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Compact Superconducting Kinetic Inductance Traveling Wave Parametric Amplifiers with On-chip Bias Circuitry

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J. Wheeler, J. Austermann, J. Hubmayr, J. Ullom

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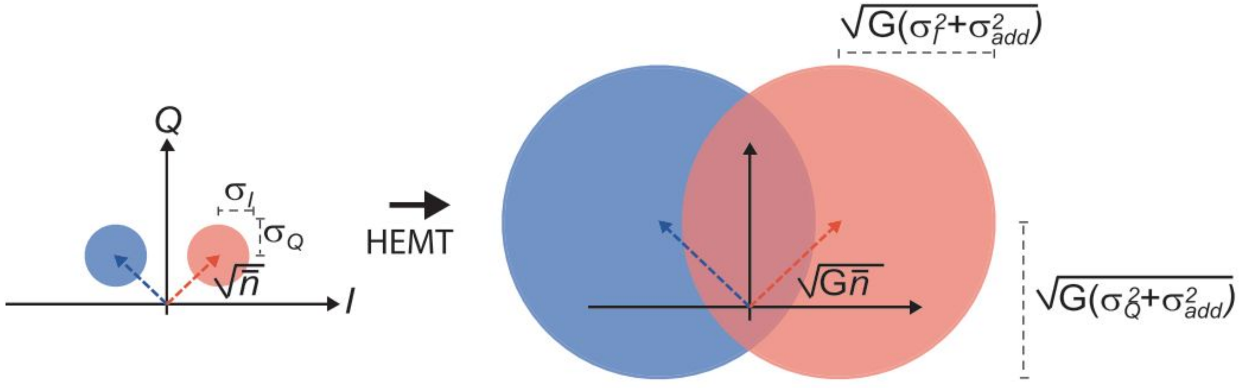
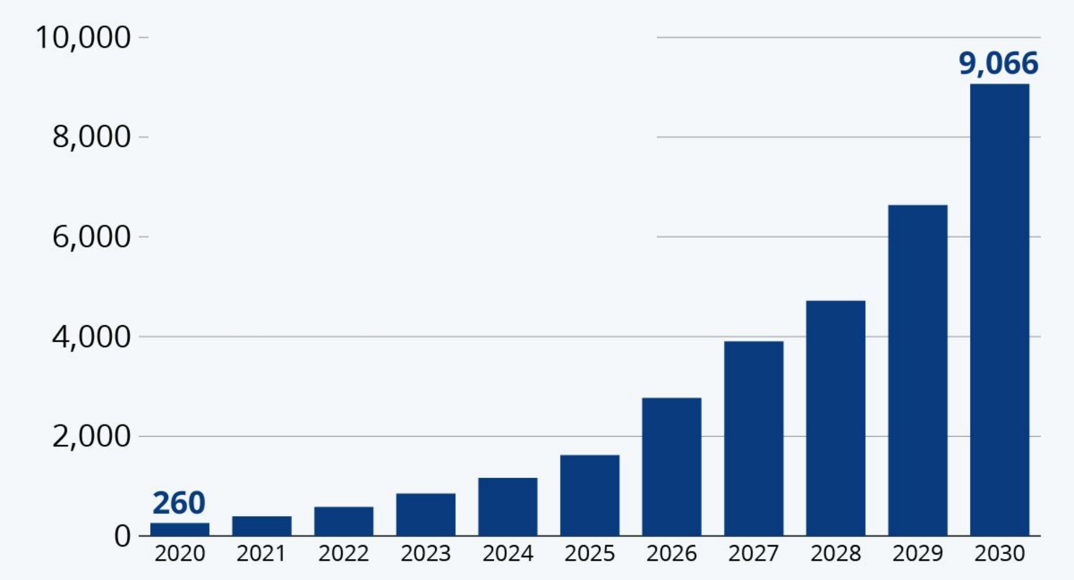
Parametric Amplifier Motivation

- Linear amplifiers **always** add noise
  - Minimum added-noise given by the Quantum Limit (QL) of 0.5 quanta
- Need high-bandwidth amplifiers operating near the QL with increased power handling
  - Quantum tech.
  - Rare physics searches
  - Cryogenic detector readout
- **K**inetic **I**nductance **T**WPAs (KITs) a possible solution
  - High device yield (simple fab.)
  - Elevated temperature operation (~10 K)
  - High maximum frequency (~1 THz)
  - Large dynamic range (P_{1dB} ~ -70 dBm)
  - B-field-resilient (>1 T)





K. Sliwa - Yale Thesis (2016)

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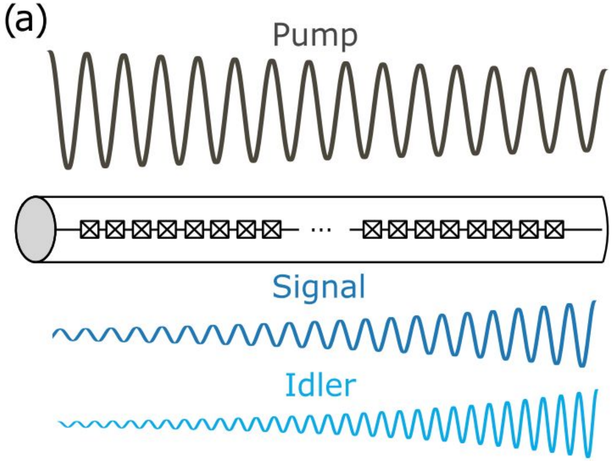
Kinetic Inductance TWPAs (KITs)

- Energy conversion via modulation (pumping) of some parameter
  - Three-wave mixing (3WM): $\omega_p = \omega_s + \omega_i$
  - Four-wave mixing (4WM): $2\omega_p = \omega_s + \omega_i$

(a)



- Josephson-based amps modulate L_J
  - Instead use the superconducting kinetic inductance L_k

$$L_k(I) \sim L_{dc}\left[1 + \left(\frac{I}{I_*}\right)^2 + \left(\frac{I}{I_*}\right)^4 + \ldots\right]$$

$$L = L_{dc}\left[1 + \varepsilon I_p + \xi I_p^2 + \mathcal{O}(I^3)\right]$$

3WM

$$\varepsilon = \frac{2I_{dc}}{I_*^2 + I_{dc}^2}$$

4WM

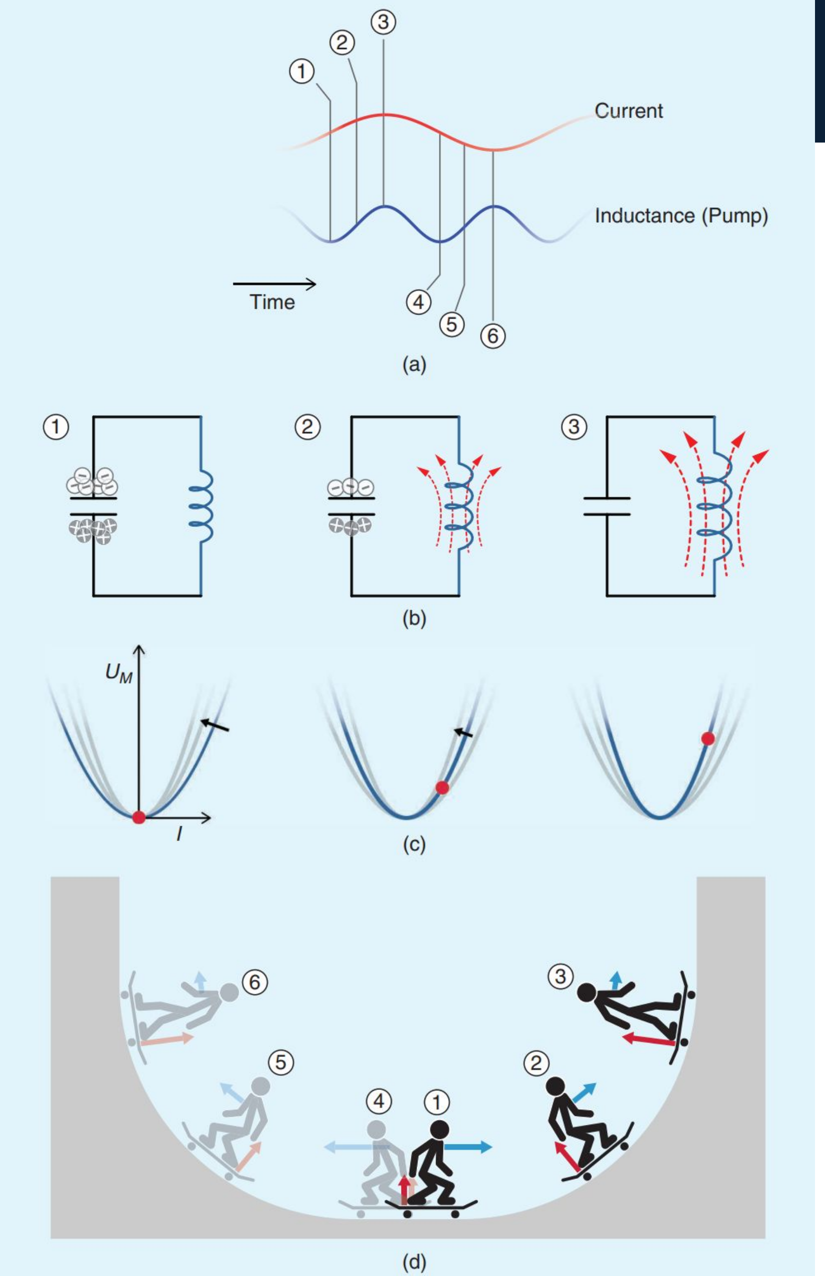
$$\xi = \frac{1}{I_*^2 + I_{dc}^2}$$

Can "turn off" 4WM with dc bias!

- Need high-kinetic-inductance materials

$$L_k = \frac{\hbar R_n}{\pi \Delta} \approx \frac{\hbar R_n}{1.76\ \pi k_B T_c}$$

  - → Thin, disordered superconductors are ideal!



