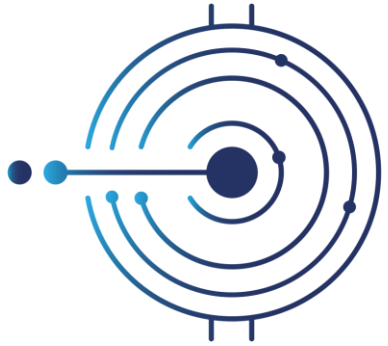

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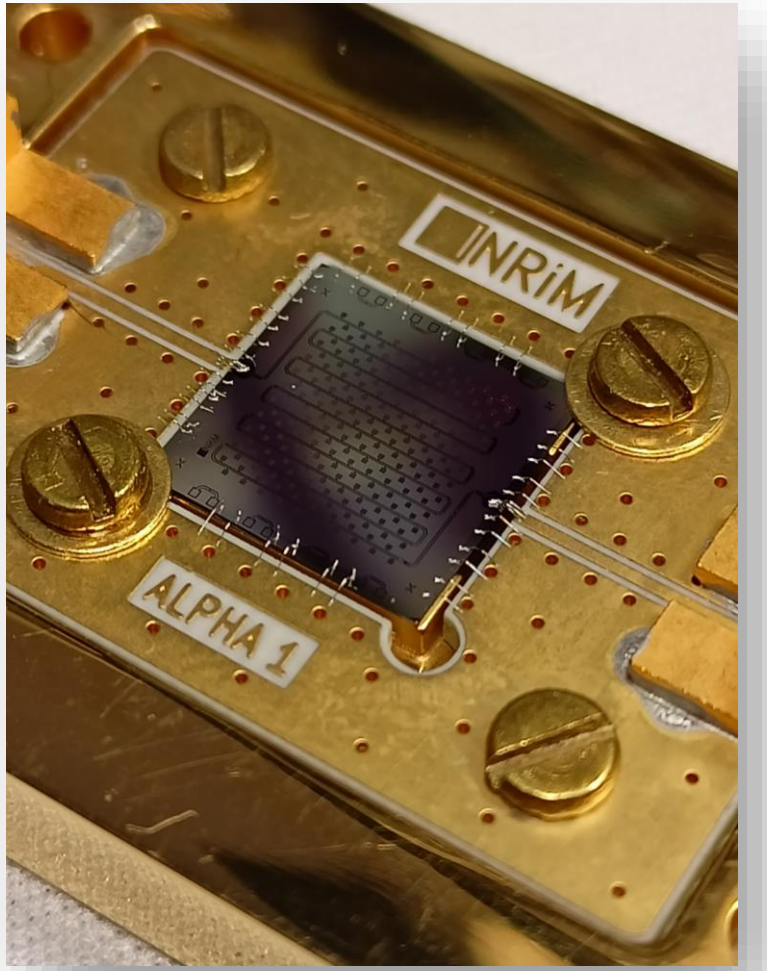
Experimental characterization of RF-SQUIDs based Josephson Traveling Wave Parametric Amplifier exploiting Resonant Phase Matching scheme

DARTWARS annual meeting – 6 Feb 2023

Emanuele ENRICO

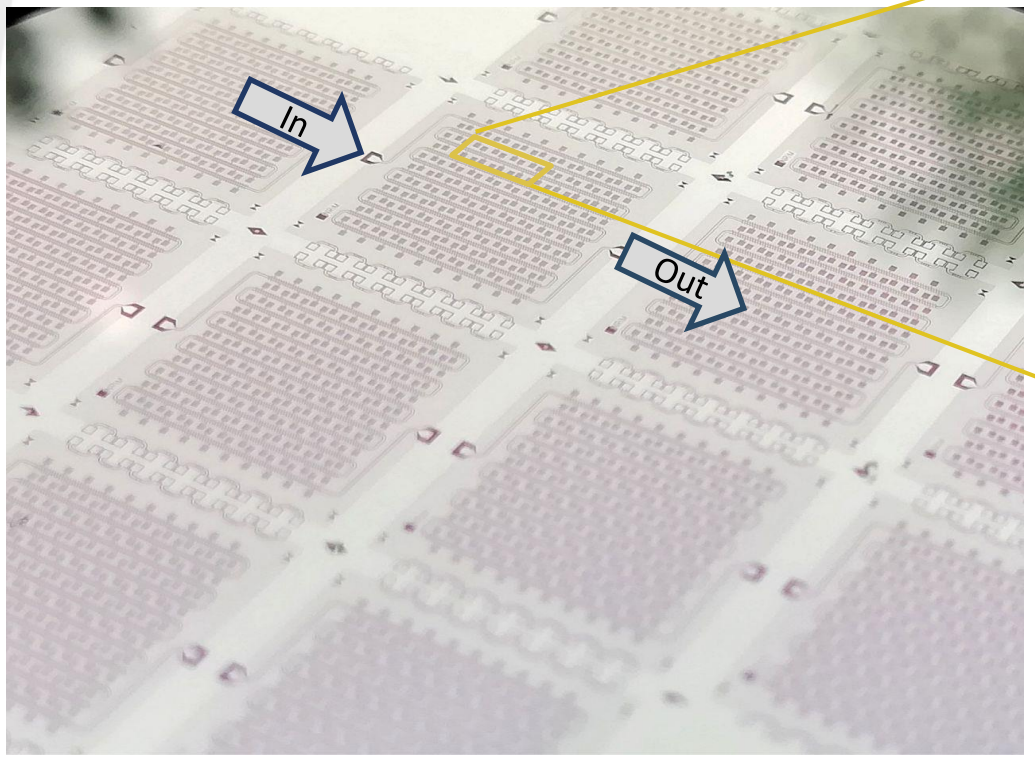
Introduction

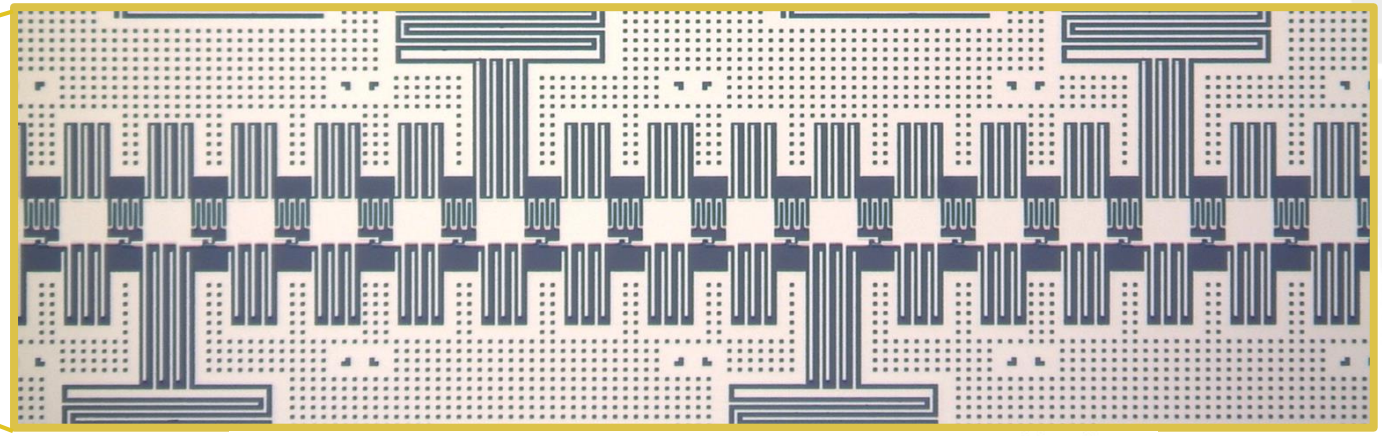
- JTWPA preliminary characterization **recap.**
- JTWPA based on Resonant Phase Matching (**RPM**) optimization and fabrication
- Preliminary **cryogenic characterization**

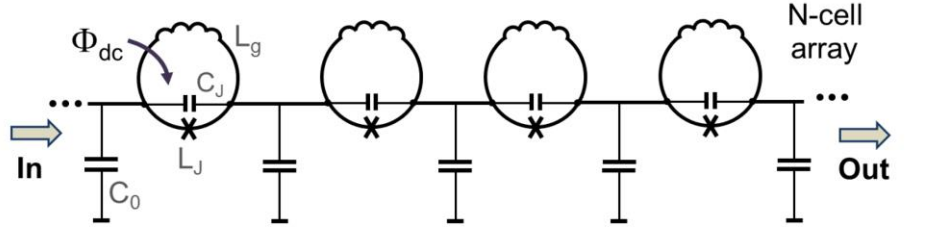


Nonlinear (meta) materials - µWaves

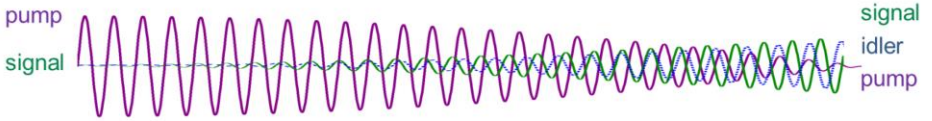
- Transmission line (eg. CPW or stripline) + **identical** meta-atom (with JJ nonlinearity)
- Effects of the interaction with the single cell are perturbative -> avoid abrupt changes that acts like point defects or scattering sites (crystal analogy)







Very small phase mismatch ⇒ almost exponential gain, $\sqrt{G} \propto e^{gN}$



S. Pagano et al., *Development of Quantum Limited Superconducting Amplifiers for Advanced Detection*, IEEE Trans. Appl. Supercond, **32**, 4 (2022)

Zorin, *Phys. Rev. Appl.* **6**, 034006 (2016)

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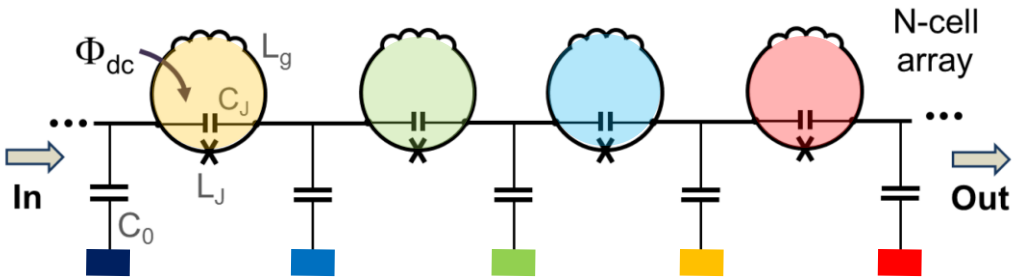
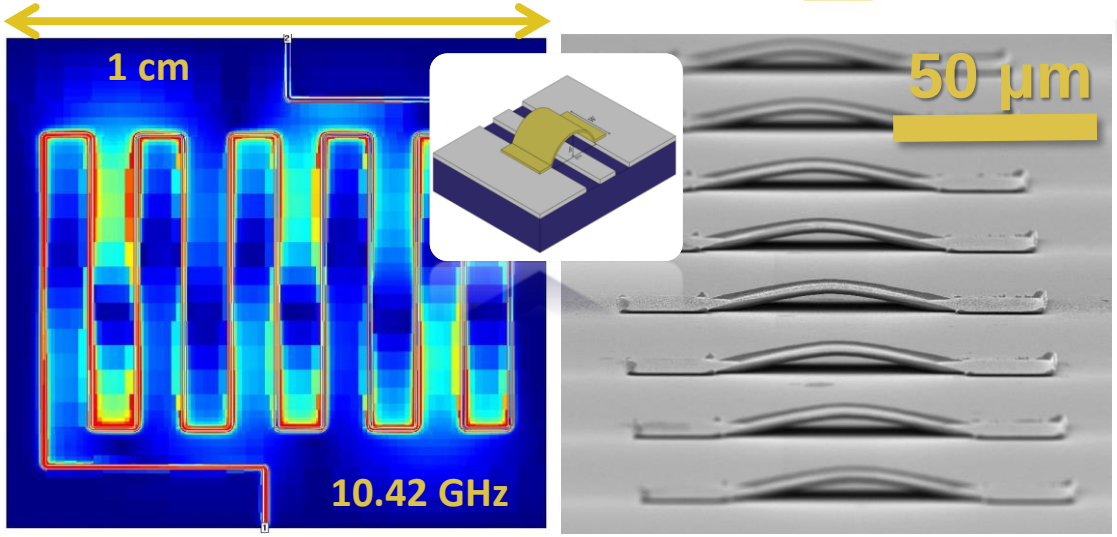
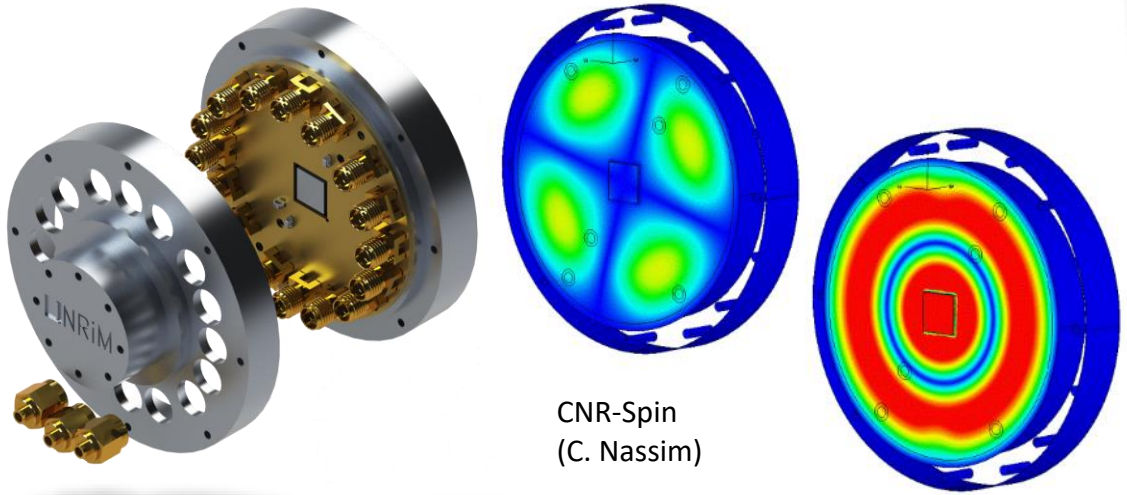
Transmission lines peculiarities

- Packed CPW/stripline
- Influenced by substrate/dielectrics choice
  materials losses (eg. TLS)
- Total size vs. chip size
  slotline modes -> Airbridges
- Chip and connectors size influence packaging
  cavity modes







CNR-Spin
(C. Nassim)

