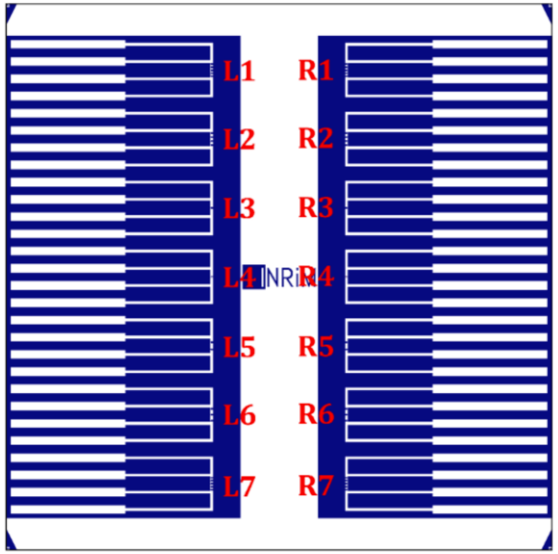
ID_013_01 JTWPA

- Complete redesign of TW
- Added lumped resonant structure for resonant phase matching
- No EBL lithography (faster turnaround)
- Added Ti underlayer for base electrode to improve surface uniformity

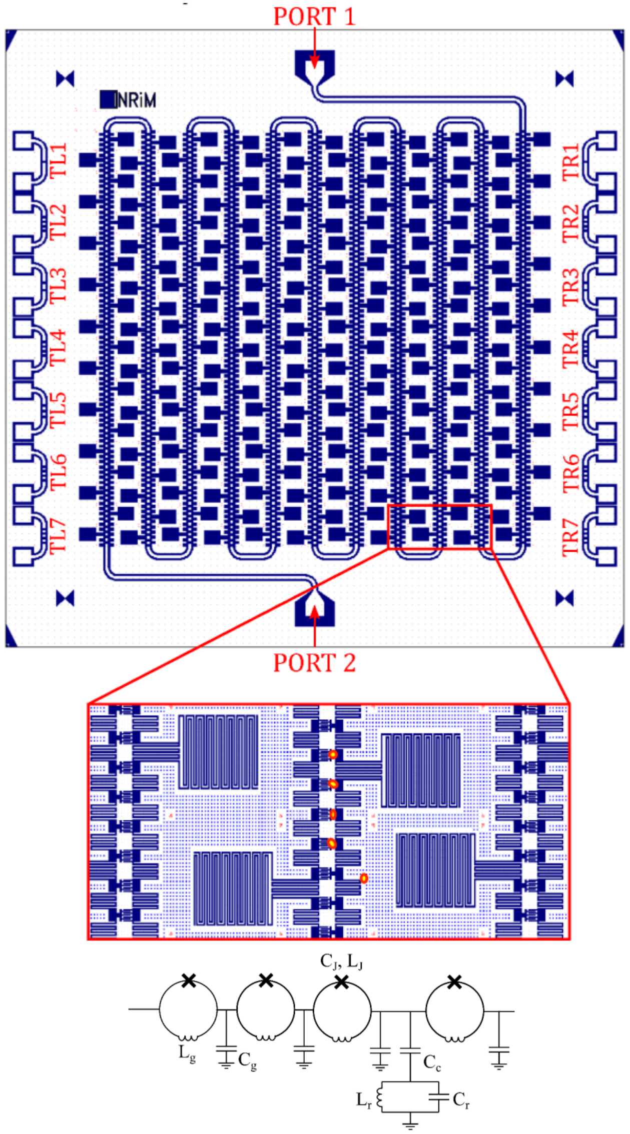
SUB_02 Test chip

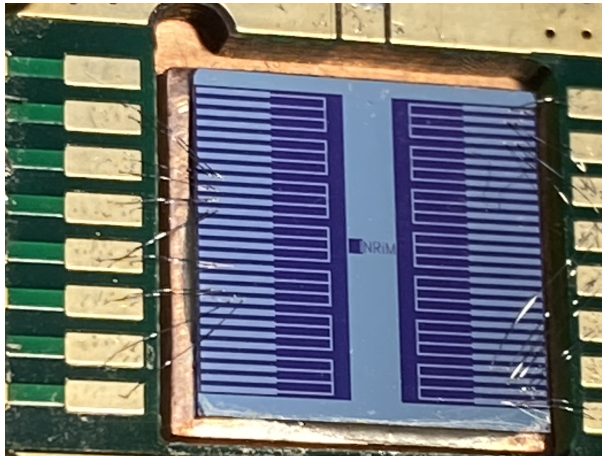
- Test chip with several JJ arrays with 1 to 5 junctions
- JJ resistance measured at MIB at room temperature

