Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Superconducting Parametric Amplifier Design

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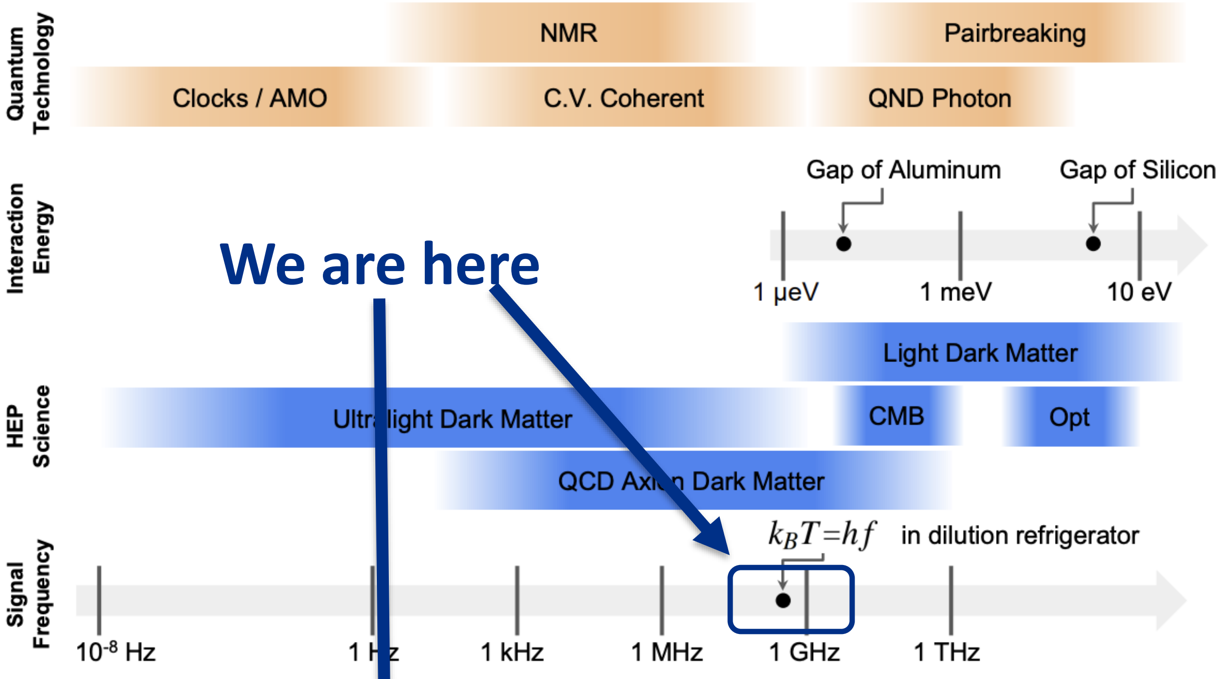
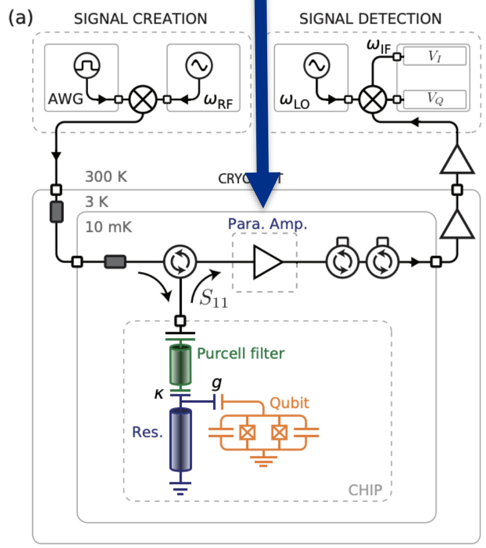
Why Parametric Amplifiers

- Experiments in HEP and QIS
- Cryogenic temperature operation
- High Quantum Efficiency
- General Purposed Quantum readout chains

