

# High Efficiency Floquet-Mode Traveling Wave Parametric Amplifier

**Jennifer Wang**<sup>1,2</sup>, Kaidong Peng<sup>1,2</sup>, Jeffrey Knecht<sup>3</sup>, Gregory Cunningham<sup>1,2</sup>, Andres Lombo<sup>1,2</sup>, Alec Yen<sup>1,2</sup>, Jeremy Kline<sup>1,2</sup>, Daniela Zaidenberg<sup>1,2</sup>, Michael Gringras<sup>3</sup>, Bethany M. Niedzielski<sup>3</sup>, Hanna Stickler<sup>3</sup>, Katrina Sliwa<sup>3</sup>, Kyle Serniak<sup>3</sup>, Mollie E. Schwartz<sup>3</sup>, William D. Oliver<sup>1,2</sup>, Kevin P. O'Brien<sup>1,2</sup>

<sup>1</sup> Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

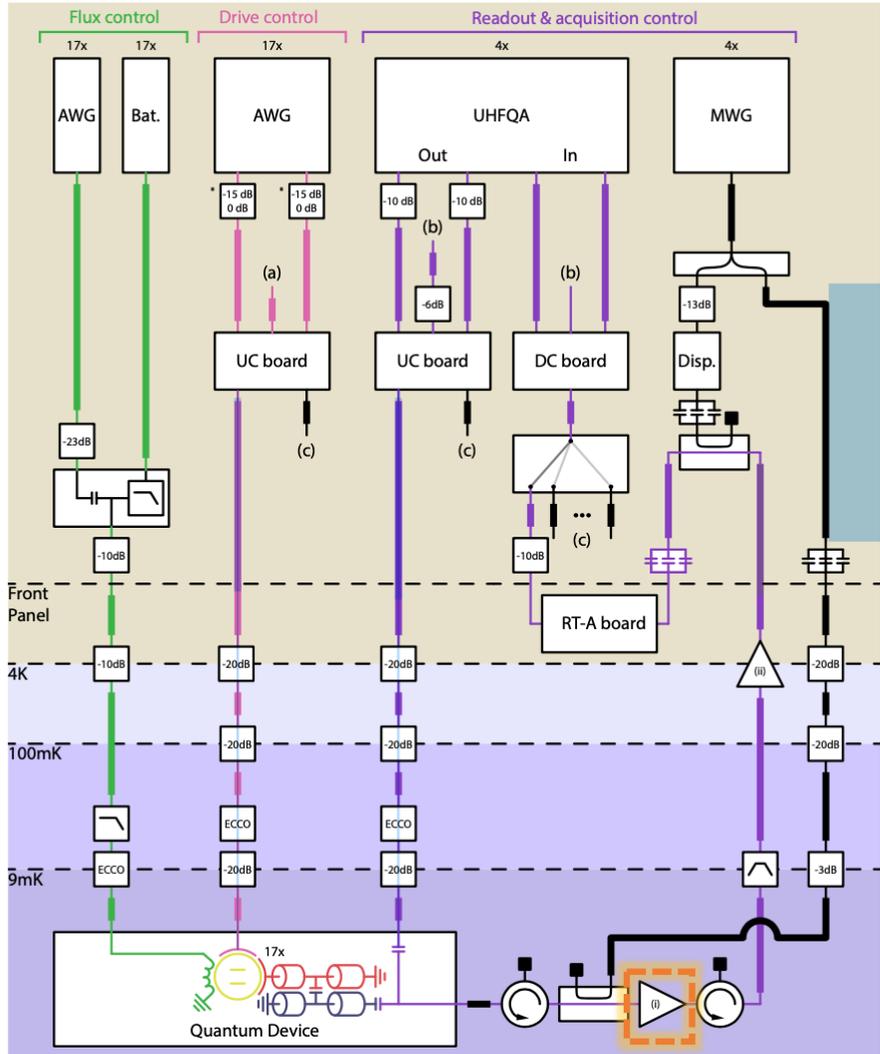
<sup>2</sup> Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>3</sup> MIT Lincoln Laboratory, Lexington, Massachusetts 02421, USA



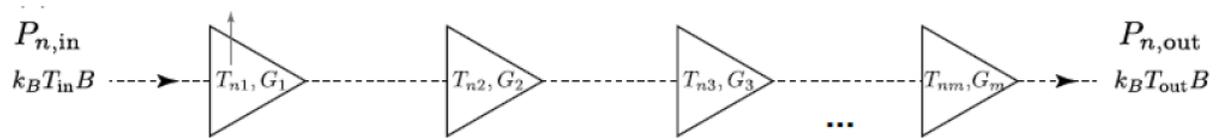
SQUAT Workshop  
Oct 29<sup>th</sup>, 2025





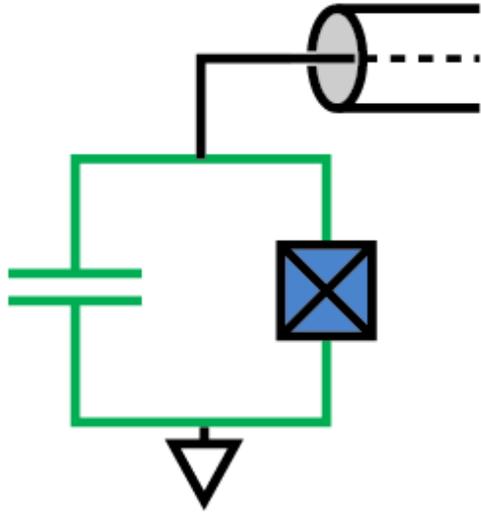
- Superconducting qubits readout utilizes weak microwave frequency signals
- First stage amplifier limits performance
- Broad amplifier bandwidth (few GHz) and high dynamic range enables qubit multiplexing

$$T_{\text{out}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \dots + \frac{T_{N-1}}{G_1 G_2 \dots G_N}$$



# Josephson effect-based parametric amplifier types

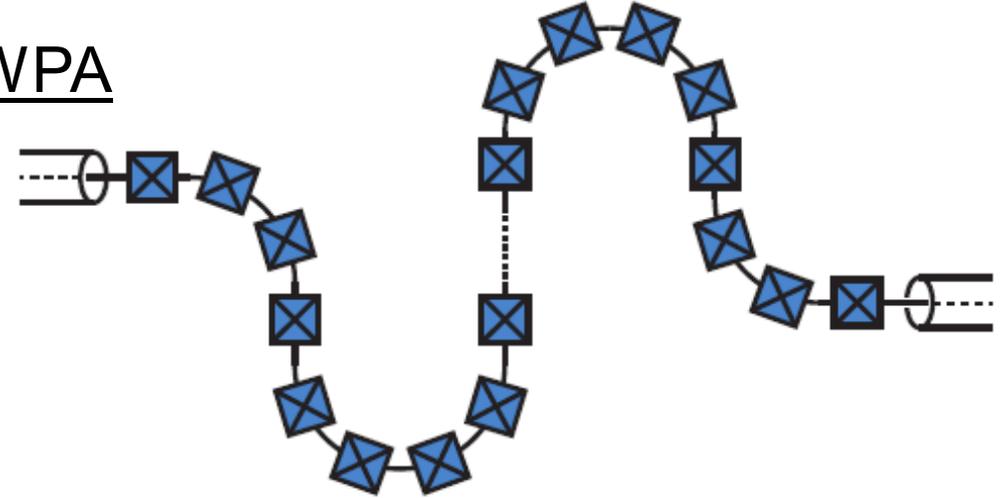
JPA



- Single or few spatial modes
- Tens of MHz bandwidth for 20 dB gain
- Dynamic range around -110 dBm
- Lossless or better noise performance

Boutin, S. et al., *Phys. Rev. Appl.* 8, 054030 (2017).

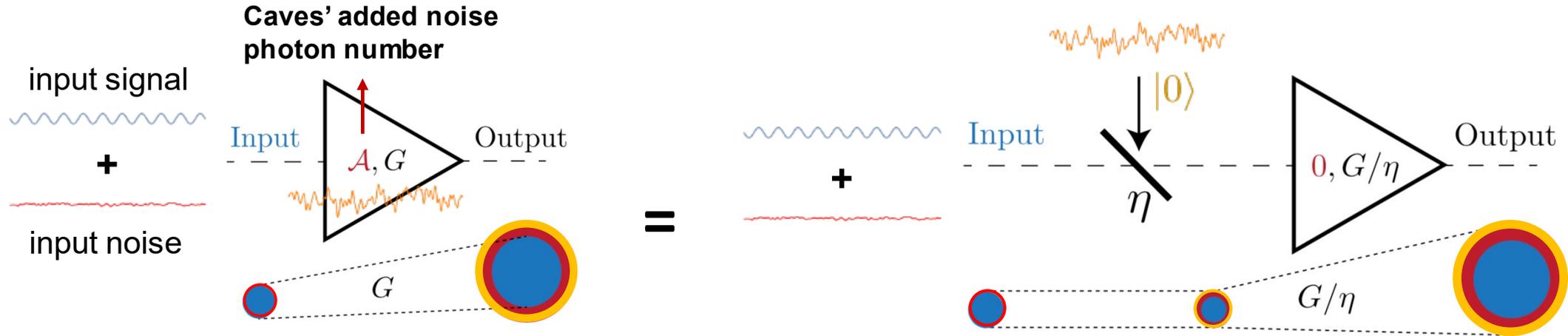
JTWPA



- Thousands of spatial modes
- Several GHz bandwidth for 20 dB gain
- Dynamic range from -110 dBm to -90 dBm
- **Typical quantum efficiency for uniform JTWPA is 20% below Standard Quantum Limit (SQL)**

Macklin C., O'Brien K., et al., *Science* 350, 6258 (2015).

# The Quantum Limit of Phase-Preserving Amplification



Noise Figure

$$F = \frac{\text{SNR}_{in}}{\text{SNR}_{out}} = 1 + 2\mathcal{A}$$

Quantum Efficiency

$$\eta = \frac{\text{SNR}_{out}}{\text{SNR}_{in}} = \frac{1/2}{1/2 + \mathcal{A}}$$

$G \gg 1$

Noise Temperature

$$T_N = \frac{P_N}{k_B B} = \frac{\hbar\omega}{k_B} (1/2 + \mathcal{A})$$

$$\geq 2$$

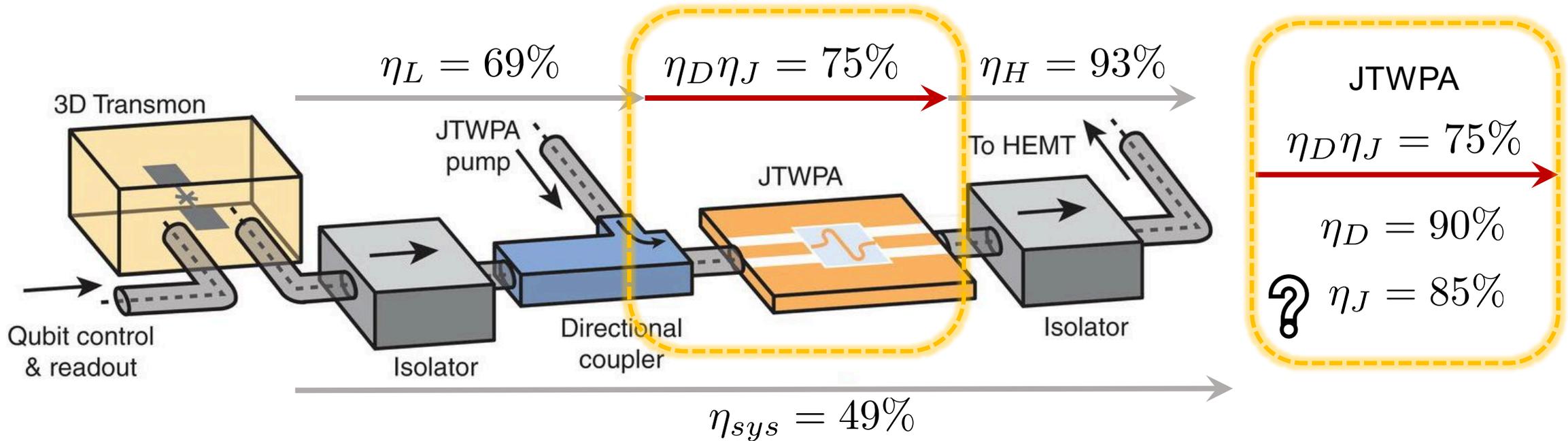
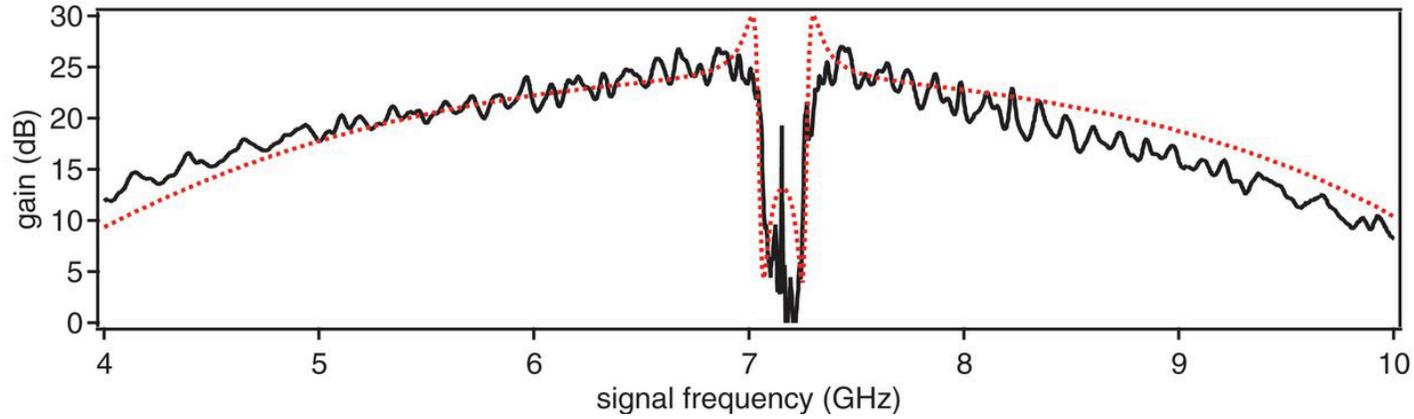
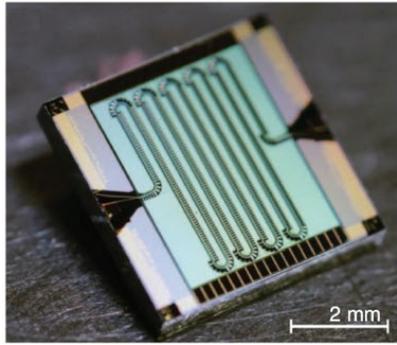
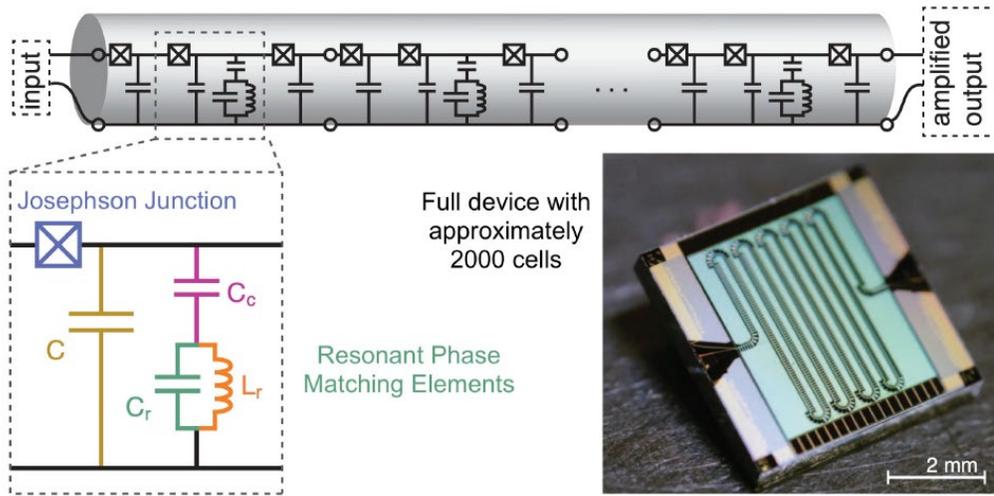
**Quantum Limit**

$$\leq \eta_{ideal} = \frac{1/2}{1/2 + (1 - 1/G)/2} \approx 50\%$$

$$\geq \frac{\hbar\omega}{k_B}$$

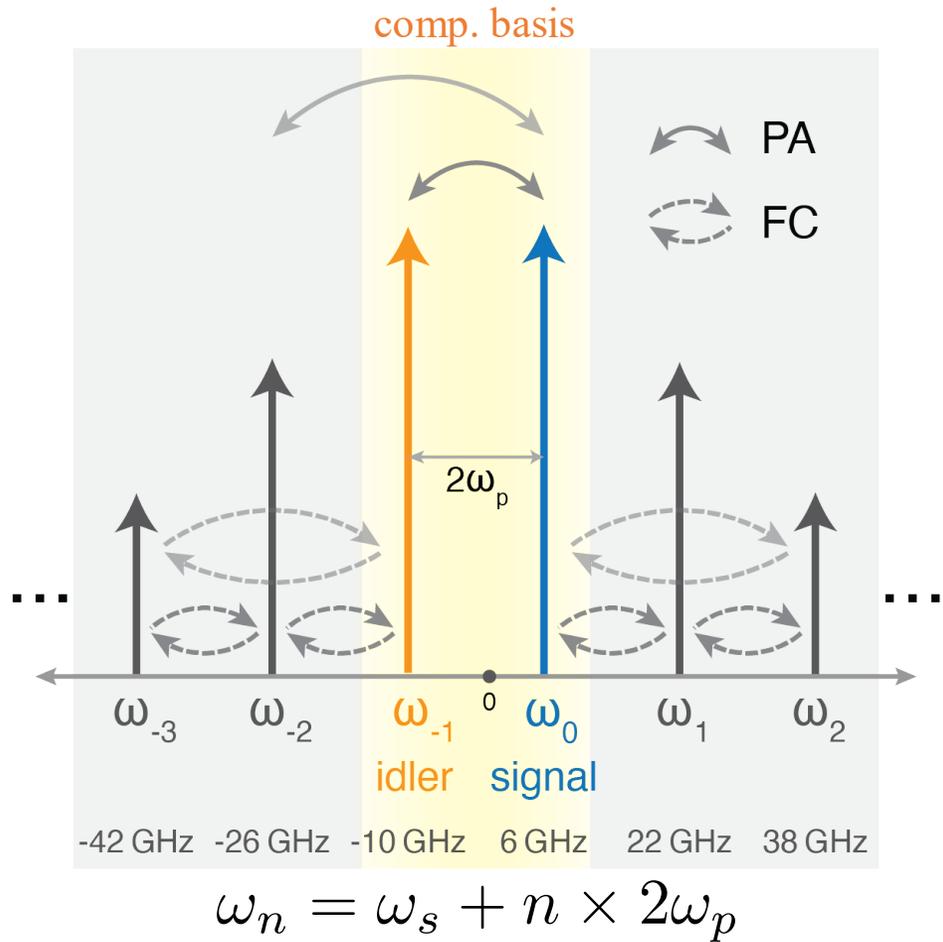
From now on, we will use the normalized measures  $\tilde{\eta} = \frac{\eta}{\eta_{ideal}} \leq 100\%$  and inefficiency  $\bar{\eta} = 1 - \tilde{\eta} \geq 0$