SUB_02



ID_013_01





Chips delivered

ID_013_01_A JTWPA

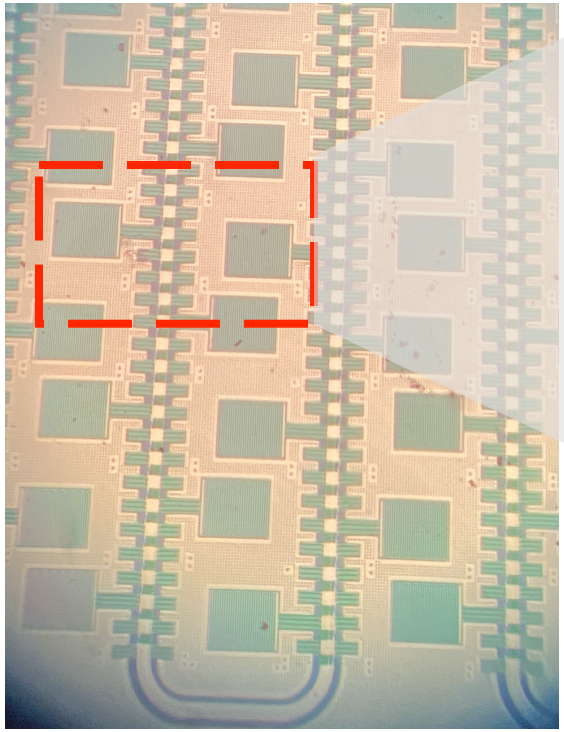
ID_013_01_B JTWPA

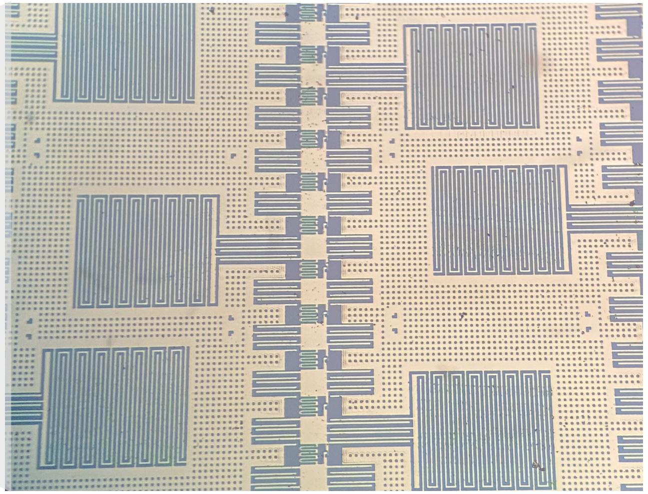
