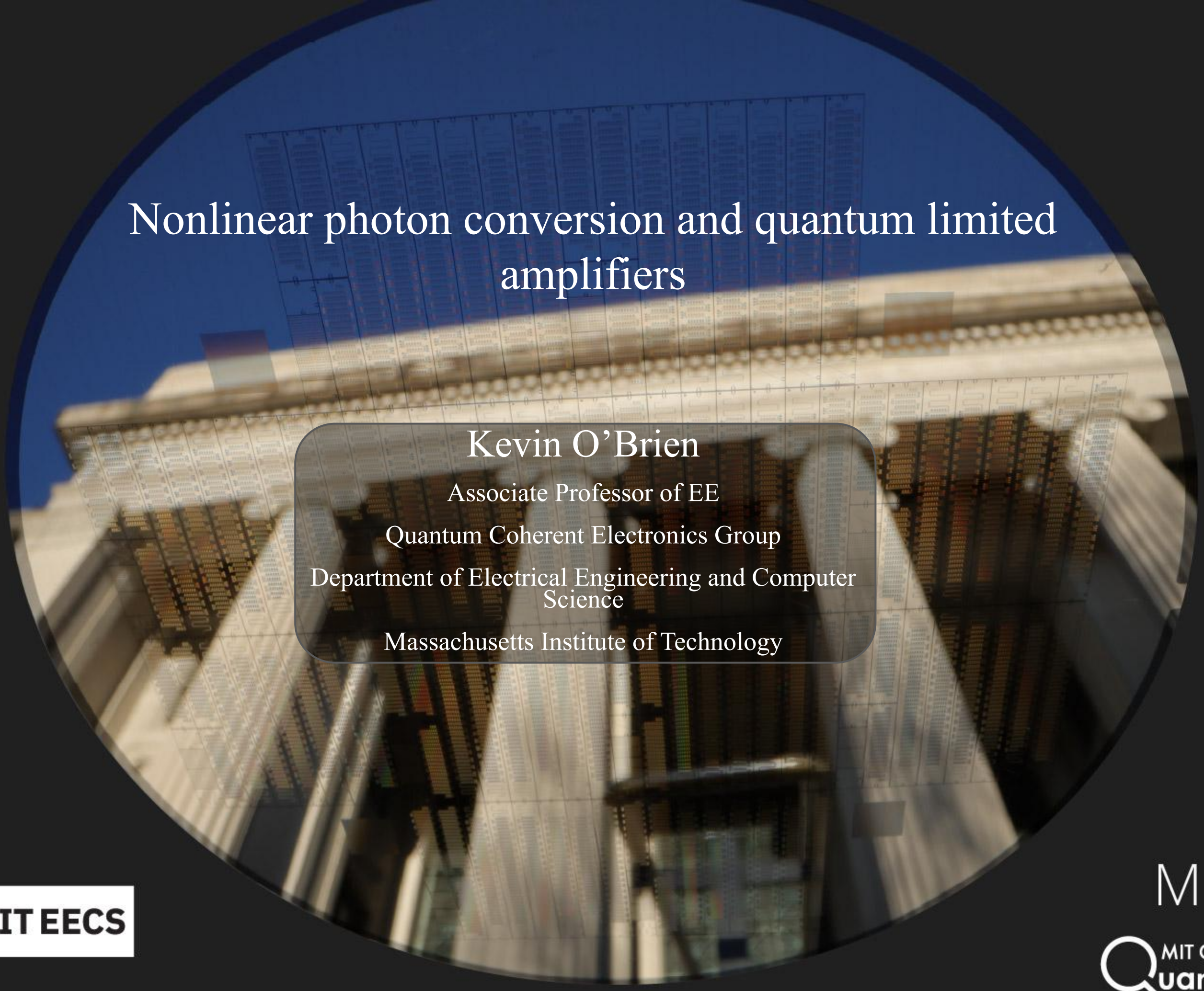
qce.mit.edu



Nonlinear photon conversion and quantum limited amplifiers

Kevin O’Brien

Associate Professor of EE

Quantum Coherent Electronics Group

Department of Electrical Engineering and Computer Science

Massachusetts Institute of Technology

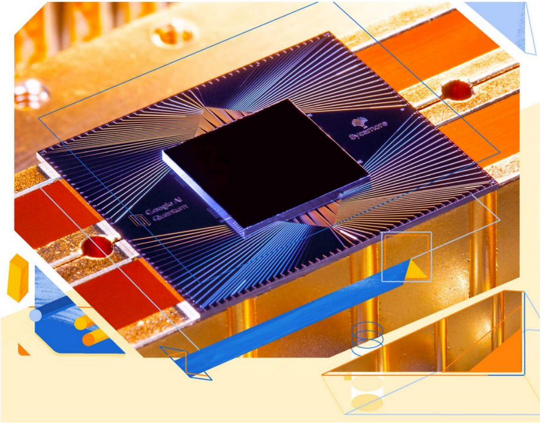
MIT.nano

MIT Center for QuantumEngineering

SSI 2026, Aug 10, 2026

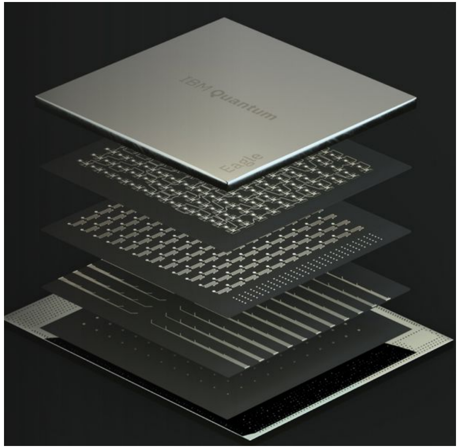
Quantum computing is happening now!

Google

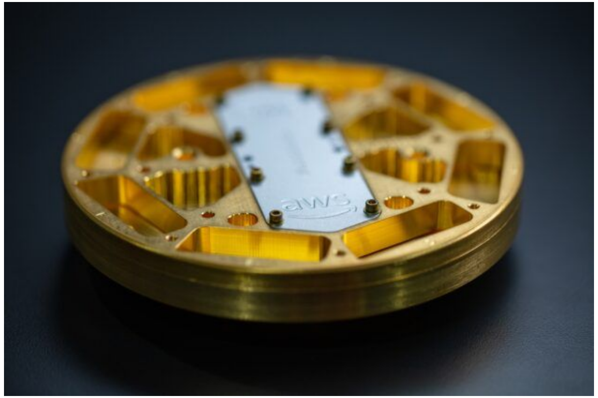


Examples of companies building superconducting quantum computers

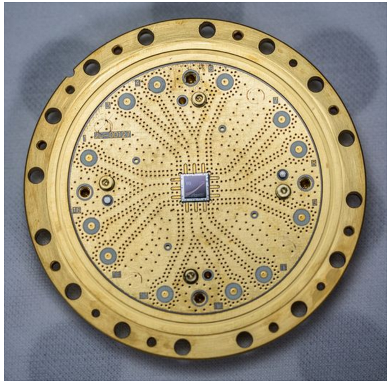
IBM



AWS

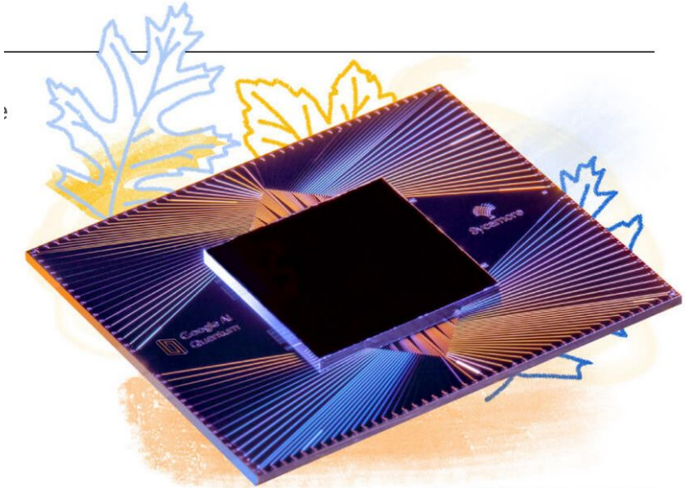


Rigetti

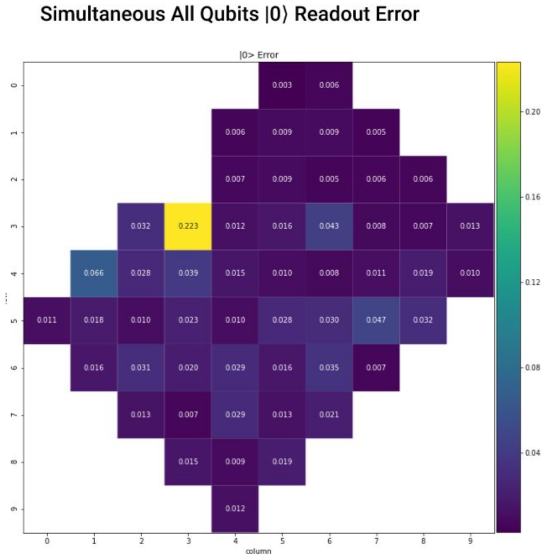


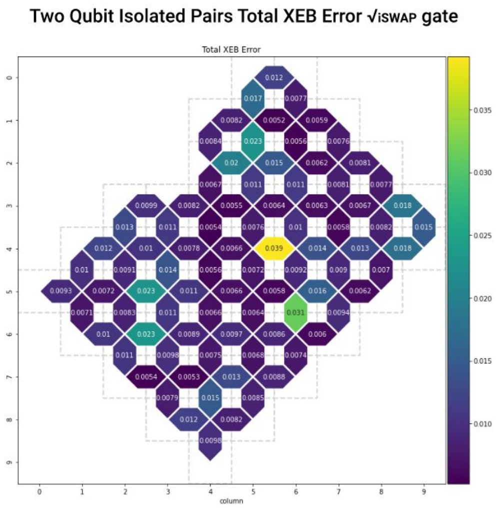
- Current state of the art: few hundred *non-error corrected* qubits
- Necessary for practical applications: hundreds - thousands of *error corrected* qubits

Quantum computers now have datasheets!



54-qubit Sycamore processor





https://quantumai.google/hardware/datasheet/weber.pdf

Quantity and quality required

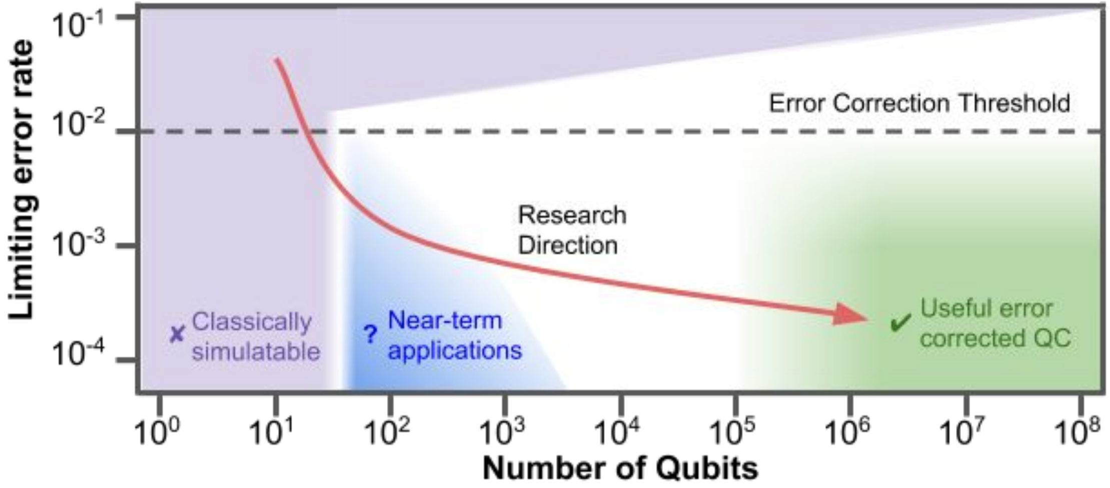


Image credit: Google AI Blog

Current state of the art

Expected in several months - years

How far do we have to go? Ex: cryptography

Cryptos ystem	Category	Key Size	Security Parameter	Quantum Algorithm Expected to Defeat Cryptosystem	# Logical Qubits Required	# Physical Qubits Required[a]	Time Required to Break System[b]	Quantum-Resilient Replacement Strategies
AES-GCM [5]	Symmetric encryption	128 192 256	128 192 256	Grover's algorithm	2,953 4,449 6,681	4.61×10^6 1.68×10^7 3.36×10^7	2.61×10^{12} yrs 1.97×10^{22} yrs 2.29×10^{32} yrs	
RSA [6]	Asymmetric encryption	1024 2048 4096	80 112 128	Shor's algorithm	2,290 4,338 8,434	2.56×10^6 6.2×10^6 1.47×10^7	3.58 hours 28.63 hours 229 hours	Move to NIST-selected PQC algorithm when available
ECC Discrete -log problem[c] [7,8]	Asymmetric encryption	256 386 512	128 192 256	Shor's algorithm	2,330 3,484 4,719	3.21×10^6 5.01×10^6 7.81×10^6	10.5 hours 37.67 hours 95 hours	Move to NIST-selected PQC algorithm when available
SHA256 [9]	Bitcoin mining	N/A	72	Grover's Algorithm	2,403	2.23×10^6	1.8×10^4 years	
PBKDF 2 with 10,000 iteration s[d]	Password hashing	N/A	66	Grover's algorithm	2,403	2.23×10^6	2.3×10^7 years	Move away from password-based authentication

Millions of physical qubits

Assumptions:

- 2d nearest neighbor connectivity
- Surface code
- Gates applied at 10 MHz
- Error rate 10^{-5}

Orders of magnitude beyond current state of the art, but not infeasible. Does not take into account improved error correction schemes or coherence improvements.

Quantum Computing: Progress and Prospects (2018), National Academies Report

Superconducting quantum computer example

~1 m

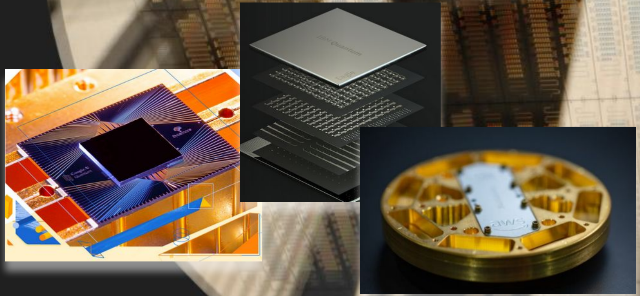
Image credit: IBM Q

Quantum processor:

~1 cm

qce.mit.edu

Superconducting quantum computing



?

rle AT MIT

MIT EECS

MIT.nano

MIT Center for QuantumEngineering

qce.mit.edu

My interest in paramps

- What are the fundamental limits on device performance imposed by quantum mechanics?
- How can we engineer devices to reach these limits?
- Can those limits be surpassed?

Outline

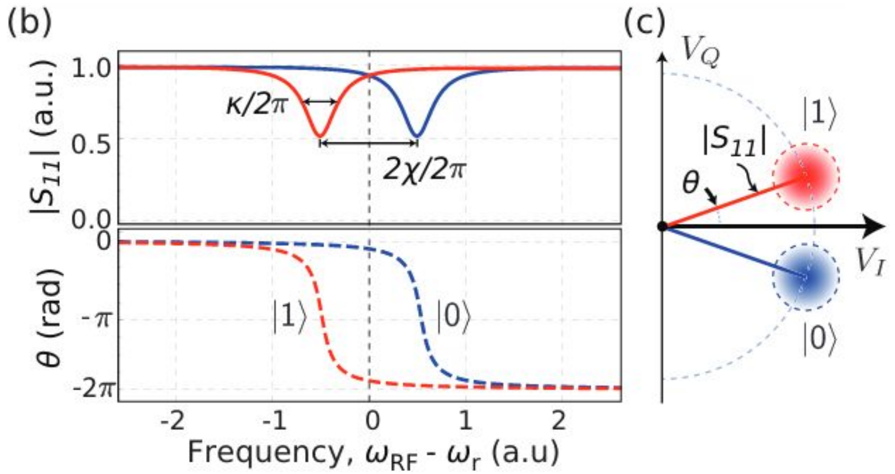
- Introduction.
- Why did broadband amplifiers (until very recently) have lower quantum efficiency than narrowband amplifiers?
- Simulating gain and noise performance of parametric amplifiers.
- Demonstration of a high quantum efficiency Floquet Josephson traveling wave parametric amplifier (TWPA).

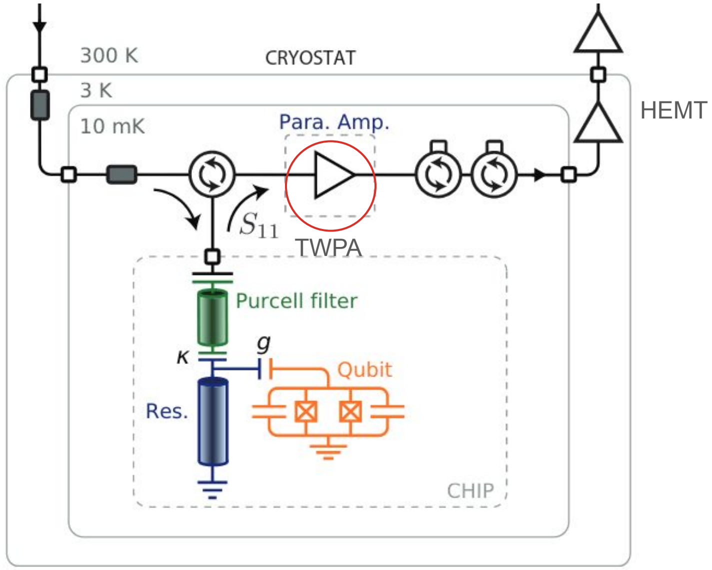
qce.mit.edu

Importance of quantum limited amplifiers for qubit readout

- Quantum limited preamplifiers improve SNR enabling faster higher-fidelity readout with fewer photons: $SNR^2 \propto \eta\ \kappa\ n\ t$
- Quantum limited amplifiers may hurt (e.g. dephasing) or help (e.g. isolation) qubit coherence.
- Enable multiplexing to reduce resource requirements for scaling.

