IBS Conference on Dark World 2025, Daejeon, Korea, 2025-10-29

Low-intrinsic-loss Josephson traveling-wave parametric amplifiers (JTWPAs)

C. W. Sandbo Chang[1], Shintaro Ae[2],

Arjan F. van Loo[1,2], Chih-Chiao Hung[1], Yu Zhou[1,3], Shuhei Tamate[1], Yasunobu Nakamura[1,2]

[1]RIKEN Center for Quantum Computing
[2]Department of Applied Physics, Graduate School of Engineering, The University of Tokyo
[3]Fujitsu Limited

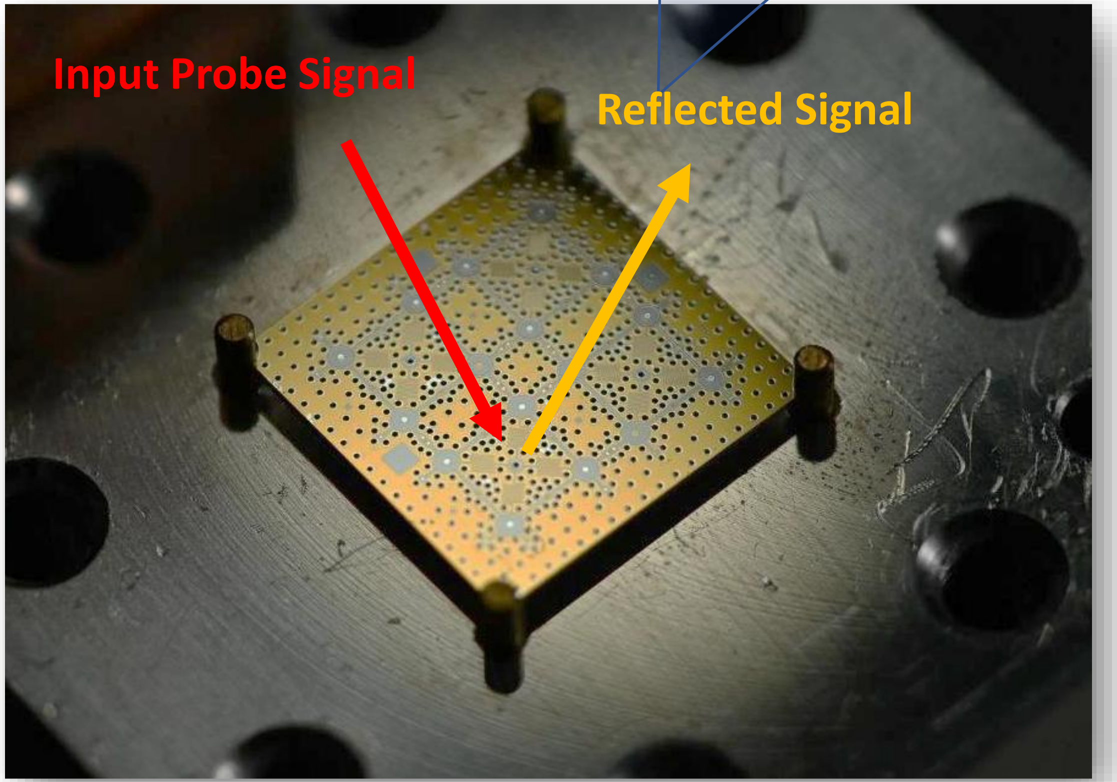
Our journey of developing JTWPAs at RIKEN

- Background, working principles of JTWPAs
- Periodic-modulation JTWPAs with windowed modulations
- Distributed-coupling resonant-phase-matching JTWPAs

Key to building larger quantum computer

Better amplifier

State of qubit?