# The quantum efficiency of a uniform JTWPA & measurement chain

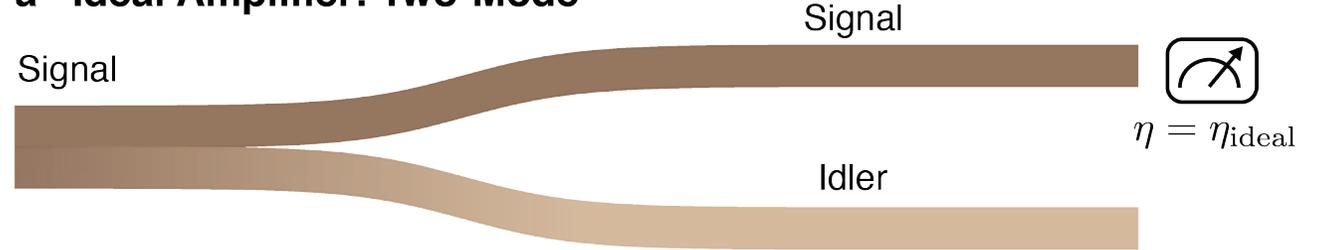




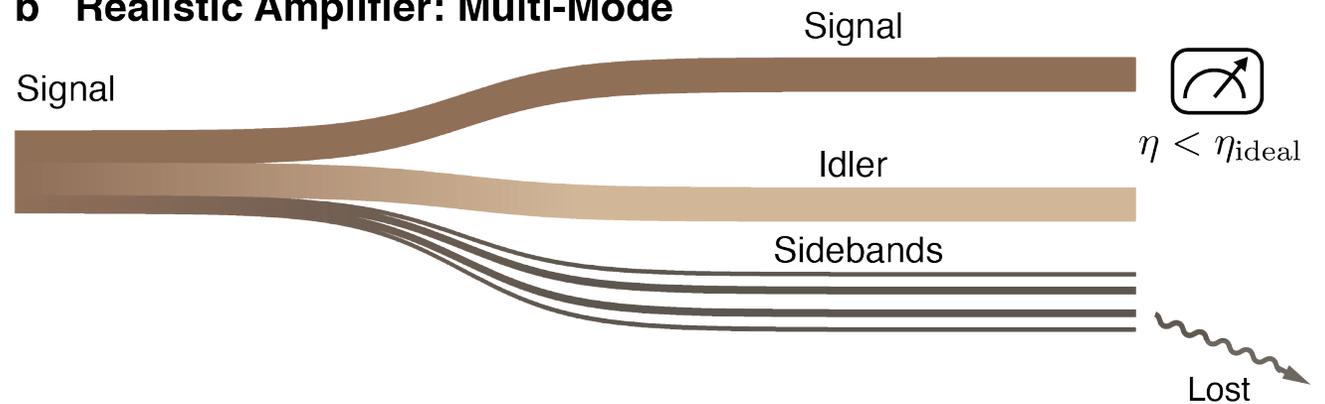
# JTWPA noise performance is limited by lossy sidebands



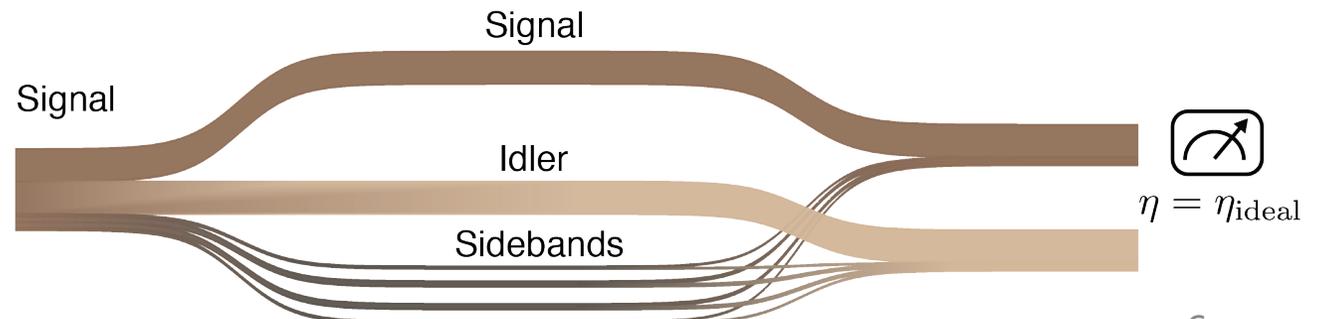
## a Ideal Amplifier: Two-Mode



## b Realistic Amplifier: Multi-Mode

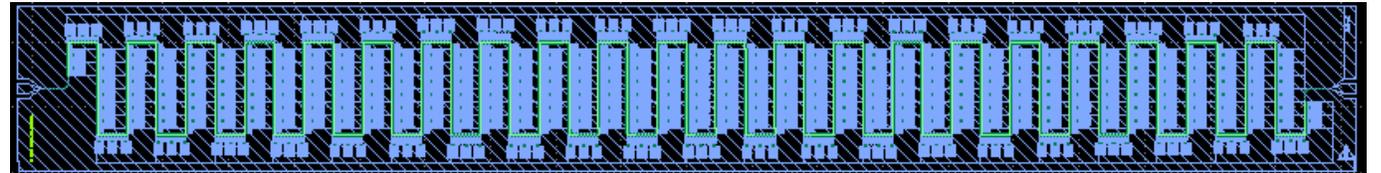
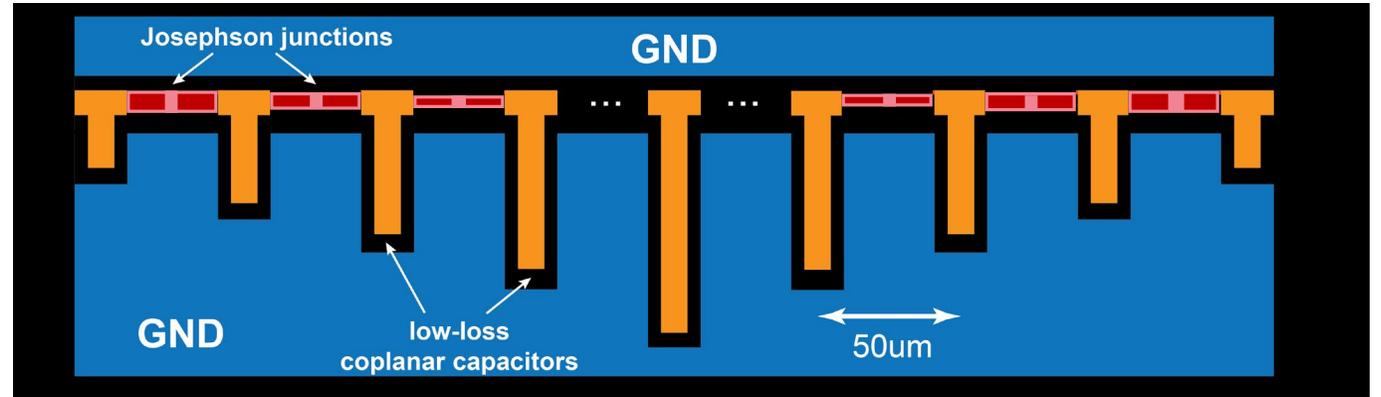


## c Floquet Mode Amplifier



# Floquet TWPA fabrication and design

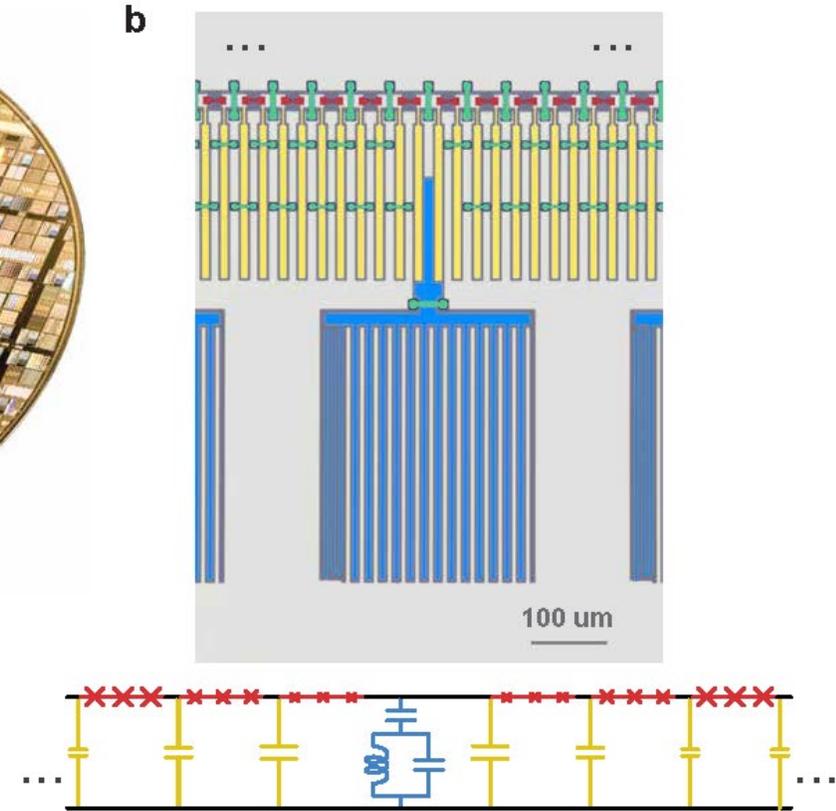
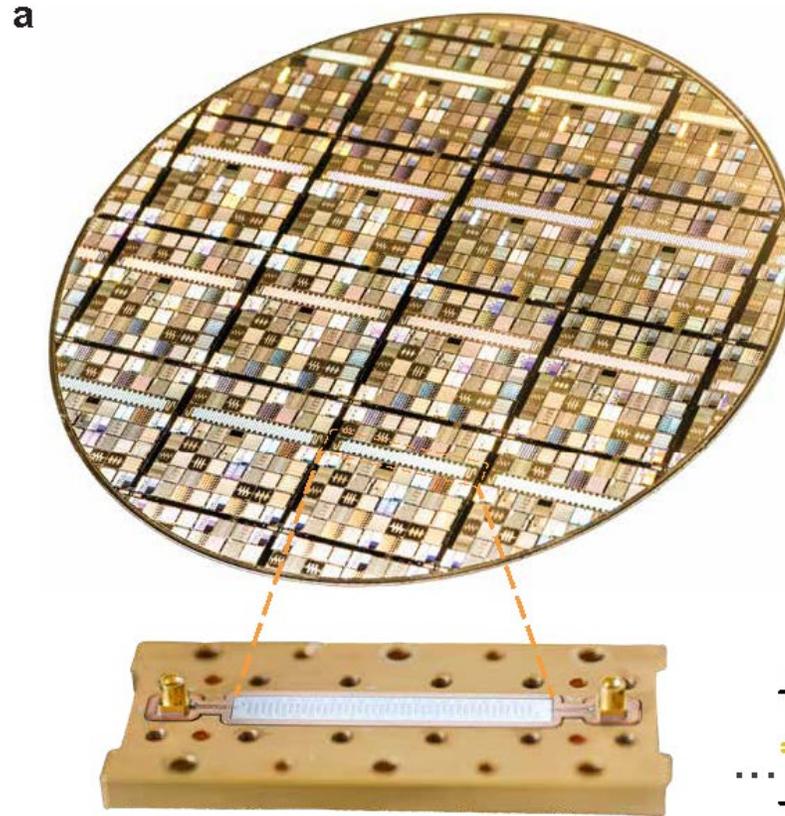
- Adiabatically varying junction and capacitor parameters over device length helps **improve mode-matching**
- **5 mm x 40 mm** chip size with meandered line of **3008 unit cells**. Lumped LC resonators are repeated every 8 unit cells to phase match the 4WM process.



Device fabricated at MIT Lincoln Laboratory by: Jeffery M. Knecht, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Katrina Sliwa, Kyle Serniak, Mollie Schwartz.

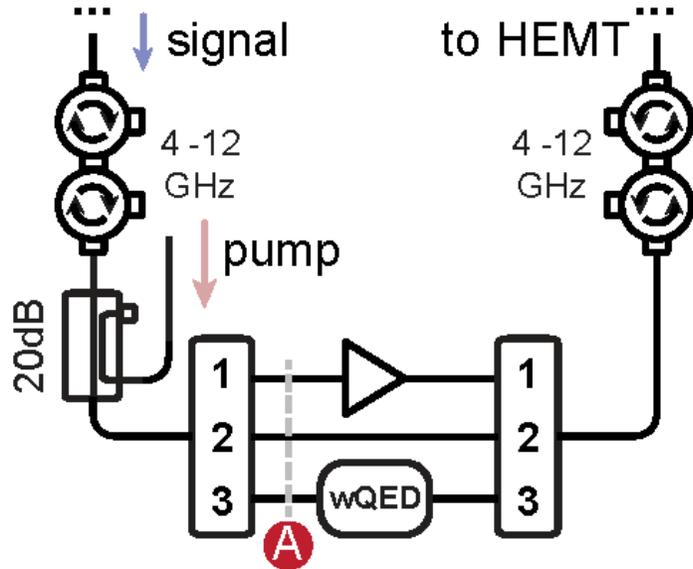
# Floquet TWPA fabrication and design

- **Superconducting-qubit compatible & integrable** aluminum Floquet TWPA
- Packaged in house with optimized impedance matching; modular and fast turnaround for testing.
- Distributed CPW high-Q capacitors for minimum insertion loss