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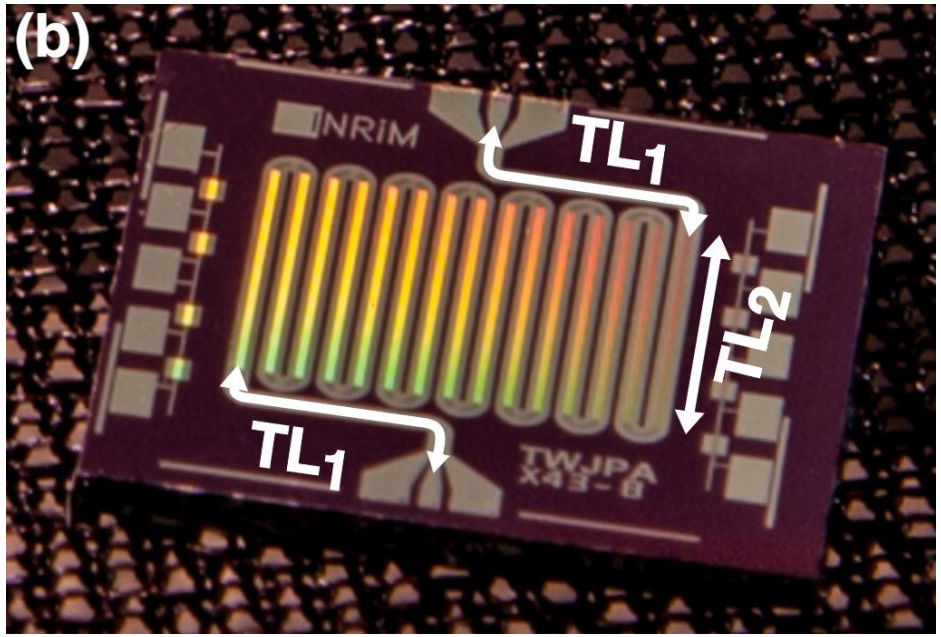
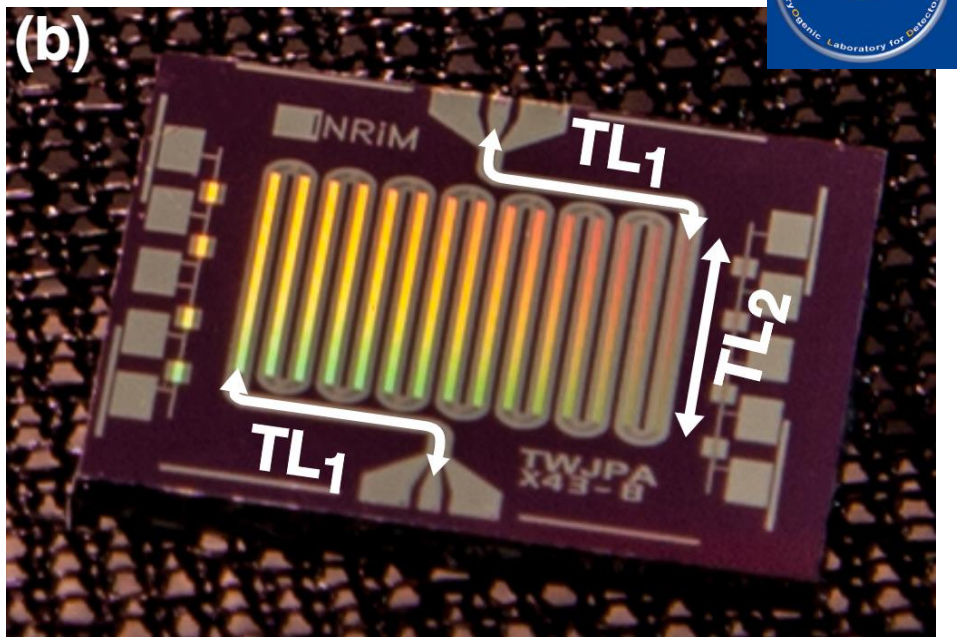
Preliminary characterization

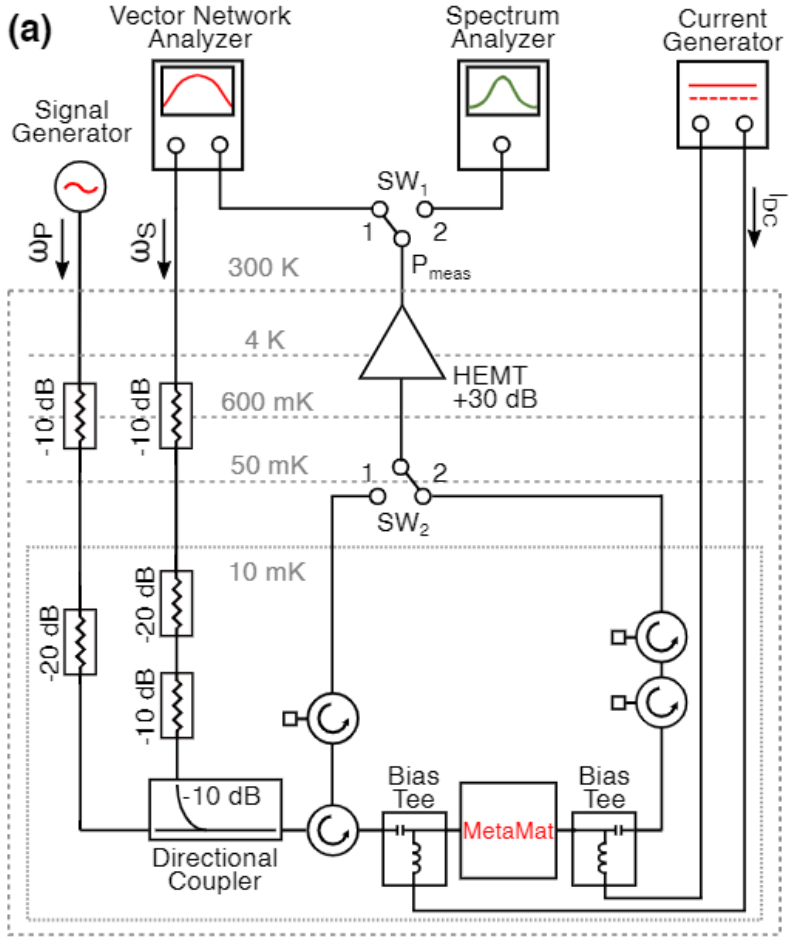


Preliminary samples

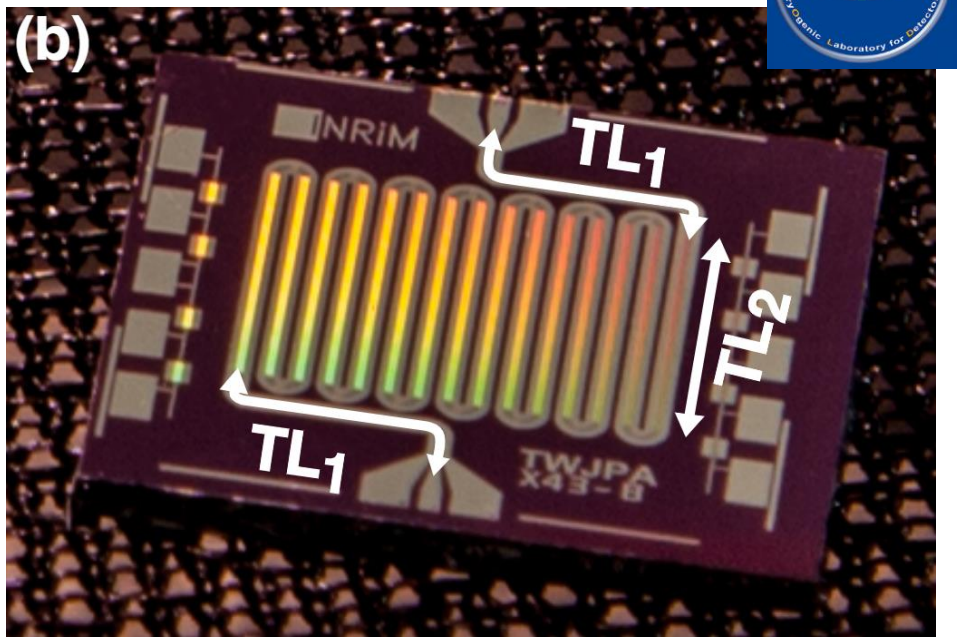
- Poor impedance matching of TL1, TL2 and 50 Ω
- No dispersion engineering
- High Josephson Junctions parameters spread
- No sloline modes rejection techniques

