Development of JPA and Magnetic Shielding for Axion Search

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Taiwan Axion Search Experiment with Haloscope, NCU

Axion Detection Sensitivity

Cavity & Magnet

$$P_a = \left(g_{a\gamma\gamma}^2 \frac{\hbar^3 c^3 \rho_a}{m_a^2}\right) \times (\omega_c \frac{1}{\mu_0} B_0^2 V C Q_L \frac{\beta}{1+\beta})$$

$$SNR = \frac{P_a}{\sigma}$$

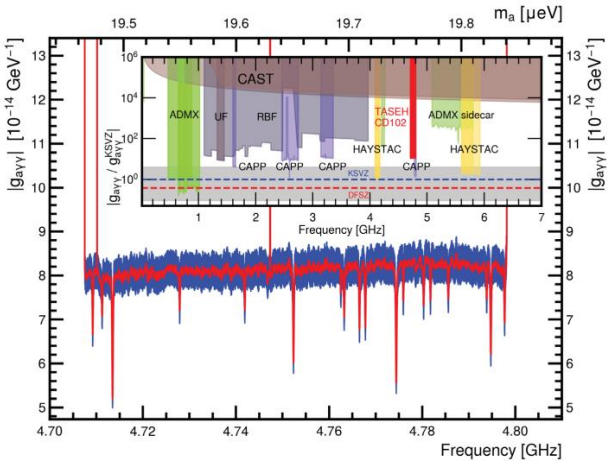
$$\sigma = \frac{k_B T_{sys} \Delta f}{SSE\sqrt{N}}$$

JPA & data taking strategy

parameter	Remarks
SNR	Signal to noise ratio
P_a	Typical axion signal power
σ	Average noise power
T_{sys}	Effective system noise temperature
Δf	Resolution bin width
N_{a102}	Amount of data
SSE	Scan

The efficiency of reducing "σ"

1. T_{sys} factor of 1
2. N: factor of square root



From TASEH CD102 result :

