Development of Josephson Parametric Amplifiers for Axion Search and Quantum Information Applications

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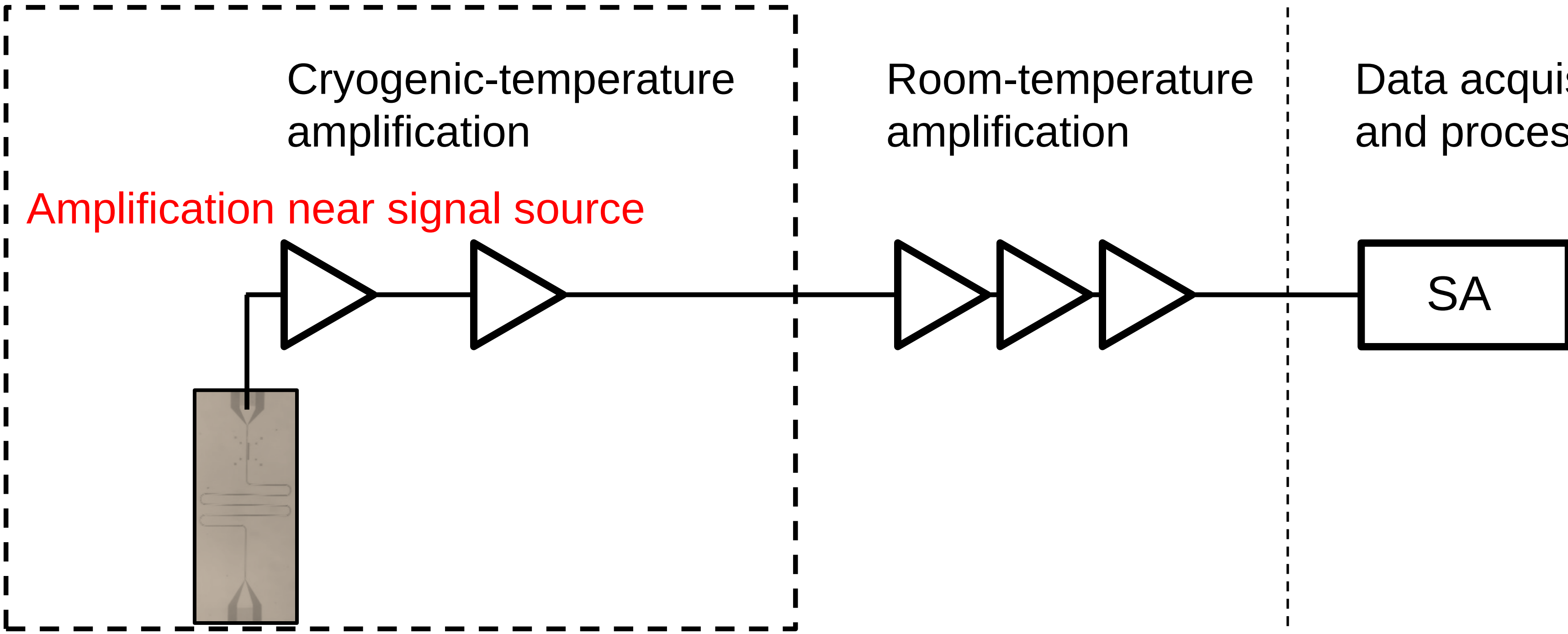
Mini-workshop on quantum sensing and applications for physics, NCU, Oct. 30th, 2025

Weak Signal – Linear Amplification

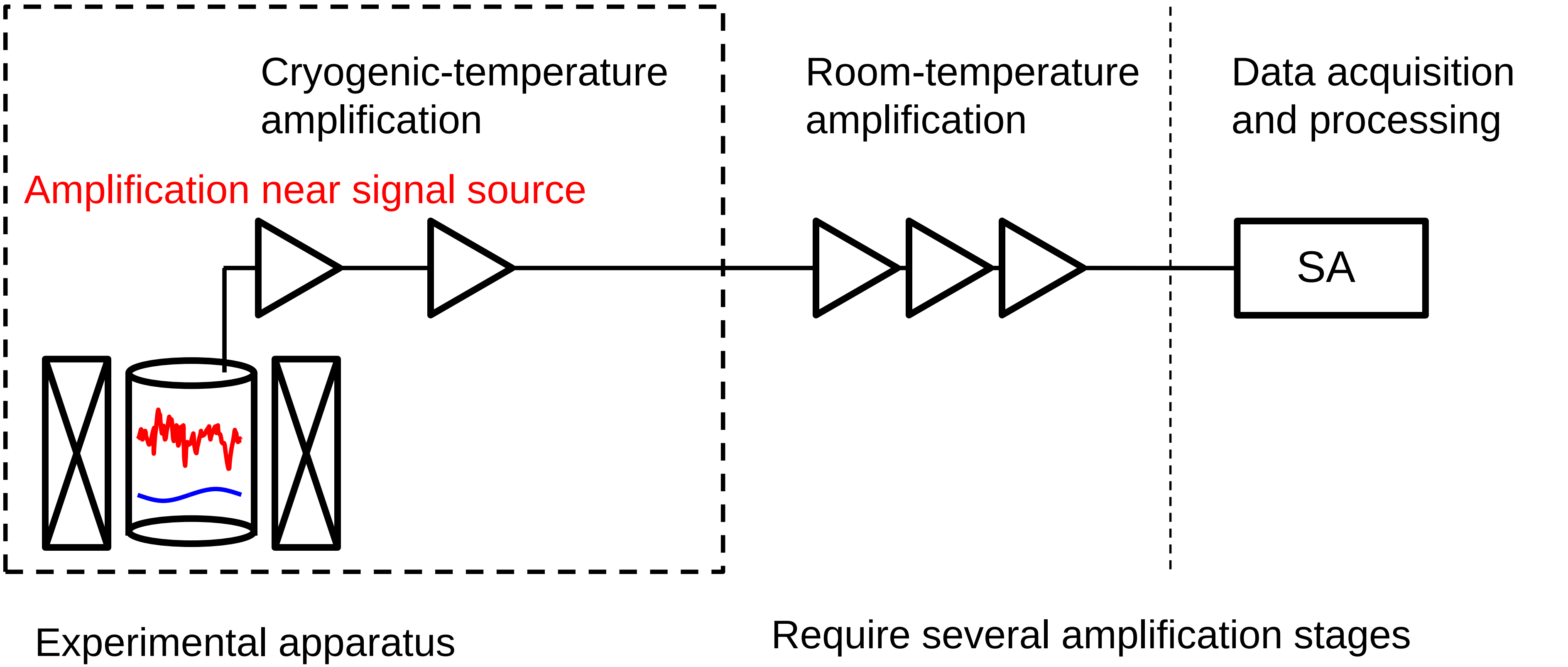


Experimental apparatus

Require several amplification stages

$\sim 10^{-15}$ W at ~5 GHz for superconducting qubit readout

Weak Signal – Linear Amplification



$\sim 10^{-15}$ W at ~5 GHz for superconducting qubit readout

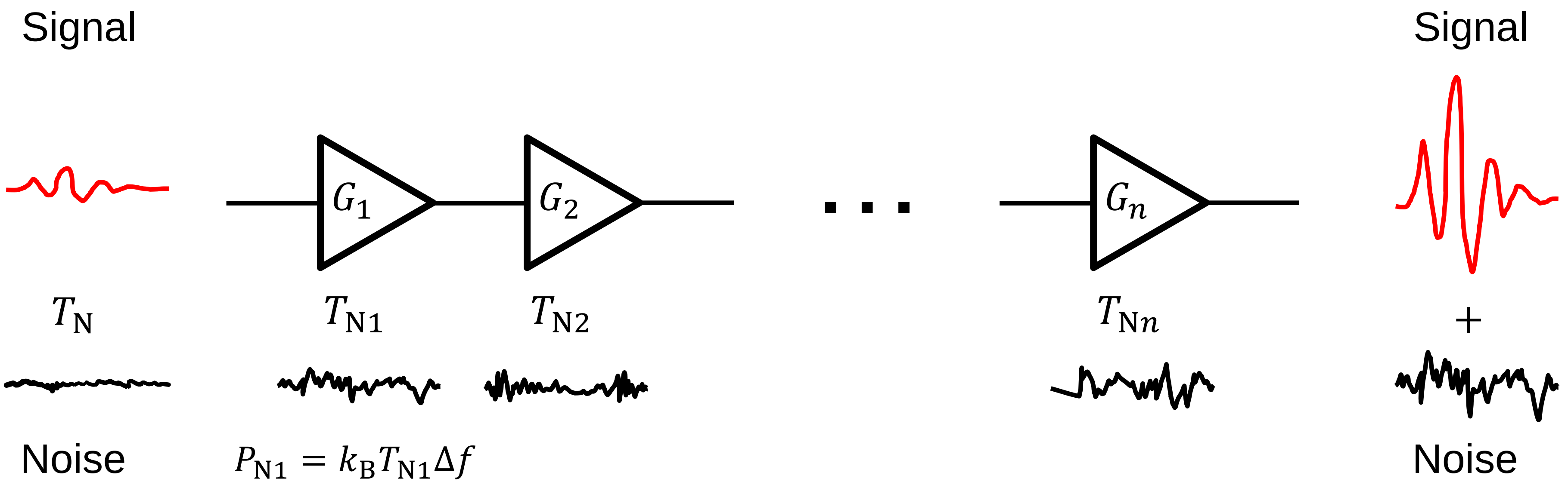
$\sim 10^{-23}$ W for axion haloscope detection

Amplifier Performance

- Gain
- Bandwidth
- Saturation power
- Added noise

For Josephson parametric amplifier (JPA): low noise, low power

Amplifier Added Noise and System Noise



Overall amplification effect

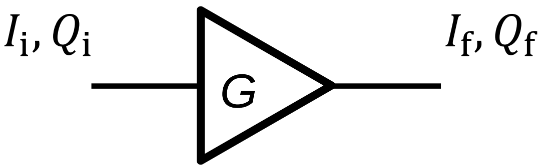
Signal gain $G = G_1 G_2 \cdots G_n$

Added noise power
$$P_{Na} = k_B T_{N1} \Delta f G_1 G_2 \cdots G_n + k_B T_{N2} \Delta f G_2 G_3 \cdots G_n + \cdots + k_B T_{Nn} \Delta f G_n$$
$$= k_B \left(T_{N1} + \frac{T_{N2}}{G_1} + \frac{T_{N3}}{G_1 G_2} + \cdots + \frac{T_{Nn}}{G_1 G_2 \cdots G_n} \right) \Delta f G$$

Added noise temperature
$$T_{Na} = T_{N1} + \frac{T_{N2}}{G_1} + \frac{T_{N3}}{G_1 G_2} + \cdots + \frac{T_{Nn}}{G_1 G_2 \cdots G_n}$$

System noise temperature $T_{sys} = T_N + T_{Na}$

Quantum-Limited Added Noise of Linear Amplifier



$$I_\mathrm{f} = \sqrt{G} I_\mathrm{i} + I_\mathrm{a}$$

$$Q_\mathrm{f} = \sqrt{G} Q_\mathrm{i} + Q_\mathrm{a}$$

Commutation relation

$$[I_\mathrm{i}, Q_\mathrm{i}] = i\hbar$$

$$\begin{aligned}[I_\mathrm{f}, Q_\mathrm{f}] &= i\hbar \\ &= \left[\sqrt{G} I_\mathrm{i}, \sqrt{G} Q_\mathrm{i}\right] + [I_\mathrm{a}, Q_\mathrm{a}] \\ &= iG\hbar + [I_\mathrm{a}, Q_\mathrm{a}]\end{aligned}$$

$$[I_\mathrm{a}, Q_\mathrm{a}] = i(1-G)\hbar$$

Uncertainty principle

$$\langle|\Delta I_\mathrm{i}|^2\rangle\langle|\Delta Q_\mathrm{i}|^2\rangle \geq \frac{\hbar^2}{4}$$

Zero-point energy

$$\frac{\hbar\omega}{2}$$

Refer to amplifier input

$$\frac{\hbar\omega}{2} + \frac{G-1}{G}\frac{\hbar\omega}{2}$$

Half-photon added noise due to amplification

For ω ~ 5 GHz amplifier

$$T_\mathrm{sys} = T_\mathrm{N} + T_\mathrm{Na} \approx \hbar\omega/k_\mathrm{B} \equiv T_\mathrm{q} \approx 0.24\ \mathrm{K}$$

A. Clerk *et al.*, *RMP* **82**, 1155 (2010)

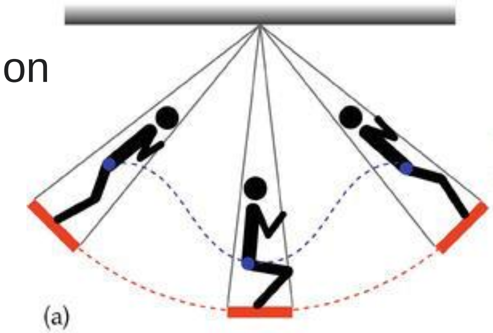
S. Lamoreaux *et al.*, *PRD* **88**, 035020 (2013)

Working Principle of Parametric Amplifier

- Principle: parametric process

L. Fasolo *et al.*, "Superconducting Josephson-Based Metamaterials for Quantum-Limited Parametric Amplification: A Review" in "Advances in Condensed-Matter and Materials Physics", 495 (2019)