SUB_02_F test JJ arrays

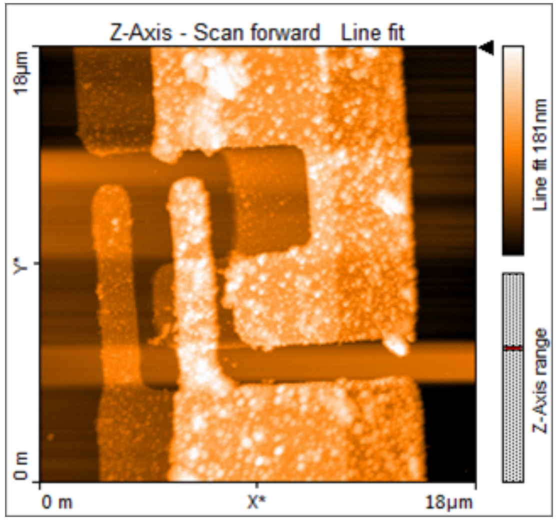
SUB_02_J test JJ arrays

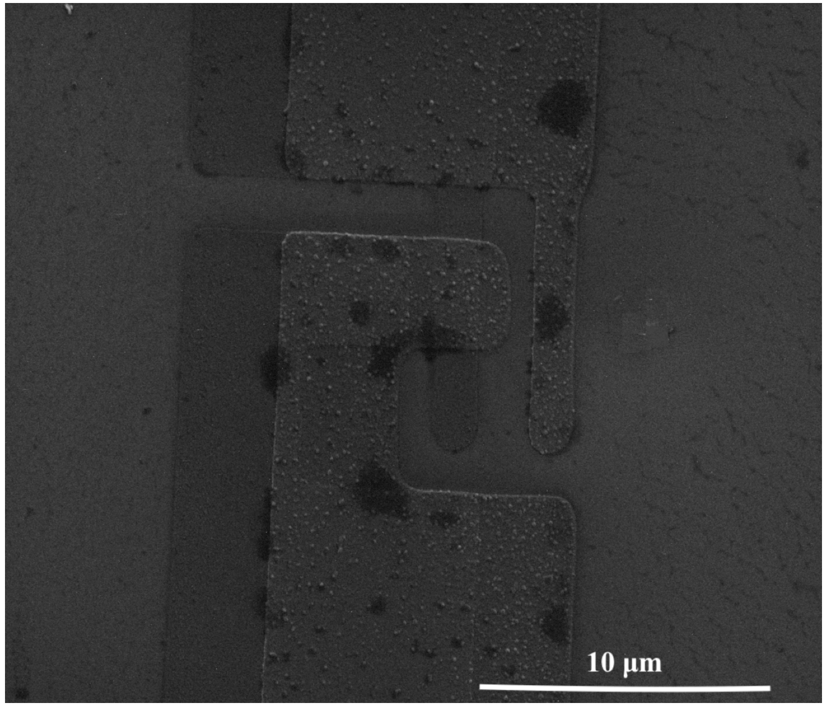
JTWPA: samples description – 2nd generation