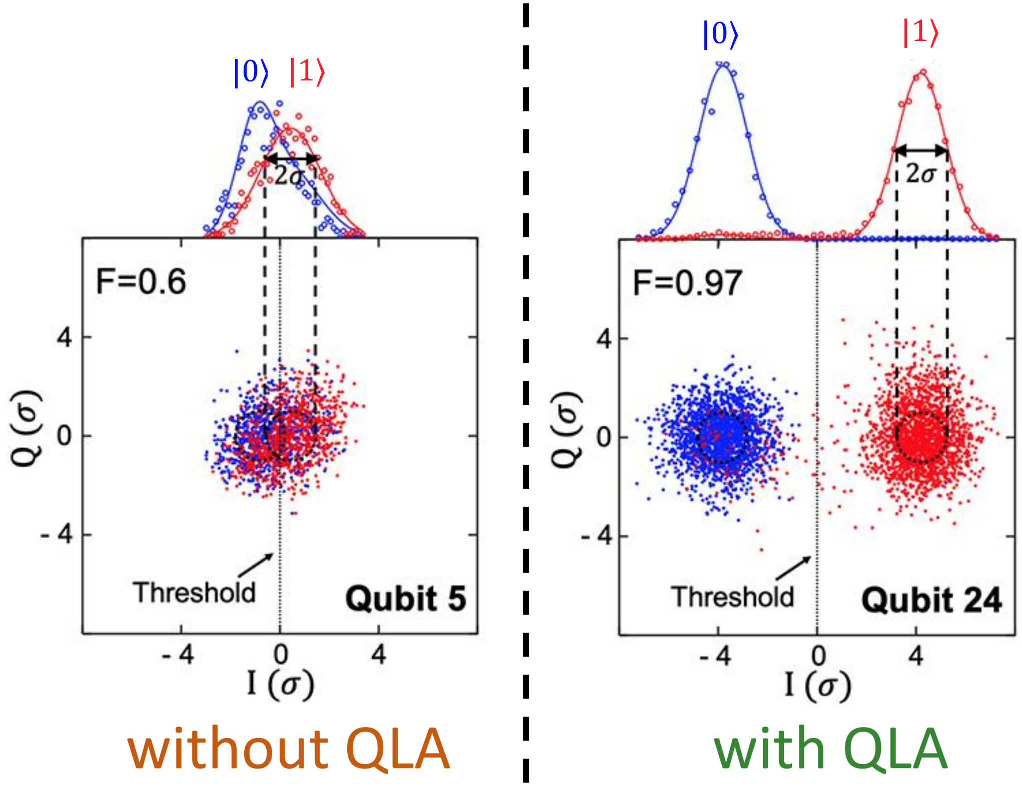
16-qubit device

SQERT, RIKEN Center for Quantum Computing

- Need to amplify weak signals

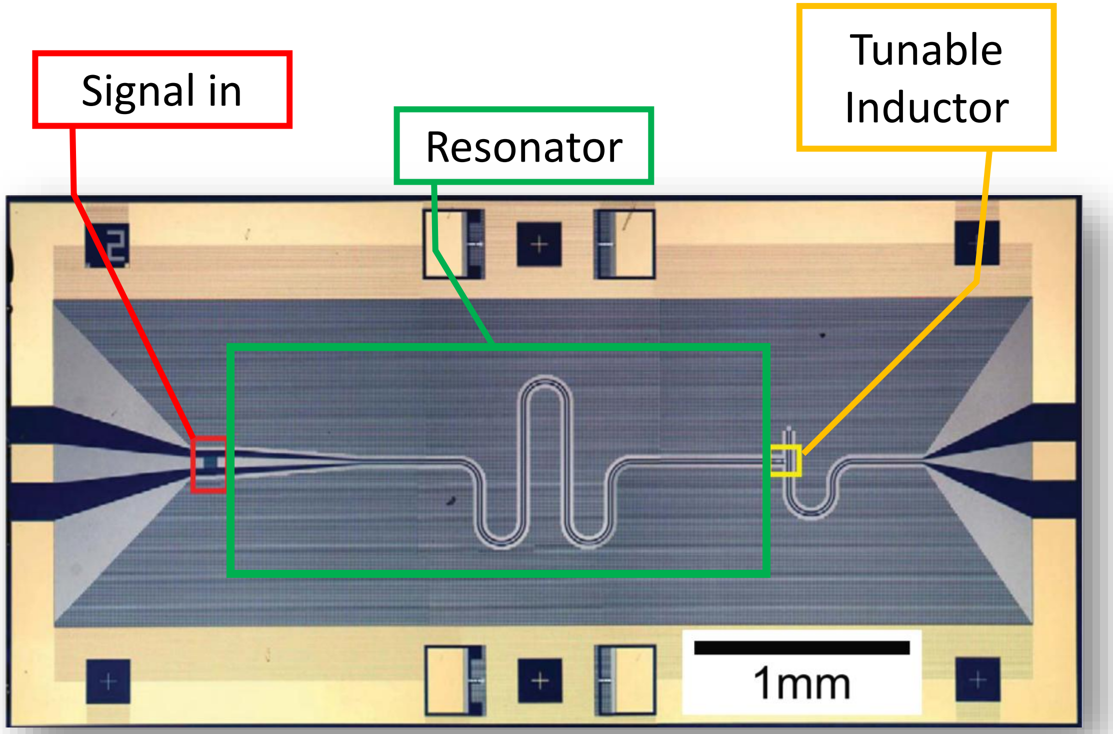
Solution: Quantum-limited amplifiers (QLA) base on parametric amplifications

➢ Lowest possible noise allowed by quantum physics



B. Abdo, IBM Research Blog (2020)
https://www.ibm.com/blogs/research/2020/01/quantum-limited-amplifiers/

Josephson Parametric Amplifiers (based on resonators)



Resonator-based JPA

L. Zhong et al., NJP **15**, 125013 (2013)

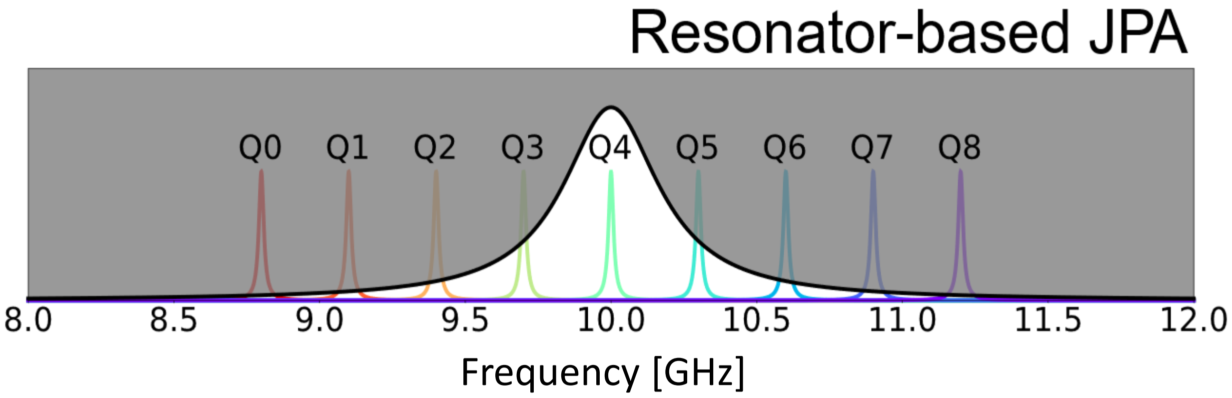
Strength

- Easy fabrication, high-gain (20 dB+)
- Quantum-limited noise (≈0.5 quanta)