Swing oscillation



Natural frequency ω_{r}

Modulation frequency ω_{p}

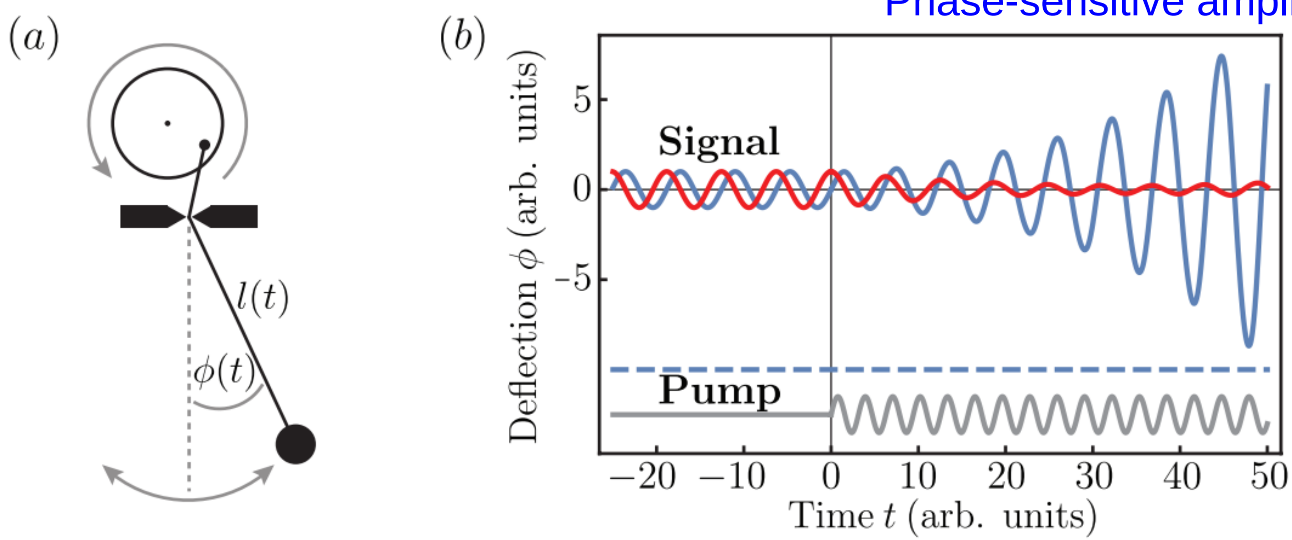
Adjustable parameter of the oscillator

$\omega_{\mathrm{p}} \approx 2\omega_{\mathrm{r}}$

Energy transfer from pump to in-phase signal

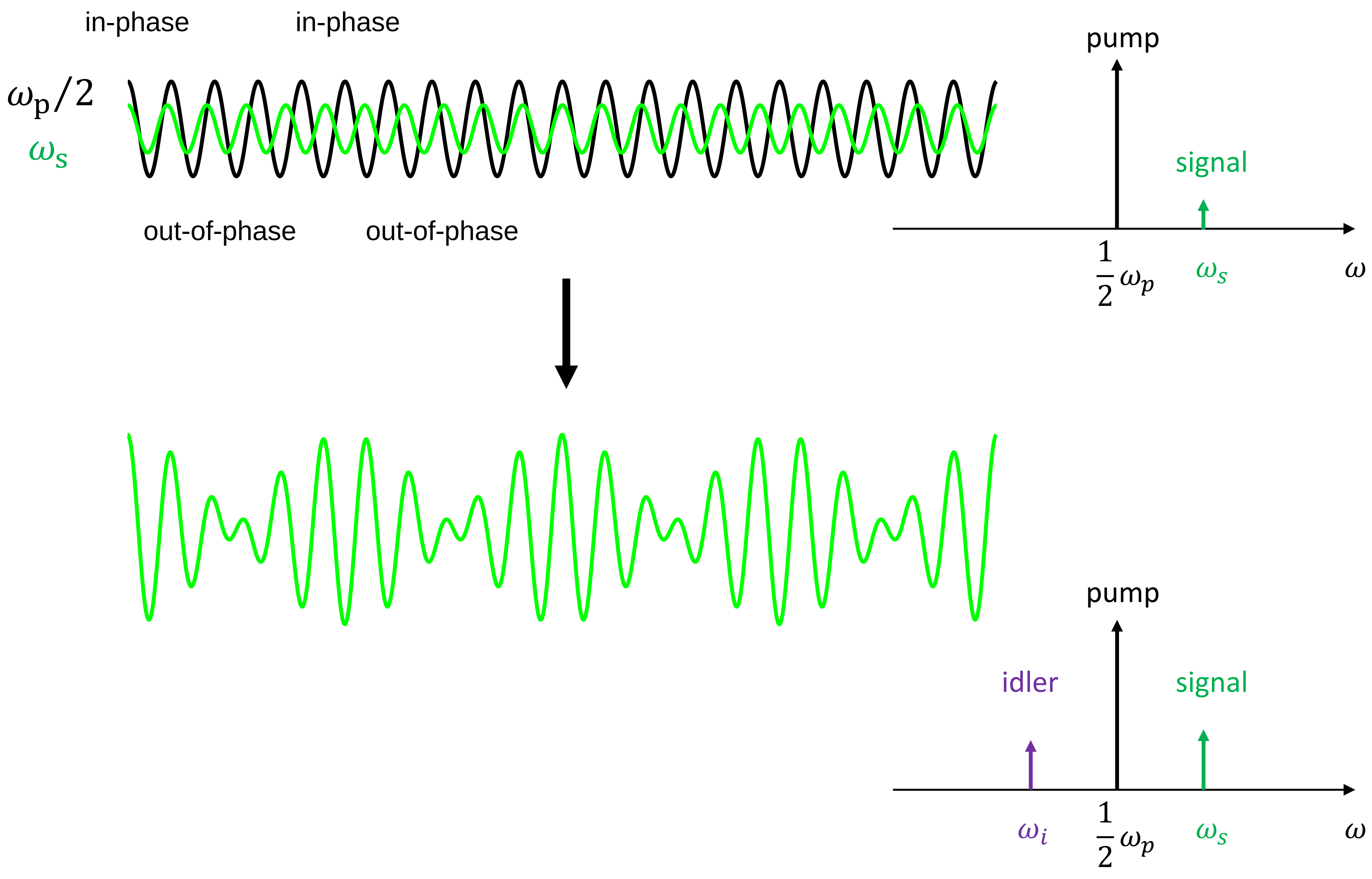
Deamplification for out-of-phase signal

Phase-sensitive amplification



Resource: Eng. SALUM, Juan Manuel, "Superconducting Travelling Wave Parametric Amplifier: reaching quantum noise limit" in the presentation on 09/23/2019

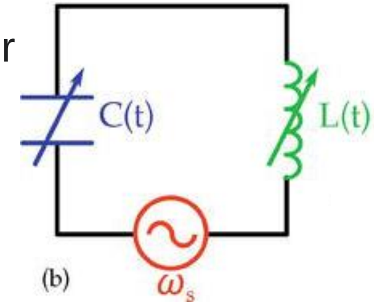
Occurrence of Idler Light



Josephson Parametric Amplifier (JPA) Principle

- Principle: parametric process

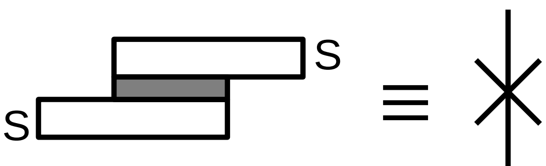
LC oscillator

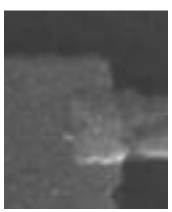


L. Fasolo *et al.*, “Superconducting Josephson-Based Metamaterials for Quantum-Limited Parametric Amplification: A Review” in “Advances in Condensed-Matter and Materials Physics”, 495 (2019)

- Tunable element for modulation: Josephson junction or SQUID

Josephson junction





nonlinear inductor

$$L_{\mathrm{J}}(\delta(t)) = \frac{L_{\mathrm{J0}}}{\cos\delta(t)}$$

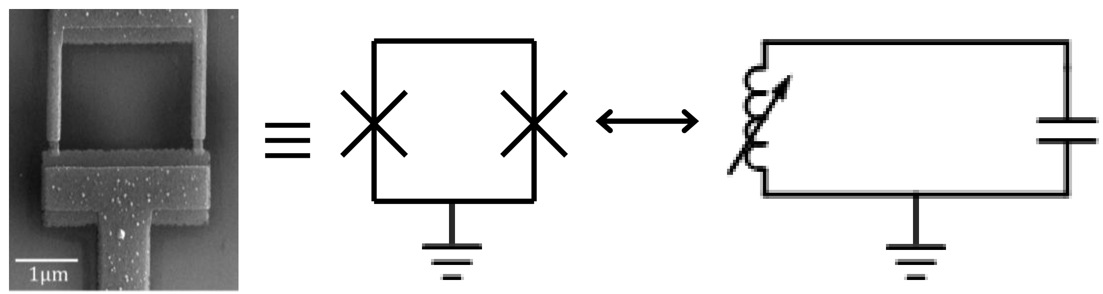
$$I(t) = \sin\delta(t)$$

$$L_{\mathrm{J0}} = \frac{\Phi_0}{2\pi I_{\mathrm{c}}}$$

$$I_{\mathrm{c}} R_{\mathrm{n}} = \frac{\pi}{2}\frac{\Delta}{\mathrm{e}}$$

Current pump

SQUID



Tunable inductor

$$L_{\mathrm{sq}}(\Phi(t)) = \frac{L_{\mathrm{sq0}}}{\cos\left|\pi\frac{\Phi(t)}{\Phi_0}\right|}$$

Flux pump

Superconducting Parametric Amplifier Category

- Nonlinear element

  Josephson junction vs. kinetic inductance in superconducting film

- Amplification mechanism

  Resonator-based vs. traveling wave

- Pumping scheme

  Three-wave mixing (2ω pumping) vs. four-wave mixing (ω pumping)

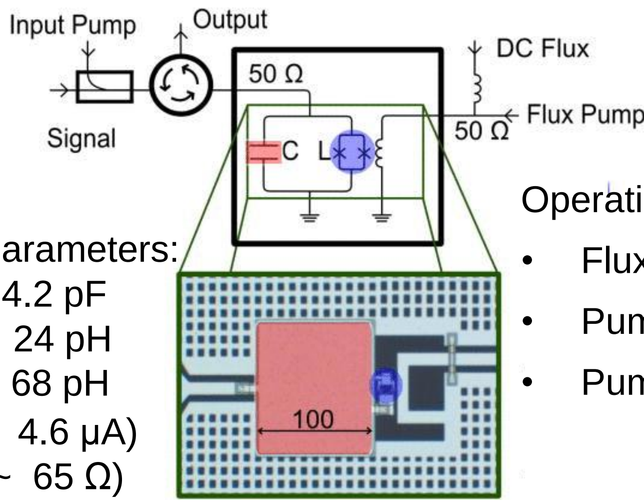
- We develop

  Lumped-element Josephson Parametric Amplifier (LJPA):
  Josephson junction + resonator-based + 2ω pumping

  Traveling-wave Josephson Parametric Amplifier (TWPA):
  Josephson junction + traveling wave + ω pumping

Lumped-Element JPA (LJPA)

Lumped-element LC resonator coupled to 50 Ω signal line



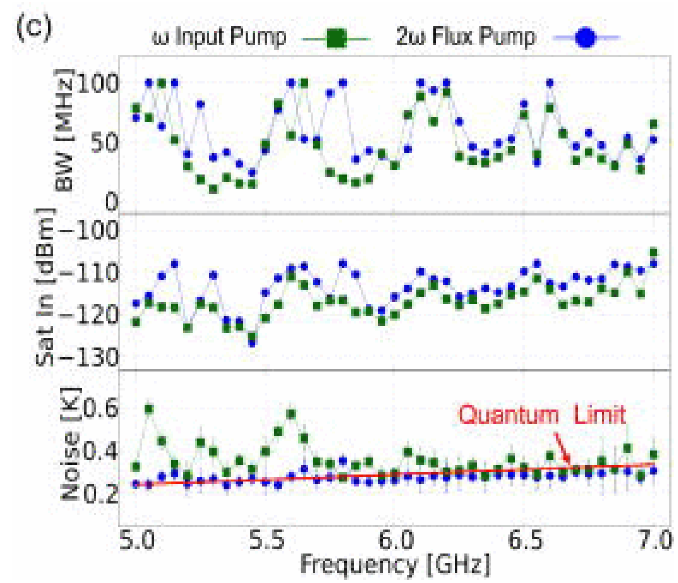
Circuit parameters:

- C ~ 4.2 pF
- L_s ~ 24 pH
- L_J ~ 68 pH
- (I_c ~ 4.6 μA)
- (R_n ~ 65 Ω)

Operation parameters:

- Flux bias
- Pump frequency
- Pump power

Performance



J. Mutus *et al.*, *APL* **103**, 122602 (2013)

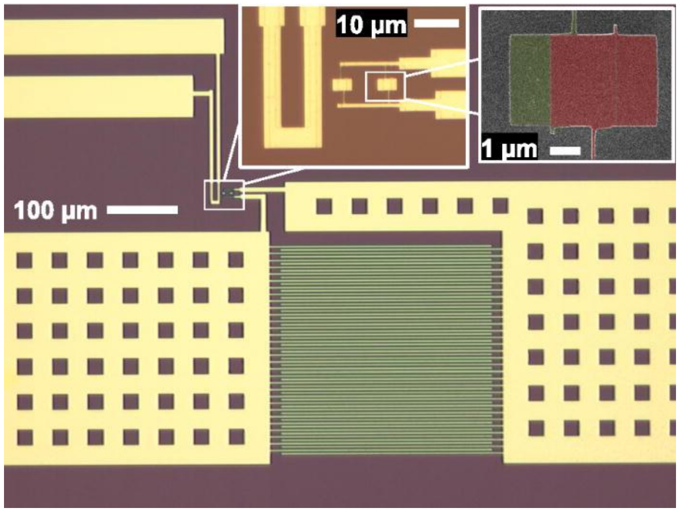
$$\mathrm{BW} \propto \kappa_c \propto L_{sq}$$

$$\mathrm{SP} \propto I_c \propto 1/L_{sq}$$

Gain	15 – 20 dB
Bandwidth	50 – 100 MHz
Frequency tuning range	5 – 7 GHz
Saturation power	-115 dBm
System noise	0.3 K (1 photon)

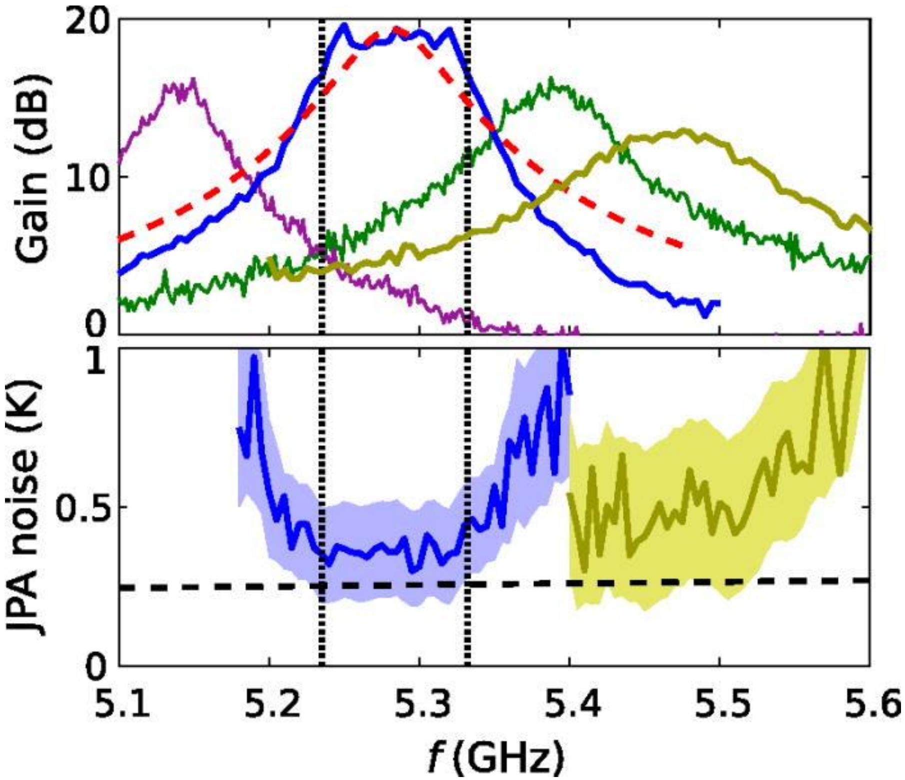
Single-Step LJPA

LJPA made of single-step e-beam lithography



C ~ 1.2 pF
L_J ~ 0.26 nH
(I_c ~ 1.2 µA)

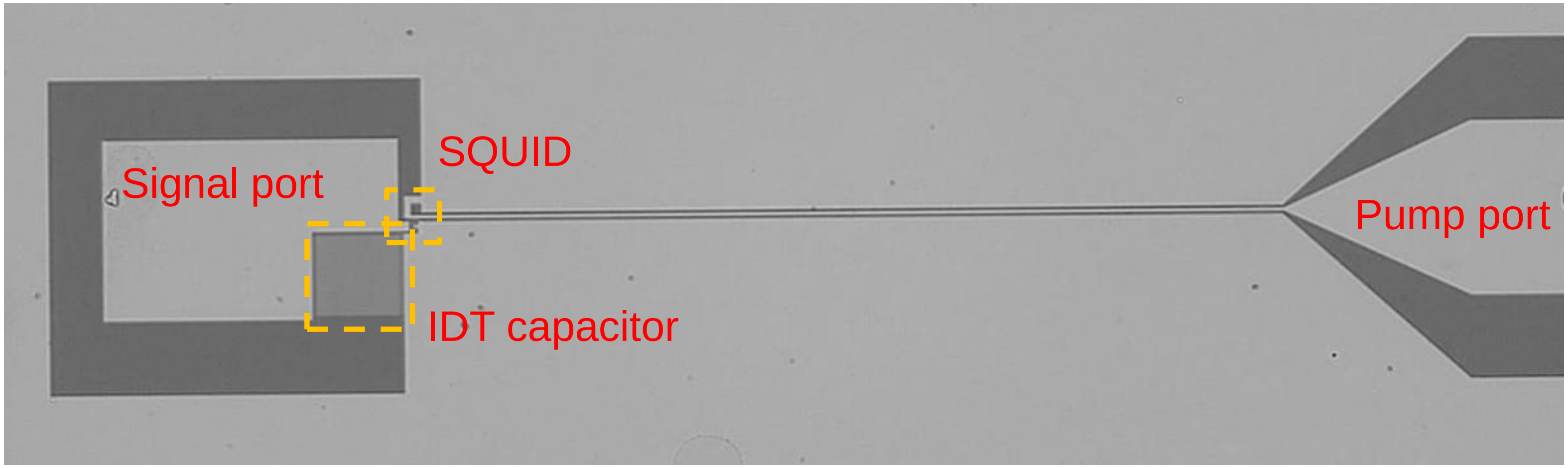
T. Elo *et al.*, *APL* **114**, 152601 (2019)

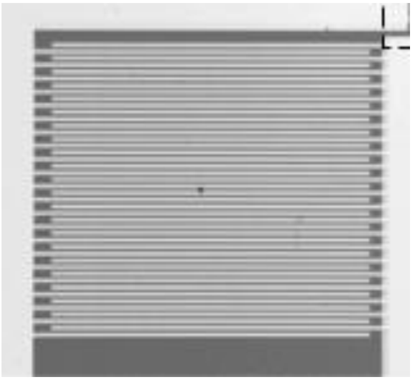


Gain	20 dB
Bandwidth	95 MHz
Frequency tuning range	1 GHz
Saturation power	-125 dBm
System noise	0.37 K (1.5 photon)

Single-Step Optical Lithography LJPA

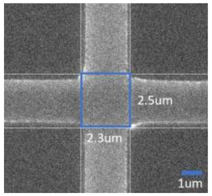
We develop single-step optical lithography for LJPA





IDT capacitor

SQUID and pump line

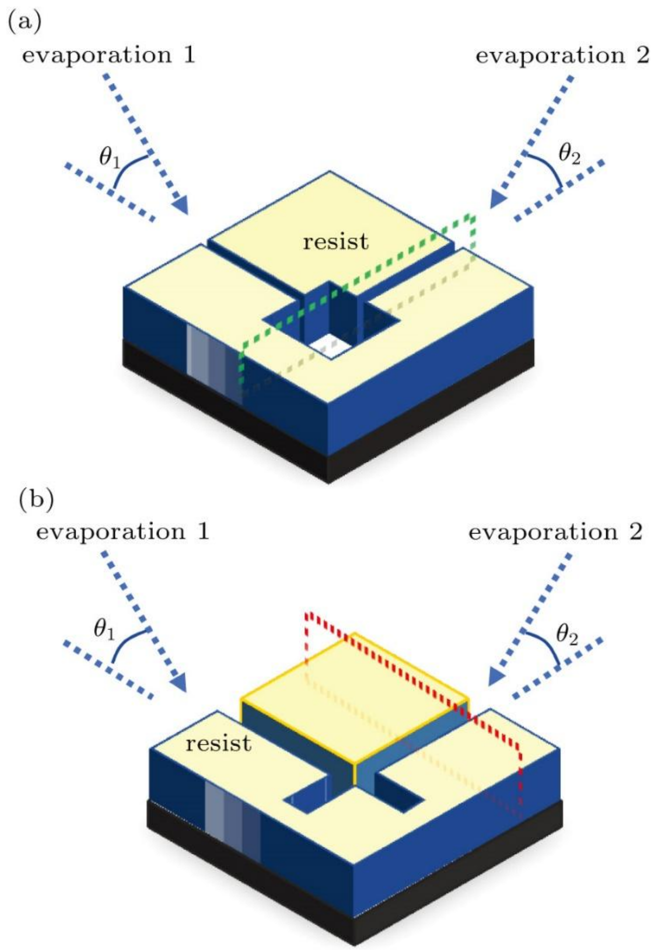


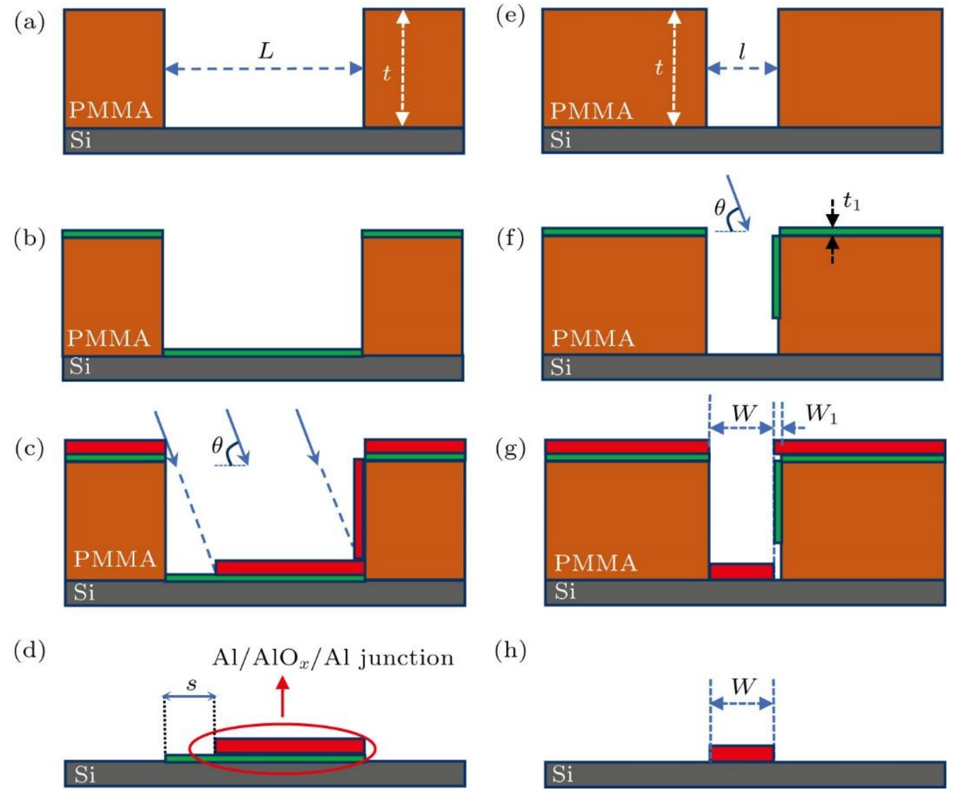
Junction

Fab features

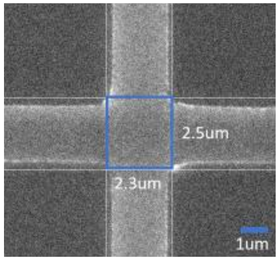
- Single-step optical lithography (NCHU laser writer)
- Manhattan-style junction (In-house e-beam evaporator)

Cross Junction (Manhattan-Style) Method





Josephson is done in a single vacuum



Advantage:

Large area junction

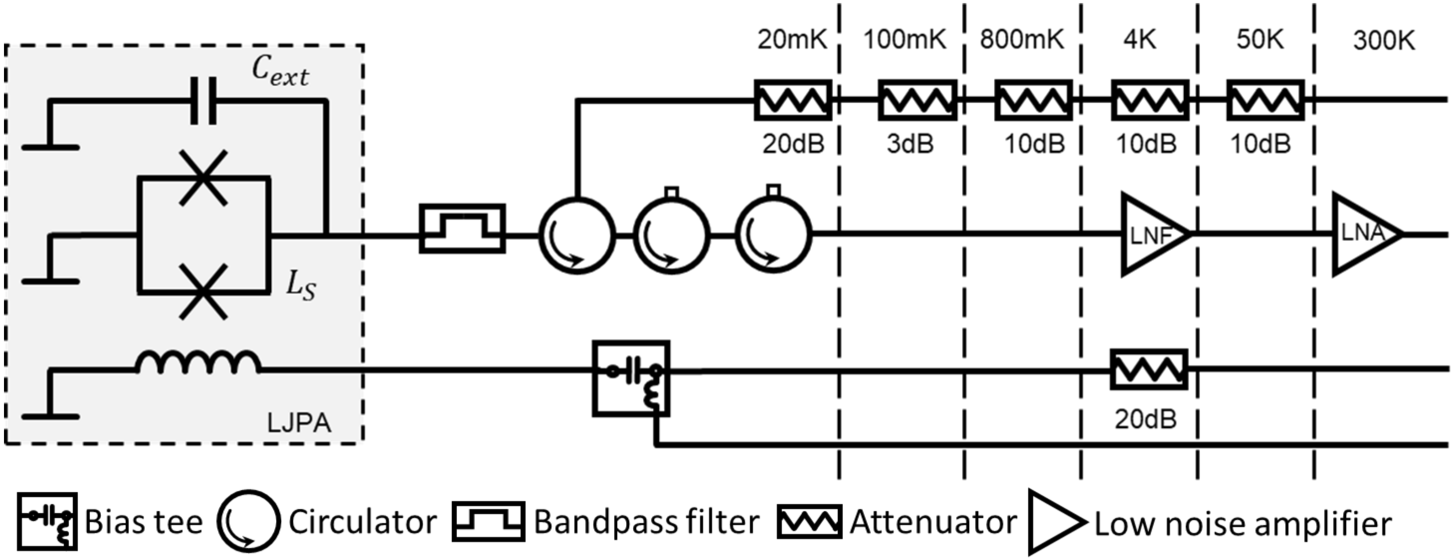
More controllable, higher yield

M. V. Costache *et al.*, *J. Vac. Sci. Technol. B* **30**, 04E105 (2012)

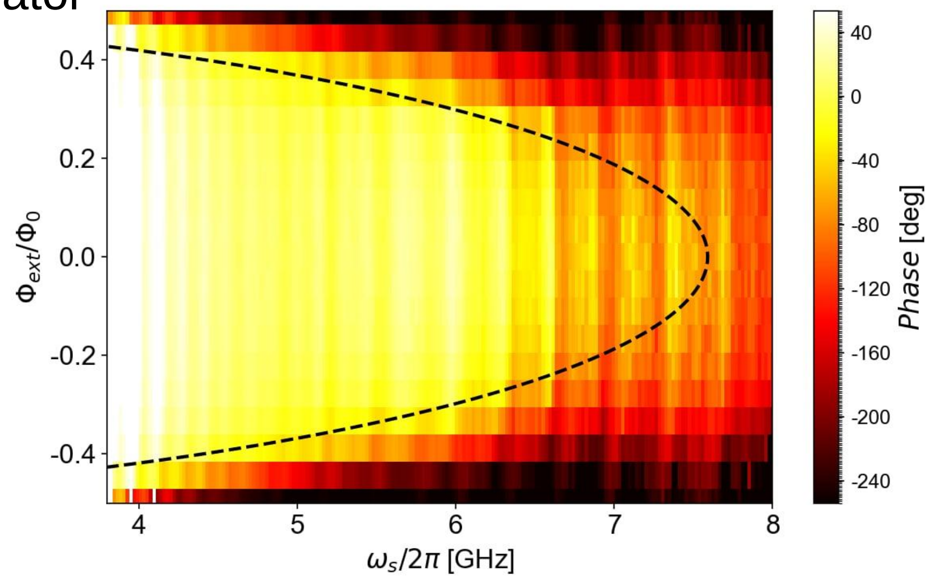
Z. Ke *et al.*, *Chin. Phys. B* **26**, 078501 (2017)

LJPA Measurement

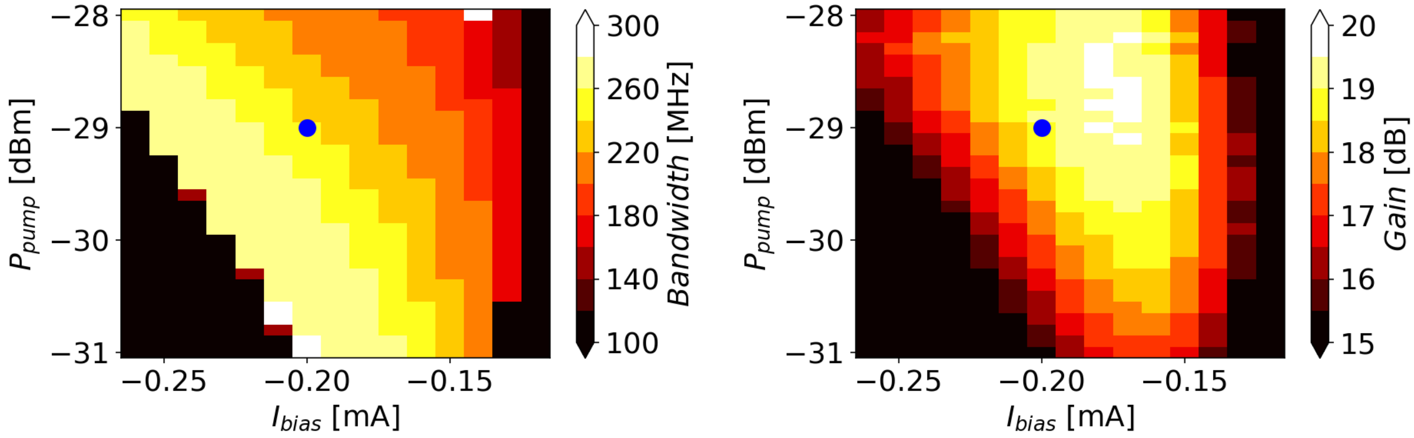
Measurement circuitry

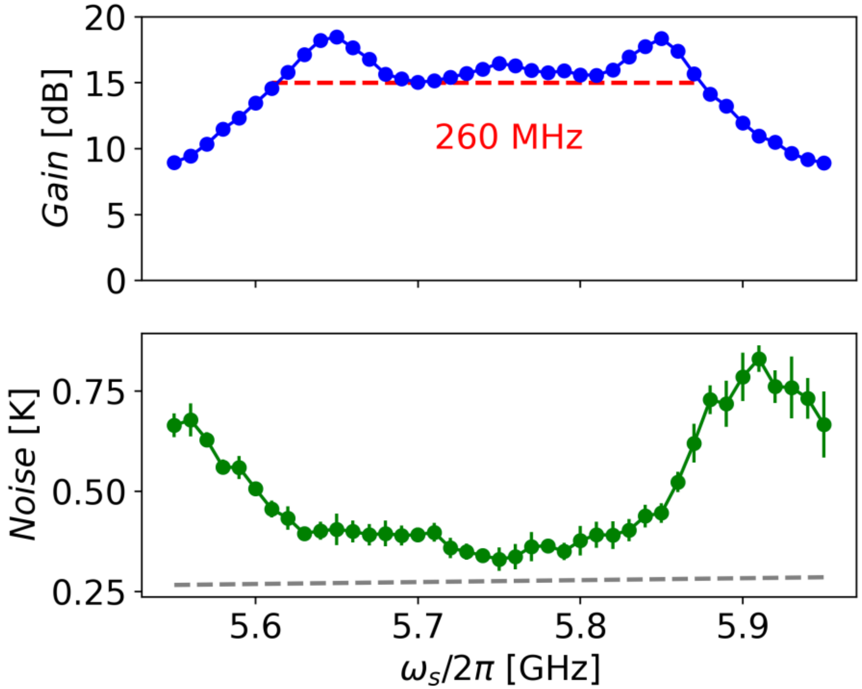


Tunable resonator

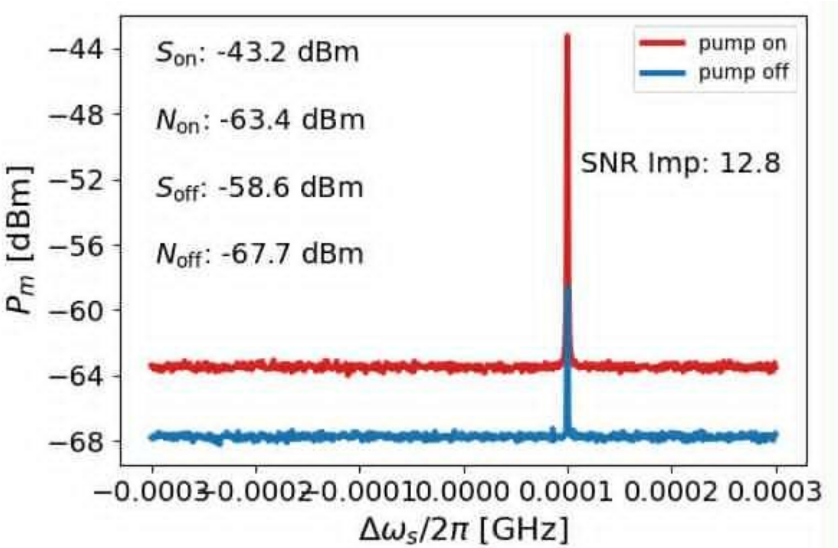


Operation Condition Search





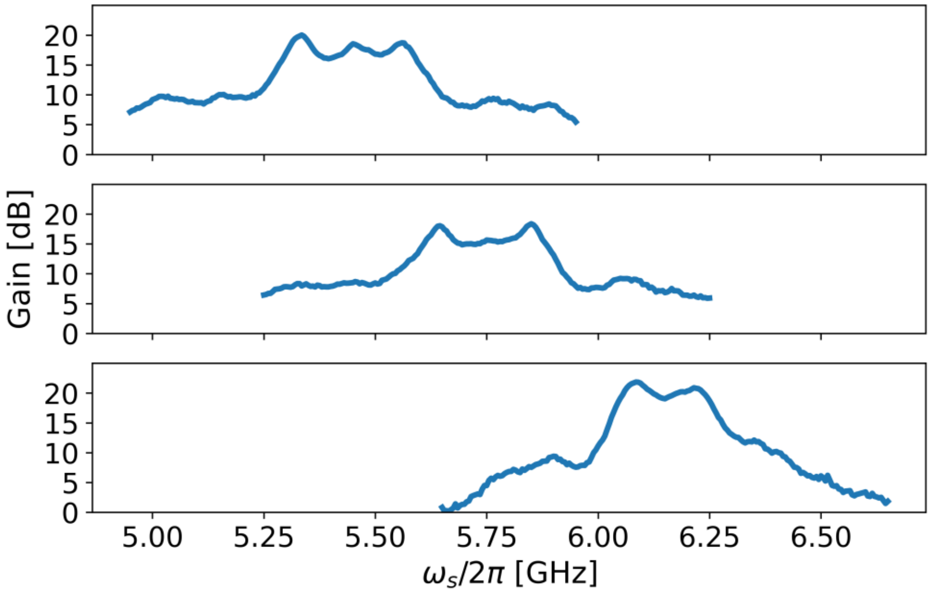
SNR improvement



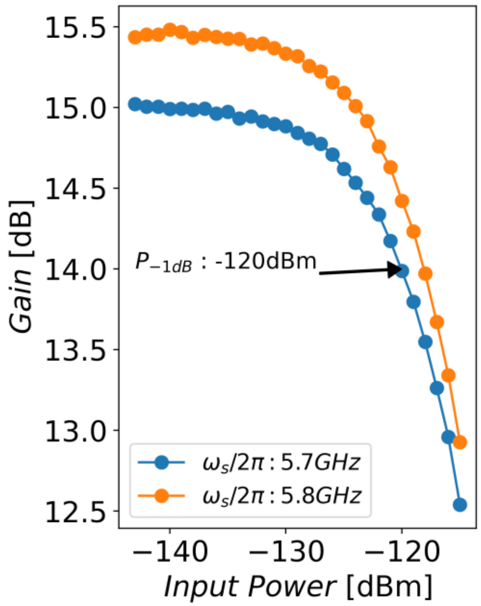
LJPA Performance

- Design frequency: 2–6 GHz
- Frequency tuning: ~ 1 GHz
- Bandwidth: 30–250 GHz
- Noise: ~ 1 photon (nearly quantum-limited)
- Saturation power: ~ -120 dBm