① $P_a \sim 1.4 \times 10^{-24} W$

② $\boldsymbol{T_{sys} \sim 2K}, \rightarrow \sigma \sim 1.4 \times 10^{-23} W$

$\rightarrow \sim 8.1 g_{a\gamma\gamma}$

After integrating JPA in detection chain

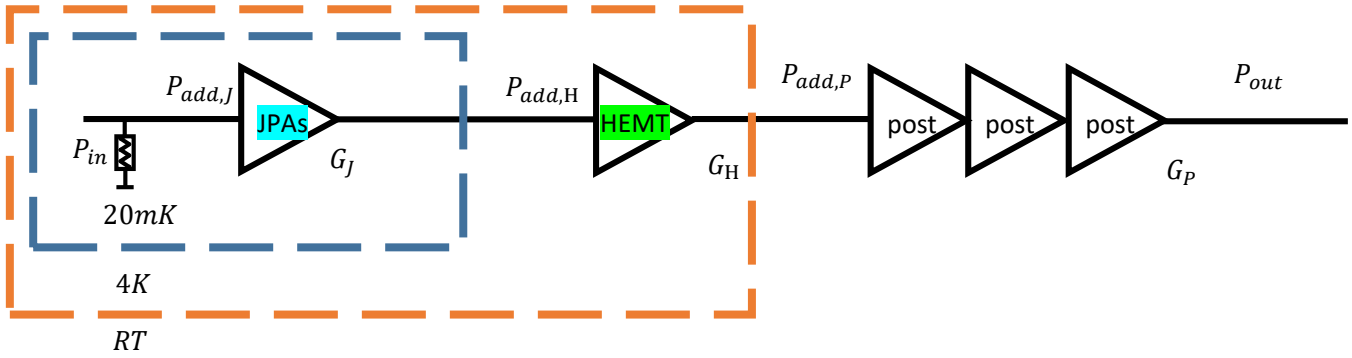
① $P_a \sim 1.4 \times 10^{-24} W$

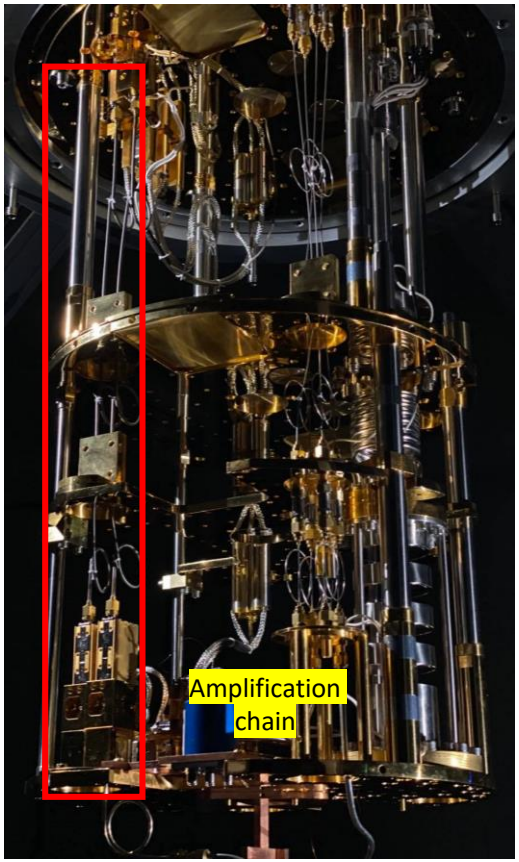
② $\boldsymbol{T_{sys} \sim 0.3K}, \rightarrow \sigma \sim 2.1 \times 10^{-24} W$

$\rightarrow \sim 3.13 g_{a\gamma\gamma}$ (with the same data taking time)

Hsin Chang et al, Phys. Rev. Lett. **129**, 111802 (2022)

Amplification Chain





Noise power after sequential Amplifiers:

$$P_{out} = G_p(G_H(G_J(P_{vc} + P_{add,J}) + P_{add,H}) + P_{add,P})$$

$$P_{out} = G_p G_H G_J \left(\left((P_{in} + P_{add,J}) + \frac{P_{add,H}}{G_J} \right) + \frac{P_{add,P}}{G_J G_H} \right)$$

$$P_{out} = G_{tot} k_B T_{sys} \Delta f = G_p G_H G_J \Delta f (\mathrm{T_{in}} + \mathrm{T_{add,J}} + \frac{\mathrm{T_{add,H}}}{G_J} + \frac{\mathrm{T_{add,P}}}{G_J G_H})$$

$$T_{sys} = \mathrm{T_{in}} + \mathrm{T_{add,J}} + \frac{\mathrm{T_{add,H}}}{G_J} + \frac{\mathrm{T_{add,P}}}{G_J G_H}$$

parameter	Remarks
G	Gain from amplifier
P_{add}	Add noise from amplifier
T	Effective noise temperature

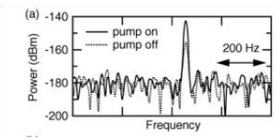
Quantum Parametric Amplifier

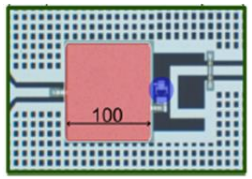
Phase I

Reflection Type (LJPA, IMPA):

- **FDJPA**
- 20dB Gain
- 2*SQL system noise
- 2MHz BW
- -135dBm saturation power
- citation 450

Appl. Phys. Lett. 93, 042510 (2008)



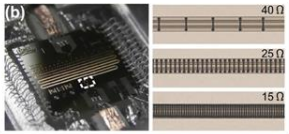


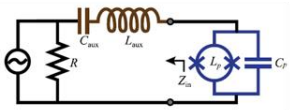
- **LJPA (Mutus)**
- 20dB Gain
- SQL system noise
- 50MHz BW
- -115dBm saturation power
- citation 108

Appl. Phys. Lett. 103, 122602 (2013)

- **IMPA (Mutus)**
- 20dB Gain
- SQL system noise
- 600MHz BW
- -110dBm saturation power
- citation 179

Appl. Phys. Lett. 104, 263513 (2014)



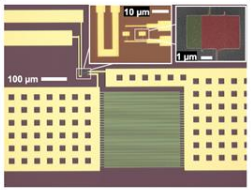


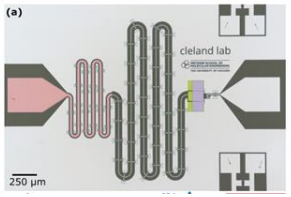
- **IMPA (Roy)**
- 20dB Gain
- SQL system noise
- 640MHz BW
- -110dBm saturation power
- citation 152

Appl. Phys. Lett. 107, 262601 (2015)

- **LJPA (Elo)**
- 20dB Gain
- SQL system noise
- 100MHz BW
- -125dBm saturation power
- citation 14

Appl. Phys. Lett. 114, 152601 (2019)



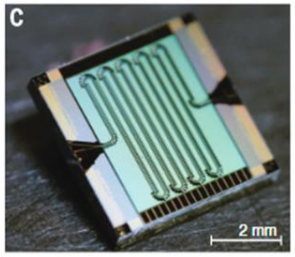


- **IMPA (Grebel)**
- 20dB Gain
- SQL system noise
- 300MHz BW
- -116dBm saturation power
- citation 29

Appl. Phys. Lett. 118, 142601 (2021)