Microwave readout of superconducting qubits

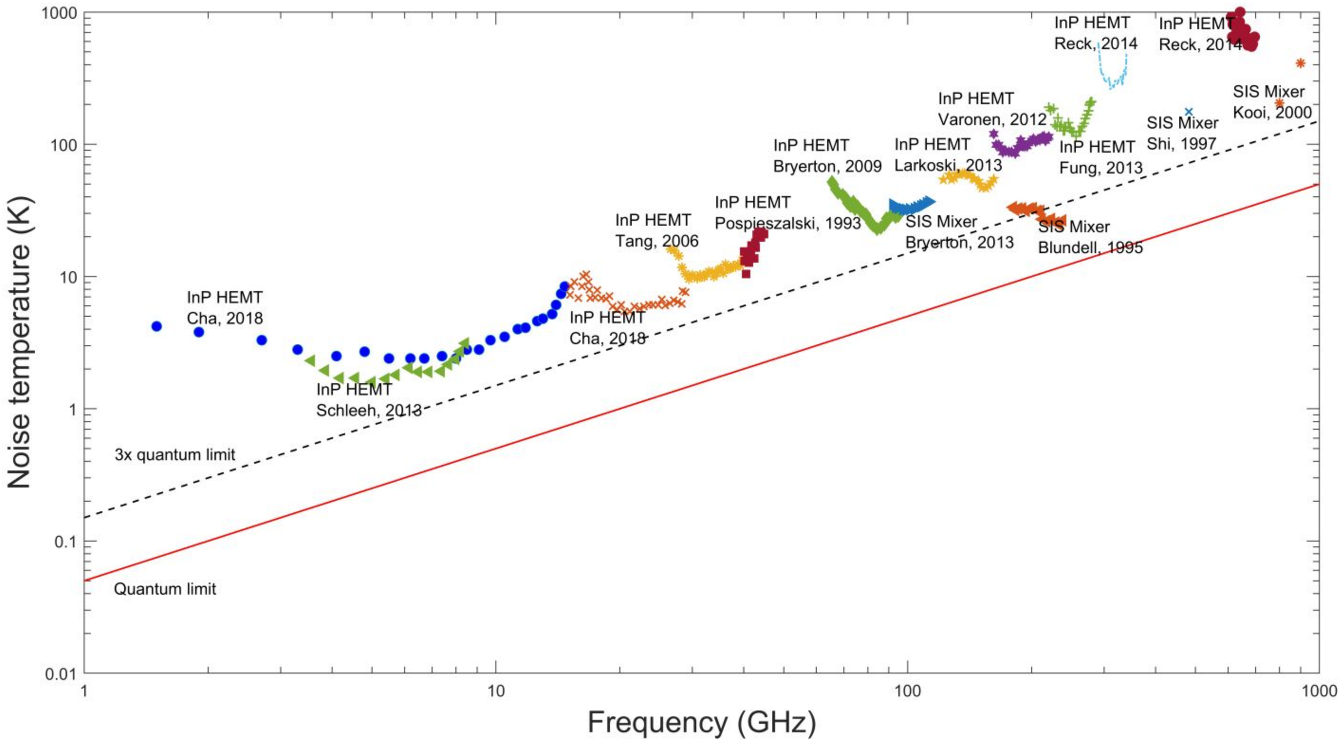




- Quantum limited preamplifiers improve SNR enabling faster higher-fidelity readout with fewer photons: $SNR^2 \propto \eta\ \kappa\ n\ t$
- The challenge: you can only use single photon level signals in the resonator and must read out in <100 ns for error correction.

P. Krantz et al. “A Quantum Engineer’s Guide to Superconducting Qubits” Applied Physics Reviews 6, 021318 (2019)

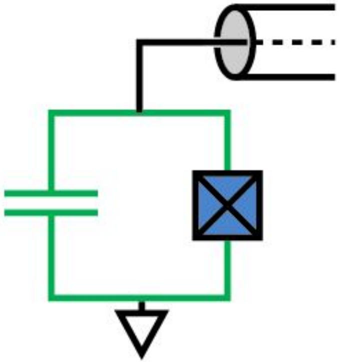
Why paramps?

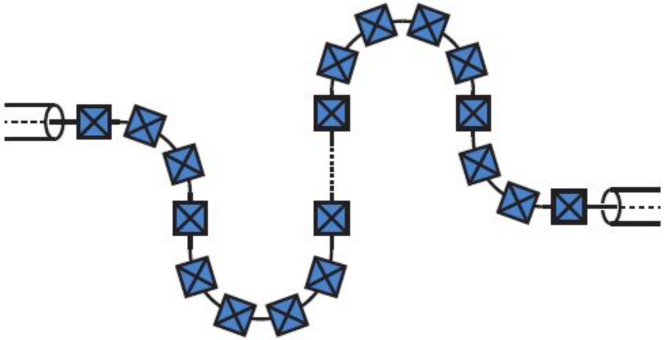


Semiconductor amplifiers are too noisy, dissipate too much heat (so far)

“Towards quantum-limited transistor microwave amplifiers” Austin Minnich, Snowmass 2021
https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF7_IF9-CF2_CF4_Austin_Minnich-117.pdf

Lumped element and traveling wave Josephson parametric amplifiers





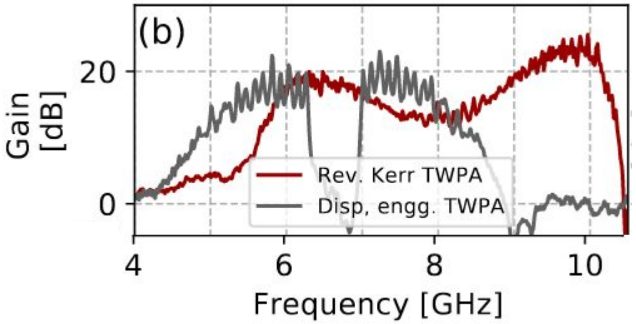
- Single or few spatial modes
- More narrow instantaneous bandwidth (10s-100s MHz)
- Well understood and near unity quantum efficiency
  80% from Eddins et al. Phys. Rev. X 9, 011004 (2019)

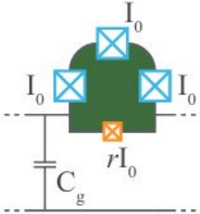
- Thousands of spatial modes.
- Wide bandwidth (few GHz)
- Potential for broadband isolation
- But can they reach the quantum limit?

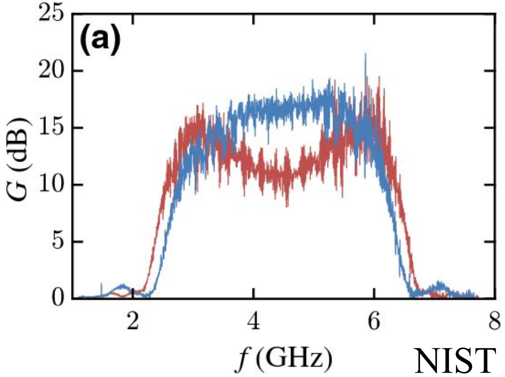
Traveling wave parametric amplifiers are widely used, but not yet ideal amplifiers

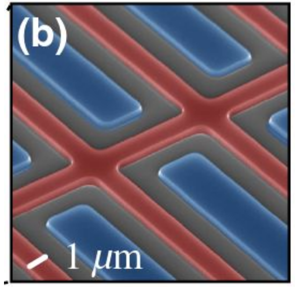
$$L_J(I) = L_J(0)/\sqrt{(1-(I/I_c)^2)} \approx L_J(0)\left(1+\frac{1}{2}\left(\frac{I}{I_c}\right)^2+...\right)$$

$$L_K(I) \approx L_K(0)\left(1+\left(\frac{I}{I^*}\right)^2+...\right)$$



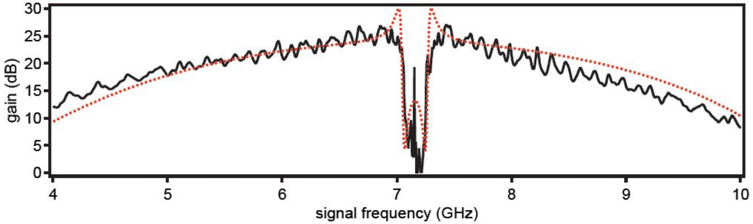


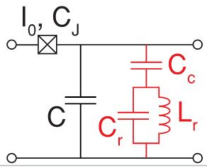


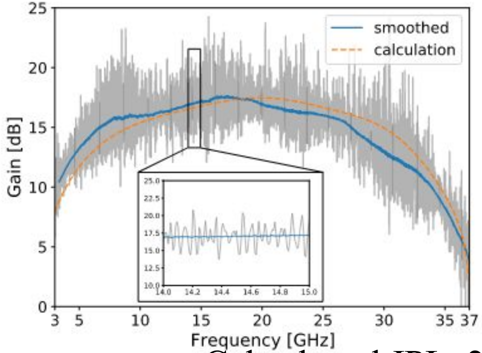


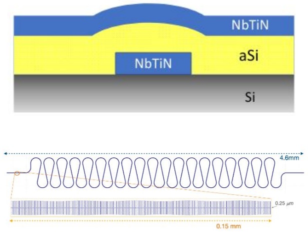
NIST and CU boulder, 2021

Grenoble, 2019, 2021







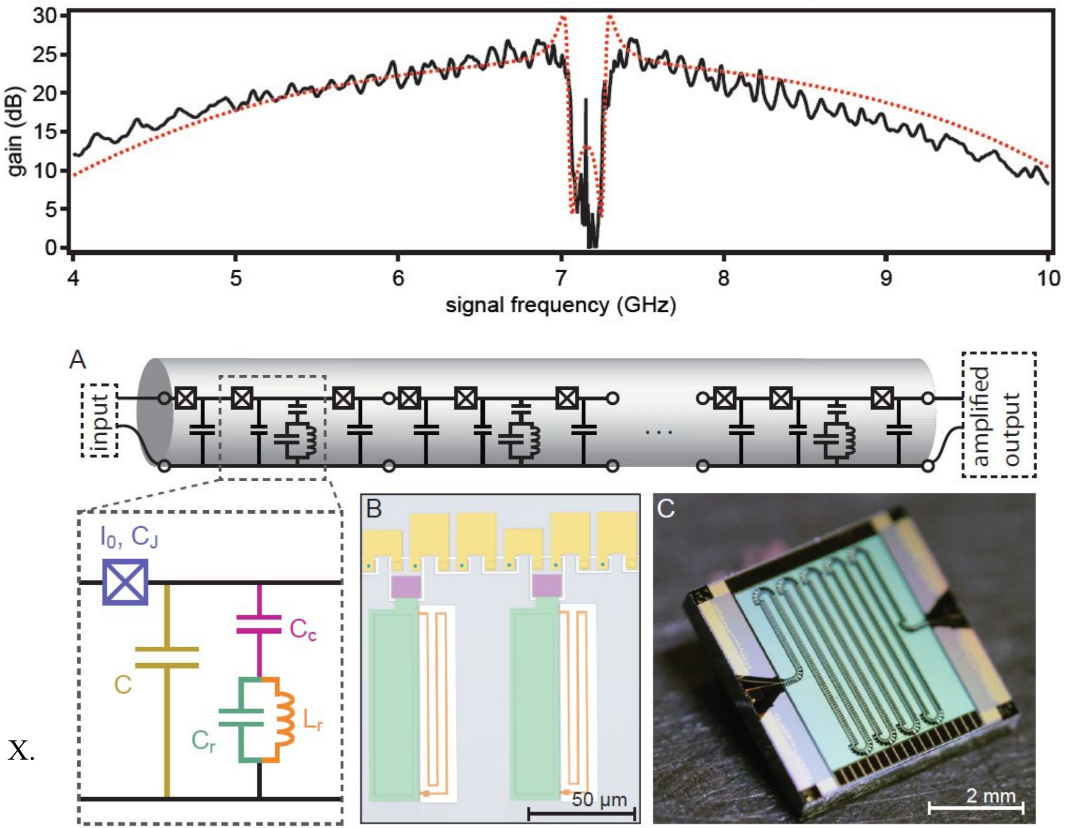


UC Berkeley and MIT, 2015
UCSB 2015

Caltech and JPL, 2021

Josephson traveling wave parametric amplifiers

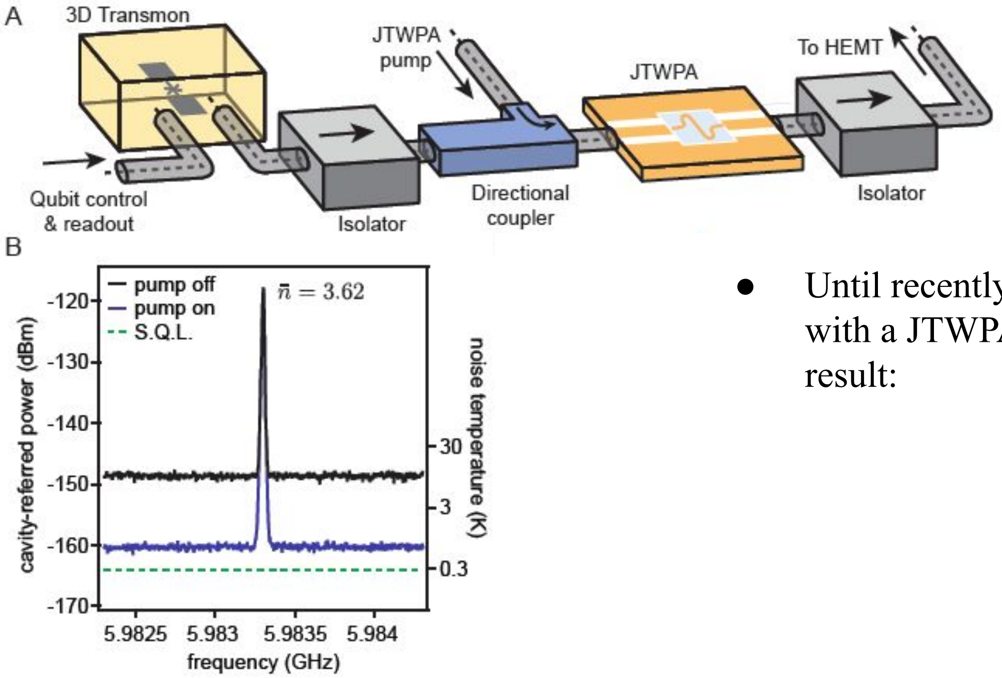
- Standard amplifier for frequency multiplexed SC qubit readout
- Bandwidth and dynamic range to simultaneously measure 10s of qubits
- P_{1dB} ~ -100 to -85 dBm
- Fabricated at Lincoln Lab
- 400+ distributed worldwide
- Now produced by several companies



C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovsky, X. Zhang, W. D. Oliver, and I. Siddiqi. Science 16 6258 (2015)

Why did TWPAs have lower quantum efficiency than JPAs?

Quantum efficiency of Josephson traveling wave parametric amplifiers

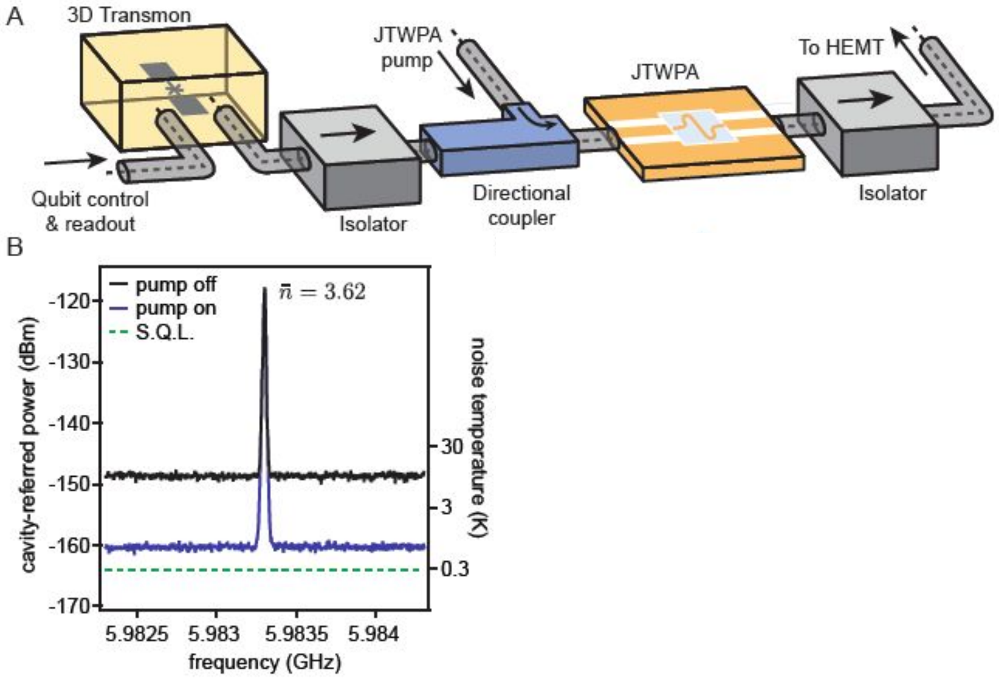


- Until recently, the best reported full chain quantum efficiency with a JTWPA remained comparable to the Berkeley 2015 result:

$$\eta/\eta_{ideal} = 0.48 \pm 0.0016$$

C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovsky, X. Zhang, W. D. Oliver, and I. Siddiqi. Science 16 6258 (2015)

Estimated quantum efficiency breakdown



<u>Non-unity intrinsic QE</u>

Total system quantum efficiency:

$$\eta = \eta_L \eta_D \eta_J \eta_H = 0.48$$

Insertion loss due to isolator and coupler: $\eta_L \approx 0.69$

Lossy dielectrics in TWPA: $\eta_D \approx 0.9$

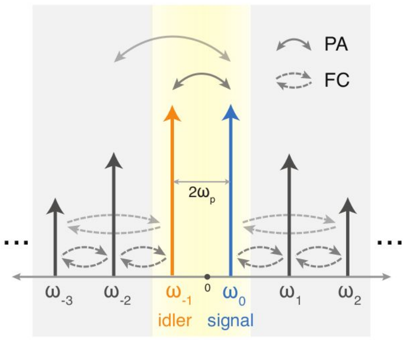
Following amplifier noise: $\eta_H \approx 0.93$