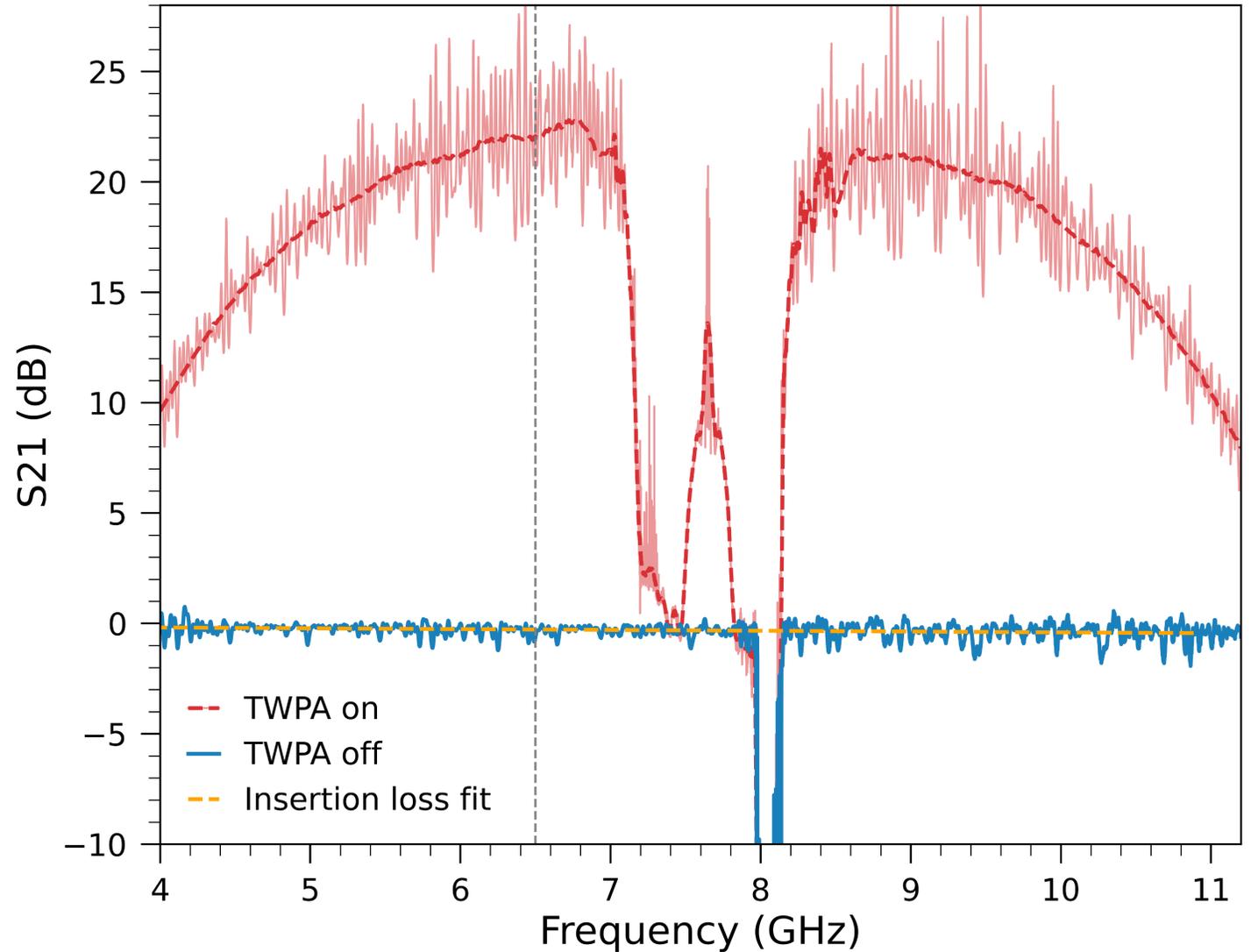




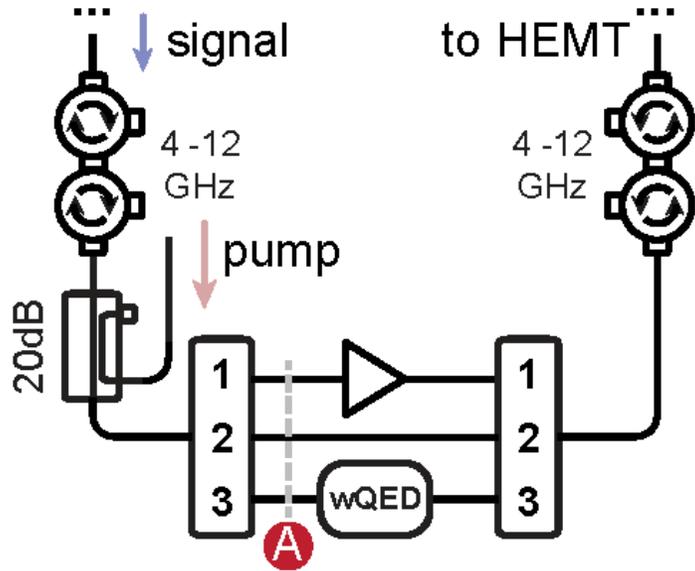
# High gain and low insertion loss



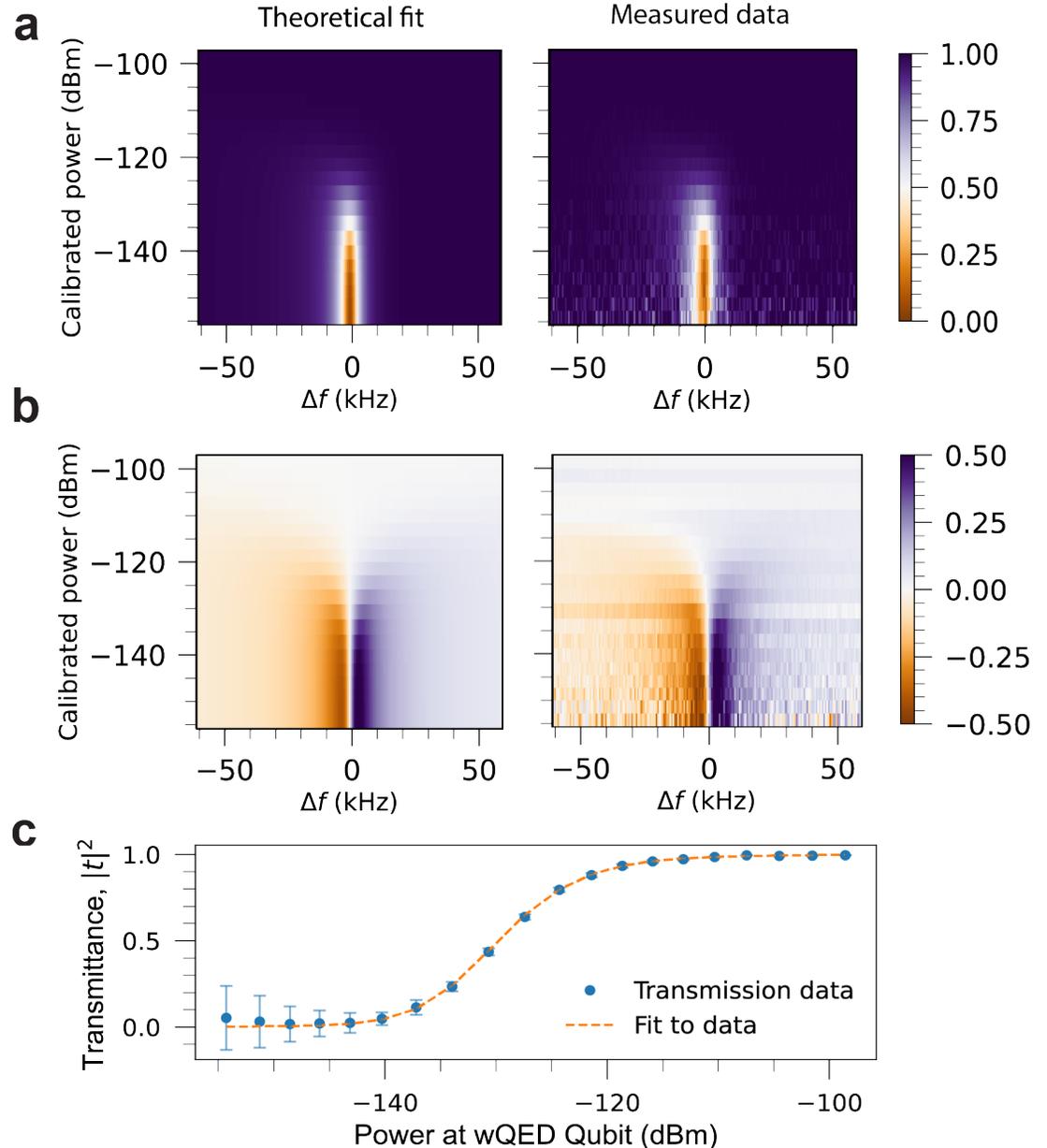
- **>20 dB gain from 5.5 to 7 GHz**
- **Average insertion loss < 0.5 dB**; from fit line, insertion loss at 6.5 GHz (dashed gray line) is **0.28 dB**
- Max ripples **~ 10 dB**, due to fabrication process variation and impedance mismatches



# Power calibration with waveguide QED device

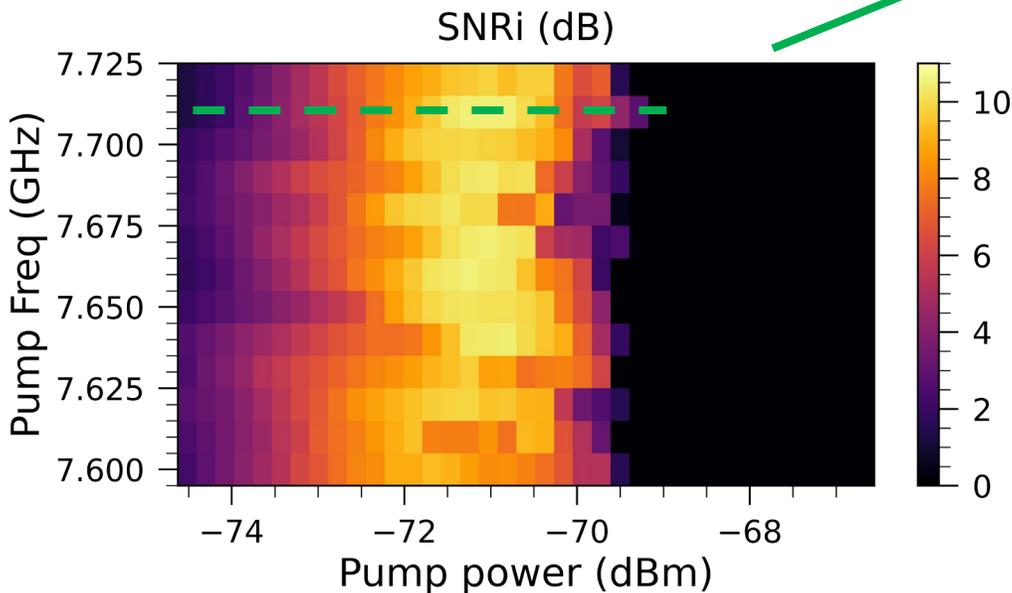
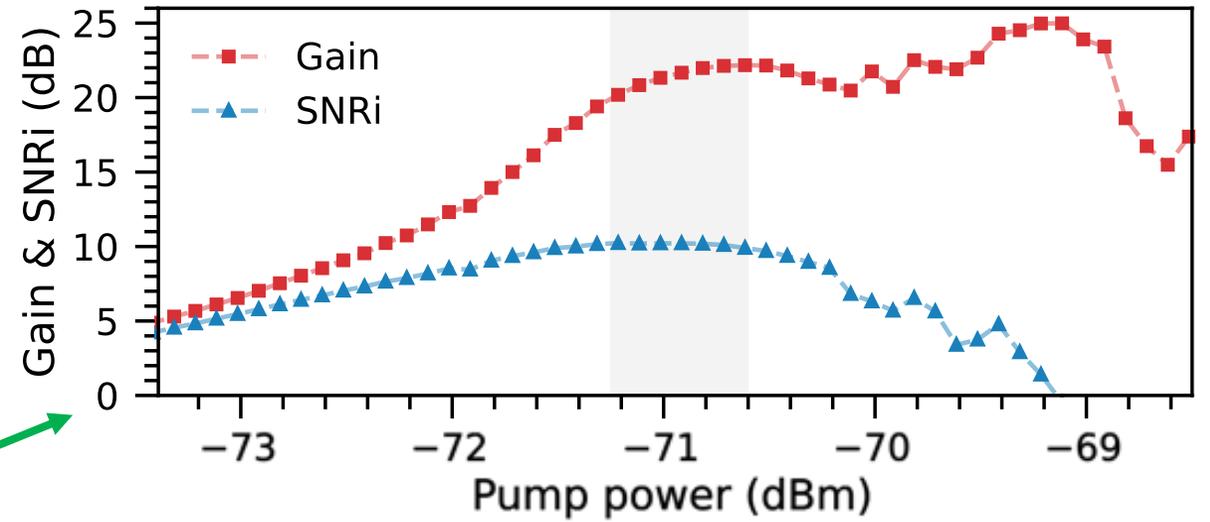
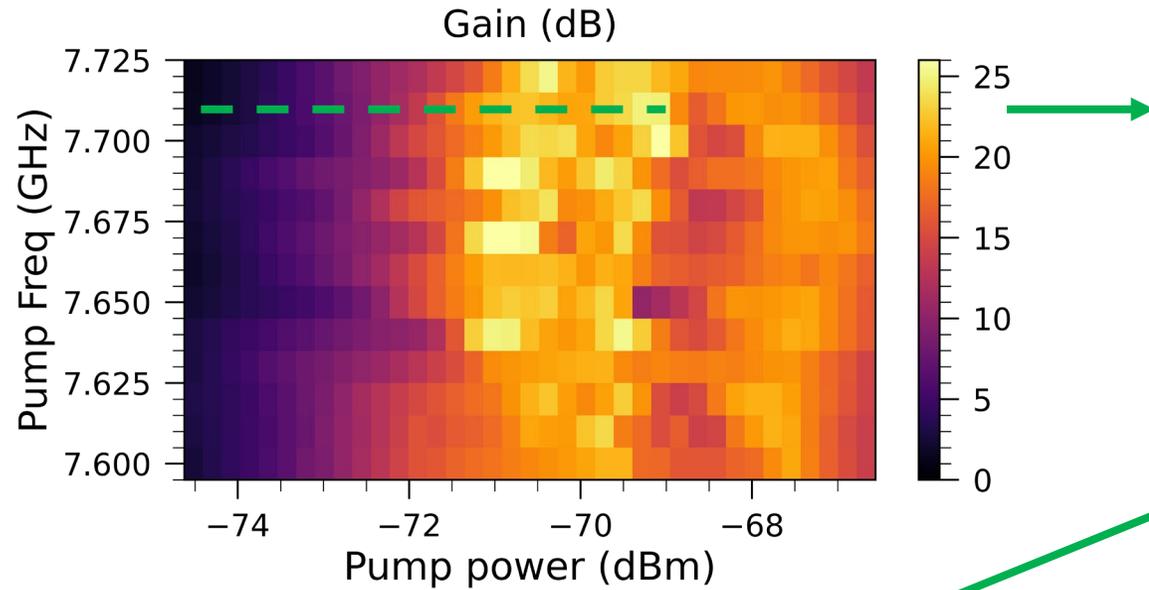


- The wQED device consists of a transmon qubit coupled to an open transmission line; it provides a power reference at **plane A**.
- Data taken at qubit sweet spot **6.59 GHz** shows the expected dip in transmission as we lower the input signal power





# Optimizing for pump frequency and power

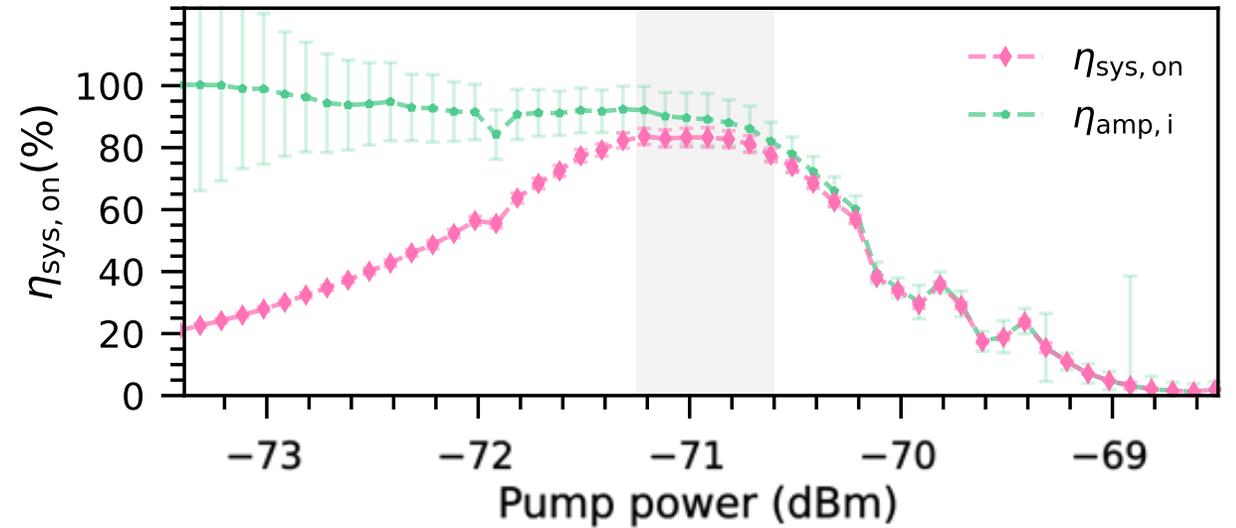
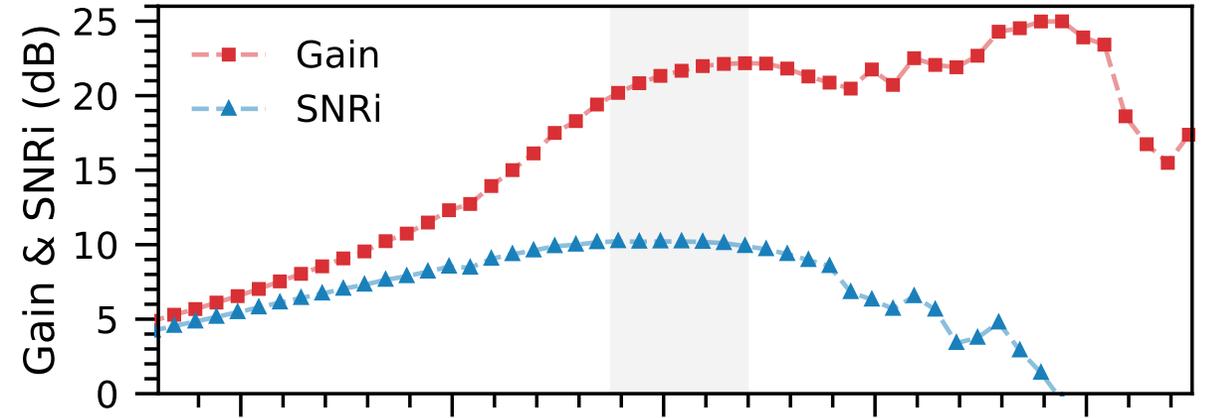
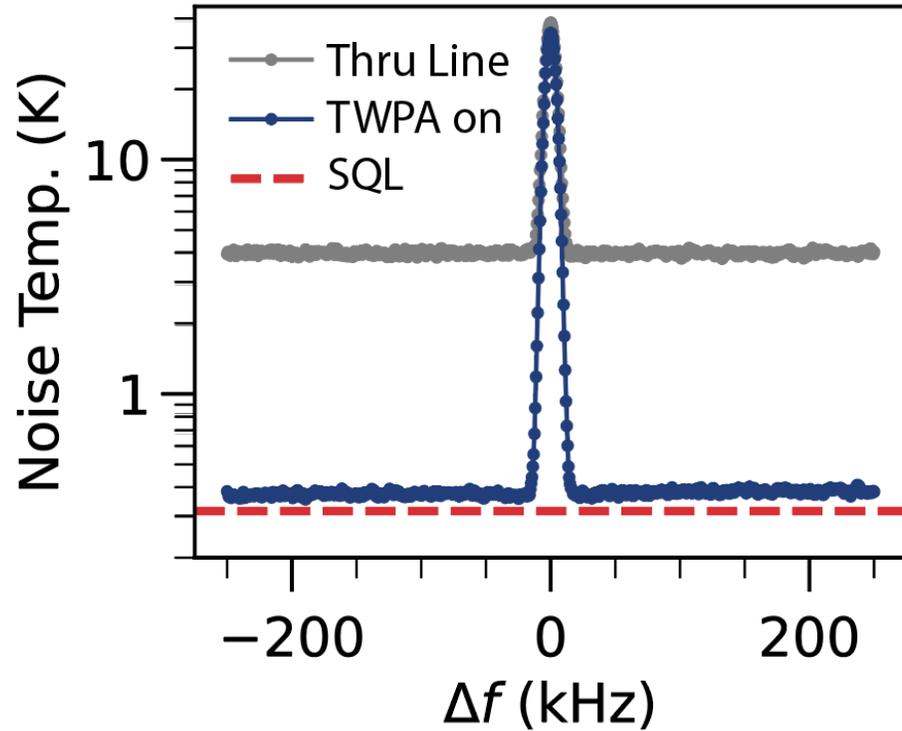


**Optimizing for: high gain and SNRi over a range of pump powers**

$$\text{SNRi} = \text{SNR}(\text{TWPA on}) - \text{SNR}(\text{thru})$$



# Record-high system and intrinsic QE

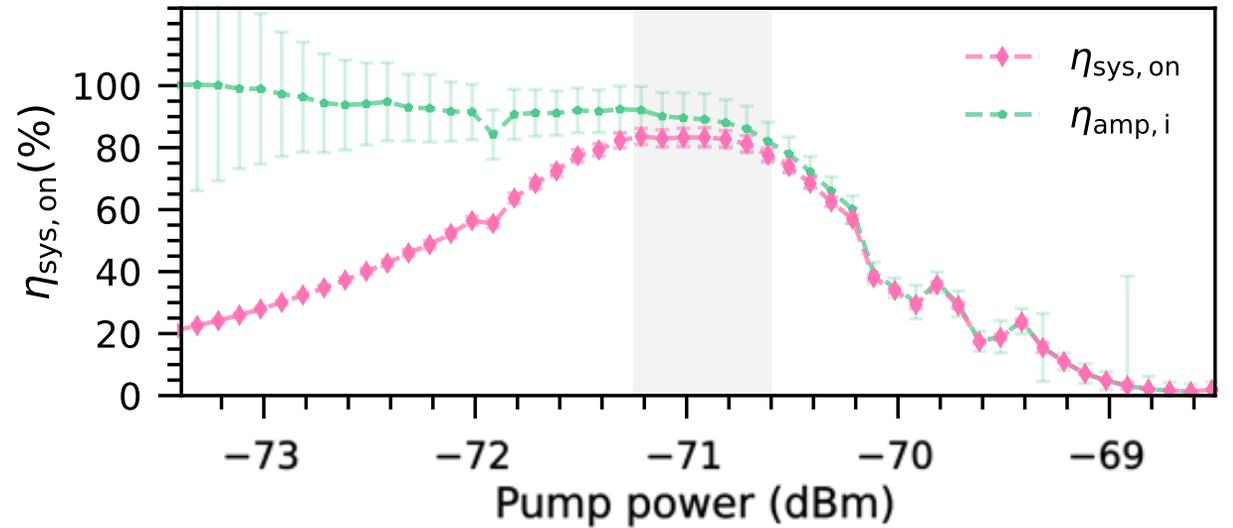
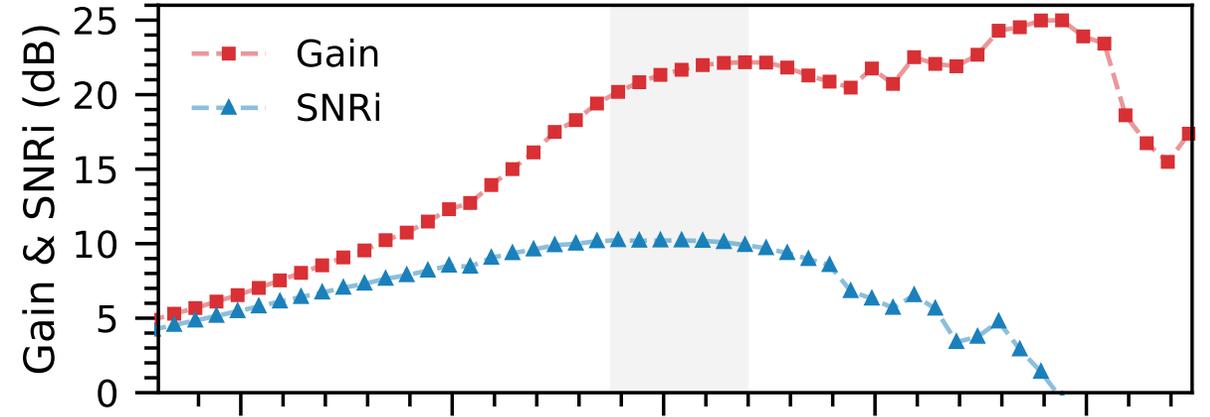
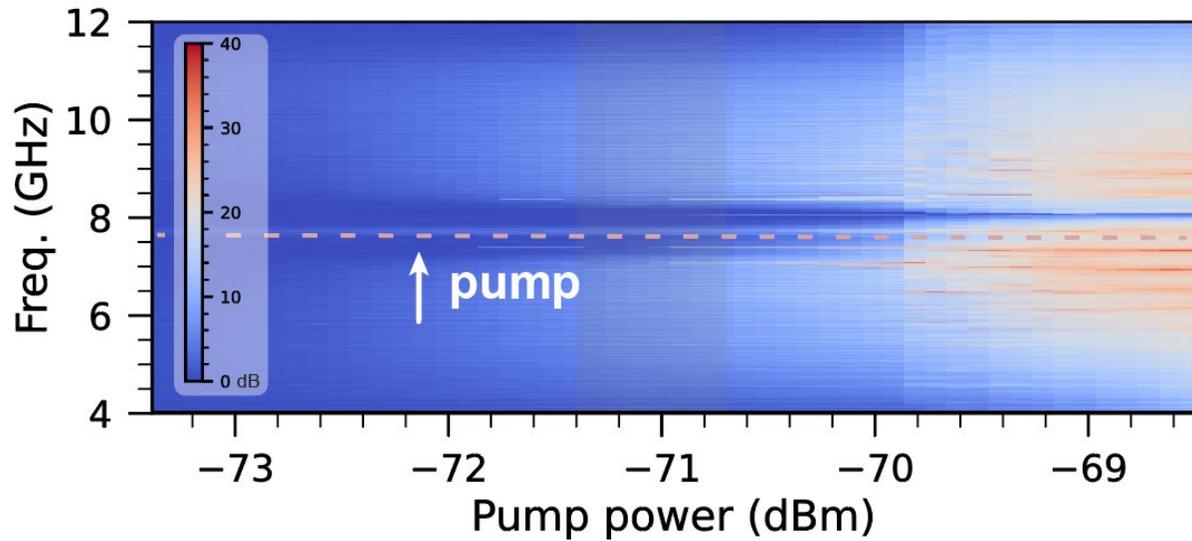


- $\text{NT}_{\text{sys,on}} = 0.38 \text{ K}$  and  $\text{NT}_{\text{sys,thru}} = 3.99 \text{ K}$
- Max  $\eta_{\text{sys,on}} = 83.6\% \pm 2.6\%$  (pink)
- Intrinsic efficiency is  $\eta_{\text{amp,i}} = 92.1\% \pm 7.6\%$  (green), among highest reported for JTWPAs.