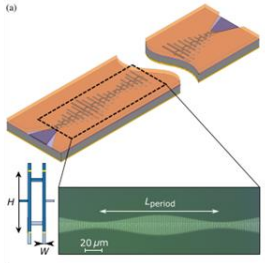
2008 2013 2018 2023

Transmission Type (TWPA) :



- **JTWPA**
- 20dB Gain
- 2*SQL system noise
- 6GHz BW
- -114dBm saturation power
- citation 667

ScienceVolume 350, Issue 6258 (2015)



- **STWPA**
- 18dB Gain
- 3*SQL system noise
- 3GHz BW
- -110dBm saturation power
- citation 49

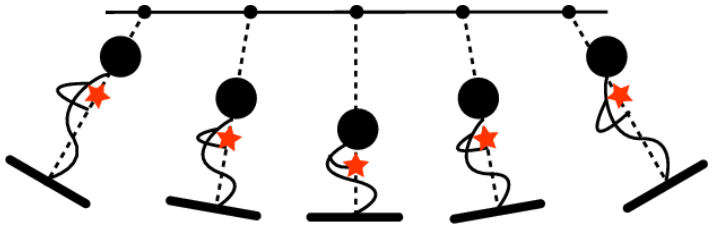
Phys. Rev. X 10, 021021 (2020)

Trade off between IMPA and TWPA : noise power & bandwidth

Perspective on traveling wave microwave parametric amplifiers, Samuel Goldstein et al, Appl. Phys. Lett. 119, 120501 (2021)

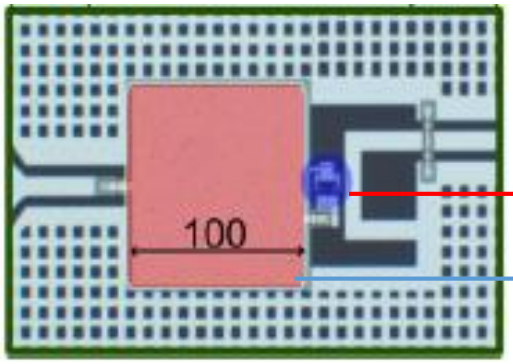
Phase II

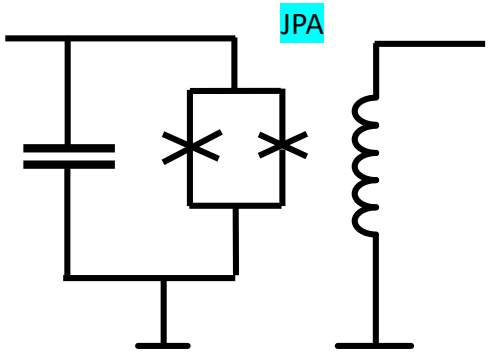
Josephson Parametric Amplifier



- LJPA (Mutus)
- 20dB Gain
- SQL system noise
- 50MHz BW
- -115dBm saturation power
- citation 108

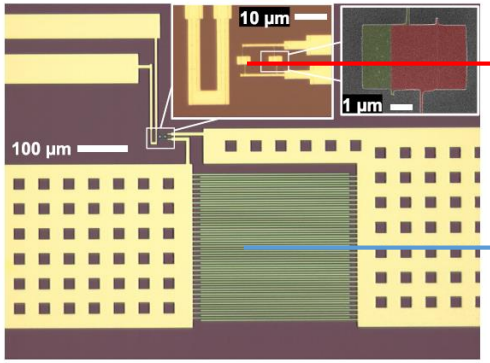
Appl. Phys. Lett. 103, 122602 (2013)





- LJPA (Elo)
- 20dB Gain
- SQL system noise
- 100MHz BW
- -125dBm saturation power
- citation 14

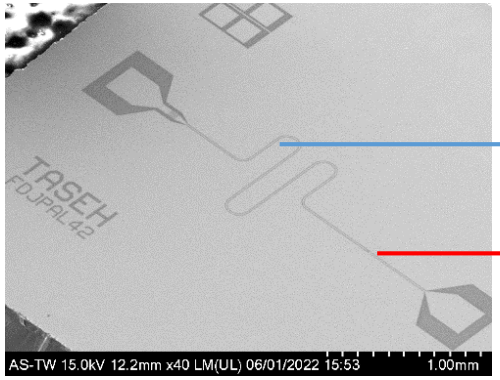
Appl. Phys. Lett. 114, 152601 (2019)