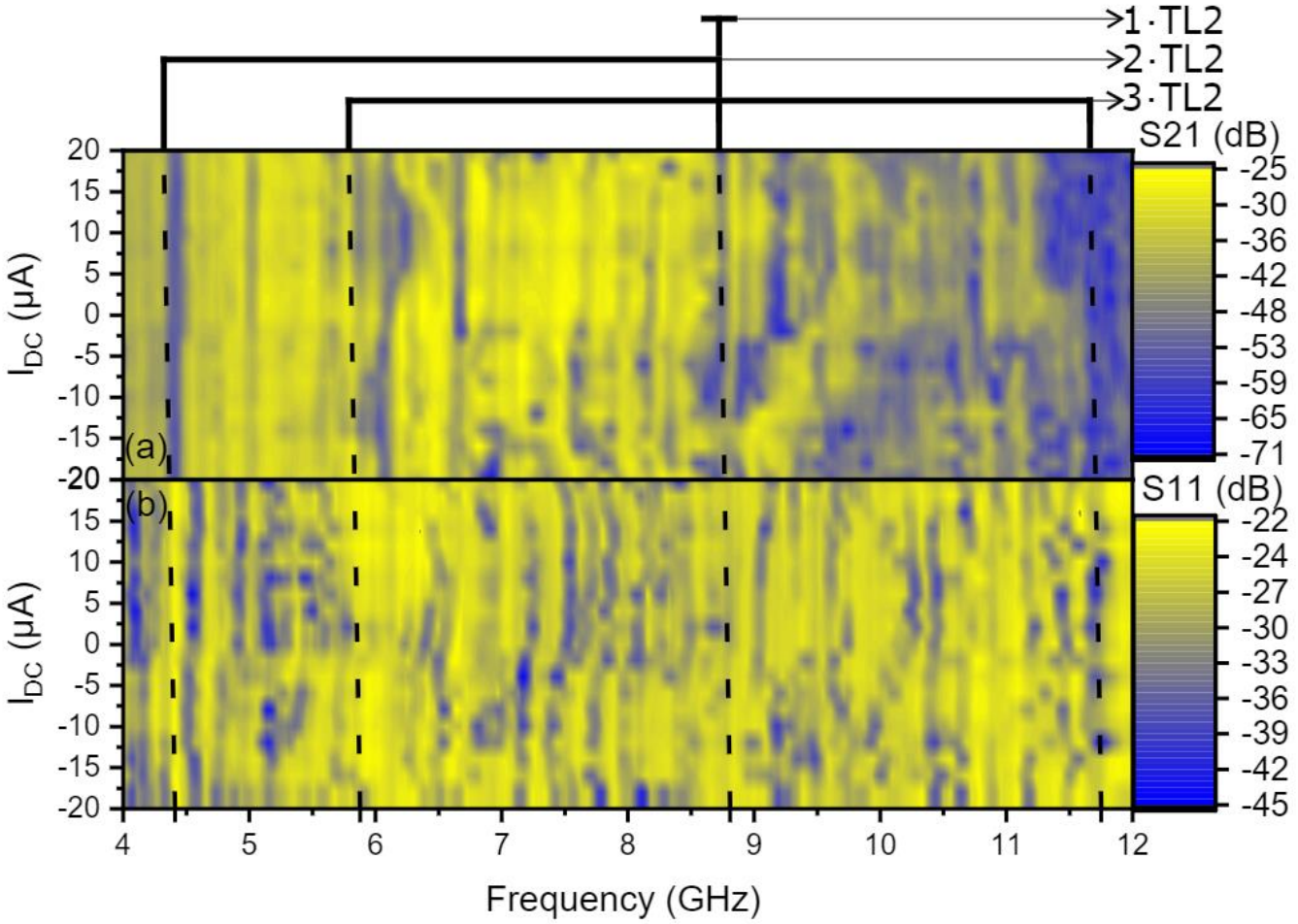
Preliminary characterization



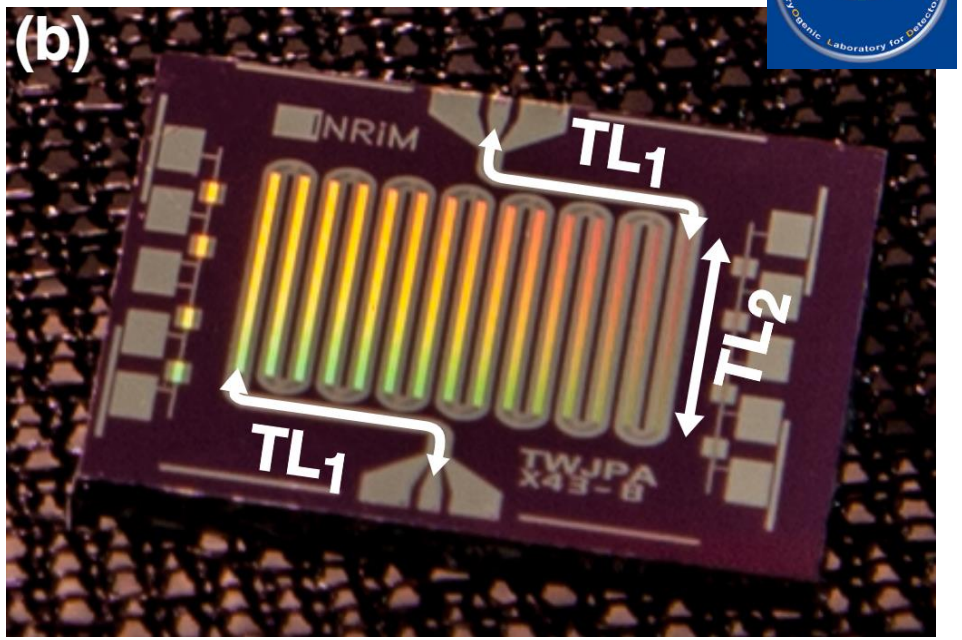


Preliminary characterization

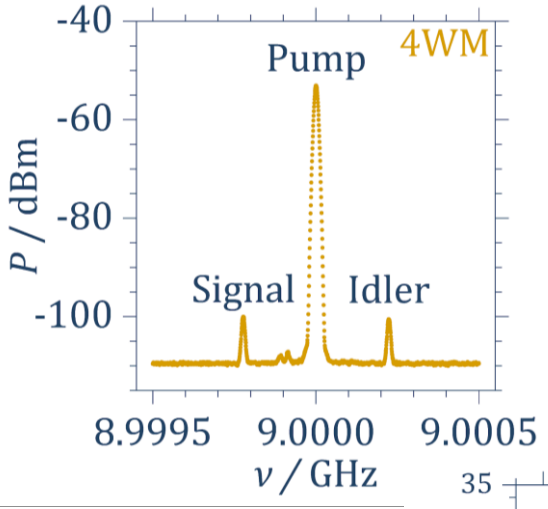


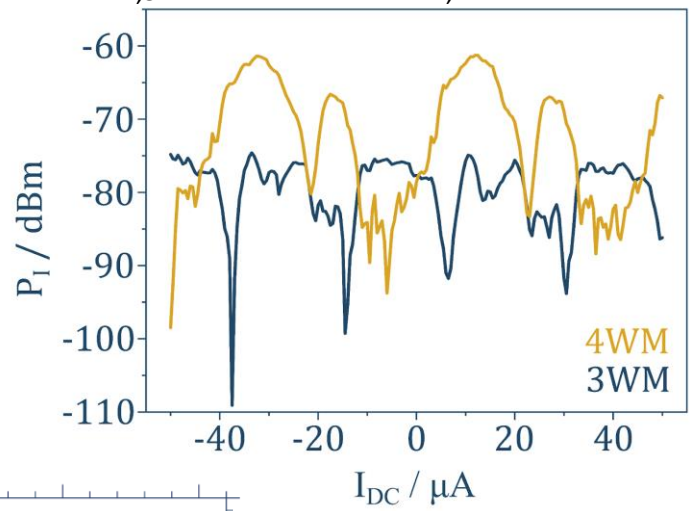


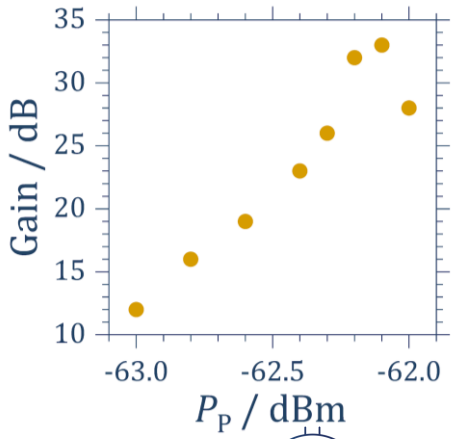
Preliminary characterization



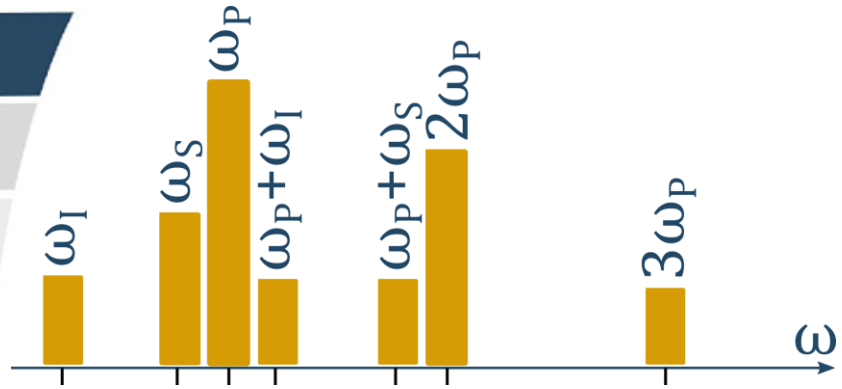
ν_p = 6.8 GHz
ν_s = 3.3 GHz
$\nu_{i,3WM}$ = 3.5 GHz $\nu_{i,4WM}$ = 10.3 GHz

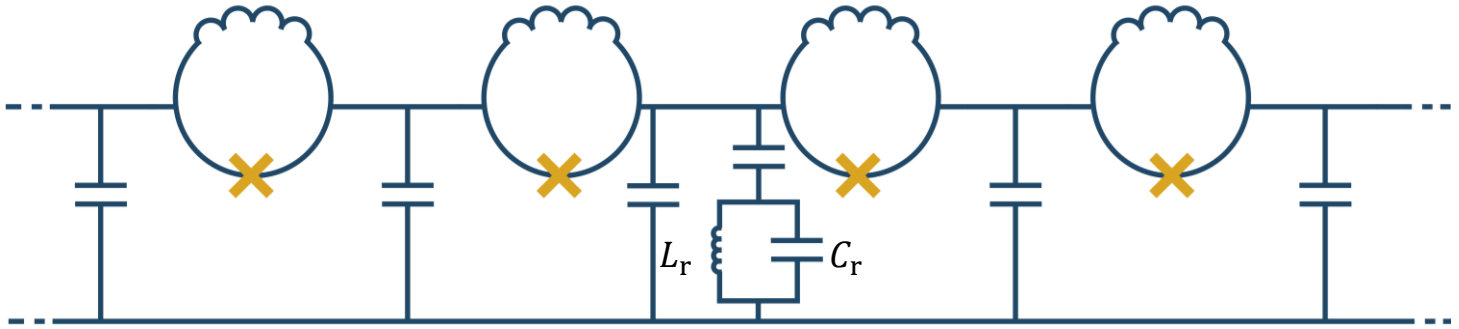




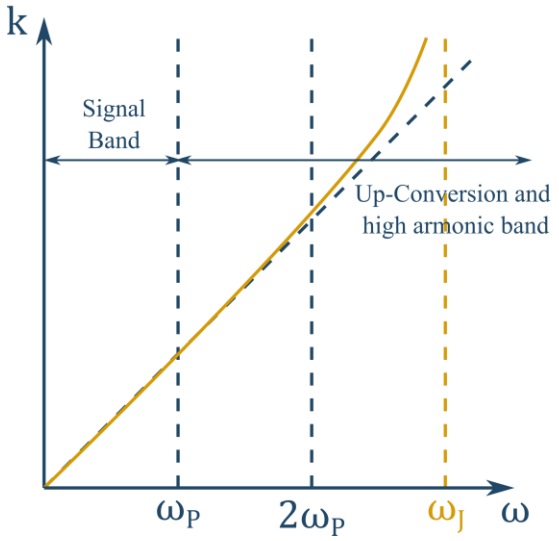


Resonant Phase Matching scheme

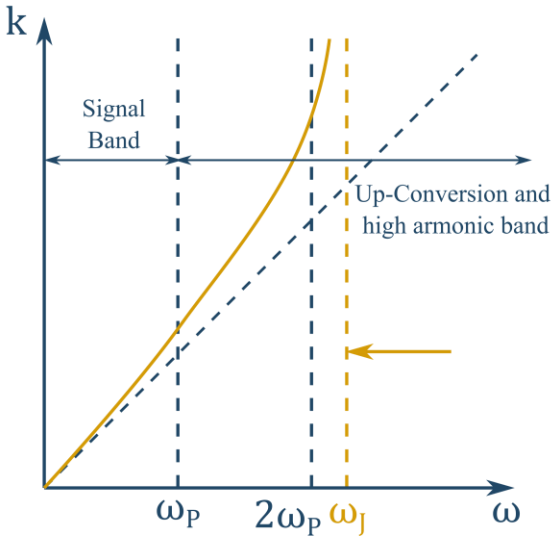




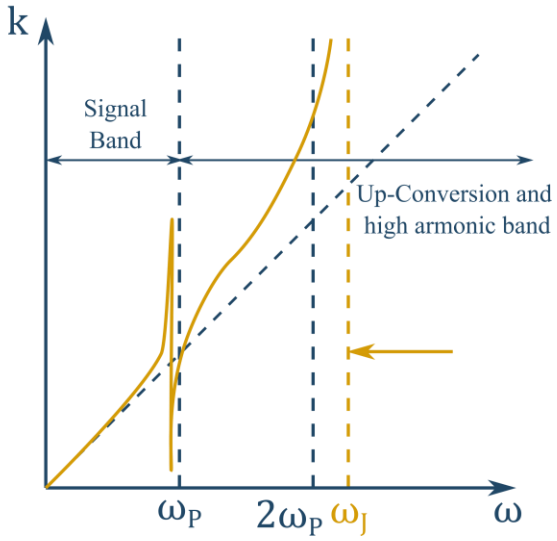
Without RPM



With lower plasma frequency



With RPM



$$\omega_J = \frac{1}{\sqrt{LC_J}}$$

O'Brien K., *et al*, "Resonant phase matching of Josephson Junction Traveling Wave Parametric Amplifiers", in *Phys. Rev. Lett.*, ***113*** (2014).

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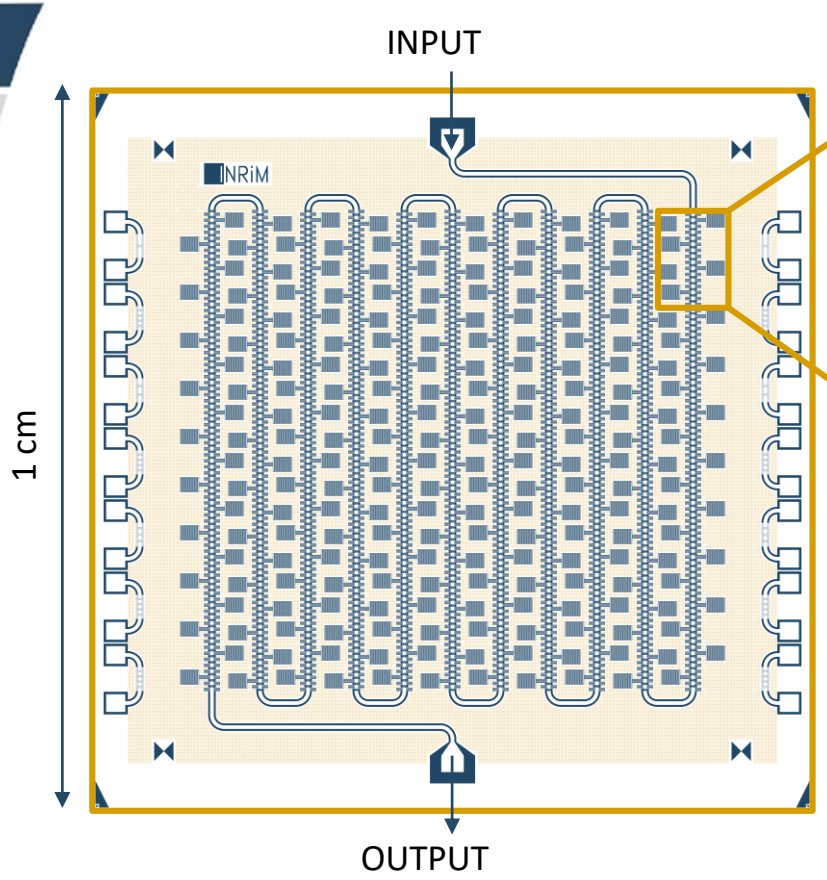
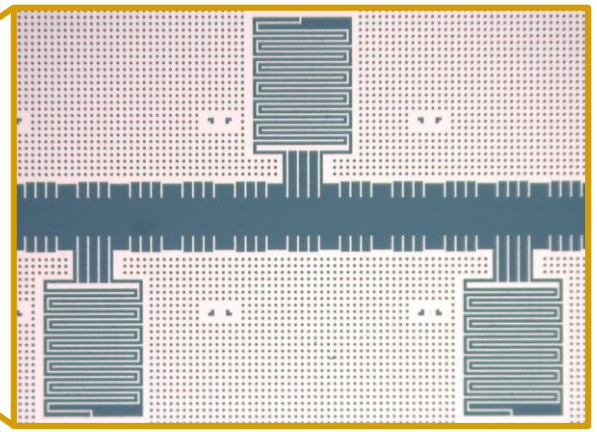
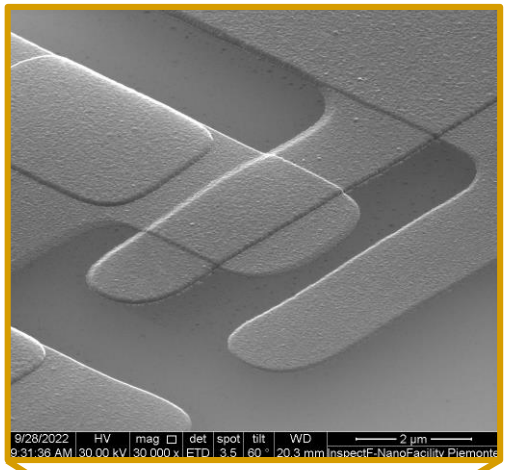
JTWPA – From Design to Fabrication



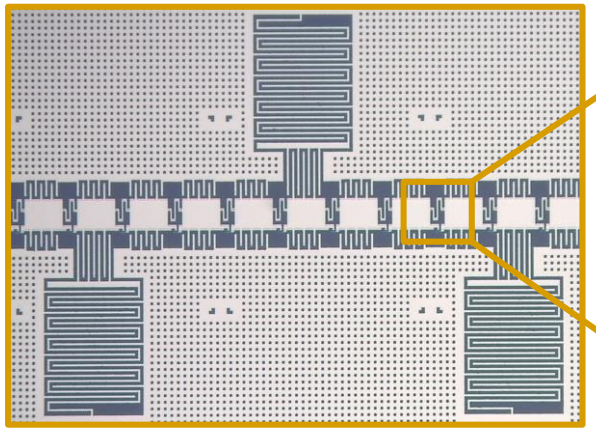
Coplanar transmission line (~7 cm) embedding
880 elementary cells