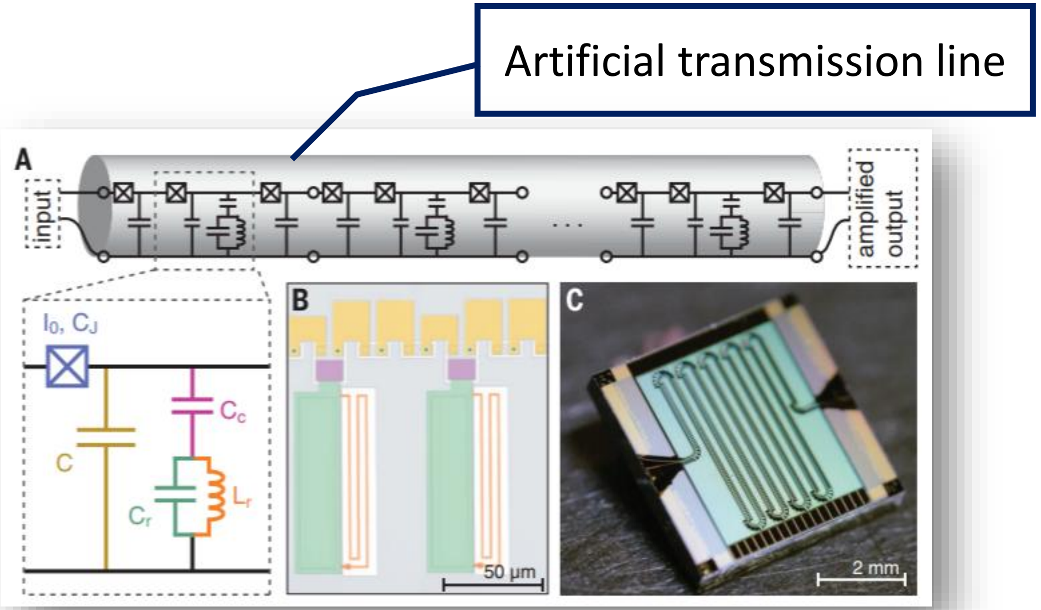
Weakness

- Narrow bandwidth (few hundreds MHz)
- Low saturation power

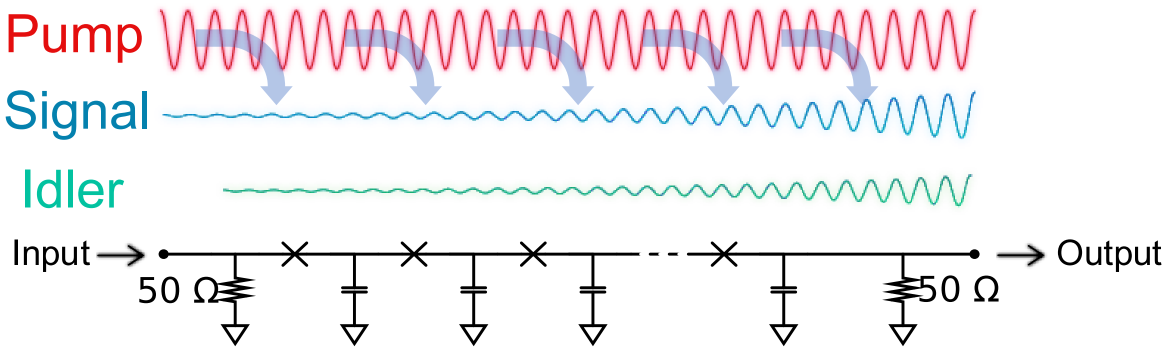
Only a few qubits can be measured



Josephson Traveling-Wave Parametric Amplifiers



C. Macklin et al., Science **350**, 6258 (2015)

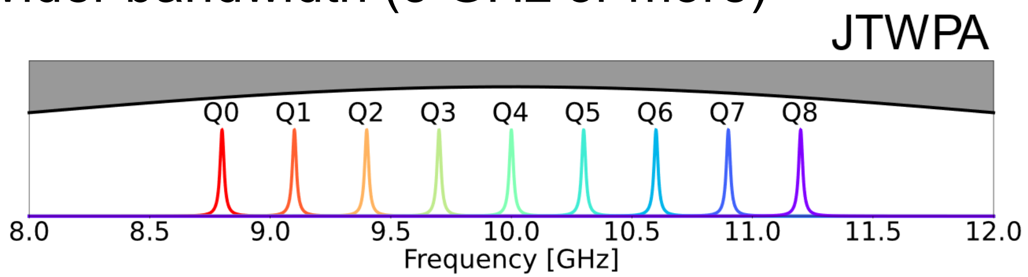


Gain can scale with length

$$a_s(x) = a_s(0)\left(\cosh gx - \frac{i\Delta k}{2g}\sinh gx\right)e^{i\Delta kx/2}$$