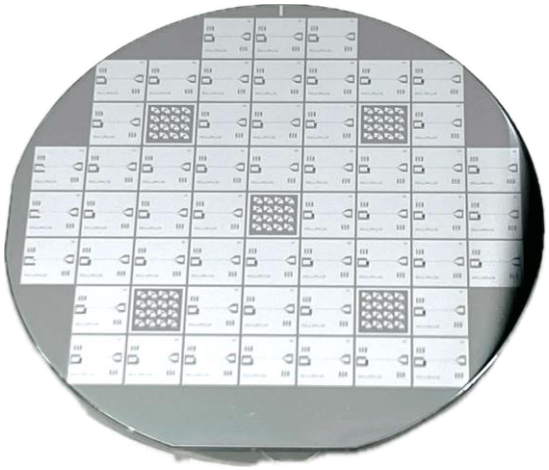
LC Circuit	Linear C/L
Nonlinear Element	Josephson Junction/ SQUID
Pump Feed line	3WM pump line

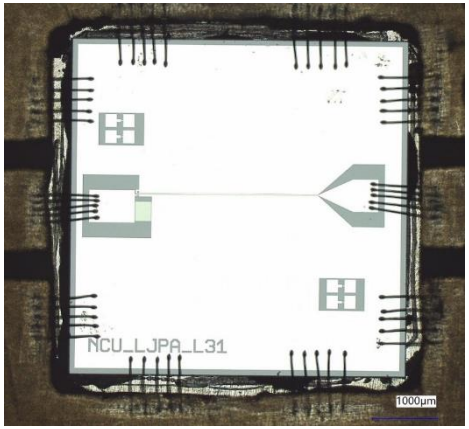
- FDJPA
- 20dB Gain
- 2*SQL system noise
- 2MHz BW
- -135dBm saturation power
- citation 450

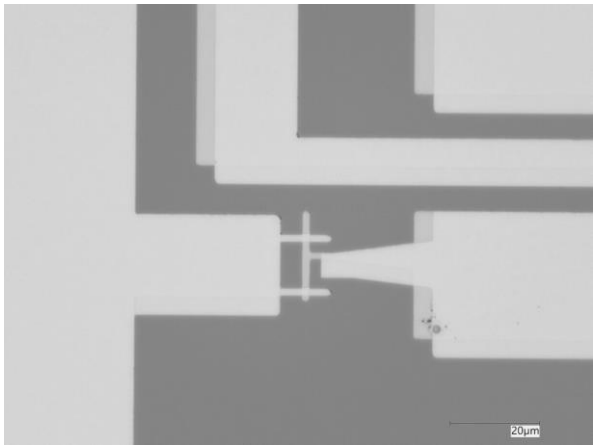
Appl. Phys. Lett. 93, 042510 (2008)

