Towards quantum limited read-out of cryogenic detectors

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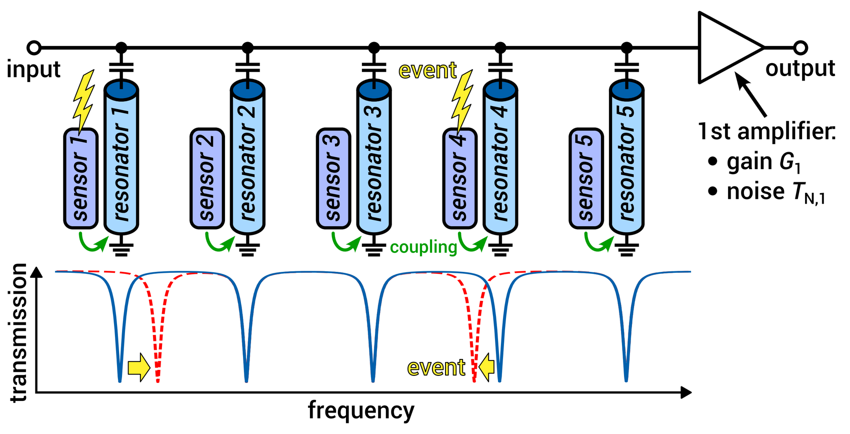
MOTIVATION

Calorimetric neutrino mass experiments

requirements:

- high energy resolution ⇒ cryogenic detectors
- high statistics ⇒ microwave multiplexing:



energy resolution is often limited by system noise:

$$T_{N,tot} = T_{N,1} + \frac{T_{N,2}}{G_1} + \frac{T_{N,3}}{G_1 G_2} + \dots + \frac{T_{N,k}}{G_1 G_2 \dots G_{k-1}}$$

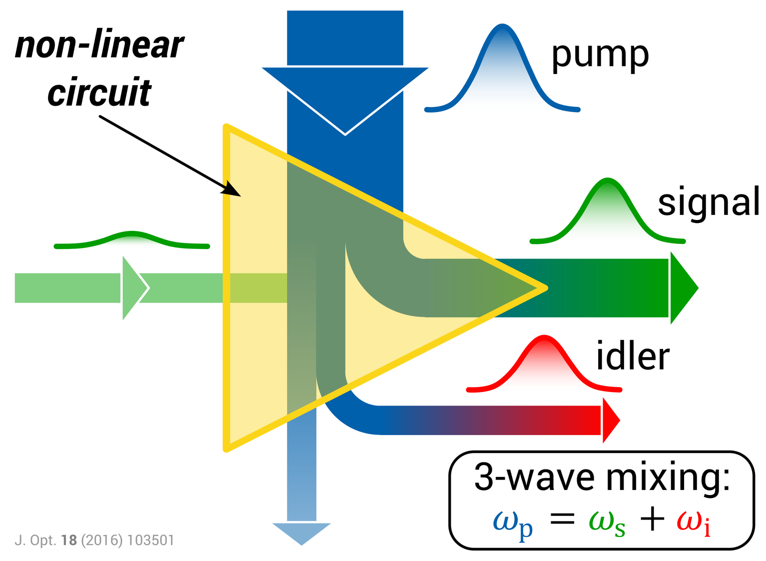
⇒ first amplification stage with:
- minimal noise
- high gain

Superconducting parametric amplifiers:

- reach the Standard Quantum Limit (SQL)

$$T_N \geq \frac{hf}{2k_B} = T_{SQL} \approx f \cdot \frac{25\ \mathrm{mK}}{\mathrm{GHz}}$$

- achieve gain > 20 dB



Parametric amplification:

energy transfer from strong pump to weak signal in non-linear circuits

SC non-linear elements:

- Josephson junctions
- high kinetic inductance lines

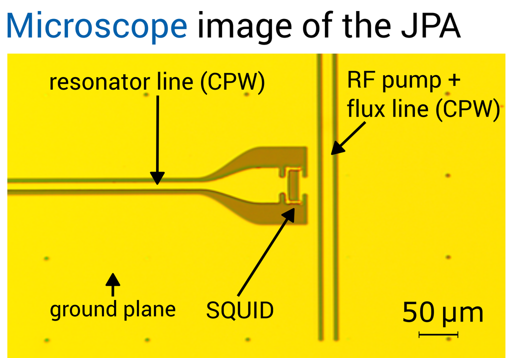
⇒ we develop superconducting parametric amplifiers based on both elements

