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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI
National Quantum Science and Technology Institute

Towards broadband quantum-limited **superconducting parametric amplifiers** for qubit read-out

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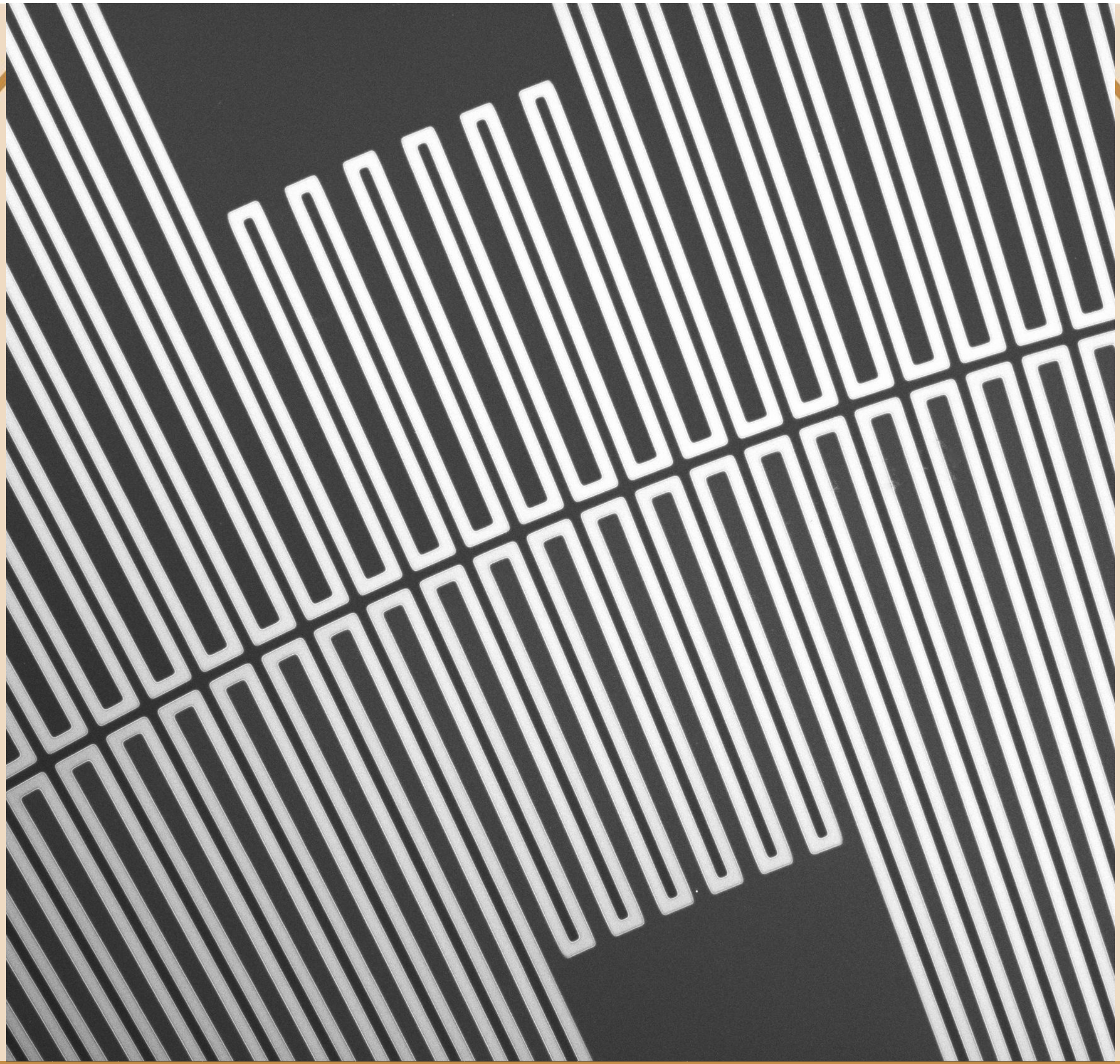
FBK SENSORS AND DEVICES
FONDAZIONE BRUNO KESSLER



First NQSTI Congress, 15-16 January 2024, Rome

A joint effort towards Qubit Integration

Superconducting electronic components → *Integration* → Qubit ● / Amplification stages ● — Read-out & control ●

Talk by Felix Ahrens (FBK)

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Talk by Andrea Giachero (UniMiB) and Simone Tocci (INFN LNF)

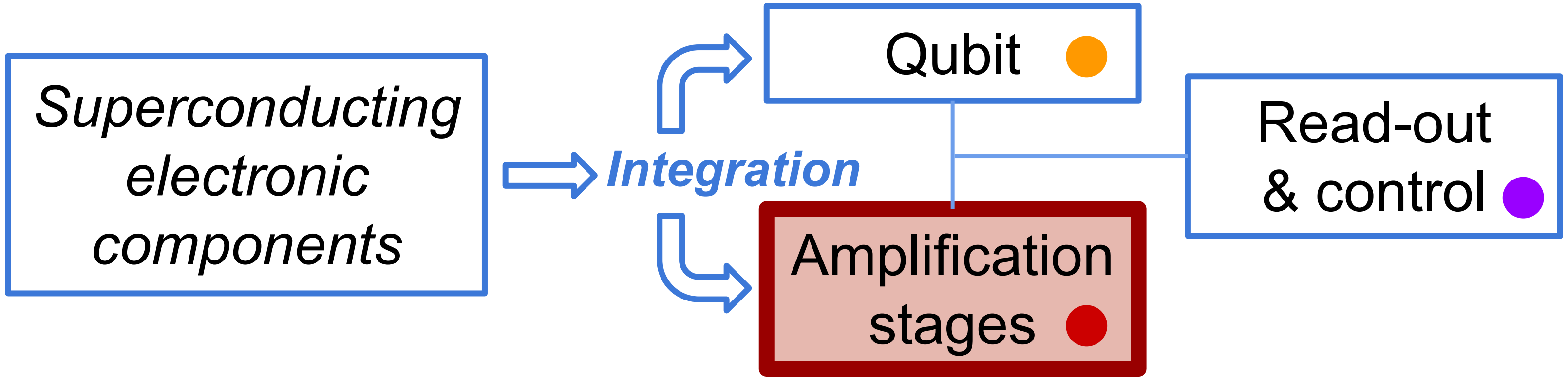
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA   INFN