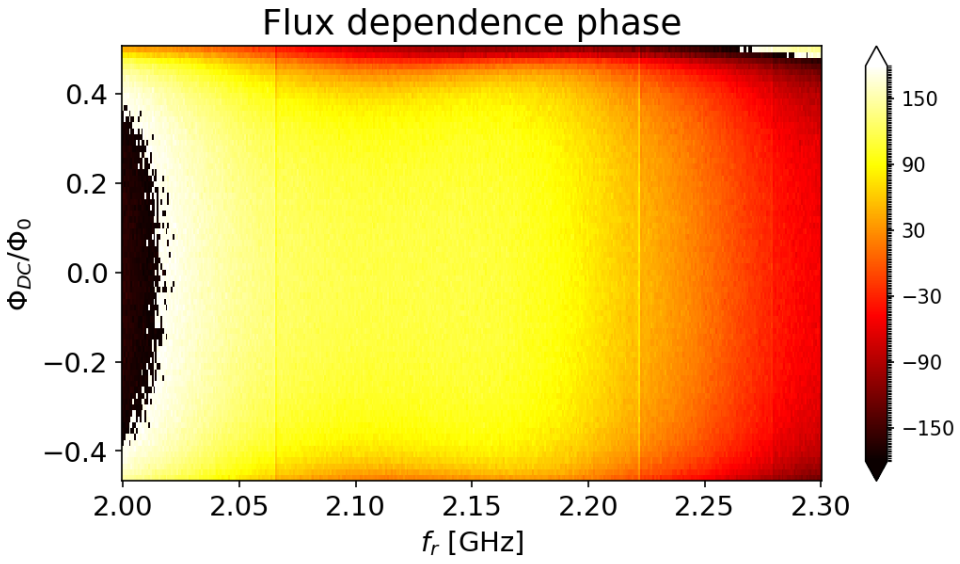


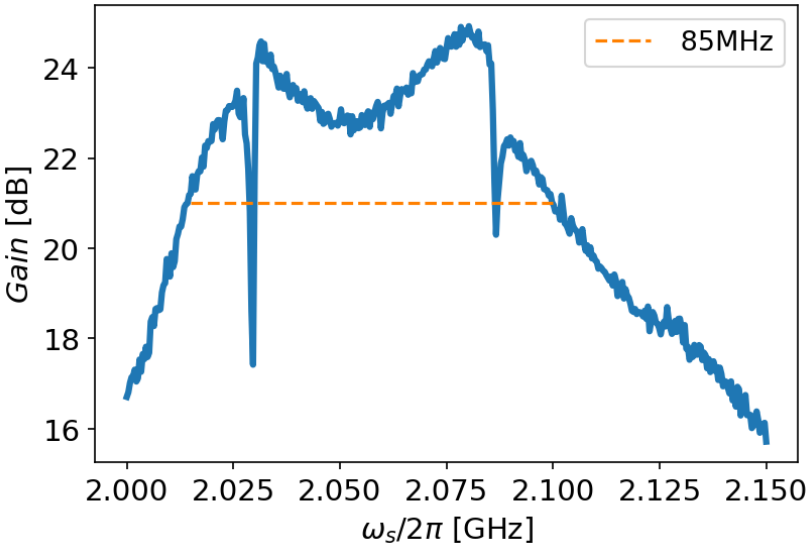
JPA at 2GHz



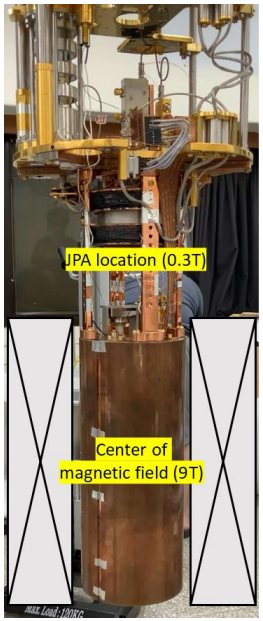

NCU_LJPA_L31
1000μm

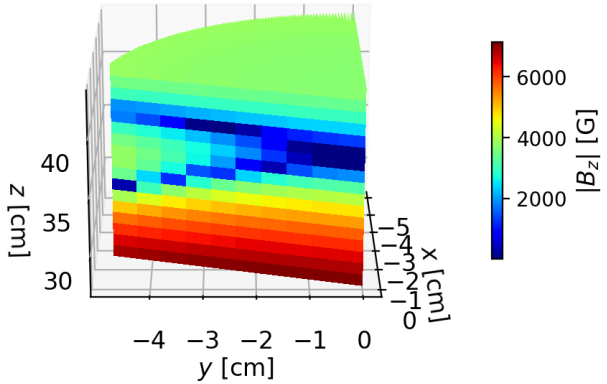

20μm

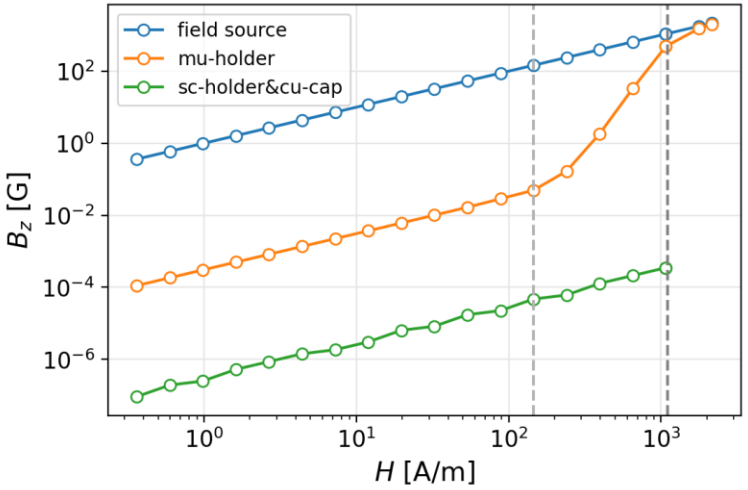

Flux dependence phase
Φ_{DC}/Φ_0
0.4
0.2
0.0
−0.2
−0.4
2.00
2.05
2.10
2.15
2.20
2.25
2.30
f_r [GHz]
150
90
30
−30
−90
−150
phase [deg]


85MHz
Gain [dB]
24
22
20
18
16
2.000
2.025
2.050
2.075
2.100
2.125
2.150
$\omega_s/2\pi$ [GHz]