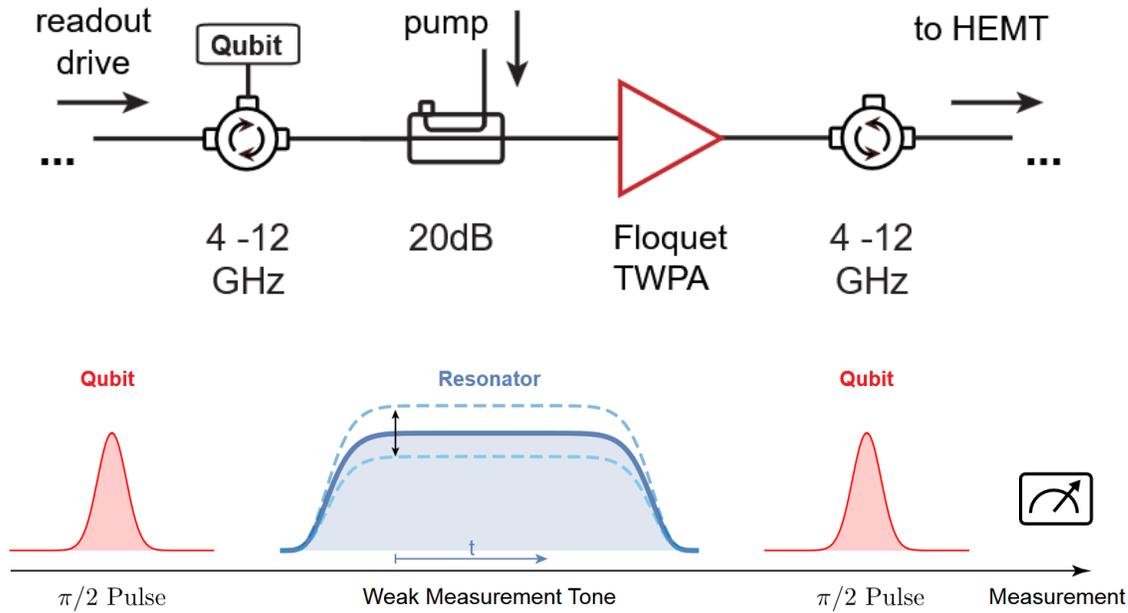


# Self-oscillations due to pump intermodulation

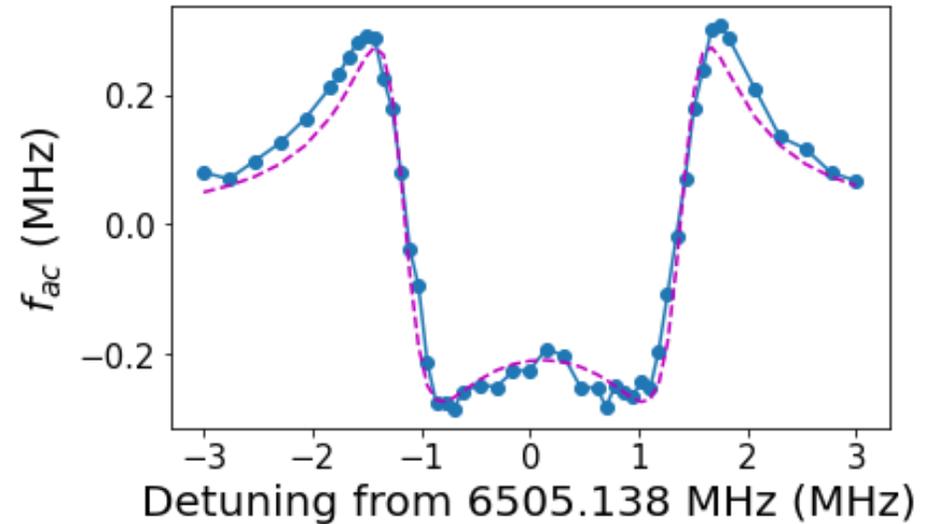
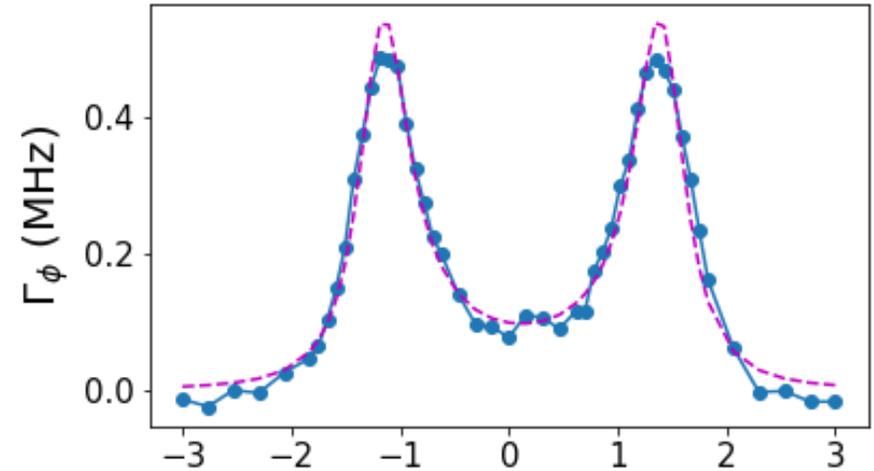
Initial onset of pump intermodulation byproducts appear in a normalized noise spectra scan at pump power around **-71 dBm**, which corresponds to the high QE region. The self-oscillatory region begins at approximately **-70 dBm**, which corresponds to swiftly dropping QE.



# System QE for qubit readout chain



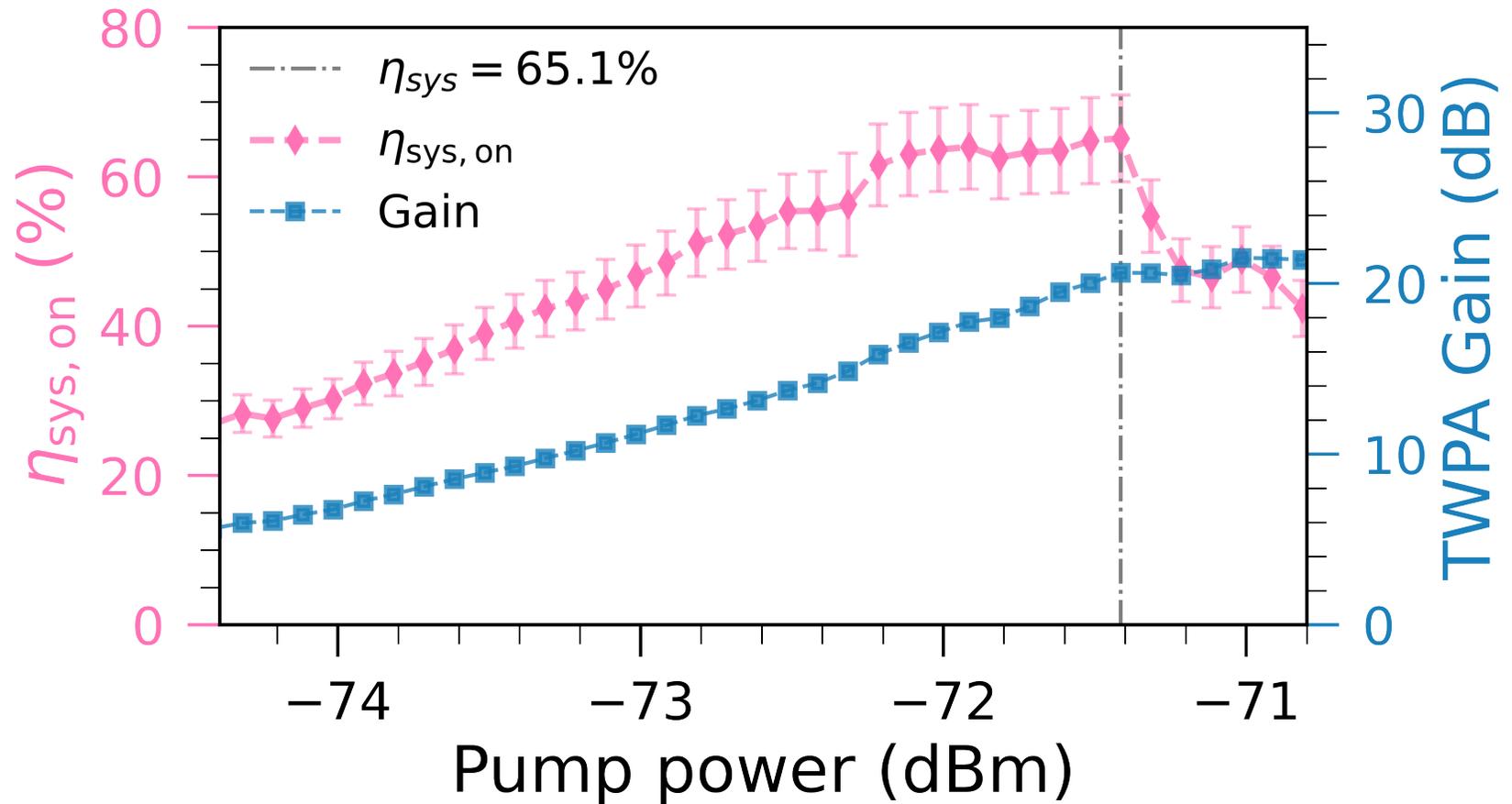
- Measurement-induced dephasing with a weak resonator drive occurs due to AC stark shift of qubit frequency; dephasing rate proportional to detuning between bare resonator and drive frequency, as well as drive power.
- Fit to the dephasing rate and AC stark shift gives us calibrated drive power at qubit **-142.49 dBm** at signal frequency **6.5 GHz**.





# System QE for qubit readout chain

- Performing the same pump optimization for the qubit readout chain, we obtain consistently high QE performance at gain **18 ~ 20 dB** (blue)
- In this configuration, the maximum system efficiency is  $\eta_{\text{sys, on}} = 65.1\% \pm 5.81\%$  (pink, gray dashed line) at **20.6 dB gain**





# QEs in recent literature: TWPAs for qubit readout chain

Reference	Amplifier	$\eta_{\text{sys, on}}$
This work (2025)	Floquet TWPA	65.1%
Ranadive et al. (2024)	TWPAI	~ 33%
Bartram et al. (2021)	TWPA	~ 25%
Malnou et al. (2021)	KI TWPA	~ 40%
Peronnin et al. (2020)	PC TWPA	11%
Planat et al. (2020)	TWPA	~ 33% - 58%
Andersen et al. (2020)	TWPA	15% - 30%
Andersen et al. (2019)	TWPA	24%
Heinsoo et al. (2018)	TWPA	42% - 52%
Bultink et al. (2018)	TWPA	16.5%
Macklin et al. (2015)	TWPA	49%
White et. al (2015)	TWPA	~ 36%



# QEs in recent literature: other phase-preserving amplifiers for qubit/cavity readout

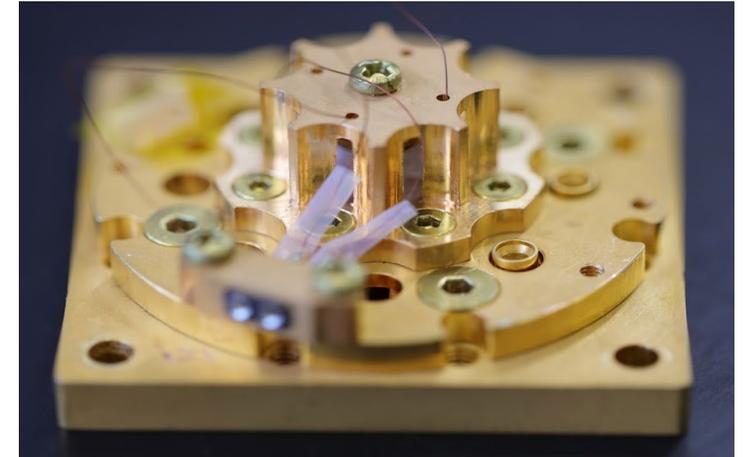
Reference	Amplifier	$\eta_{\text{sys, on}}$
This work (2025)	Floquet TWPA	65.1%
Bothara et al. (2025)	JPA	57%
Uchaikin et al. (2024)	JPA	~ 59%
Kaufman et al. (2024)	JPA	62%
Kaufman et al. (2023)	JPA	52%
Kutlu et al. (2021)	JPA	~ 59%

Floquet TWPA achieves balanced performance metrics and overcomes bandwidth-noise tradeoff

# Conclusions

- First demonstration of Floquet JTWPA featuring **>20 dB gain** from **5.5 to 7 GHz**, averaging **< 0.5 dB insertion loss over 4-12 GHz** range; among best reported for JTWPAs
- Capable of reaching **92.1% ± 7.6%** intrinsic amplifier efficiency and **83.6% ± 2.6%** system efficiency overall in direct characterization setup. To our knowledge, this is the highest reported intrinsic QE for TWPAs.
- In qubit readout chain, Floquet TWPA provides full system efficiency of **65.1% ± 5.81%** which is the highest currently reported value for phase-preserving amplifier qubit readout chains in general
- **Qubit-compatible fabrication and packaging** process leads to future work on monolithic integration of qubit, directional coupler, and Floquet TWPA