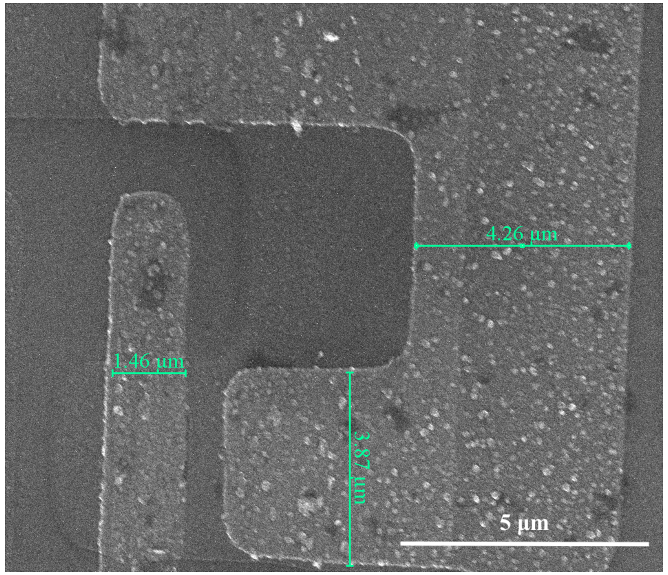
Optical and SEM Images



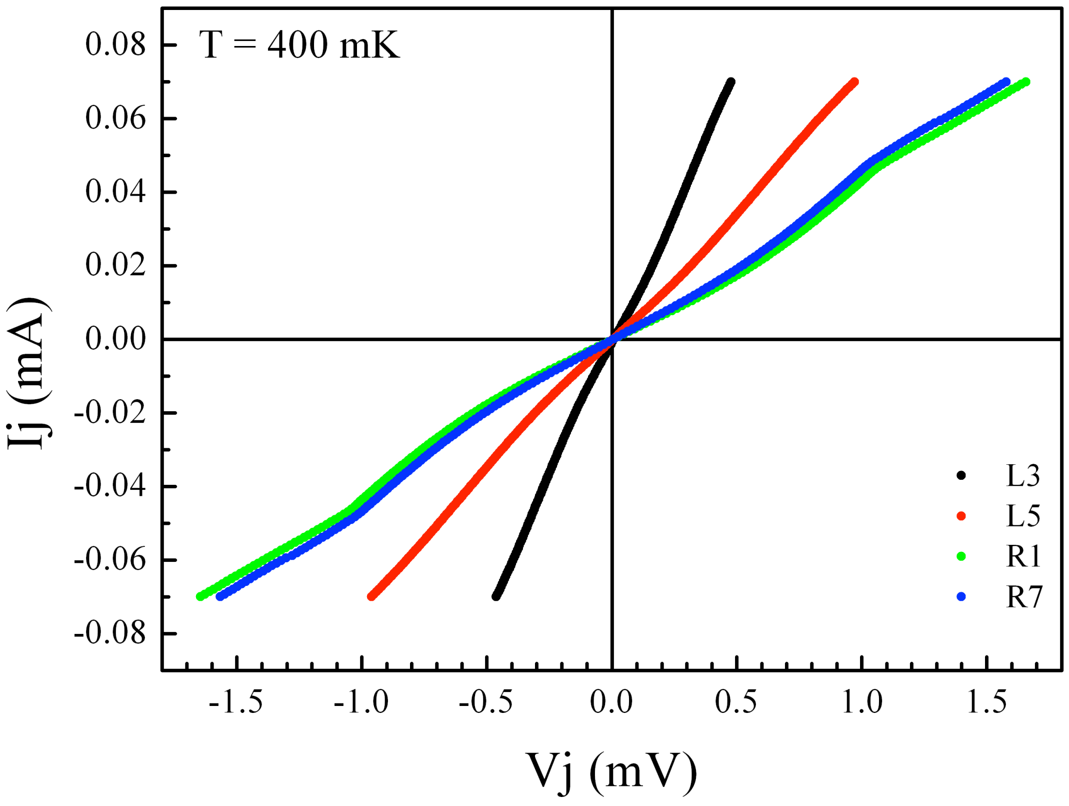








DC Measurement Resultsof JTWPA 2nd generation



Chip SUB_02F

The I-V curves show signatures of superconducting gap

No critical current visible.