Talk by Rodolfo Carobene (UniMiB)

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Credits: IBM

A joint effort towards Qubit Integration



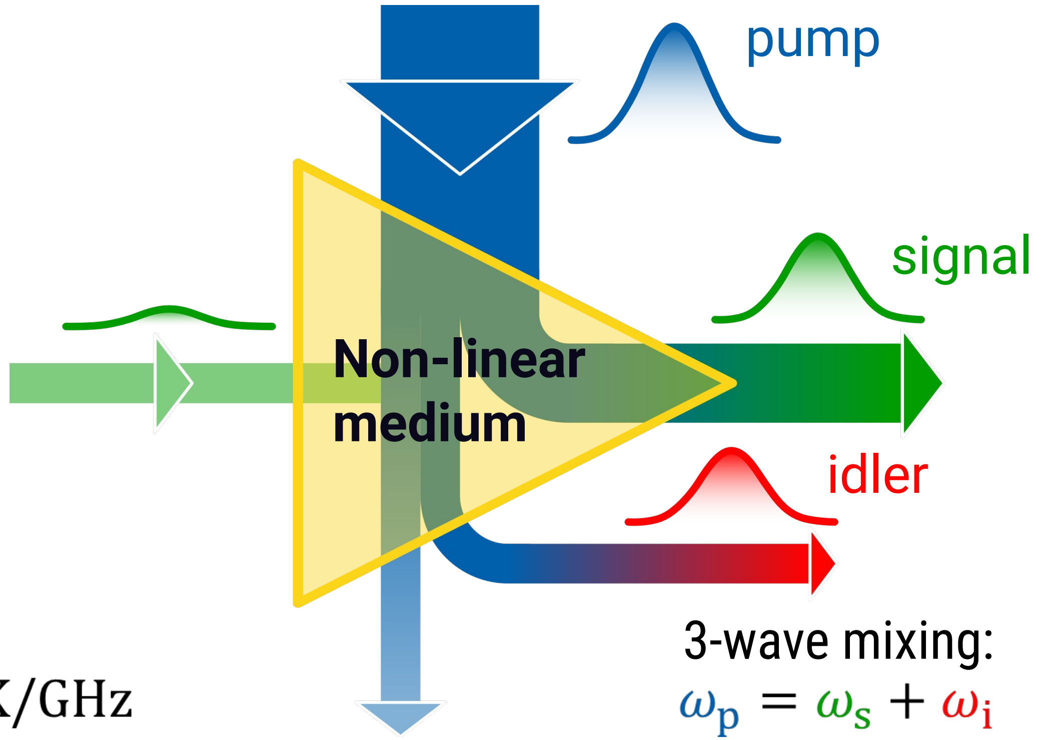
Crucial requirement for qubit read-out: minimise noise and maximise linear gain of first amplification stage

Friis formula: $$T_{\mathrm{N,tot}} = T_{\mathrm{N},1} + \frac{T_{\mathrm{N},2}}{G_1} + \frac{T_{\mathrm{N},3}}{G_1 G_2} + \cdots + \frac{T_{\mathrm{N},k}}{G_1 G_2 \cdots G_{k-1}}$$

Credits: IBM

Superconducting Parametric Amplifiers

Parametric amplification = wave-mixing process based on parametric **non-linearity**



Superconducting amplifiers
for microwave amplification:

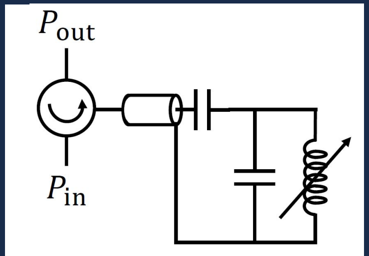
- (Ideally) non-dissipative
- Ultra-low-noise amplification
  → Quantum noise limit: $T_N/f \sim h/2k_B \sim 25 \text{ mK/GHz}$

Different approaches: JPAs vs TWPAs

Increasing **signal gain** by *increasing* the **interaction time** in the non-linear medium

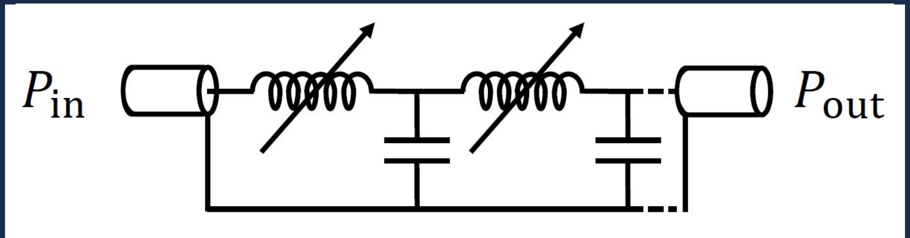
Resonator-based paramp:

Josephson Parametric Amplifiers JPAs



Long **non-linear medium**:

