Josephson Parametric Amplifiers

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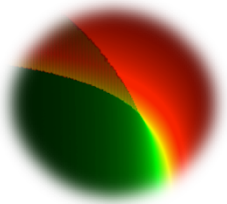
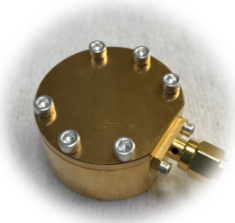
Outline

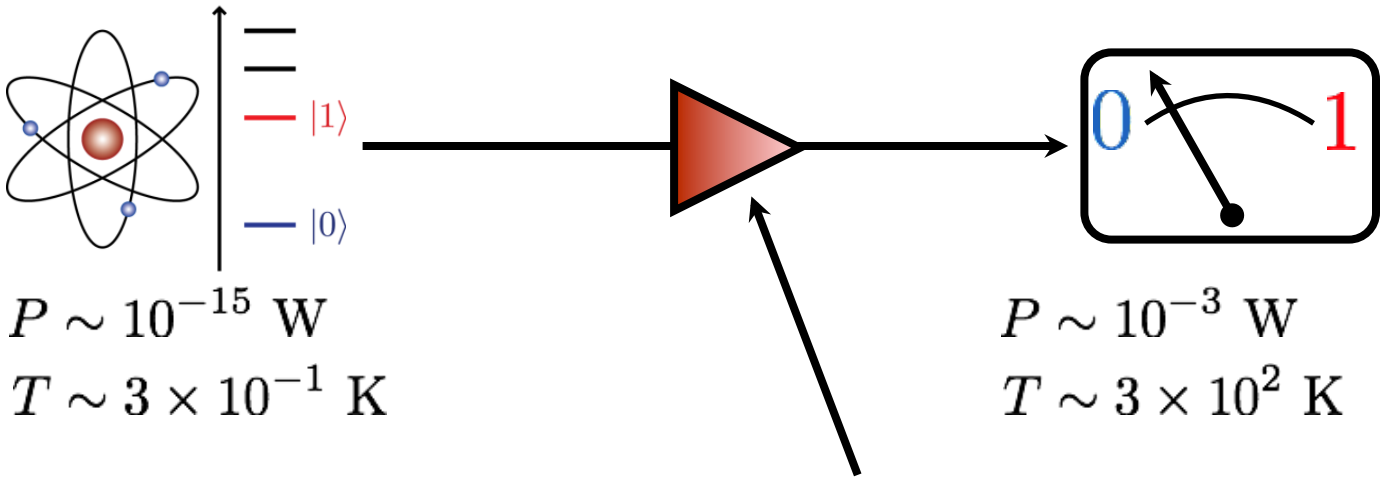
- **Introduction**:
  - Amplification & SNR Improvement
  - Parametric Amplification
- **Variants of JPAs developed at QNL**:
  - Design
  - Performance
  - Testing Environment
- **Future direction**





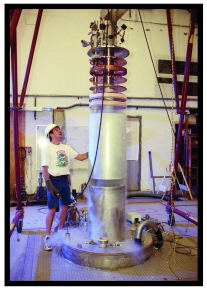
Why Do We Need Amplifiers for Quantum Signals?

At microwave frequencies (6 GHz or so), the situation is:



We need one (probably several) amplifiers to bridge these extremely different orders of scale.

Why Strive for the Quantum Limit?

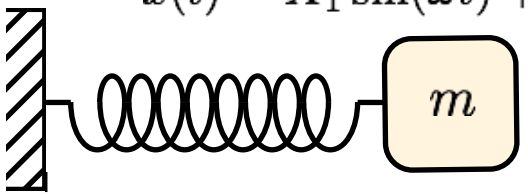




Sometimes you really need all the SNR you can get.

Quantum Limitation on Measurement

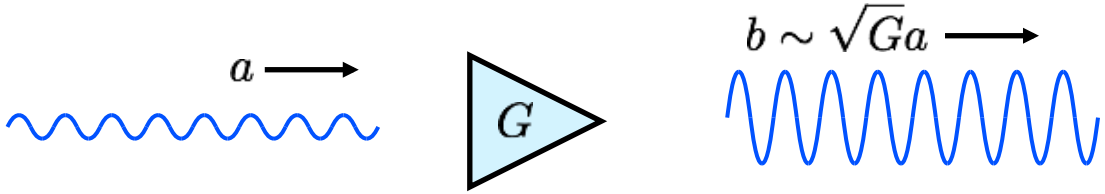
Quantum systems have intrinsic fluctuations:

$$x(t) = X_1 \sin(\omega t) + X_2 \cos(\omega t)$$



$$\Delta X_1 \Delta X_2 \geq 1/2$$

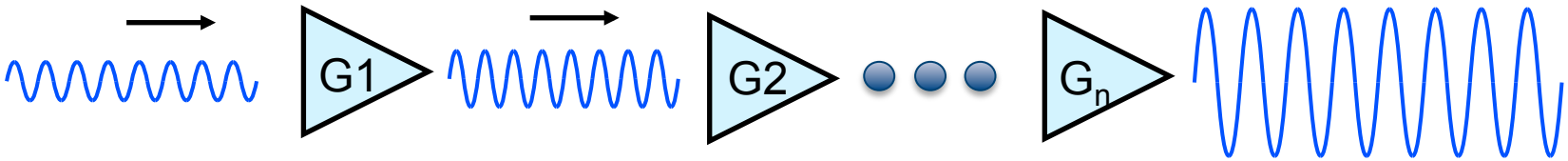
Amplifying small signals adds additional fluctuations:



$$\frac{(\Delta b)^2}{G} \geq (\Delta a)^2 + 1/2$$

Noise Propagation

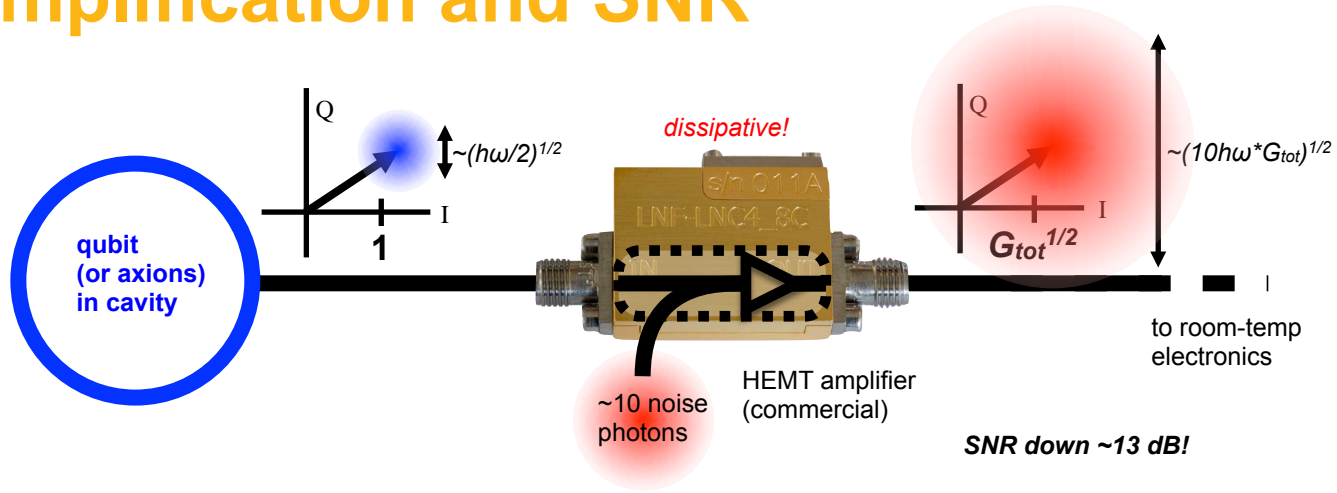
When we have multiple stages of amplifiers:

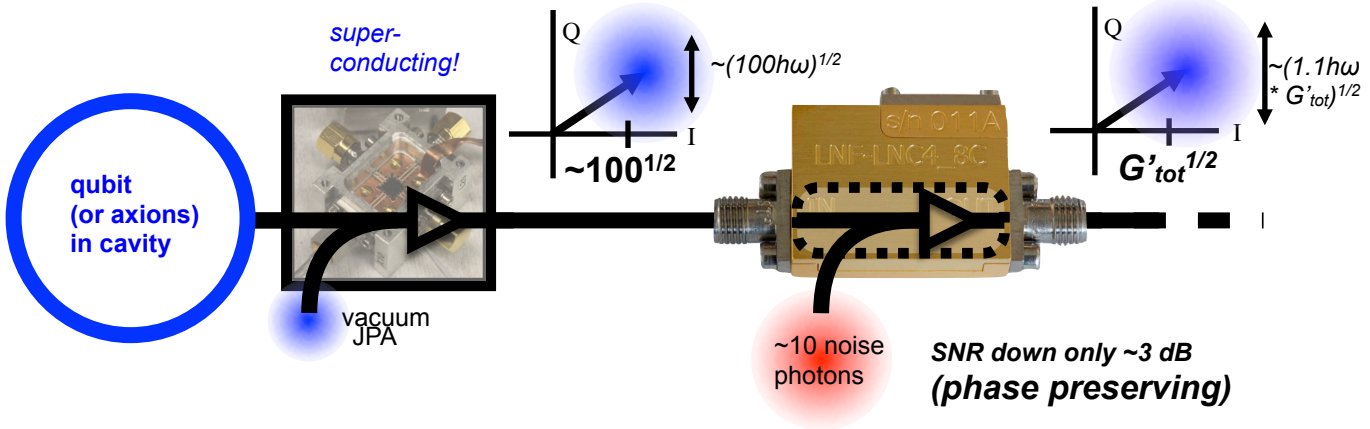


Noise propagates as the following:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

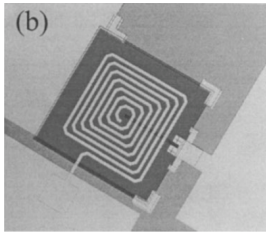
Amplification and SNR

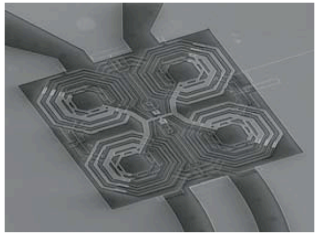


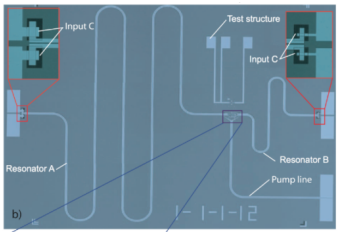


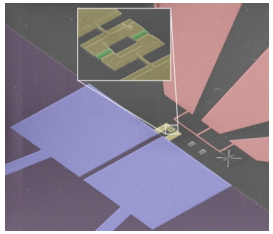
- **JPA improves SNR ~10dB** → **Averaging time dramatically reduced!**

Quantum-Limited Amplifiers









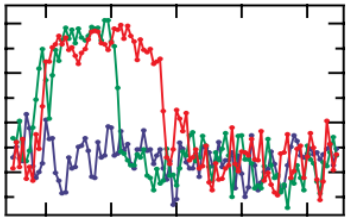
- Microstrip SQUID Amplifier (MSA) – Berkeley, Wisconsin, Gießen…
- Lumped-element SQUID amplifier – NIST…
- Josephson Parametric Converter – Yale…
- Josephson Parametric Amplifier (4WM, single-JJ/array) – QNL, CU …
- Josephson Parametric Amplifier (3WM) – NEC …

…

Josephson Parametric Amplifiers

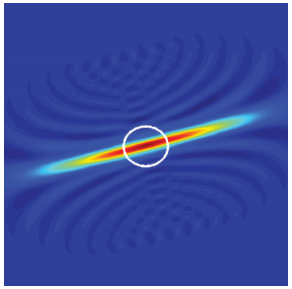
Josephson parametric amplifiers (JPA) are an enabling technology for superconducting qubit measurement.

Quantum Jumps



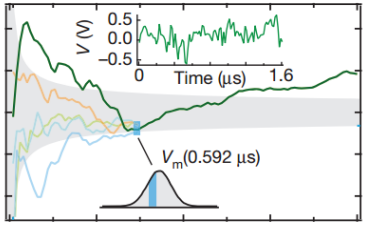
R. Vijay *et al.*, *PRL* (2011)

Squeezed microwaves



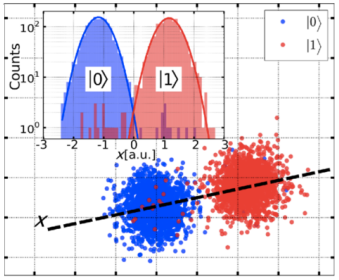
F. Mallet *et al.*, *PRL* (2011);
C. Eichler *et al.*, *PRL* (2011);
E.P. Menzel *et al.*, *PRL* (2012);
K.W. Murch *et al.*, *Nature* (2013)

Weak measurements



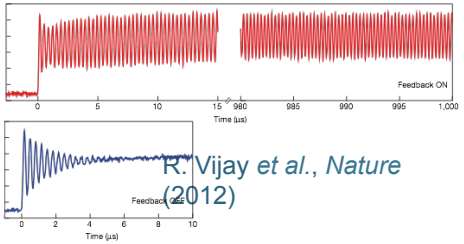
M. Hatridge, *et al.*, *Science* (2013);
K.W. Murch *et al.*, *Nature* (2013);
S. Weber *et al.*, *Nature* (2014);

High-Fidelity Readout



E. Jeffrey *et al.*, *PRL* (2014)

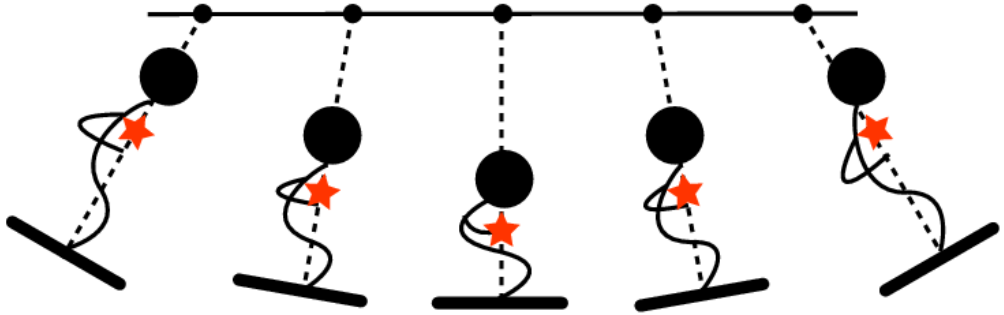
Quantum Feedback



R. Vijay *et al.*, *Nature* (2012)

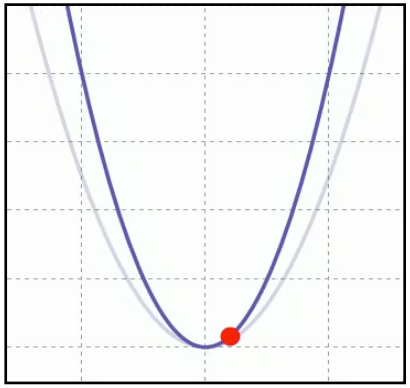
Seminal work on parametric amplifiers: B. Yurke
Many related approaches: Yale, JILA, Saclay, UCSB, and others…

