IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Invited presentation Wk2EOr5B-01 given at the virtual ASC 2020, October 29, 2020.

Superconducting electronics at 4 K for control and readout of qubits

ASC 2020

Adam Sirois, Manuel Castellanos-Beltran, Logan Howe, David Olaya, Anna Fox, John Biesecker, Justus Brevik, Paul Dresselhaus, Samuel Benz, Peter Hopkins

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Talk outline:

1.) Introduction & motivation

2.) Experimental results

  Spectroscopy using JAWS of:

    Linear resonators (4 K)

    Qubit in an ADR (100 mK)

  Qubit control using JAWS (10 mK)

3.) Metrology

4.) Future work and conclusions

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Quantum-Computing Efforts Worldwide

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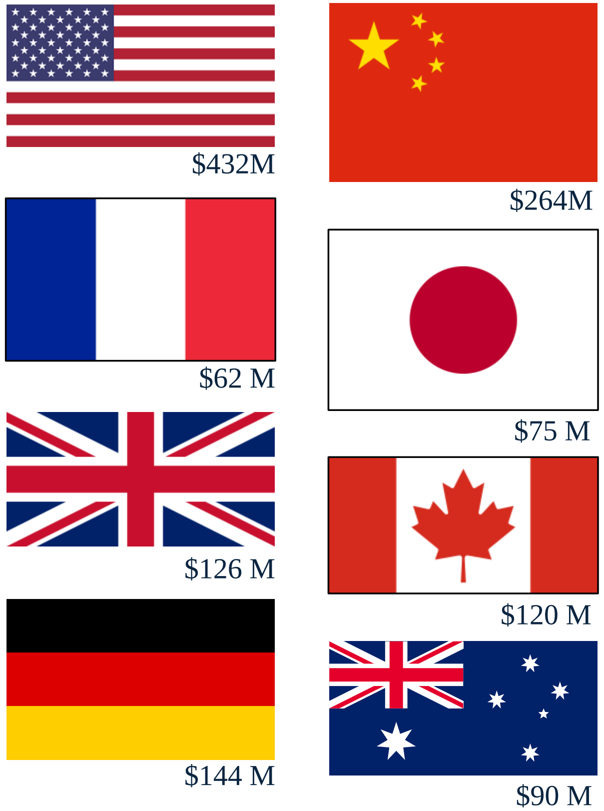
Key Government Investments



Companies Investing in Quantum Computing

Accenture
Alice&Bob
AmberFlux
Airbus
AT&T
Aliyun (Alibaba Cloud)
Atos
Baidu
Carl Zeiss AG
Cambridge Quantum Computing
CogniFrame Inc
ColdQuanta Inc.
D-Wave
Fujitsu
Google
HP
Hitachi
Honeywell
HRL Laboratories
Huawei Noah's Ark Lab
IBM
ID Quantique
imec
Intel
Infineon Technologies
ionQ
KPN
Lockheed Martin
main incubator
MagiQ
Microsoft Research
Mitsubishi
NEC Corporation
Nokia Bell Labs
Northrop Grumman
NTT Laboratories
PsiQuantum
QRDLab
Quantum Benchmark
QxBranch
Quantum Brilliance
Quantum Circuits, Inc.
Quantum Thought
Raytheon/BBN
Rigetti Computing
Toshiba
Xanadu Quantum Technologies Inc.
Zapata Computing
1QBit

and many more…

Slide courtesy of Dylan Williams

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Introduction and Motivation

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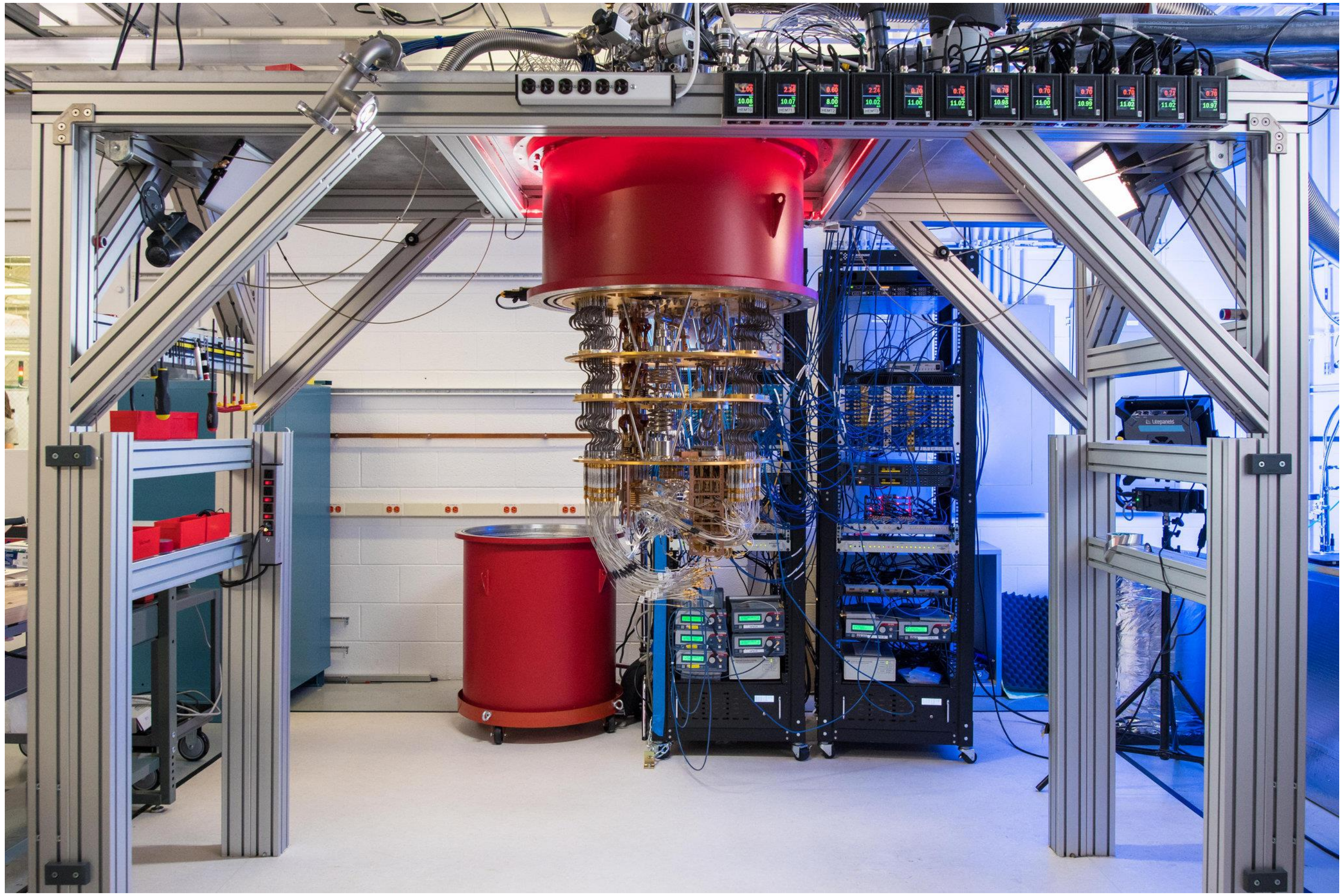
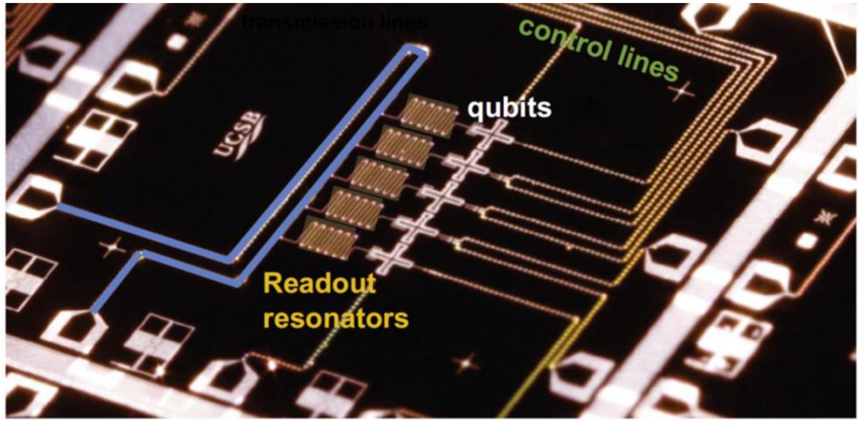


One example:

Google's 53 superconducting qubit experiment and associated control electronics.