Unaccounted for drop in quantum efficiency $\eta_J \approx 0.83$

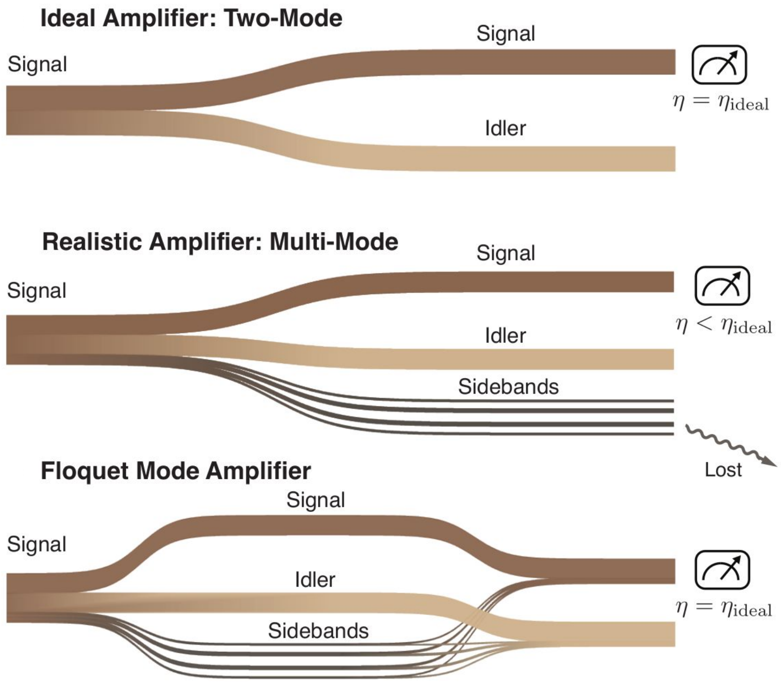
C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovsky, X. Zhang, W. D. Oliver, and I. Siddiqi. Science 16 6258 (2015)

Quantum efficiency of traveling wave parametric amplifiers

“computational basis”



$$\omega_n = \omega_s + n \times 2\omega_p$$

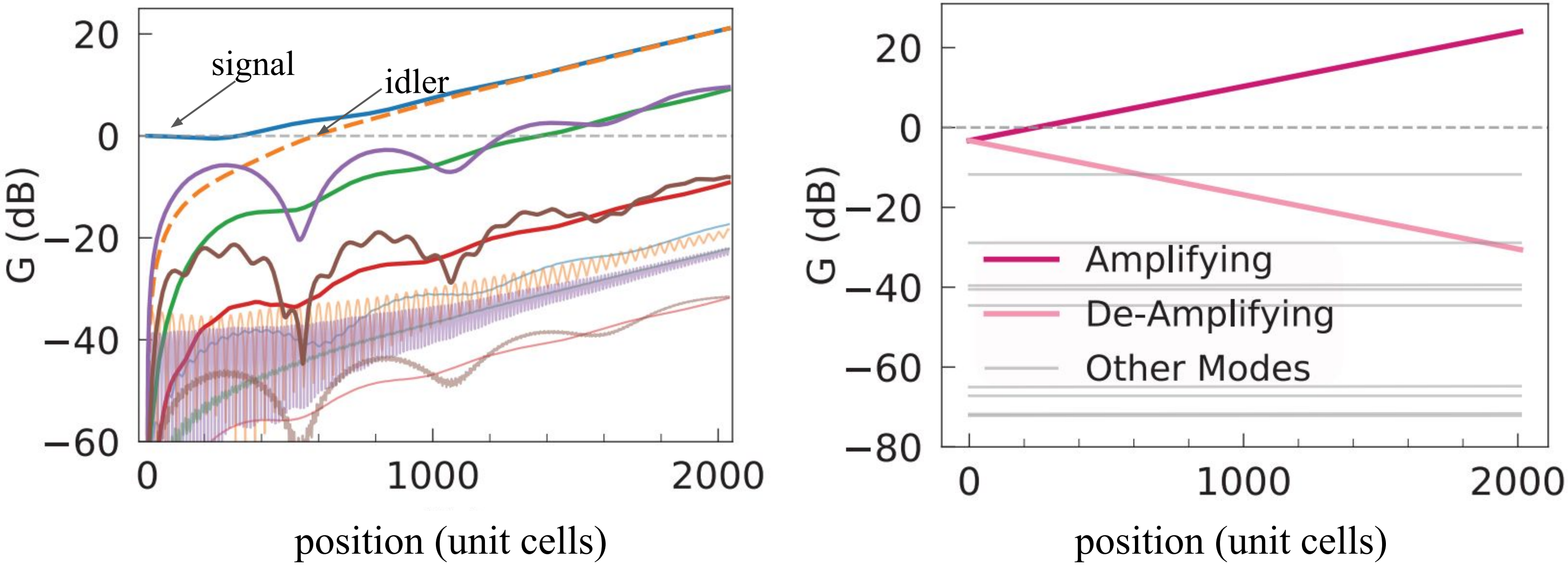


Analogous to leakage from computational subspace in qubits

[1] Sakuraba Proc IEEE 52 2 371-371 (1963).
[2] McKinstrie, C. J. et al., Opt. Express, OE 13, 4986–5012 (2005).
[3] Chaudhuri, S. et al., IEEE Trans. Appl. Supercond. 25, 1–5 (2015).
[4] Erickson, R. P et al., *Phys. Rev. B* **95**, 104506 (2017).
[5] Dixon, T. et al. Phys. Rev. Appl 14, 034058 (2020).
[6] S. Zhao et al., arxiv 2104.06350 (2021)

K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O’Brien "Floquet-Mode Traveling-Wave Parametric Amplifiers" PRX Quantum 3, 020306 (2022)

Dynamics in the Floquet basis



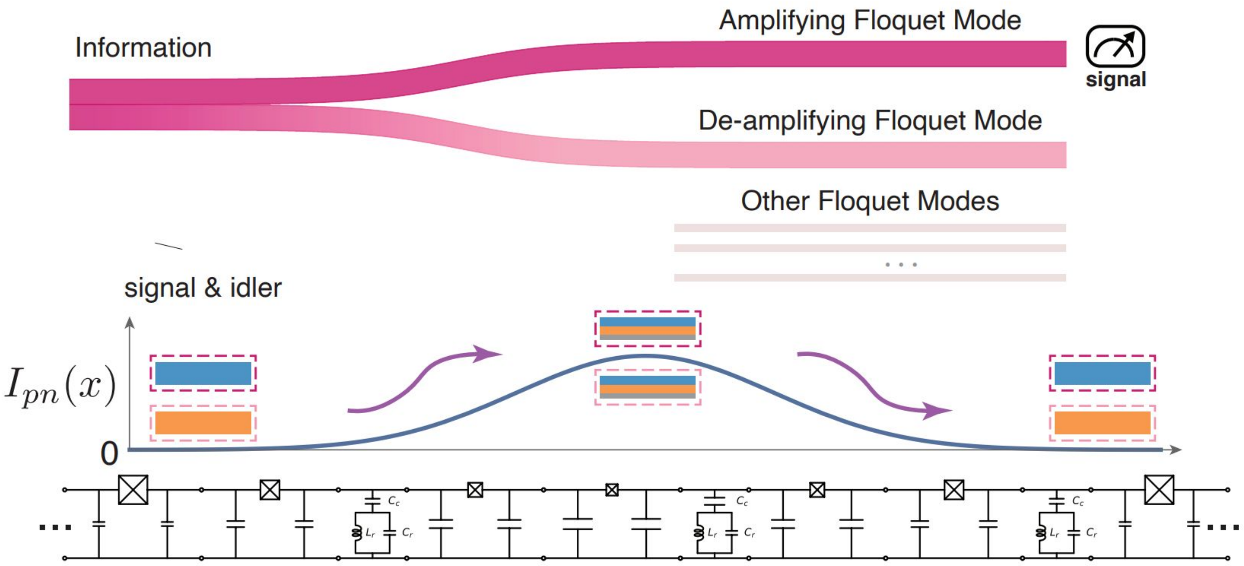
- Floquet modes: solutions of a <u>periodically driven system</u> expressed as a space-periodic function times a complex exponential:

$$\hat{Q}_\alpha(x) = e^{r_\alpha x}\hat{\alpha}(x)$$

- Dynamics become very simple, but each Floquet mode is composed of multiple frequencies

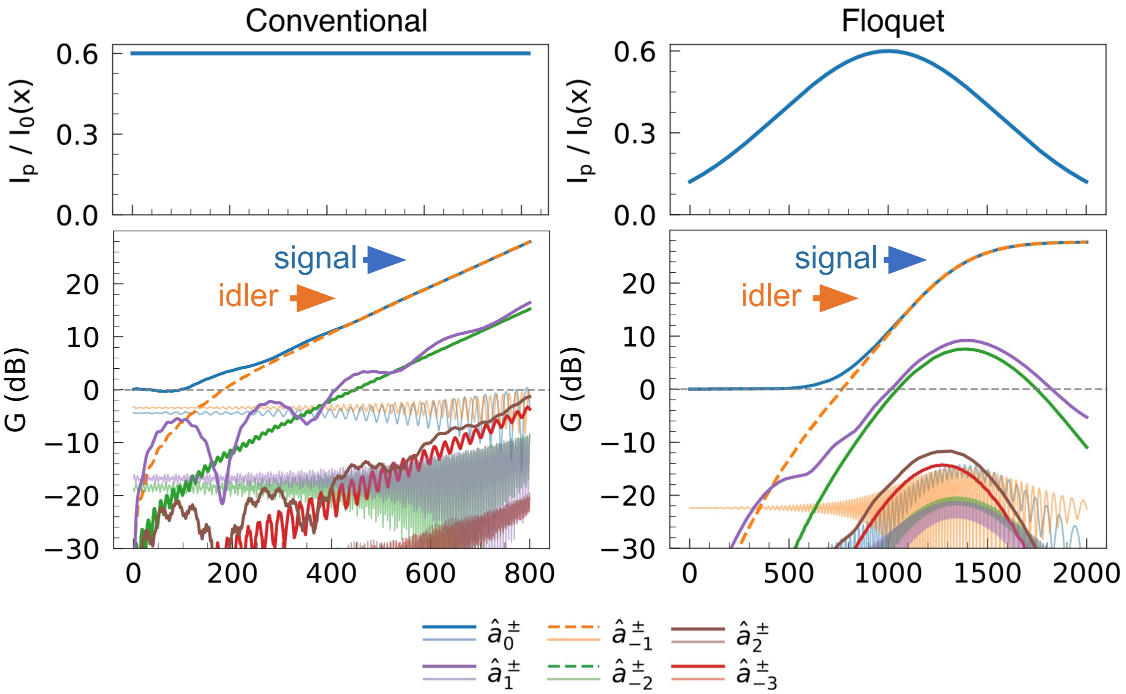
Adiabatic Floquet mode scheme

- Two-“frequency mode” amplifier → **two-“Floquet mode” amplifier**
- Inject & collect information still at signal & idler frequencies – adiabatic theorem!
- Implement with position dependent nonlinearity
- Larger JJs at beginning and end of TWPA



Dynamics Comparison

System response for input signal

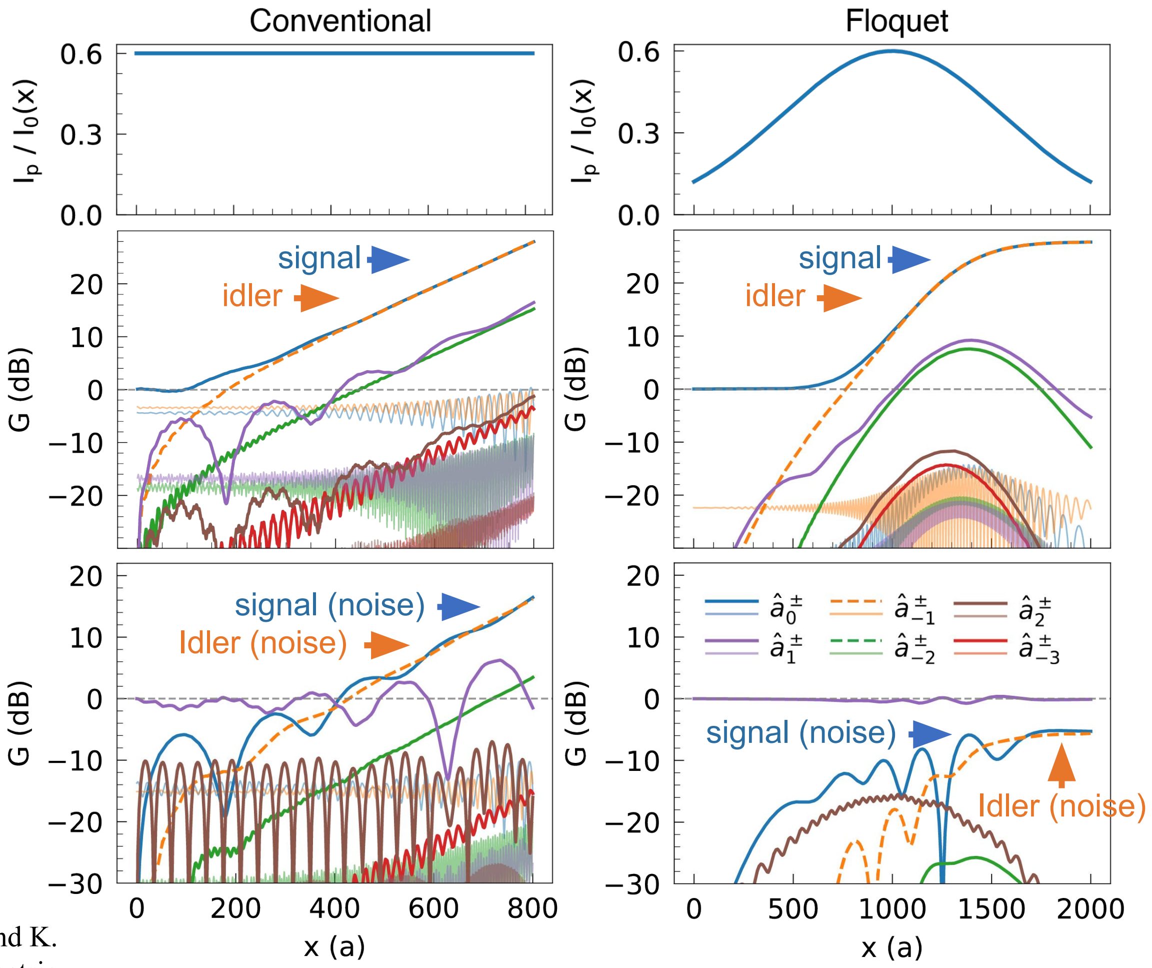


K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien "Floquet-Mode Traveling-Wave Parametric Amplifiers" PRX Quantum 3, 020306 (2022)

Dynamics Comparison

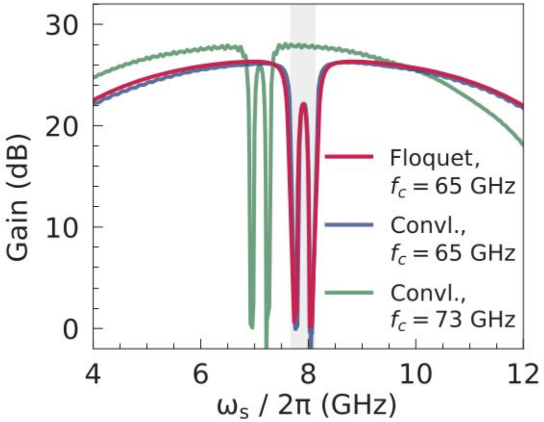
System response for input signal

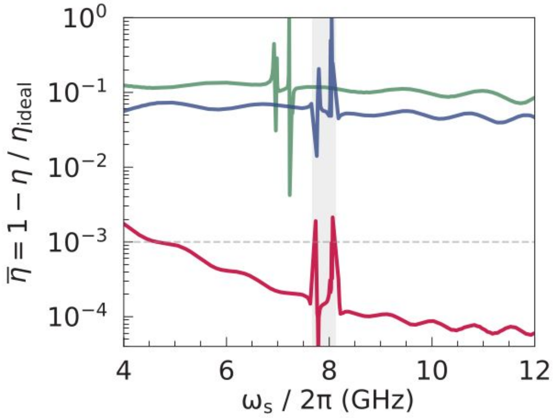
System response for input sideband
(eg. vacuum fluctuations)



K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien "Floquet-Mode Traveling-Wave Parametric Amplifiers" PRX Quantum 3, 020306 (2022)

Simulated gain and quantum efficiency





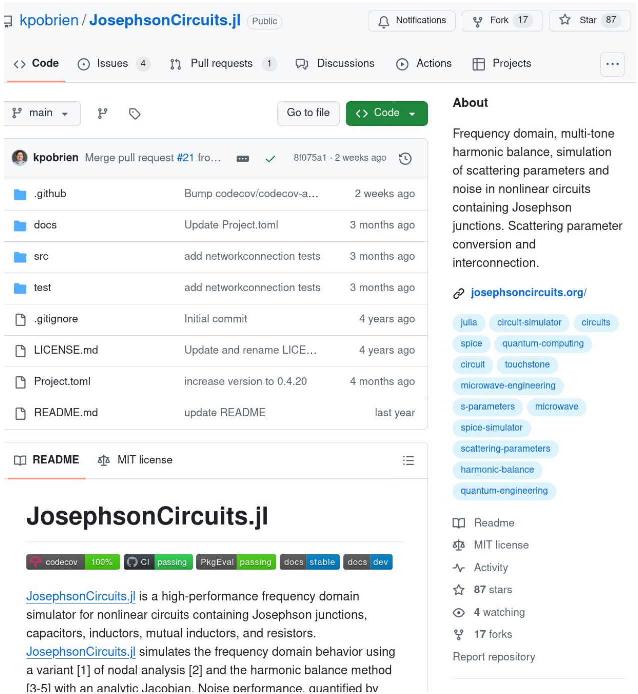
- Orders of magnitude improvement in amplifier inefficiency
- No quantum efficiency - bandwidth tradeoff

K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien "Floquet-Mode Traveling-Wave Parametric Amplifiers" PRX Quantum 3, 020306 (2022)