8-port qubit package



# Thank you! Questions?

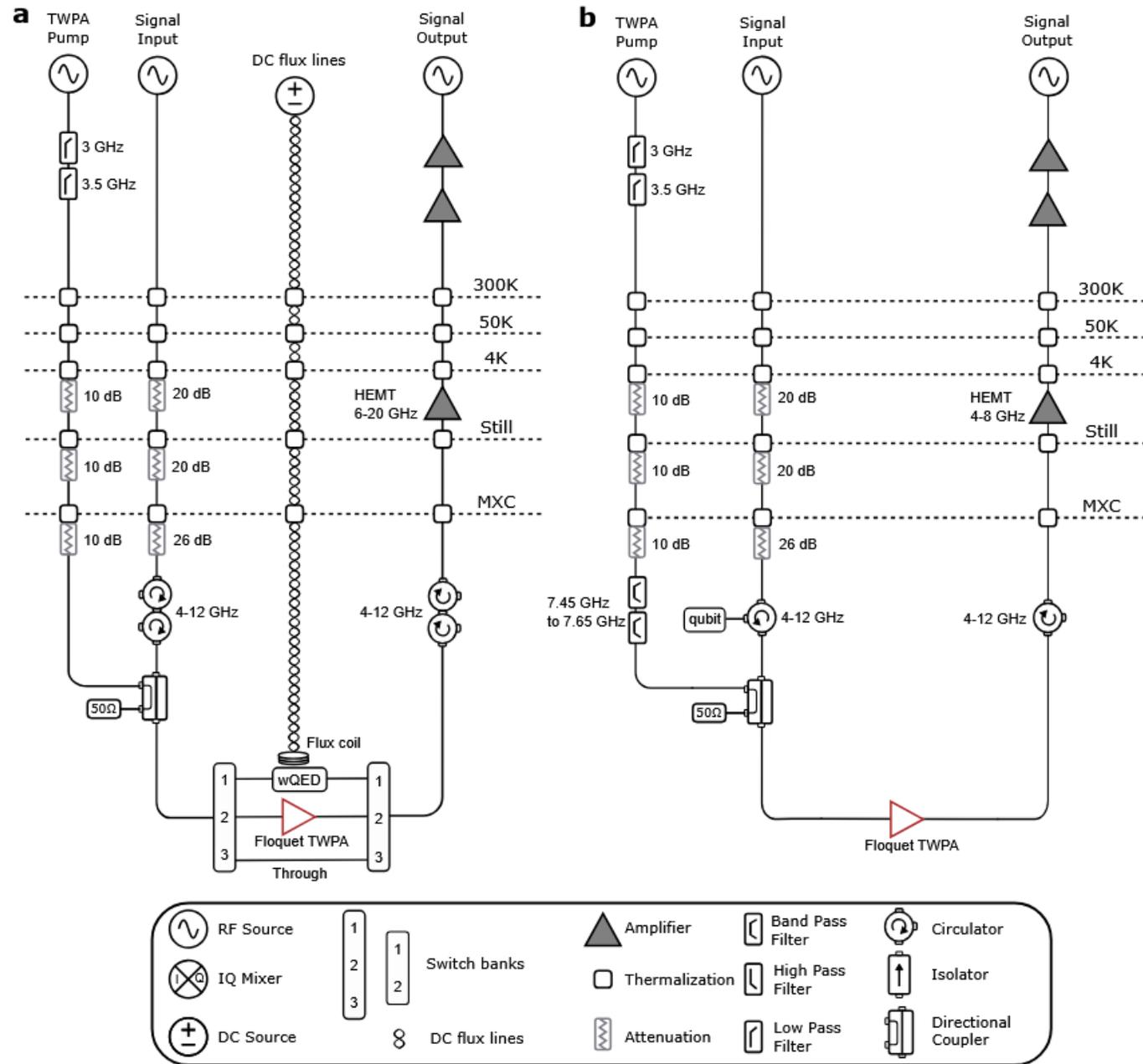


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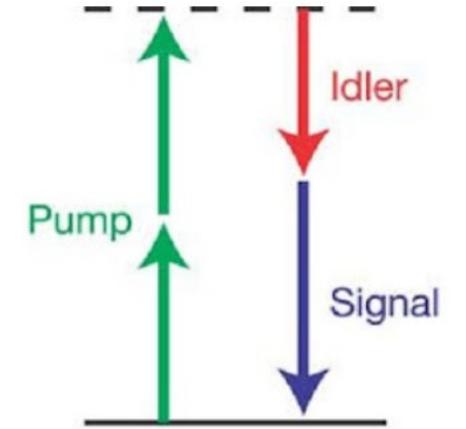
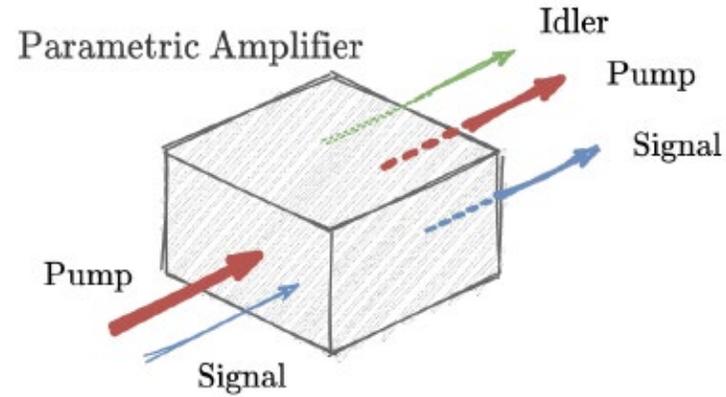
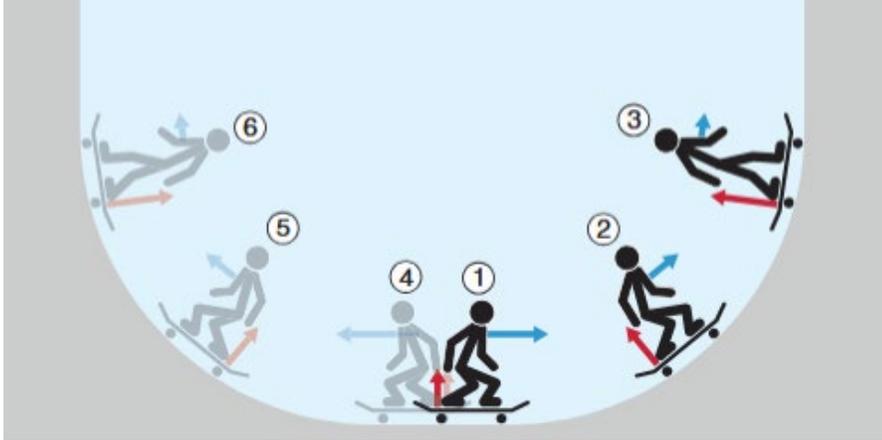
Thank you to the Quantum Coherent Electronics Group, our MIT Lincoln Laboratory collaborators, and Dr. Nagle of the MIT Rodgers Laboratory!



# Full fridge diagram



# Parametric amplification and examples



**Four-wave mixing**

- **Parametric oscillators** are driven by varying parameters of the system at a certain frequency
- **Parametric amplification** utilizes this to achieve **low-noise, high-gain** amplification (example: optical parametric amplifiers, etc.)

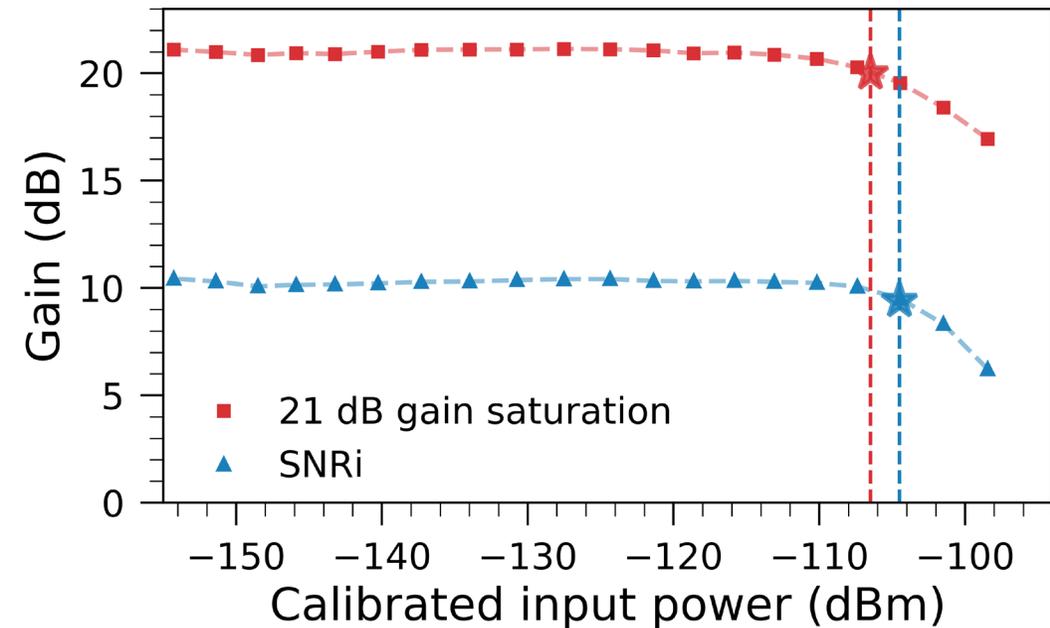


# Dynamic range

- The 1-dB gain compression point at **-106.5 dBm, 21 dB parametric gain** is well within typical JTWPA values of -95 to -110 dBm

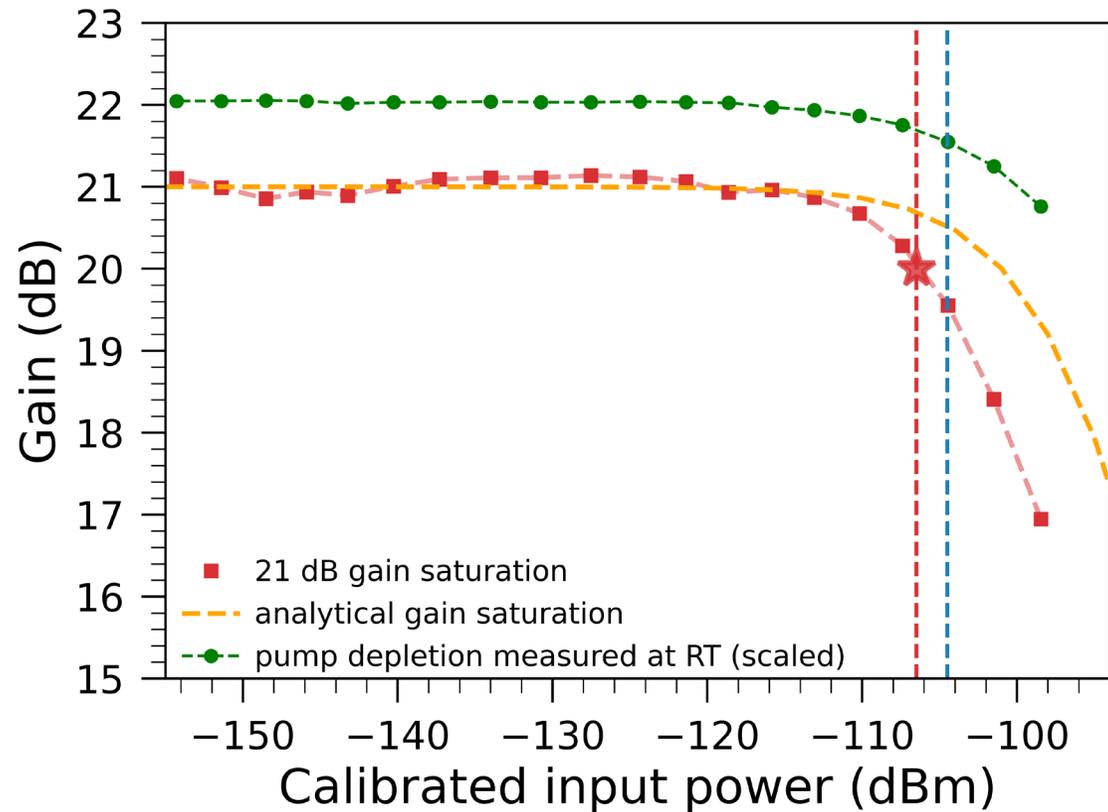
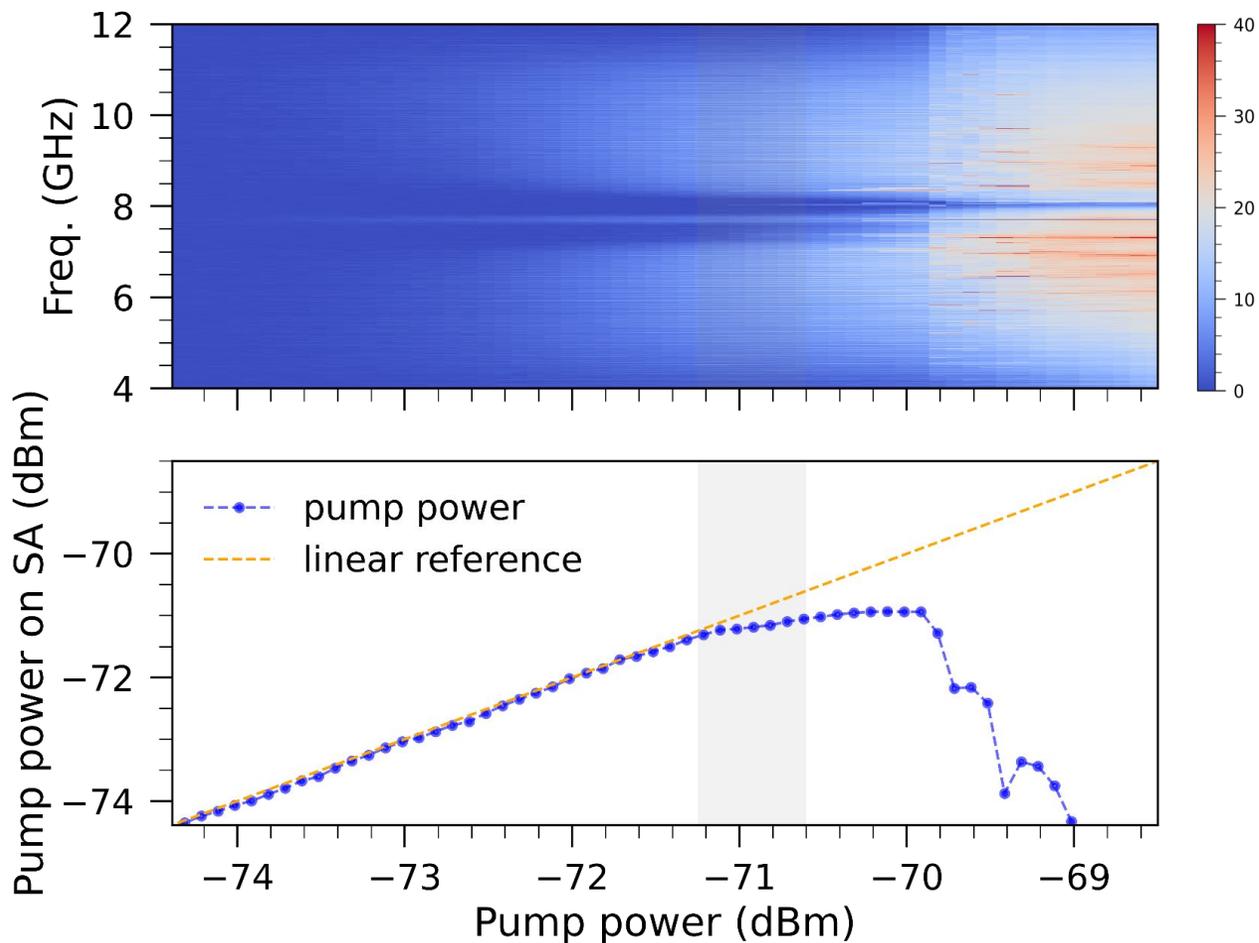
**SNRi = SNR(TWPA on) - SNR(thru)**

- SNRi 1-dB compression point at -104 dBm occurs **2.5 dB above** the 21-dB gain compression point, unlike that of uniform JTWPAs)





# Pump depletion/saturation

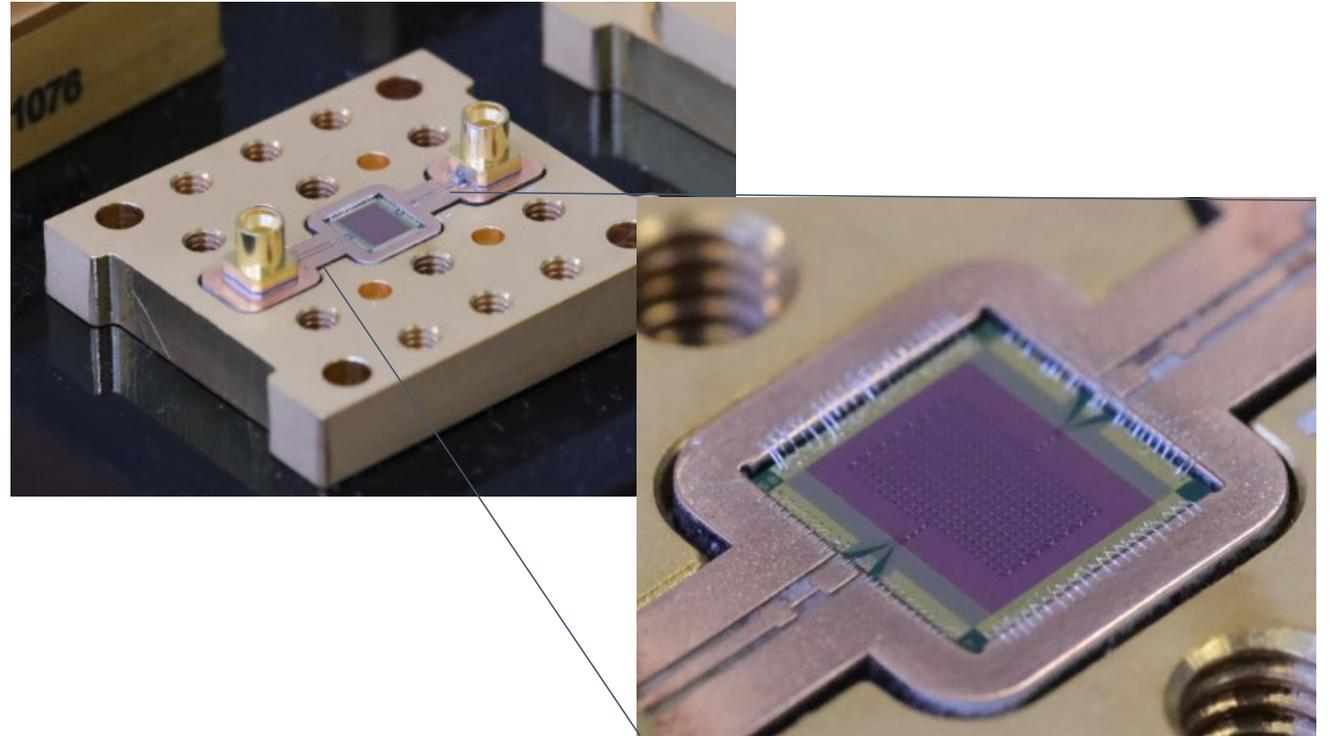


Keeping pump config constant & increasing signal power has the effect of depleting pump power; similar shape to analytical curve.

# Improved JTWPA package

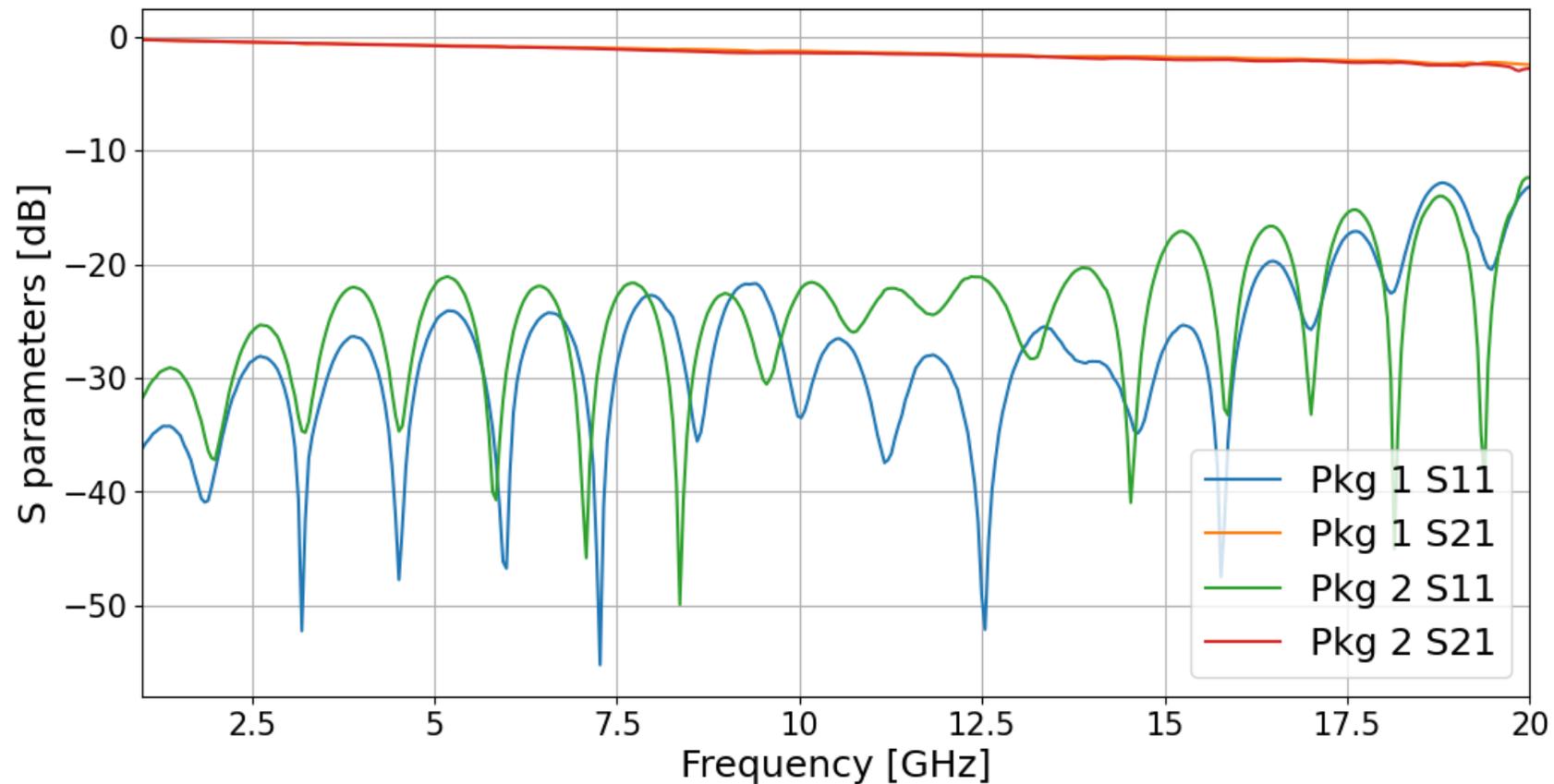
## Design goals:

1. Modularity
2. Custom chip and via placement
3. Compensation structures to improve wirebond impedance matching



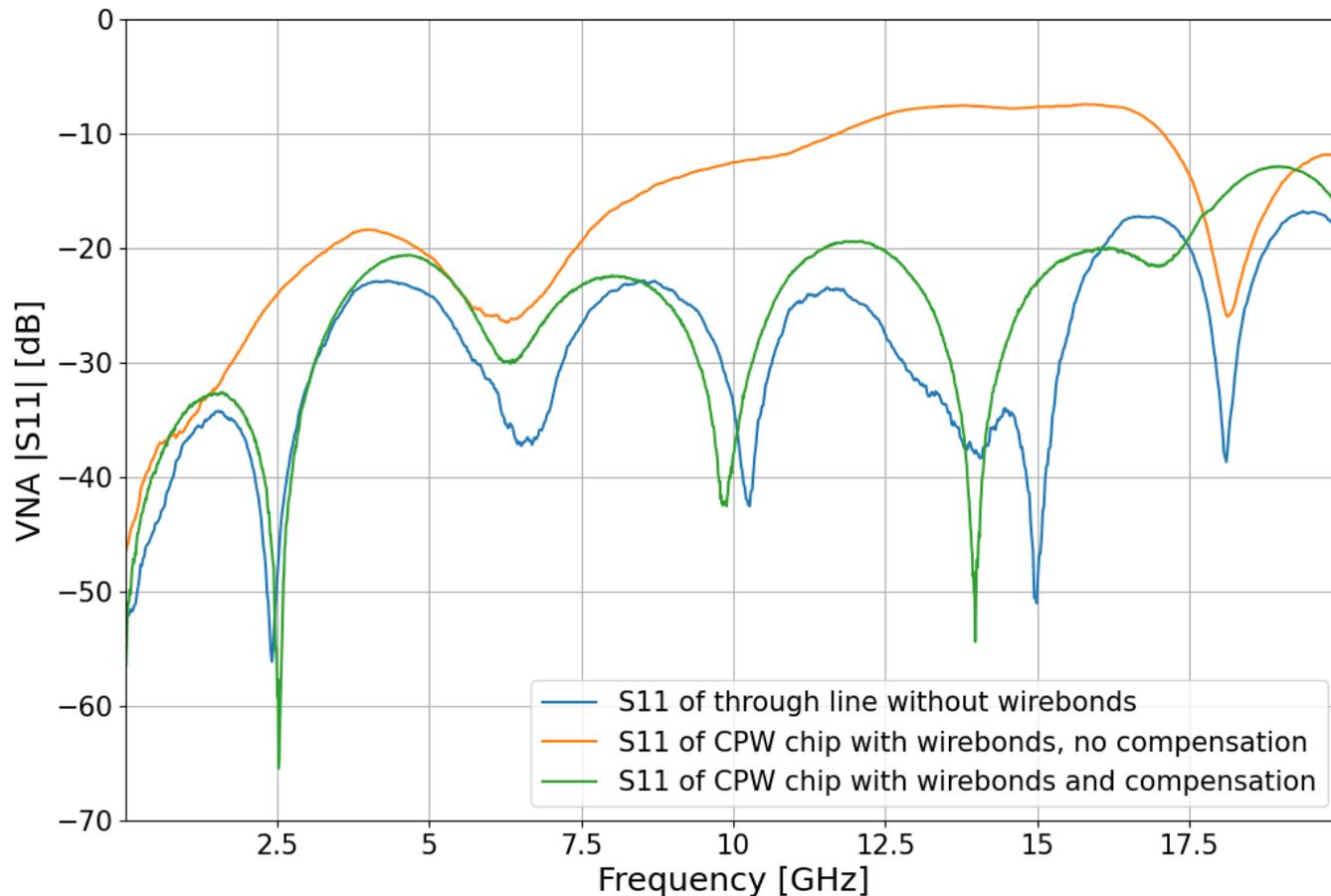
# Floquet TWPA packaging

In-house packaging used for Floquet TWPA features  $< -20$  dB reflections up to 15 GHz

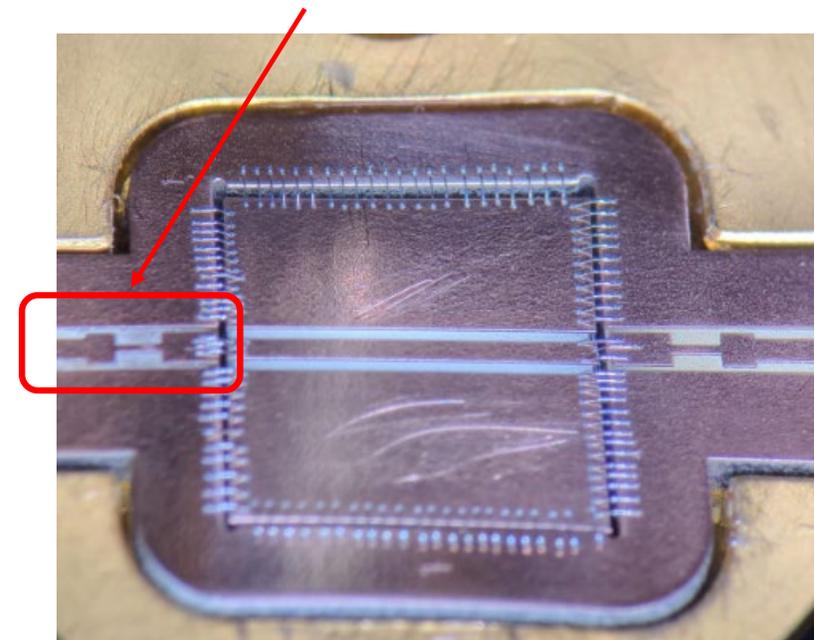


# Compensation structures for impedance matching

- Compensate for connector and wirebond parasitics.
- Room temperature measurement around -20 dB return loss up to 18 GHz.



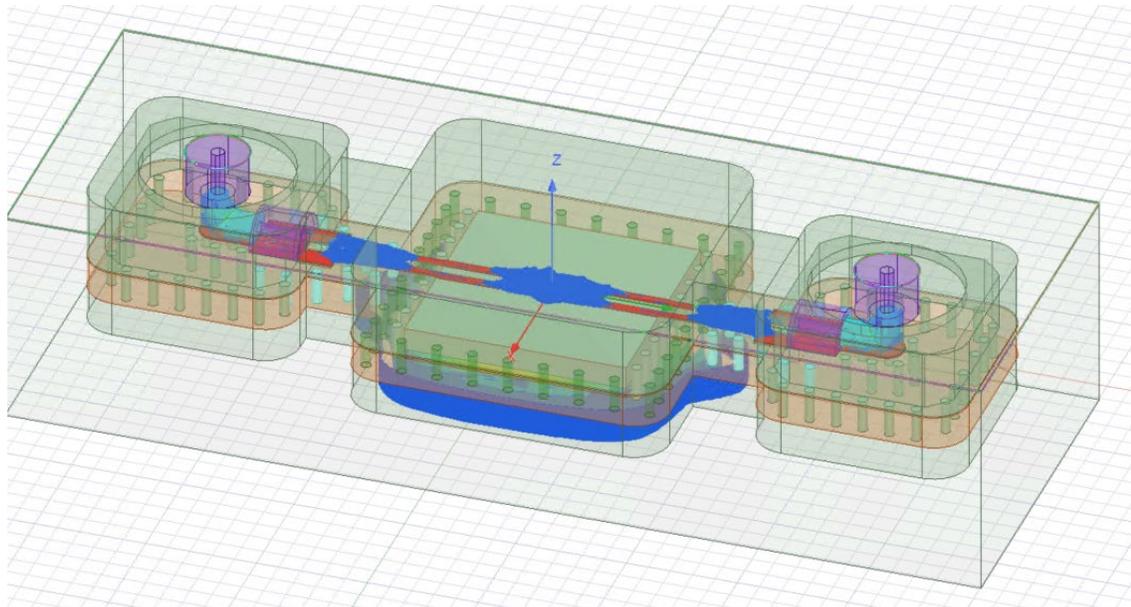
**Chebyshev lowpass filter with wirebond as last inductor**



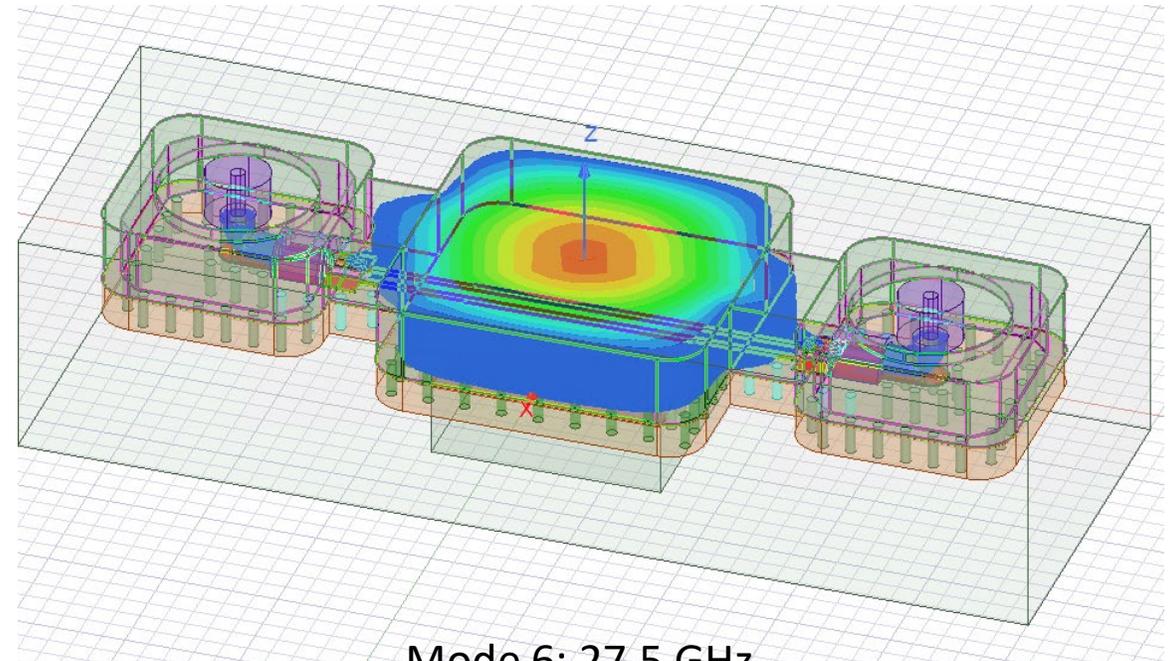


# Package eigenmode simulations

Solved Modes		Export	
	Eigenmode	Frequency (GHz)	Q
	Mode 1	16.1547 +j 0.00954693	846.068
	Mode 2	19.9219 +j 0.0135067	737.482
	Mode 3	22.0982 +j 0.00369021	2994.17
	Mode 4	23.8898 +j 0.0138072	865.119
	Mode 5	25.2706 +j 0.00202252	6247.30
	Mode 6	27.4995 +j 0.0165650	830.049



Mode 5: 25.3 GHz

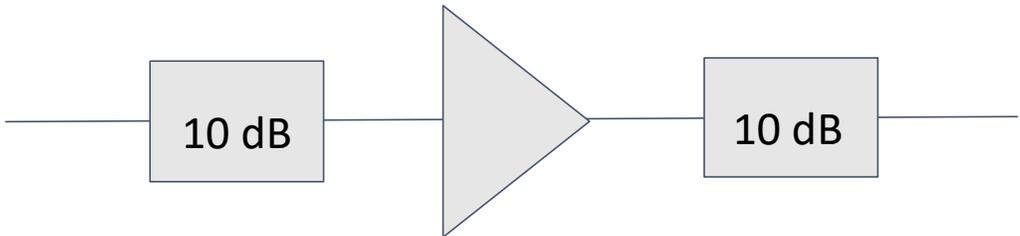


Mode 6: 27.5 GHz

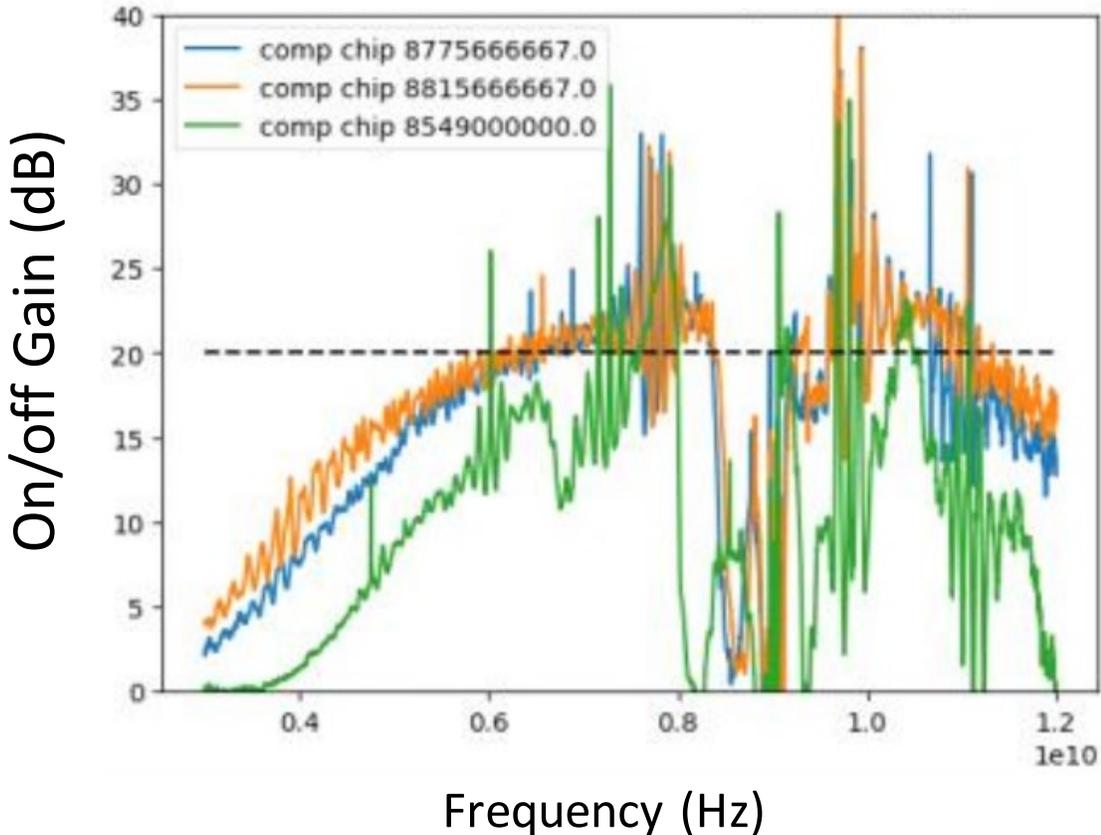
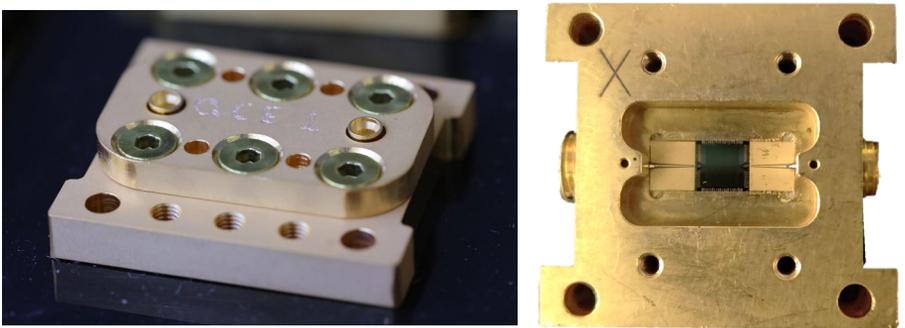


# Cryo measurement: impact of packaging improvements

TWPAs sandwiched with 10 dB attenuators to reduce impact of environmental impedance and isolate package mismatch impact