Parametric Amplification Mechanism I

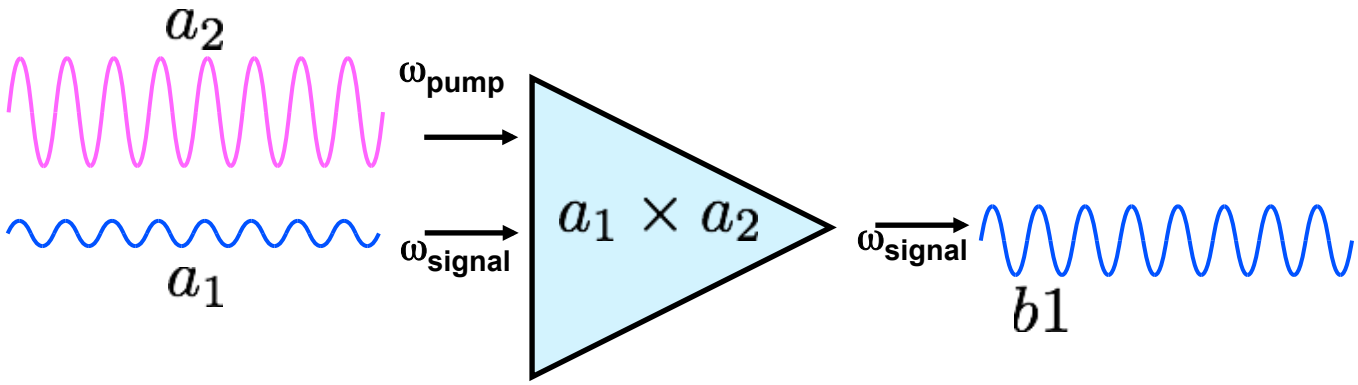


Classic example of parametric amplification is a child on a swing

- Resonance frequency ω_0 modulated at ~$2\omega_0$
- The energy from this pump is transferred into the two degenerate normal modes of the swing and causes the amplitude of the swing's oscillations to increase.



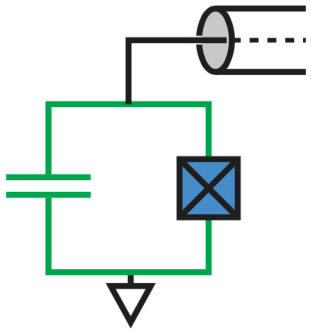
Parametric Amplification Mechanism II

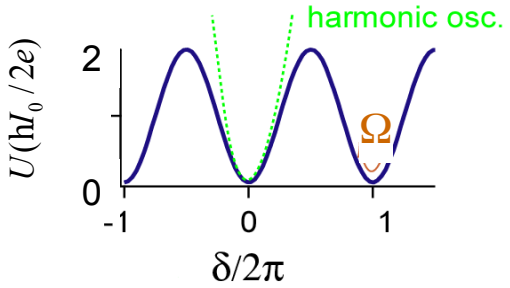


Some non-linear element providing coupling between different modes!

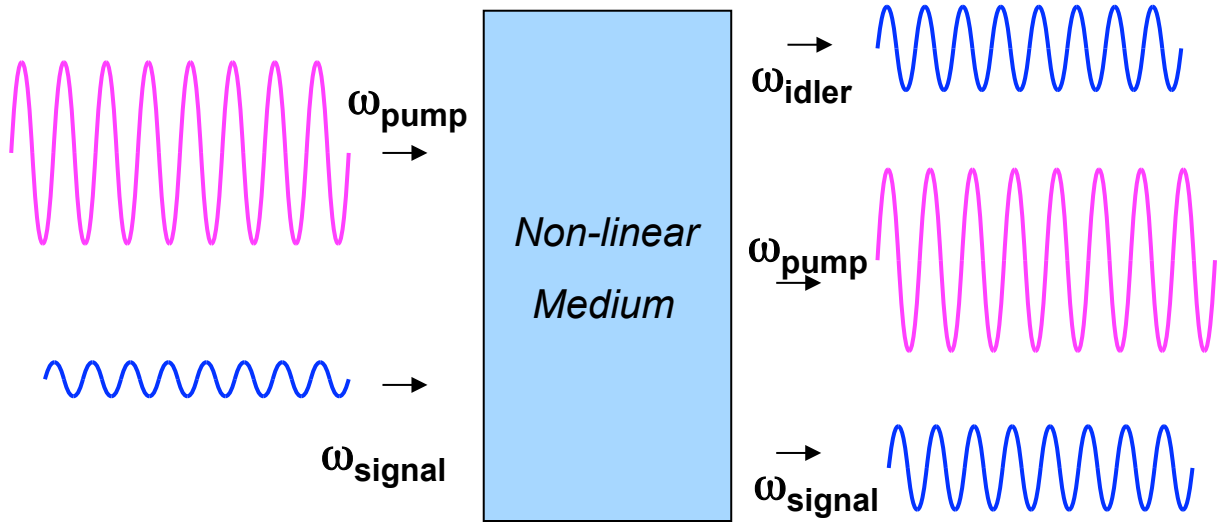
Josephson tunnel junction is non-linear and non-dissipative

$$L(I) = \frac{\Phi_0}{2\pi I_0 \sqrt{1-(I/I_0)^2}}$$





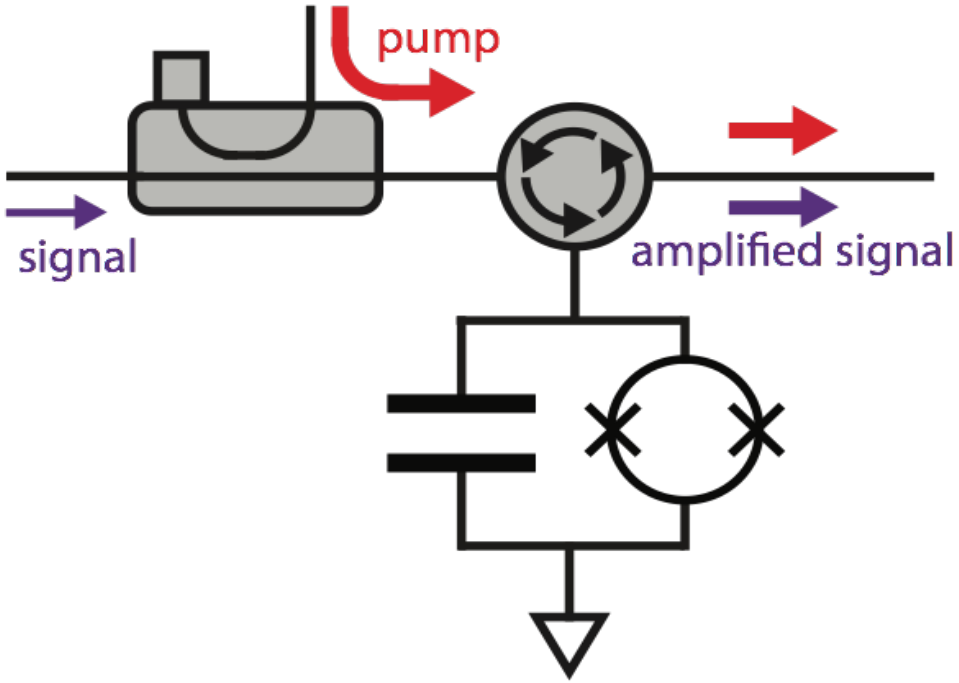
Wave Mixing Processes



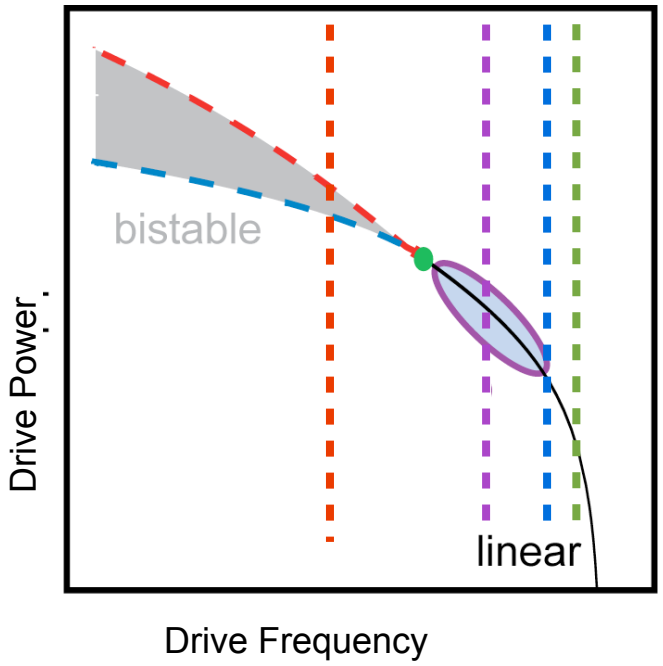
Three types:

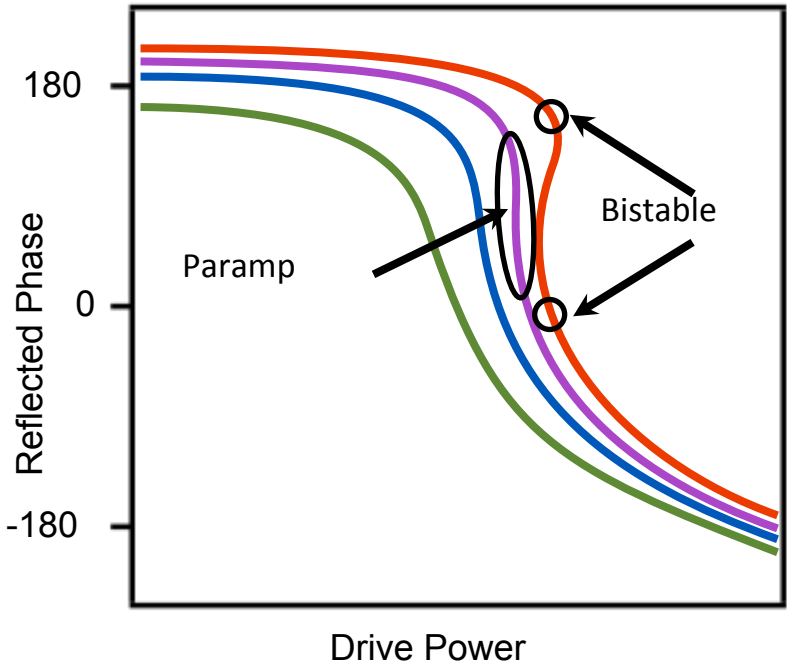
1. $\omega_{pump} = \omega_{signal} + \omega_{idler}$ → non-degenerate
2. $2\omega_{pump} = \omega_{signal}$ → degenerate
3. $2\omega_{pump} = \omega_{signal} + \omega_{idler}$ → doubly degenerate

JPA Operation

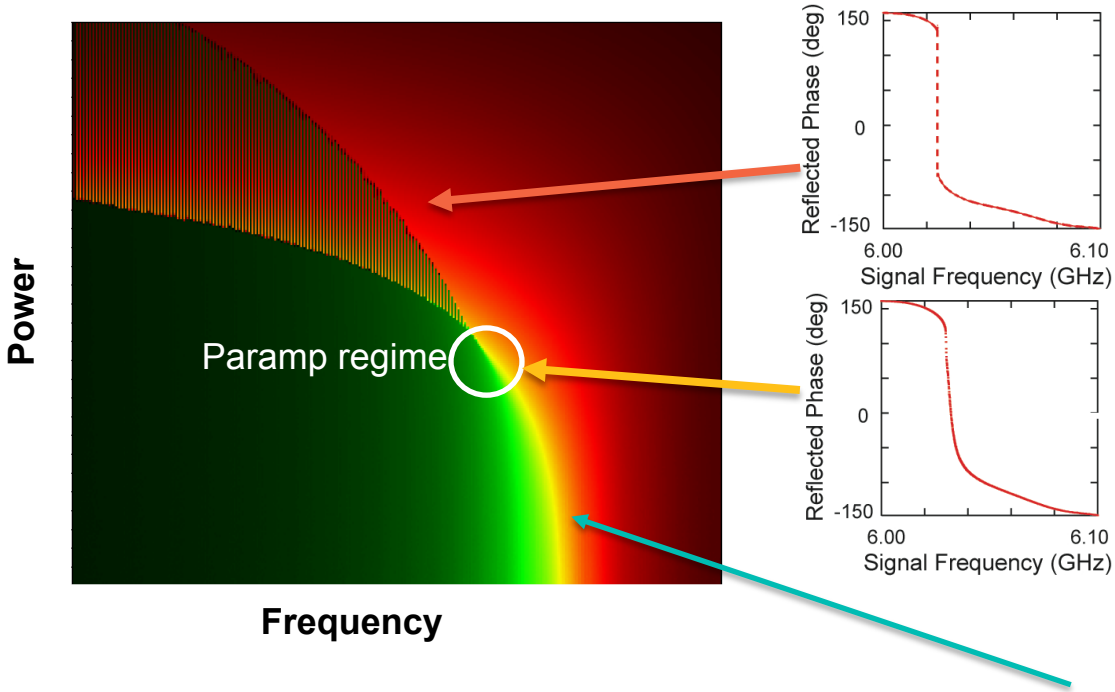


JPA Operation



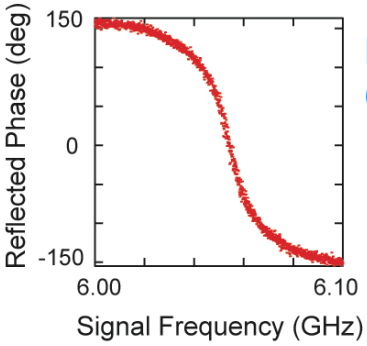


Resonator Nonlinearity



Bifurcation (Digital)

Parametric Amp. (Continuous)



Linear Regime (Continuous)

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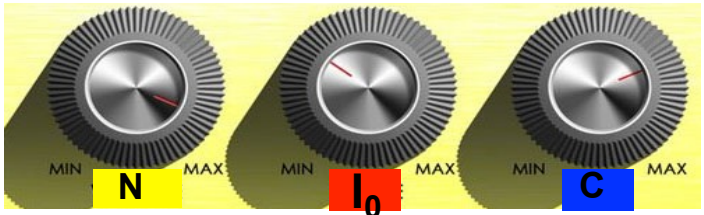
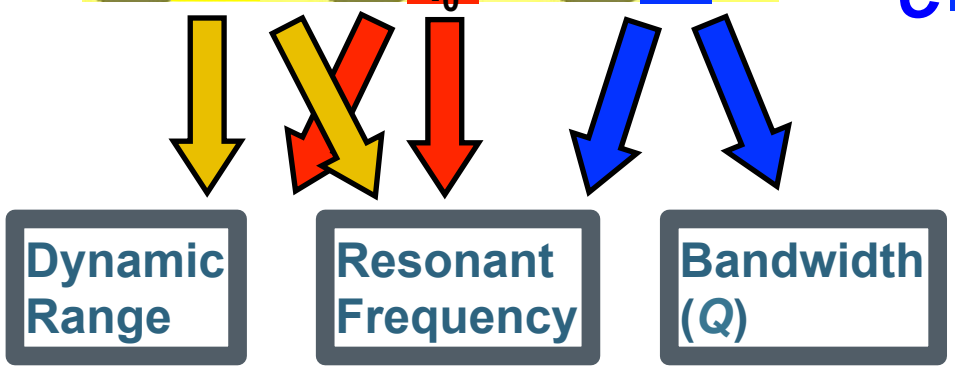
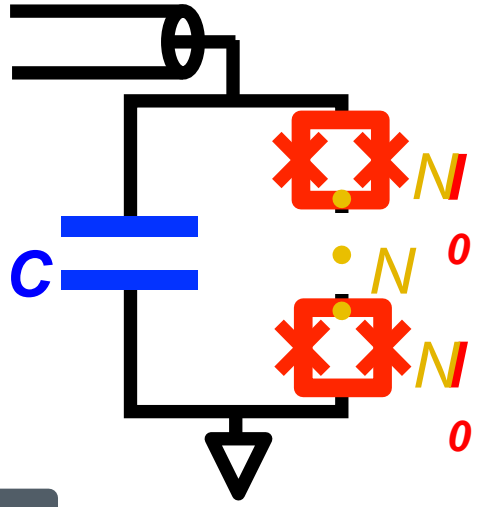
Standard JPA Design