Shielding

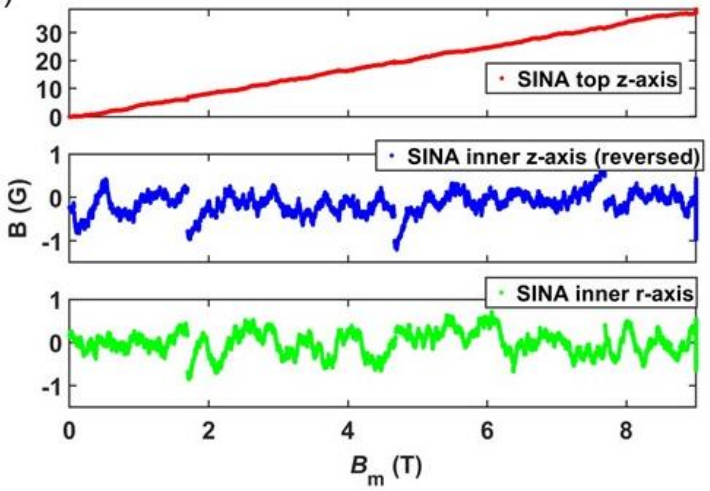




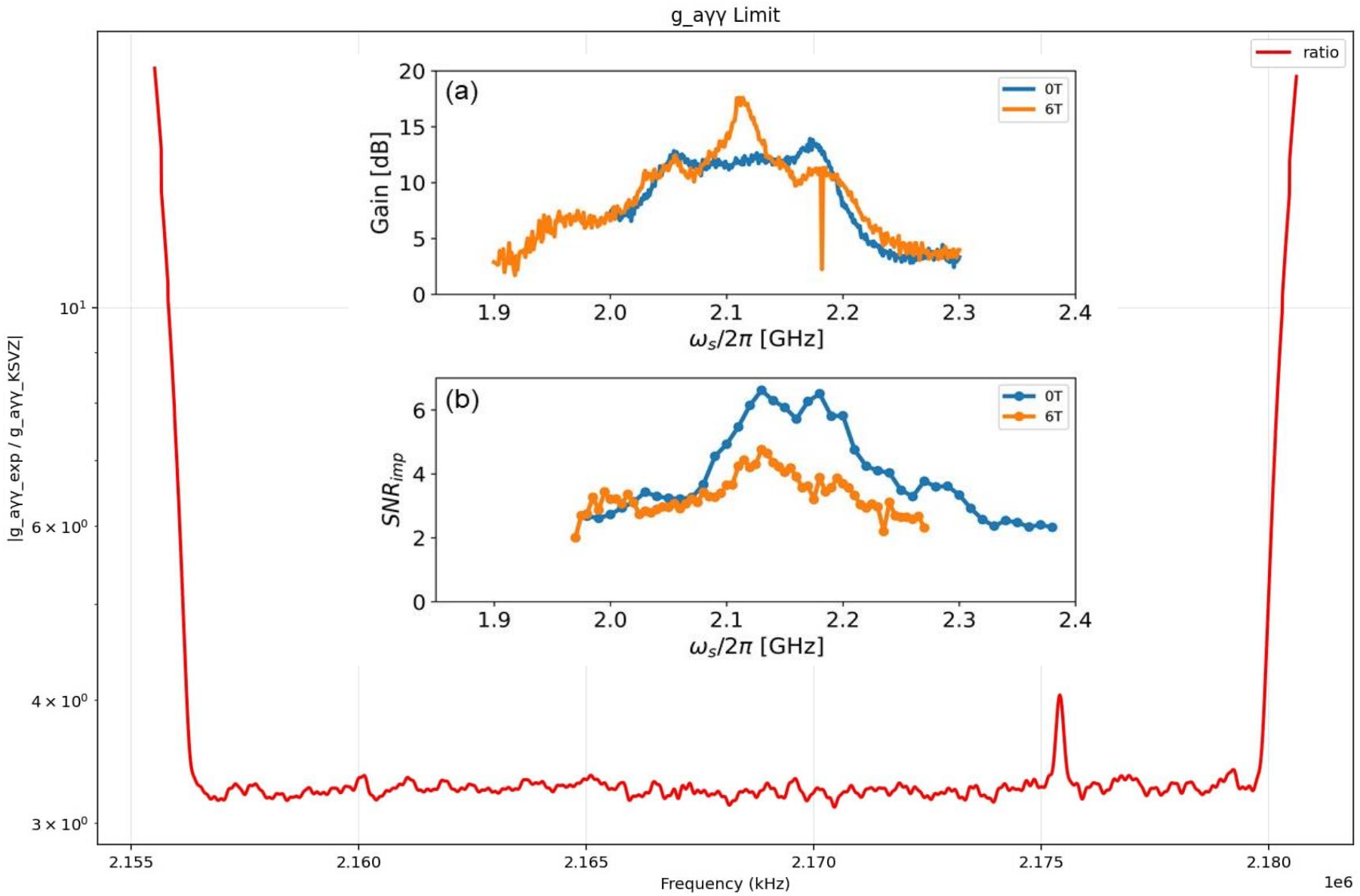


(a)