5 qubit chip from UCSB:



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Introduction and Motivation

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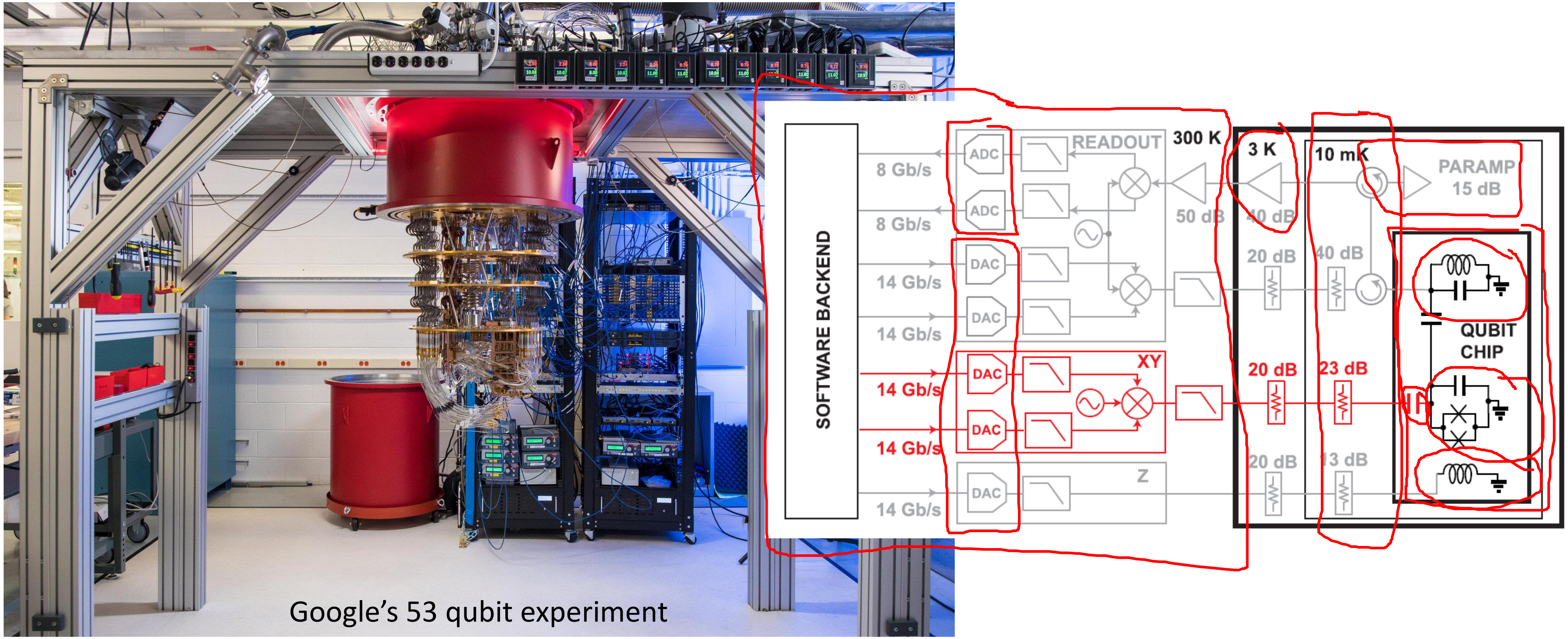

Google's 53 qubit experiment

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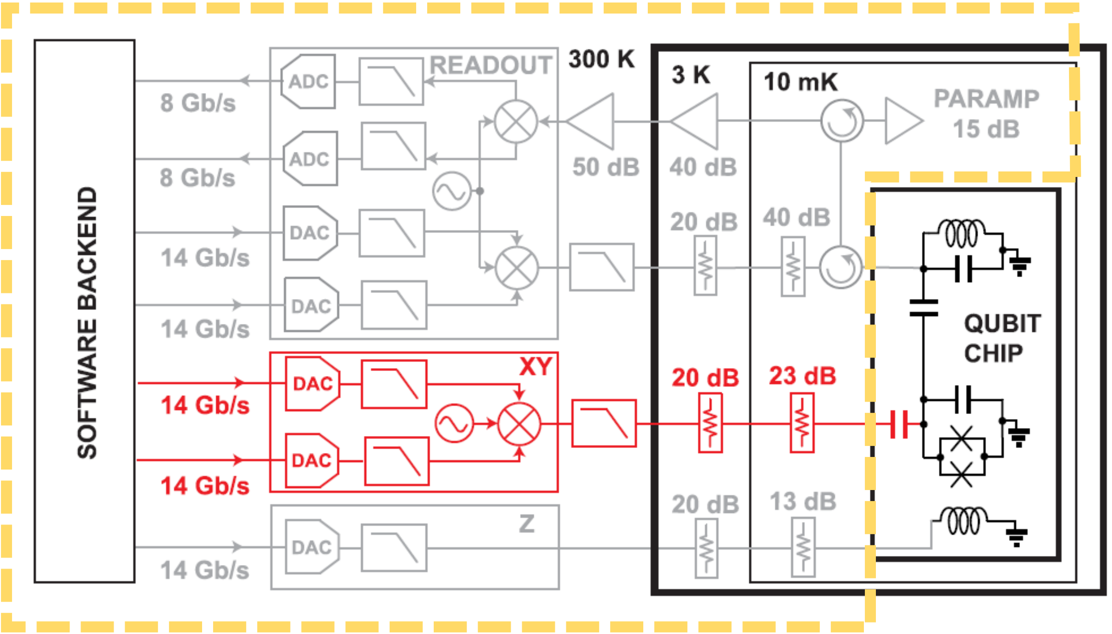
Introduction and Motivation

NIST

Our work focuses here:

- Demonstrate scalable control/readout circuits at (or below) 4 K?
- What advantages are there for quantum computing by using superconducting electronics?
- Qubit agnostic!



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Previous work

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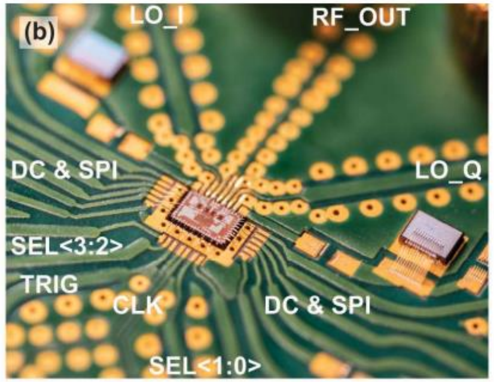
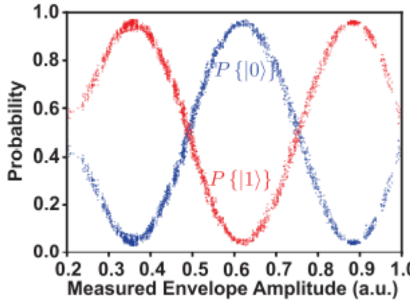
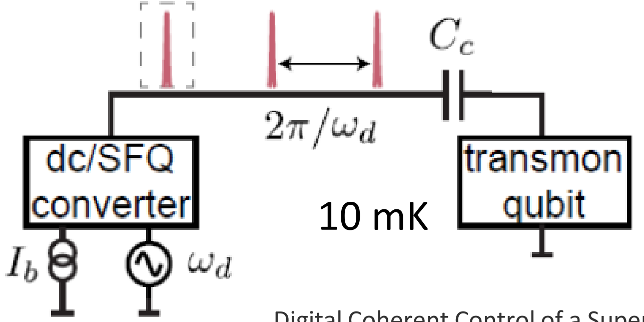
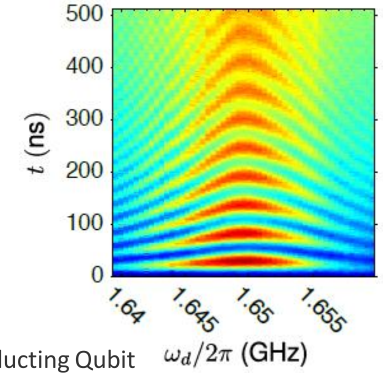
Cryo-CMOS (Bardin, *et al.* Google)





SFQ electronics (McDermott/Plourde)





Digital Coherent Control of a Superconducting Qubit
E. Leonard, Jr., et al, Phys. Rev. Applied **11**, 014009

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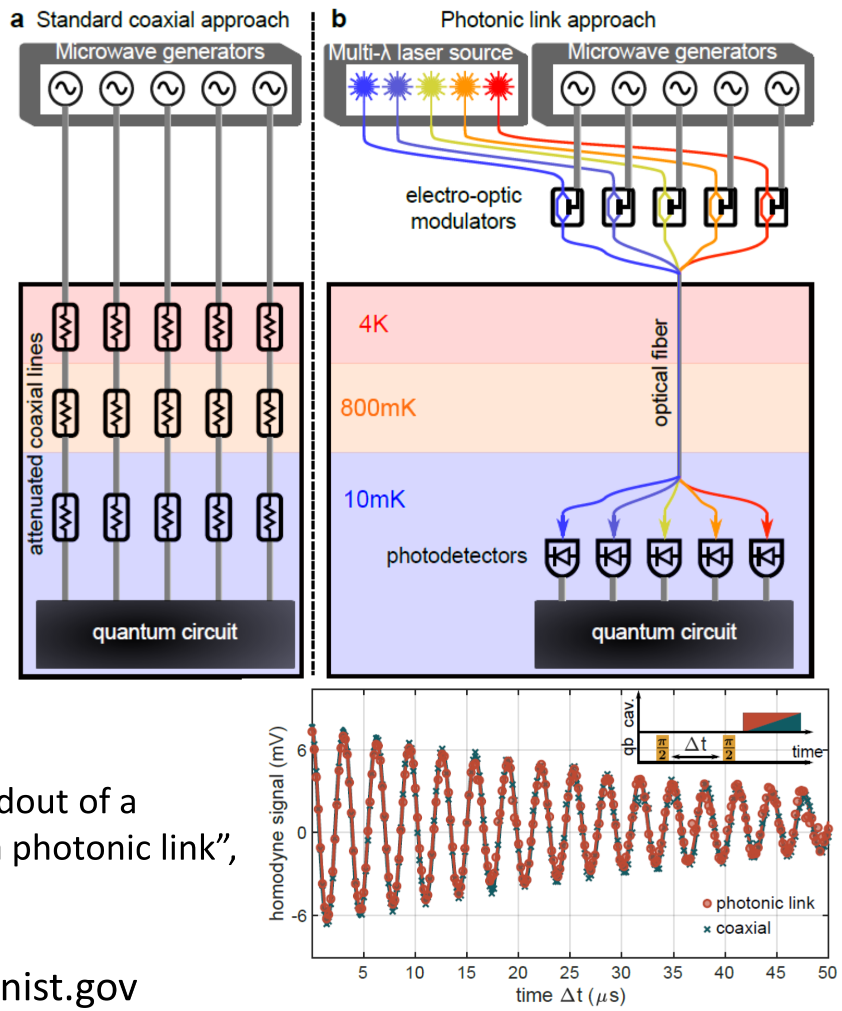