Simulating multi-mode parametric amplifiers with dissipation

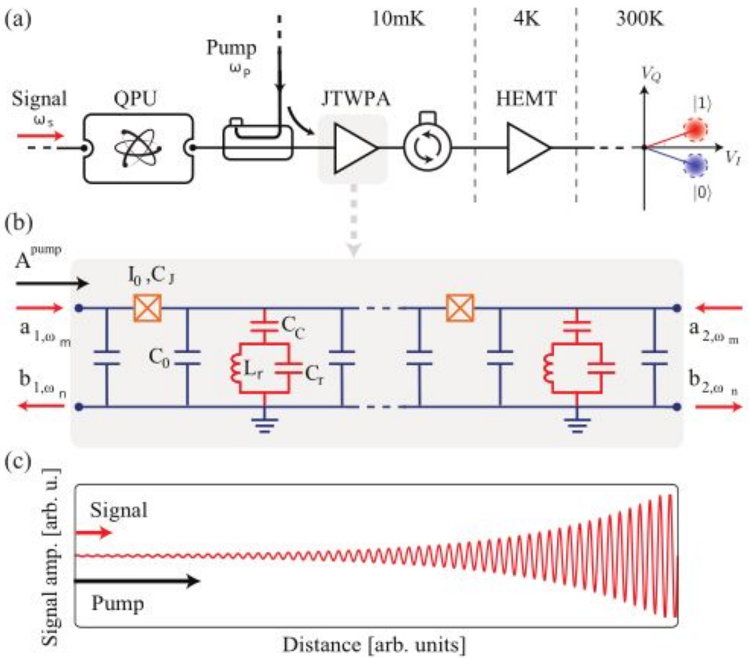
Open-source EDA (electronic design automation) for Quantum

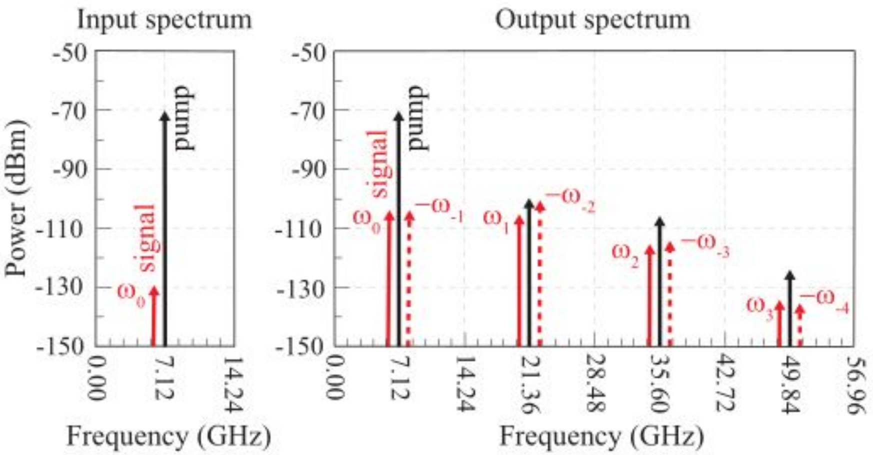
- **Input SPICE style netlist containing capacitors, inductors, Josephson junctions, resistors, and mutual inductors.**
- **JosephsonCircuits.jl: Open-source harmonic balance simulator [1] for parametric processes in superconducting circuits.**
- **Simulate frequency domain scattering parameters for netlist with full JJ nonlinearity, user specified number of harmonics for pump and signal/idlers, 3WM and 4WM.**
- **Computationally efficient implementation of beamsplitter model for lossy elements using adjoint method/Lorentz reciprocity**
- **Benchmarked against Keysight ADS and WRspice [2]**
- **Used at MIT, Google, NIST, Riken, and others**
- **10,000x faster than WRspice**



[1] https://github.com/kpobrien/JosephsonCircuits.jl
[2] K. Peng, R. Poore, P. Krantz, D. E. Root, and K. P. O'Brien IEEE QCE22 (2022)
[3] K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien. PRX Quantum 3, 020306 (2022)

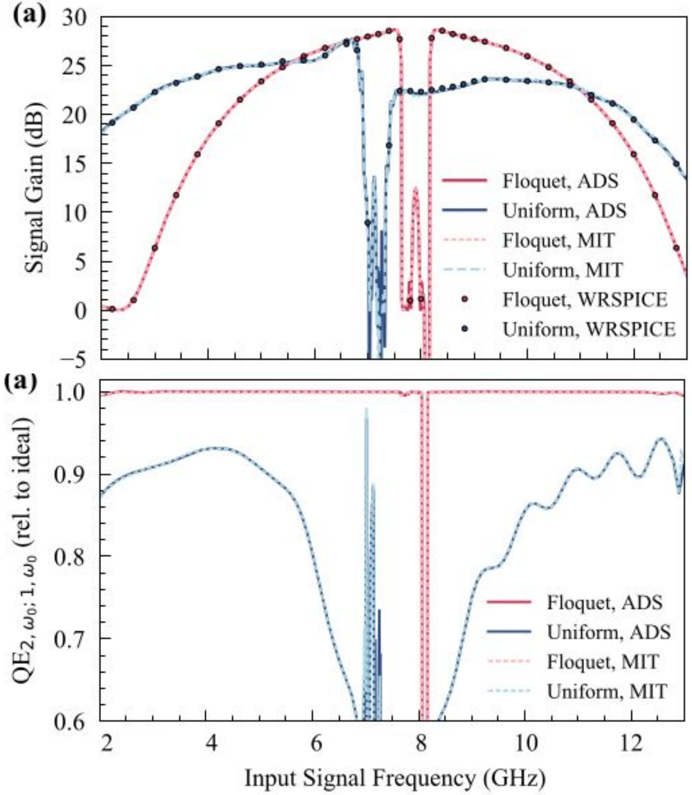
Harmonic balance simulations of JTWPAs





"X-parameter based design and simulation of Josephson traveling-wave parametric amplifiers for quantum computing applications" K. Peng, R. Poore, P. Krantz, D. E. Root, K. P. O'Brien, IEEE Quantum Week QCE 2022 (arxiv 2211.05328)

Harmonic balance simulations of JTWPAs



Device designs from:
K. Peng, et al. PRX Quantum 3, 020306 (2022), C. Macklin, et al. Science 16 6258 (2015)

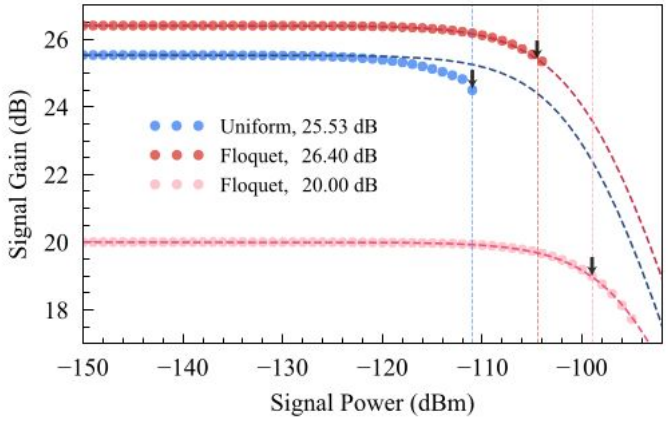
- Simulate gain and quantum efficiency of JTWPA in with Keysight ADS, home built harmonic balance solver, and WRSPICE
- Describe system in terms of X parameters, a nonlinear generalization of scattering parameters.
- Relate classical X parameters to "quantum" X par r opera

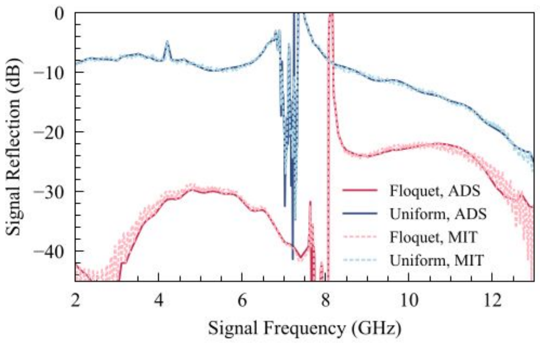
$$x_{p,\omega_j;q,\omega_k} \equiv X_{p,\omega_j;q,\omega_k}\sqrt{\left|\frac{\omega_k}{\omega_j}\right|}.$$

- Formulate gain and quantum efficiency in terms of X parameters:

$$\mathrm{QE}_{p,\omega_n;q,\omega_l} = \frac{\left|x_{p,\omega_n;q,\omega_l}\right|^2}{\sum\limits_{\substack{q'=1,2 \\ k=-\lfloor m/2\rfloor,\ldots,\lfloor (m-1)/2\rfloor}} \left|x_{p,\omega_n;q',\omega_k}\right|^2},$$

Harmonic balance simulations of JTWPAs



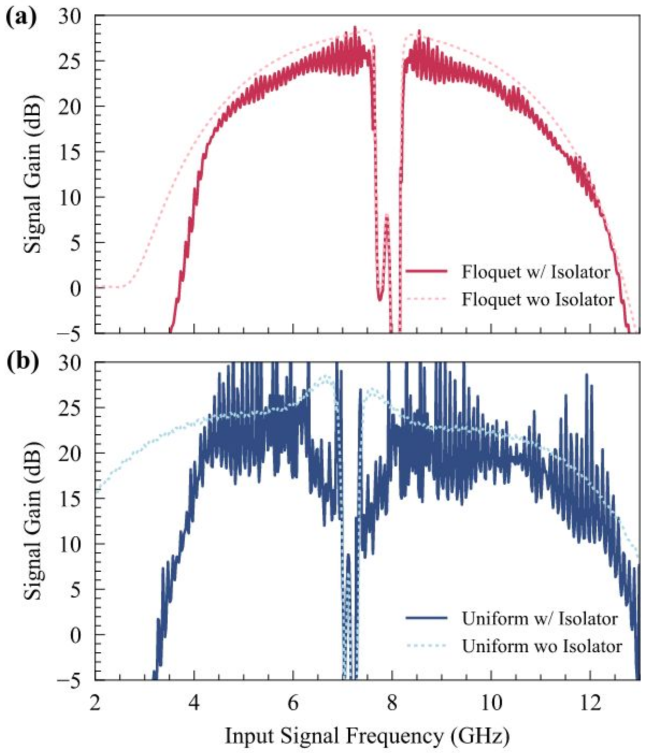


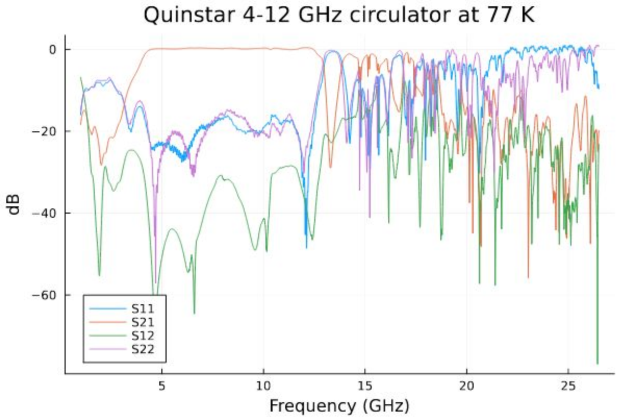
- Full description of the system including often ignored effects like pump harmonics, effect of each individual circuit component, etc.
- Critical to model driven design of superconducting nonlinear devices.
- Enables simulation of gain compression point
- Interactions with the rest of the measurement chain using the X parameter formalism.

Reducing sensitivity to out of band impedance mismatch

- Isolators are poorly impedance matched outside of rated band.
- Simulate uniform and Floquet JTWPAs with Quinstar 4-12 GHz isolator before and after.
- Observe less gain ripple in Floquet JTWPA due to reduced sideband/idler generation.

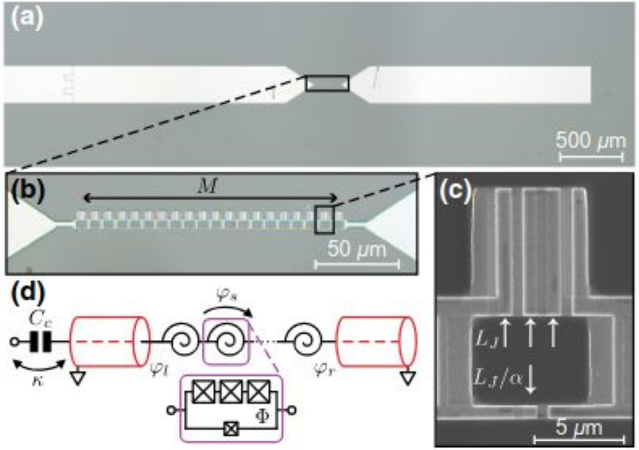
Simulations (tandelta=3e-3):





"X-parameter based design and simulation of Josephson traveling-wave parametric amplifiers for quantum computing applications" K. Peng, R. Poore, P. Krantz, D. E. Root, K. P. O'Brien, IEEE Quantum Week QCE 2022 (arxiv 2211.05328)

JosephsonCircuits.jl: SNAIL parametric amplifier

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0.010345 seconds (16.74 k allocations: 40.025 MiB)
0.011252 seconds (16.68 k allocations: 39.985 MiB)
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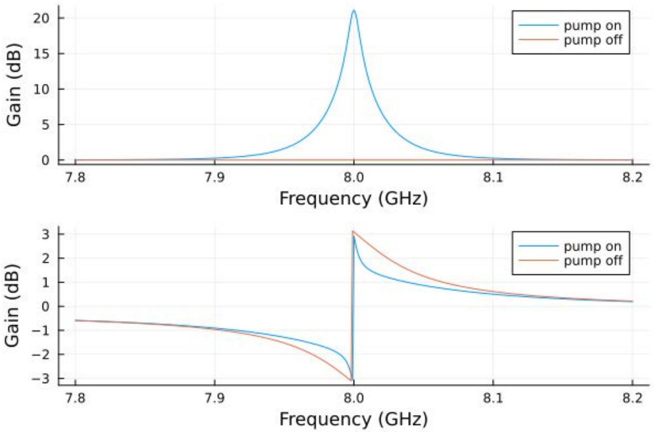
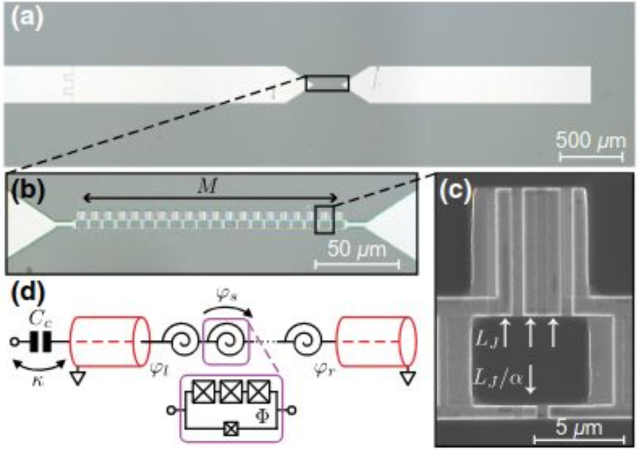


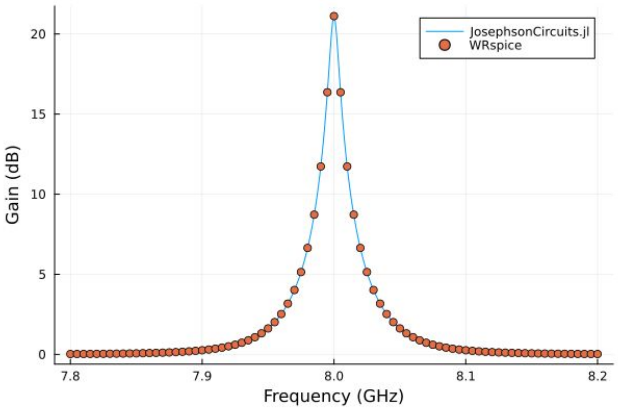
- Simulate any device you can describe with a netlist of capacitors, inductors, JJs, and resistors. For example, current driven JPAs, flux pumped JPAs, SNAIL paramps, TWPAs, and impedance engineered JPAs.
- Simulation above uses 16 pump harmonics and 17 signal/idler modes and takes 20 ms.
- Note the pump on and pump off resonance frequencies are similar, so we are operating near the Kerr-free point.

N. E. Frattini, V. V. Sivak, A. Lingenfelter, S. Shankar, and M. H. Devoret, "Optimizing the Nonlinearity and Dissipation of a SNAIL Parametric Amplifier for Dynamic Range" Phys. Rev. Applied 10, 054020 (2018)

JosephsonCircuits.jl: SNAIL parametric amplifier



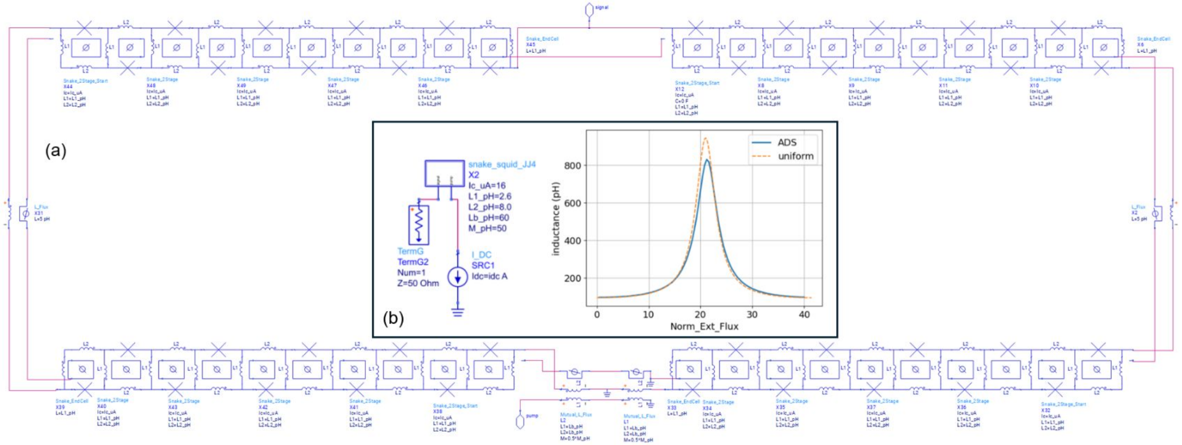

```
2067.364975 seconds (149.73 k allocations: 29.873 GiB, 0.01% gc time)
```



- Compare against WRspice time domain simulations for an independent crosscheck.