JOSEPHSON PARAMETRIC AMPLIFIERS

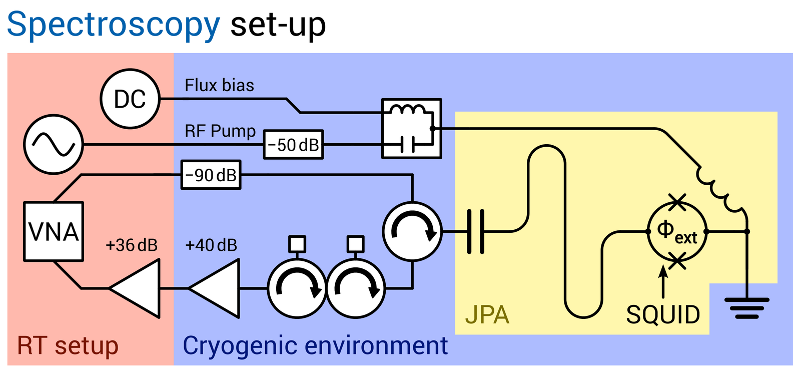
Parametric oscillator **with resonant geometry:** quarter-wave resonator terminated by a flux-tunable non-linear inductance (SQUID)

$$L(\Phi_{ext}) = \frac{\Phi_0 (4\pi I_c)^{-1}}{\left|\cos\left(\pi \frac{\Phi_{ext}}{\Phi_0}\right)\right|}$$

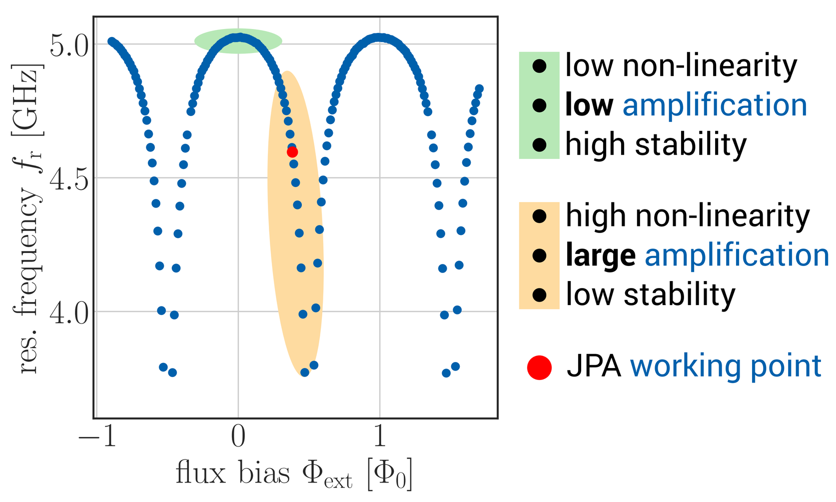
Microscope image of the JPA



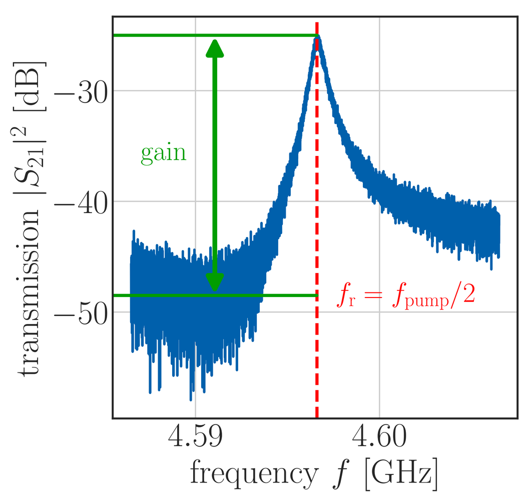
Spectroscopy set-up



Frequency modulation upon DC flux bias



JPA gain profile



JPA - pros and cons

- large gain
- quantum limited noise
- simple microfabrication
- small amplification bandwidth (few MHz)
- travelling wave geometry allows for large amplification bandwidth