Strength compared to JPAs

- Wider bandwidth (3 GHz or more)

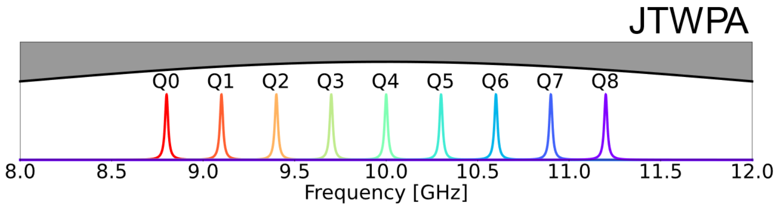


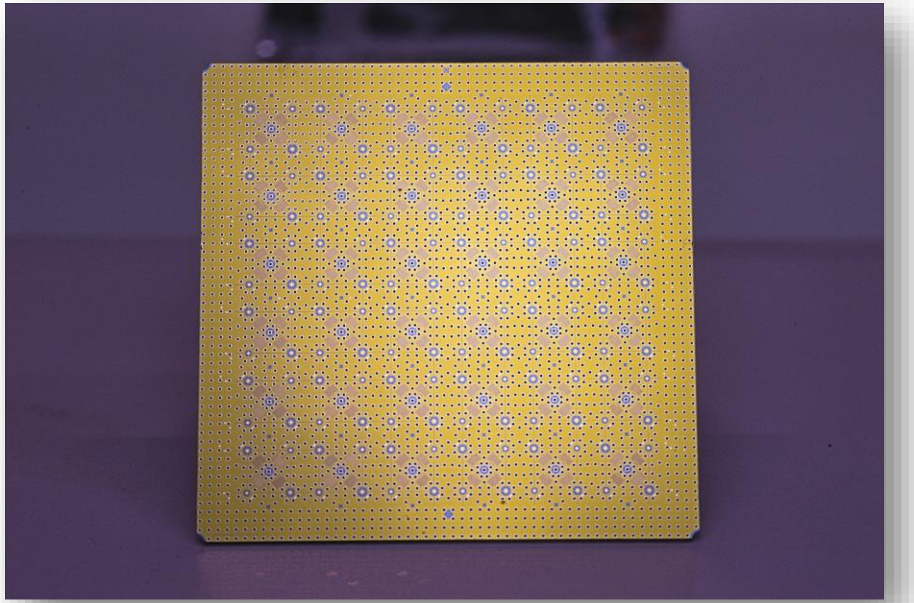
- Higher-saturation power (≈ -100 dBm)
- Near quantum-noise-limited performance (added noise ≈ 1-1.5 quanta)
- High-gain (15-20 dB)

Eq. from K. O'Brien *et al.*, *Phys. Rev. Lett. 113, 157001*

Background, working principles of JTWPAs

Applications





RIKEN 144-Q

Qubit readout

Towards a many-qubit system

JTWPAs are critical for single-shot frequency-multiplexed readout

(amplify readout signals simultaneously for multiple qubits)

Broadband microwave signal detection

JPAs are already being used in axion-search experiments

ADMX

- T. Braine et al., PRL **124**, 101303 (2020)
- C. Bartram et al., PRL **127**, 261803 (2021)

CAPP

- Jinsu Kim et al., PRL **130**, 091602 (2023)
- Saebyeok Ahn et al., PRX **14**, 031023 (2024)

HAYSTAC

- B. M. Brubaker et al., PRL, **118**, 061302 (2017)
- K. M. Backes et al., Nature **590**, 238–242 (2021)

JTWPAs provides the extension to broader bandwidth operation

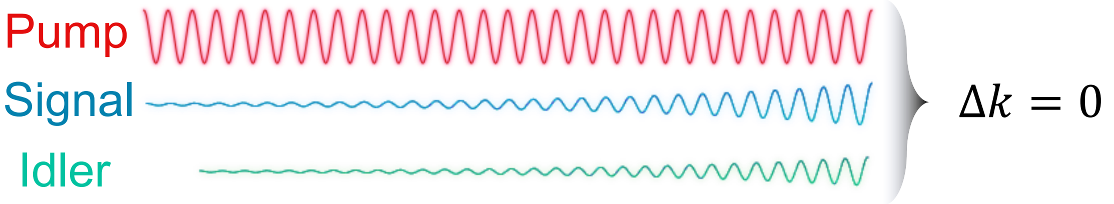
Some recent work in axion search has started incorporating JTWPAs

- C. Bartram et al., Rev. Sci. Instrum. **94**, 044703 (2023)

Challenges in implementing JTWPAs

Phase (wave vector, k) mismatches

due to self- and cross-phase modulation



$$a_s(x) = a_s(0)\left(\cosh gx - \frac{i\Delta k}{2g}\sinh gx\right)e^{i\Delta k x/2}$$