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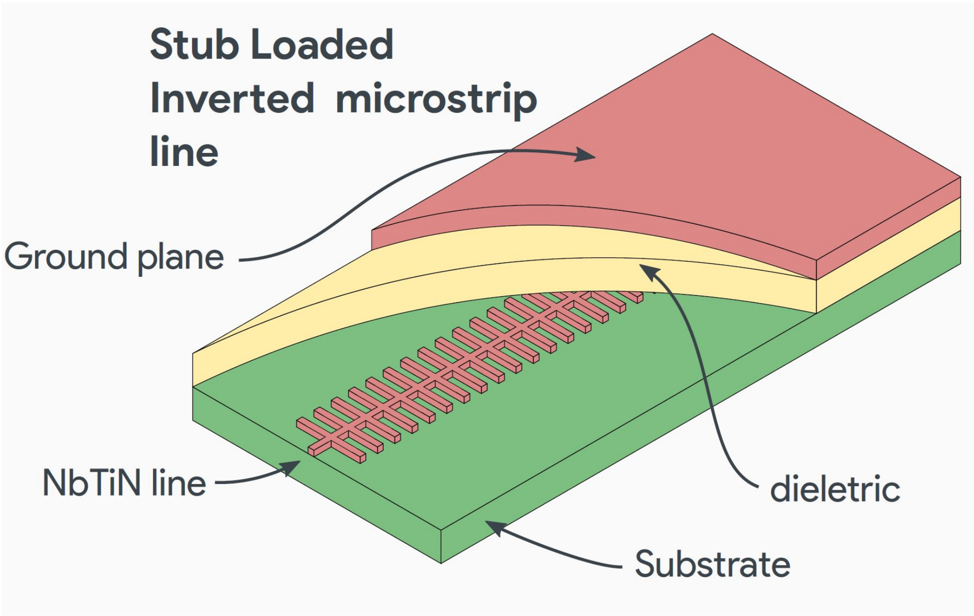
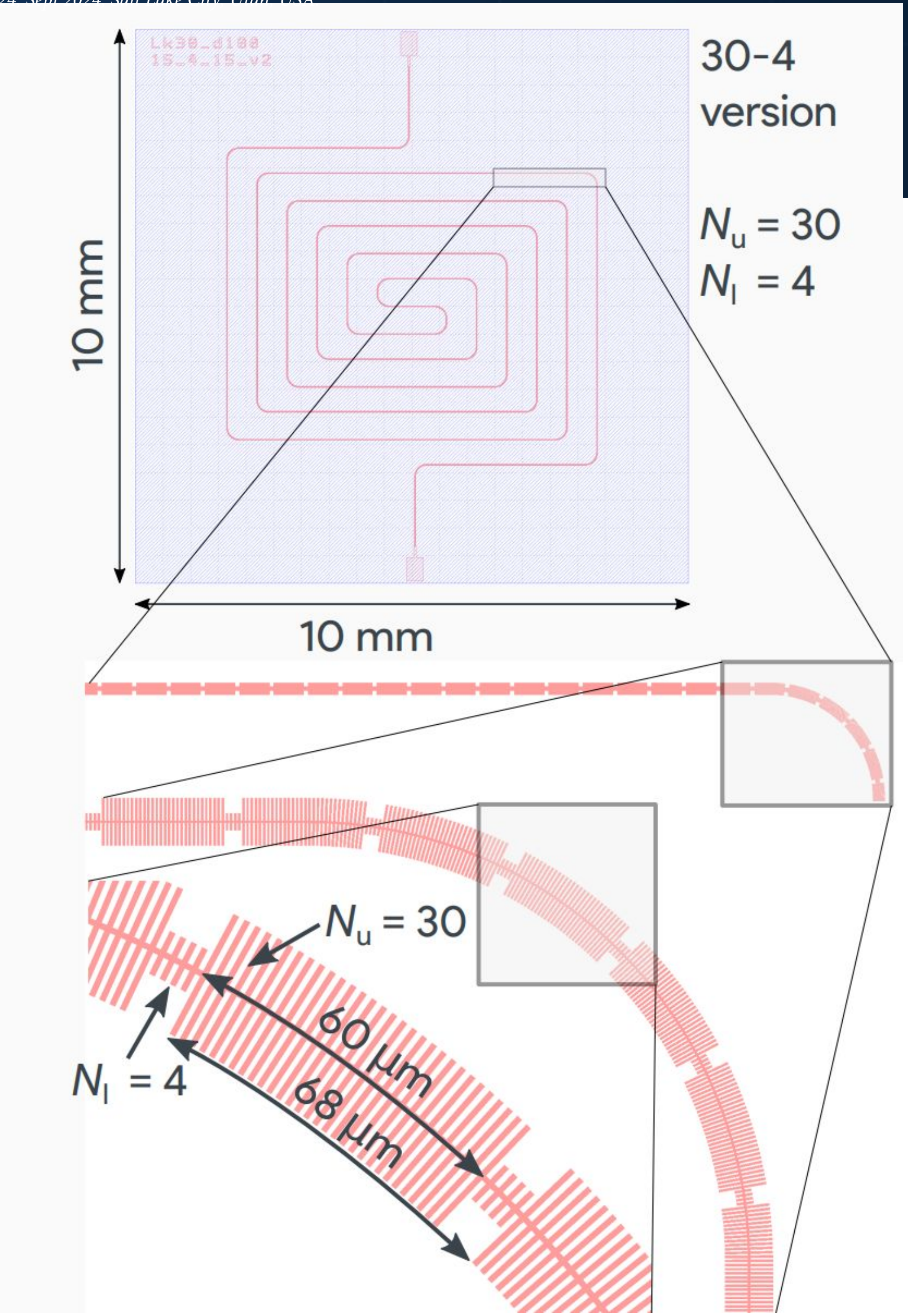
NIST KIT Design

- Stub-loaded inverted microstrip
  - Broadband phase-matching via dispersion engineering
- ~40k unit cells → ~8 cm length
- 10 nm NbTiN → L_k = 25 pH/sq
  - 100 nm low-loss α-Si dielectric





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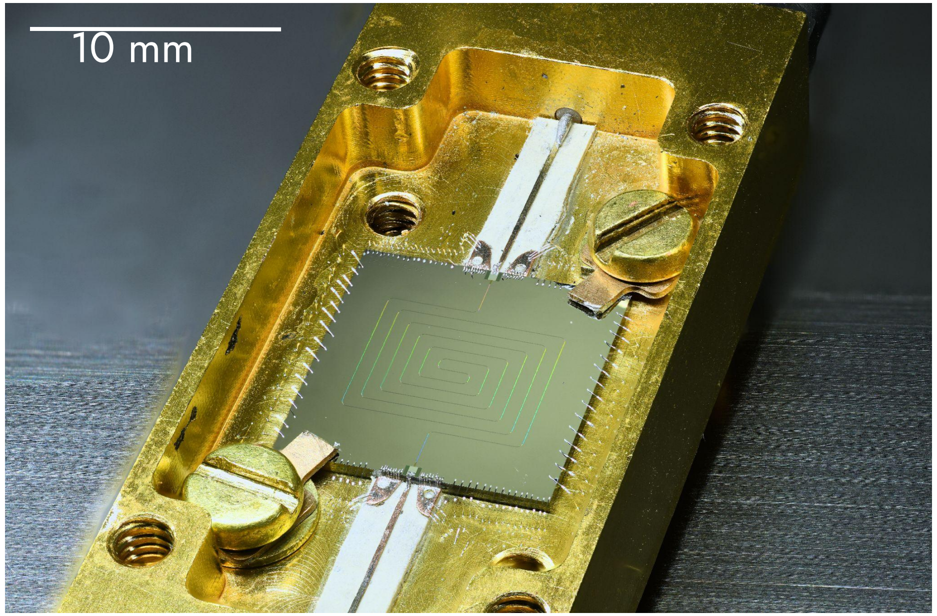
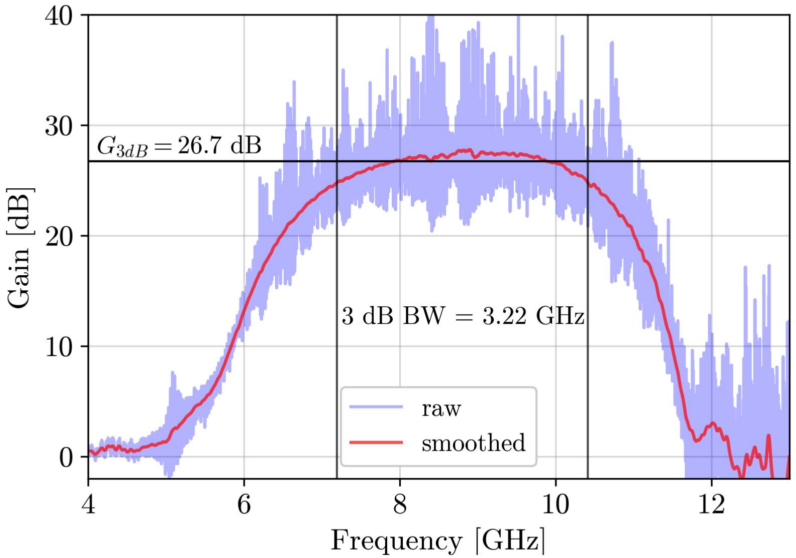
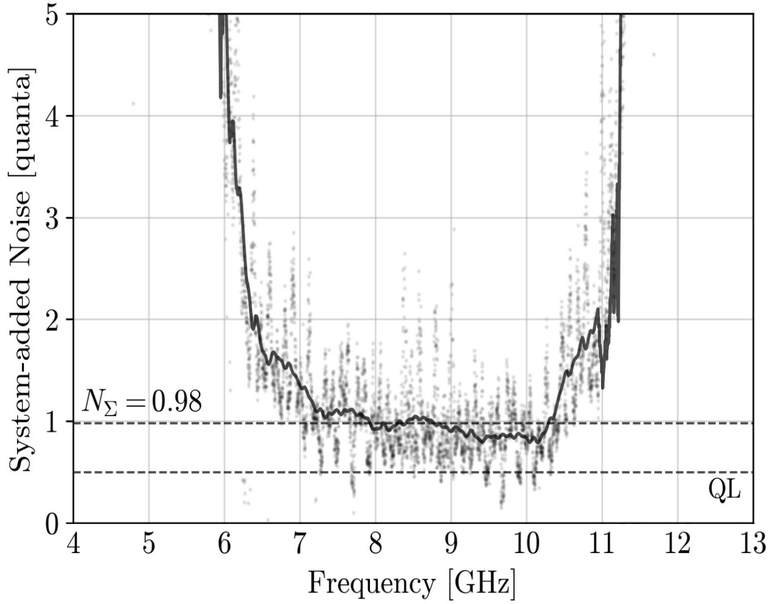
NIST KIT v2 Performance