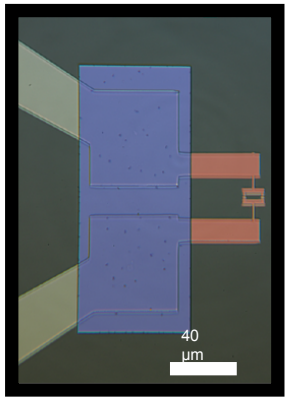




$P_{max} \sim I_0^2$

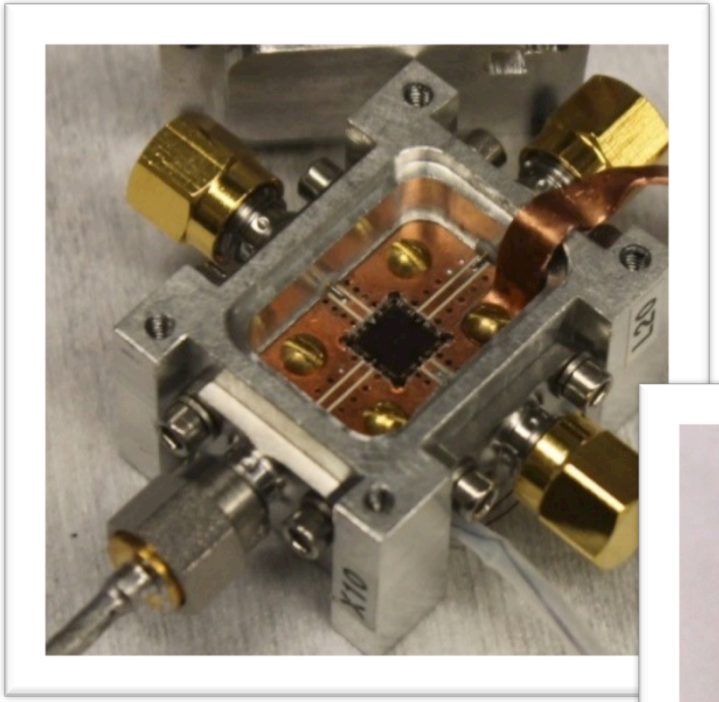
$L_{jn} = \varphi_0 / I_0$

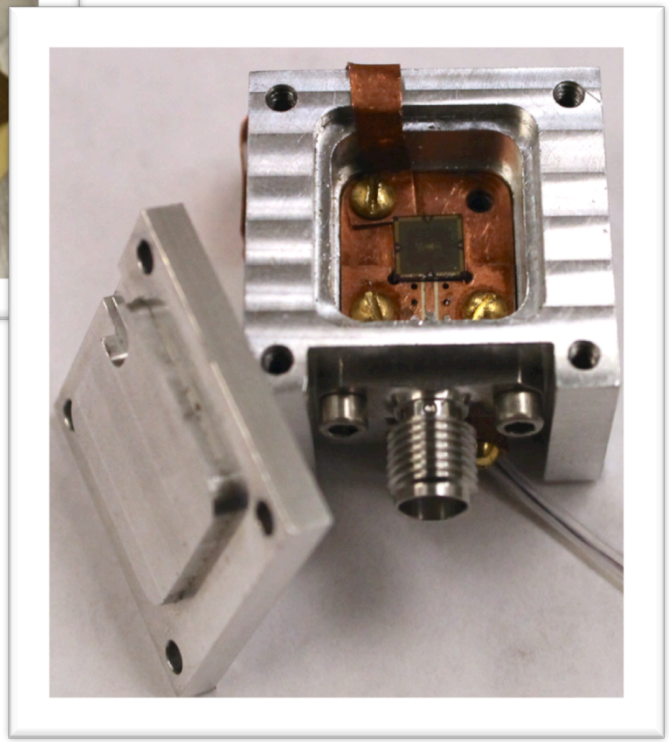
$Q = Z_0 \omega C$



JPAs For ADMX

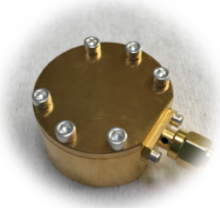
- Amplifier Package Design
- Testing Environment
- Variants of JPAs
- Performance

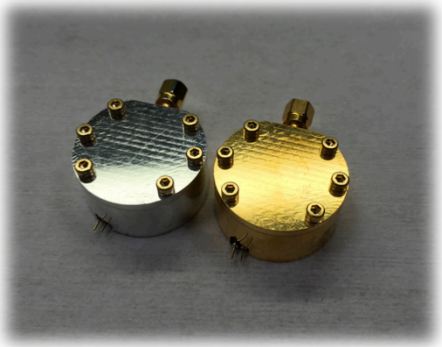


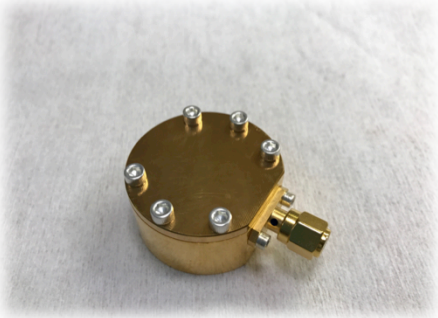


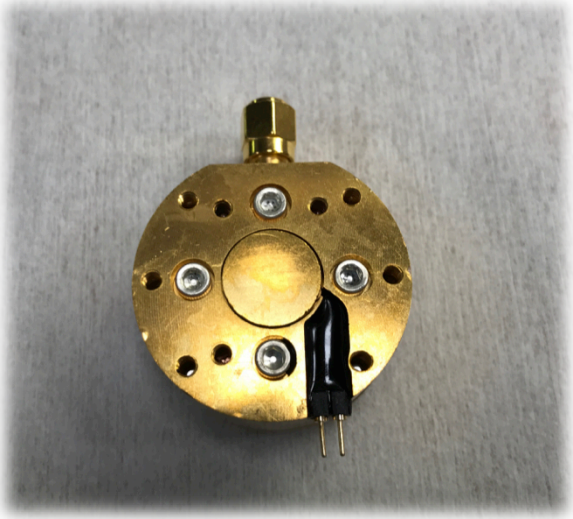
Previous generations of single-ended JPAs