TRAVELLING WAVE PARAMETRIC AMPLIFIERS

***Non-linear medium*:** high kinetic inductance superconductor

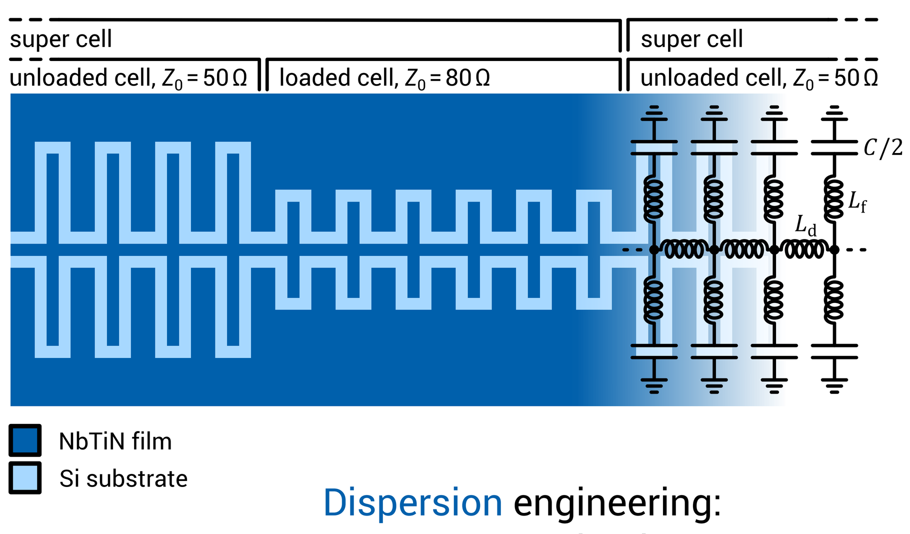
$$L_k(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

with $I_* \propto 1/\sqrt{R_n}$

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

Our choice: NbTiN

KI-TWPA based on artificial transmission line

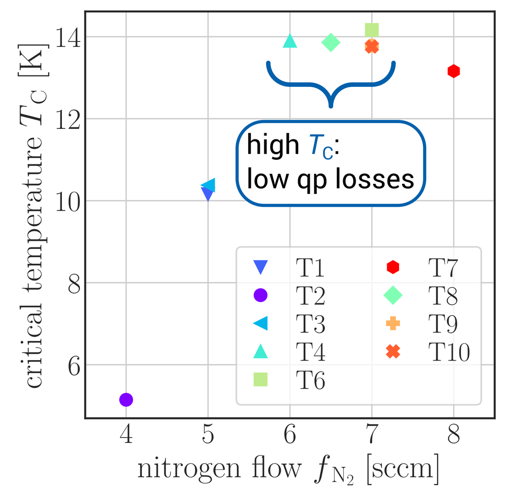


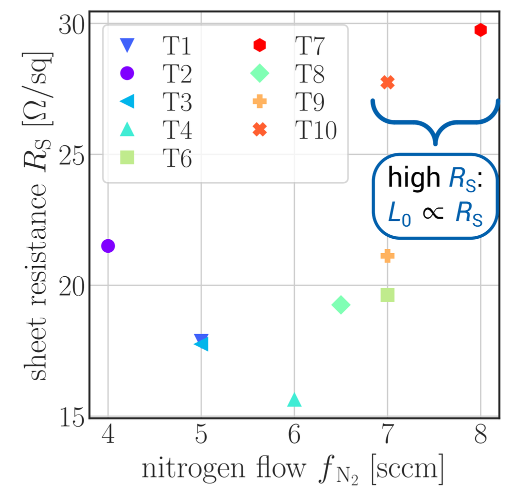
Dispersion engineering:
- suppresses shock-waves
- allows for exponential gain

Step 1: Exploration of the NbTiN film deposition parameters

- magnetron rf sputtering ($Nb_{80\%}Ti_{20\%}$ target), deposition time = 6 minutes
- default parameters: P = 700 W, $p = 2 \times 10^{-3}$ mbar, f_{Ar} = 50 sccm, T = 400 °C