- Gain (on/off) ~ 20 – 27 dB
- Pump power ~ -45 to -30 dBm (package input)
- I_c ~ 800 μA
- I_* ~ 2.8 mA
- Bandwidth (3dB) ~ 3.2 GHz
- Compression ~ -75 dBm
- System noise ~ 1 quanta







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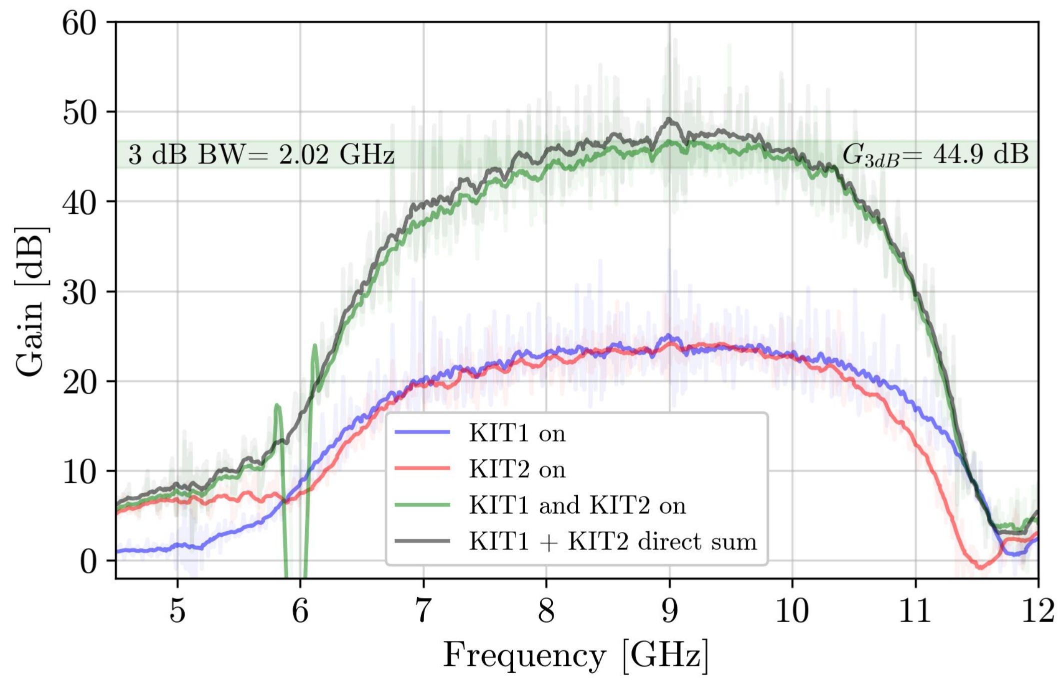
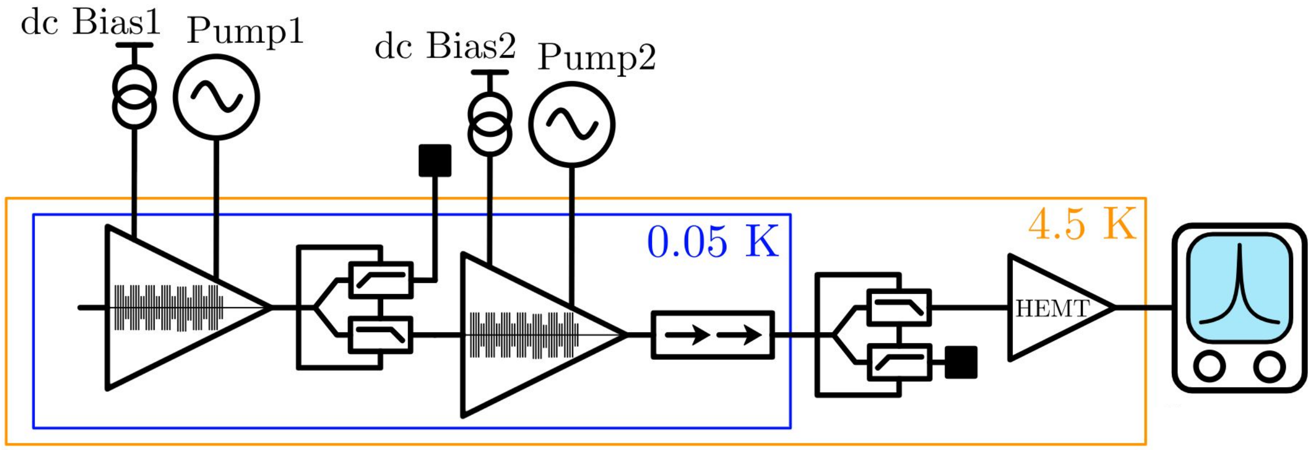
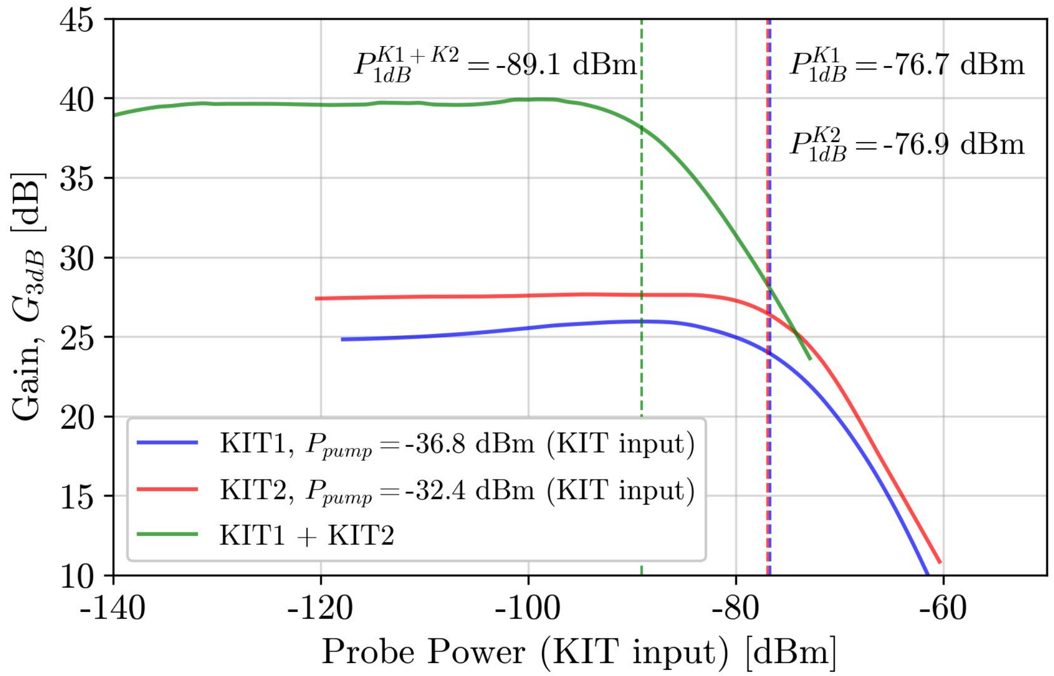
Double KIT?

- 2 KITs in series?
  - Independent biases and pumps
- HEMT no longer necessary...? 🤔
- Possible to readout entire quantum processors with 1 KIT