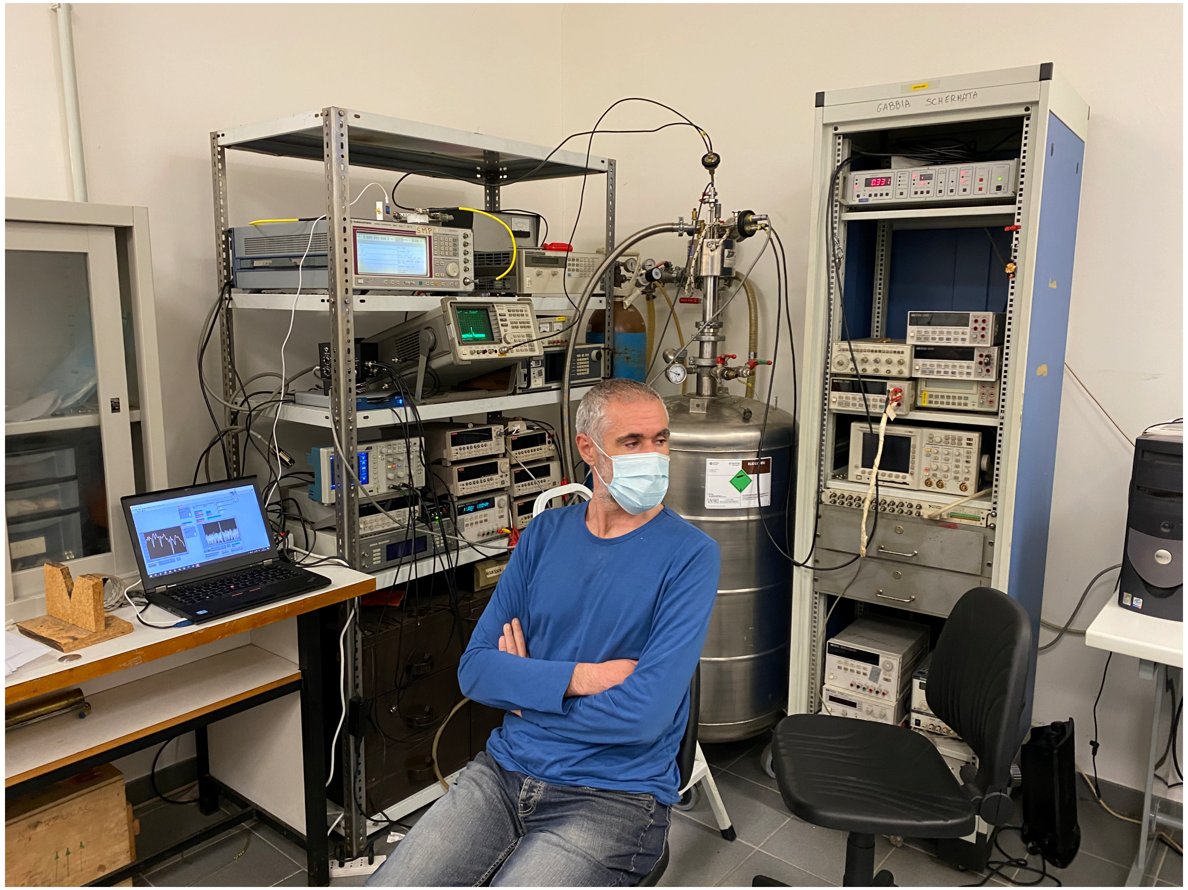
At T = 400 mK one at least of the junction electrodes is still in the normal state.

This is most probably due to the bilayer Ti(5nm)/Al(25nm) used as base electrode which has decreased its T_c below 400 mK

Therefore it is not possible to test the RF properties of JTWPA

Preliminary Results

The Salerno group



Conclusions and Outlook

- JTWPA are promising candidates as quantum limited microwave amplifiers for applications in fundamental physics experiments and quantum computing

- Within the DARTWARS collaboration we are developing JTWPA with different designs

- We have setup a cryogenic and RF system to test the amplifier, operating at 0.3 K and based on a relatively easy to use cryostat with fast turn around

- The preliminary results show that the system is operating; further work to optimize it is in progress

- The DC measurements of the 1^{nd} generation JTWPA (X_52) show JJ with critical current in the correct range, but with a relatively high dispersion, the chip is very sensitive to ESD and a more accurate handling procedure is necessary

- The 2_{nd} generation chips do not show critical currents down to 350 mK. The opening of superconducting gap is evident at 400 mK but at least one of the electrodes is still in the normal state. After discussion with colleagues at INRIM, we have concluded that this is due to the presence of a bi-layer Ti/Al as base electrode in the 2^{nd} generation chips, which strongly decreases its critical temperature. Such bilayer will be eliminated in next chips

Thanks for your attention