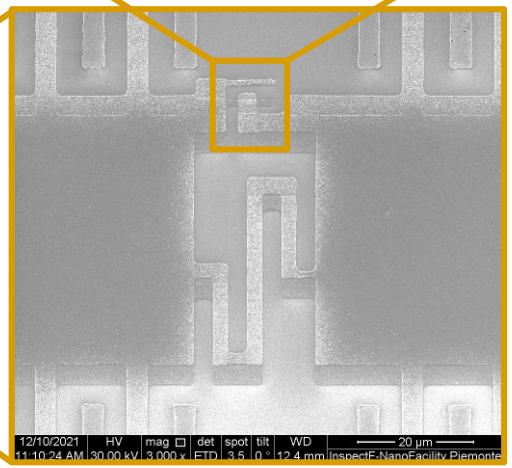
First UV Lithography





Second UV Lithography





Double Angle Evaporation

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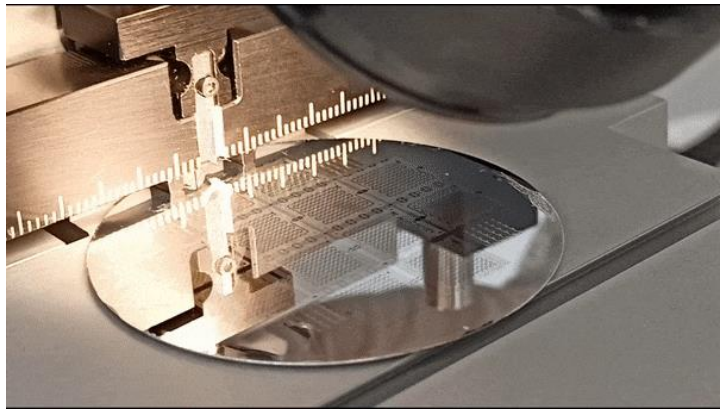
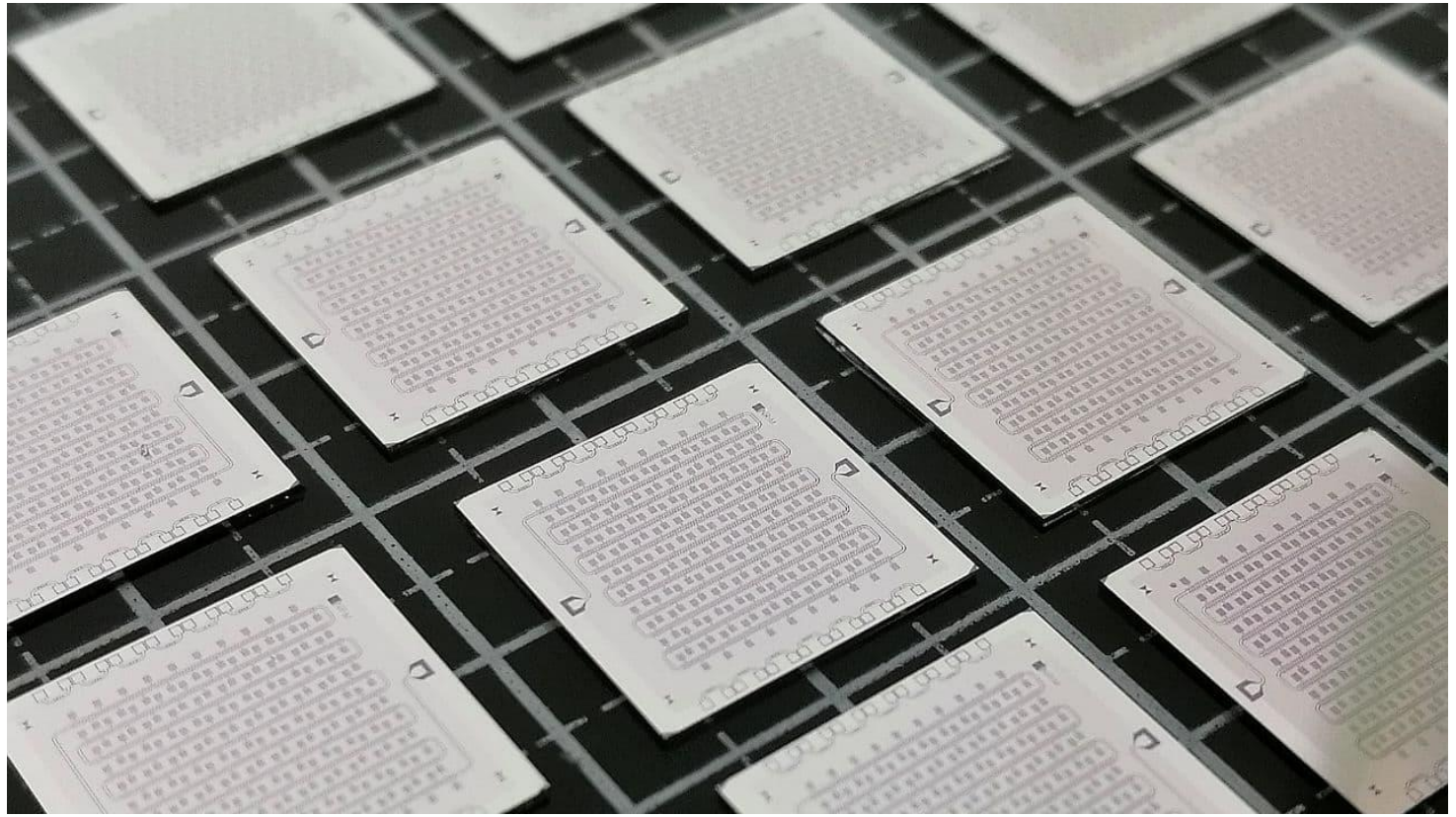
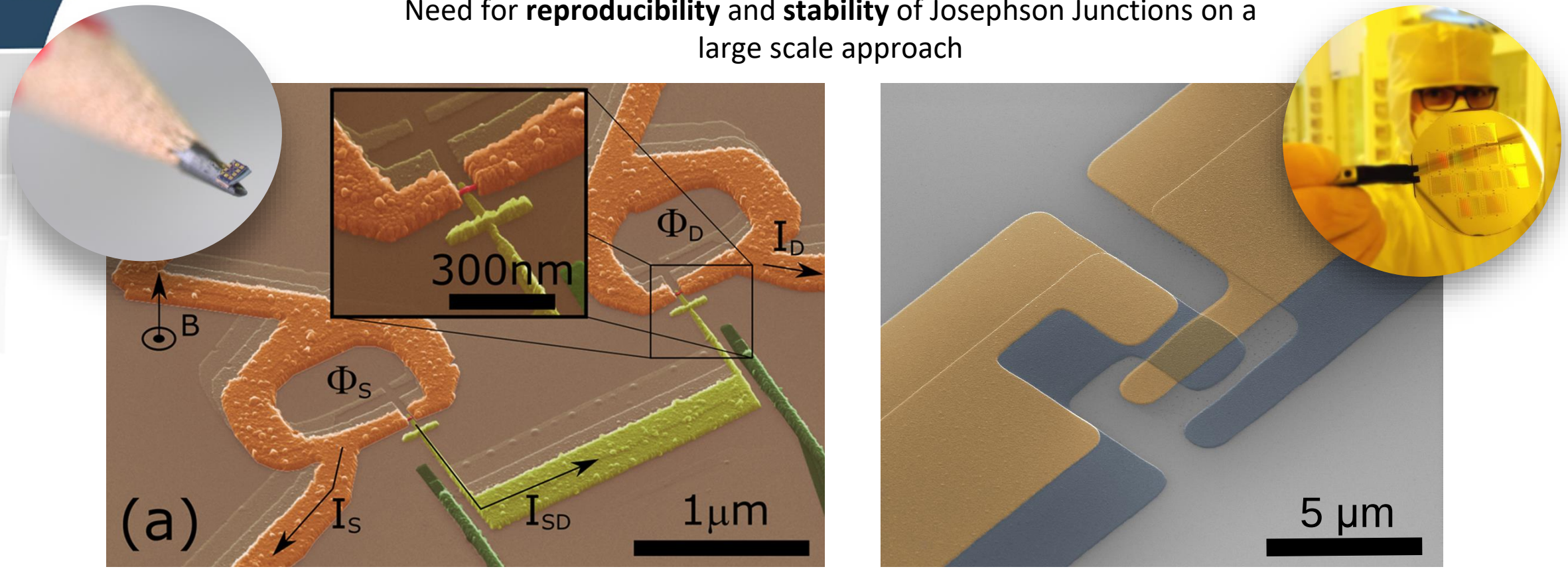
RPM-based JTWPA





Technological challange

Need for **reproducibility** and **stability** of Josephson Junctions on a large scale approach



E. Enrico, et al., *Single charge transport in a fully superconducting SQUISET locally tuned by self-inductance effects*, AIP Advances **12**, 055122 (2022)

UV shadow lithography based Josephson Junction

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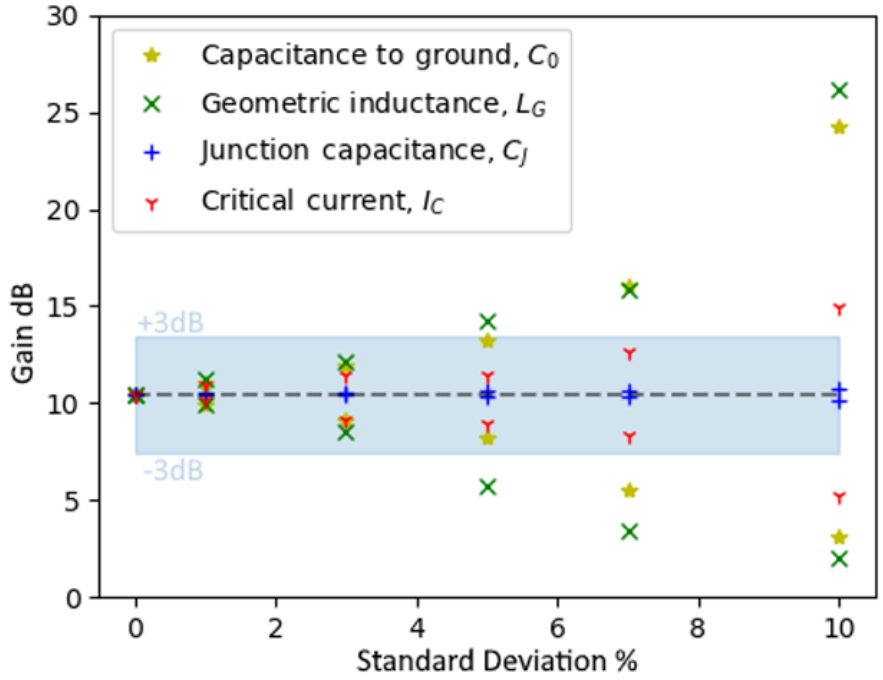
The role of Josephson Junction parameters spread

- Josephson Junction **spread** of parameters deeply affect the amplifiers performances (eg. Gain)
- Due to the exponential dependence of its properties, Josephson tunnel junctions are the **bottleneck** of the whole JTWPAs operation

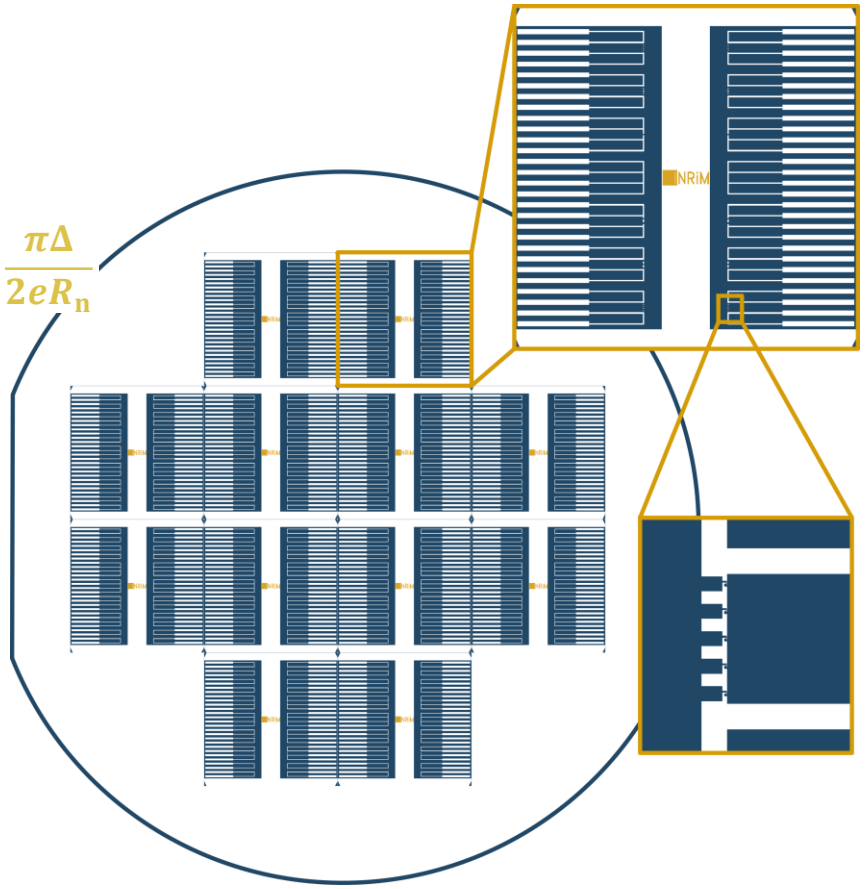


The Effect of Parameter Variations on the Performance of the Josephson Travelling Wave Parametric Amplifiers, https://arxiv.org/abs/2112.07766

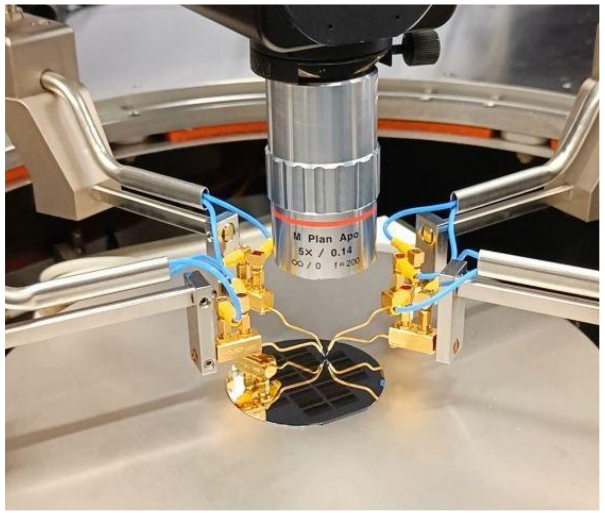
Josephson junction testing

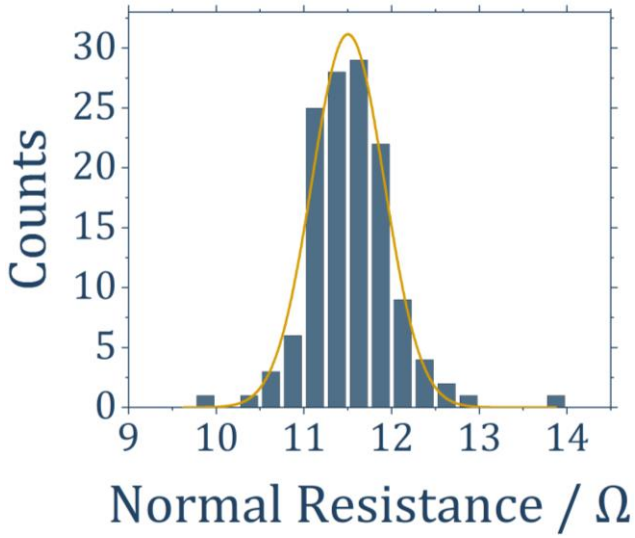
Test on a 2” wafer scale of JJs **normal resistance spread** by means of a 4-terminal measurement with a semi-automatic probe.

$$I_C = \frac{\pi \Delta}{2eR_n}$$



Each wafer contains 480 JJs organized in 144 series of different length (1-5)