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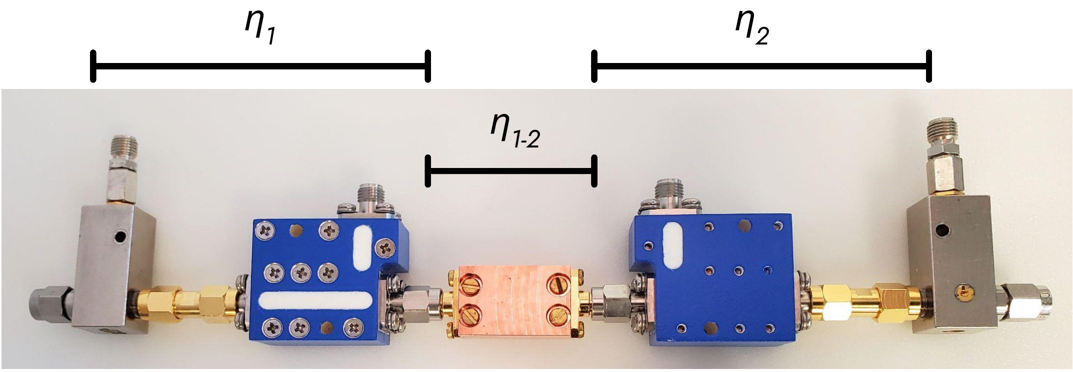
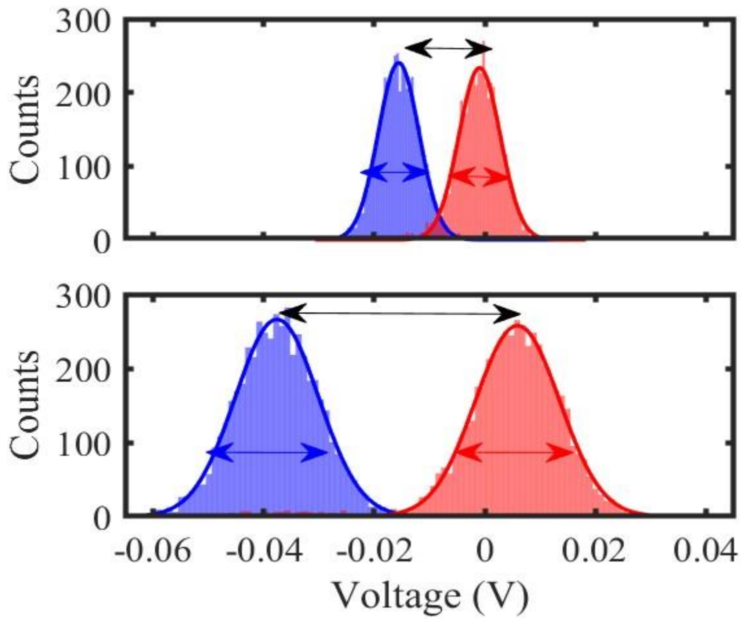
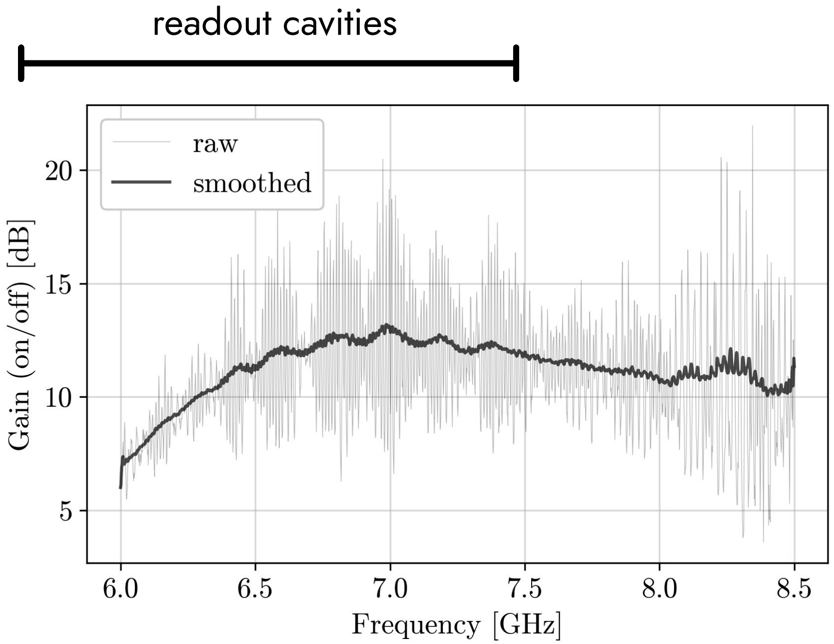
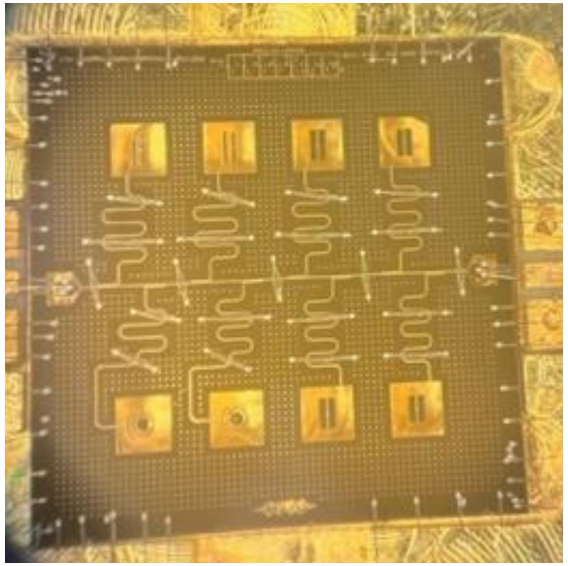
8-qubit Readout Demo

- Goal: show a measurable improvement in readout fidelity with KIT as 1st-stage amplifier
- Results
  - Fidelity improvement from 96.2% to 97.8%
  - Signal-to-noise increase of 1.45x
  - Limited by sub-optimal KIT bandwidth / gain









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Improving KIT performance

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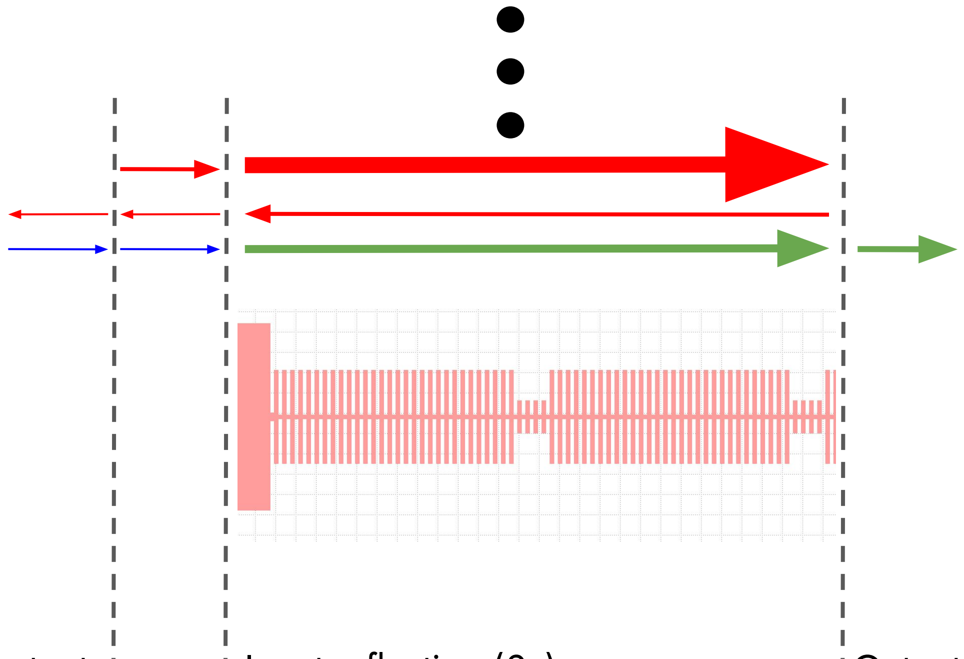
Impedance Mismatch and Reflections

- Parametric oscillations grow exponentially
  - Pump depletion limits gain everywhere
- Consider a single mode's journey:

$$I_{out,1} = S_{21} I_{in} (1 + S_{22} S_{12} S_{11} S_{21})$$

$$S_{21} = G_K \eta_K, \quad S_{12} = \eta_K$$

$$I_{out,n} = S_{21} I_{in} \sum_{k=0}^{n} (S_{22} S_{12} S_{11} S_{21})^k$$



- Sum diverges when $G_K \eta_K^2 \geq S_{22} S_{11}$
  - **For 30+ dB gain (on/off) need reflections below -15 dB**
  - Smaller reflections mitigate reverse-prop. amplified noise

N. Kilmovich - Caltech Thesis (2022)

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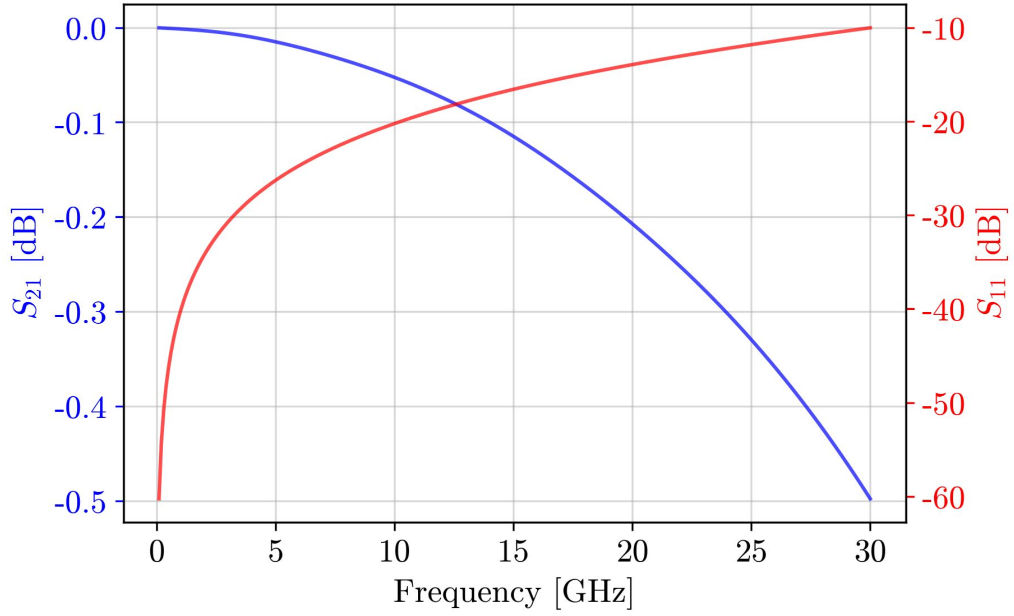
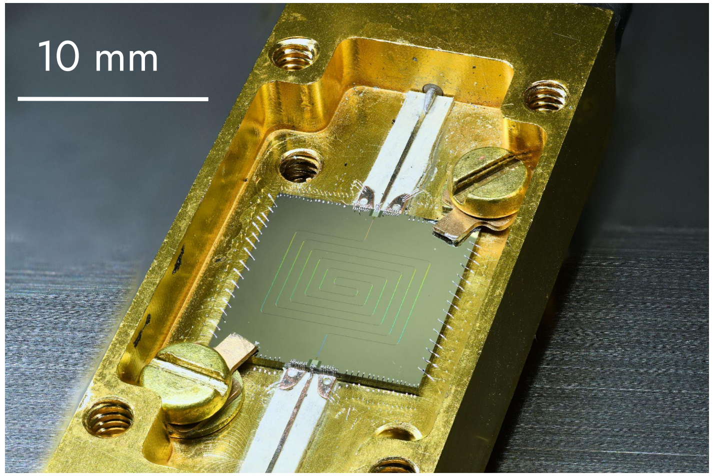
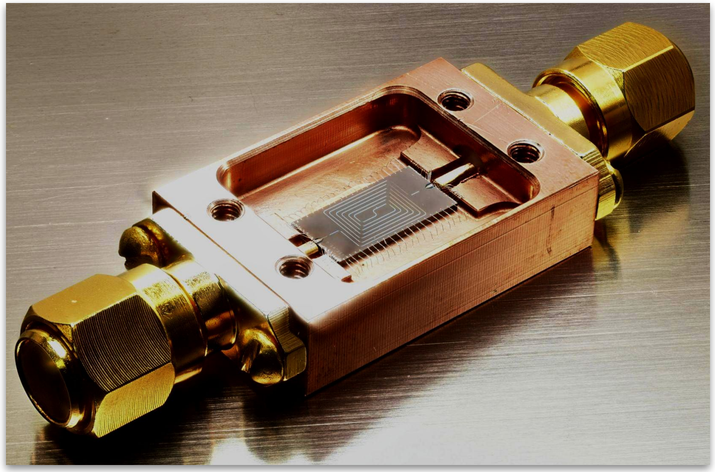
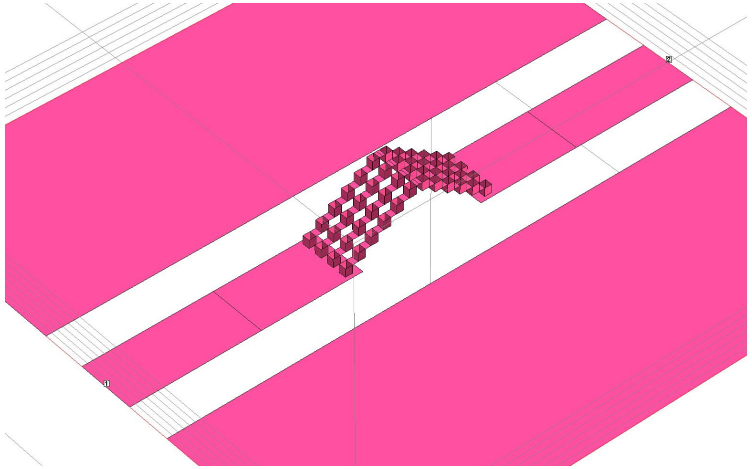
Improving Match, Reducing Reflections