Travelling Wave Parametric Amplifiers TWPAs



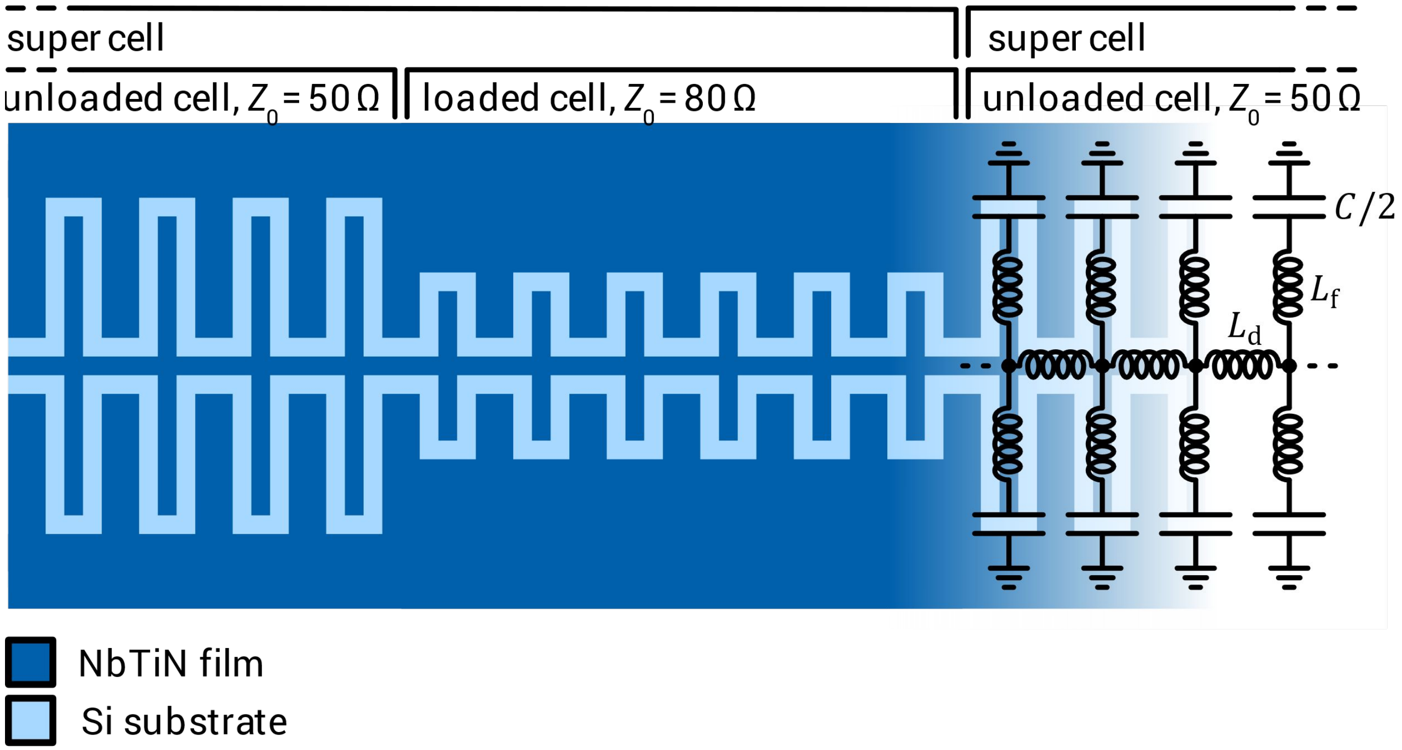
- ✔ Larger bandwidth
- ✔ Larger saturation power

KI-TWPA design

DARTWARS Detector Array Readout with Traveling Wave AmplifieRS

- Non-linear element: kinetic inductance of NbTiN film
- Artificial transmission line: increased interaction time
- Unloaded/loaded segments: phase matching

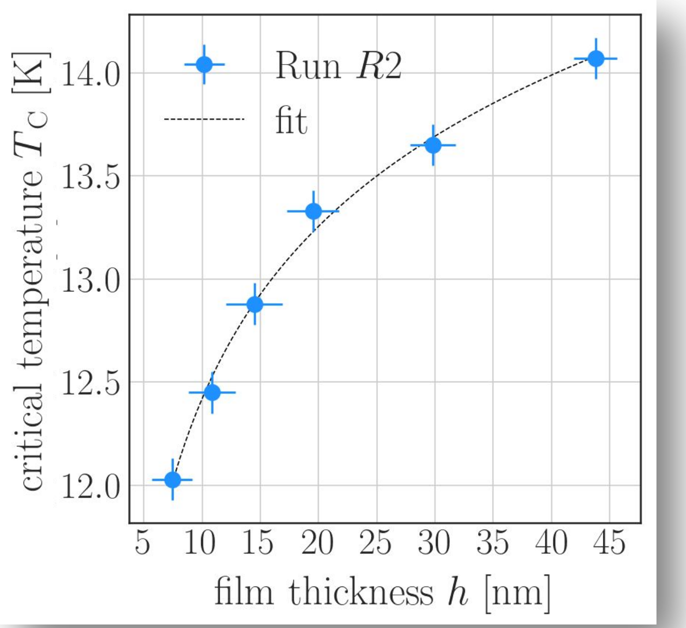
→Suppresses shock-waves
→exponential gain



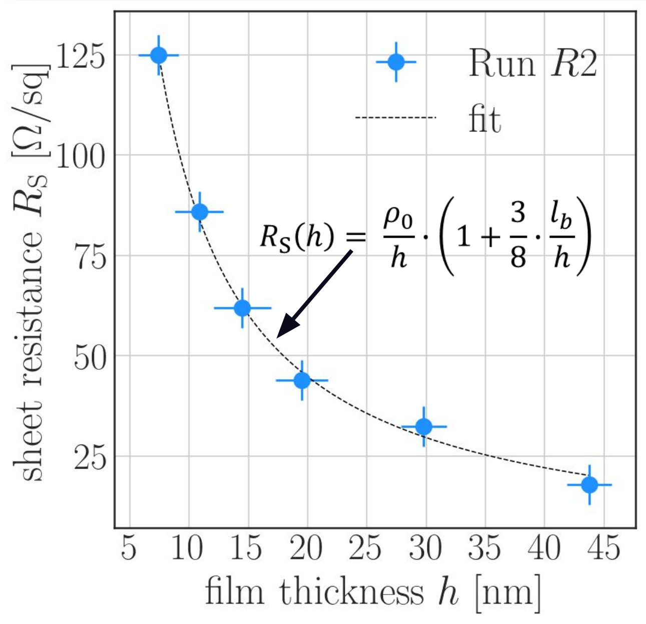
Calibrate film thickness *h* vs kinetic inductance L_0

Talk by Felix Ahrens

Measured T_c:

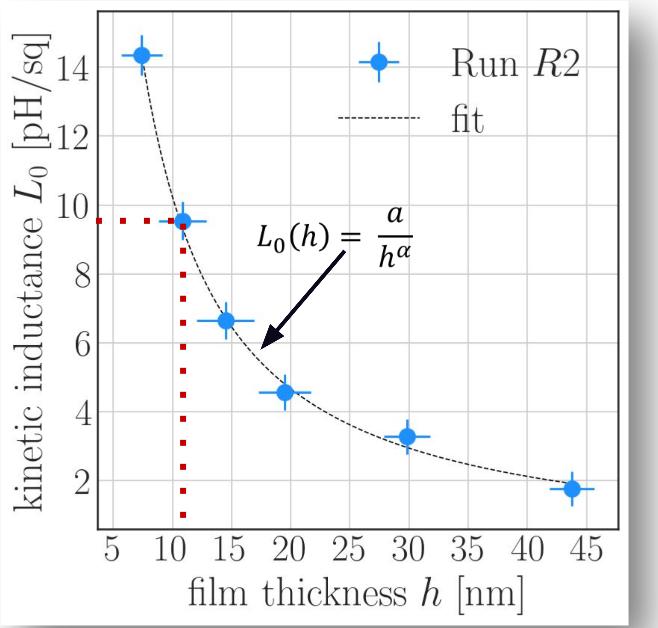


Measured R_s:



Fuchs' model (doi: 10.1017/S0305004100019952)

$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$

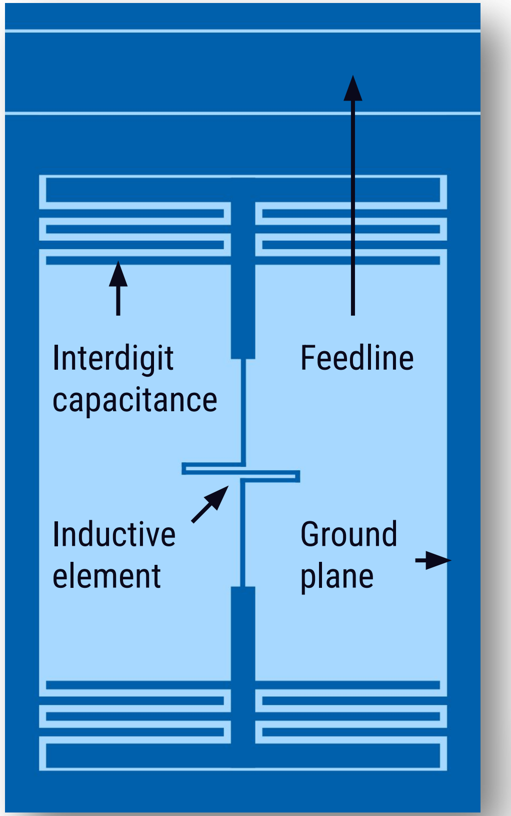


Phenomenological model

→Use film thickness *h* as L_0 tuning parameter

Measurement of the kinetic inductance

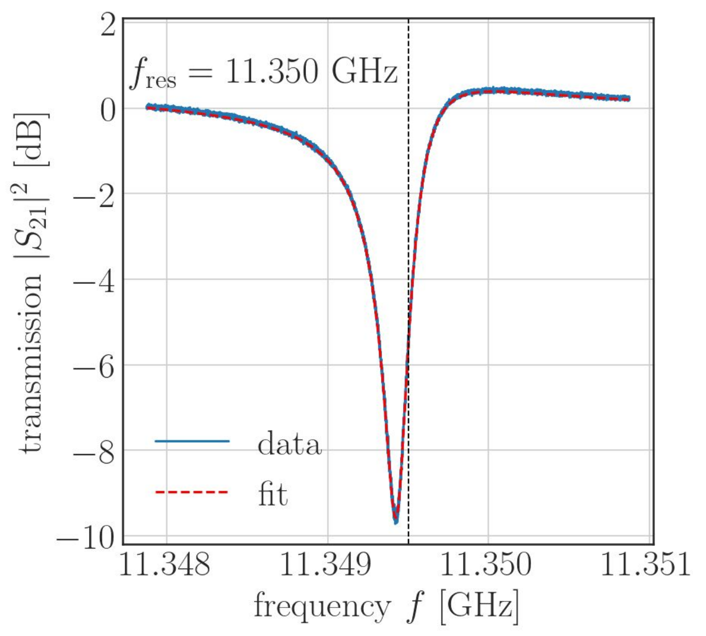
Lumped element resonator



doi: 10.1007/s10909-019-02251-1

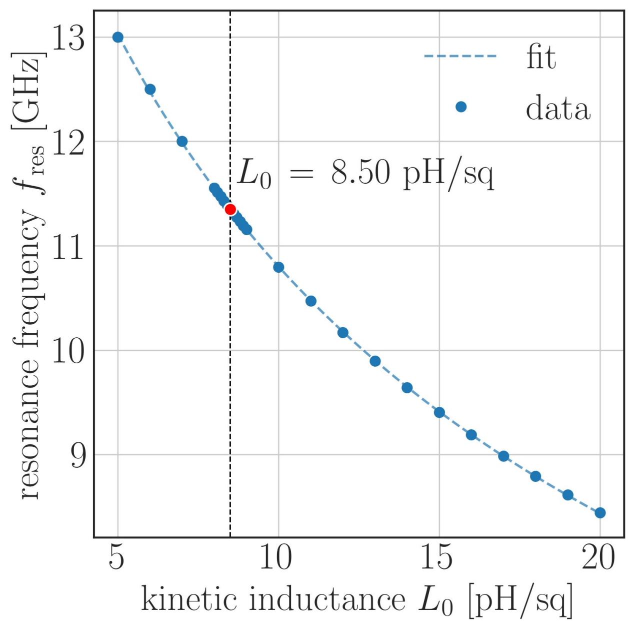
NbTiN film
Si substrate

Transmission measurement at mK



$$f_{\mathrm{res}} = \frac{1}{\sqrt{(L_{\mathrm{g}} + L_{\mathrm{k}})C}}$$

Comparison with simulation



- Discrepancy of ~10% (within stat./syst. uncertainties)