Tuning of gain curve

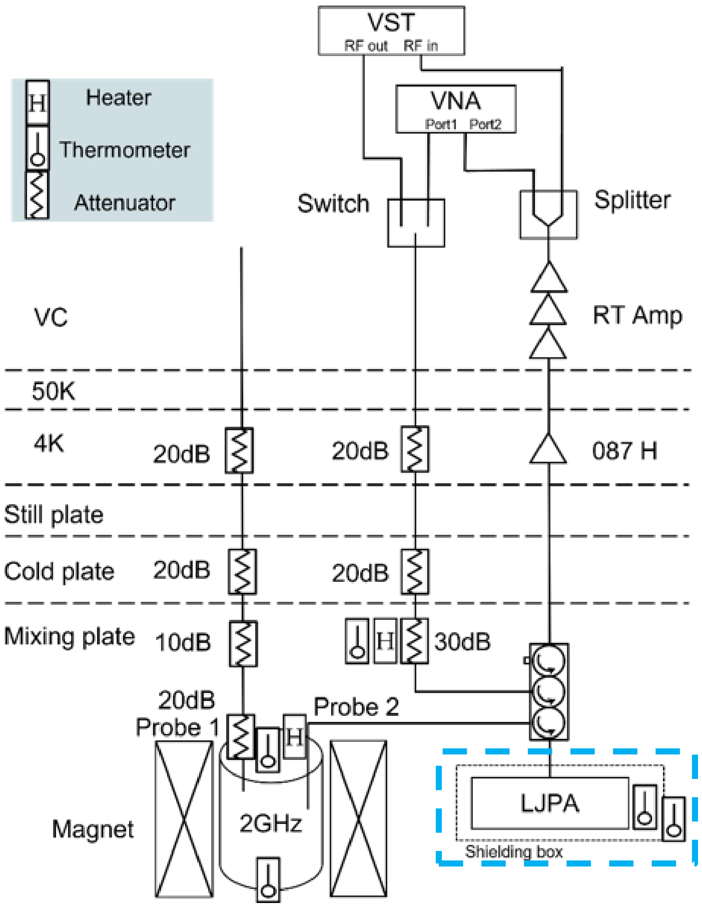


Saturation power



Application: Axion Haloscope Readout

2-GHz haloscope setup schematic

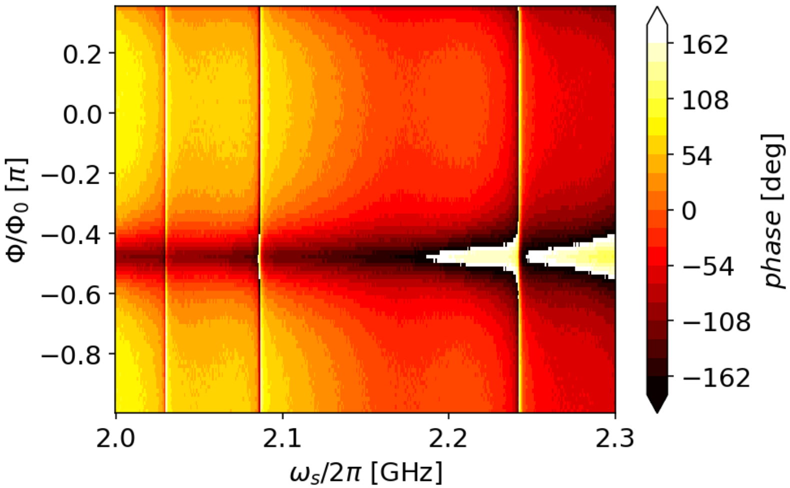


- Stronger magnet with a larger bore
- Larger cavity
- LJPA (quantum-limited amplifier)

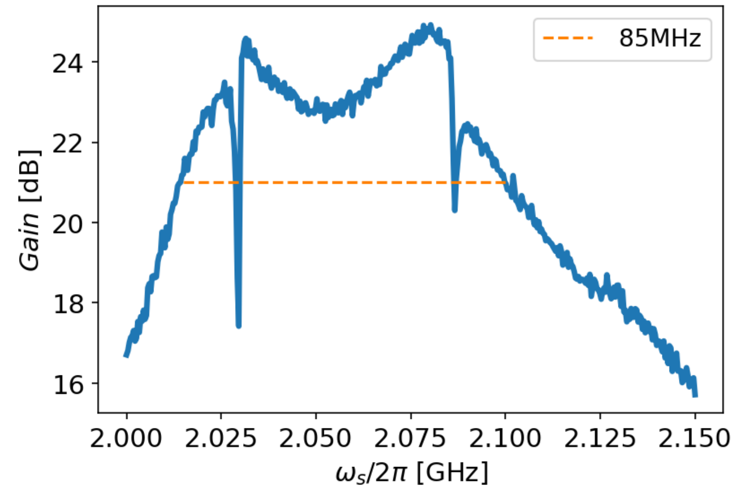
Setup overview

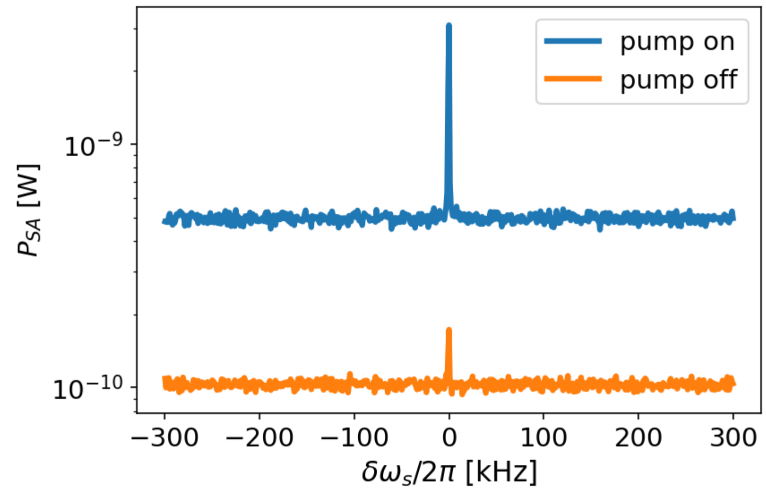
LJPA Performance at 2 GHz

Resonator frequency tuning



Gain and noise





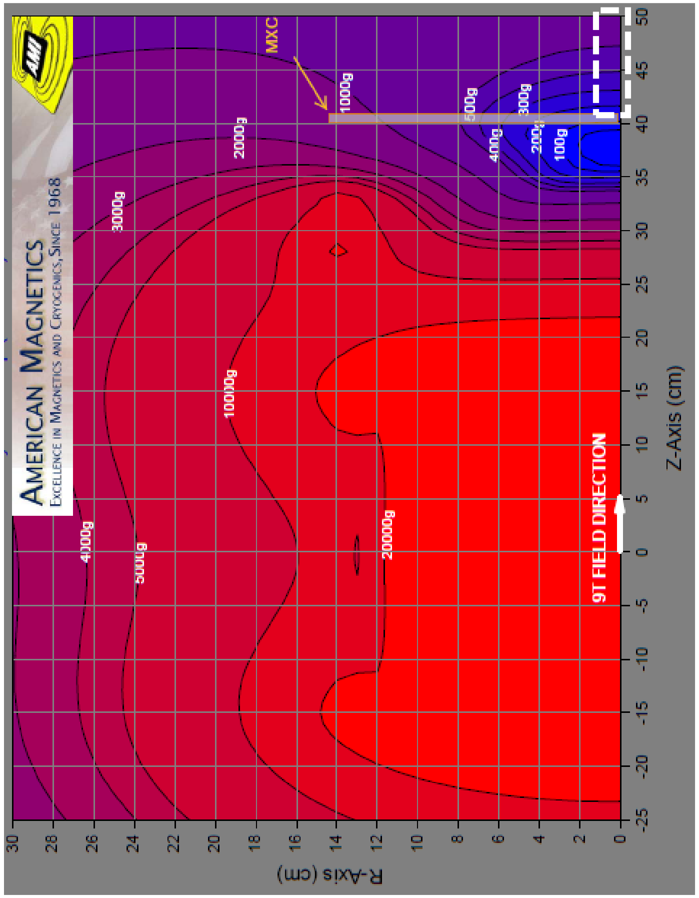
Performance at 2 GHz

Gain	> 15 dB
Bandwidth	85 MHz
Frequency tuning range	2 – 2.3 GHz
Saturation power	-125 dBm
System noise	< 0.25 K (2 photons)

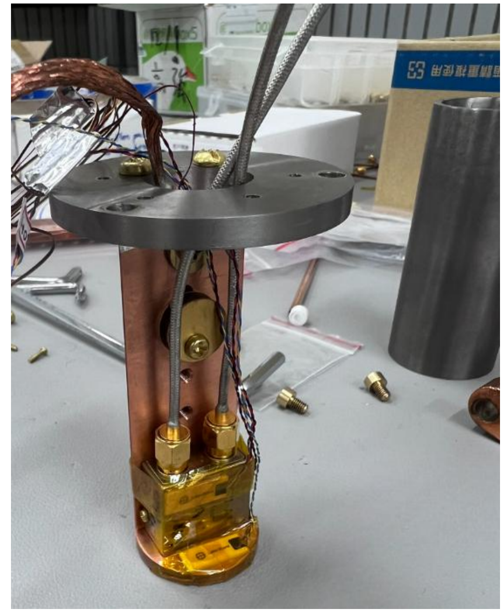
Magnetic Field Shielding: Single-Layer Niobium

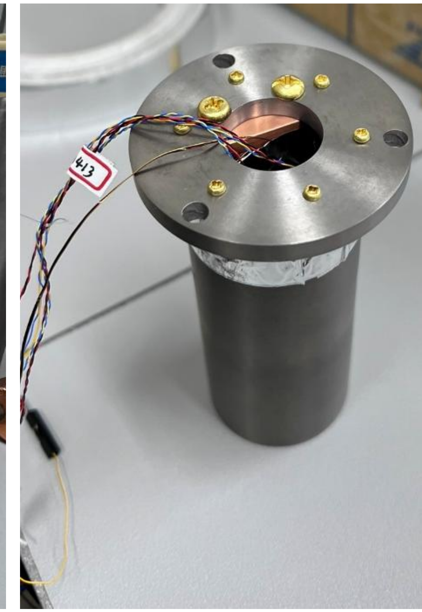
Field map of magnet

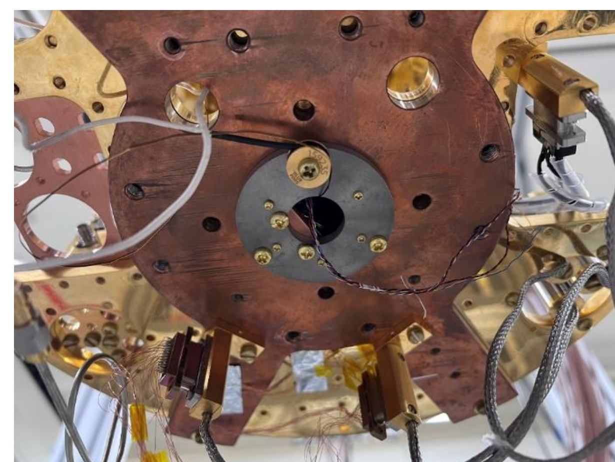
Shielding location
A few hundred Gauss



Magnetic field shielding assembly





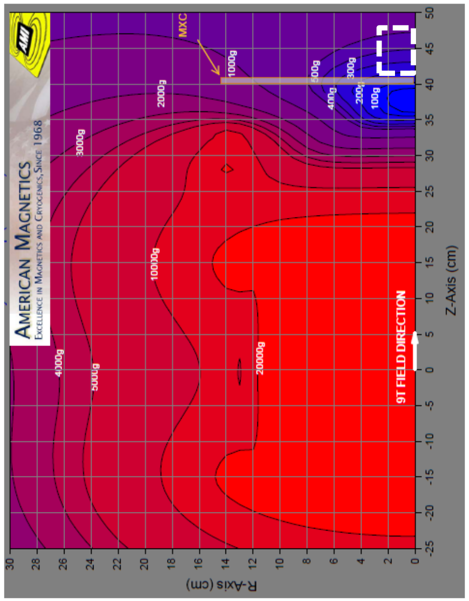


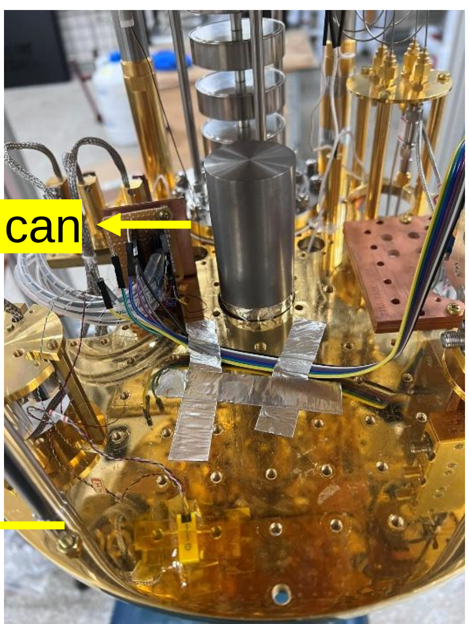
Features

- Niobium (superconducting) shield
- Simple one-layer design
- Goal: field reduced by a factor of 10,000