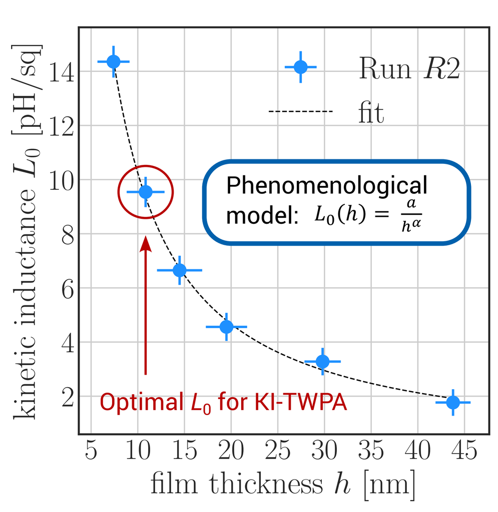
Wafer	f_{N_2} / sccm	Note
T1	5.0	$p = 2 \times 10^{-3}$ mbar
T2	4.0	
T3	5.0	
T4	6.0	
T5	5.0	P = 1200 W
T6	7.0	
T7	8.0	
T8	6.5	
T9	7.0	T = 300 °C
T10	7.0	P = 600 W



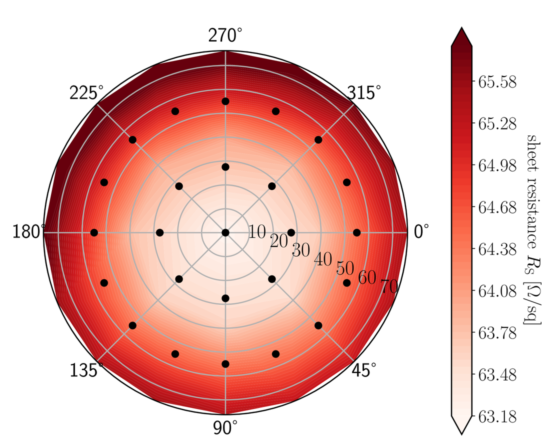


Step 2: Optimisation of the NbTiN film

Fine-tuning of L_0



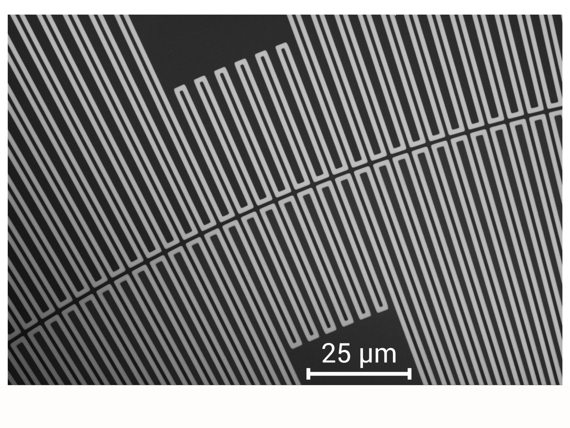
Wafer scale homogeneity



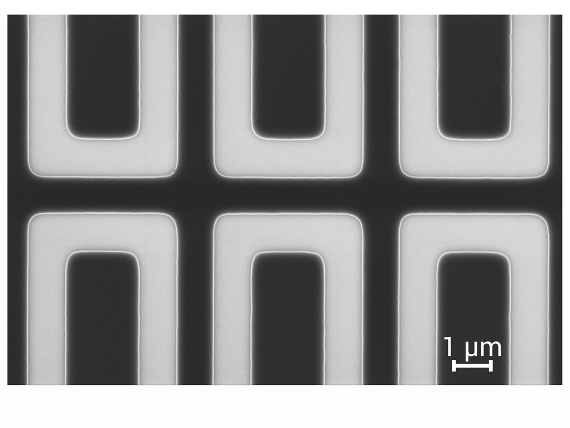
Radial variation of about 4 %

Step 3: Fabrication of the KI-TWPA

SEM images of the microfabricated artificial transmission line



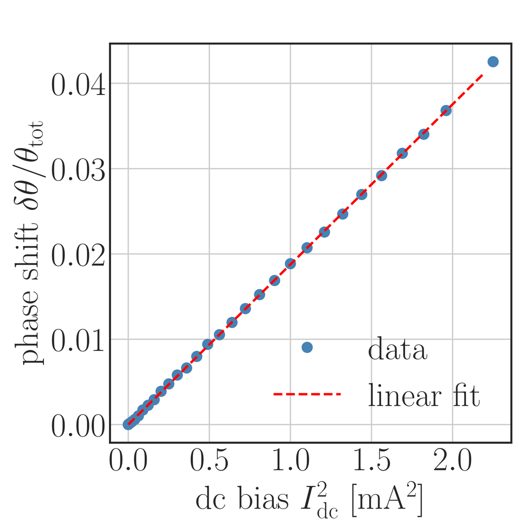
transmission line length = 17 cm



number of fingers ~ 10^5

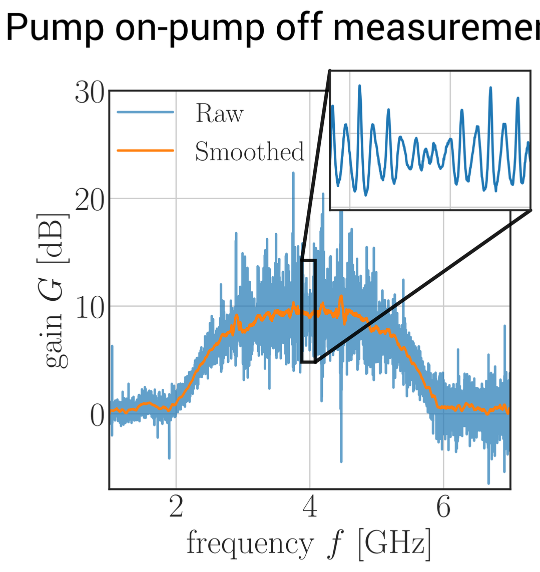
Step 4: Characterisation of the KI-TWPA

Phase shift measurement



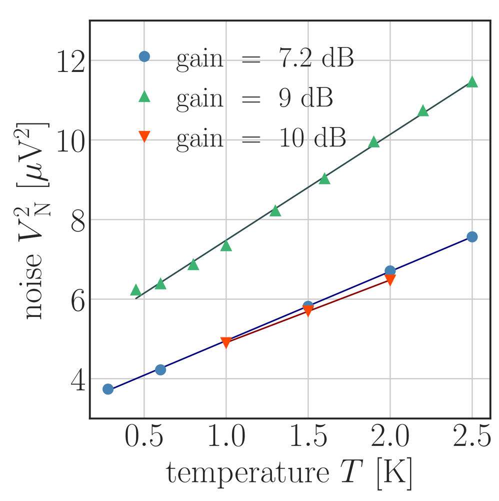
Non-linearity due to L_k