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KI-TWPA prototype

DARTWARS Detector Array Readout with Traveling Wave AmplifieRS
CSN5 Ricerca Tecnologica
MARIE CURIE ACTIONS
GA ID: 101027746
FONDAZIONE BRUNO KESSLER SENSORS AND DEVICES
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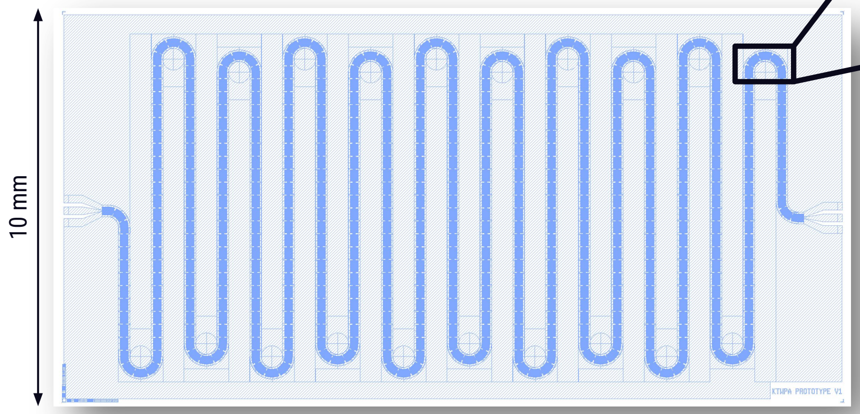
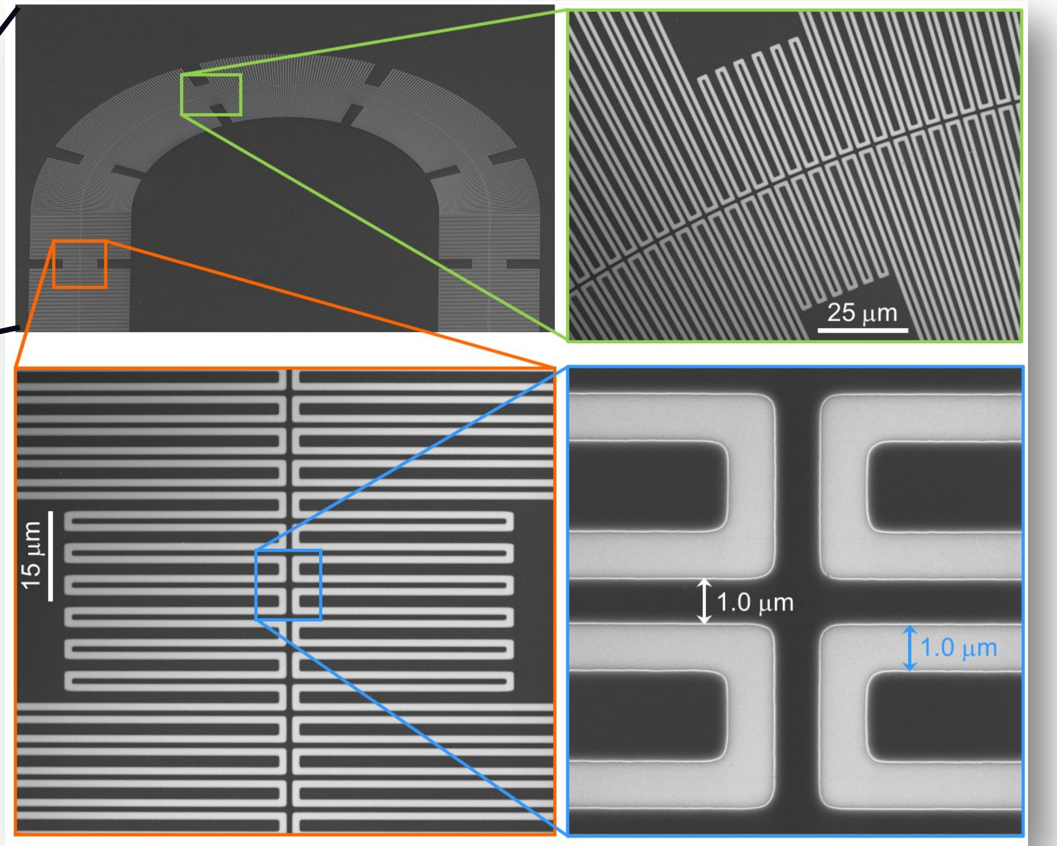
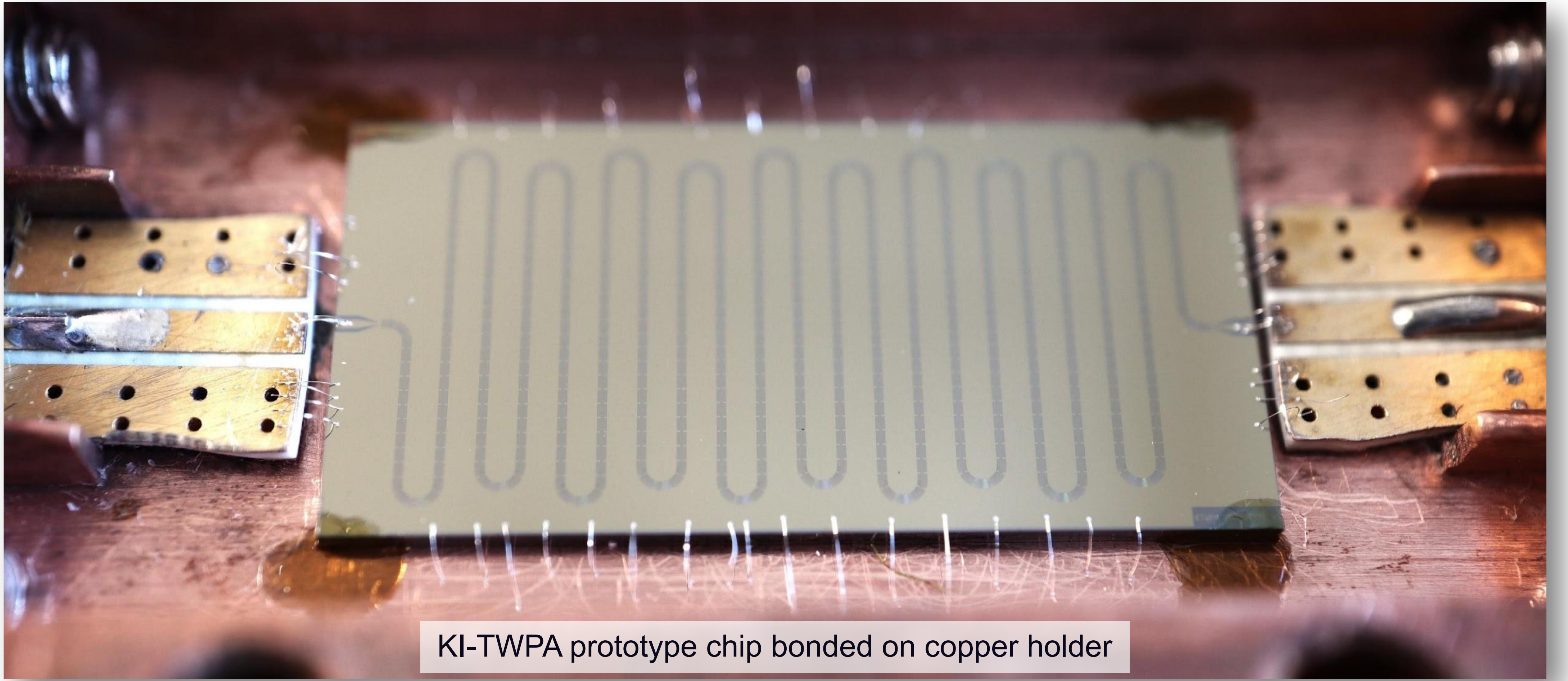