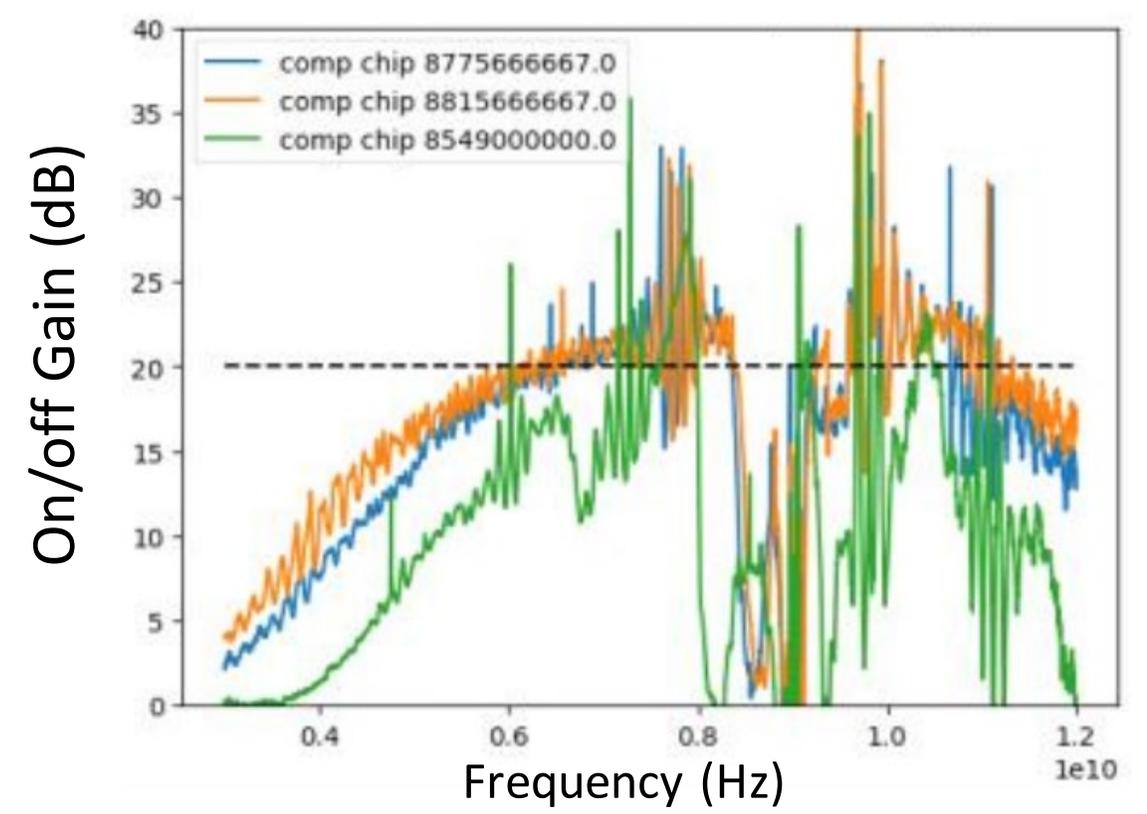
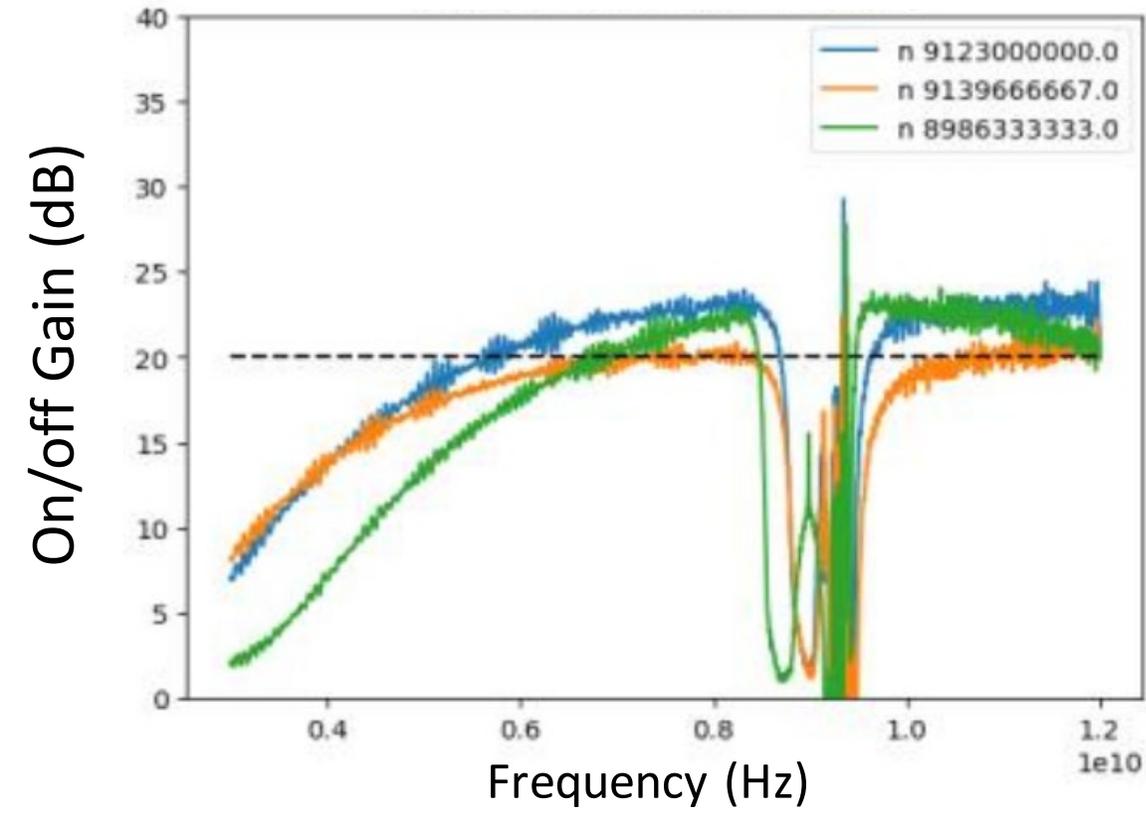


TWPA in new package or old package

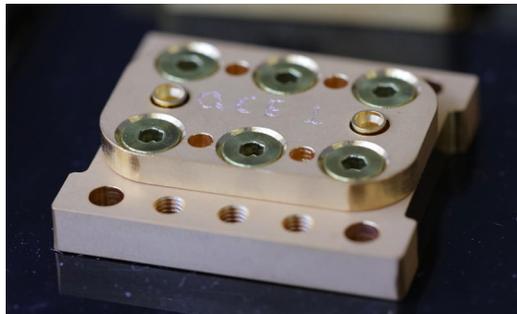


Data provided by:  
MIT Lincoln Laboratory  
(Katrina Sliwa, Arjan Sevi)

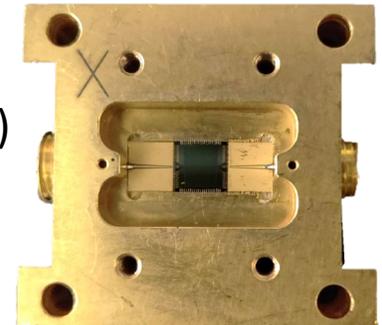
# Cryo measurement: impact of packaging improvements



New package



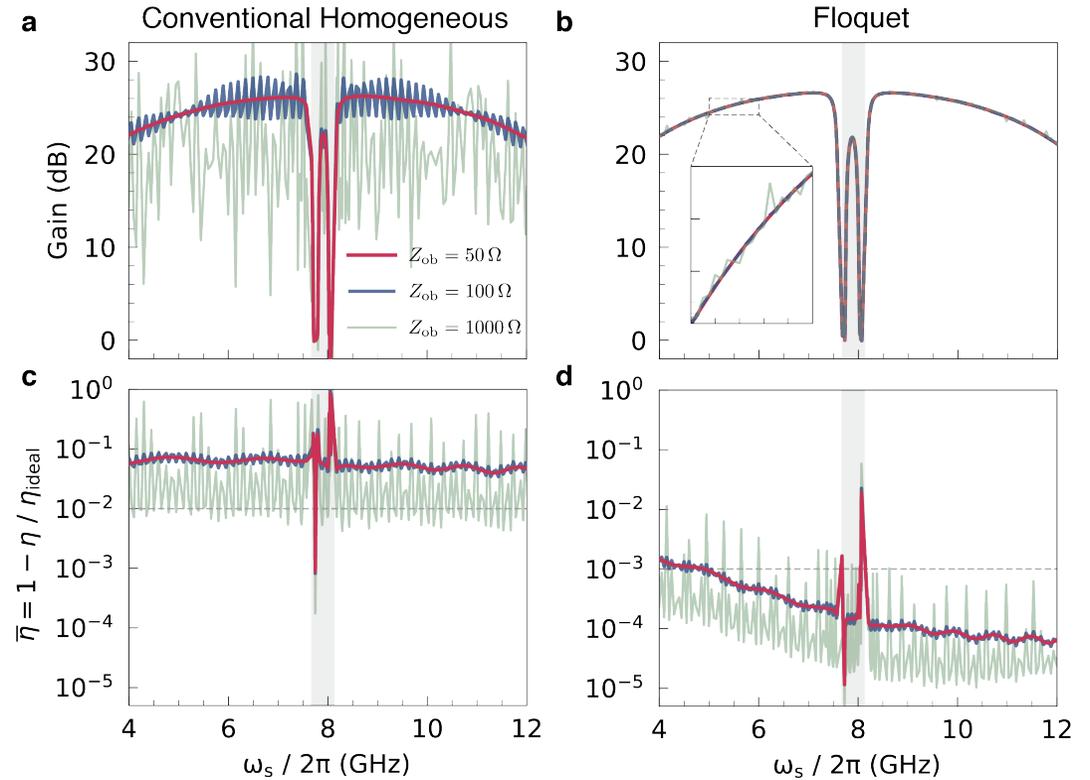
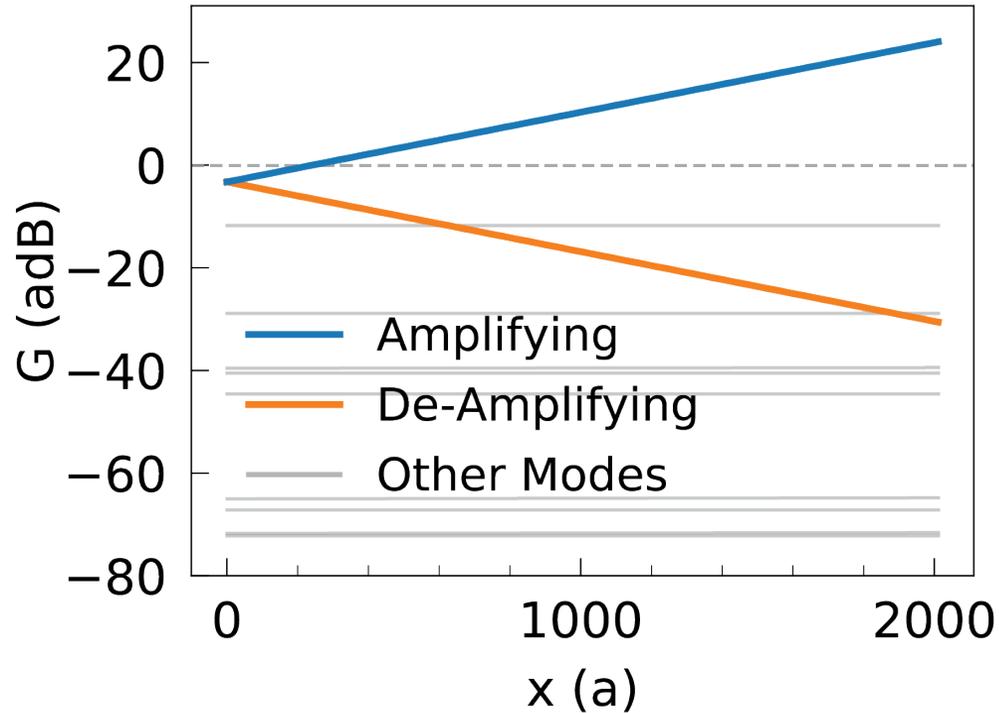
Old package (comparable chip)





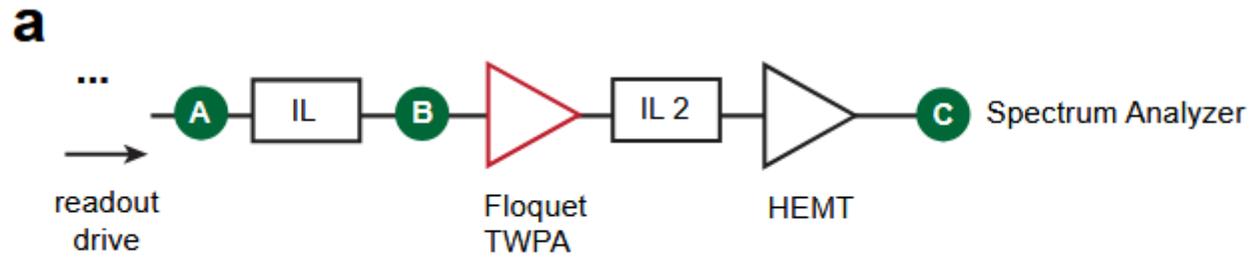
# Floquet theory inspires JTWPA design

Gain Dynamics (Floquet Basis)



- Floquet modes: solutions of a periodically driven system expressed as  $\hat{Q}_\alpha(x) = e^{r_\alpha x} \hat{\alpha}(x)$  with space-periodic function  $\hat{\alpha}(x)$  and a dynamic factor  $e^{r_\alpha x}$
- **Floquet TWPA**s are robust to out-of-band impedance mismatch due to sideband generation suppression

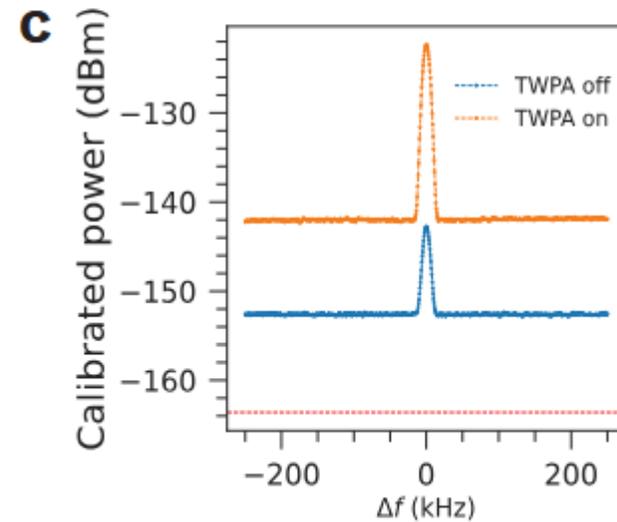
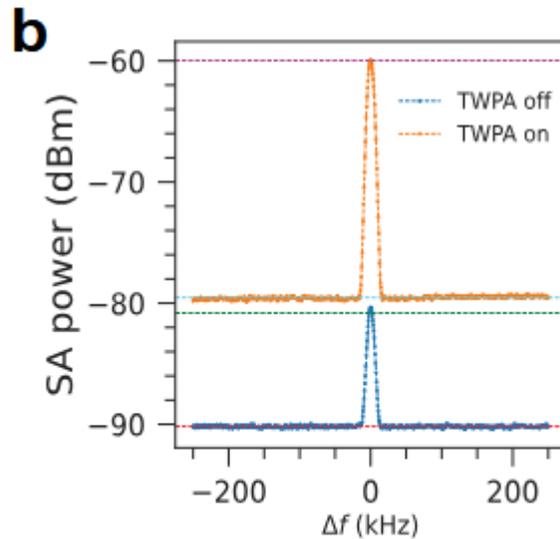
# Calculation of quantum efficiency: system



$$G_{\text{sys,on}} = S_{C,\text{sys,on}}/S_{A,\text{sys,on}}$$

$$G_{\text{sys,off}} = S_{C,\text{sys,off}}/S_{A,\text{sys,off}}$$

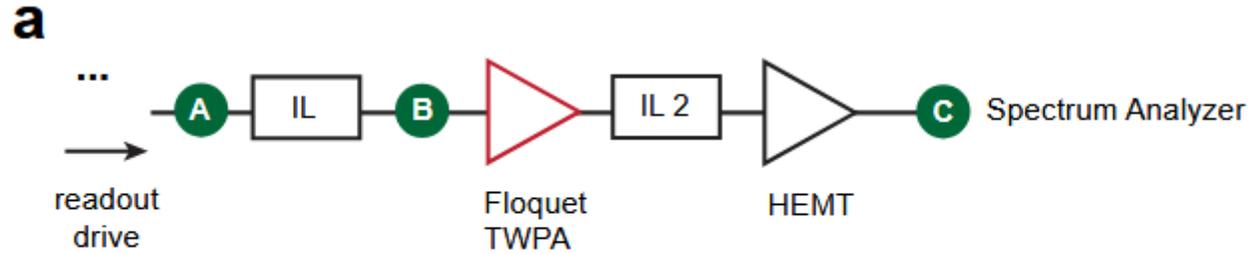
$$G_{\text{amp,i}} = S_{C,\text{sys,on}}/S_{C,\text{sys,off}}.$$
(D1)



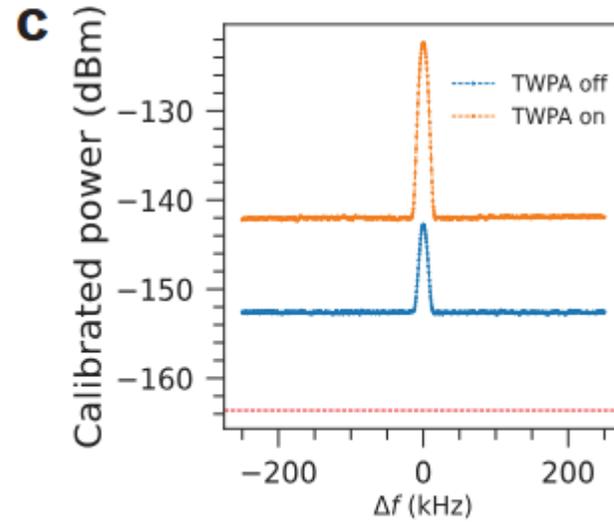
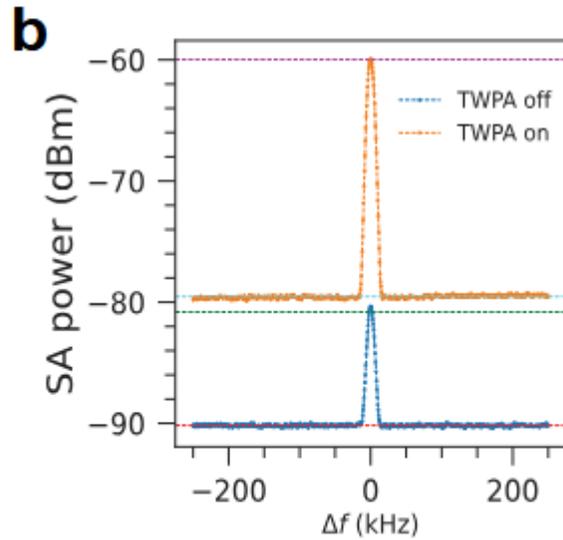
$$T_{\text{sys,on(off)}} = \frac{N_{C,\text{sys,on(off)}}/G_{\text{sys,on(off)}}}{k_B B}.$$
(D2)

$$\eta_{\text{sys,on(off)}} = \frac{\hbar\omega}{k_B T_{\text{sys,on(off)}}}$$
(D3)

# Calculation of quantum efficiency: intrinsic



$$n_{\text{sys,on(off)}} = \frac{k_B T_{\text{sys,on(off)}}}{\hbar\omega} = 1/\eta_{\text{sys,on(off)}}, \quad (\text{D4})$$



$$A_{\text{amp},i} = (n_{\text{sys,on}} - 1/2) - \left( \frac{n_{\text{sys,off}} - 1/2}{G_{\text{amp},i}} \right), \quad (\text{D5})$$

$$\begin{aligned} \tilde{\eta}_{\text{amp},i} &= (1 + 2A_{\text{amp},i})^{-1} / \eta_{\text{ideal}}(G_{\text{amp},i}) \\ &= \frac{2 - 1/G_{\text{amp},i}}{1 + 2A_{\text{amp},i}} \\ &= \left( \frac{2}{\eta_{\text{sys,on}}} - \frac{2}{G\eta_{\text{sys,off}}} + \frac{1}{G} \right)^{-1} / \eta_{\text{ideal}}(G) \end{aligned} \quad (\text{D6})$$



## Fitting method: additional information

Calibration continued:

Perform global fit to calibrated 2D transmission data (power step size determined by prior Vaunix variable attenuator calibration)

$$t = 1 - \frac{\Gamma_1}{2\Gamma_2} \frac{1 - \frac{i\Delta}{\Gamma_2}}{1 + \left(\frac{\Delta}{\Gamma_2}\right)^2 + \frac{\Omega^2}{\Gamma_1\Gamma_2}}.$$

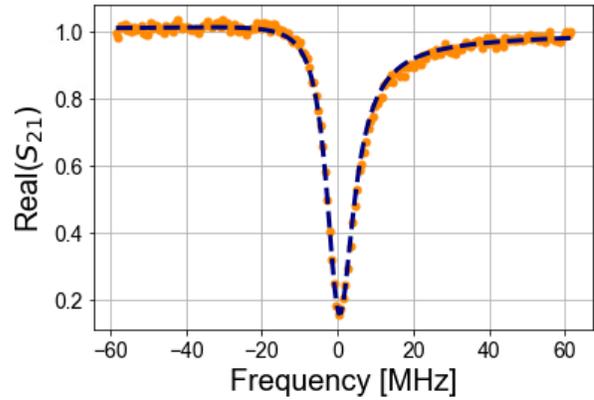
Obtain absolute power at qubit for the desired power steps

$$P = \pi\hbar\omega_i\Omega^2/2\Gamma_1$$

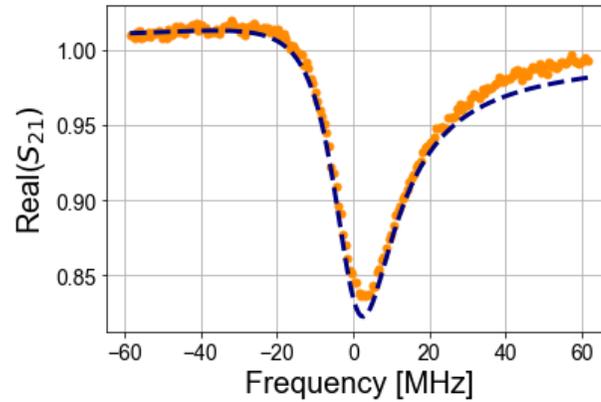
Choose the power with 1) least % error in transmittance, and 2) far below P1dB of TWPA and similar to qubit output signal power, usually around -145 dBm. Use this to obtain “calibration factor” for converting nominal VNA/Windfreak input power to absolute power at the qubit.