Lecocq et al, "Control and readout of a superconducting qubit using a photonic link", arXiv:2009.01167v1

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Benefits of 4 K control circuits

NIST

Our work focuses here:

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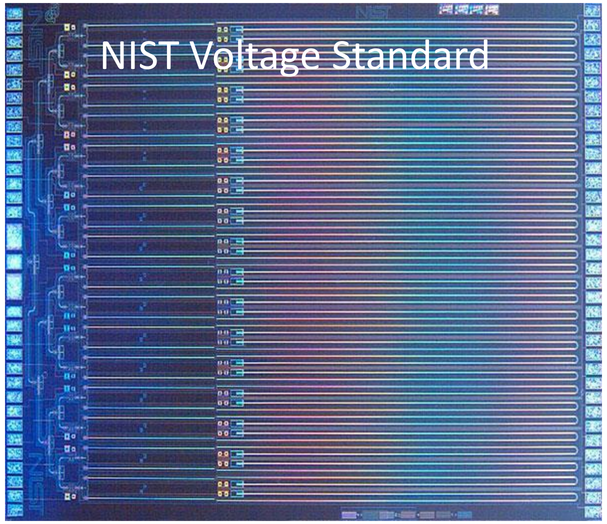
- What advantages are there for quantum computing by using superconducting electronics?
- Qubit agnostic!

- Dissipation: ample cooling power at 4 K
- Quasiparticle poisoning w/ 10 mK SFQ
- Speed: potential low-latency feedback
- Quantum-based accuracy/repeatability



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Experimental Results: SFQ synthesis

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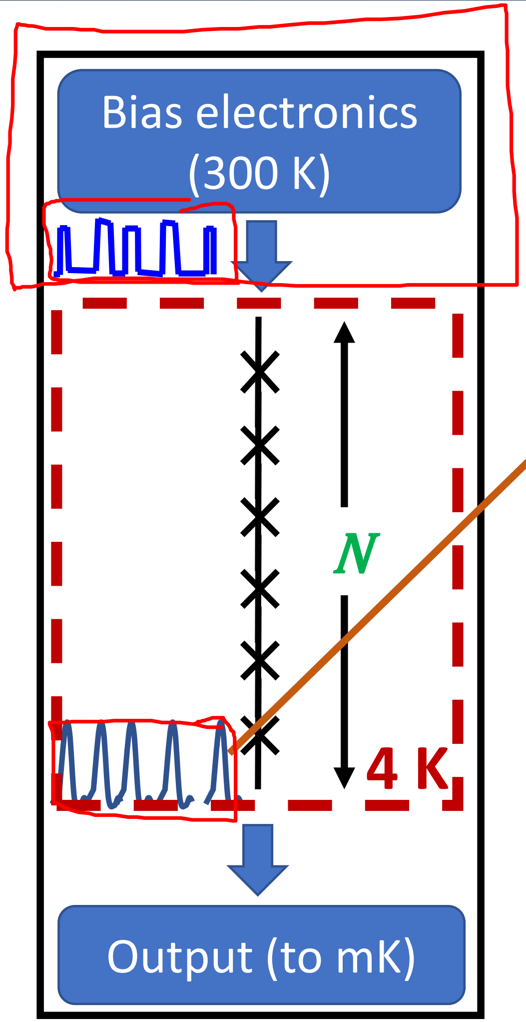
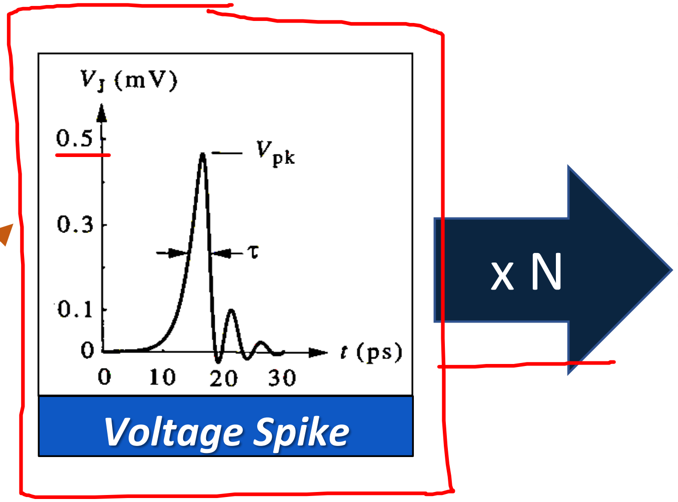
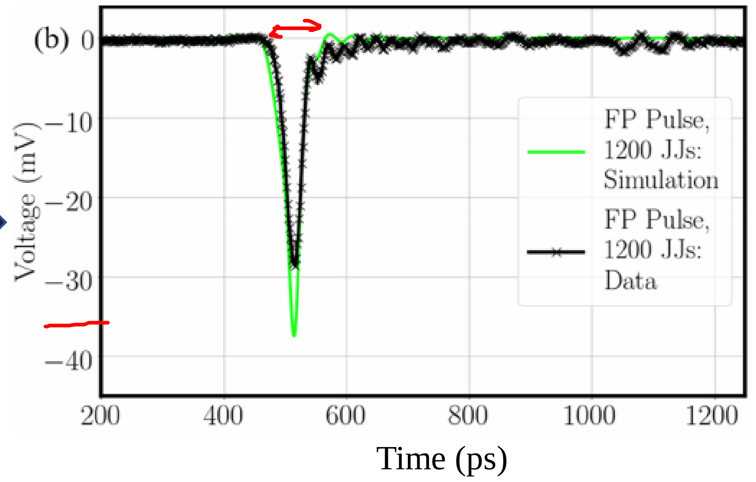




$$\int V dt = \Phi_o$$

For N=1200



C. A. Donnelly *et al.*, "Quantized Pulse Propagation in Josephson Junction Arrays," in *IEEE Transactions on Applied Superconductivity*,

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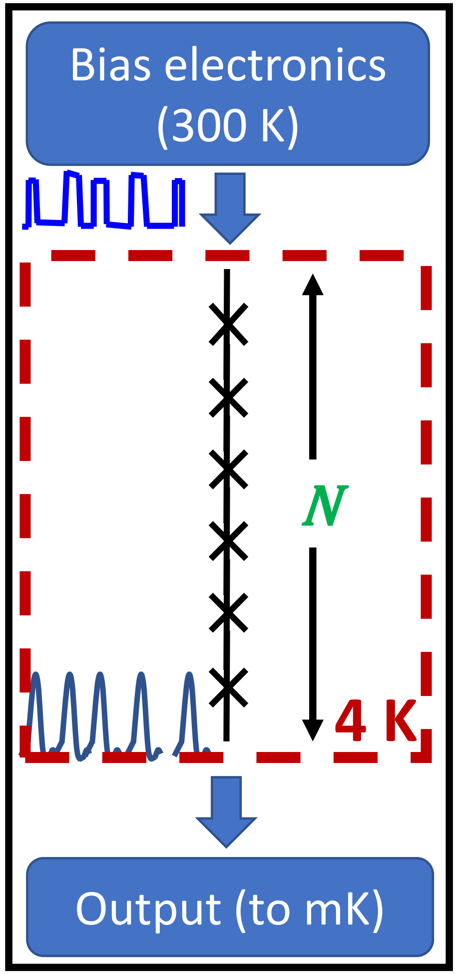
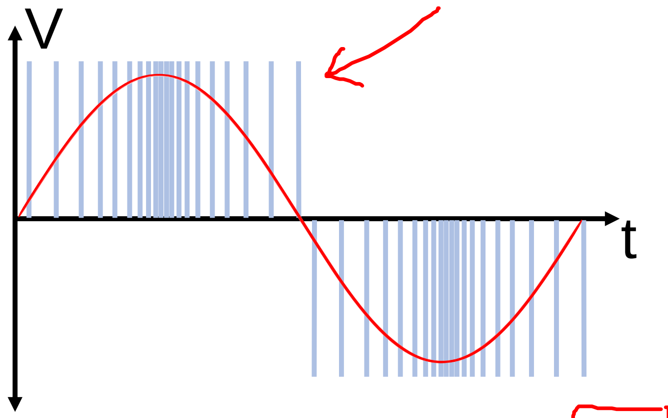
Experimental Results: delta-sigma encoding