Prototype device:
17 cm long NbTiN artificial transmission line

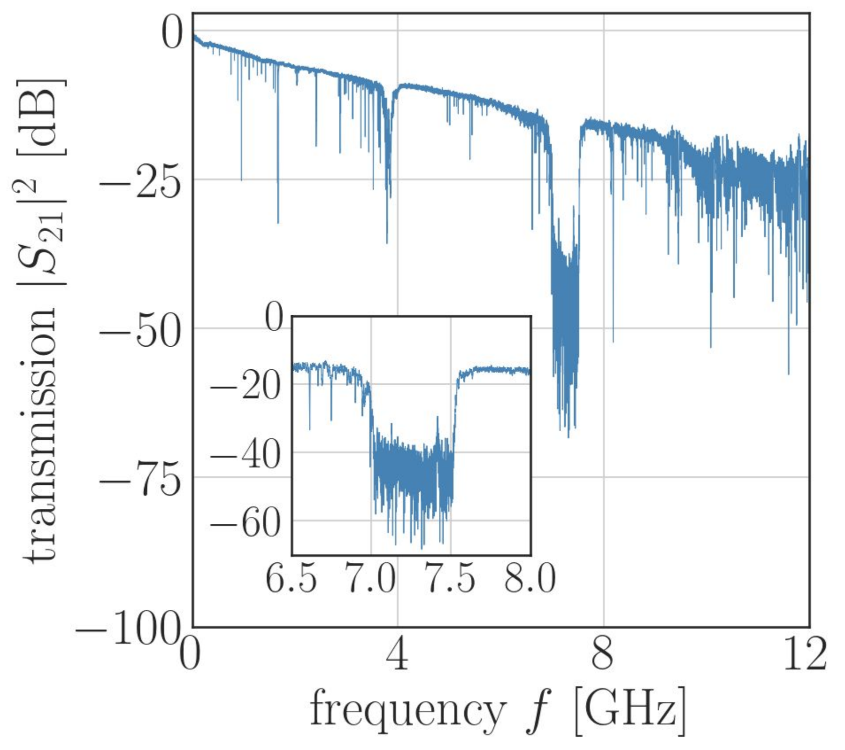


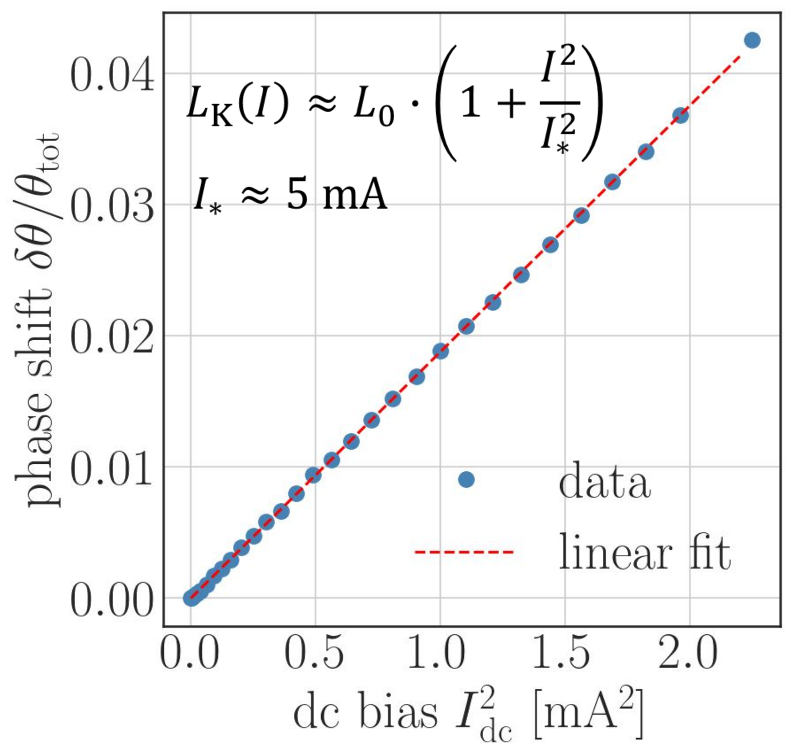
PFIB-SEM Helios 5 ThermoFisher Scientific Helios 5 CXe