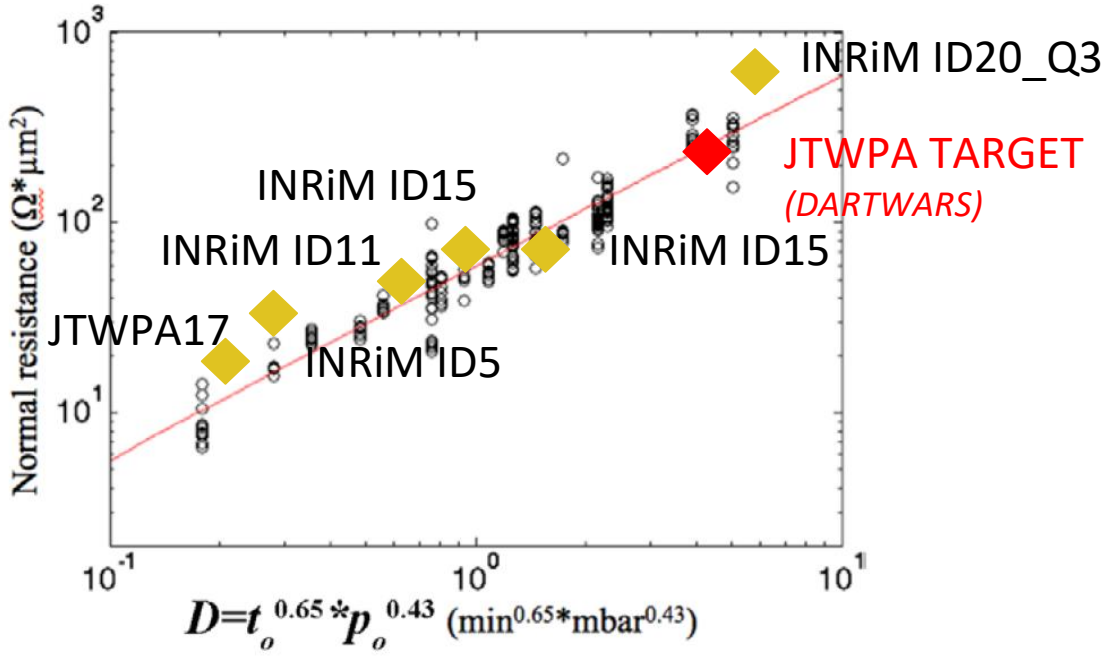


After several improvement of the fabrication protocol, we obtain a relative standard deviation

$\sigma_{rel} \sim 3.6\ \%$

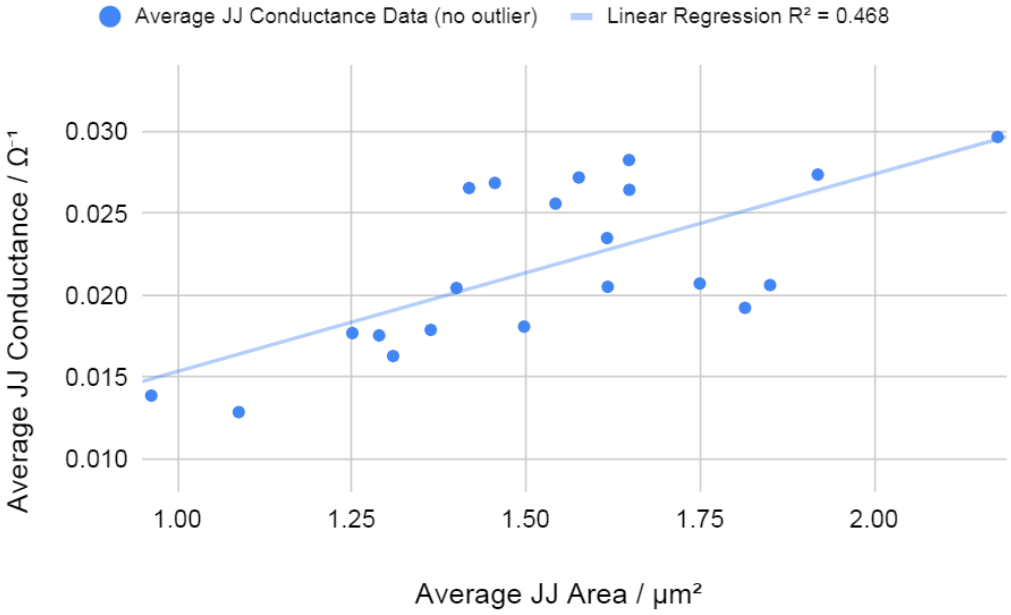
Josephson Junctions - area/oxidation interplay

Calibration points following the model presented in
L J Zeng *et al* 2015 *J. Phys. D: Appl. Phys.* **48** 395308)



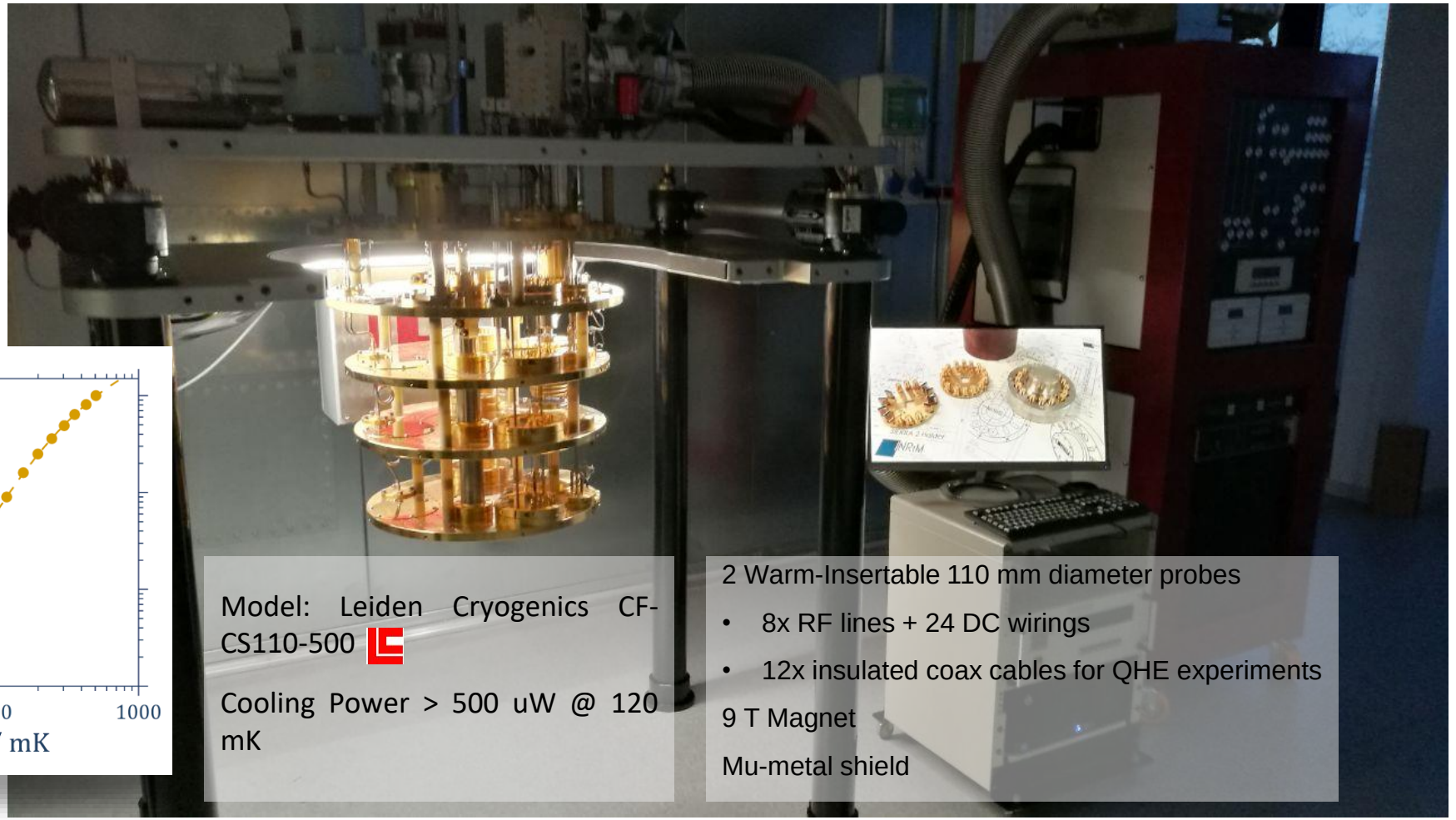
Run to run predictability and repeatability

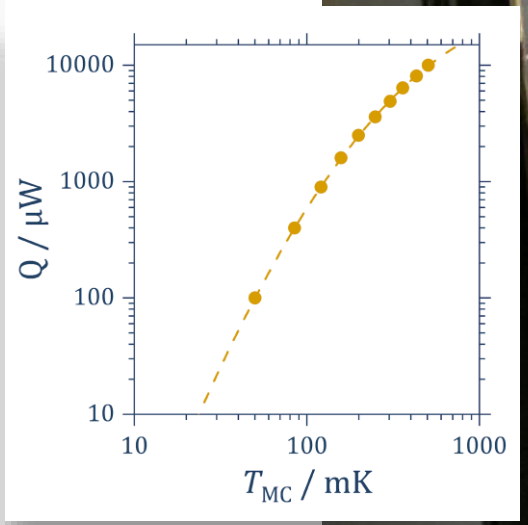
INRiM ID15 - Area vs. Conductance correlation



On-Wafer reproducibility and homogeneity

Quantum Signals Processing Lab.





Model: Leiden Cryogenics CF-CS110-500

Cooling Power > 500 uW @ 120 mK

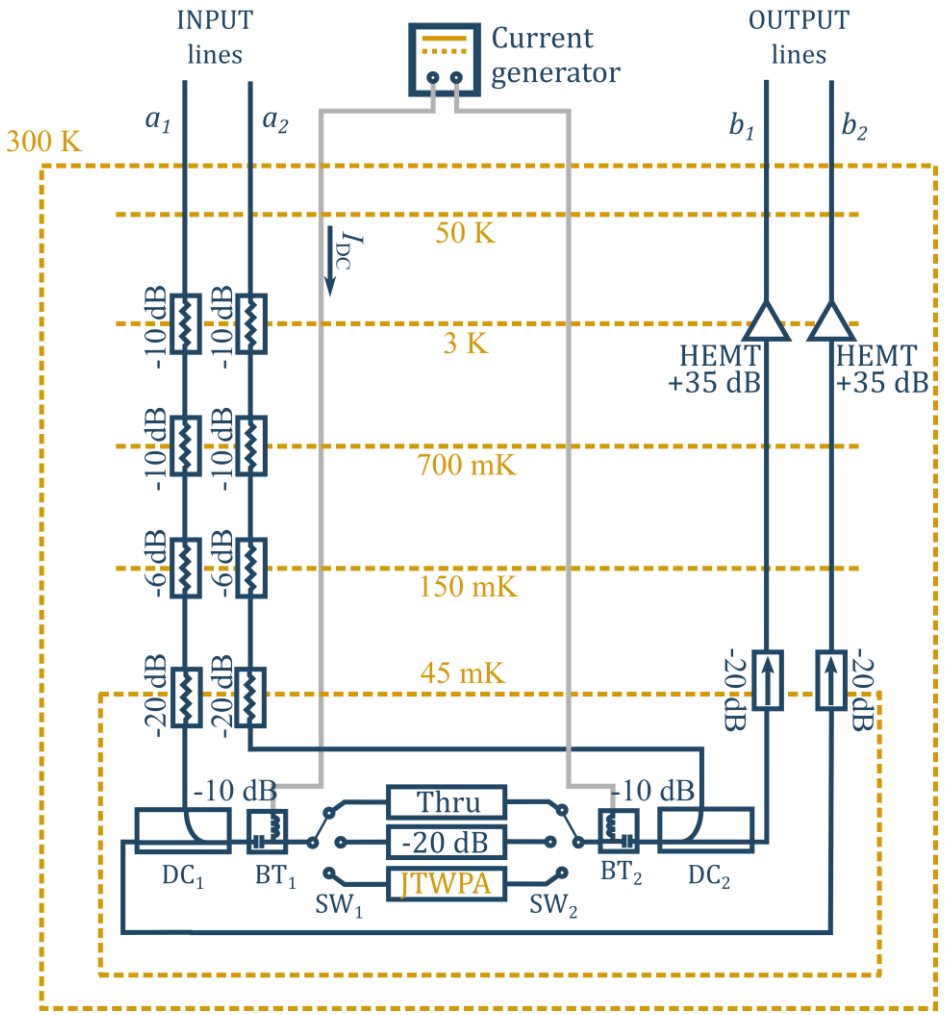
2 Warm-Insertable 110 mm diameter probes

- 8x RF lines + 24 DC wirings
- 12x insulated coax cables for QHE experiments

9 T Magnet

Mu-metal shield

Cryogenic probe for TRL calibration



Two-ports microwave **S-parameters calibration** scheme at cryogenic temperature

Uncertainty budget contributions:

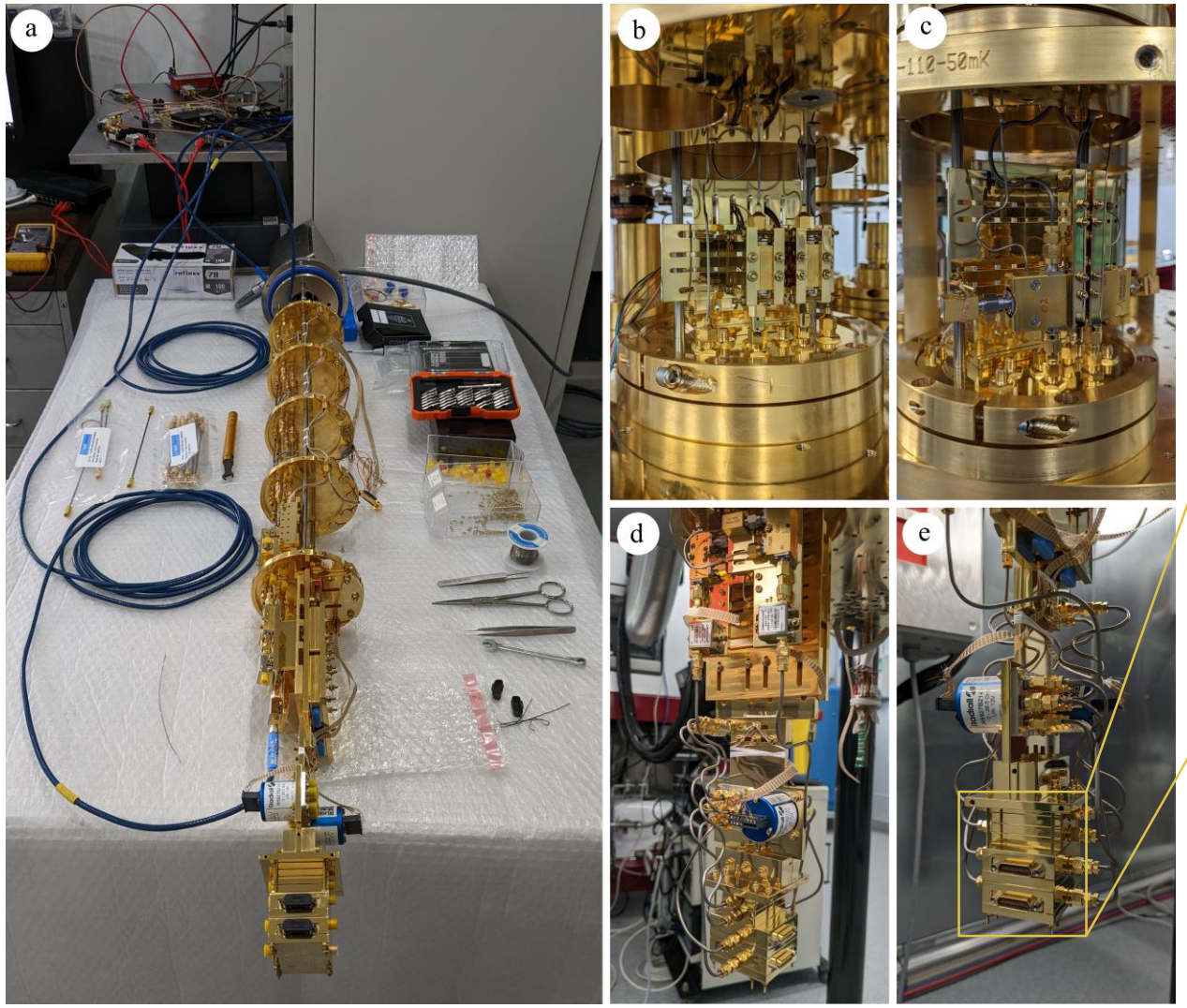
- Reproducibility
- Stability
- Standards