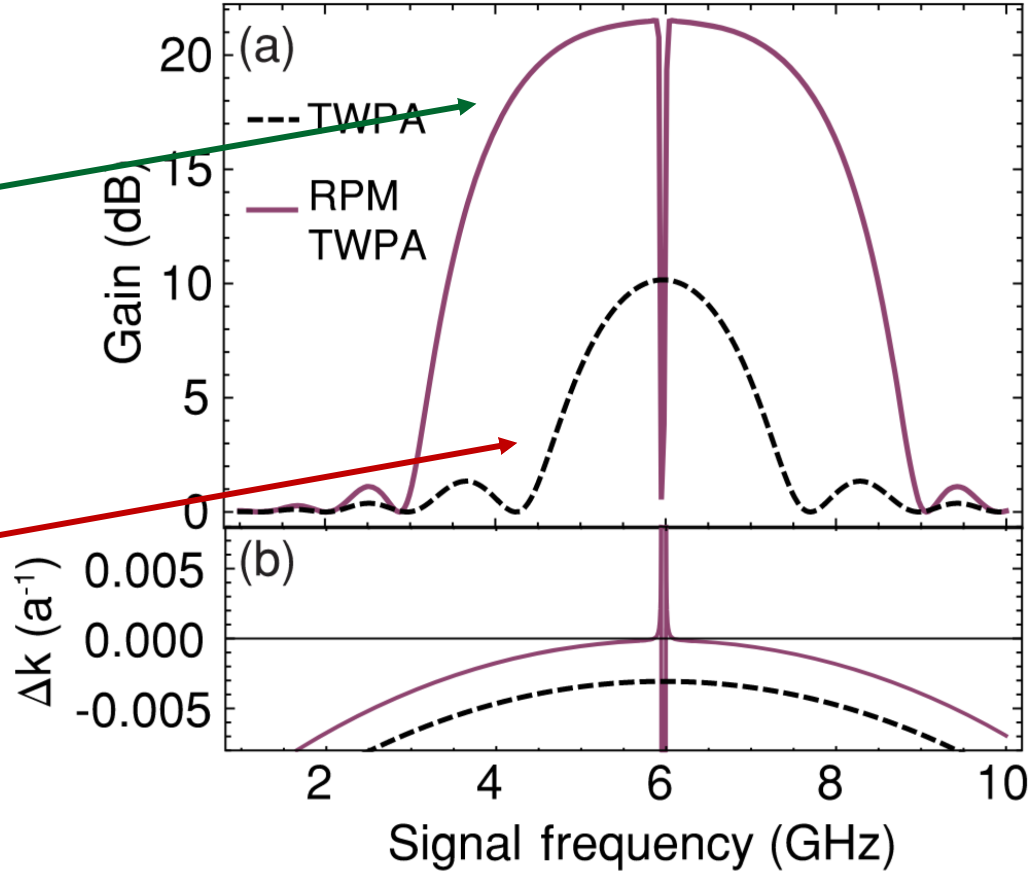
$$g = \sqrt{\kappa_s \kappa_i^* - (\Delta k/2)^2}$$

Phase matched $(\Delta \mathrm{k} = 0)$

- Gain $(a_s(x)/a_{s(0)})$ scales exponentially with length (as $\cosh gx$)
- High gain, large bandwidth

Phase mismatched $(\Delta \mathrm{k} \neq 0)$

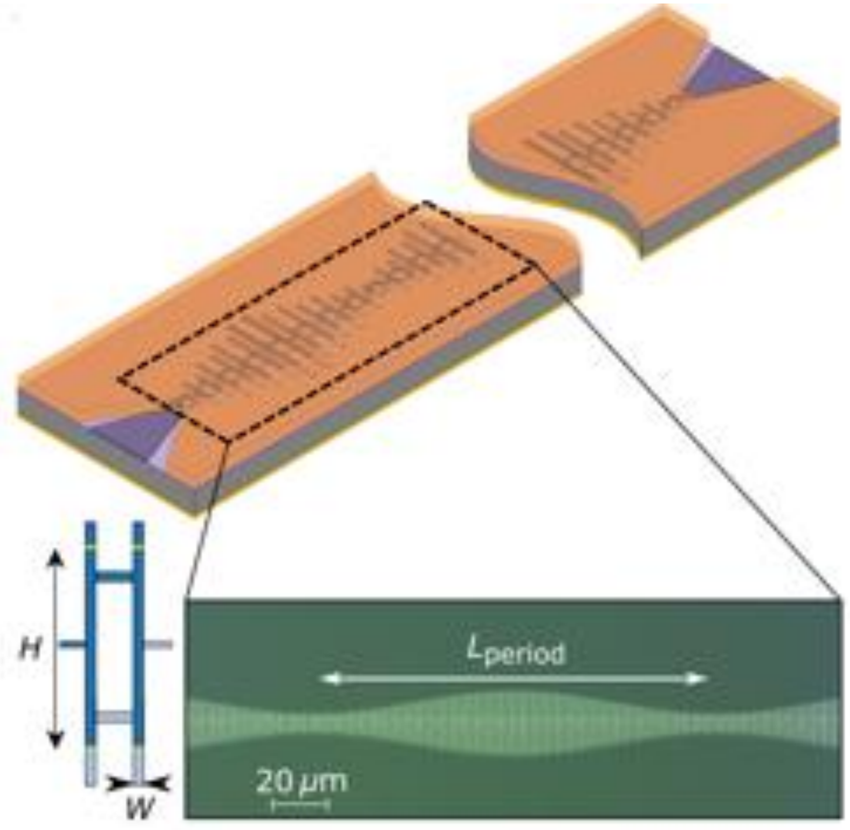
- Gain scales only quadratically with length (as g can be imaginary)
- Limited gain and bandwidth