KI-TWPA prototype characterisation


KI-TWPA prototype chip bonded on copper holder

KI-TWPA prototype characterisation

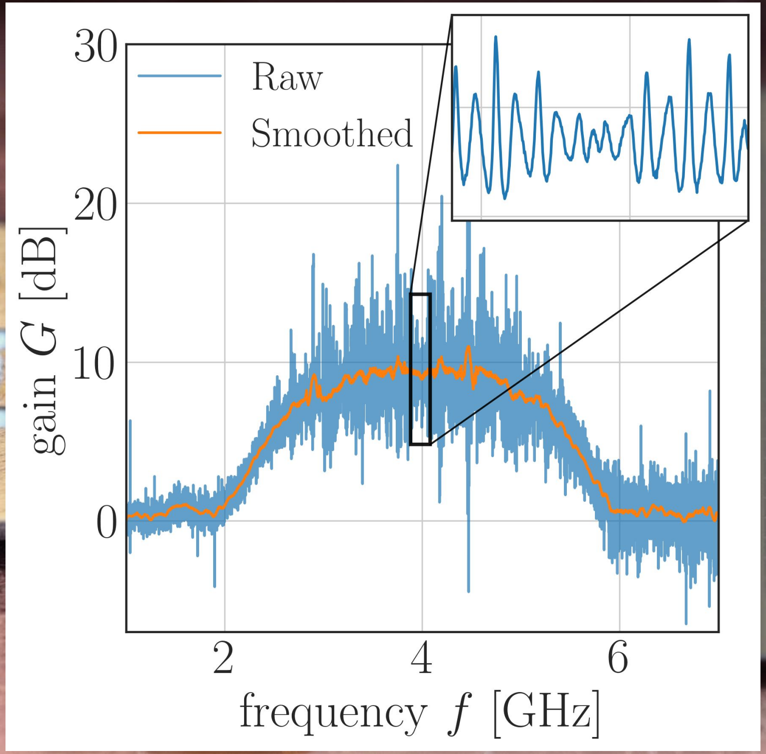


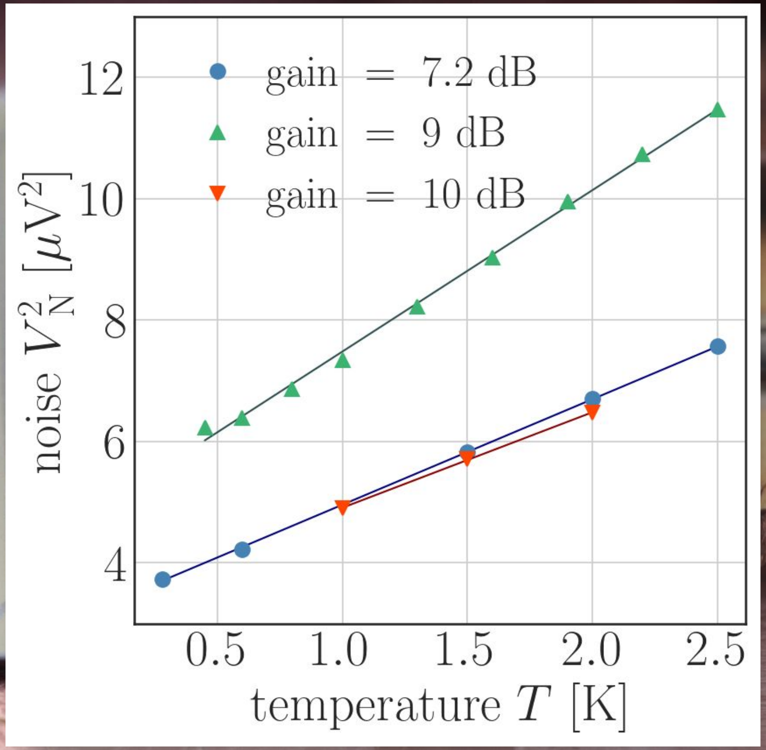


✔ Transmission with **bandgap** at ~ 7 GHz

✔ **Non-linearity** due to kinetic inductance

KI-TWPA prototype characterisation



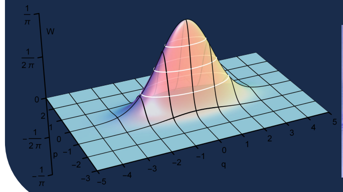
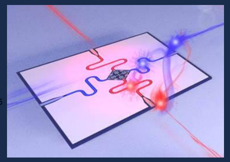


✔ **Gain**: up to ~ 10 dB (with I_{dc} = 1.2 mA)

✔ **Noise**: down to 2.5-3 noise quanta

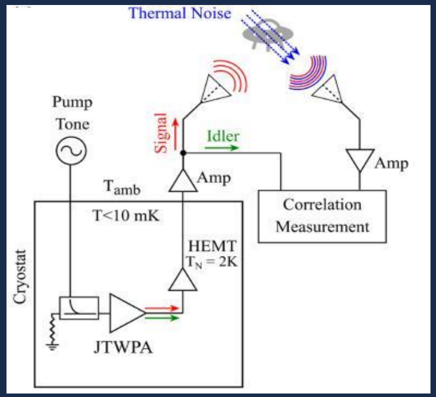
Superconducting amplifiers beyond amplification