N. E. Frattini, V. V. Sivak, A. Lingenfelter, S. Shankar, and M. H. Devoret, "Optimizing the Nonlinearity and Dissipation of a SNAIL Parametric Amplifier for Dynamic Range" Phys. Rev. Applied 10, 054020 (2018)

JosephsonCircuits.jl: Impedance engineered JPA (LESA)

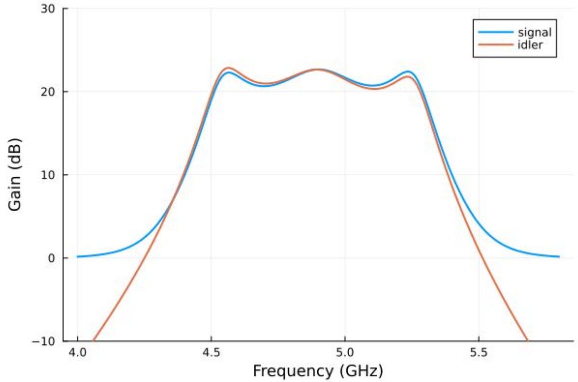


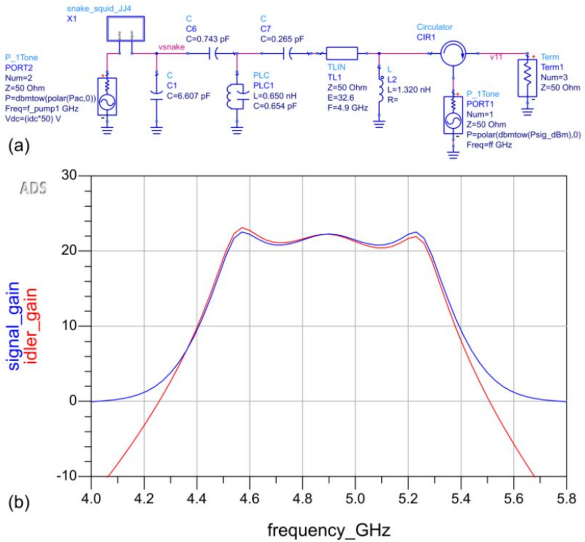
- Simulating flux-quantization in commercial circuit simulations requires an auxiliary circuit.
- JosephsonCircuits.jl simulates in the branch and node flux basis, eliminating the requirement for auxiliary circuits.

O. Naaman, T. White, M. A. Hassan, D. Slater, S. Mcilvane, E. Yeung, P. Krantz, "Modeling flux-quantizing Josephson junction circuits in Keysight ADS" arXiv:2408.07861

JosephsonCircuits.jl: Impedance engineered JPA (LESA)

```
0.081631 seconds (34.78 k allocations: 67.609 MiB, 48.06% gc time)
```

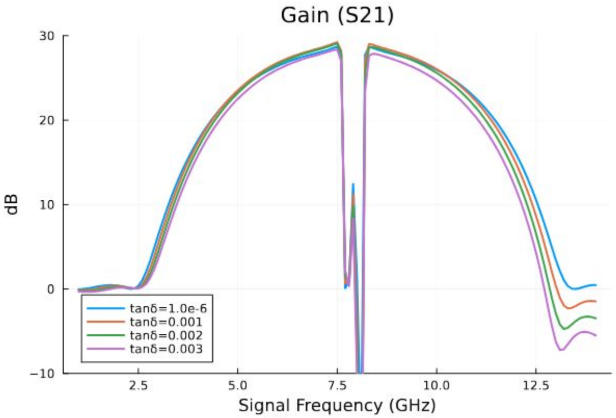


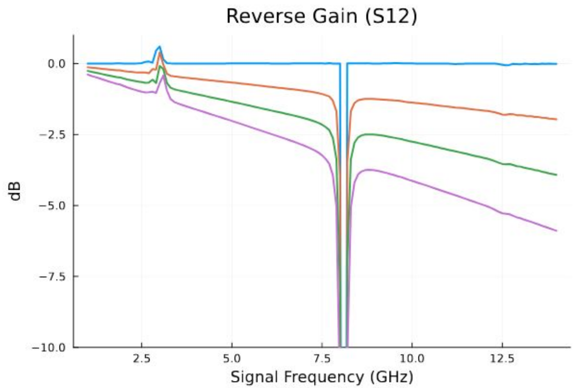


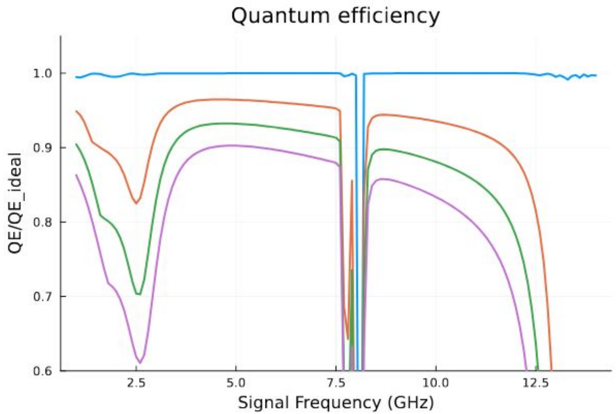
- Agrees well with literature results for the lumped element snake amplifier (LESA).

O. Naaman, T. White, M. A. Hassan, D. Slater, S. Mcilvane, E. Yeung, P. Krantz, "Modeling flux-quantizing Josephson junction circuits in Keysight ADS" arXiv:2408.07861

JosephsonCircuits.jl: Floquet TWPA with dissipation



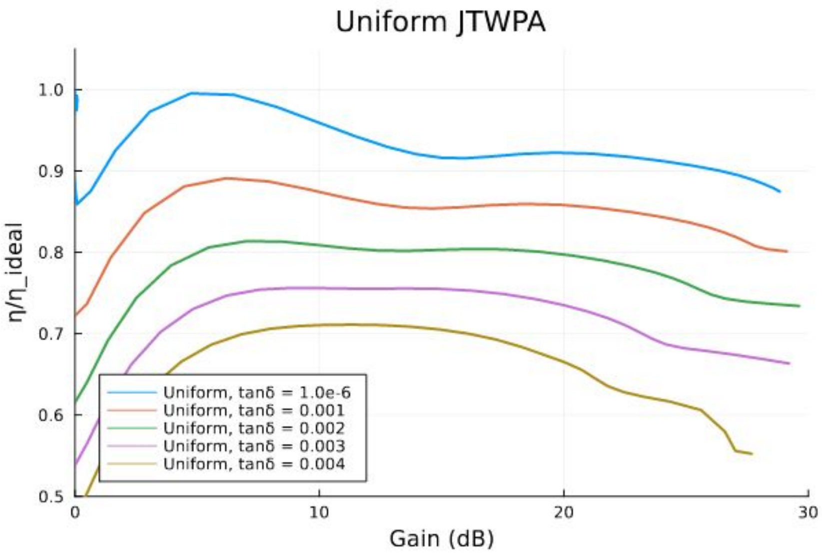


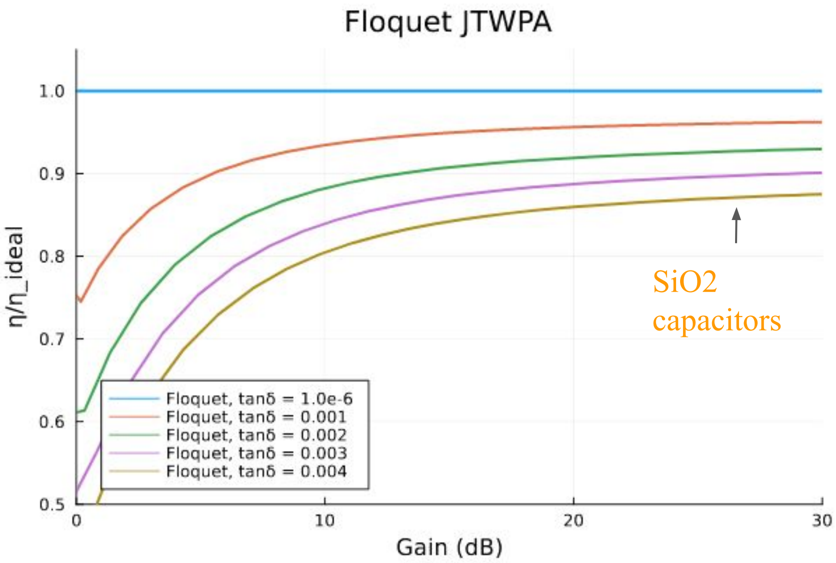


- Beamsplitter model provides a semi-classical description of the impact of loss on dynamics and efficiency, but doesn't scale.
- For example, a TWPA with 2000 lossy capacitors and 16 modes would require a 32000*32000 scattering parameter matrix.
- We use an adjoint method to simulate the quantum efficiency with only one extra time-reversed simulation (~4 s per curve above)
- We welcome you to use this open source tool, find bugs, and contribute new features!

K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien. PRX Quantum 3, 020306 (2022)

Vicious cycle with QE and dissipation

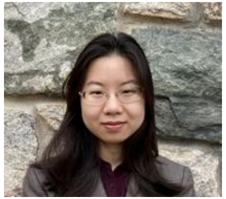




- In uniform TWPAs, dielectric loss reduces gain, requiring a stronger pump which causes more sideband generation, further reducing QE.
- In Floquet mode TWPAs, in which the sidebands are eliminated by adiabatically varying junction critical current, only dielectric loss impacts QE.
- Desirable to build Floquet TWPAs using capacitors with a small loss tangent.

Demonstration of a high quantum efficiency Floquet TWPA

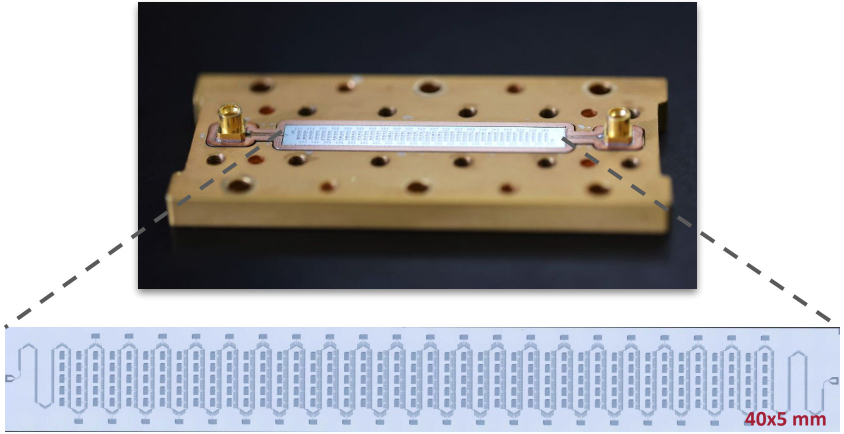
Low-loss Floquet TWPA

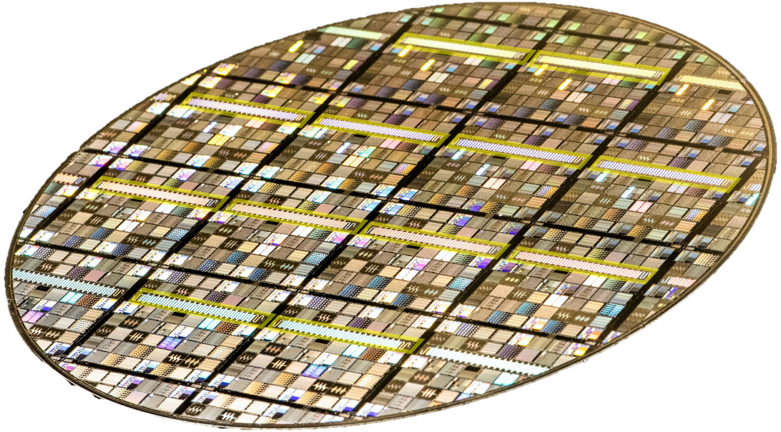


Jenn Wang

Kaidong Peng

- Devices fabricated using **an all-aluminum qubit process** to minimize dielectric loss
- Coplanar waveguide capacitors lead to **near-zero dissipation** & **high reproducibility**

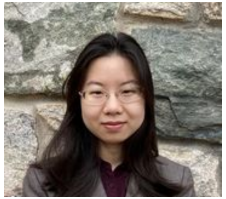




Devices fabricated using the 200mm-wafer process at the Super-conducting Qubits at Lincoln Laboratory (SQUILL) Foundry

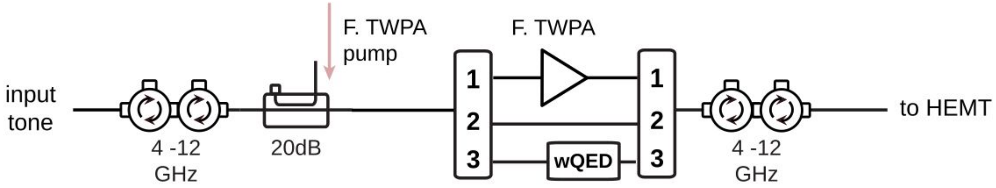
J. Wang*, K. Peng*, … K. P. O’Brien, "High-Efficiency, Low-Loss Floquet-Mode Traveling-Wave Parametric Amplifier" arxiv 2503.11812
See also: Sandbo Chan et al. “Josephson traveling-wave parametric amplifier based on low-intrinsic-loss coplanar lumped-element waveguide” arxiv 2503.07559

Floquet TWPA characterization

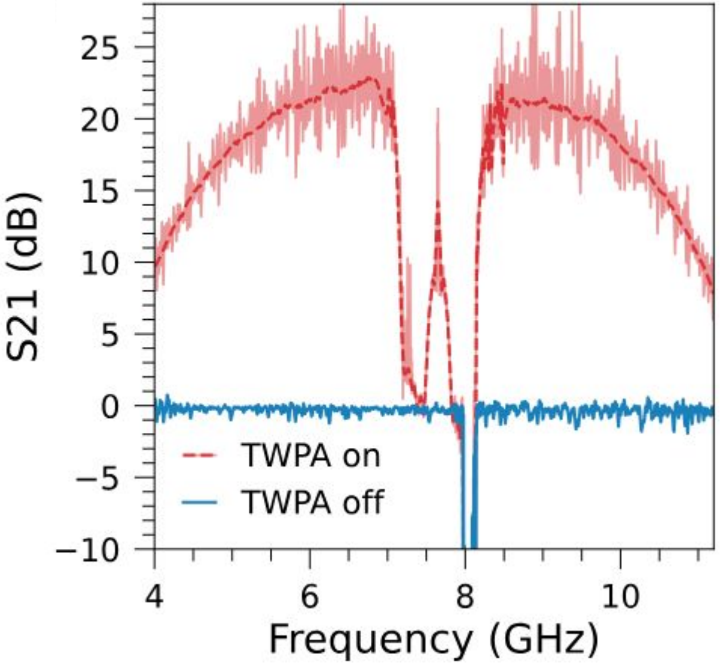


Jenn Wang

Kaidong Peng

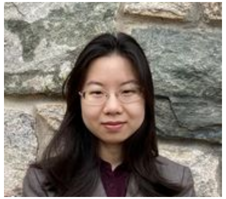


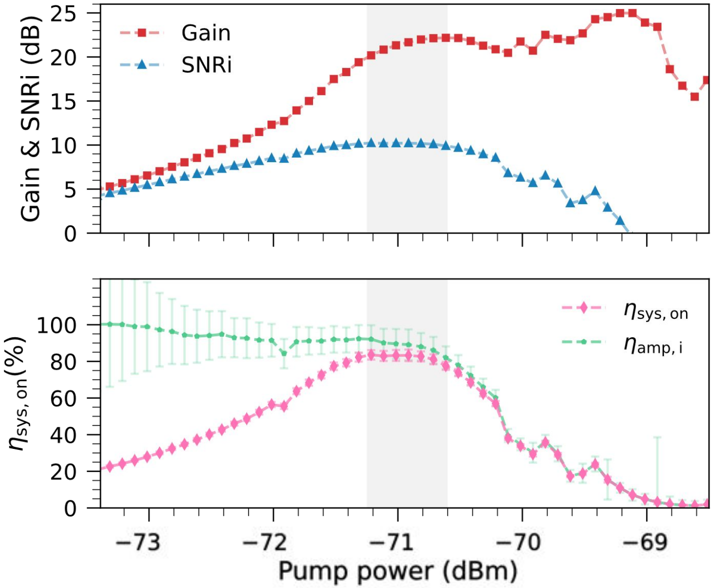
- > 20 dB gain
- < 0.5 dB average in-band insertion loss

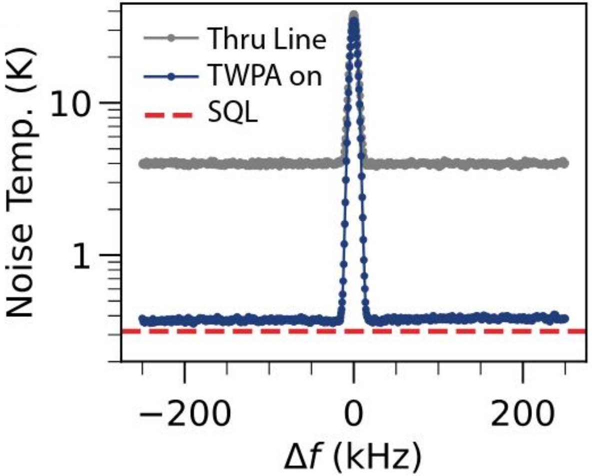


J. Wang*, K. Peng*, … K. P. O'Brien, "High-Efficiency, Low-Loss Floquet-Mode Traveling-Wave Parametric Amplifier" arxiv 2503.11812

Floquet TWPA characterization







- Full system quantum efficiency relative to ideal phase preserving amplifier of 83.6 ± 2.6%, intrinsic 92.1 ± 7.6%.
- 65.1 ± 5.8% full system efficiency for qubit readout.