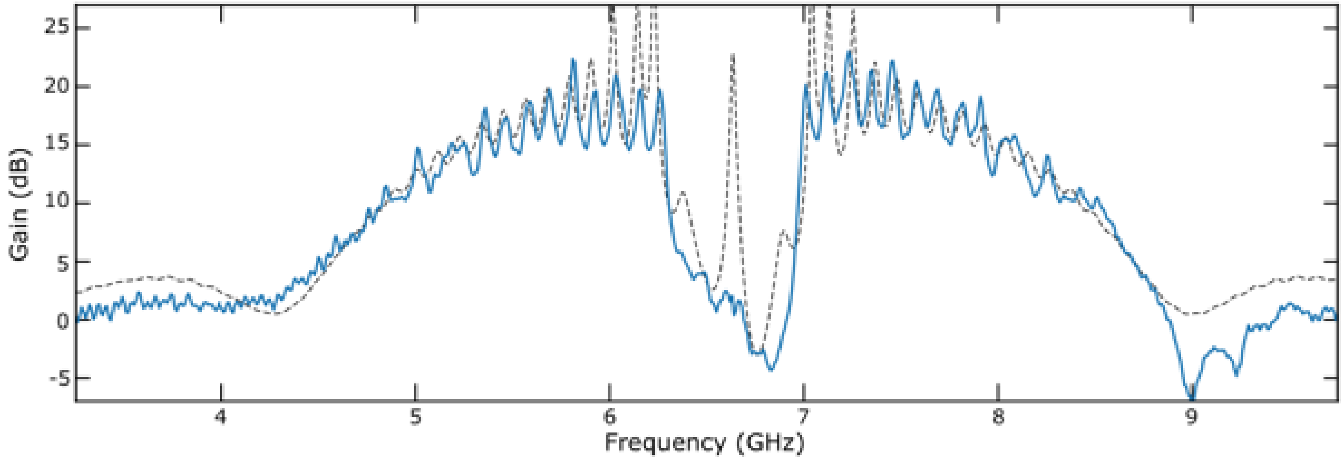


K. O'Brien *et al.*, *Phys. Rev. Lett. 113, 157001*

Prefer to operate JTWPA without DC/flux bias – Phase matching design?

Periodic-modulation[1]





Periodic change in line impedance (by geometry)

→ create a bandgap in transmission

Q: How does phase correction work to get $\Delta k = 0$?

L. Planat *et al.*, *PRX* **10**, 021021 (2020)

Phase matching by periodic modulation

Phase-matching condition for four-wave-mixing gain

Phase mismatches Δk is given by

$$\Delta k = \underbrace{2k_p - k_s - k_i}_{} + \underbrace{2\alpha_p - \alpha_s - \alpha_i}_{}$$ [1]

Linear phase mismatch
- Slightly negative, due to the discreteness of unit cells

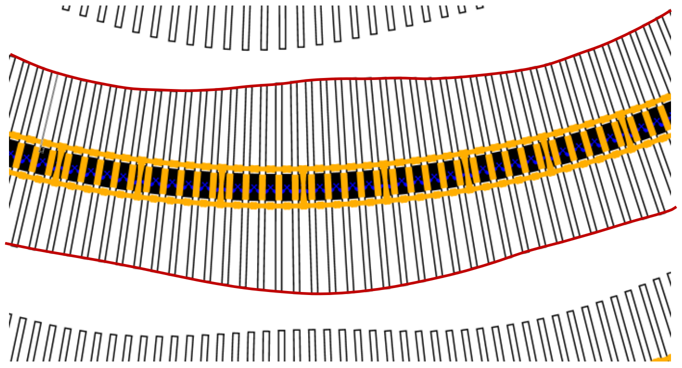
Nonlinear phase mismatch
- Negative for a junction array
- Significant, due to differences in self- and cross-phase modulations