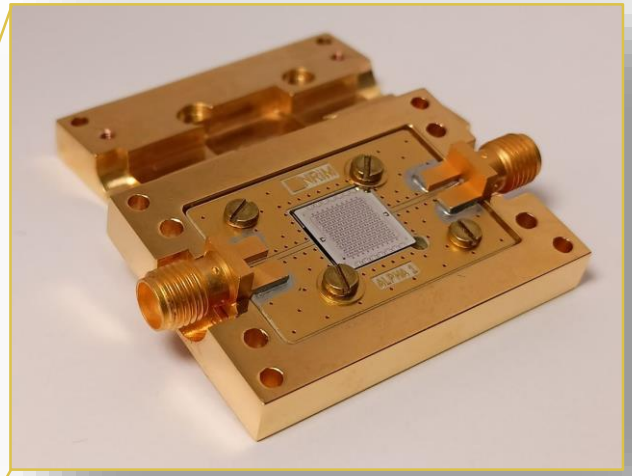
Microwave metrology for superconducting quantum circuits (20FUN07 SuperQuant)

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

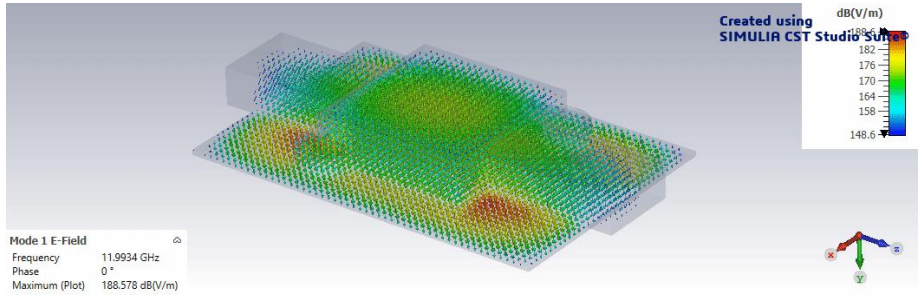
Ranzani L., Spietz L., Popovic Z., *and* Aumentado J., "Two-port microwave calibration at millikelvin temperatures", *Review of Scientific Instruments* **84**, 034704 (2013)

Cryogenic probe for TRL calibration

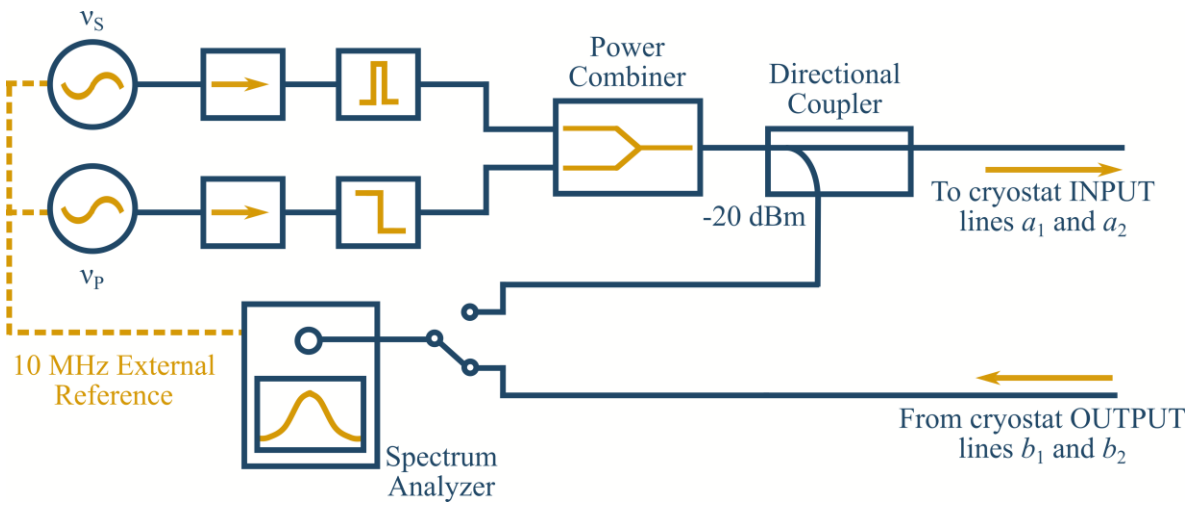


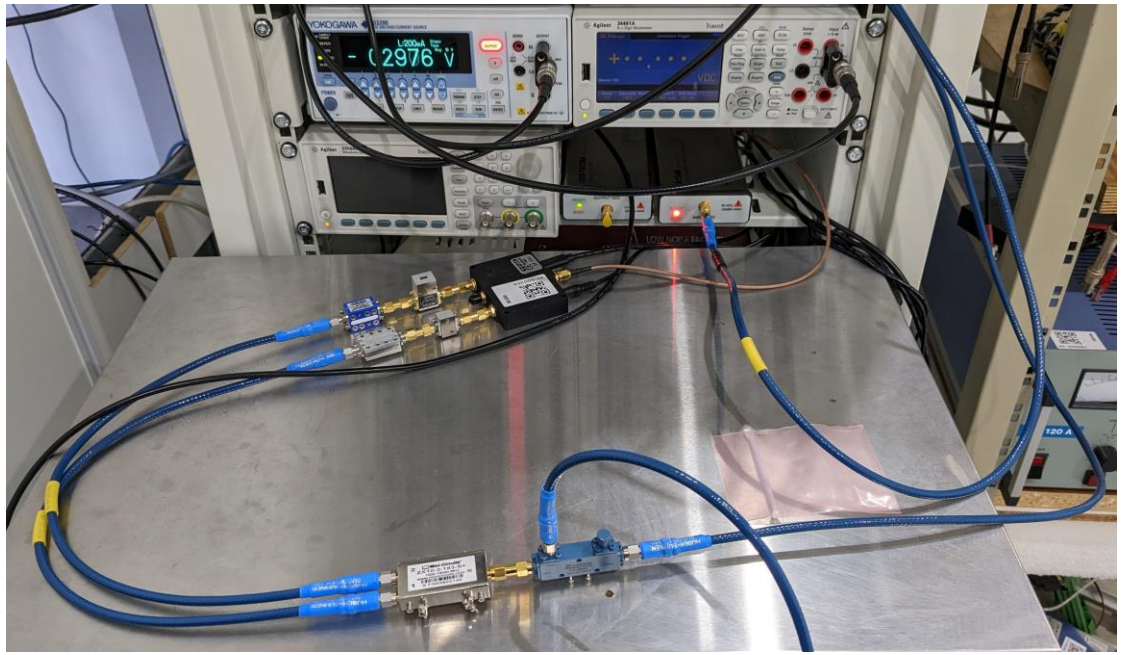


A new two-port sample holder with lowest resonant cavity mode at 12 GHz



Room Temperature Setup





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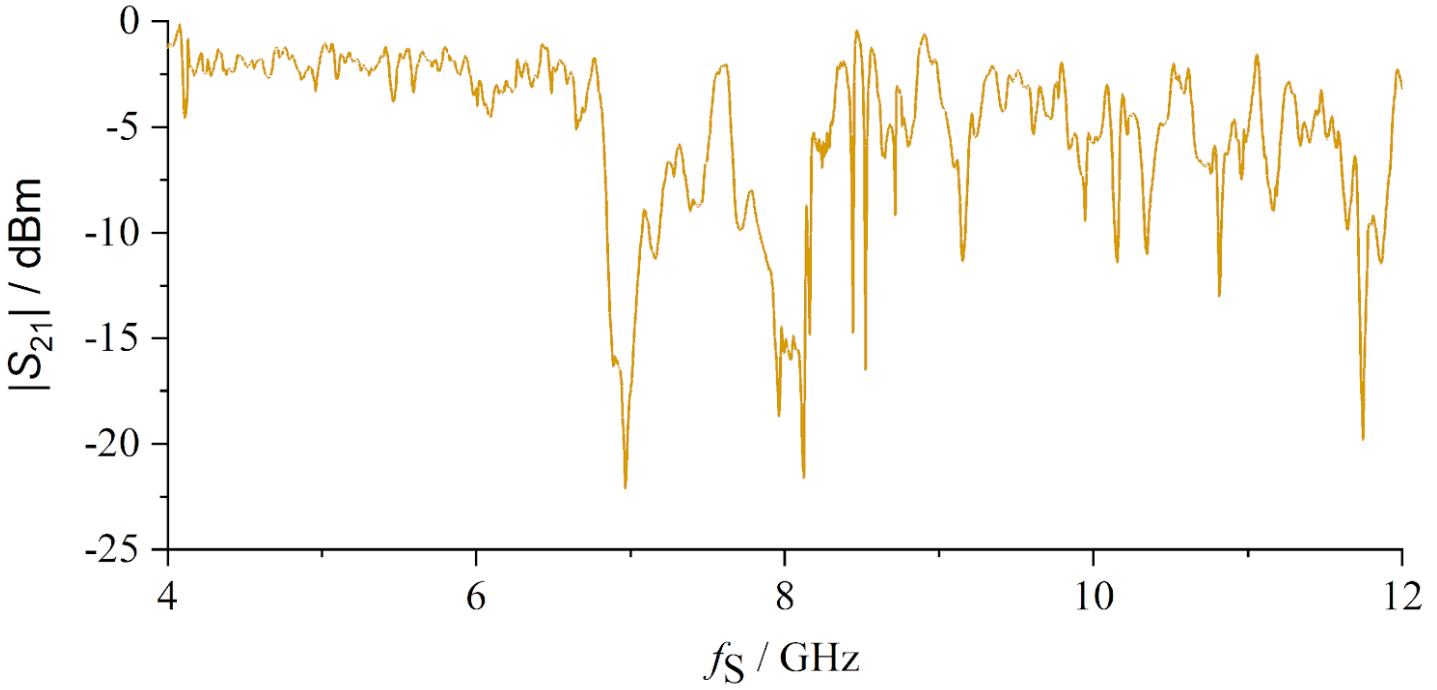
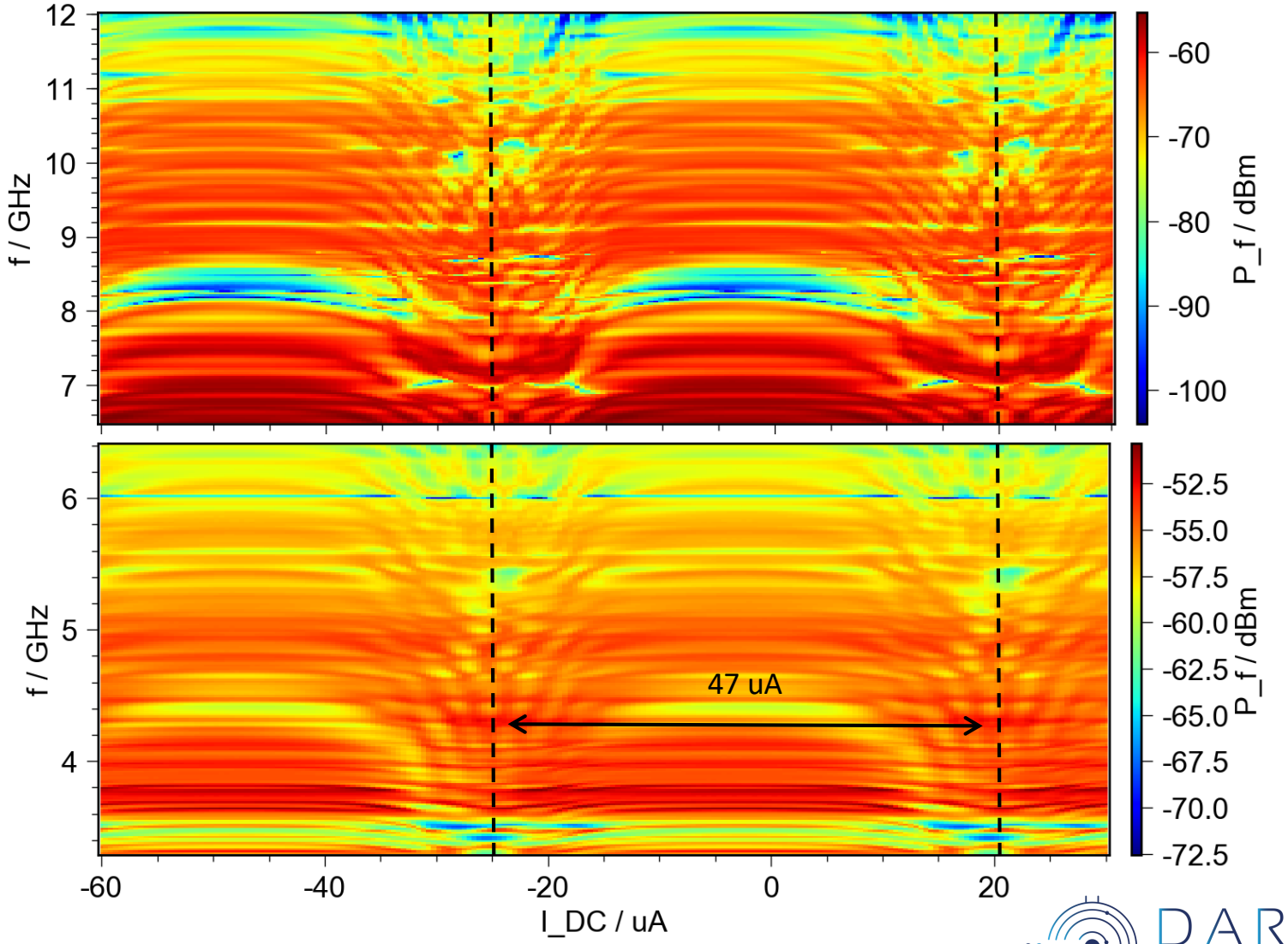
Single tone spectroscopy