Microwave squeezing & entangled microwave photons

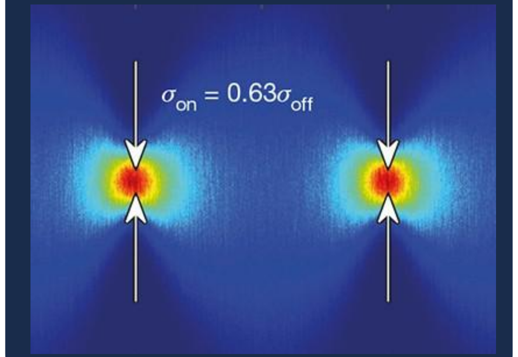



Wikipedia, electronicsweekly.com

Microwave Quantum Illumination
Quantum radar

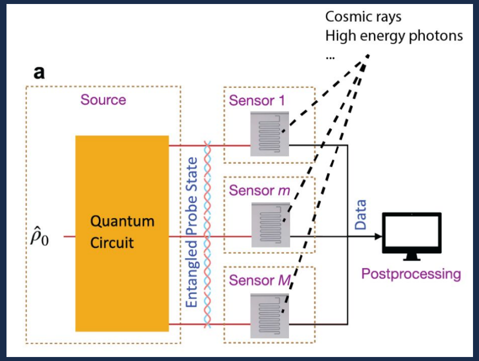


Quantum-enhanced axion detection

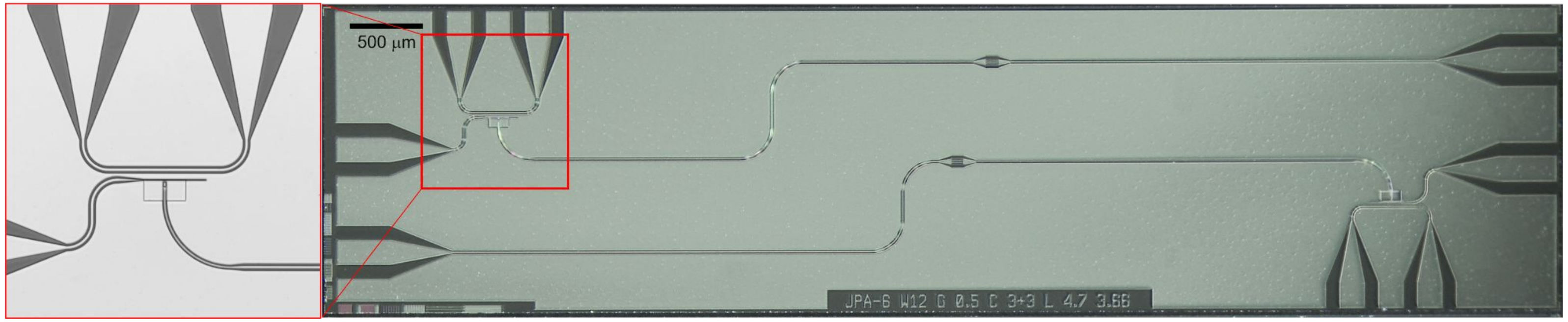


Backes, K.M. et al., *Nature* **590**, 238–242 (2021)

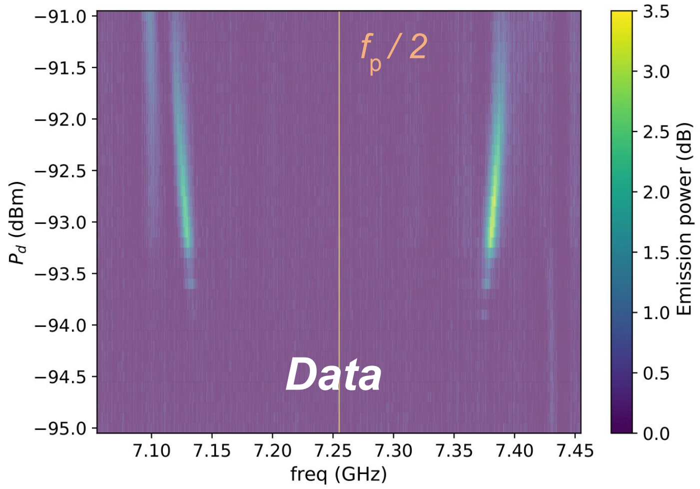
Cluster states for Distributed Quantum Sensing

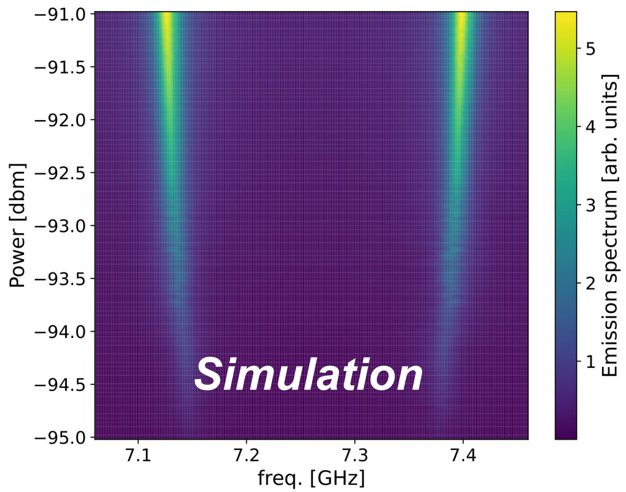


JPAs as Sources of Entangled Photons



JPA response to applied pump drive (f_p = 7.26 GHz)





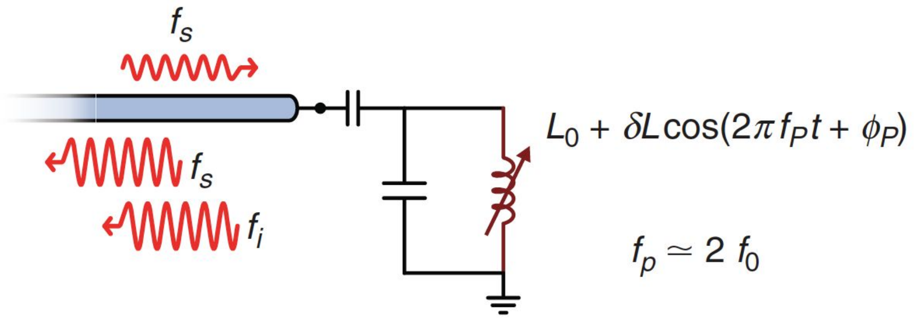


Image credits: J. Aumentado, *IEEE Microwave Magazine*, 21, 8, 45-59,2020

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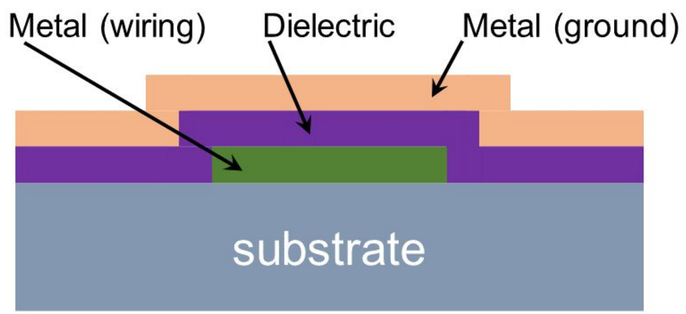
Conclusion & Outlook

- Crucial stage in the qubit read-out chain: Amplification
- TWPAs can reach quantum-limited and broadband amplification
- First half-size KI-TWPA prototypes have shown promising results

Next steps

- new layout: inverted microstrip
  → new design and new materials
- design and microfabricate a full-size prototype
- develop accurate characterisation tools, e.g. for noise measurements
  → planning an *interspoke collaboration* with Martina Esposito (Spoke 5)



BACK UP SLIDE: Noise measurement

$$N_{\mathrm{out}} = G_{\mathrm{H}} T_{\mathrm{H}} + (G_{\mathrm{K}} F_2 G_{\mathrm{H}}) T_{\mathrm{n}} + F_1 F_2 G_{\mathrm{H}} (G_{\mathrm{K}} + G_{\mathrm{K}} - 1) T.$$