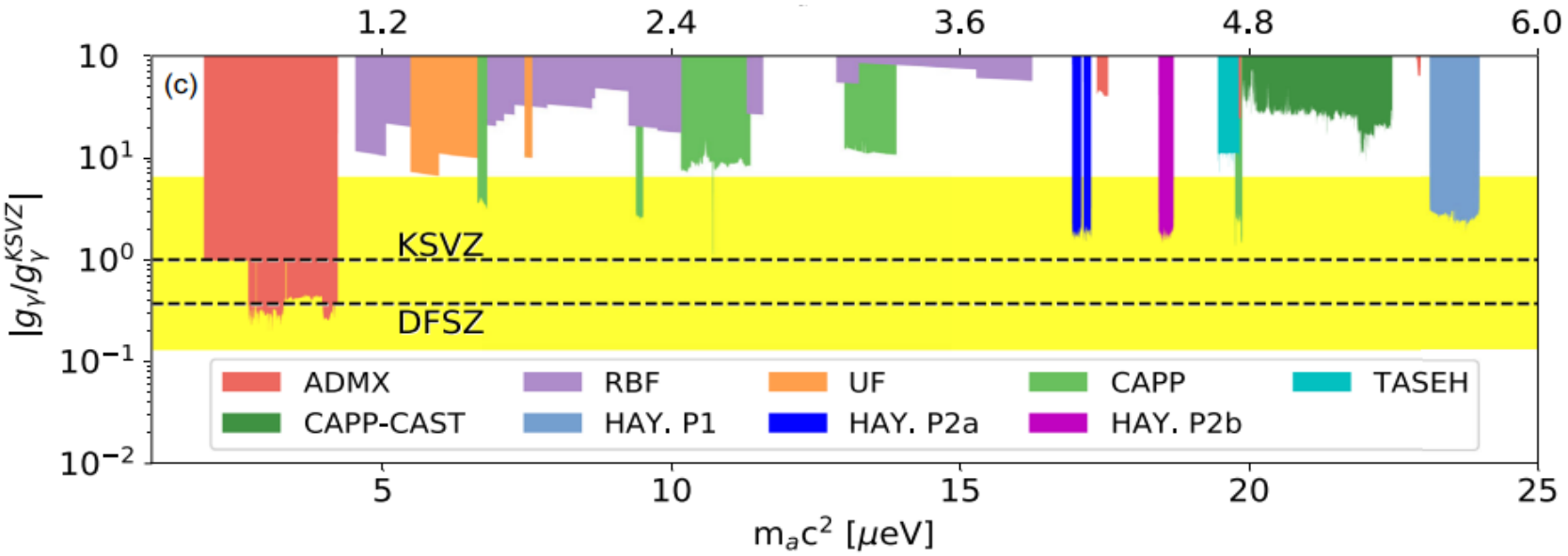
(b)