Source: QIS for HEP report arXiv:2311.01930





Source: A Quantum Engineer's Guide to Superconducting Qubits arXiv:1904.06560

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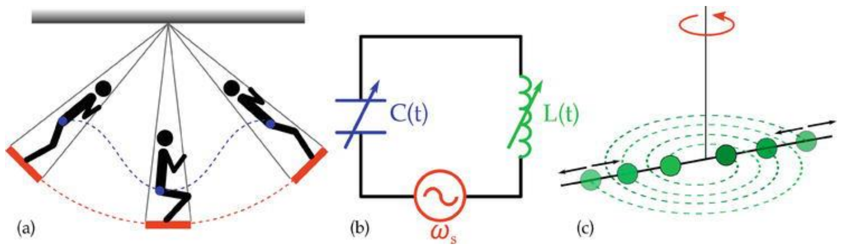
Parametric Amplifiers At Fermilab

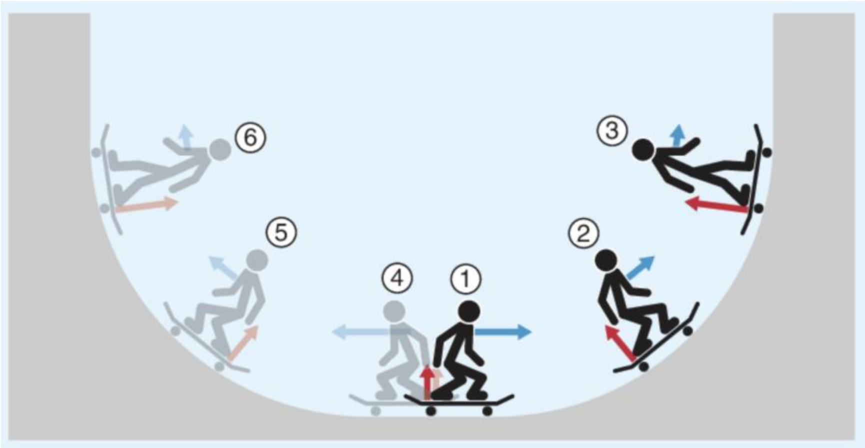
- Tape-out: March of 2023
- Fab: MIT-LL SFQ5ee [100 uA/um^2; 8 Nb Layers]
  - Established and matured superconducting JJ process
  - Repeatable and well controlled for ASIC applications
  - Frequent MPW runs
- Chip Contents
  - 2 JPA experiments
  - 2 JTWPA experiments
  - Test Structures

What is a Parametric Amplifier?

- RF Mixer combined with amplifier
- Parametric refers to the process of modulating a parameter of a system of equations
- Signal tone is mixed with pump tone via non-linearity
- Energy from pump is converted into signal photons
- Akin to being pushed on a swing or skating in a half pipe



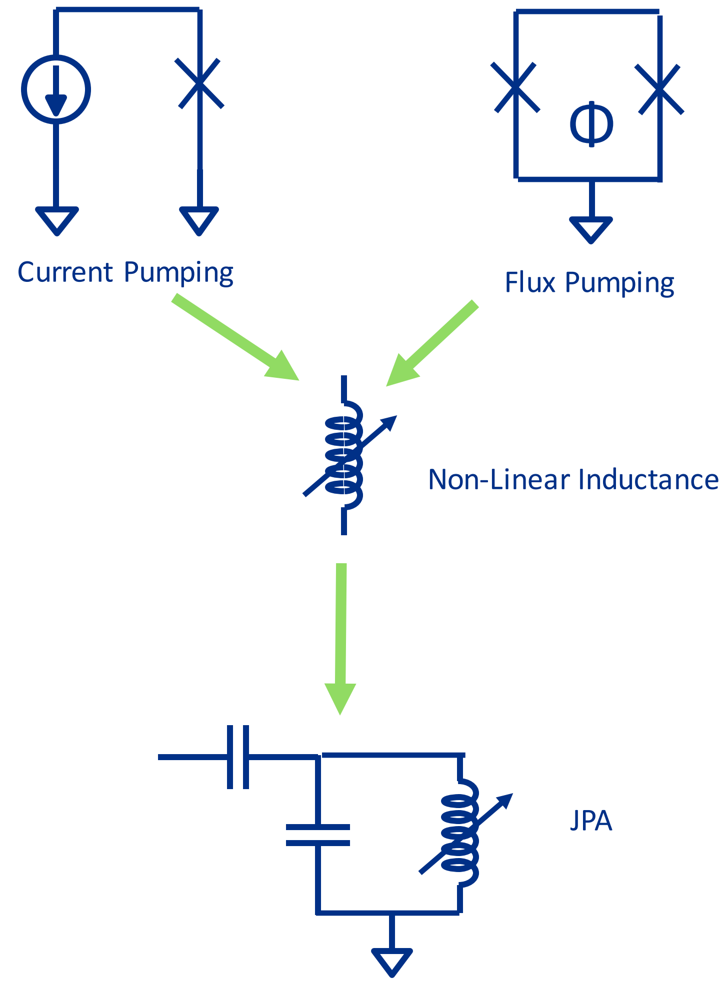
Source: Superconducting Josephson-Based Metamaterials for Quantum-Limited Parametric Amplification: A Review