Shielding Performance

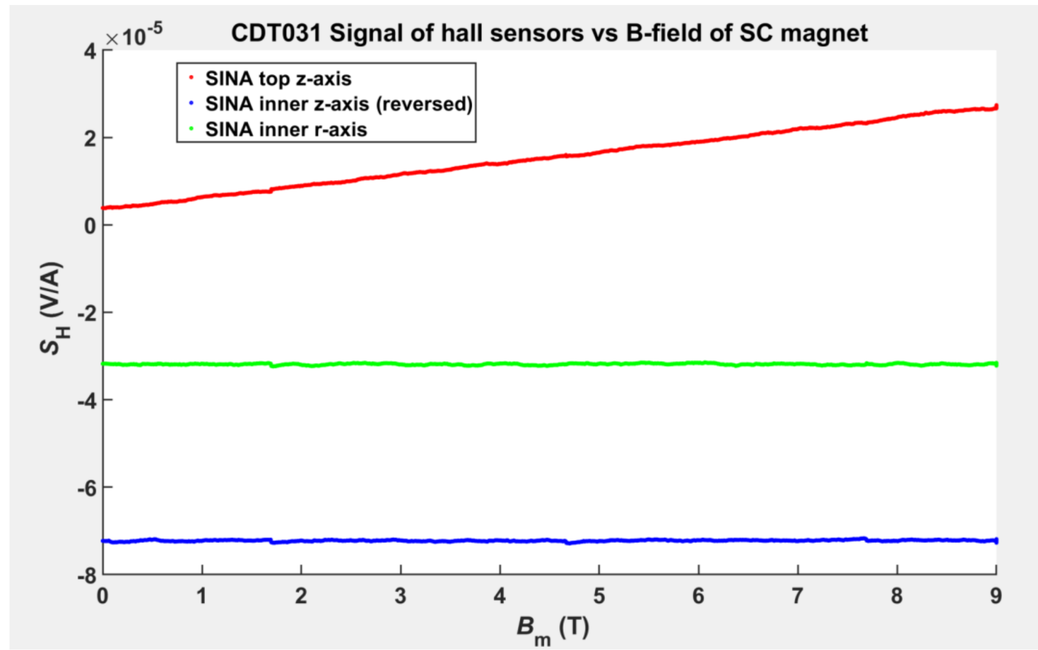
Field map of superconducting magnet





Nb shielding can

MXC plate

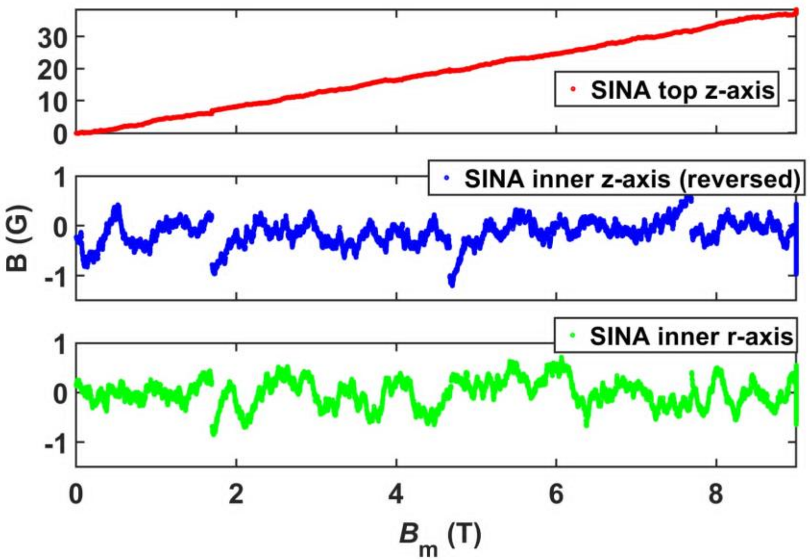


Test results:

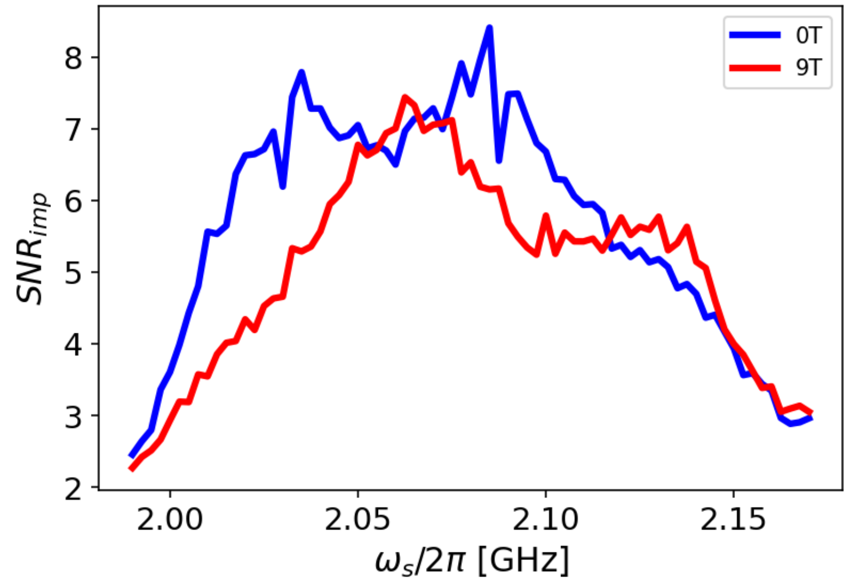
- No significant field change (> 0.1 G) in the shielding is detected when a 9T magnet is energized.
- Field reduced by a factor of > 5000 (residual field of < 0.1 G)

Shielding Effect

Hall sensor measurement



LJPA performance

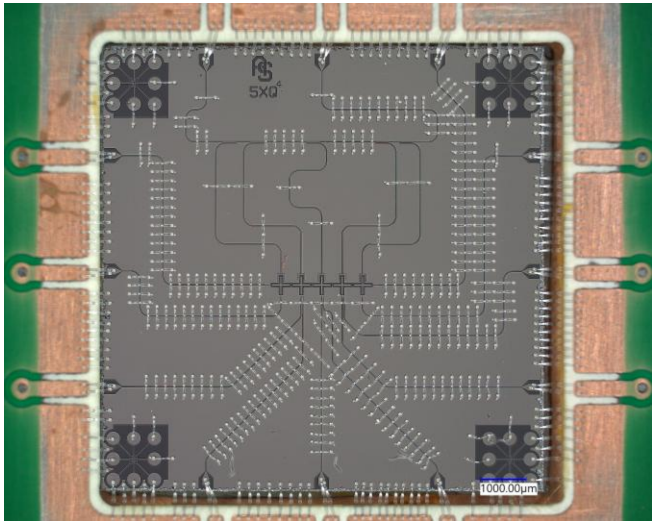


- No significant field change (> 0.1 G) in the shielding is detected when a 9T magnetic field is applied to the cavity.
- However, LJPA is affected, but still maintains good noise performance.