Pump on-pump off measurement



Measured gain of ~ 10 dB

Hot-cold noise measurement



Amplifier noise: 2.5 - 3 quanta

TWPAs - pros and cons

- large gain
- large amplification bandwidth (few GHz)
- quantum limit achievable
- more complex design (phase-matching)
- extremely long CPW line (~ 20 – 40 cm)
- new layout: inverted microstrip line KI-TWPA

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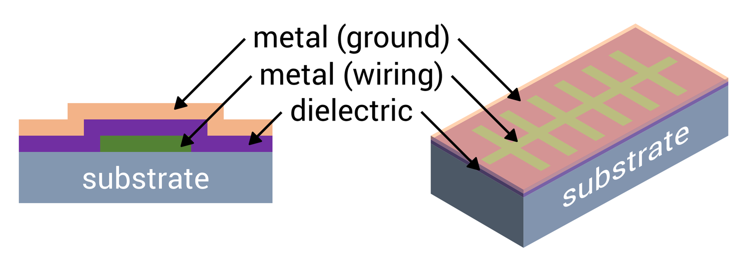
OUTLOOK - NEXT GENERATION TWPAs

Applications

- Cryogenic detectors read-out e.g. neutrino mass experiments
- Qubit arrays read-out
- Microwave quantum illumination

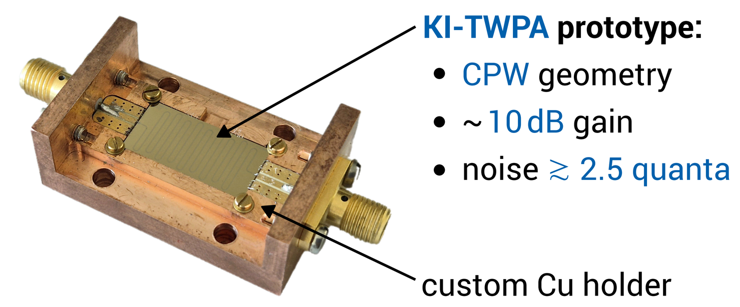
New layout

Develop inverted microstrip KI-TWPA



Prototype

Realisation of first half-size CPW KI-TWPA



Technological platform

Development and characterisation of high-kinetic inductance NbTiN film