- Hitting Z_0 = 50 Ω target
  - $Z_{0,v1}$ = 33 Ω → G ~ 13 dB
  - $Z_{0,v2}$ = 39 Ω → G ~ 26 dB
  - $Z_{0,v3}$ = 42 – 50 Ω → G > 28 dB
- Packaging improvements
  - Remove interface PCB (and optimize resulting launch)
  - **Stop wirebonding!**









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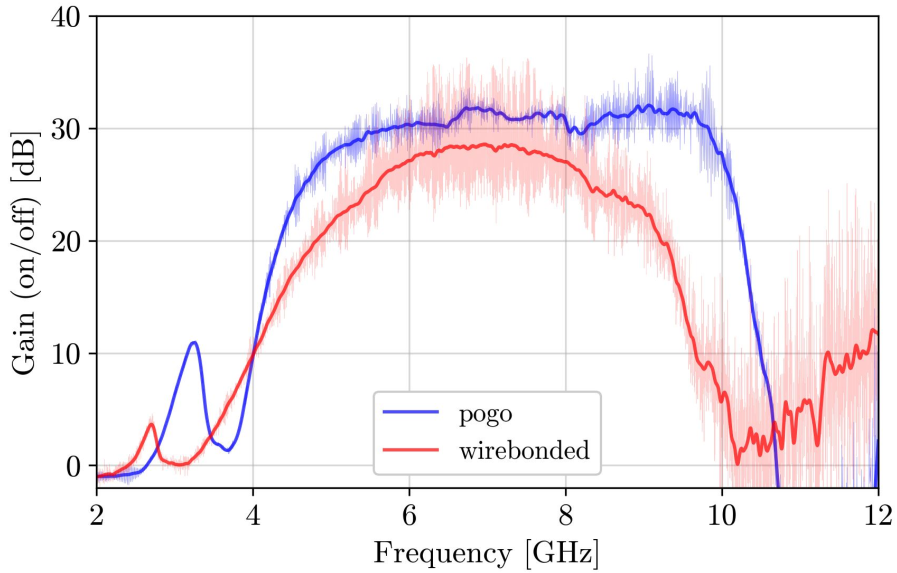
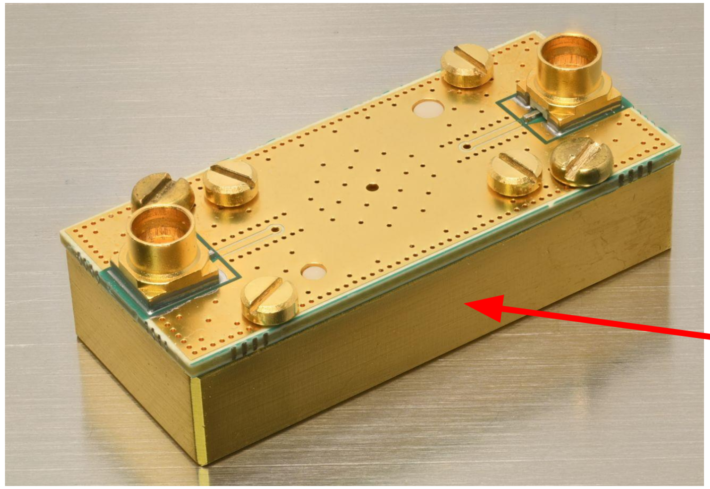
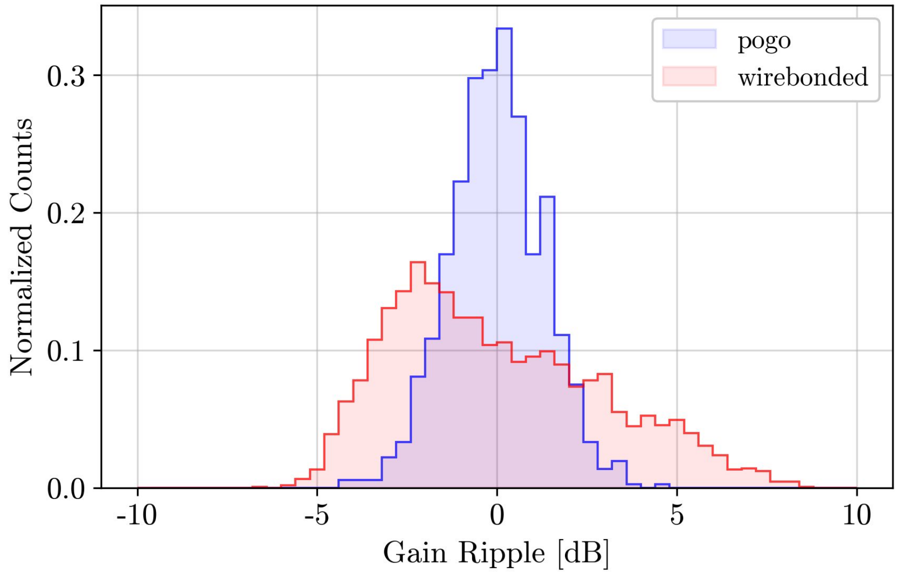
Eliminating Wirebonds – Pogo Pins

- Pogo pin benefits:
  - Drastic reduction of packaging inductance
  - Fully optimized launch: S_{11} < -10 dB at 70 GHz
  - Simple, repeatable assembly: <5 min
- Results:
  - Greater max gain, lower ripple
  - Beyond-octave (4.96 GHz) bandwidth
  - Operation at higher frequencies possible (future)







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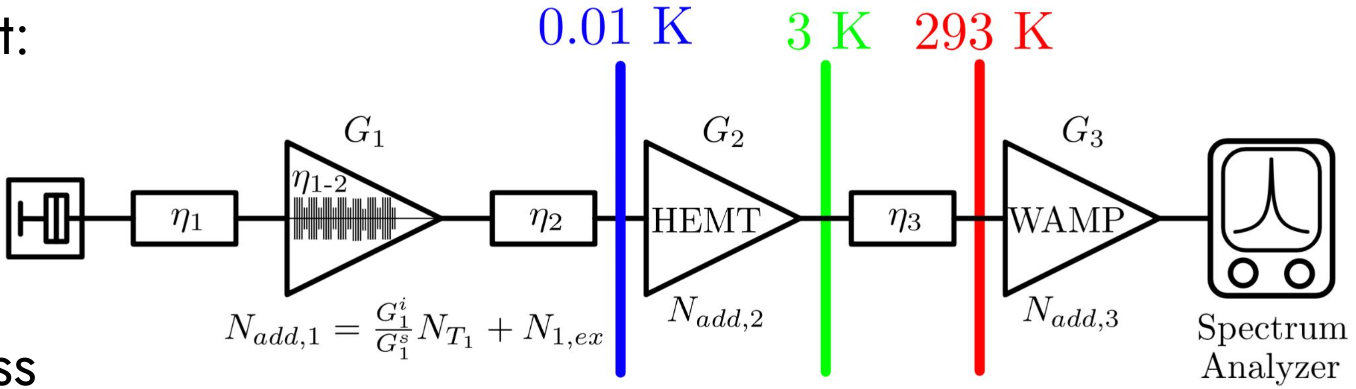
System Noise and the Impacts of Loss

- Real TWPAs are "non-ideal," cannot neglect:
  - Frequency-dependent loss
  - Signal-idler gain asymmetry