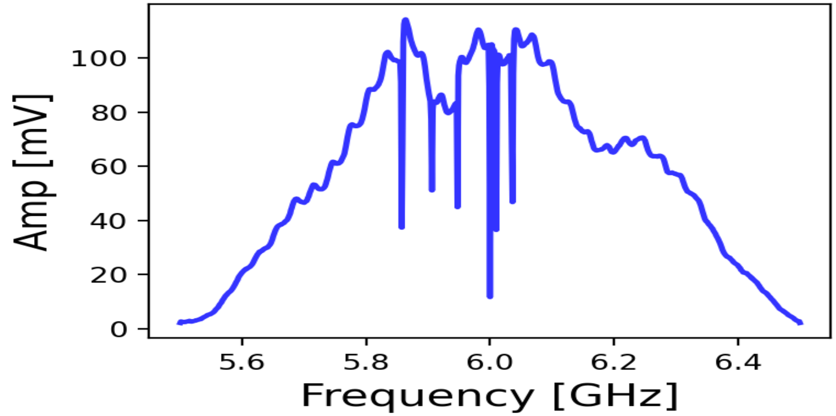
Application: Qubit Readout

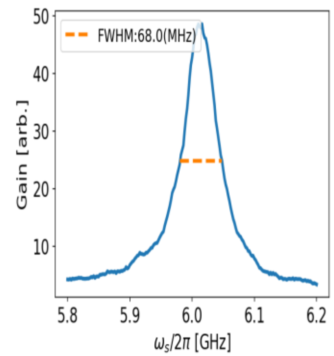
Academia Sinica 5-qubit QPU

Source: Prof. Chii-Dong Chen

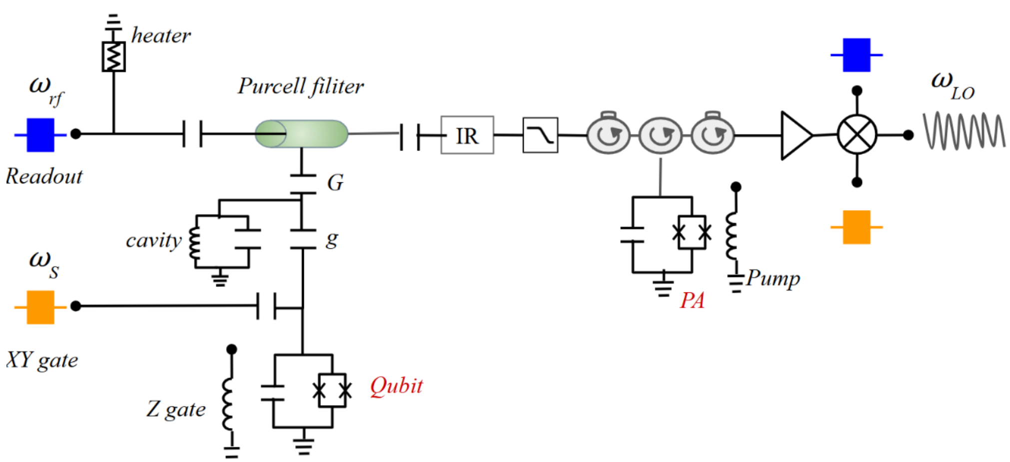


QPU readout and LJPA gain profiles

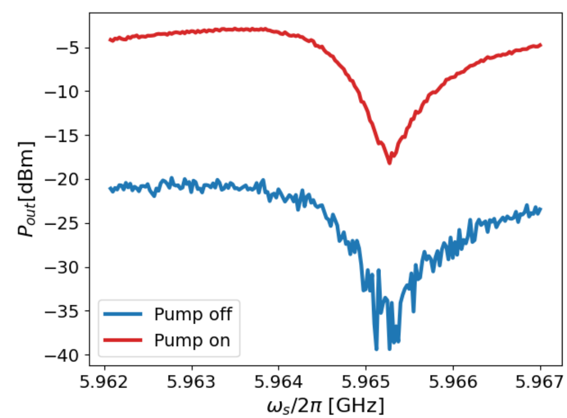




Wiring of qubit readout via LJPA

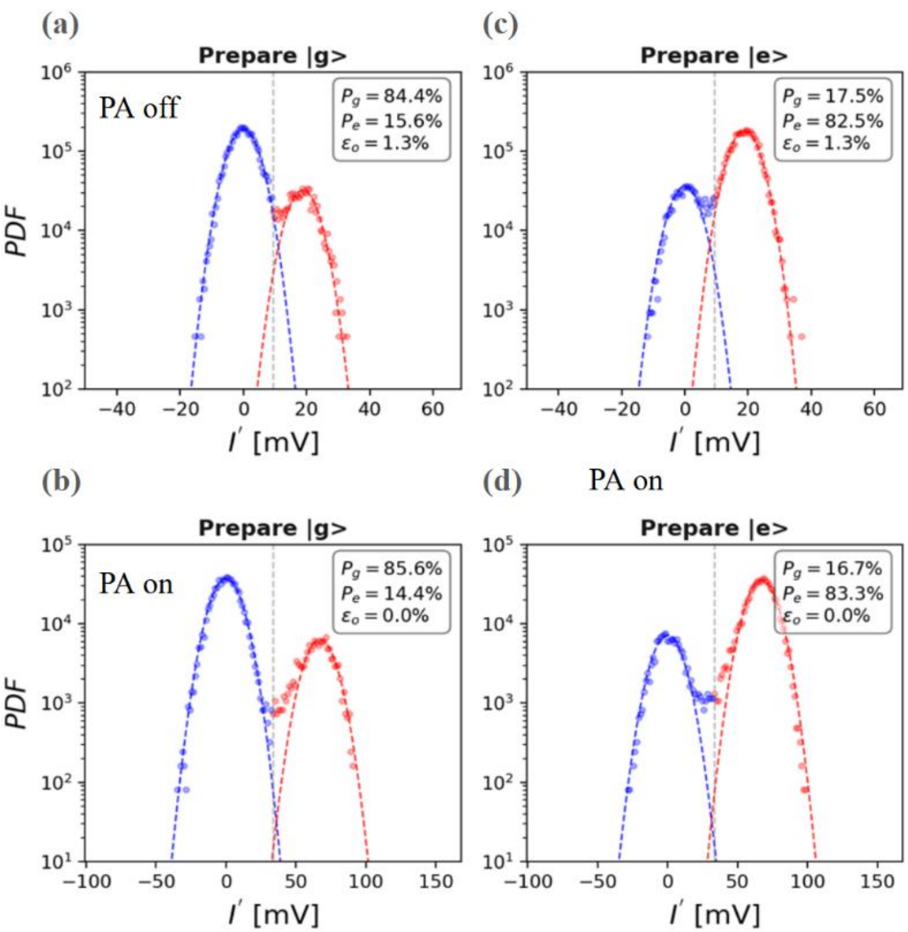


Resonator spectrum as LJPA on/off

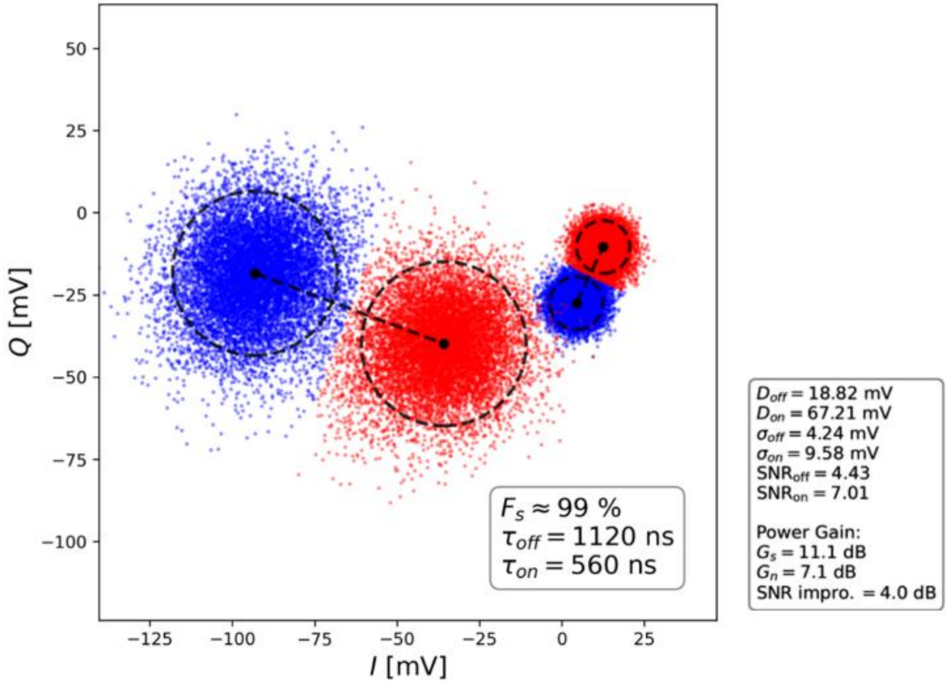


Single-Shot Readout

The same readout time



The same readout fidelity

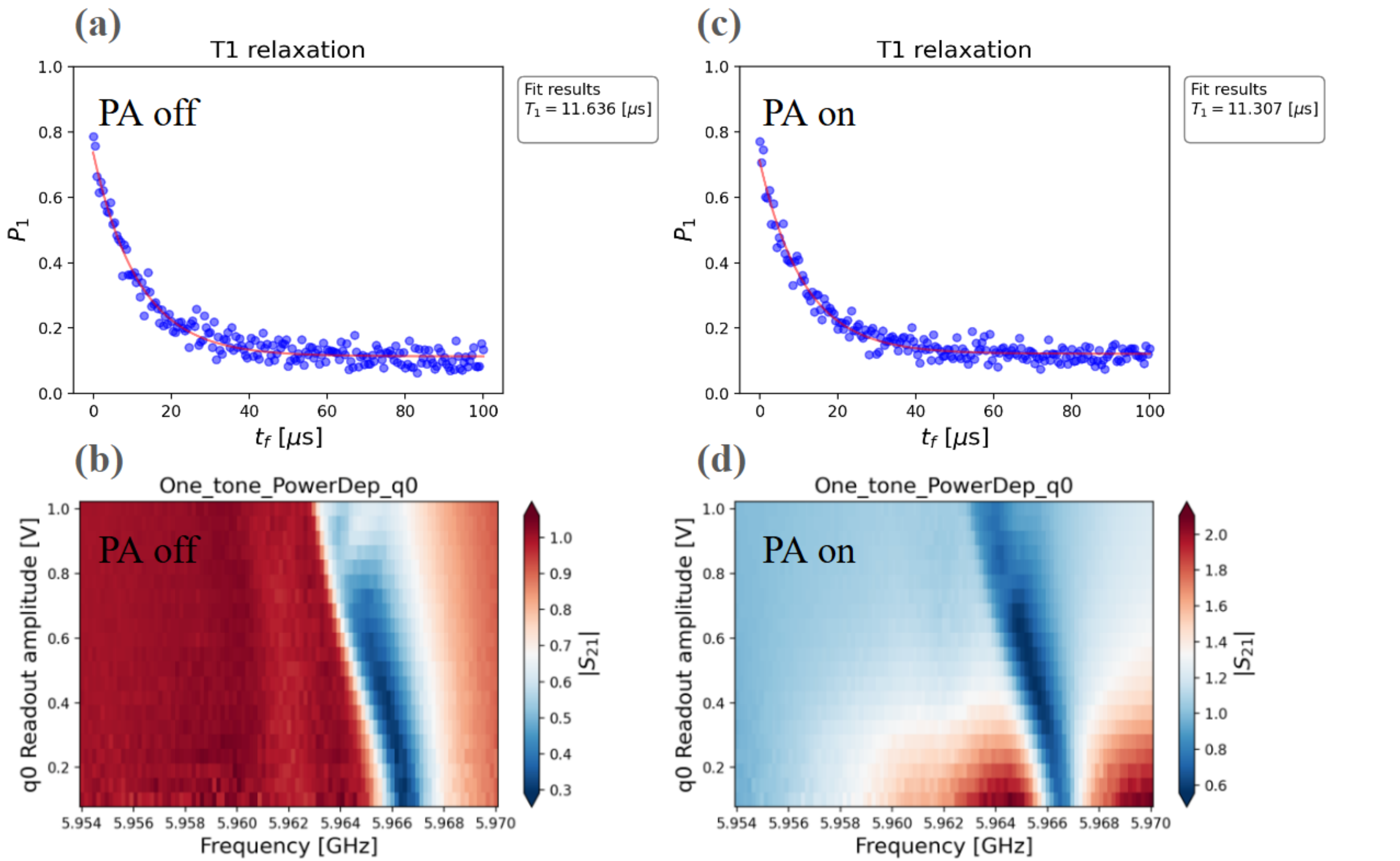


LJPA operation increases readout fidelity

Shorten the needed integration time

Back Action Check

Comparison of qubit readout with LJPA off and on



Readout with LJPA pump off and on shows no difference in qubit coherence.

Need for Qubit Multiplexed Readout

- Higher power (> -115 dBm)
- High bandwidth (> 300 MHz)

Striving Direction

- Develop multistep lithography for compact circuit layout design

J. Mutus *et al.*, *APL* **103**, 122602 (2013)

- Use SQUID array to increase saturation power

N. Frattini *et al.*, *PRApplied* **10**, 054020 (2018)

T. White *et al.*, *APL* **122**, 014001 (2023)

- Add an Input impedance transformer on LJPA to enhance bandwidth (IMPA)

T. Roy *et al.*, *APL* **107**, 262601 (2015)

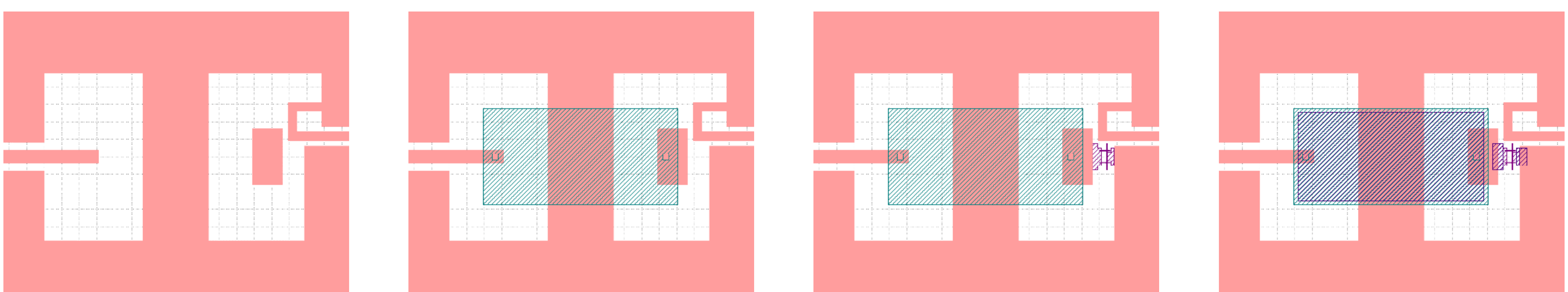
J. Grebel *et al.*, *APL* **118**, 142601 (2021)

- Develop TWPA

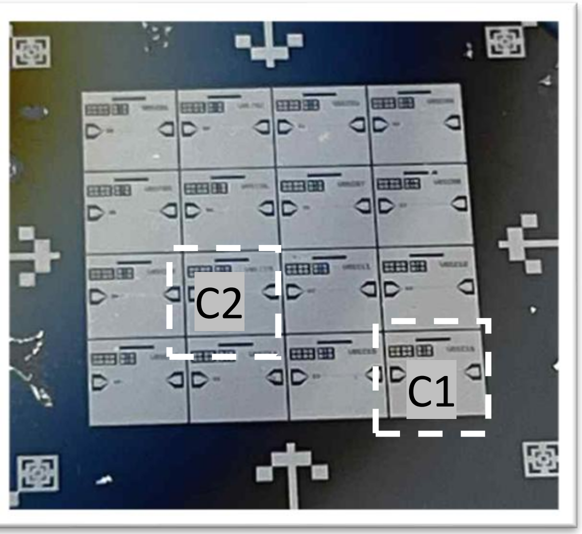
C. W. S. Chang, *et al.*, arXiv:2503.07559

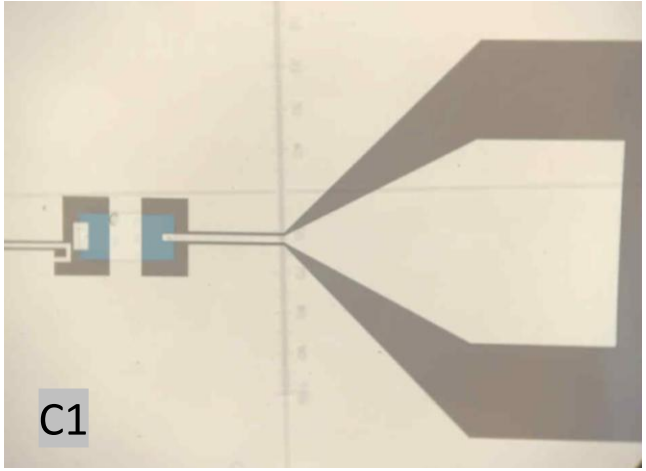
Multi-layer Fabrication Development

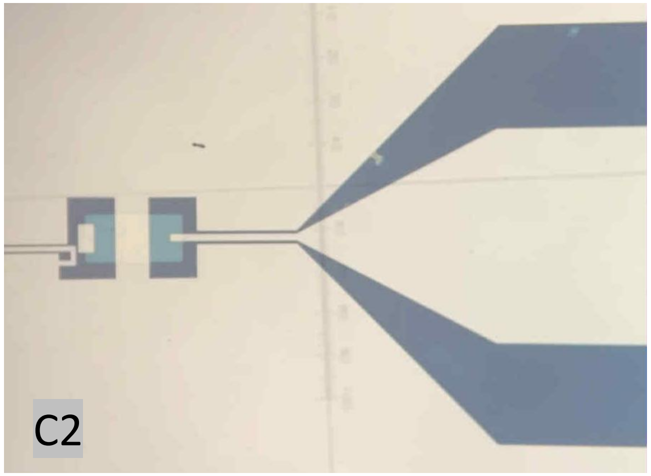
First layer (GND + $C_{bot\ elect}$)	Dielectric layer (Silicon dioxide)	Second layer (JJ)	Contact layer (Contact + $C_{up\ elect}$)
Deposit (100 nm Al) Lithography Etching	Deposit (150 nm SiO2) Lithograph Etching	Lithography Deposit (100 nm Al) Lift off	Lithography Ion milling Deposit (100 nm Al) Lift off
NCHU – MLA150 NCU - Egun (Ohmiker 50 BIS)	TSRI - Oxford PECVD TSRI - I-line stepper TSRI - Oxford PECVD	NCHU – MLA150 NCU - Egun (Ohmiker 50 BIS)	NCHU – MLA150 NCU - Egun (Ohmiker 50 BIS)



Early Tries



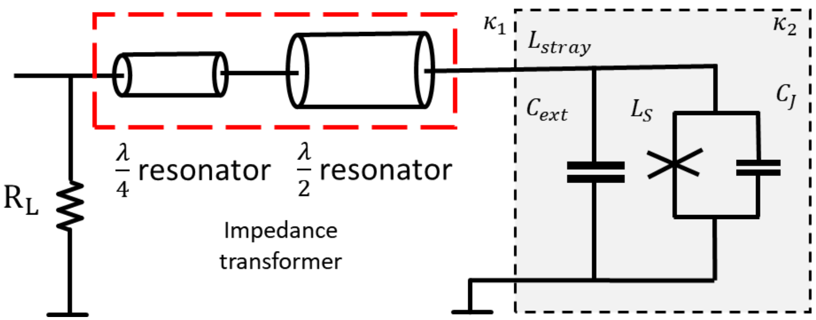




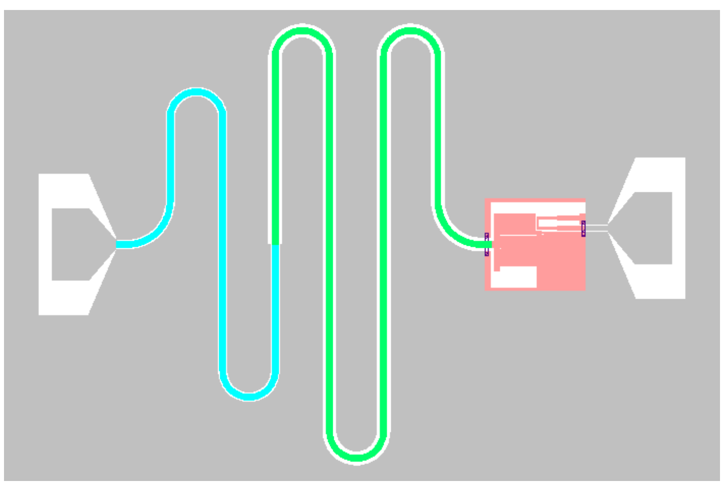
- Developing SiOx fabrication for a parallel capacitor
- Uneven SiOx etching rate