JPA Package Redesign for ADMX





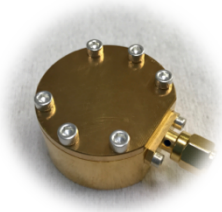


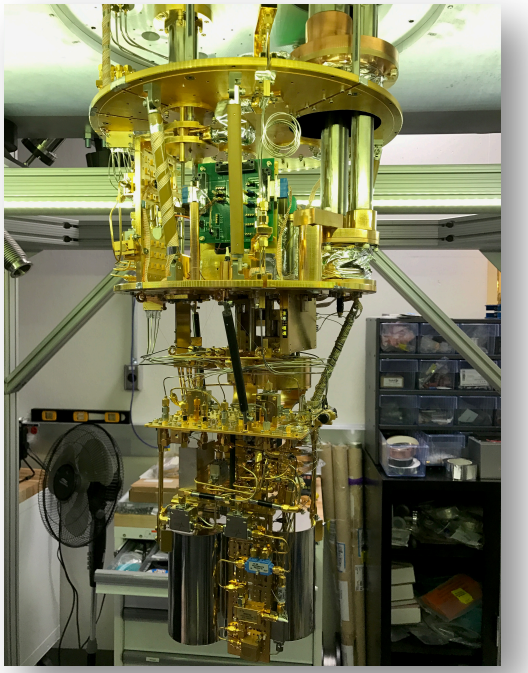


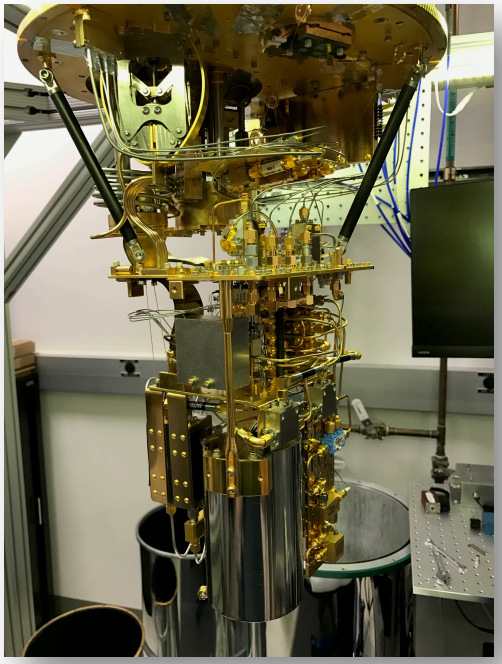
- No hanging thermalization strap

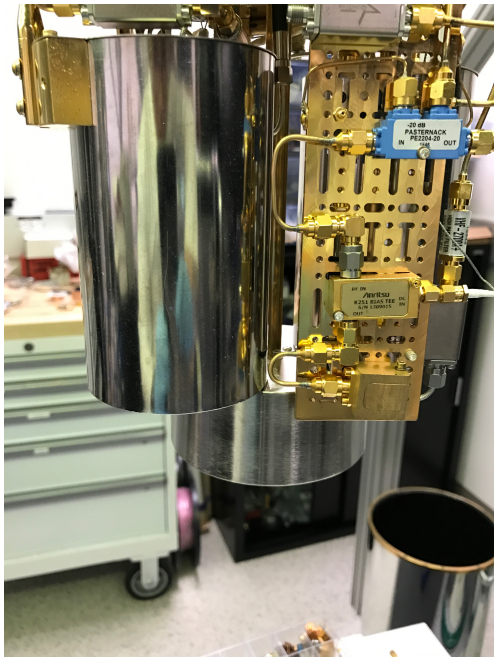
- Built-in dc connections reinforced with Stycast

Testing Environment



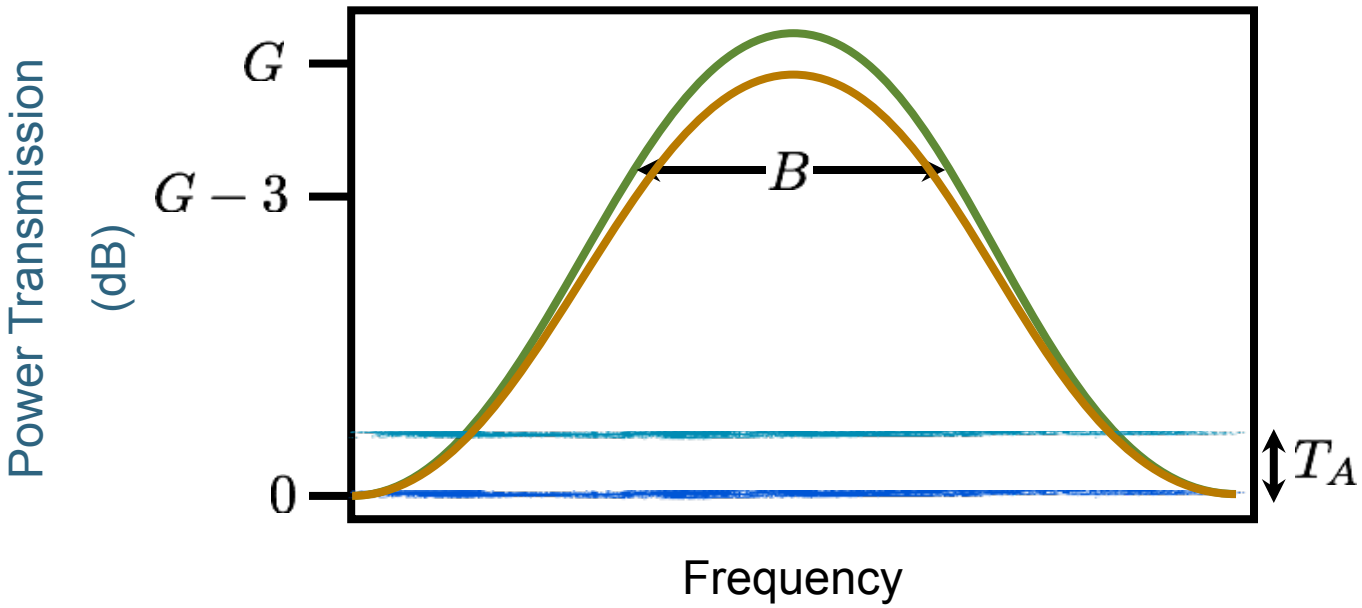






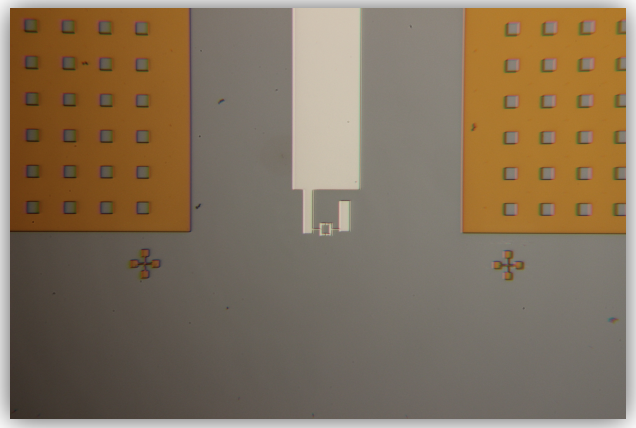
Customized closed single-shot DR with base temperature 69 mK.
Cool down time less than 24 hours.

Amplifier Performance Metrics

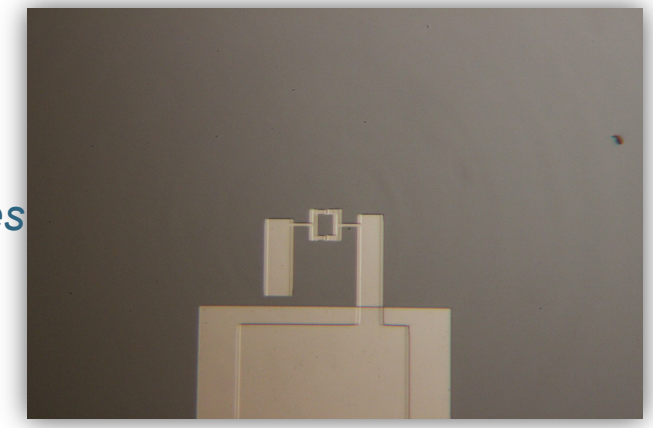


- G: increase in signal power provided by the device
- B : bandwidth over which the device gain is acceptably linear
- T_A: noise added by the device, referred to the input
- DR: input signal range over which the device gain is acceptably linear