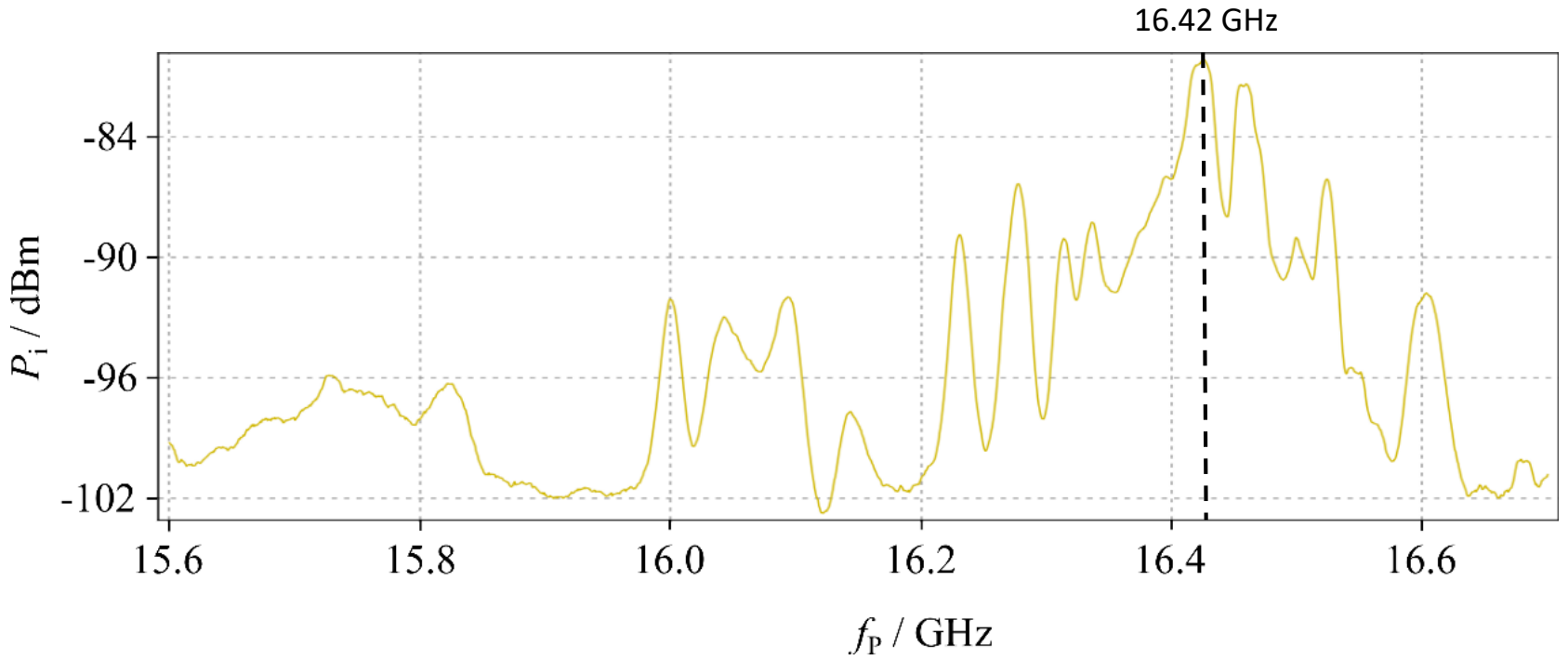


Single tone spectroscopy *vs* I_{DC}



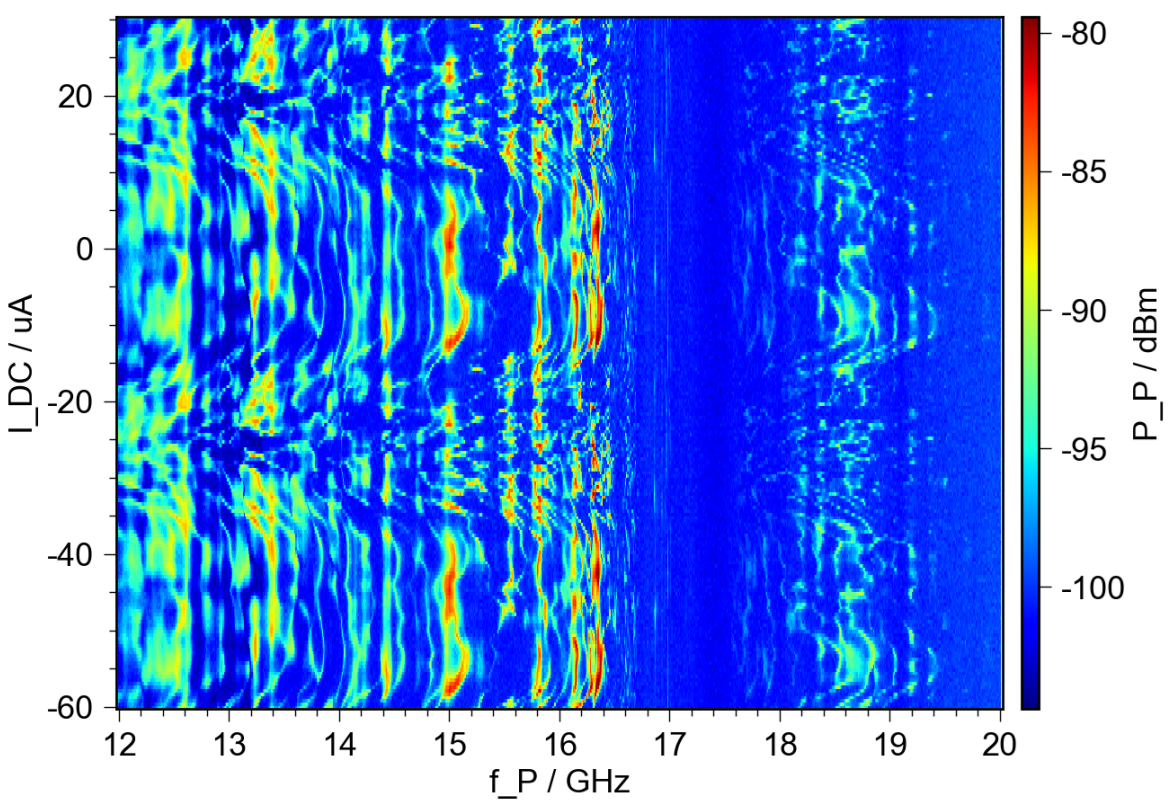
Pump spectroscopy *vs* I_{DC}

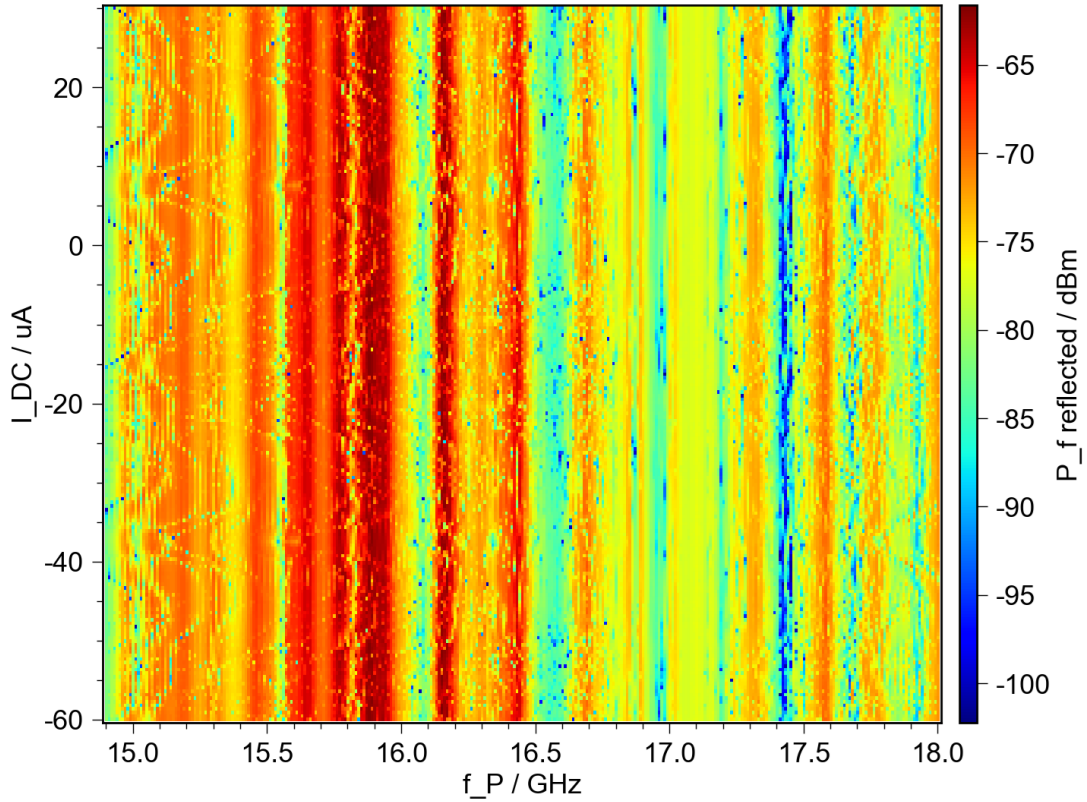
fixed f_P =7.5 GHz



Pump spectroscopy *vs* I_{DC}

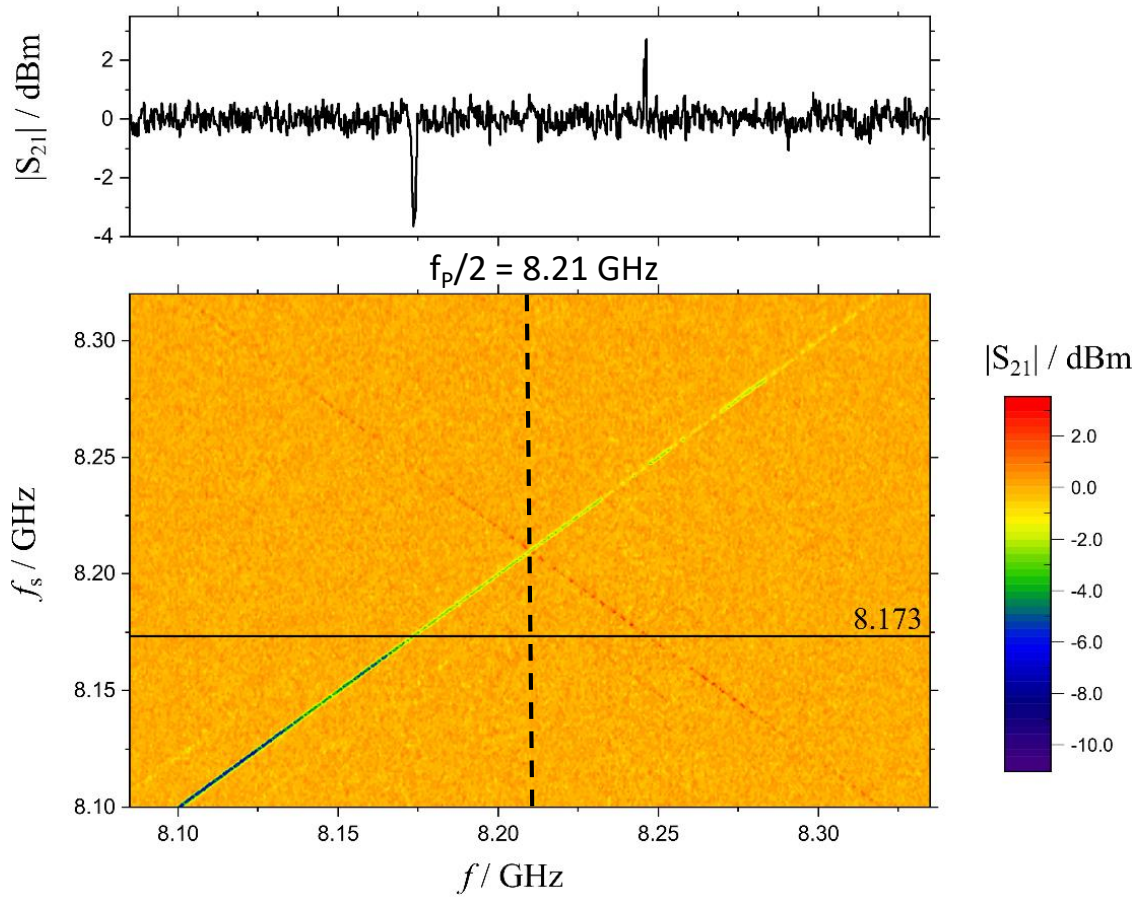
fixed f_P =7.5 GHz





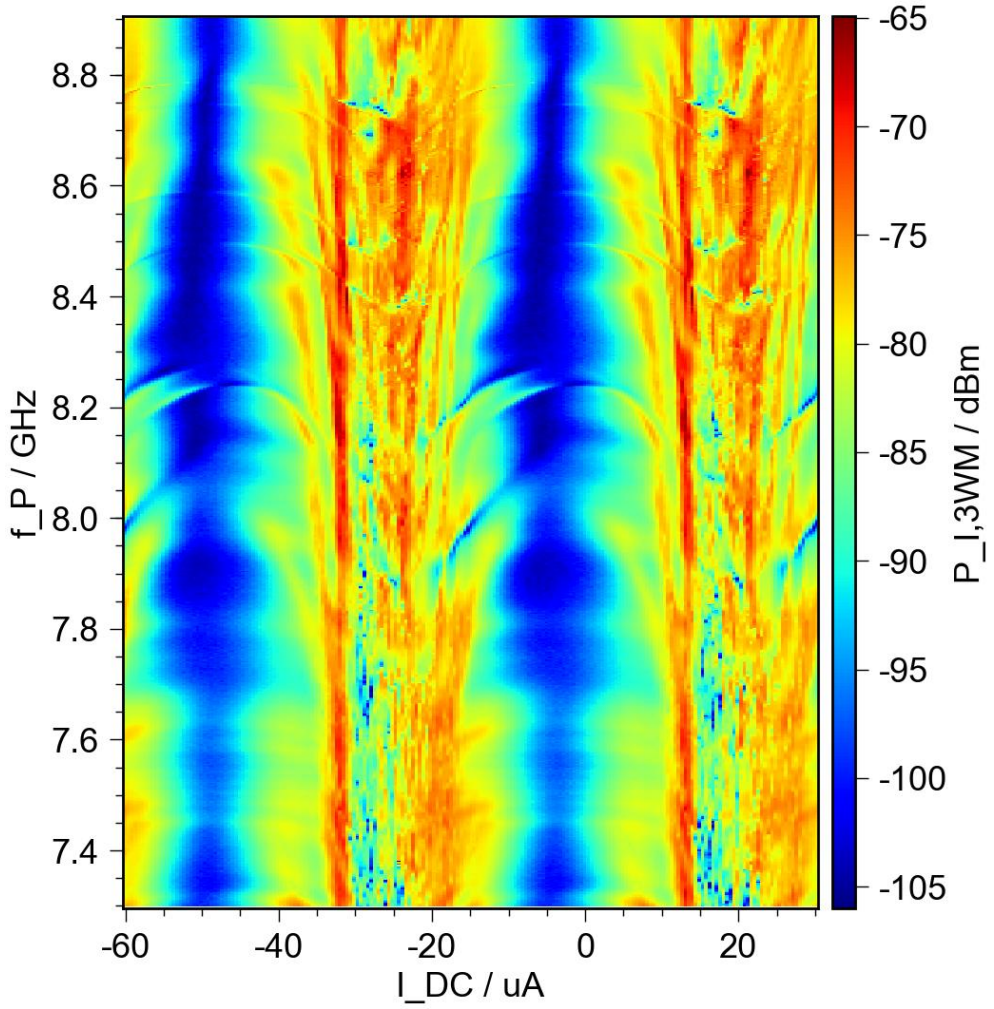
S/I frequency correlation

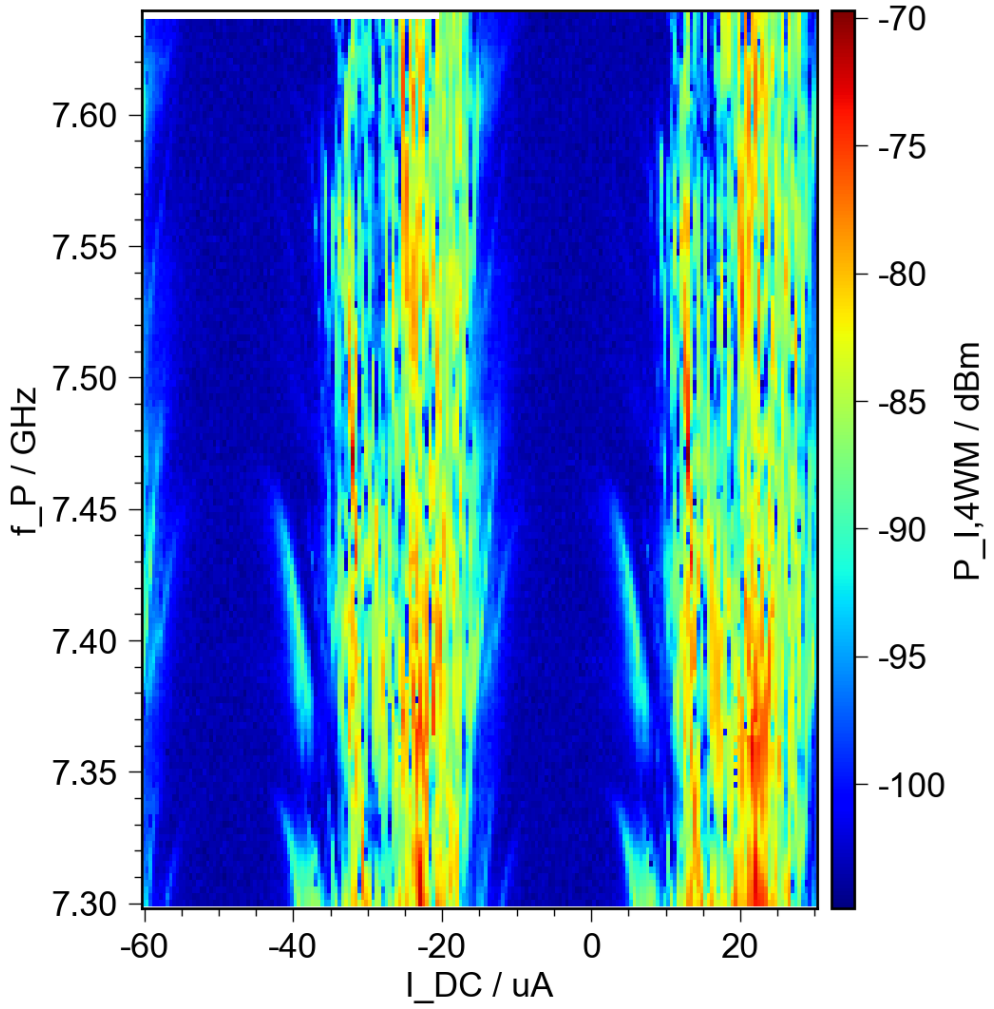
fixed f_P =16.42 GHz



3WM and 4WM idlers *vs* I_{DC}

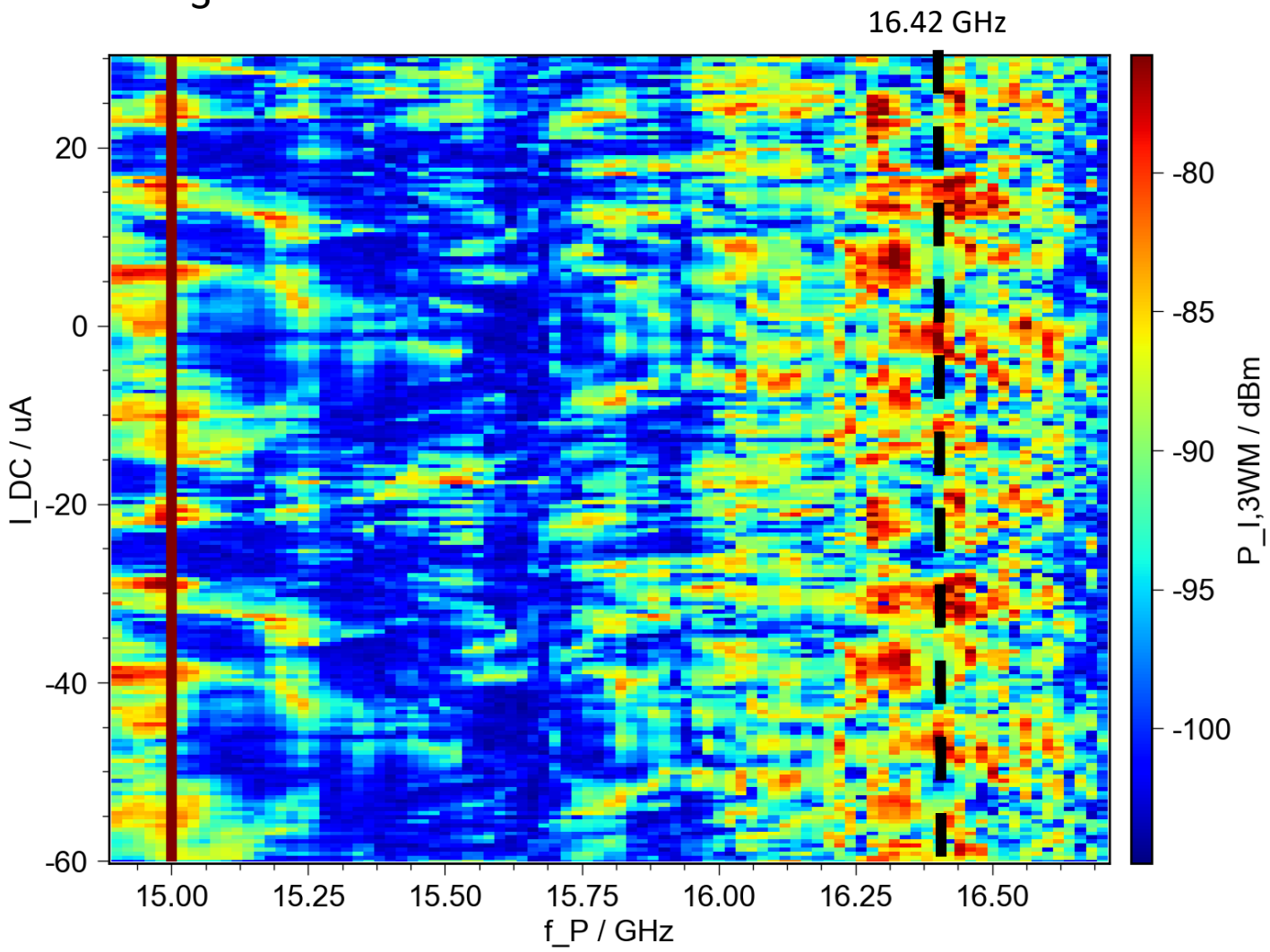
fixed f_S = 3.5 GHz

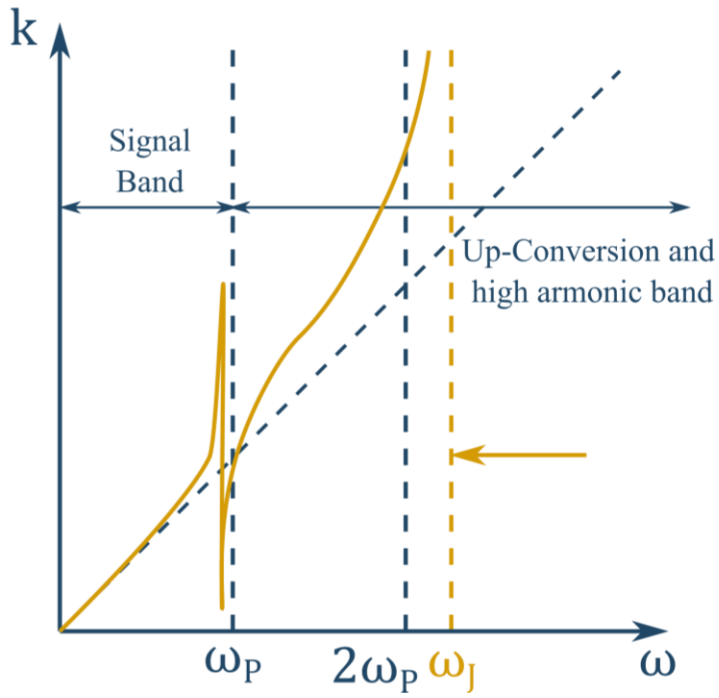