IMPA Physics and Design

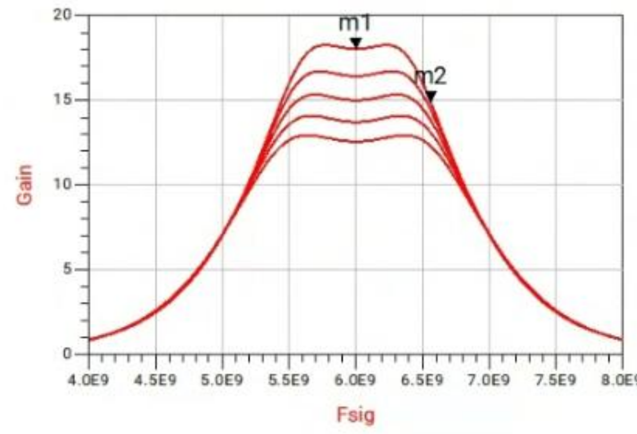
Circuit



Layout

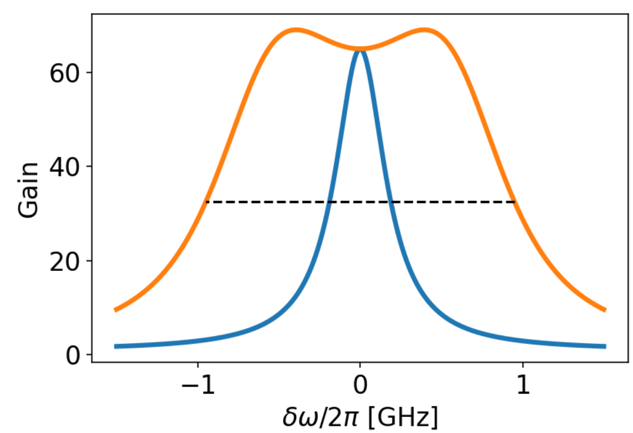


Theory



Gain	18 dB
BW	1.1 GHz

Circuit simulation

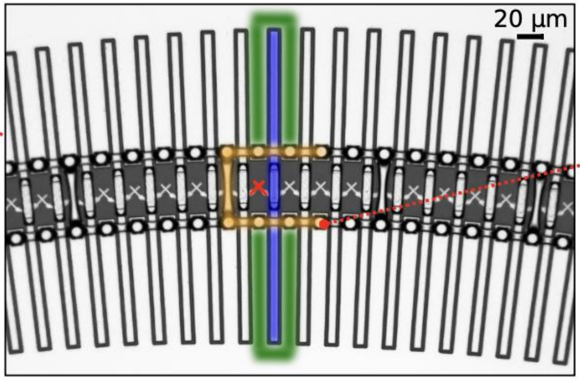


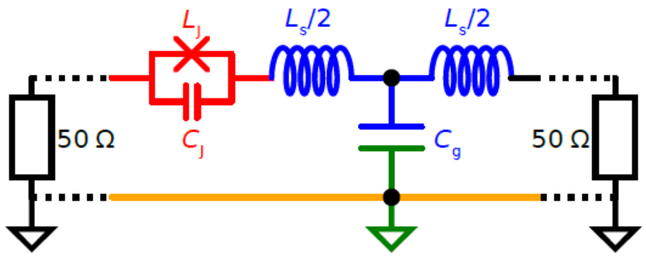
Gain	18 dB
BW	1.8 GHz

- Theory calculation and circuit simulation agree.
- The impedance transformer provides broadband performance.

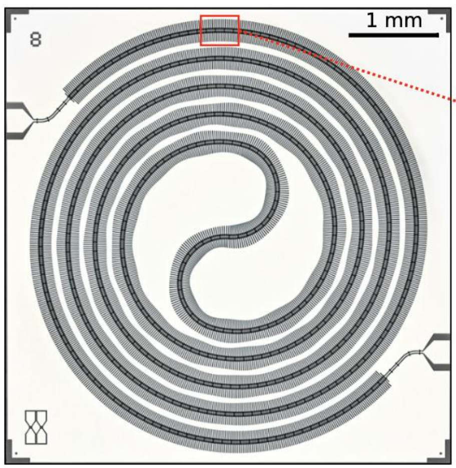
Al-Based TWPA

Work from RIKEN

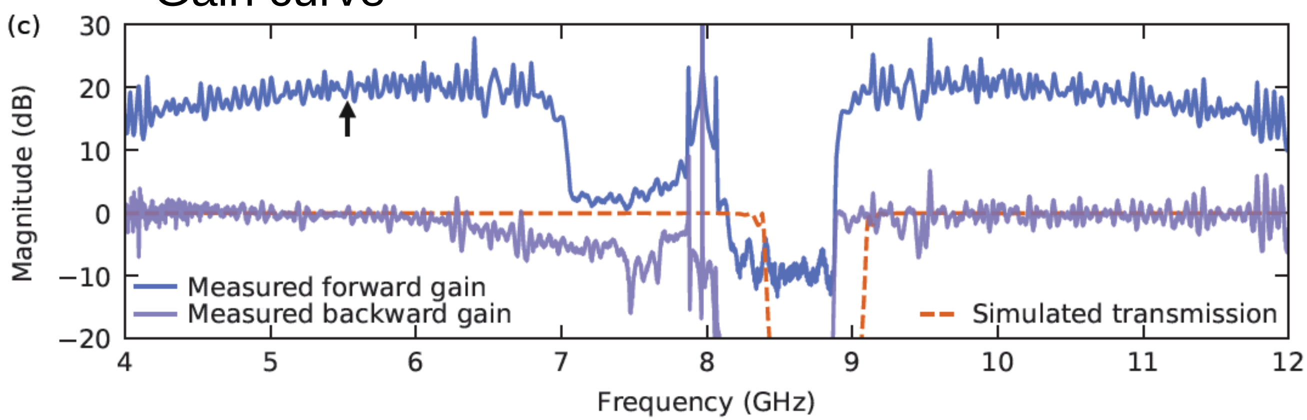




- Aluminum base layer
- Fish-bone capacitor
- Manhattan junction array
- Airbridge



Gain curve

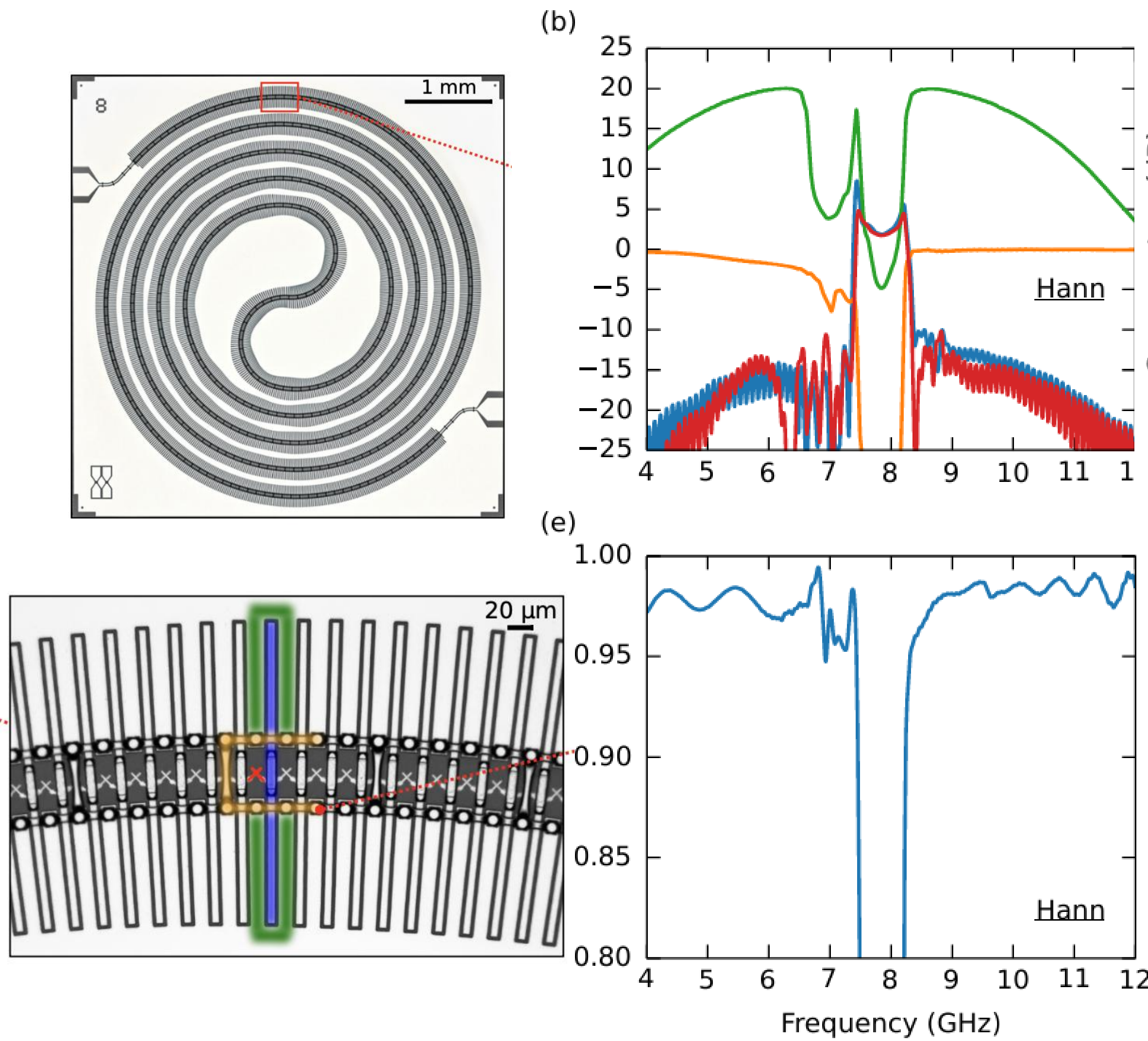


C. W. S. Chang, *et al.*, arXiv:2503.07559

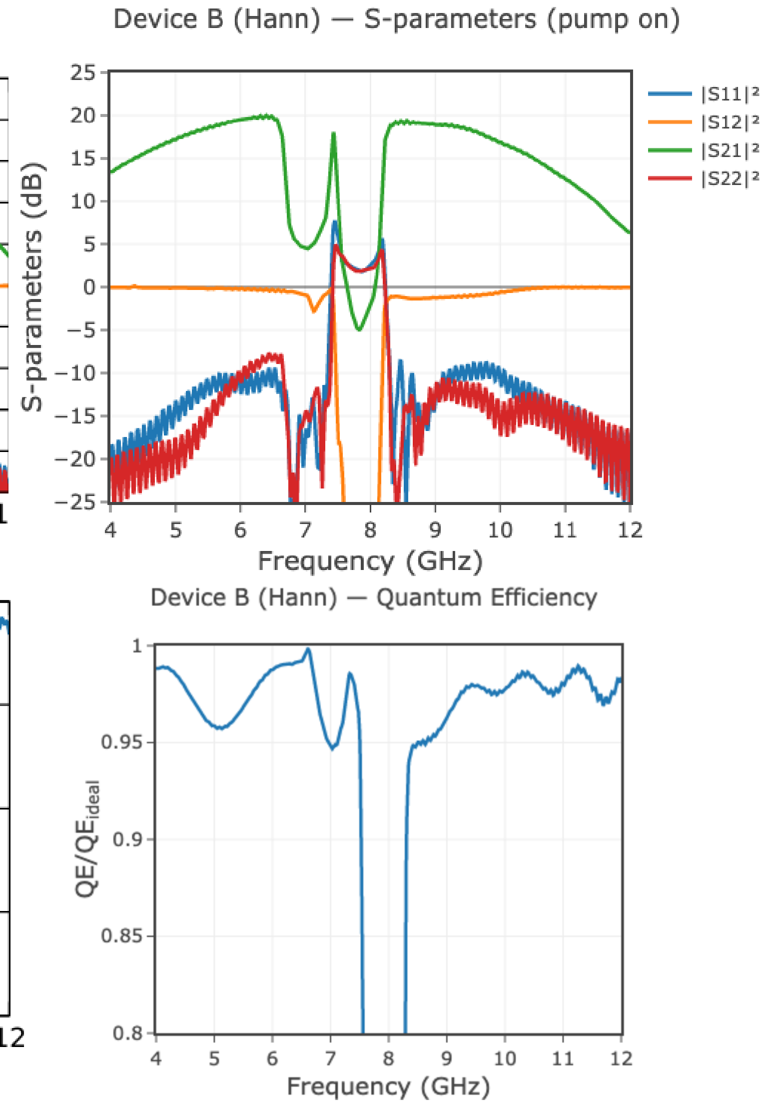
Performance

Gain	17 – 20 dB
Bandwidth	4.8 MHz
Saturation power	-99 dBm
System noise	0.32 K (1.2 photons)

Al-Based TWPA



arXiv:2503.07559 (2025) from RIKEN



Reproduction of circuit simulation

Al-Based TWPA

- Fabrication is developed together with NTHU Prof. Jeng-Chung Chen and Dr. Ching-Ping Lee.
- QC-Fab in ASSC.

Thanks to Our Team

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邱羽君	曾子揚
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Collaborators

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CENTER FOR HiGH ENERGY AND HiGH FIELD PHYSICS

中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA

Thank you for listening.

Comment/question?