4GHz - 9GHz JPA

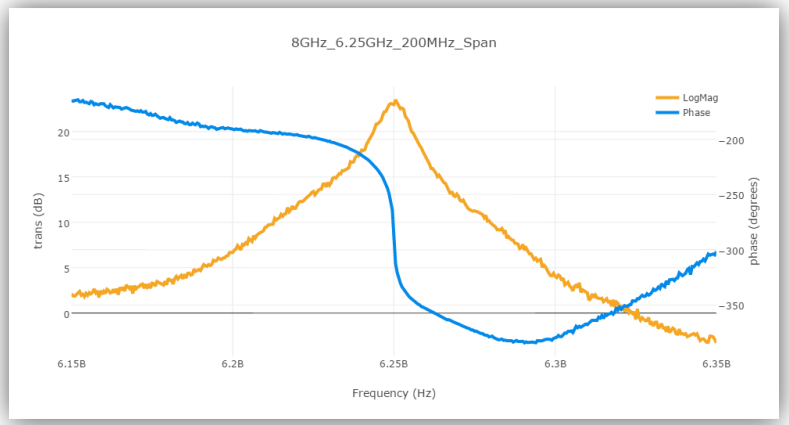


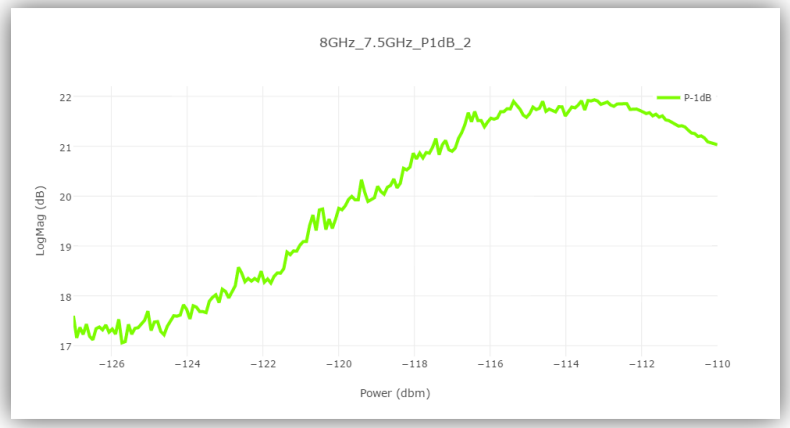
Junction Images

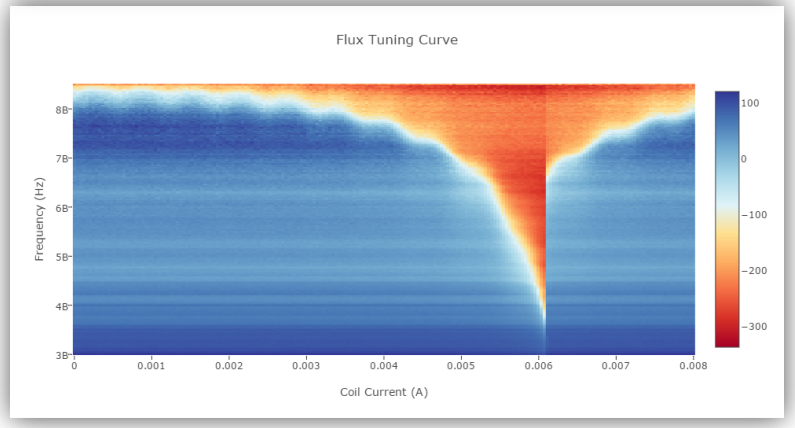


- Perforated TiN ground plane
- Josephson critical current around 3 μA
- Single SQUID design

4GHz - 9GHz JPA

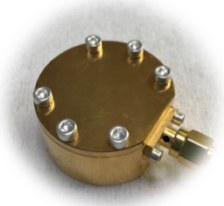


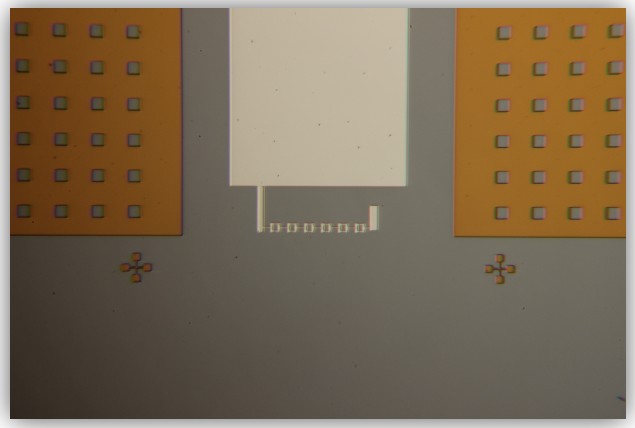




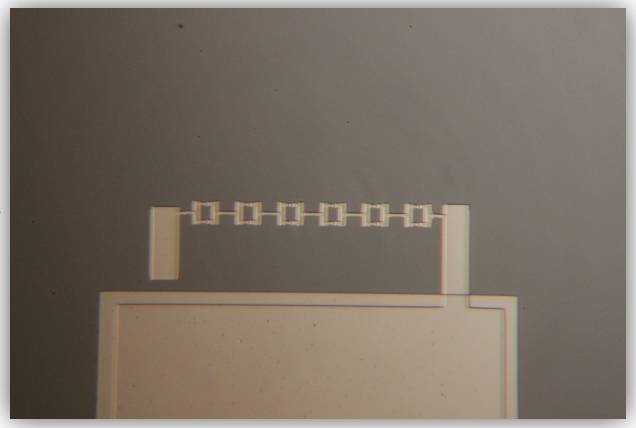
- Average gain 25dB with bandwidth around 10-20MHz
- 1dB compression point around -110dBm at the input of param
- Paramp tunes well from 8GHz to 4GHz with magnetic flux bias
- SNR Improvement 14 dB

400MHz – 900MHz JPA

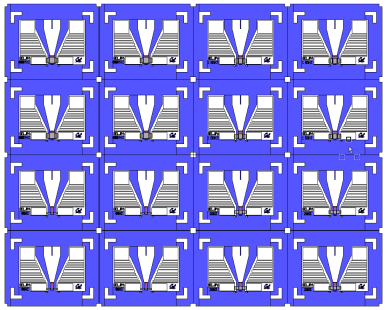




Junction Images

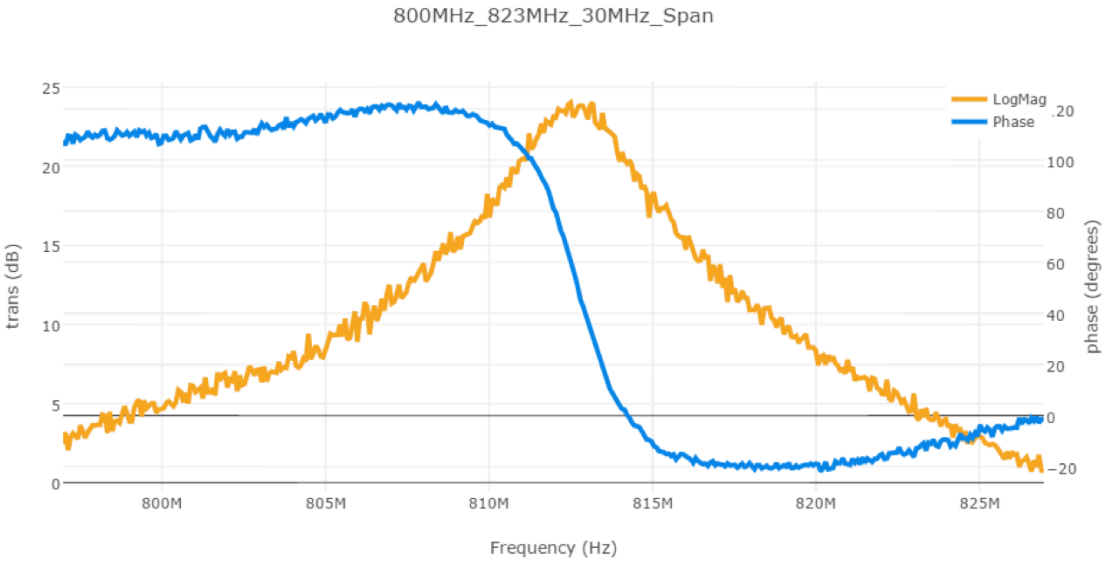


- Perforated TiN ground plane
- 6-SQUID design
- SSBW ~ 2-3.5 MHz
- P_{1dB} ~ -115 dBm