- Pulse density modulation (ΔΣ)
- Cryogenic DAC
- Quantum-locked (stability and repeatability of the source)

$$<V> = \frac{h}{2e} N f$$

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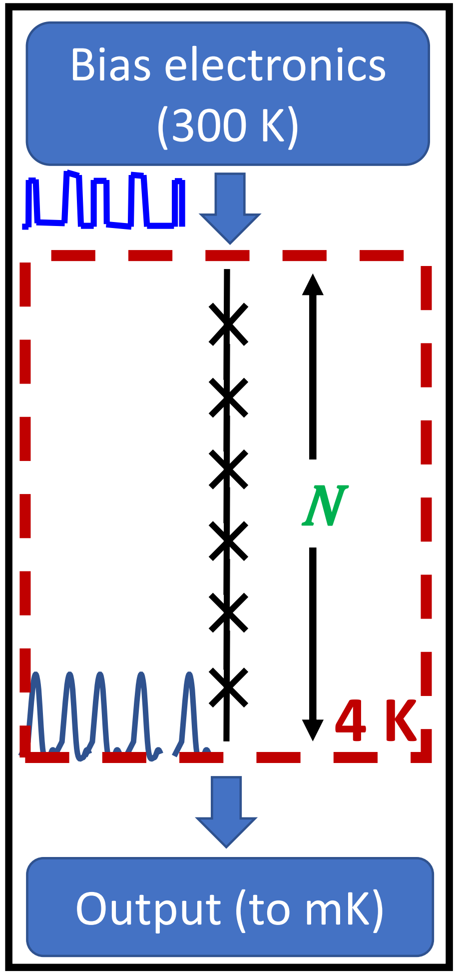

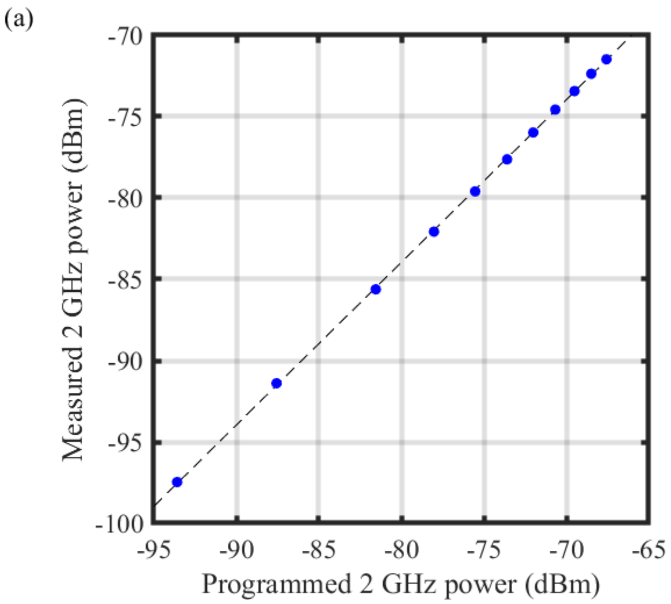

- Can program amplitude, phase (for multi-tone signals), and frequency.
- Repeatable, and stable

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Experimental Results: Nyquist sampling

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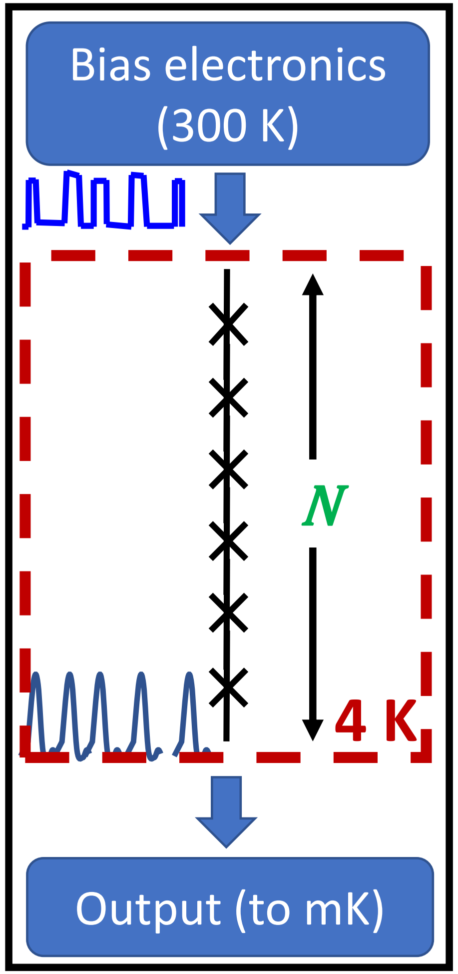
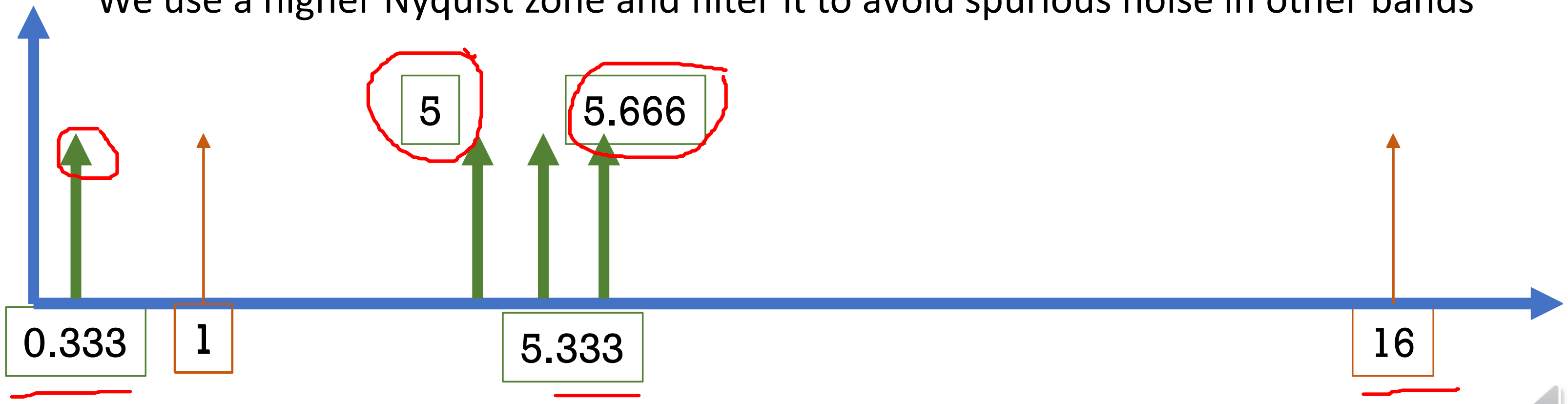


$I_c \times R_N \sim 40\ \mu V$, limited by room temperature electronics (~20 GHz)

'original code' = 11110000111000110010… at 16 GSa/s…generates 1 GHz output

'padded code' = 100 100 100 100 000 000 000 000 100 100 100 000 000 000… generates a 333 MHz signal…but gets aliased up!

We use a higher Nyquist zone and filter it to avoid spurious noise in other bands



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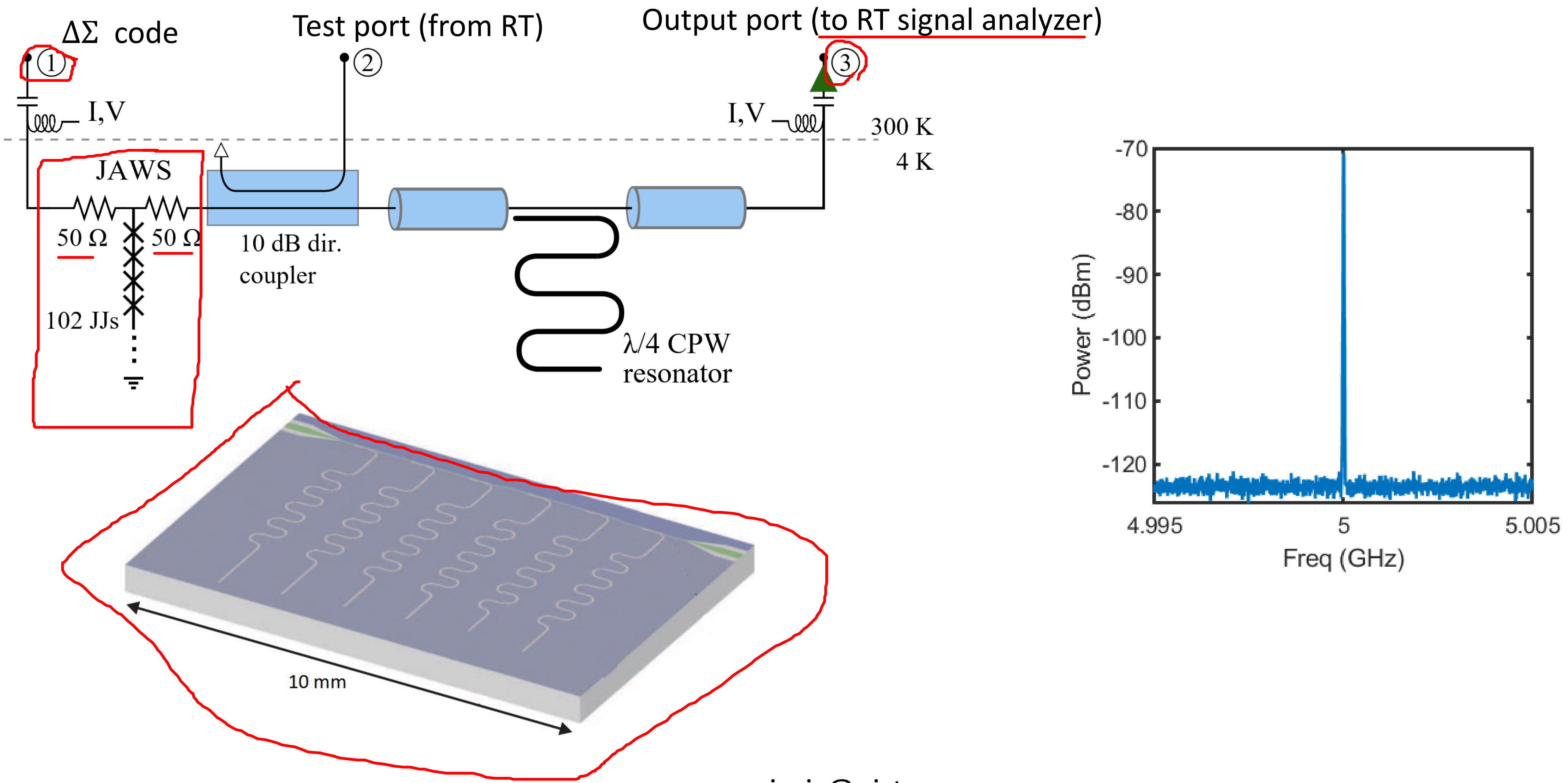
Experimental Results: JAWS & resonators (4K)