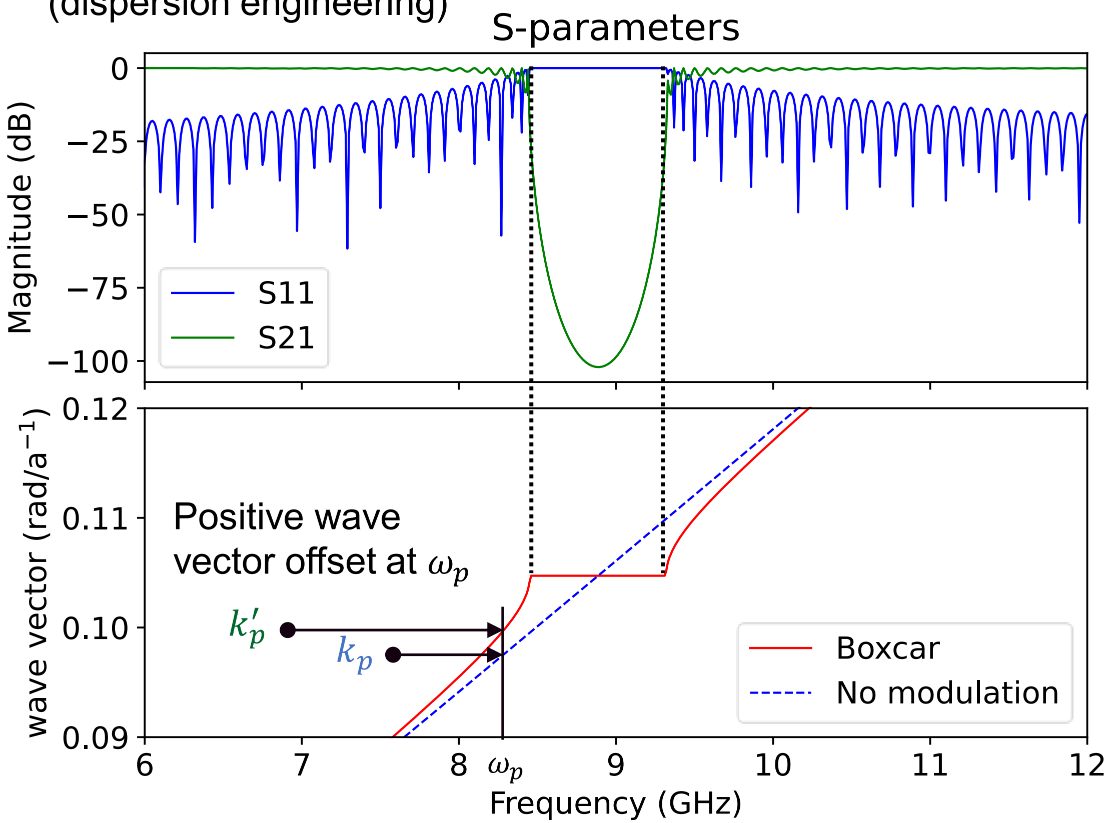
$\Delta k < 0$ if nothing is done

Dispersion engineering:

- Offset negative nonlinear mismatch by making linear mismatch positive
- Increase k_p rather than k_s, k_i for broadband compatibility
- Periodic modulation on lengths of open stubs allows the modification of dispersion relations

Stub-length modulation
↓
Impedance modulation
↓
Bandgap
(dispersion engineering)

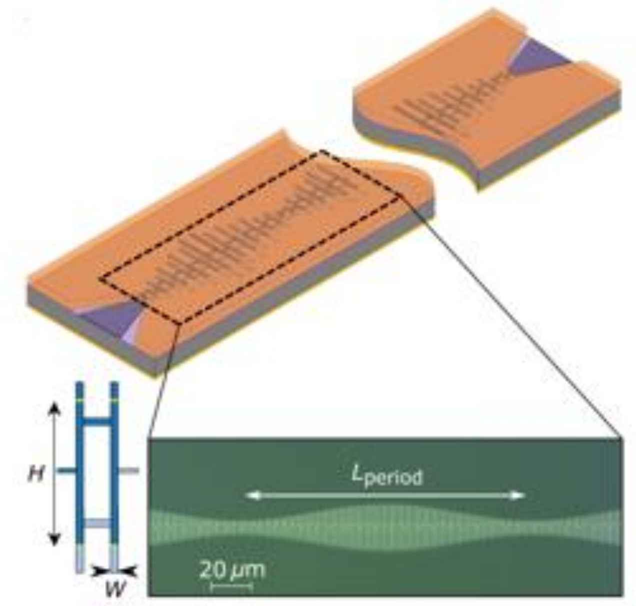


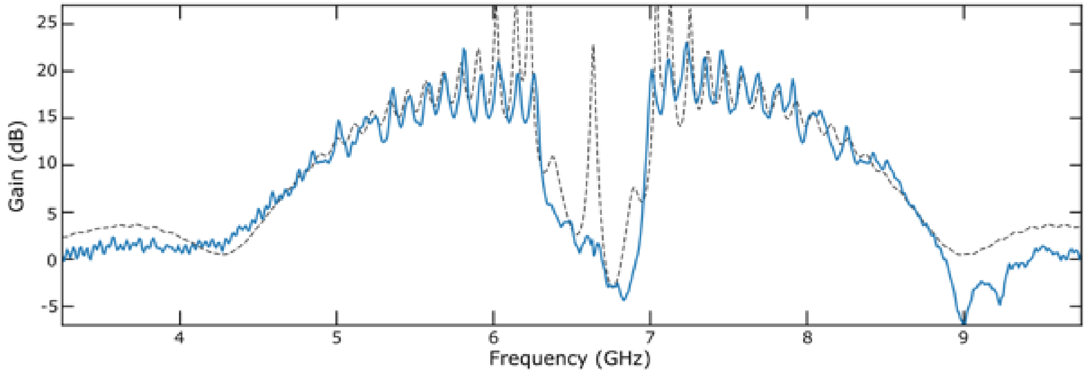


[1] K. O'Brien, *et al.*, *PRL* **113**, 157001 (2014)

Prefer to operate JTWPA without DC/flux bias – Phase matching design?

Periodic-modulation[1]





Still, insertion loss was high

(shunt capacitors formed by lossy dielectric)

- 3 to 6 dB over 4-12 GHz → >1 quanta of added noise
- Limiting JTWPA noise performance[4]

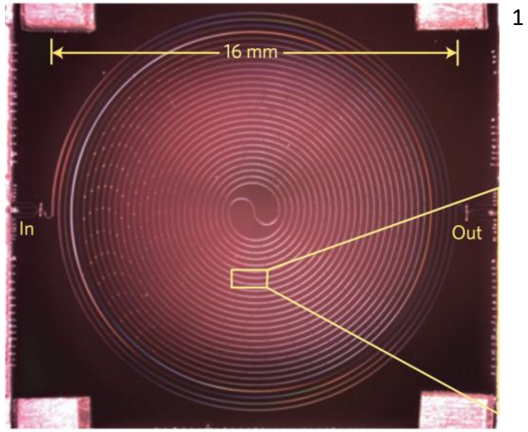
Q: How can we reduce the loss?