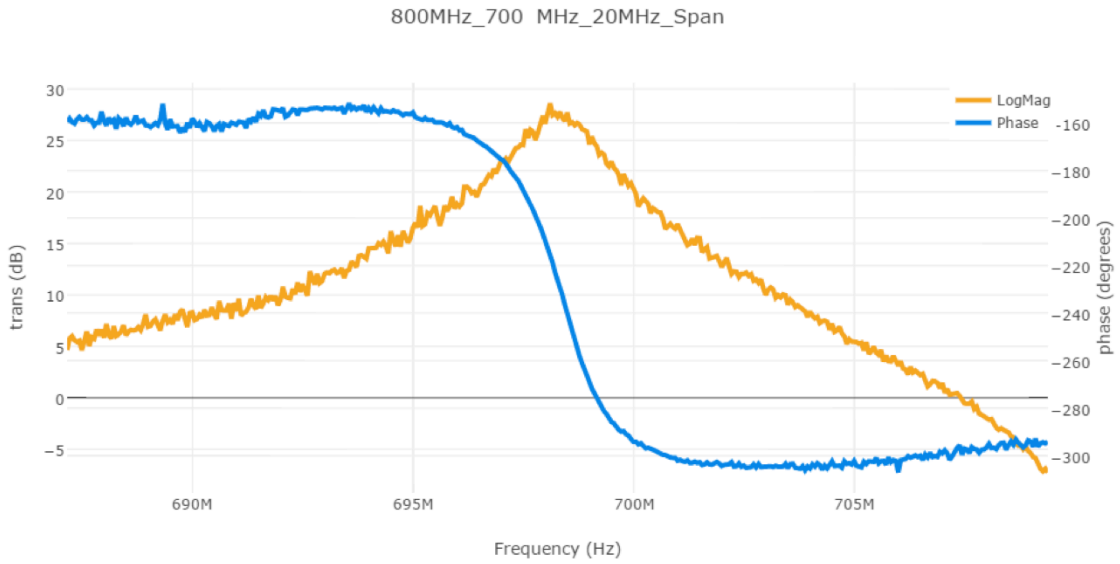
Chip Layout

800MHz JPA @823MHz



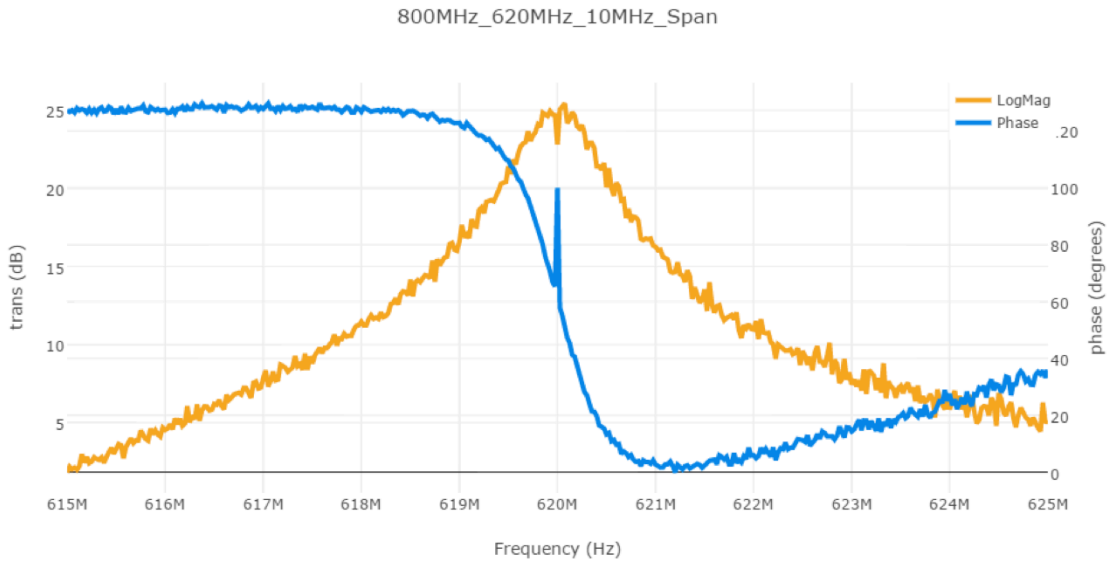
- Gain: 23 dB peak
- Bandwidth: 3.5MHz
- Pump power: -127.24dBm
- Coil current: -2.880mA

800MHz JPA @700MHz



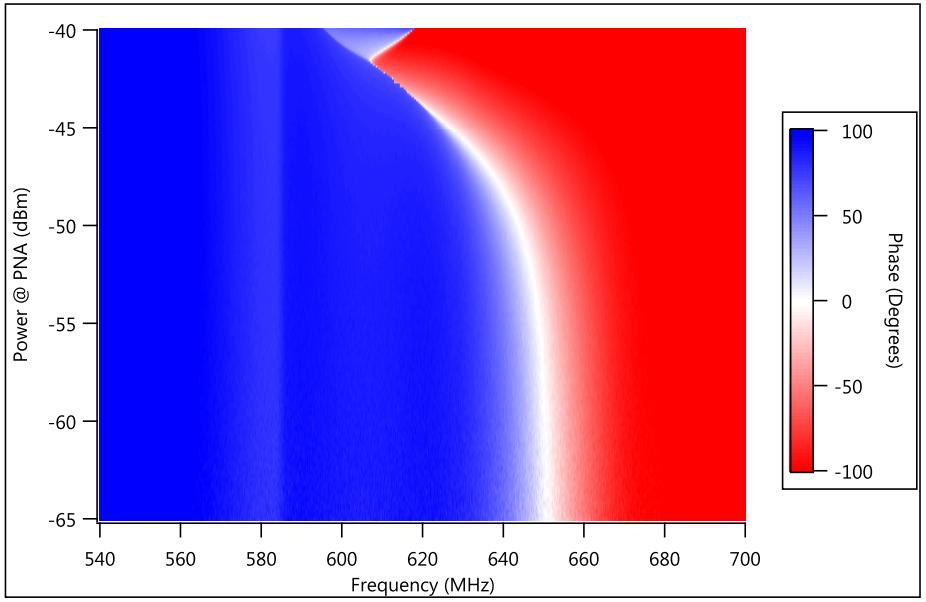
- Gain: 26dB peak
- Bandwidth: 2 MHz
- Pump power: -101.24dBm
- Coil current: -5.322mA

800MHz JPA @620MHz

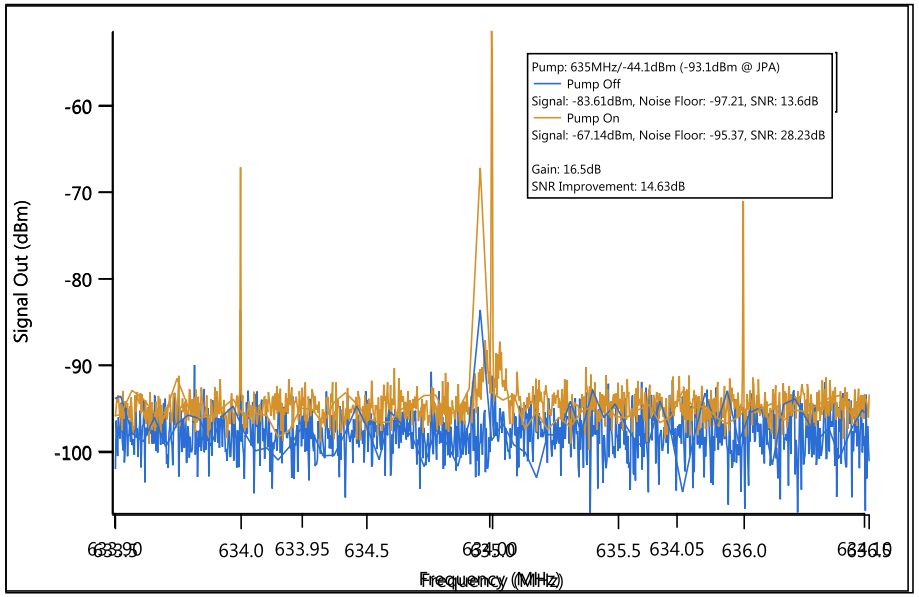


- Gain: 25dB peak
- Bandwidth: 2.5 MHz
- Pump power: -104.17dBm
- Coil current: -7.484mA

800MHz JPA Nonlinearity and SNR

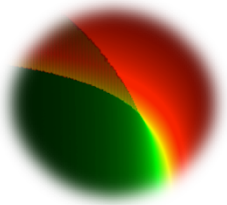


Phase Response Curve



SNR Measurement

Summary



- JPAs dramatically improve measurement efficiency of very small microwave signals
- L- , S- , C-band JPAs have been developed and tested including low-frequency JPAs (400MHz-900MHz). Most of the amplifiers are ready to be delivered.
- Working on developing a broader-band Josephson amplifier with higher dynamic ranges.

Thank you!

Workshop on Microwave Cavities and Detectors for Axion Research
Livermore Valley Open Campus
January 12, 2017

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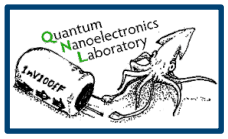

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