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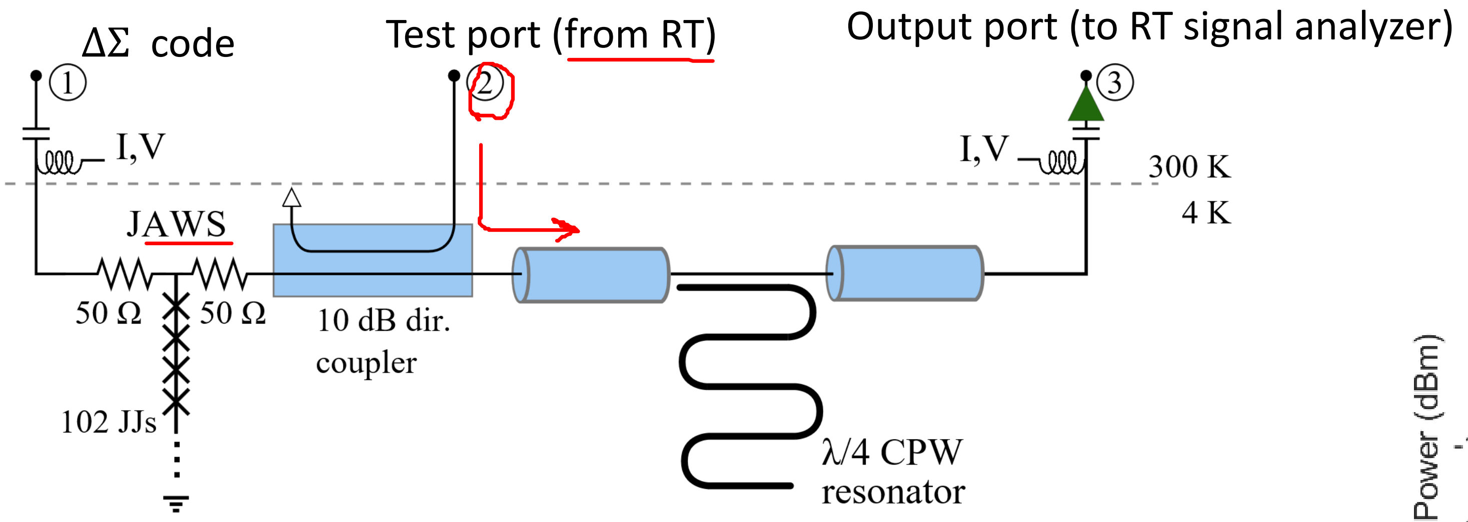

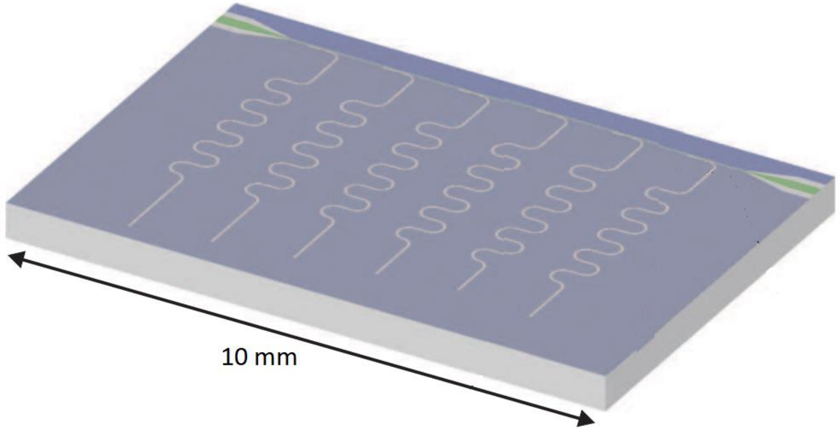

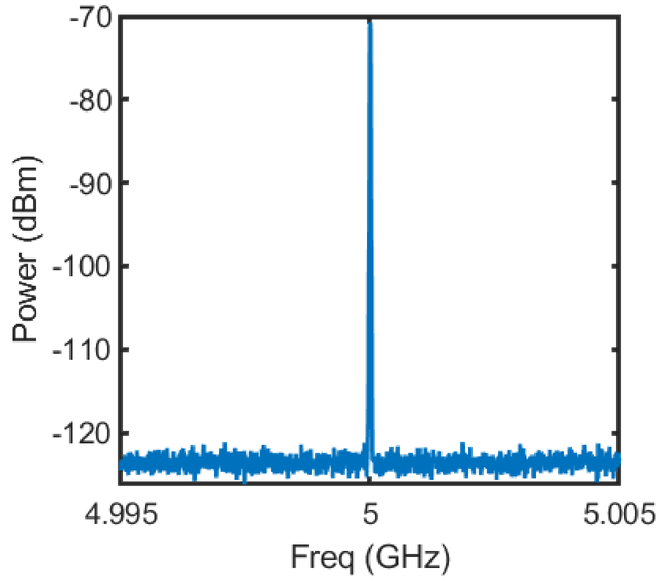

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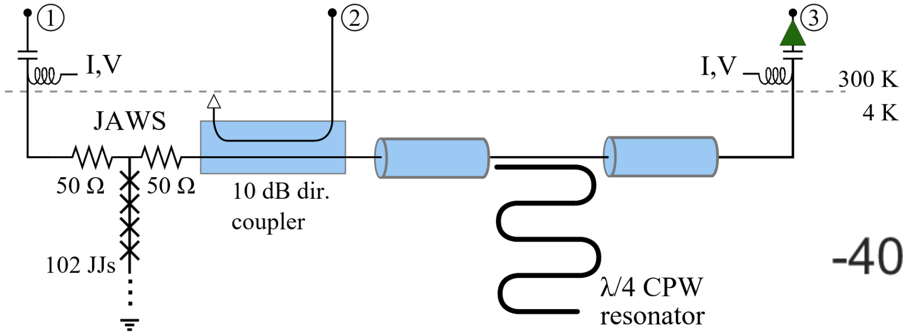
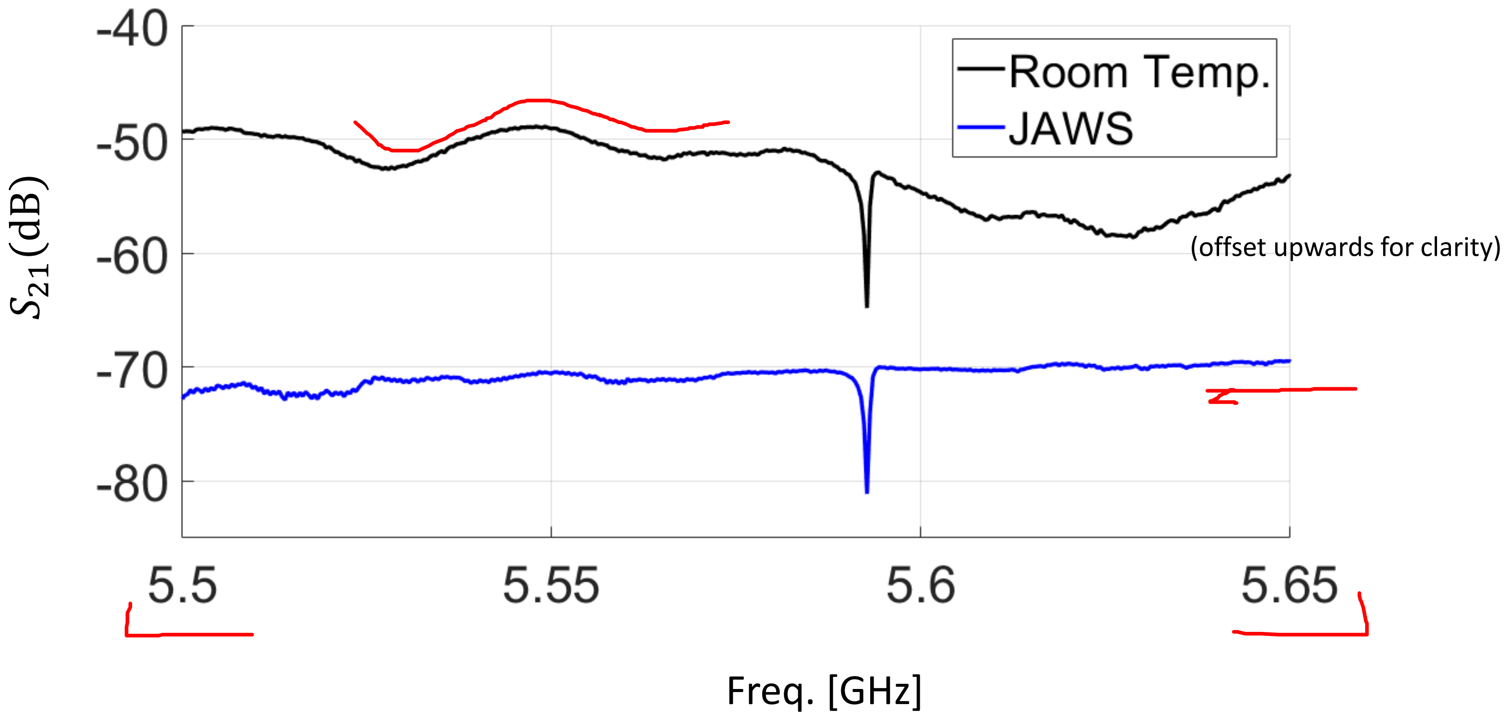
NIST