Source: Superconducting Parametric Amplifiers: The State of the Art in Josephson Parametric Amplifiers
DOI:10.1109/MMM.2020.2993476

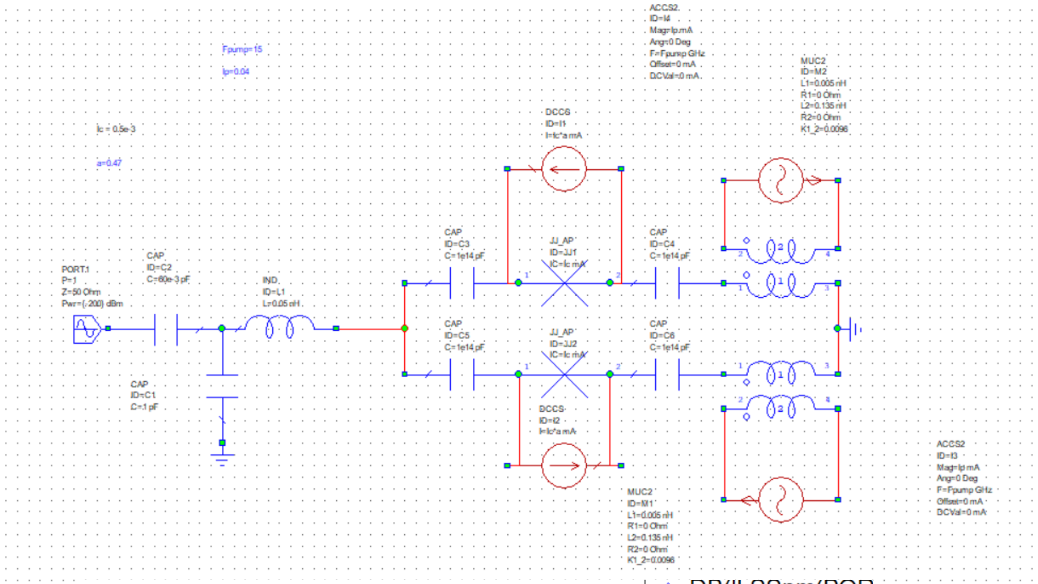
Josephson Parametric Amplifier

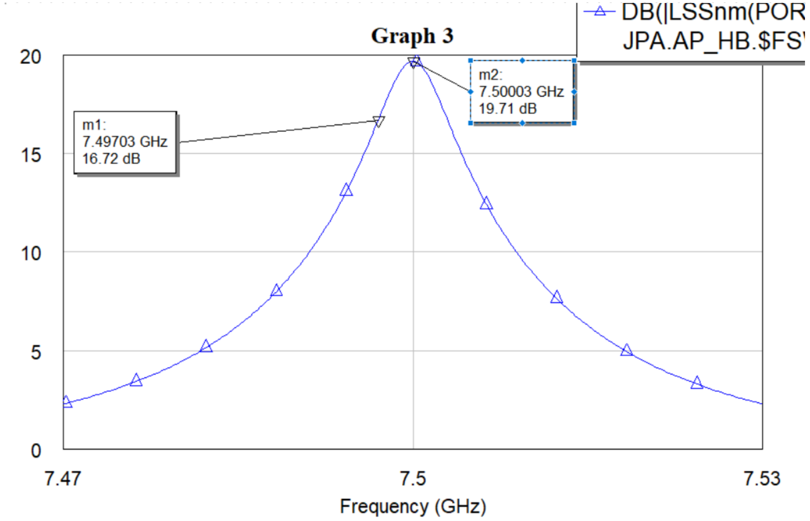
- Increasing current through JJ increases the effective inductance
- Single JJ/JJ Chain = Current Pumping via modulation of the Josephson Inductance
- DC SQUID = Flux Pumping via modulation of the effective Ic of the SQUID
- 1 Port System
- Active termination
- Very small bandwidths



JPA Circuit Simulation

- 2 different versions of JPA
  - Crossed loop (0-effective area)
  - No-crossed loop
- Original design adapted from original work by WashU collaborators
  - ADMX and BREAD
- Specifications
  - Coupling capacitance = 60fF
  - Signal Frequency = 7.5 GHz
  - Pump frequency = 15GHz
  - Pump Amplitude = 40uA
  - Gain = 20dB
  - Bandwidth = 60MHz
  - Tunable Bandwidth = <1GHz