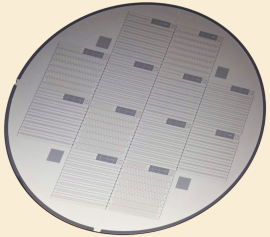
J. Wang*, K. Peng*, … K. P. O'Brien, "High-Efficiency, Low-Loss Floquet-Mode Traveling-Wave Parametric Amplifier" arxiv 2503.11812

TWPA process development in MIT.nano

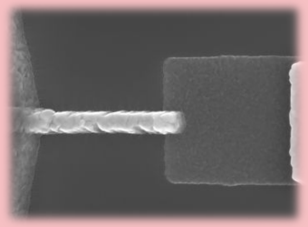

Andres Lombo


Kaidong Peng

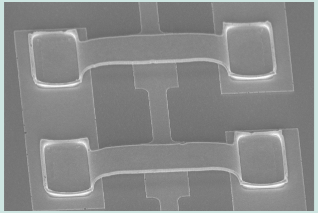
200mm Wafer Process for Co-fabricating Qubits & Amplifiers



Improving Junction Uniformity and Quality



2.5D integration



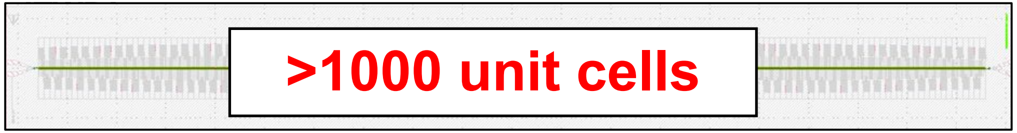
Novel Qubits and Quantum Limited Amplifiers

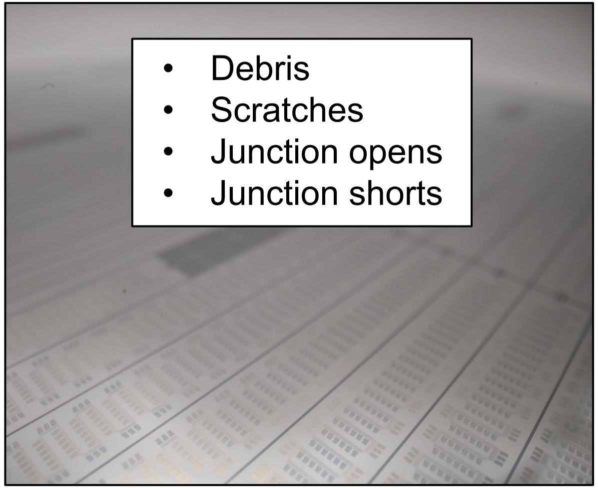
Fabricating TWPAs is challenging

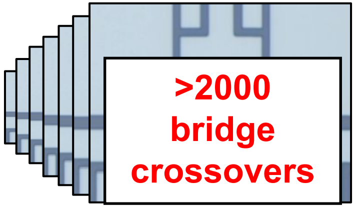

Andres Lombo


Kaidong Peng

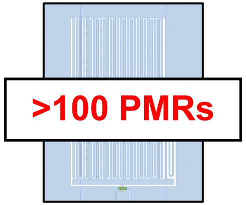
5 x 40 mm

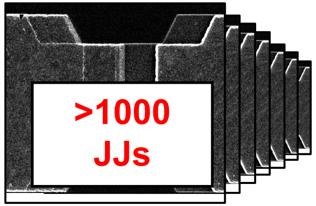






5 x 25 µm Al bridge





700 x 3600 nm Al JJ

 Fabricating JTWPAs with **>1000s** of components is **challenging**

Process Yield Requirements

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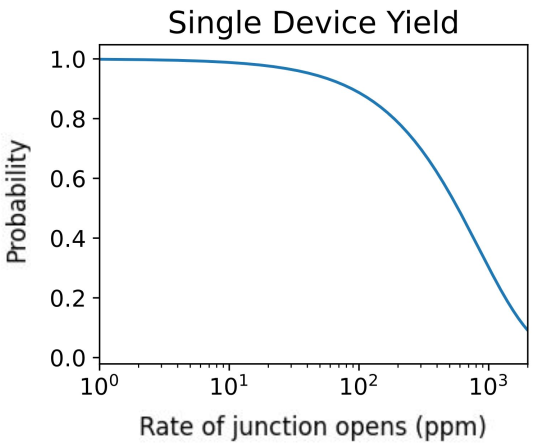
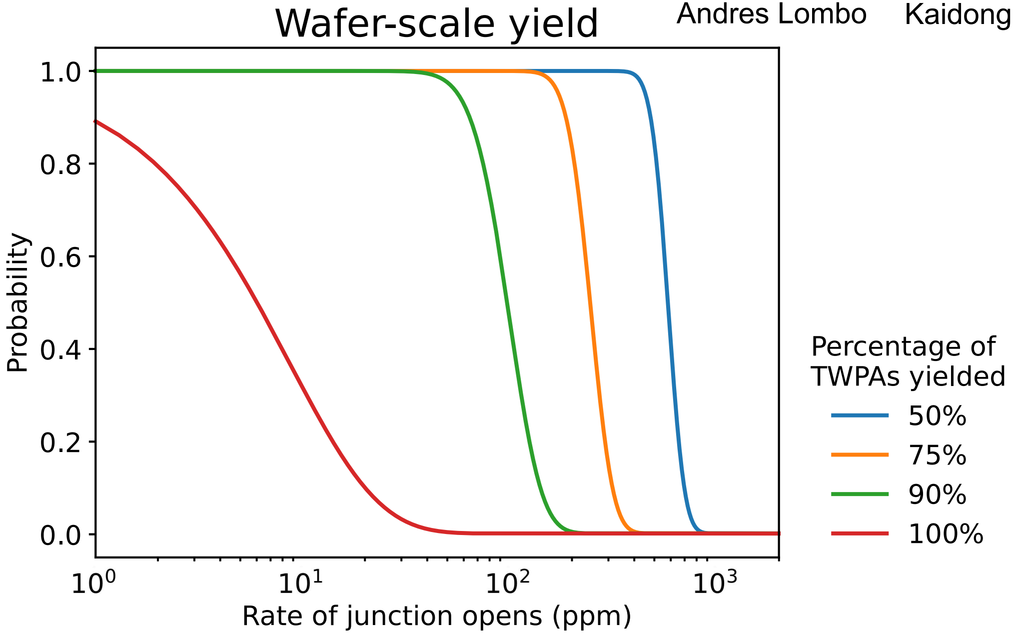
Kaidong Peng

Josephson junction yield requirements
Yield definition (this slide): JTWPA transmission line not open
Goal: O(μA) I_c junction process on a **200mm** wafer containing *84* devices



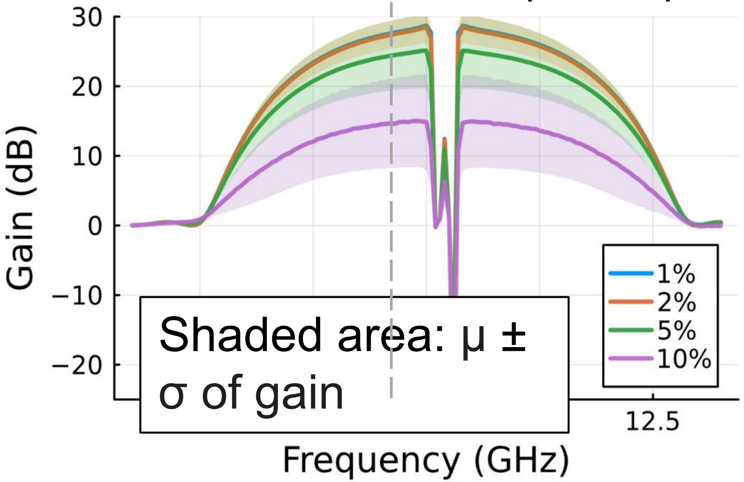


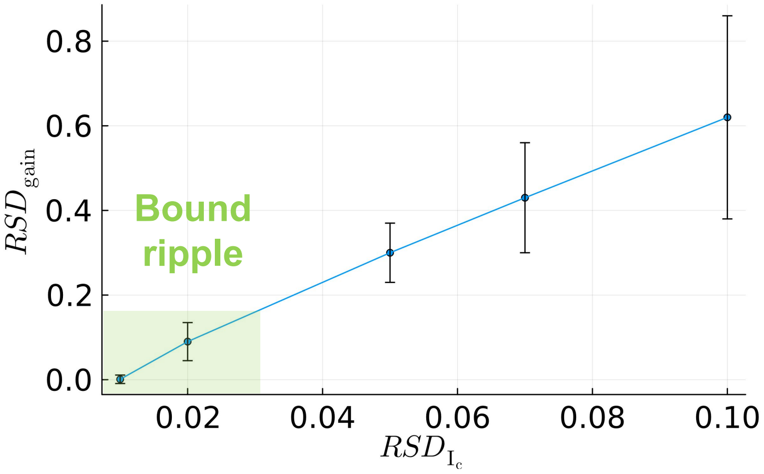
 Meeting experimental requirement for fabricating many JTWPAs is **challenging**

Gain vs junction RSD

Kaidong Peng

- **Simulate 5x40 mm Floquet TWPA**
  - Captured fluctuation in θ, t_{MMA}, t_1 and variation from junction process in Monte Carlo simulations (N=500)





- Require I_c **RSD < 3%** for ripple at 20dB gain to be less than ~3dB

Current O(μA) Junction Processes

Goal: improve relative standard deviation of Josephson junction I_c

$$RSD = \frac{\sigma_{I_c}}{\mu_{I_c}}$$

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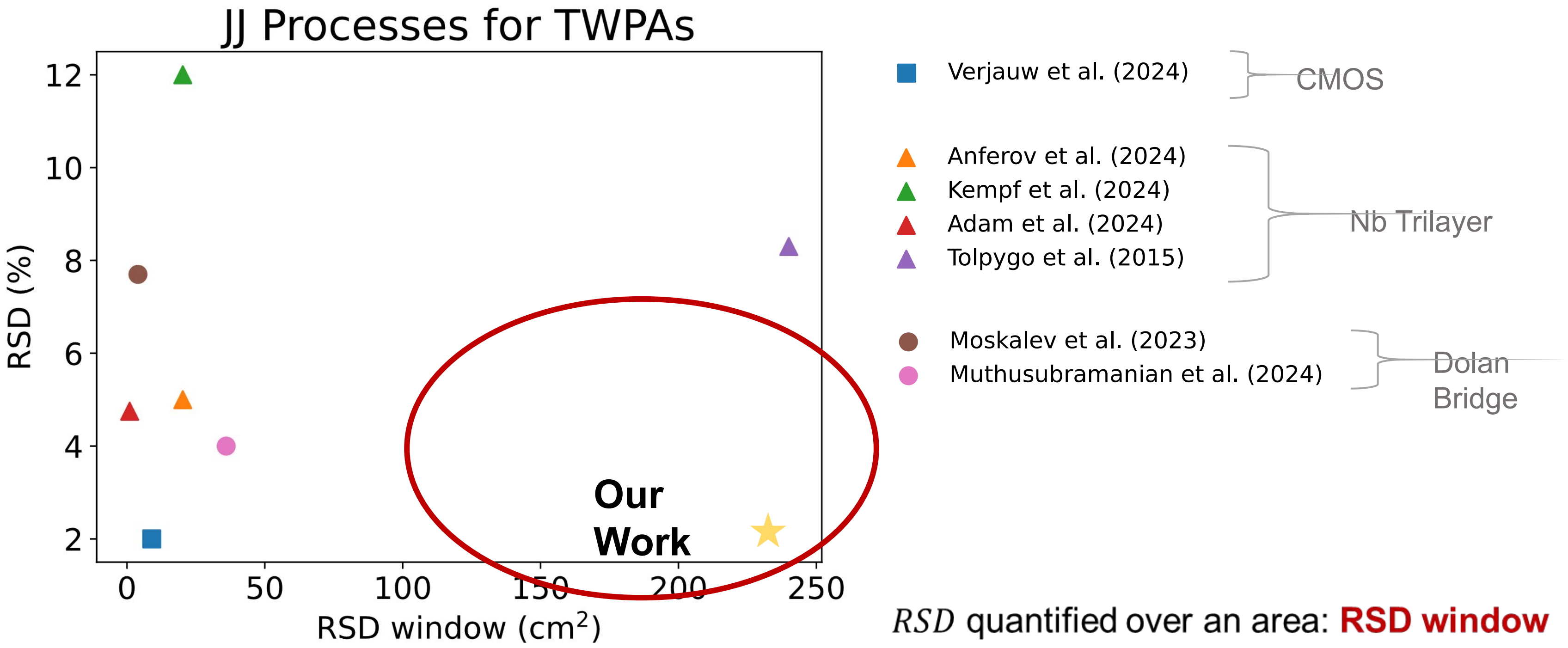
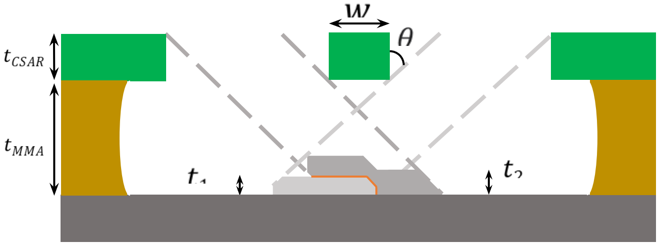


RSD quantified over an area: **RSD window**

Dolan junction process

Realizing large-area Josephson Junctions

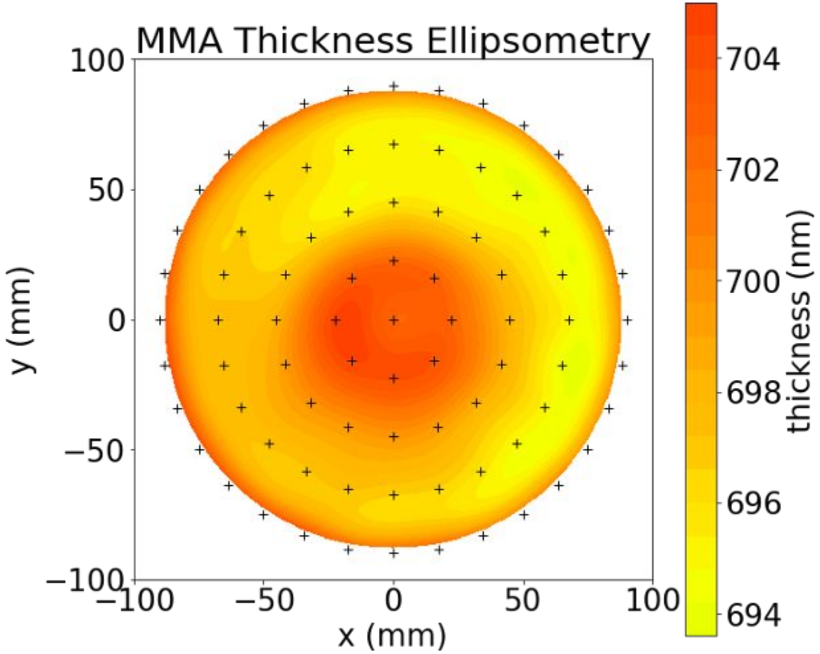


$$W_{fab} = t_{MMA}\tan(\theta) + (t_{MMA} - t_1)\tan(\theta) - w + t_1$$

$$A = W_{fab} \cdot l$$

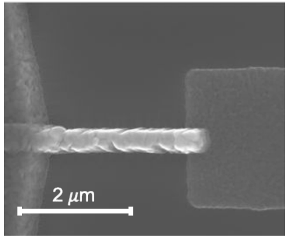
Large overlap (W_{fab}) junctions require large t_{MMA}

- **I_c variation** is directly correlated to junction **area variation**

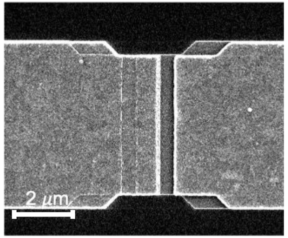


Achieved **< 1.6%** resist thickness variation on 200mm wafer

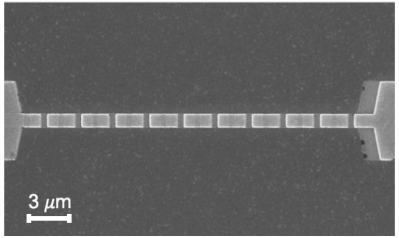
Wafer-scale Junction Yield & Uniformity



"qubit" junctions



"amplifier" junctions



19-junction chain

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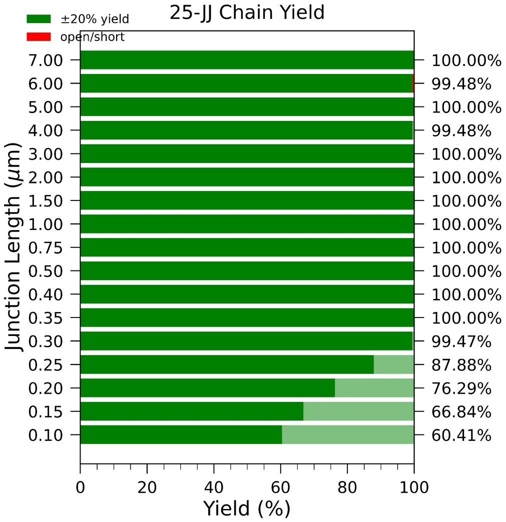
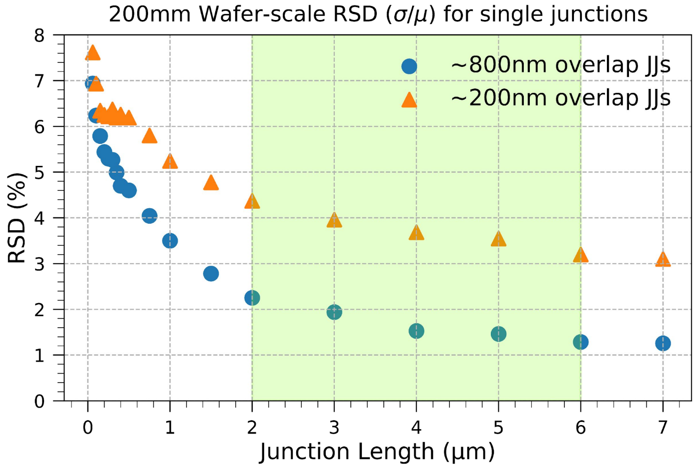
- Electrically tested on **> 85k** junctions per wafer
- Improved yield for long-array junction chains
- Achieved **< 2%** RSD on μA-sized junctions for making TWPAs
- Image failed junctions with auto SEM





1-2% rel. std. deviation comparable to best reported uniformity for Al shadow[1] and Nb trilayer [2] junctions:

[1] T. Takahashi et al Jpn. J. Appl. Phys. 62 SC1002 (2022)
[2] J. West et al. Tolypygo (MIT-LL) IEEE Trans. Appl. Supercond. 32, 5, 1-12, (2022)