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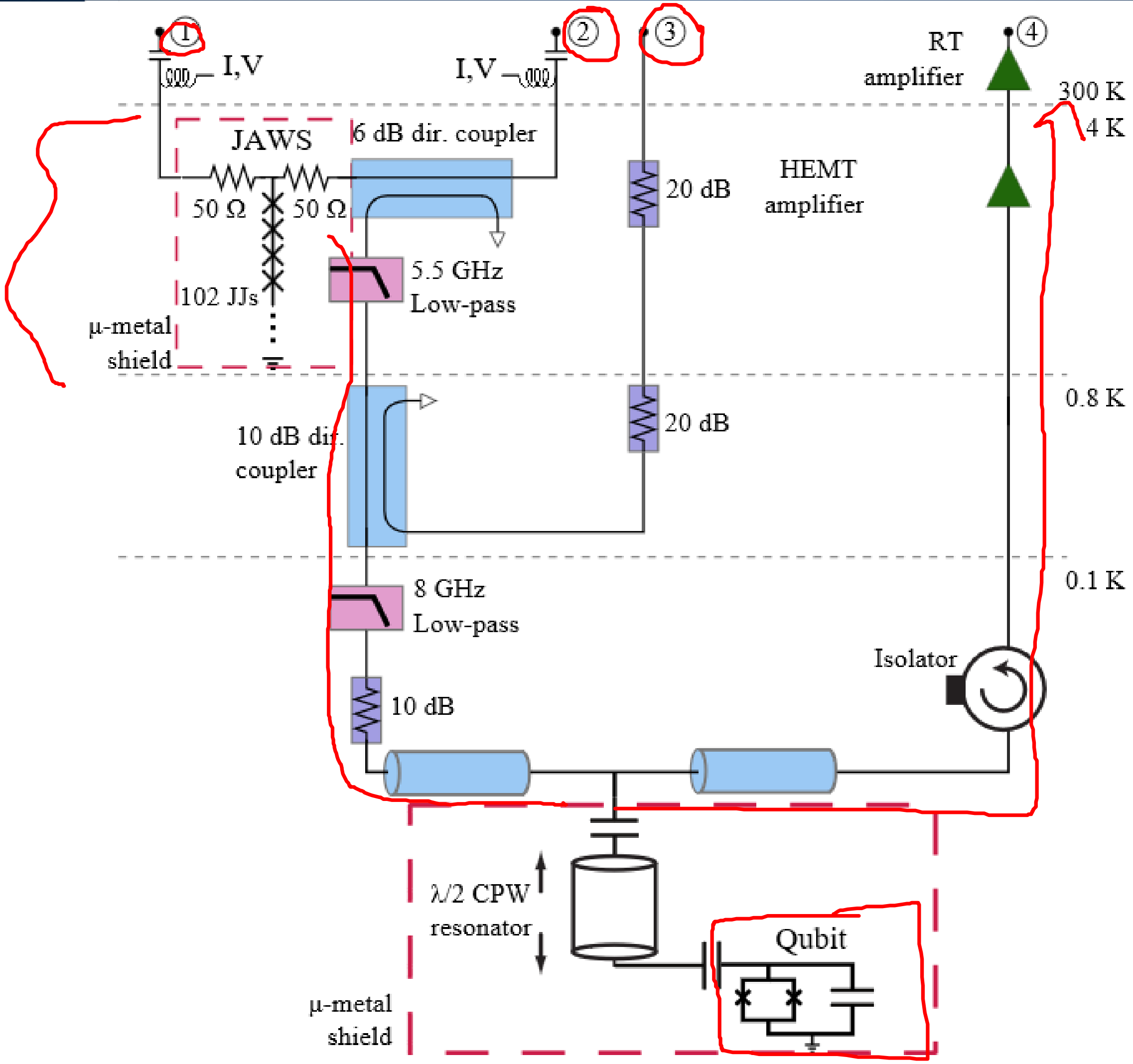
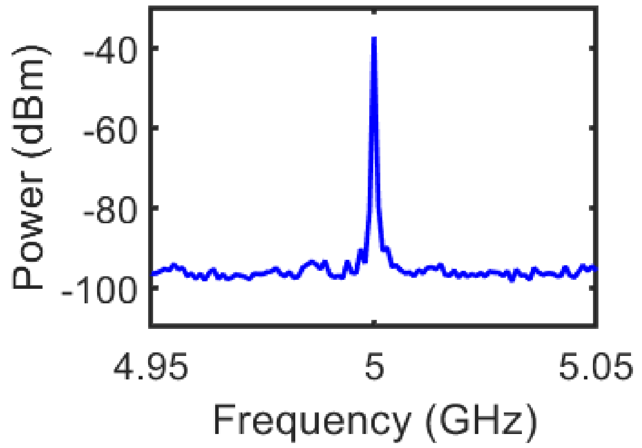
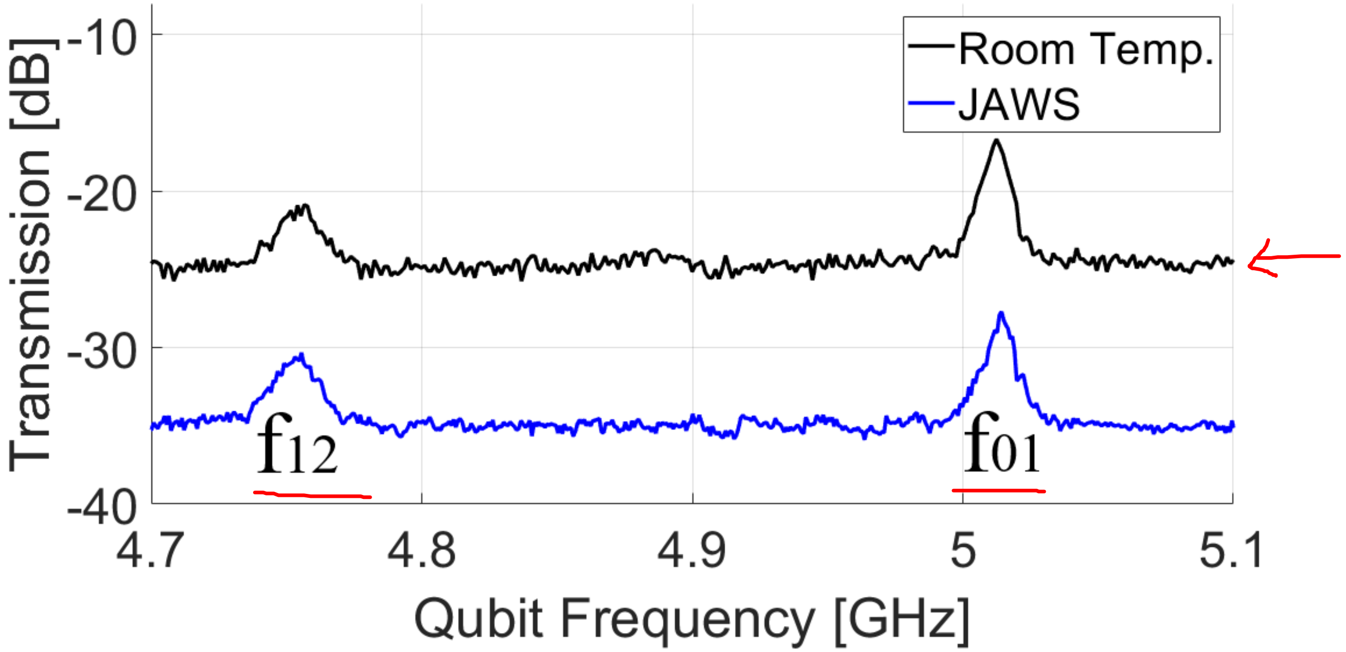
Experimental Results: spectroscopy of 100 mK qubit





Qubit courtesy of David Pappas

Experimental Results: spectroscopy of 100 mK qubit



A.J. Sirois, *et al. Josephson Microwave Sources Applied to Quantum Information Systems*. In preparation

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Experimental Results: full qubit control (10 mK)