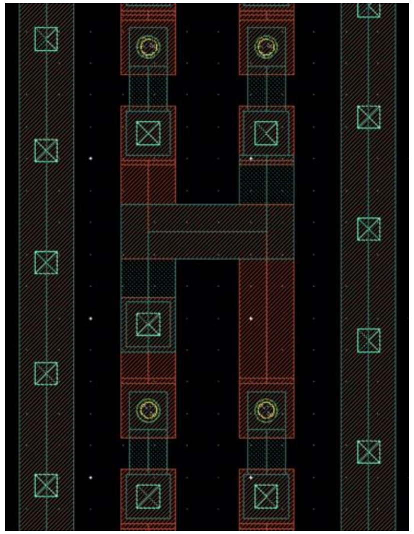


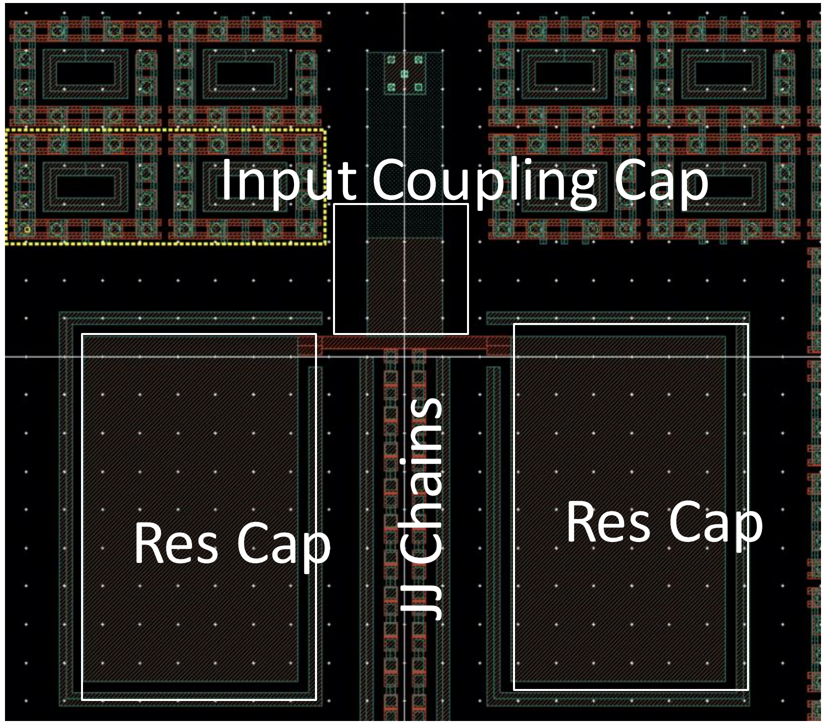


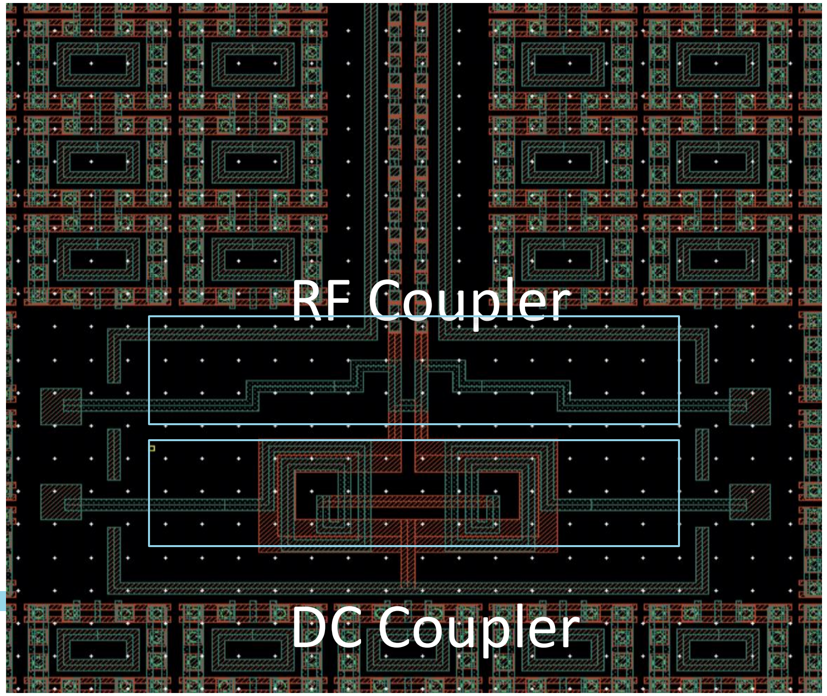
Original Theory/Designs
https://arxiv.org/pdf/0808.1386.pdf
https://www.epj-conferences.org/articles/epjconf/pdf/2019/03/epjconf_qtech2018_00008.pdf

JPA Circuit Layout

- SFQ5ee
- Original work was done with 1 layer
- RF Coupler = 0.5pH
- Minimizing capacitance between RF bias line and SQUID is essential for avoiding current pumping
- DC Coupler = 3pH