Dielectric crossover process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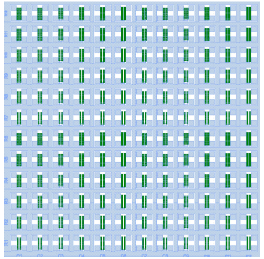
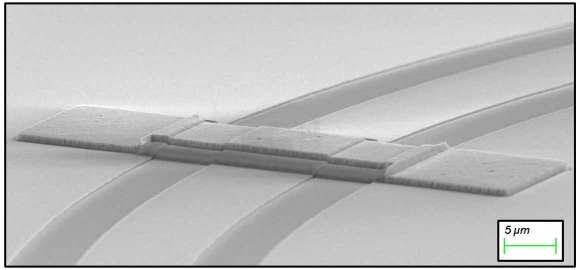
SiO2 bridge process



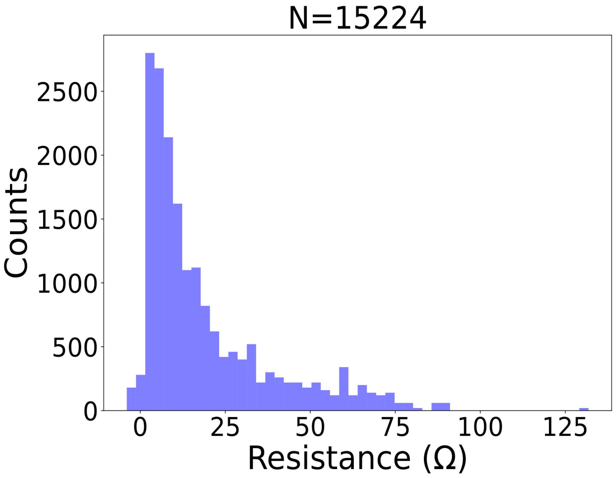
A. Dunsworth et. Al *Appl. Phys*. Lett. **112**, 063502 (2018)

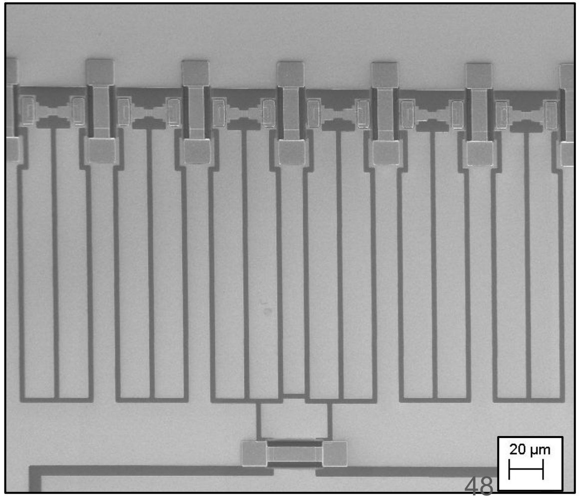


Potential Failure mechanisms
- Scaffold peeling
- Bridge collapse

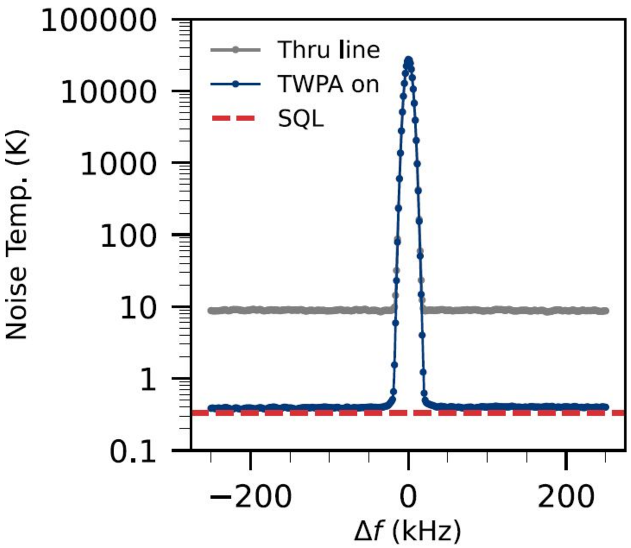
100% bridge yield
For N=15224

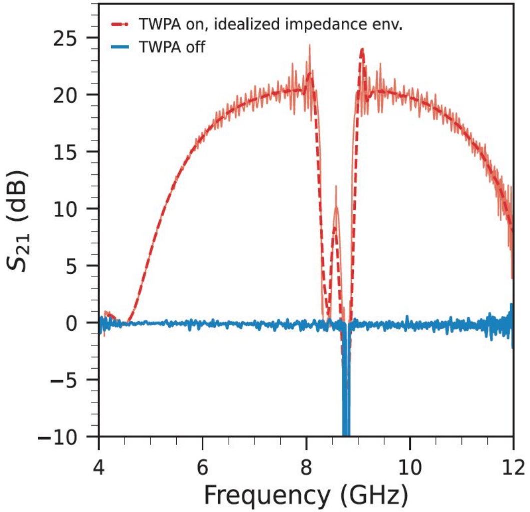
Length: 15-40 μm
Width: 5-20 μm

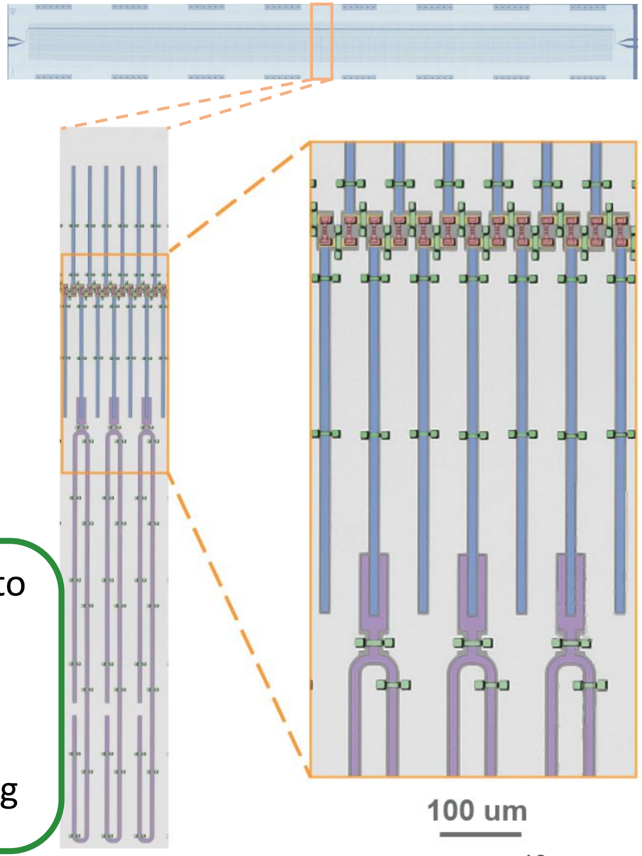




Floquet TWPAs fabricated in MIT.nano





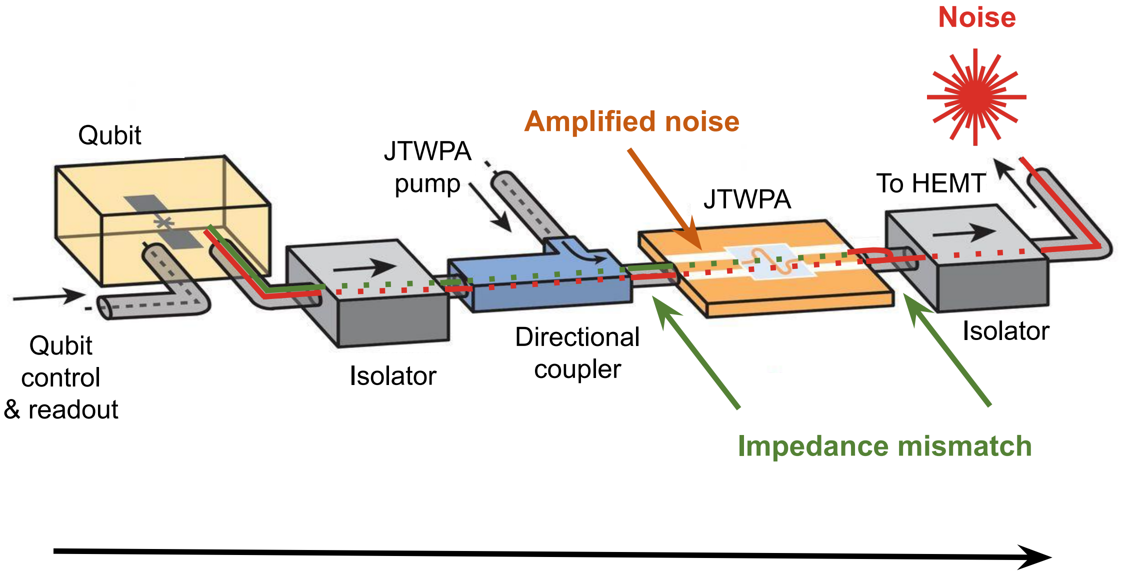


- New design utilizes **coplanar waveguide phase-matching resonators** to suppress frequency spread due to fabrication variation
- Meander-less "straightshot" geometry improves impedance targeting
- **20 dB gain** from 6.9 to 8.1 GHz with average **insertion loss < 0.5 dB**
- Intrinsic efficiency measured at 6.94 GHz is $\boldsymbol{\eta_{amp,i}}$ **= 95.4 ± 7.9%**, among highest reported for JTWPAs.

Thorbeck & Mancini, US Patent US20240029932A1, IBM (2024)

Can amplifiers protect qubits from noise?

Towards TWPAs with reverse isolation



Readout error budget (eg. Macklin et al 2015):

$$\eta = \eta_L \eta_D \eta_J \eta_H = 0.48$$

Insertion loss due to isolator and coupler: $\eta_L \approx 0.69$

Lossy dielectrics in TWPA: $\eta_D \approx 0.9$

Following amplifier noise: $\eta_H \approx 0.93$

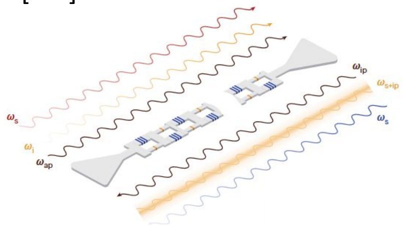
Sidebands: $\eta_J \approx 0.83$

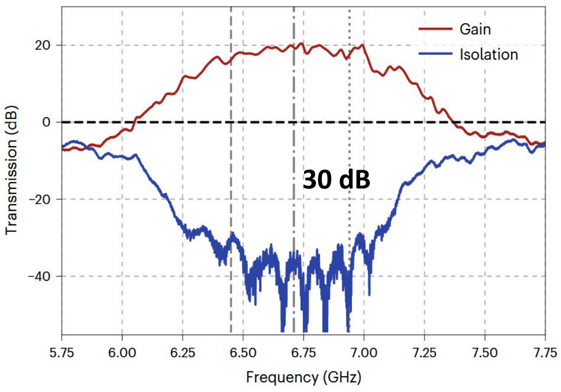
See A. Lombo et al., MAR-J05, "Qubit Readout with Integrated Traveling Wave Parametric Devices"

"The Quest for Ideal Quantum Amplifiers", K. Peng Ph.D. Thesis   Macklin et al., Science 350, 307310 (2015)   J. Wang et al., arXiv:2503.11812 (2025)

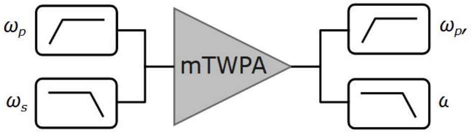
Approaches to reverse isolation

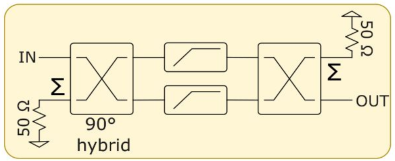
Counter-propagating pumps
[1-3]

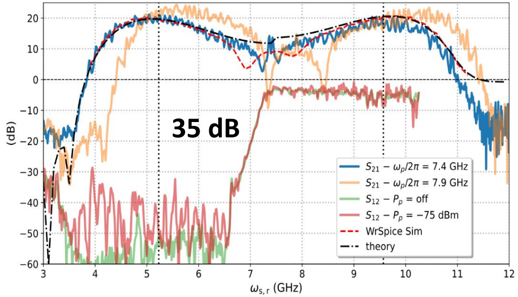




Devices with filters
[7-8]







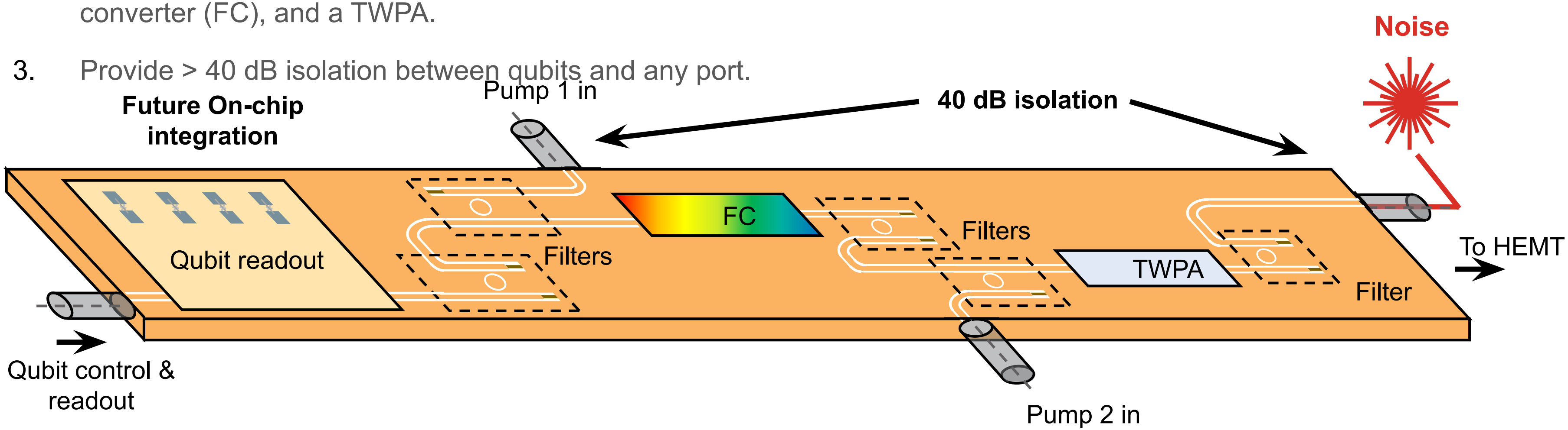
	Gain	Isolation	Bandwidth	
[1] M. Malnou et al. Nat. Elec. (2024)	7 dB	20 dB	0.8 GHz	Counter-propagating pumps
[2] A Ranadive et al. Nat. Elec. (2025)	20 dB	30 dB	0.5 GHz	
[3] M. Praquin et al Nat. Comm. (2025)	-	10 dB	0.2 GHz	
[4] L. Ranzani et al. PRA (2017)	-	4.8 dB	4.8 GHz	Theoretical
[5] M. Naghiloo et al., arXiv:2103.07793v1 (2021)	-	20 dB	4 GHz	
[6] M. Demarets et al., arXiv:2509.2455v1 (2025)	-	20 dB	4 GHz	Devices with filters
[7] C. S. Kow et al. arXiv:2505.04059v1 (2025)	20 dB	35 dB	1.6 GHz	
[8] H. Nilsson et al. PRA (2024)	20 dB	10 dB	4 GHz	

Integrated non-reciprocal amplification

Further improvements to readout chain efficiency require reduction of insertion loss between quantum processor and TWPA, which requires on-chip isolators.

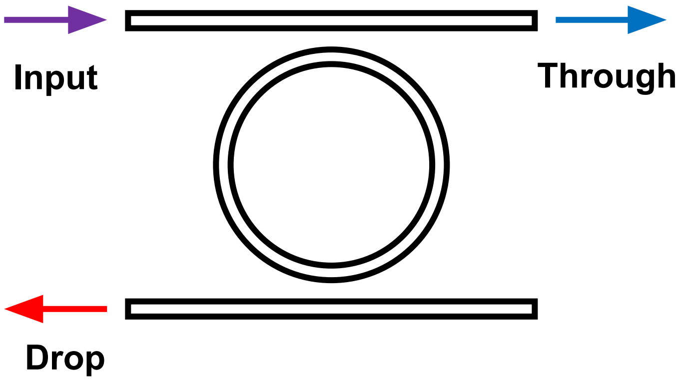
Develop a low-loss TWPA architecture with large in-band and out of band isolation

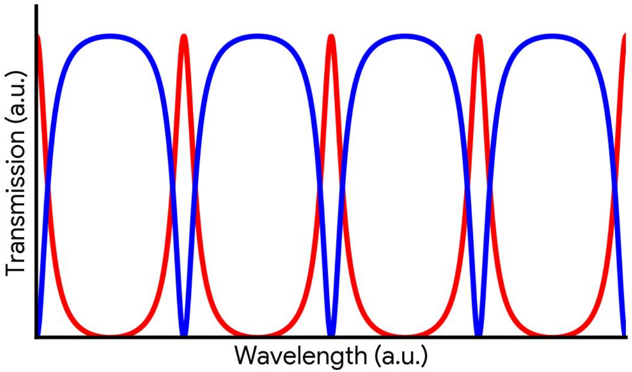
1. Reduce insertion loss of connectors & components. Full control of microwave environment.
2. Mitigate pump leakage, downstream noise, with cascade of add-drop filters, a frequency converter (FC), and a TWPA.
3. Provide > 40 dB isolation between qubits and any port.



Add-drop filters

Take inspiration from photonic ring resonators as used in wavelength division multiplexing.





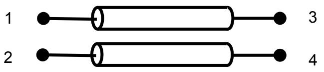
- Notice we “add” qubit signal to readout line, then the pump, and “drop” the idler

… can we make the microwave version?