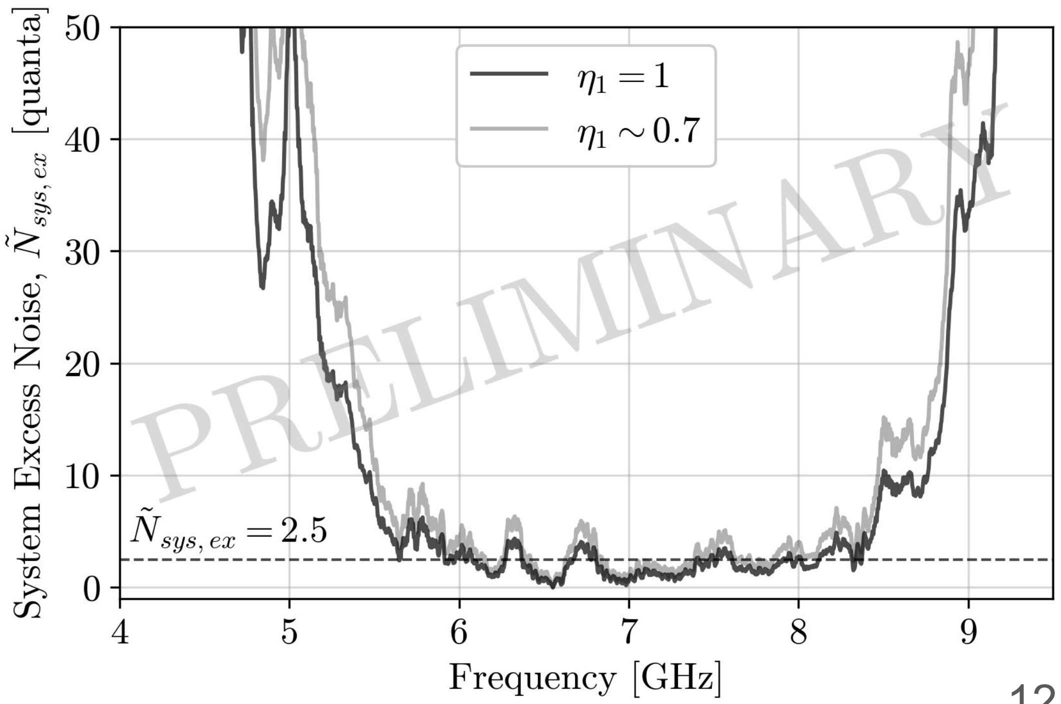
- Need to account for external component loss



$$N^s_{out,1} = \tilde{G}^s_1 \left(N^s_{in} + \frac{\tilde{G}^i_1}{\tilde{G}^s_1} N^i_{in} + \tilde{N}^s_{1,ex} \right)$$

$$N^s_{out,3} = \tilde{G}^s_3 \tilde{G}^s_2 \tilde{G}^s_1 \left(\tilde{N}^s_{in} + \frac{\tilde{G}^i_1}{\tilde{G}^s_1} N^i_{in} + \tilde{N}^s_{1,ex} \right) + \tilde{G}^s_3 \tilde{G}^s_2 N^s_{add,2}$$

$$\tilde{N}^s_{1,ex} = \frac{(1-\eta^s_1) N^s_{T_1} + N^s_{1,ex}}{\eta^s_1} + \frac{\tilde{G}^i_1}{\tilde{G}^s_1} \frac{(1-\eta^i_1) N^i_{T_1} + N^i_{1,ex}}{\eta^i_1}$$



M. Malnou et al - "Low-noise cryogenic..." (2024)

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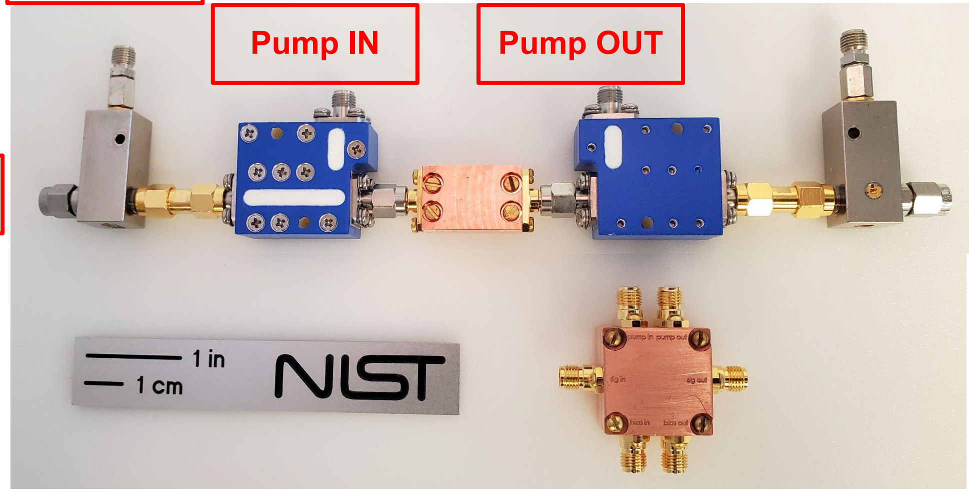
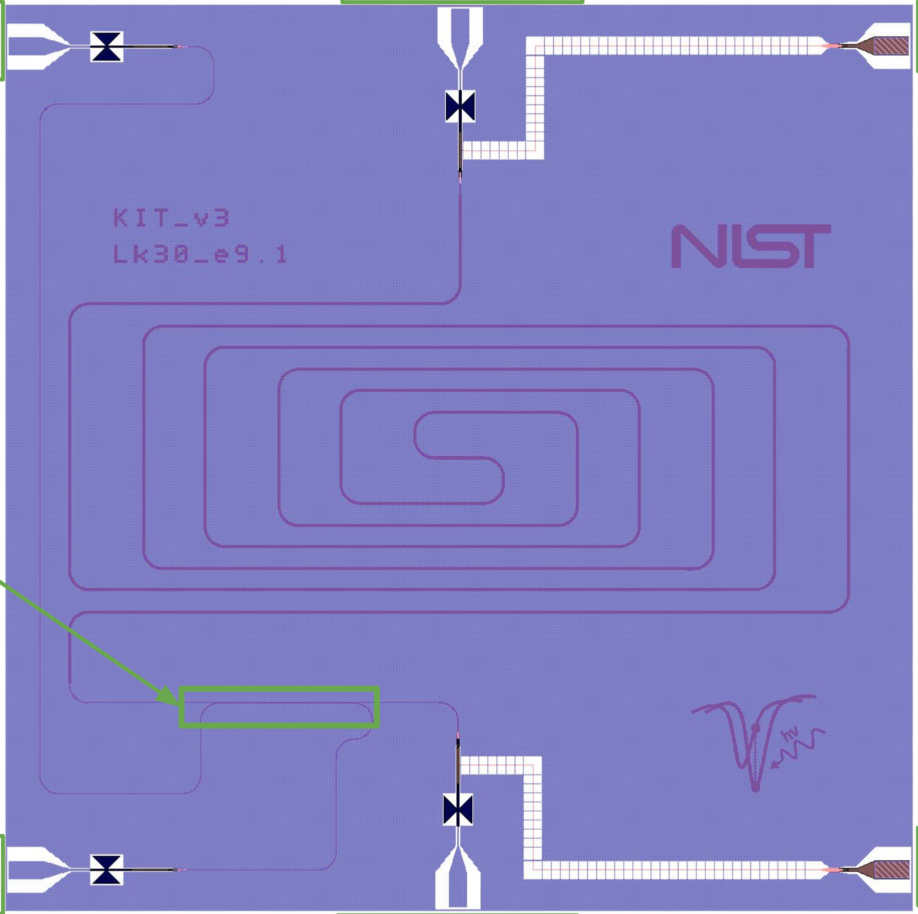
The On-chip rf Compnents KIT (ORCK)

- Why put things on-chip?
  - Decrease system noise (via increasing η_1)
  - Compactify!
  - Reduce installation complexity
- Current approach
  - Simplicity and flexibility (broadband)
    - Bias tee
    - Directional coupler





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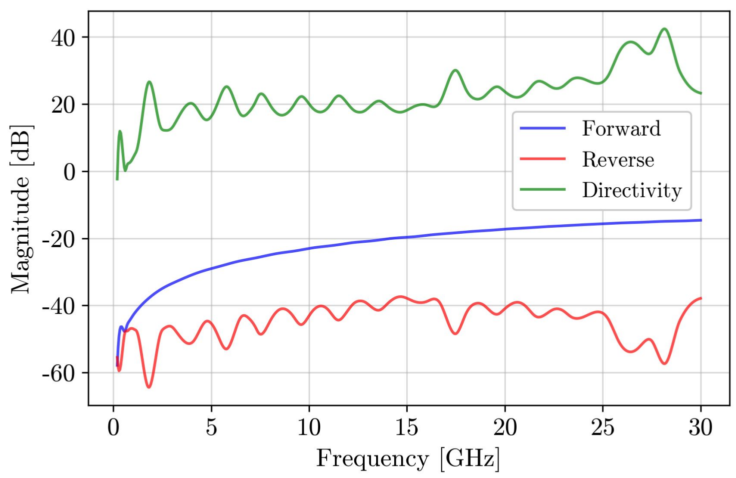
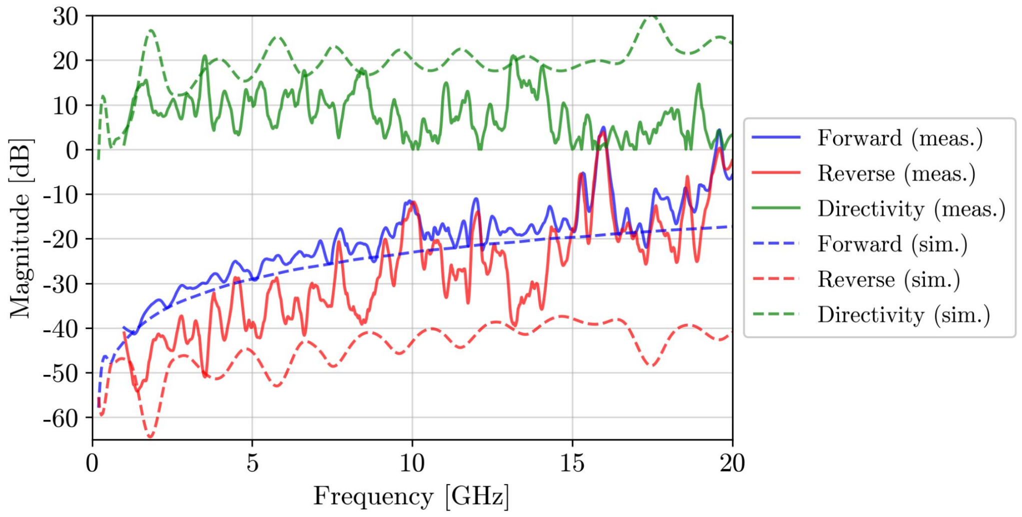
Directional Coupler