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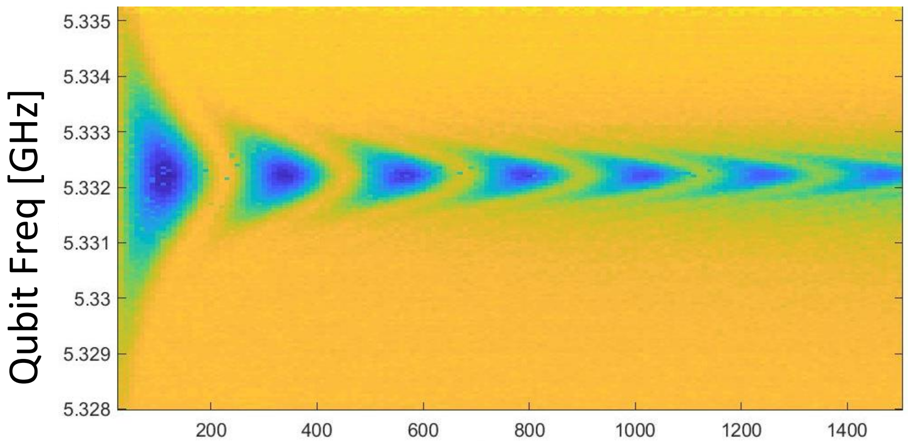
In progress (Covid delayed):

- Dilution refrigerator delivered in Feb. 2020
- Single qubit at 10 mK (3D cavity geometry)
  - Finished characterization with room temp components

Rabi Oscillations



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In collaboration with Aumentado group

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NIST

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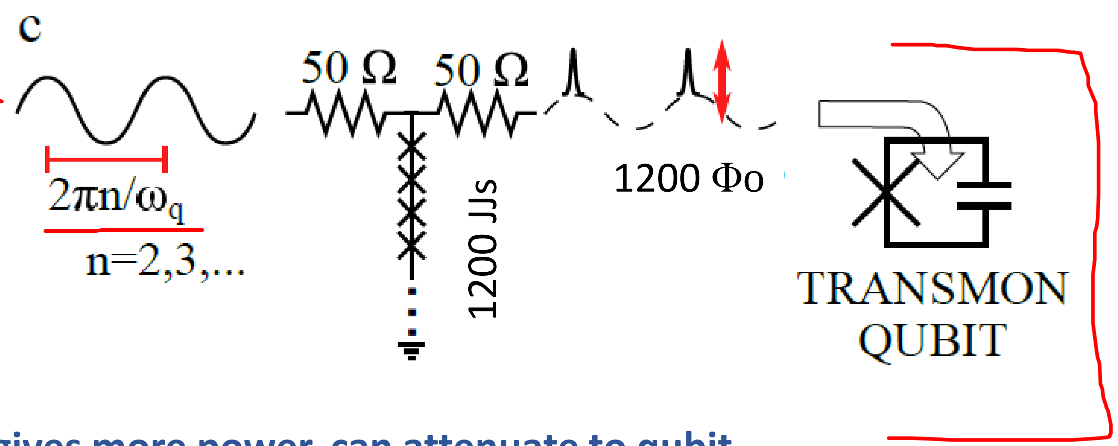
- Single qubit at 10 mK (3D cavity geometry)
  - Finished characterization with room temp components
- JAWS with 1200 JJs at 4 K
  - Qubit pulse control experiments in progress



1200 JJs gives more power, can attenuate to qubit

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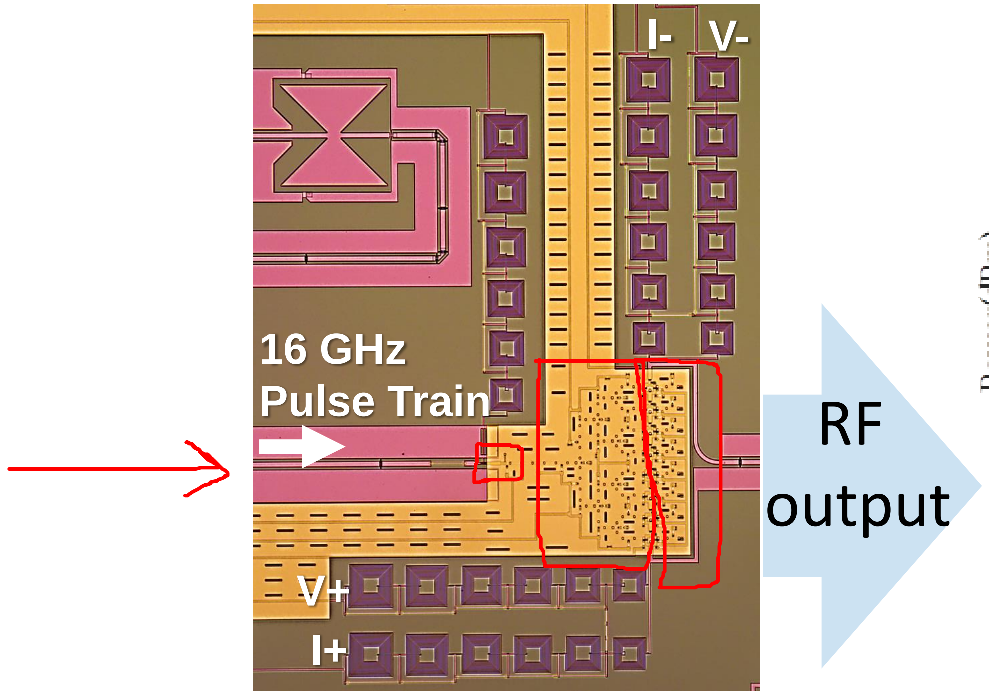
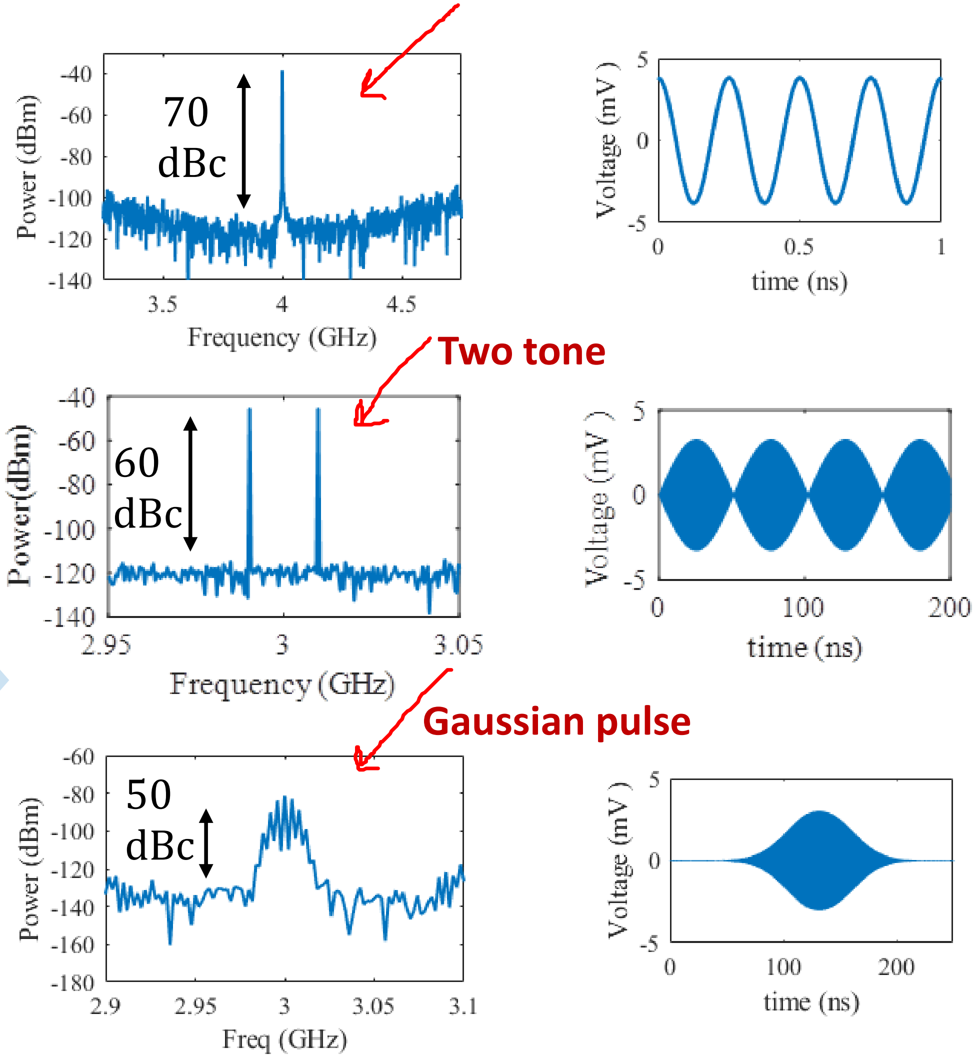
SFQ circuits for amplification