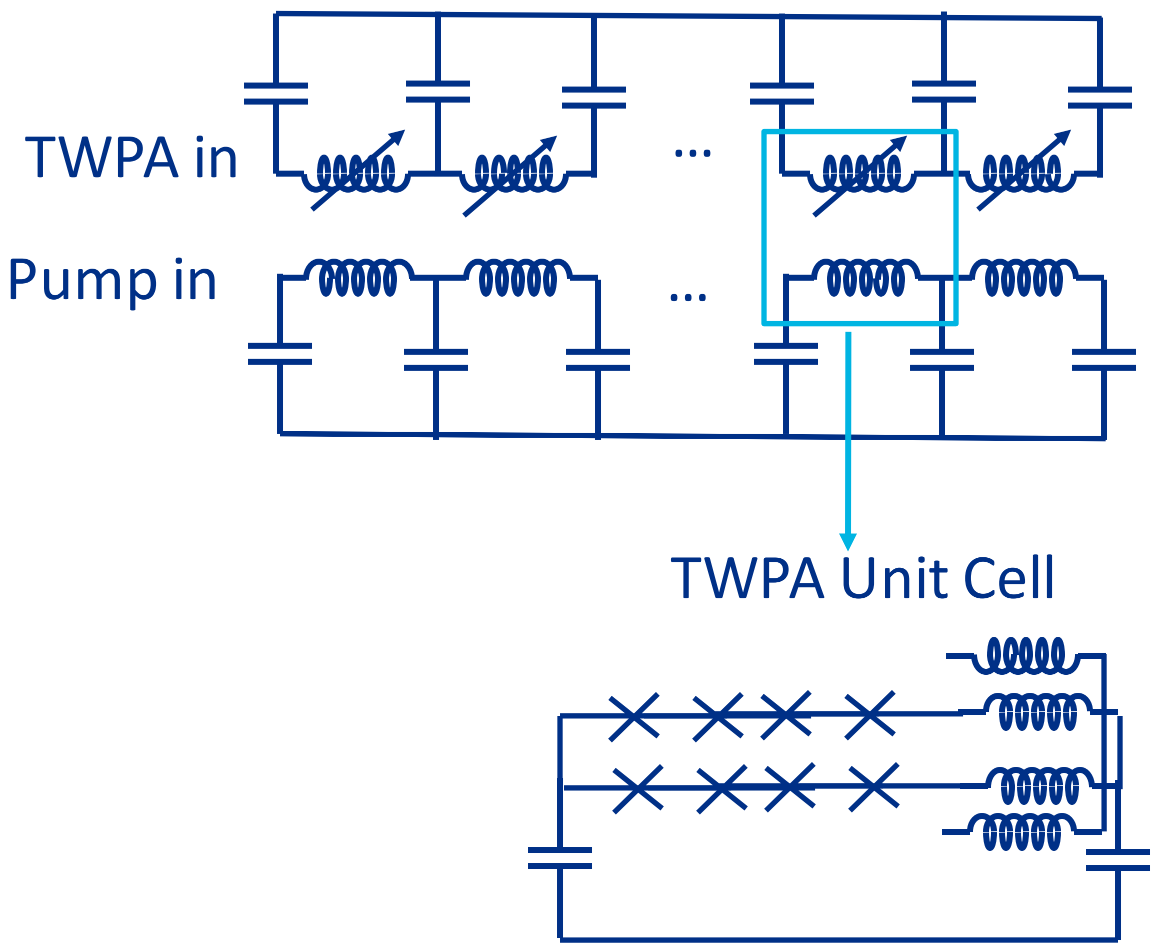






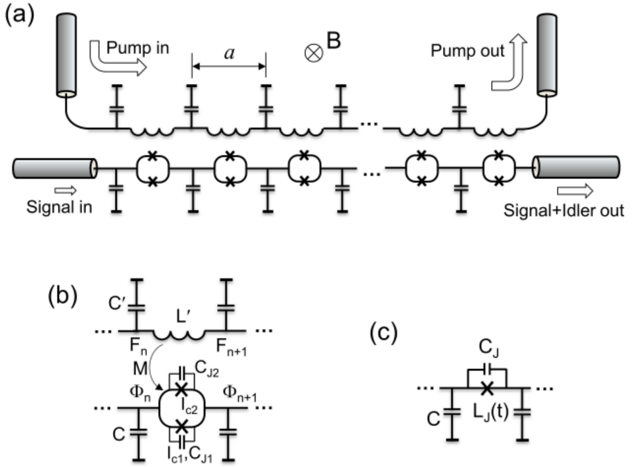
What is a TWPA?

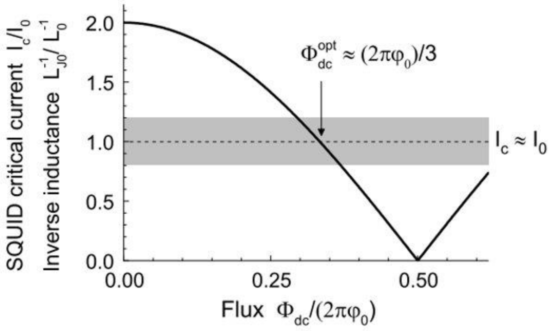
- AKA: JTWPA or Josephson Traveling Wave Parametric Amplifier
- A non-linear transmission line
- Phase matching (L-C's match)
- Current and Flux Pumping
- Much larger instantaneous bandwidth
- Floquet, SNAIL
- Theory first developed by Zorin 2019
- https://arxiv.org/pdf/1804.09109.pdf