- Podell Wiggly Coupler (WC)
  - Ultra broadband
  - Simple geometry
  - High directivity
- Challenges
  - 100 nm dielectric + 1 μm minimum feature size
  - Confines E-field in z direction → long coupler (1500 μm)
- Results (it works!)
  - Forward coupling on target
  - Directivity is lower than desired



A. Podell - A High Directivity Microstrip Coupler Technique (1970)

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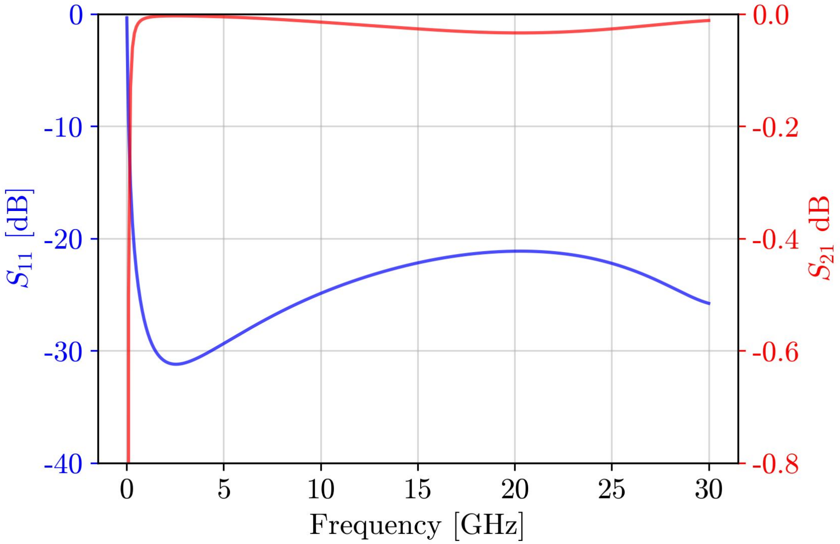
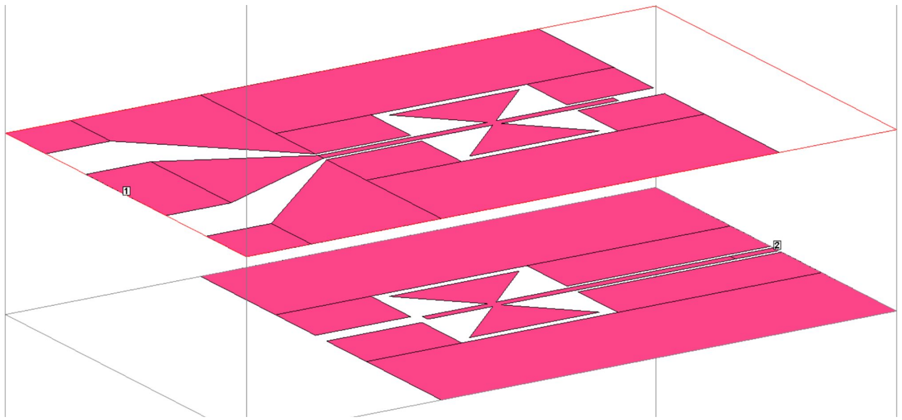
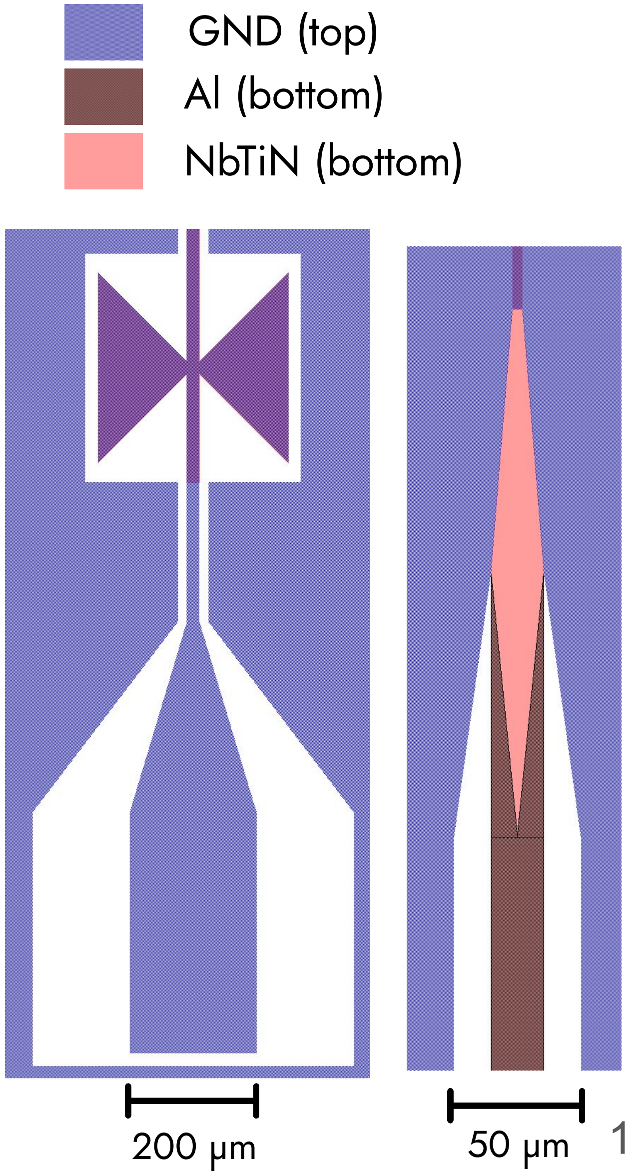
dc Block and Microstrip Transition

- dc block developed for NIST Josephson voltage standard group
  - Overlap bowtie capacitor
    - Low cutoff
    - Lumped-element at 30 GHz
- Microstrip transition:
  - Less abrupt than previous design
  - Gradually increases transmission line $\mathcal{L}$
    - Compensates via increasing $\mathcal{C}$





M. Elsbury - CU Boulder Thesis (2010)



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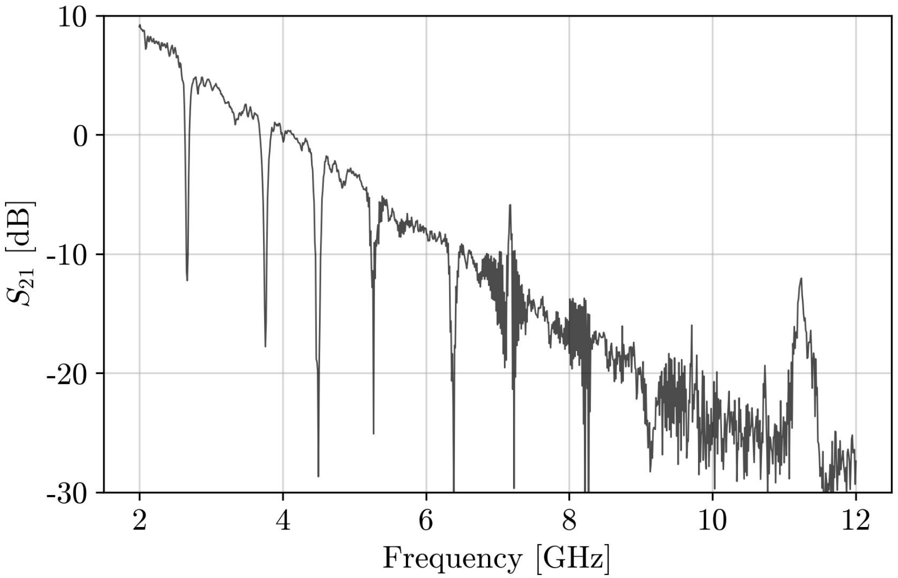
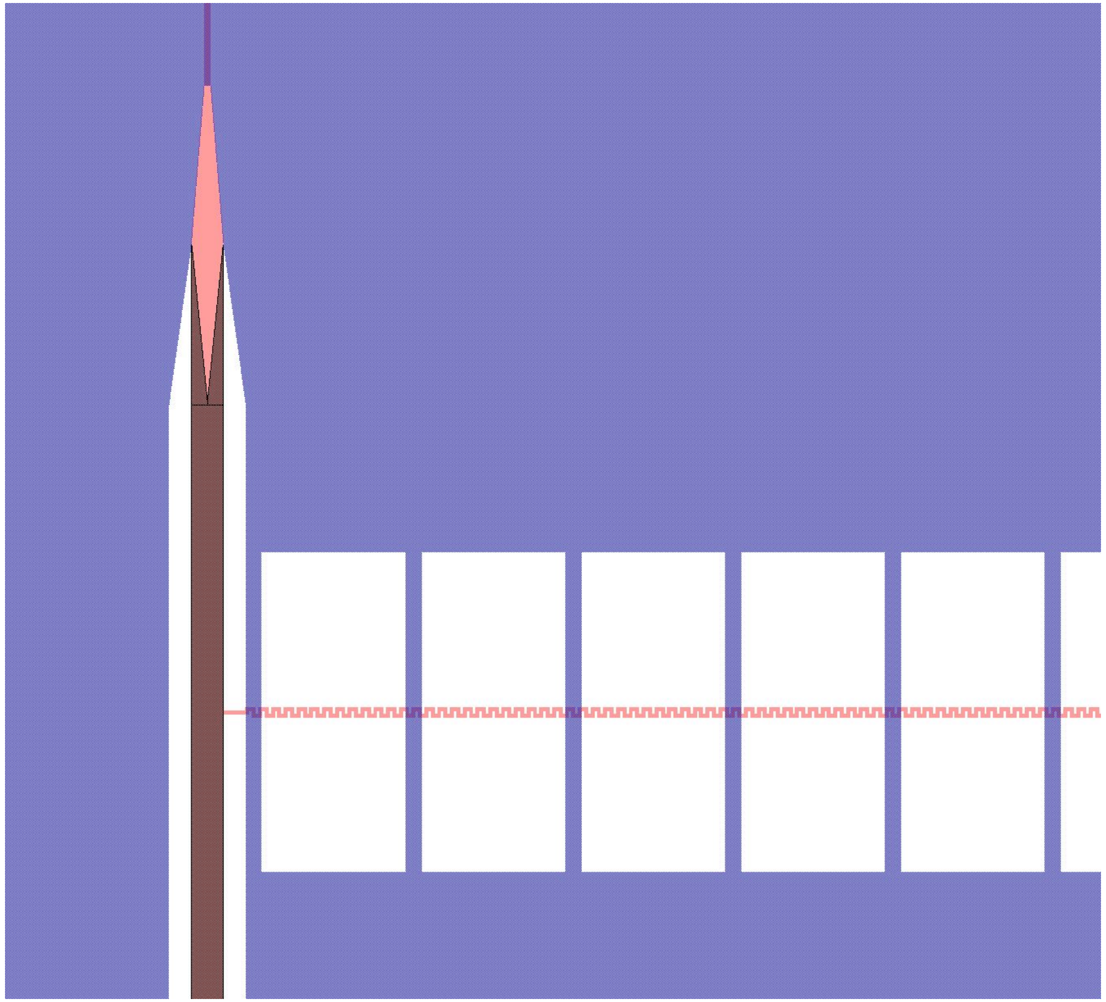
Bias Tee