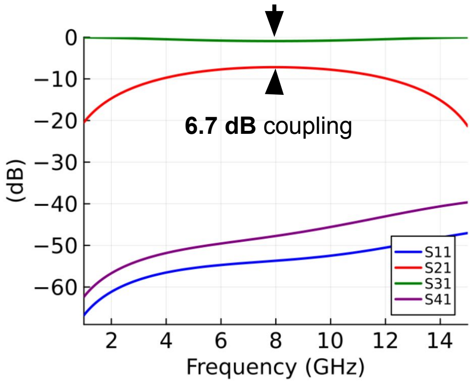
B. E. Little et al., J. of Lightwave Tech. vol. 15, no. 6, pp. 998–1005, Jun. 1997

Microwave add-drop filters

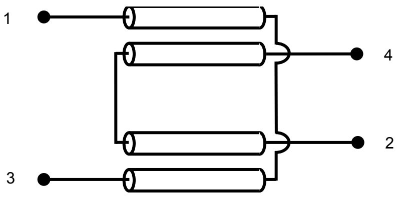
Coupled TLs

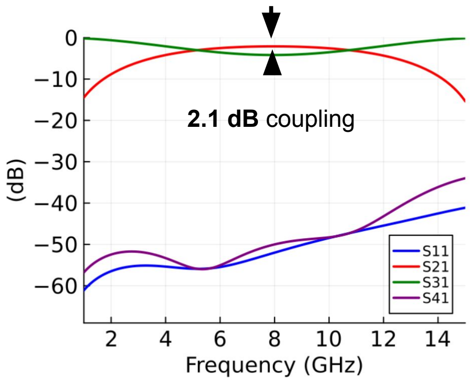


$$w = 11.6\ \mu m, g = 6.7\ \mu m,$$
$$s = 3\ \mu m$$

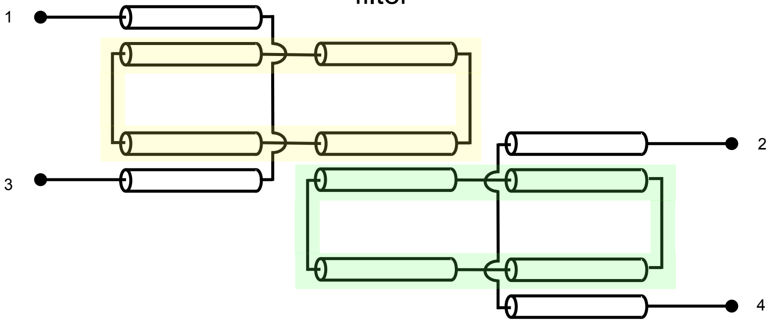


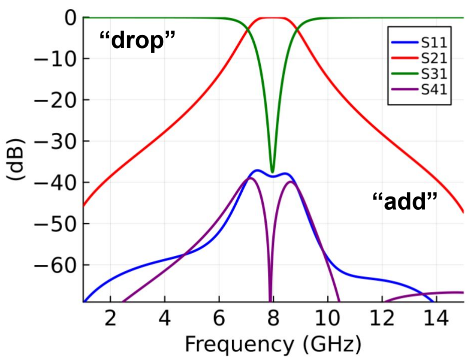
Tight coupler





Add-drop filter

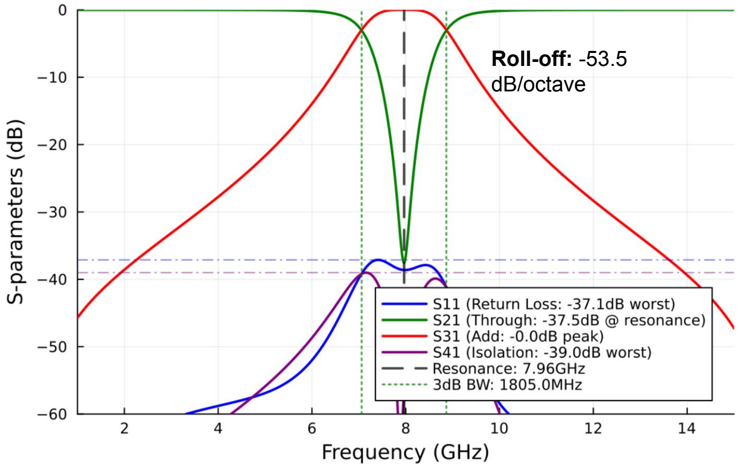


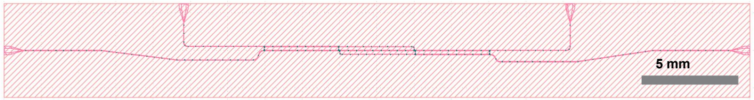


Hindin et al. IEEE Trans. Microwave Theory & Techniques vol. 16, no.2 , pp. 125-126, Feb 1968

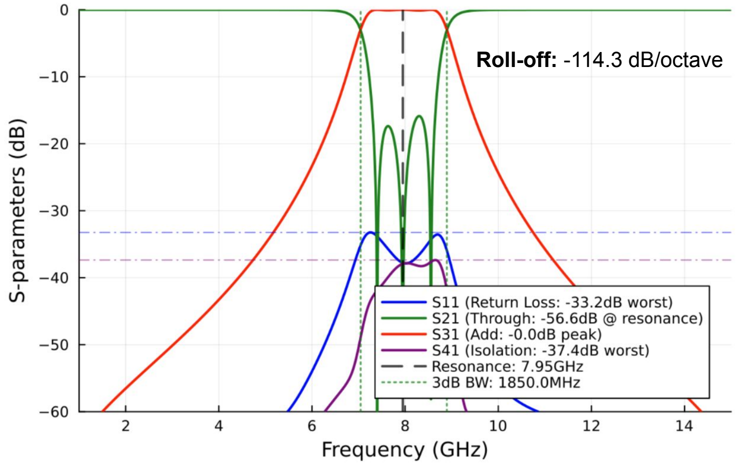
Simulated performance of add-drop filter

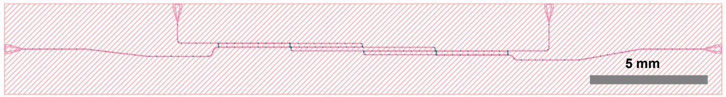
Two-ring add-drop filter





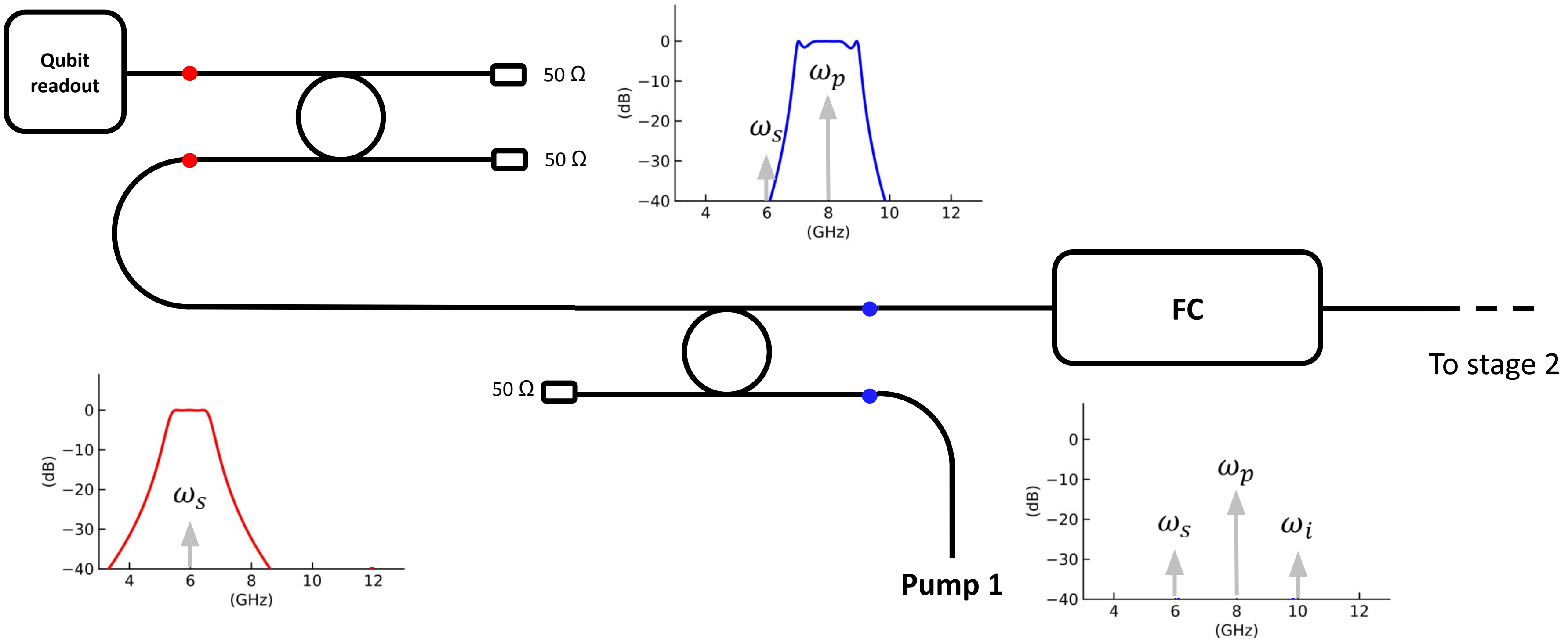
Three-ring add-drop filter



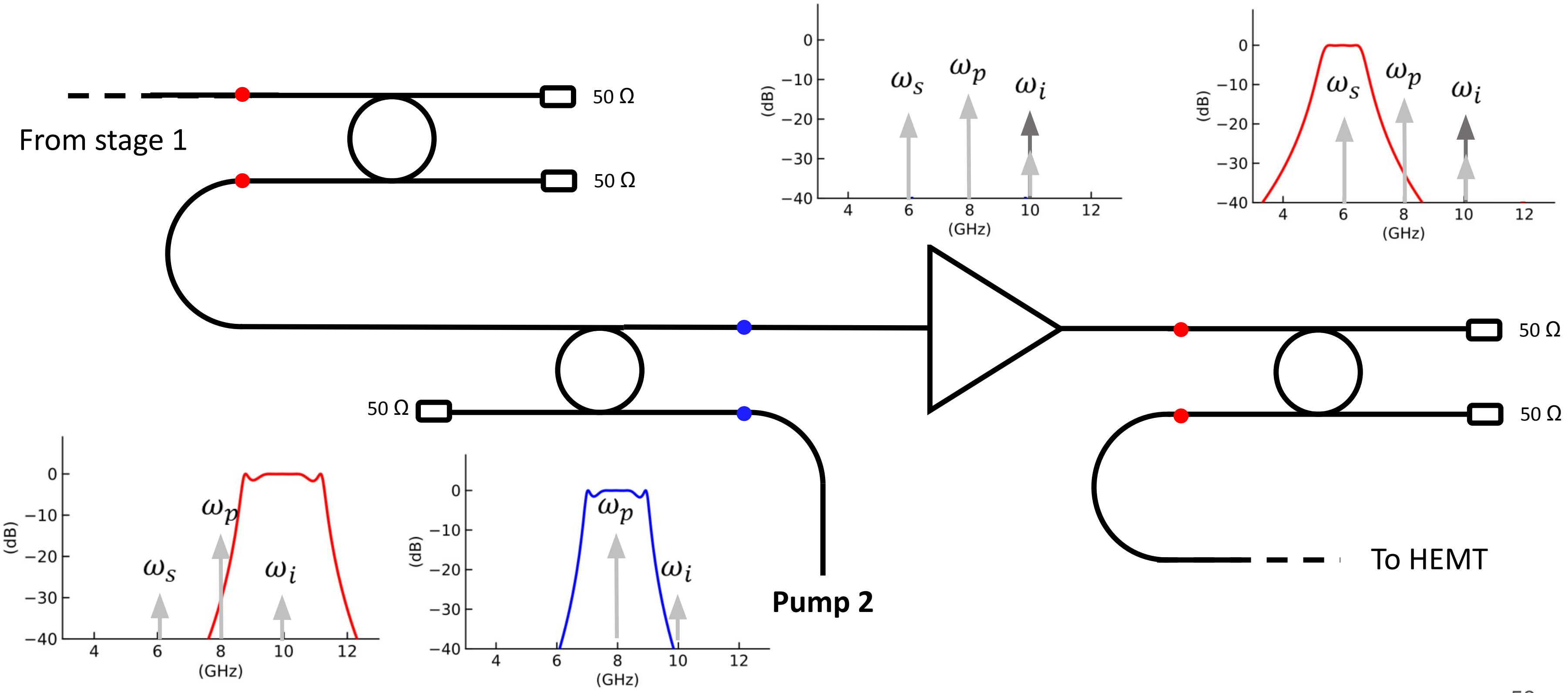


- More rings and stronger coupling lead to broader bandwidth. 1-2 GHz bandwidth feasible.

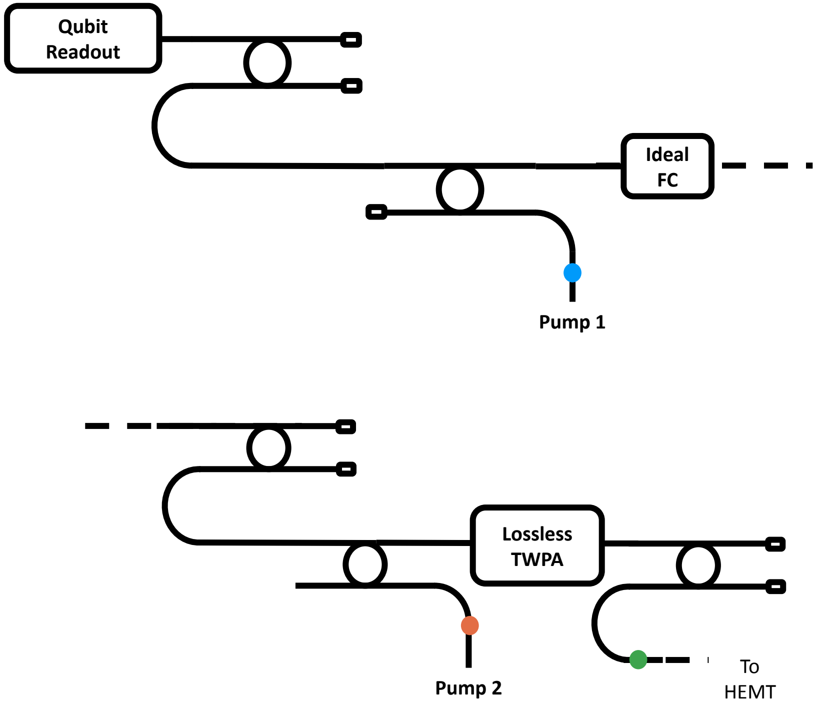
Add-drop filter with traveling-wave devices

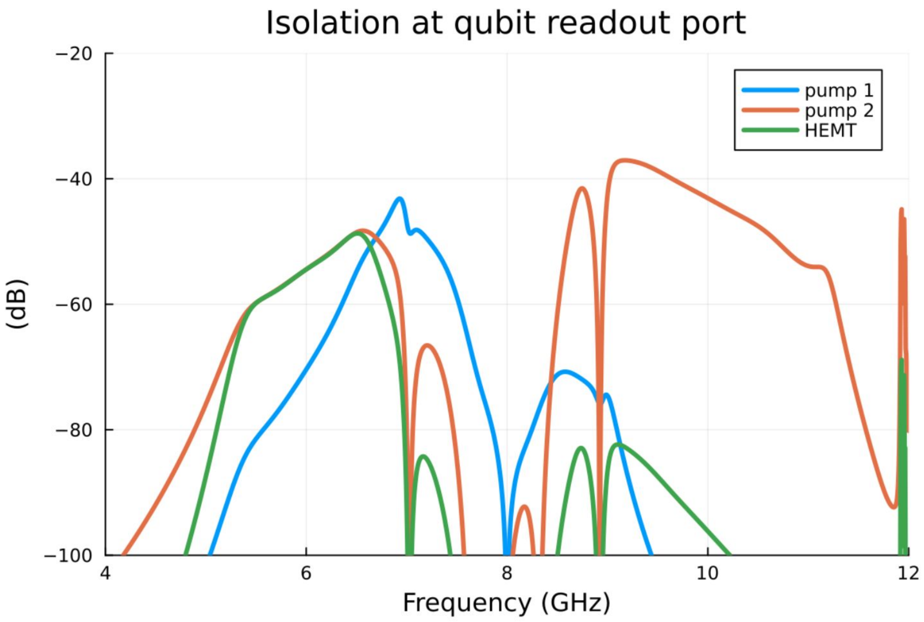


Add-drop filter with traveling-wave devices

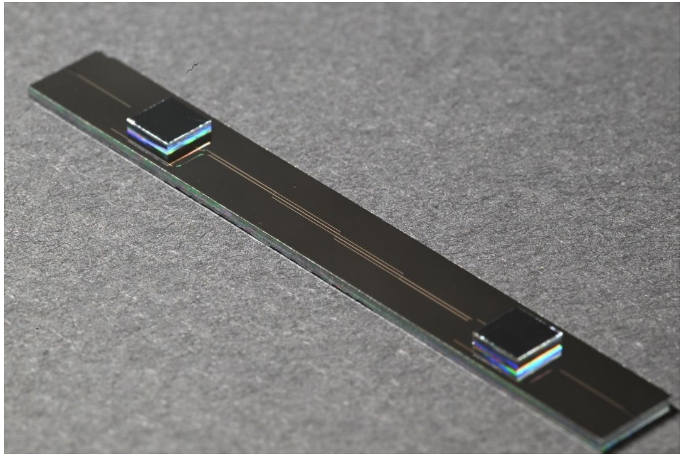


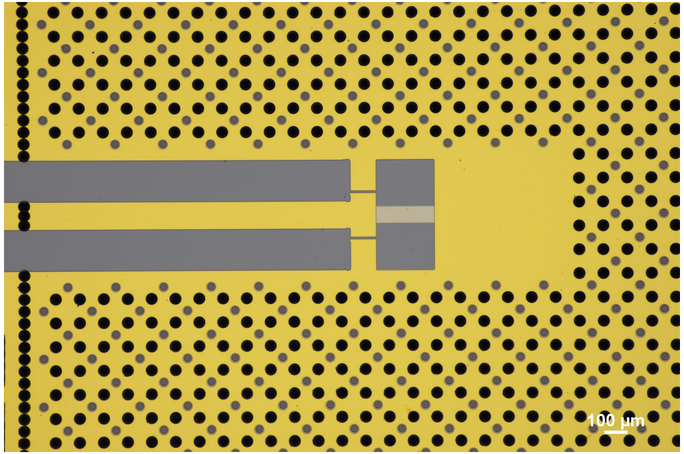
Isolation from external ports





Prototype





- Indium bump bond process developed in MIT.nano

Conclusions

- Sidebands and insertion loss reduce the QE of TWPAs
- JosephsonCircuits.jl for harmonic balance simulations of parametric amplifiers, including dissipation.
- Floquet Josephson traveling wave parametric amplifier (TWPA) (arxiv 2503.11812).

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