Dispersion Engineering

- Solutions
  - Introducing stop-bands
  - Varying size of JJ's along path
- Two parallel transmission lines
  - Pump Tone
  - Signal Tone
- Optimally bias TWPA for maximum slope of SQUID critical current





https://arxiv.org/pdf/1804.09109.pdf

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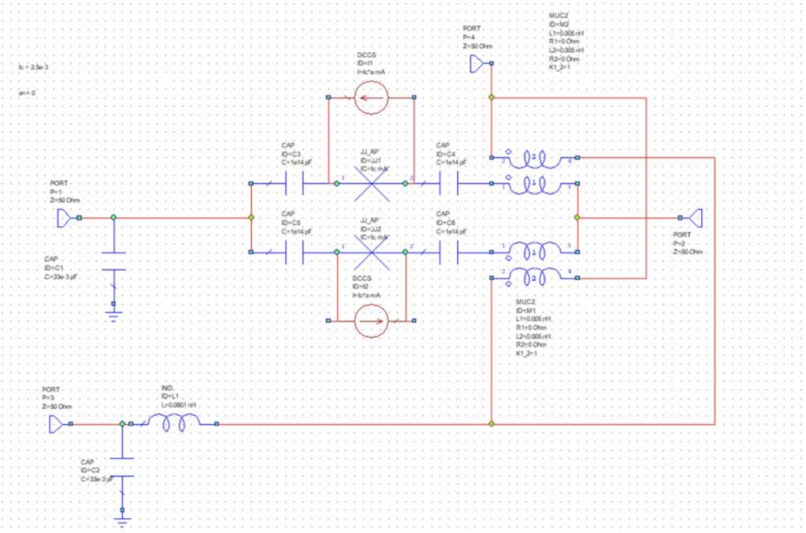
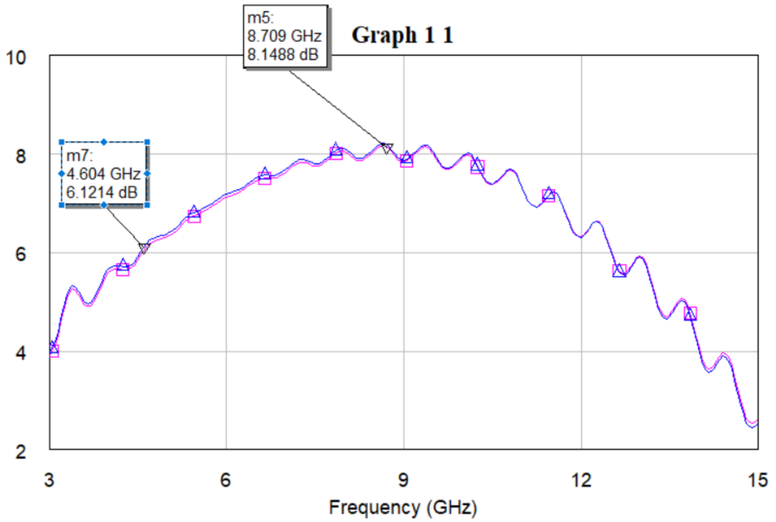
JTWPA Circuit Simulation