- Need ~100 nH of inductance on dc line
  - L_k = 25 pH/sq for 10 nm NbTiN → 4000 sq
  - Achieve 3980 sq with meander
- Results
  - Works as a bias line!
  - ~930 MHz high-Q resonance
  - Solutions / workarounds ready for next fab run





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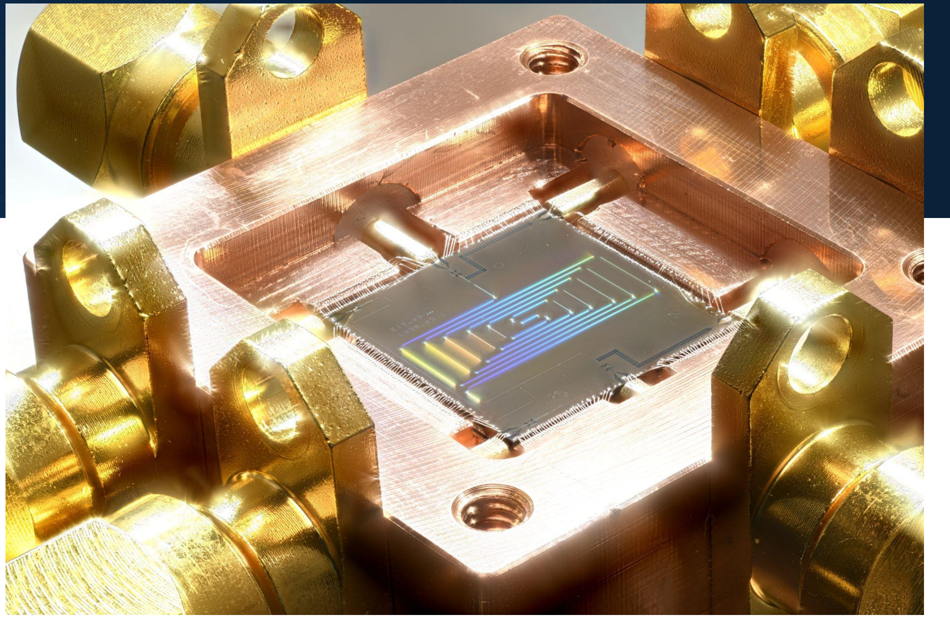
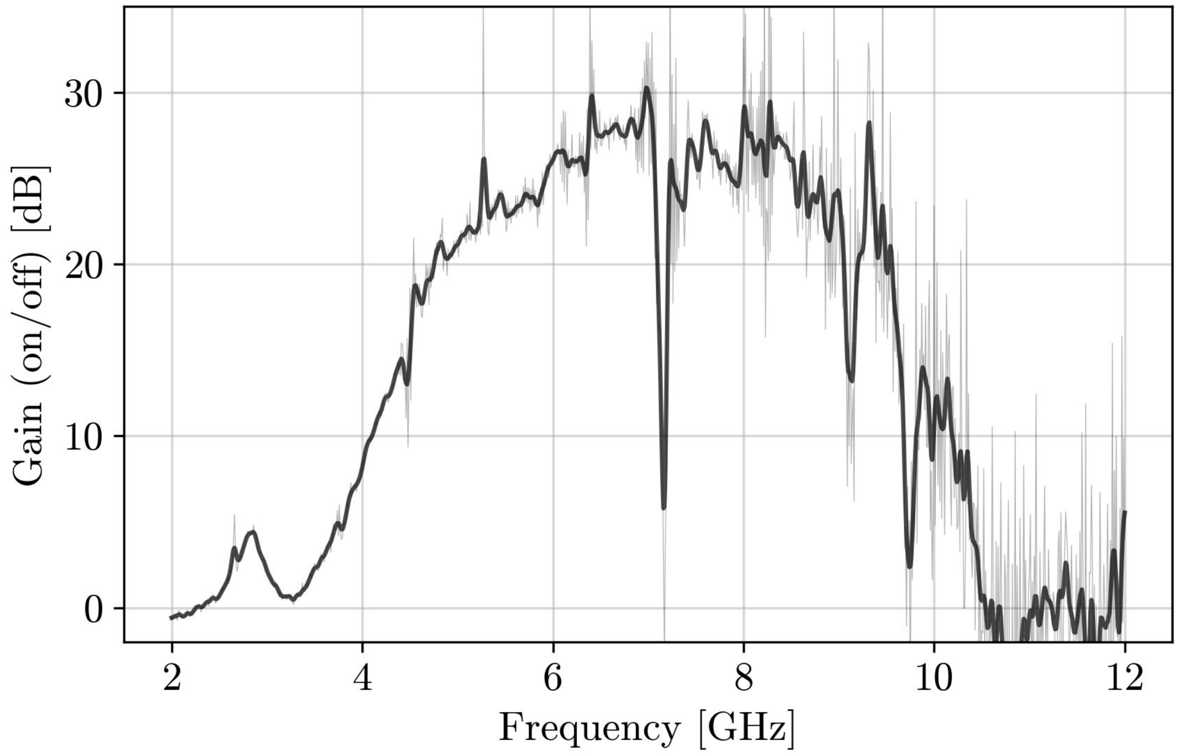
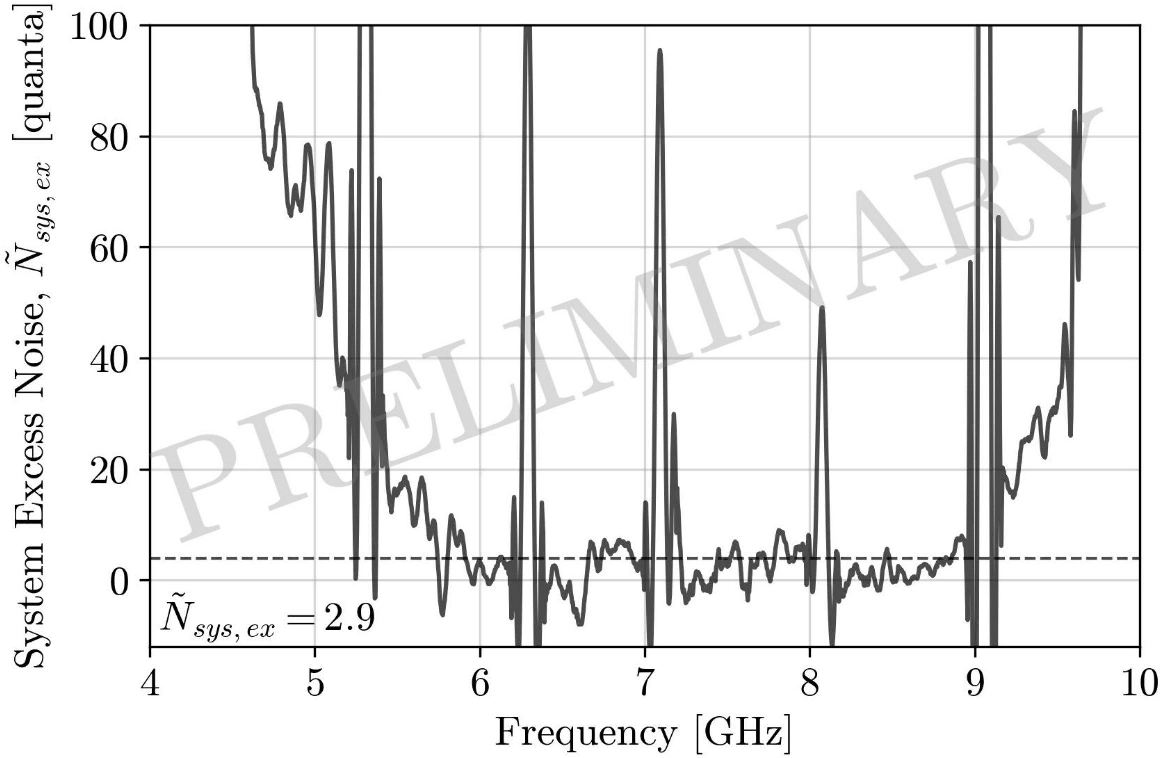
ORCK Performance



- G ~30 dB (on/off) still achievable
- Large usable bandwidth
  - Resonances are deep but high-Q
- System noise comparable to conventional KIT





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Conclusion

- Packaging improvements significantly enhance performance
  - G > 30 dB
  - Beyond-octave bandwidth
- NIST KITs are qubit-compatible
  - Demonstrated improvement in readout fidelity
- New on-chip rf bias circuits work!
  - KITs now much more compact and efficient