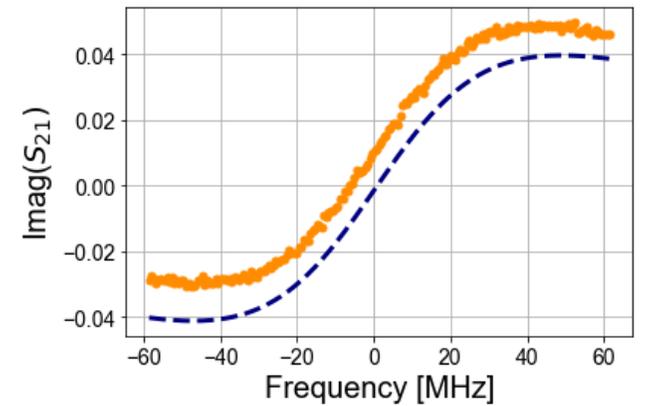
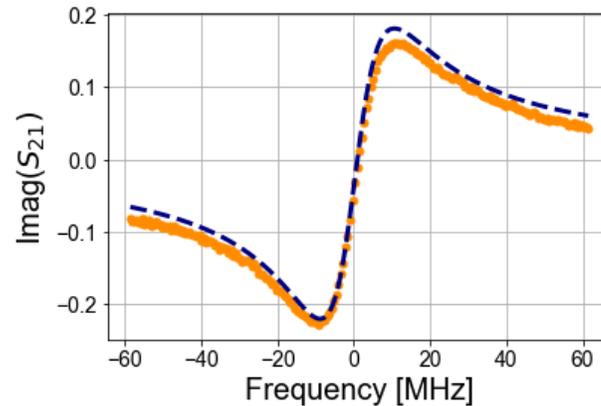
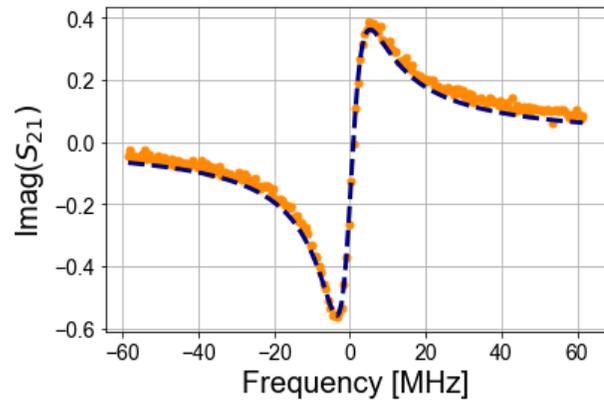
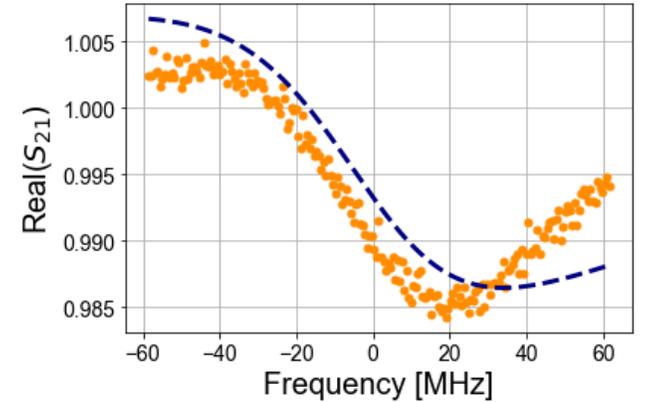
# wQED device: additional fit quality plots



• Data  
- - - Fit

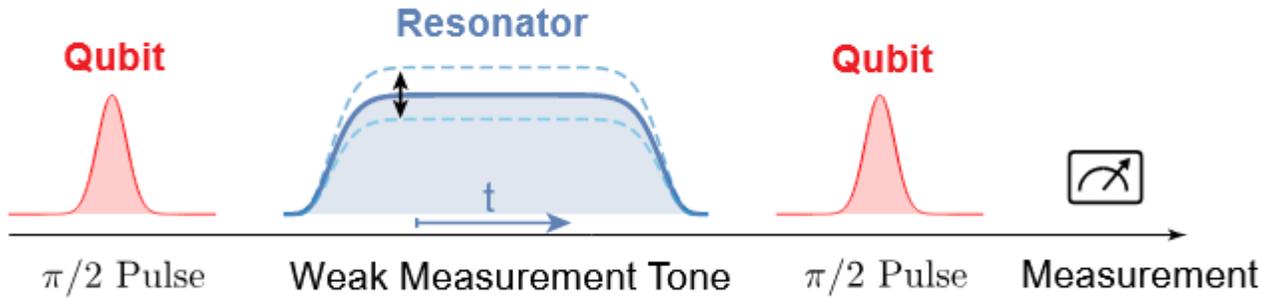


• Data  
- - - Fit



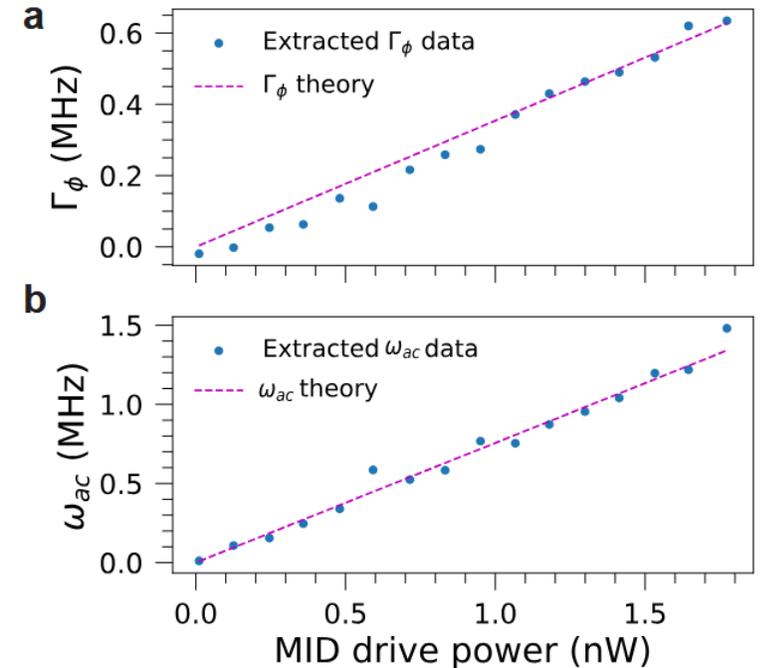
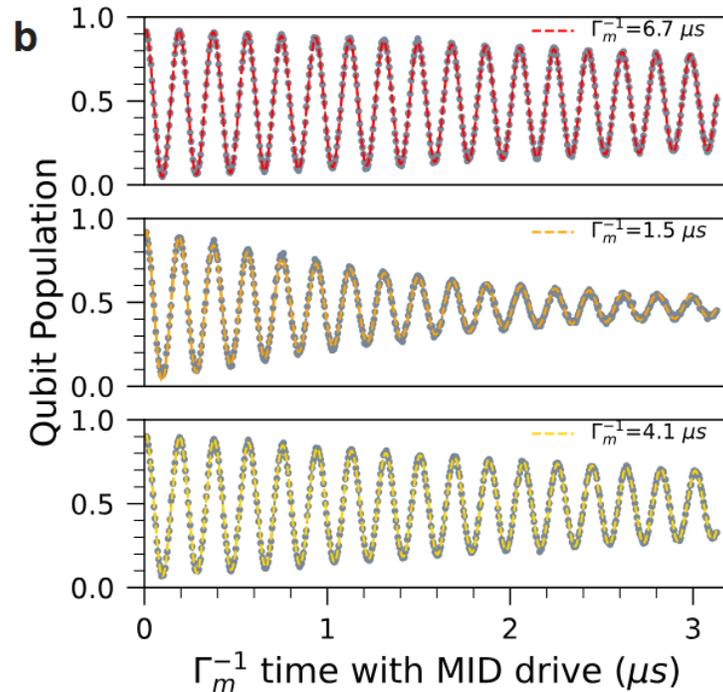
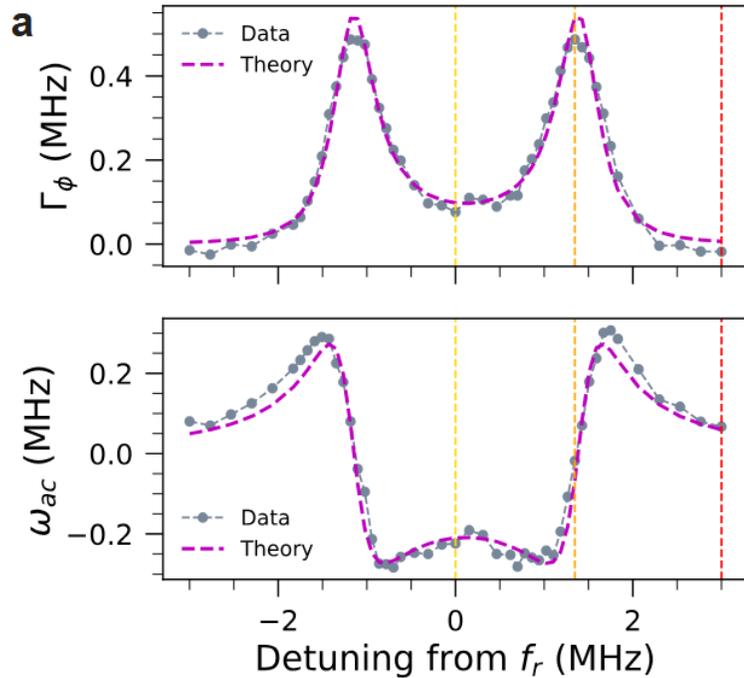


# cQED measurement-induced dephasing

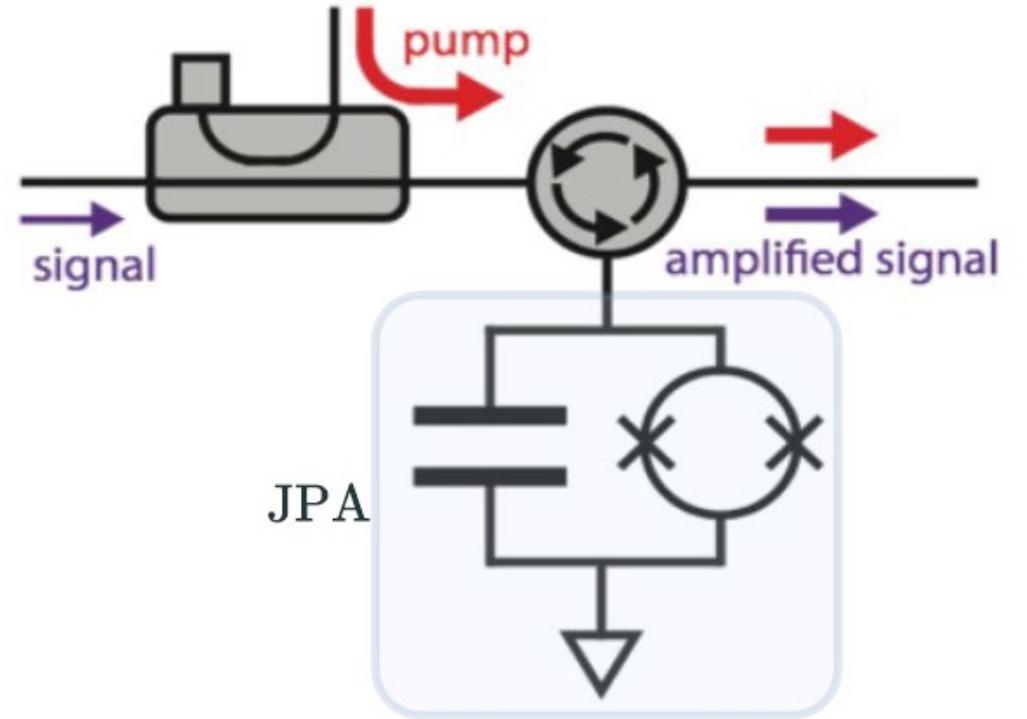


$$\delta\omega_q(\Delta) = 2\chi \bar{n}(\Delta),$$

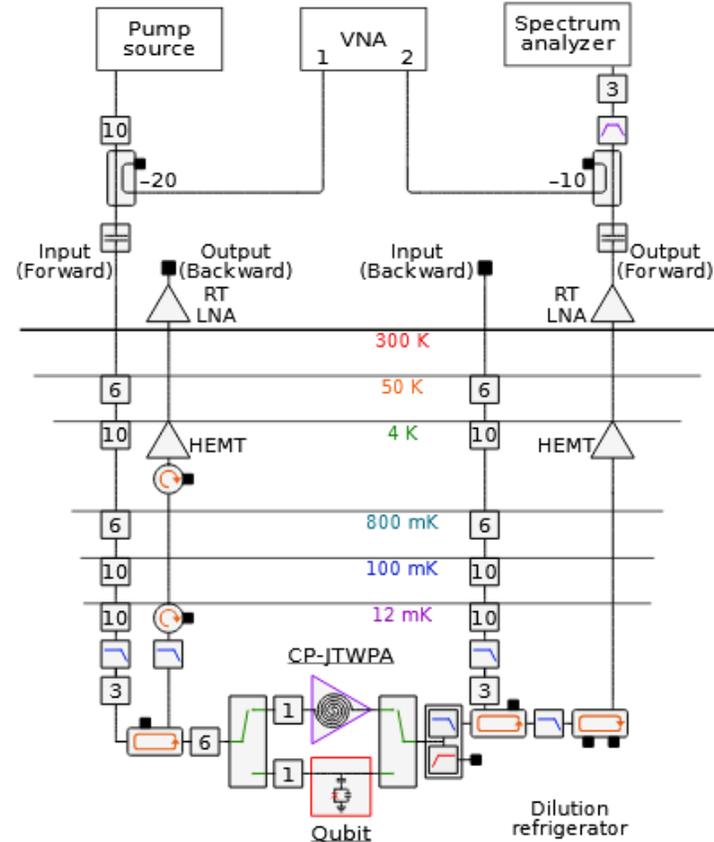
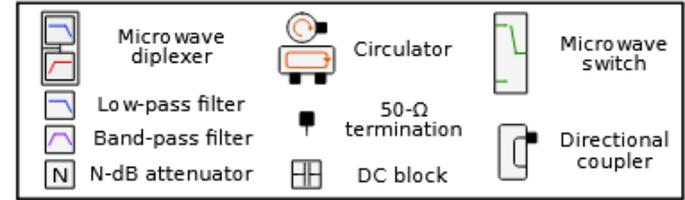
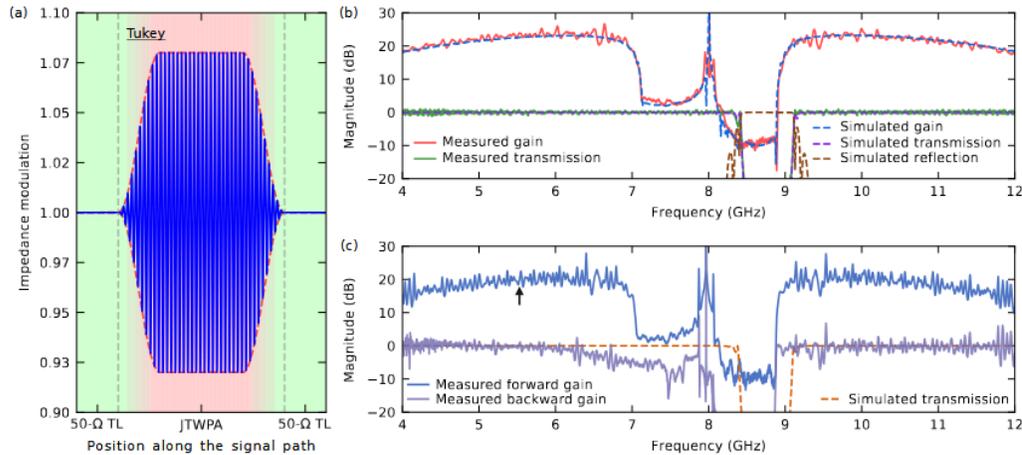
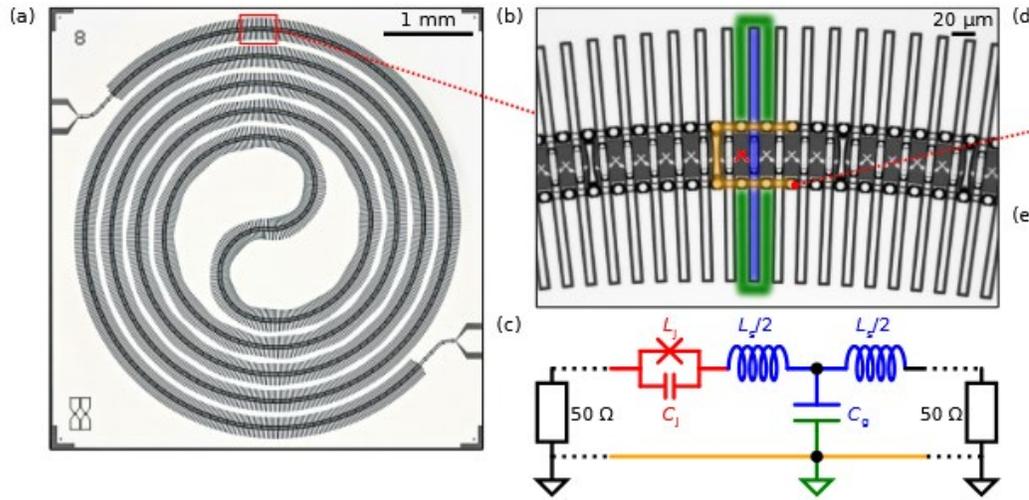
$$\Gamma_\phi(\Delta) = \frac{8\chi^2\kappa}{\kappa^2 + 4\Delta^2} \bar{n}(\Delta)$$



- Single cell with Josephson Junction, small footprint
- Circular device, input and output over same line
- Usually small amplification bandwidth of  $O(100 \text{ MHz})$ ; impedance engineered strategy to increase bandwidth
- Central frequency demonstrated from 0.6 GHz to 7 GHz
- Sensitive to magnetic fields
- Quantum efficiency near-ideal



# Compare to: CP-JTWPA from Nakamura's group





# JTWPA's compared to HEMTs