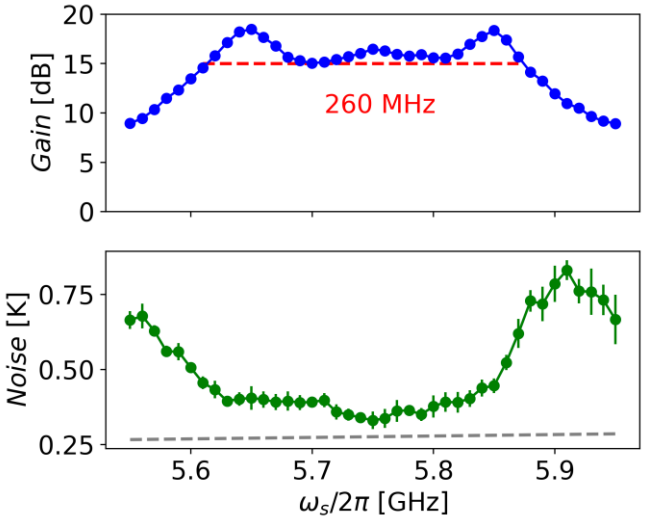


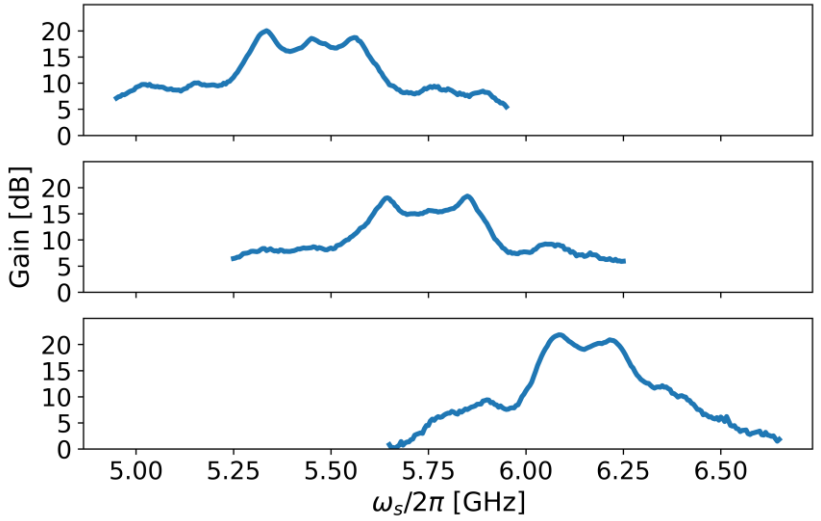
Implemented at Axion Detection Chain



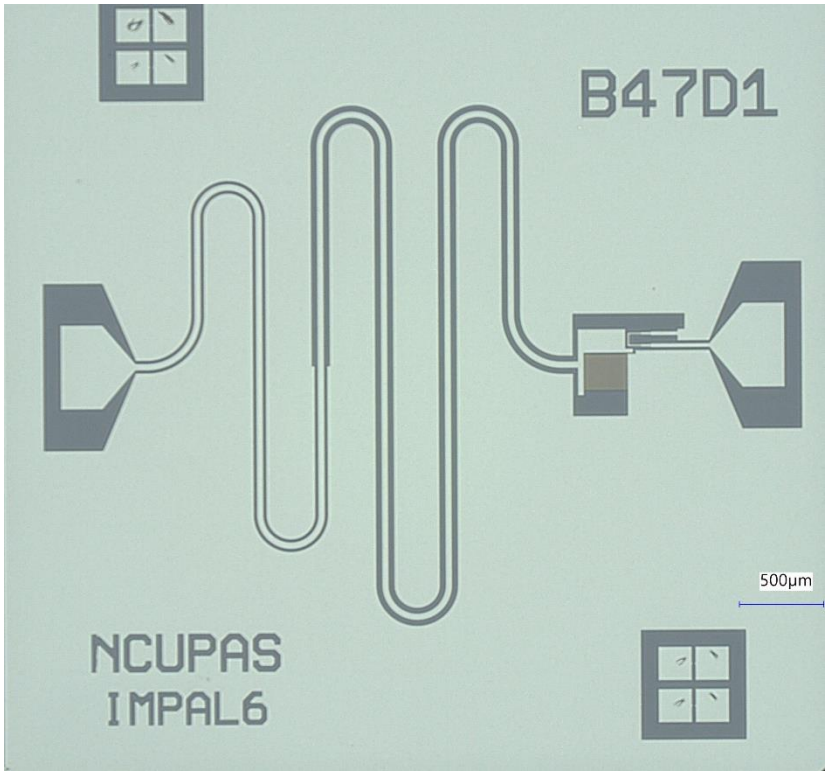
JPA in Other Frequency Band



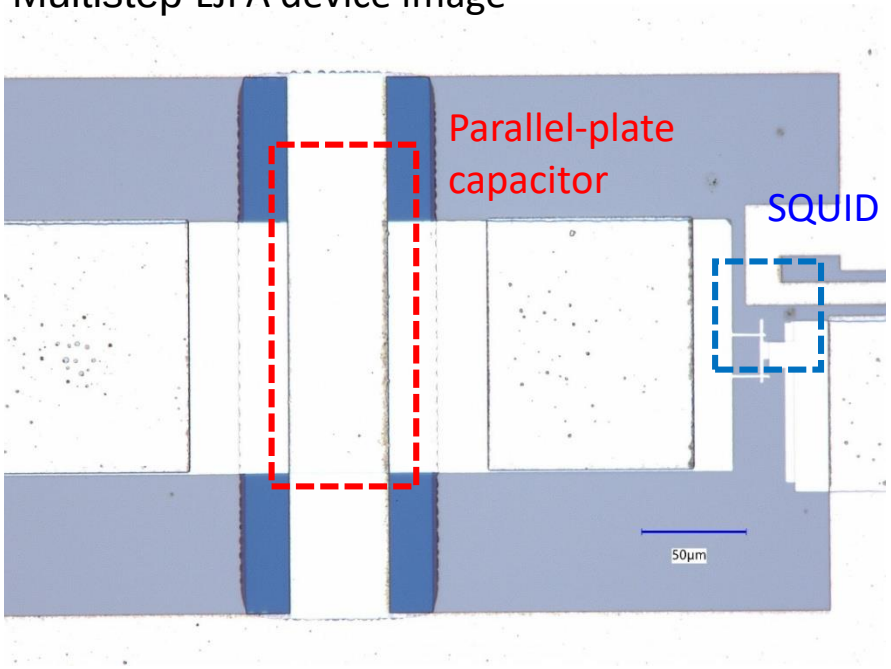




IMPA



Multistep LJPA device image



Impedance matching network
-> improving the bandwidth

Dielectric fabrication
-> developing the multilayer JPA fabrication

Phase II : TWPA