3WM idler *vs* f_P and I_{DC}

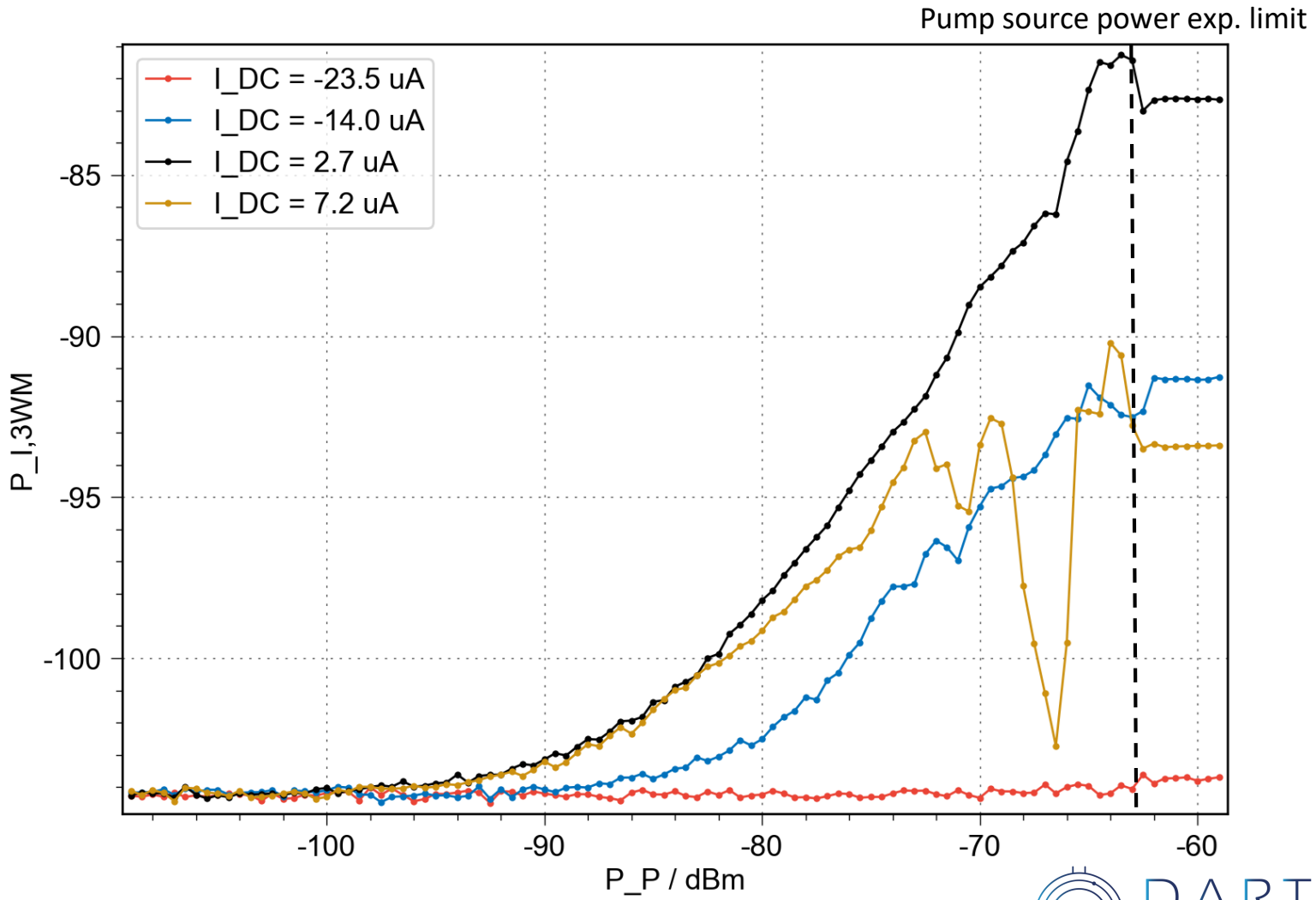
fixed f_S = 7.5 GHz





3WM idler *vs* P_P

no signal gain observed due to limited exp. conditions



Conclusions and Perspectives

- Future cryo. measurement will quantify **bandwidth** and **signal gain**
- **JTWPA** based on RPM (X-band) fabricated and **tested**
- More statistics should guarantee a better understanding of the responsible for **transmission ripples**
- JTWPA devices ready **to be shipped**
- Cryo. setup continuously improving from measurement feedback

Thanks for your attention