SFQ Pulse-Multiplier Circuit

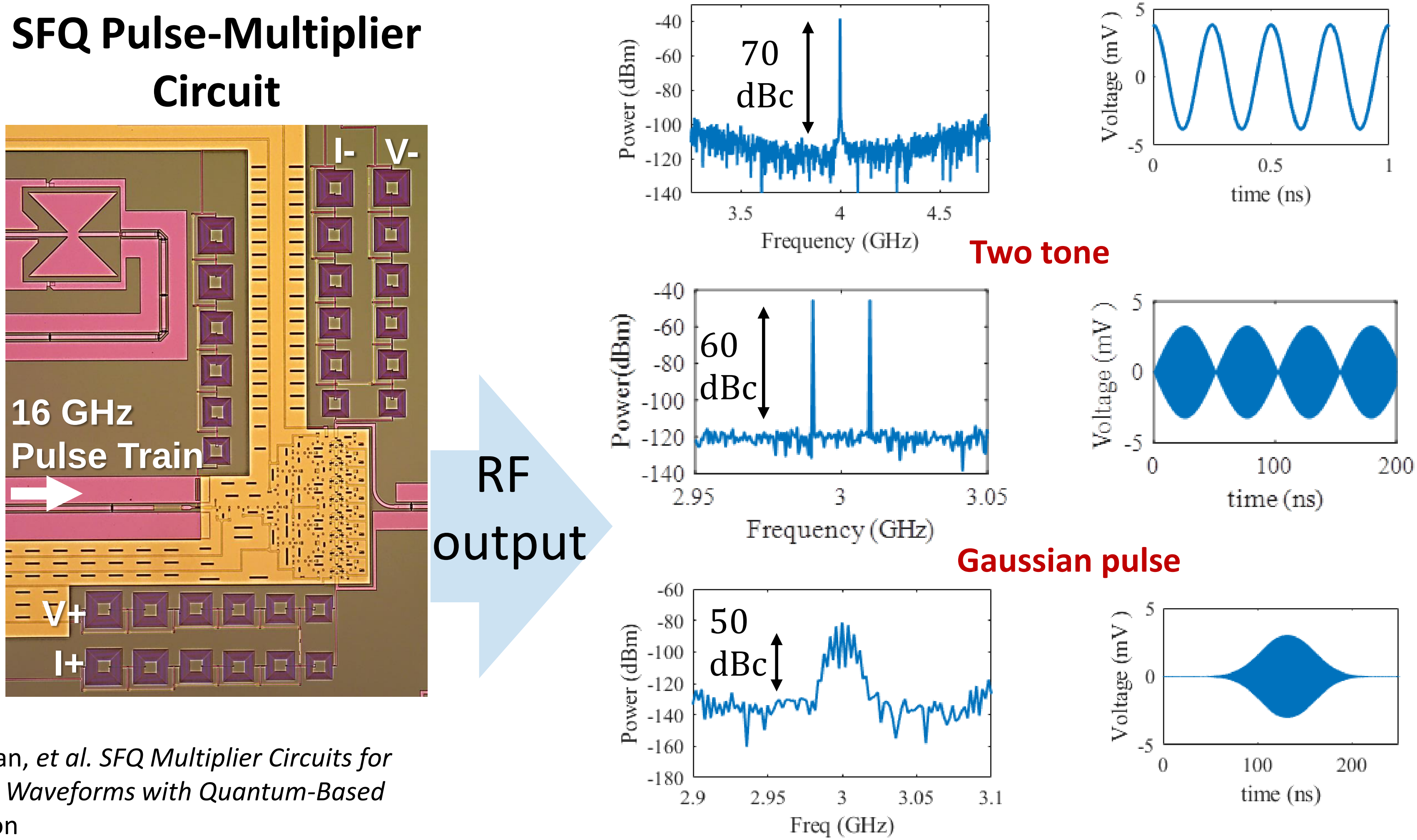




M.A. Castellanos-Beltran, *et al. SFQ Multiplier Circuits for Synthesizing Gigahertz Waveforms with Quantum-Based Accuracy*. In preparation

SFQ circuits for amplification

SFQ Pulse-Multiplier Circuit



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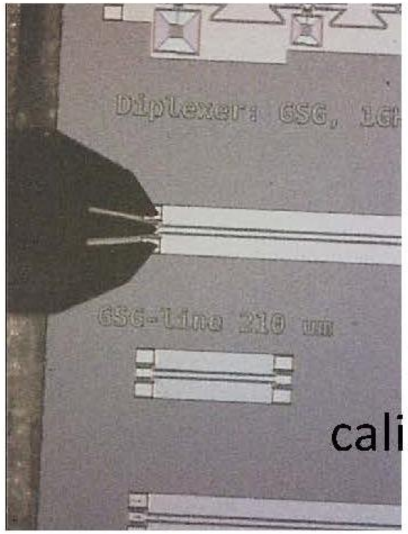
Metrology

Other than demonstrating qubit control, 4 K electronics are useful for qubit metrology!

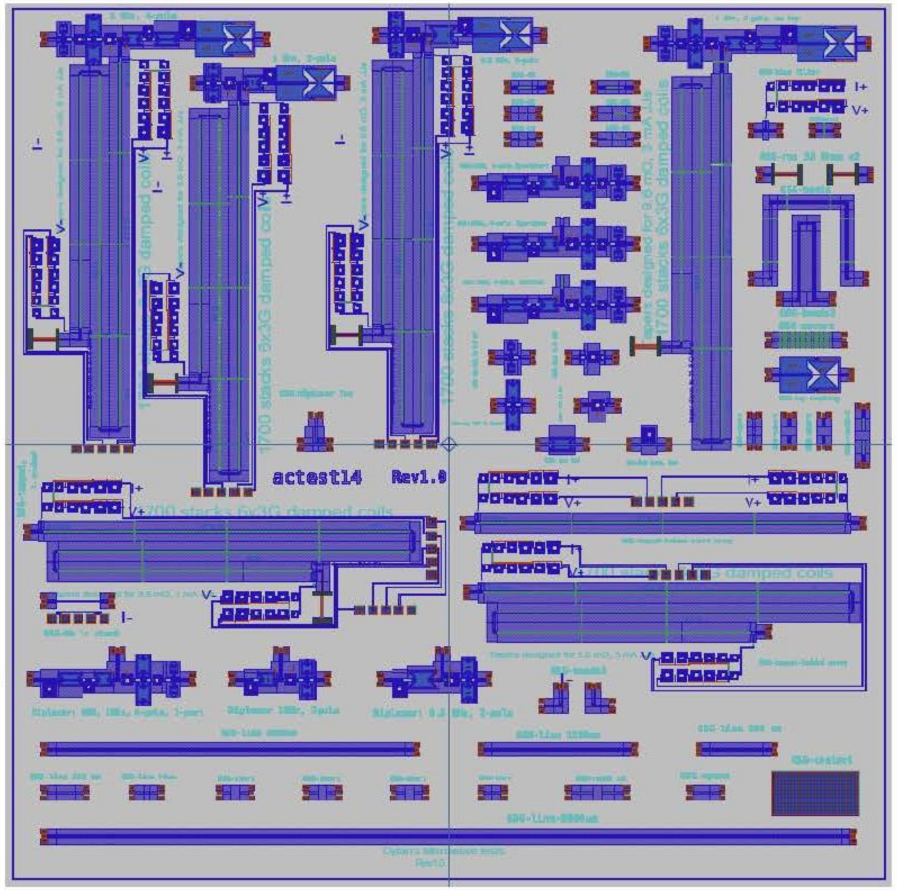
Metrology: 4 K TRL calibration kit

NIST

JJ arrays for NIST Josephson arbitrary waveform synthesizer (JAWS)



TRL calibrations



ASC 2016 11

R. Chamberlain et al., ASC 2016

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Scaling Challenges

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Develop quantum-based reference microwave sources

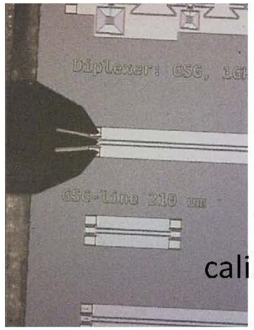
Microwave Measurement Science for QC:

- Characterizing microwave qubits, circuits, components, and interconnects.
- Quantifying manufacturing variability, crosstalk, etc.

Provide a “toolbox” and techniques for fully characterizing microwave signals

- mK temperatures
- Amplitude and Phase
- Quantum-computing-relevant power levels

JJ arrays for NIST Josephson arbitrary waveform synthesizer (JAWS)



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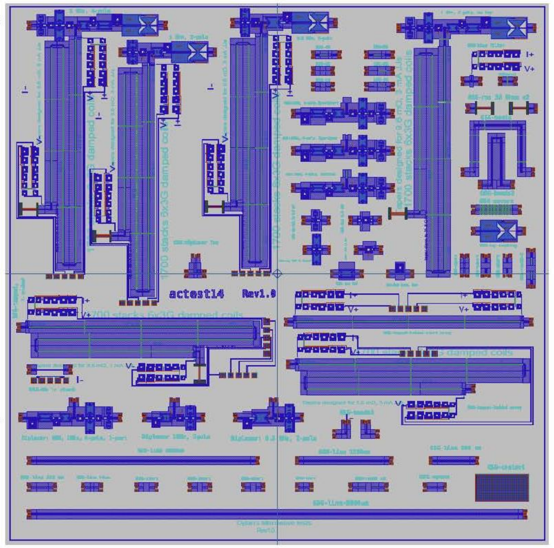

ASC 2016 11

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Future Work and Conclusions

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- Calibrated measurements of superconducting qubit control circuits
  - Power dissipation as well as TRL microwave calibrations
- Demonstrations of full qubit control with 4 K JAWS
- Novel qubit readout circuits
  - Digitizing qubit state into 0s and 1s at 4 K
  - Fast feedback or error-correction at 4 K

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