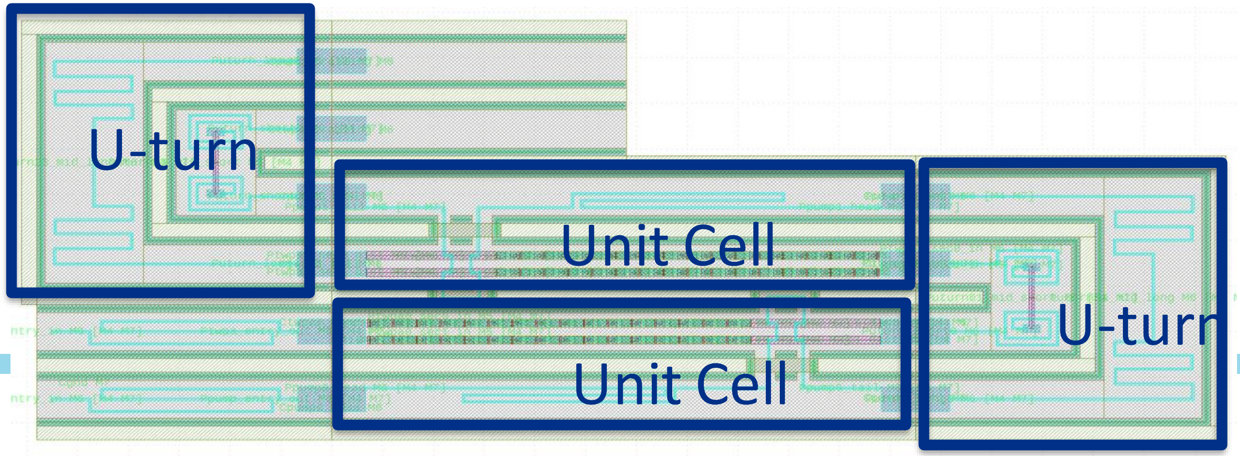
- 400x and 800x unit-cell experiments
- Dispersion/impedance engineering
  - Lumped element pump line matched to operating impedance of TWPA unit cells
- Specifications (400 unit cells)
  - Pump frequency = 20GHz
  - Pump Amplitude = 40uA
  - Gain = 8dB @ 9GHz
  - Bandwidth = 8GHz



Unit-cell Schematic

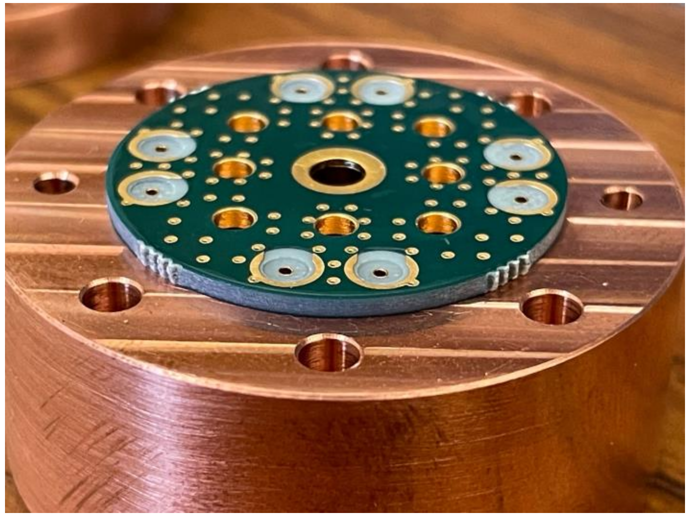


400 unit-cell Gain Simulation



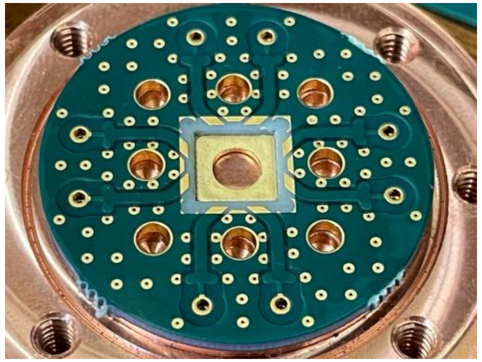
Testing

- Chips delivered December 2023
- Currently working with a group to wire-bond, solder, and assemble the testing cavity to a fridge



Bottom face of PCB

Left to Right: Bottom Cavity, DC Bobbin, Top Cavity



Top face of PCB

Future Work

- 1000x and 2000x unit cells
- Mutually coupling RF clock phase as a dispersion matching technique which can increase tunable bandwidth
- Verify against open-sourced simulation tools
- Lower critical current density fabrication
  - Shrinks SQUID loops
  - Reduces the number of junctions required
  - Increases beta