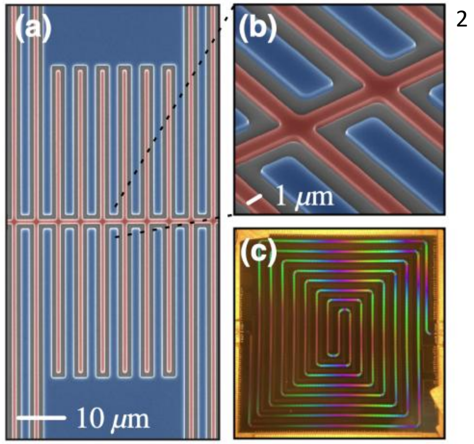
L. Planat *et al.*, *PRX* **10**, 021021 (2020)

Background, working principles of JTWPAs

Learning from kTWPAs

kTWPAs are often longer in physical length



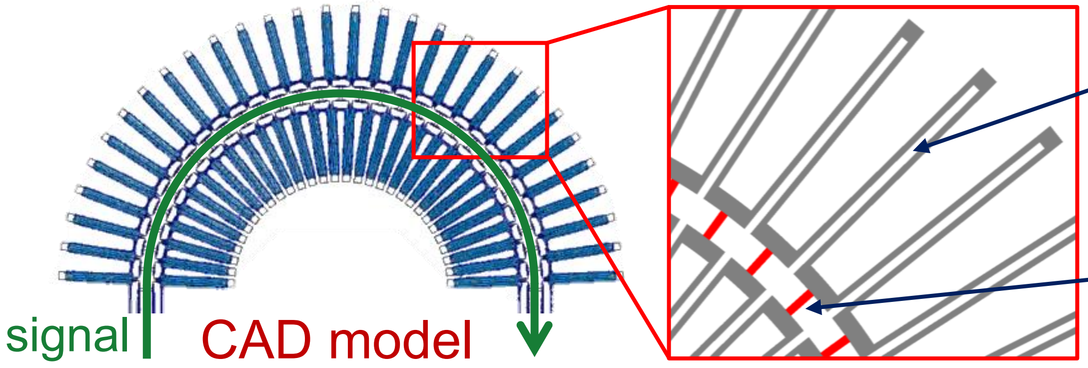


- Low loss per unit cell is critical → avoid using lossy dielectric material
- Use coplanar lumped-element waveguides

Open-stub capacitor

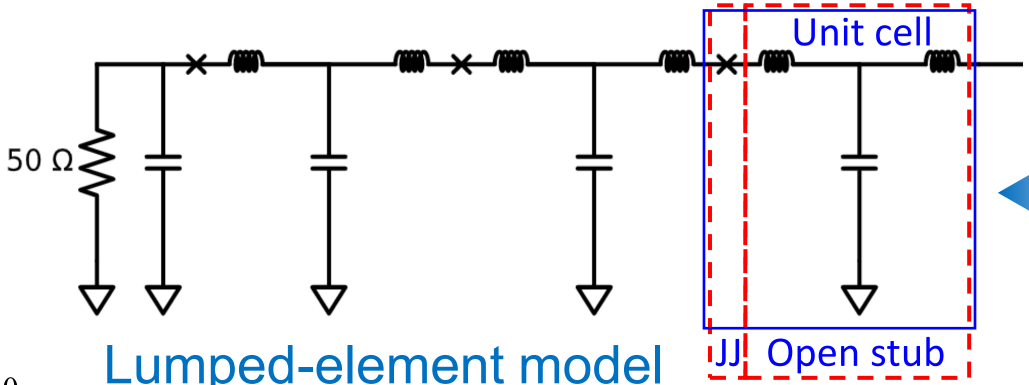
Open CPW stubs as low-loss shunt capacitors for a Josephson-junction array

Coplanar JTWPA



connected by S-parameters

FEM fitted by ABCD-matrix



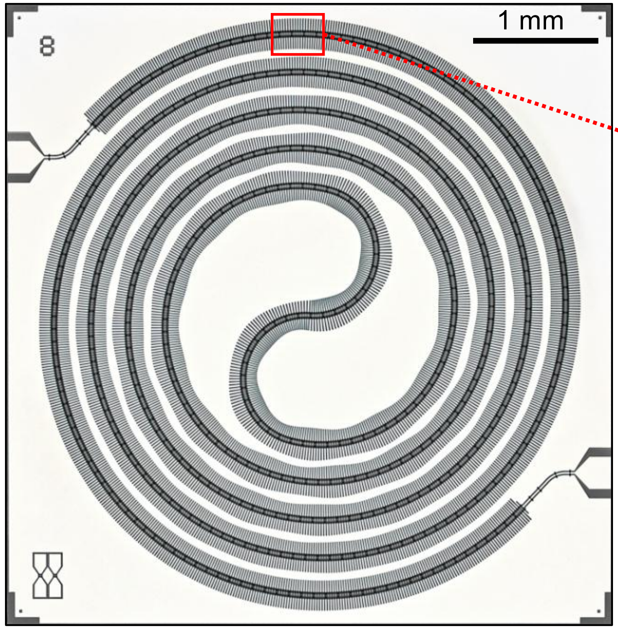
Gain simulation by harmonic balance

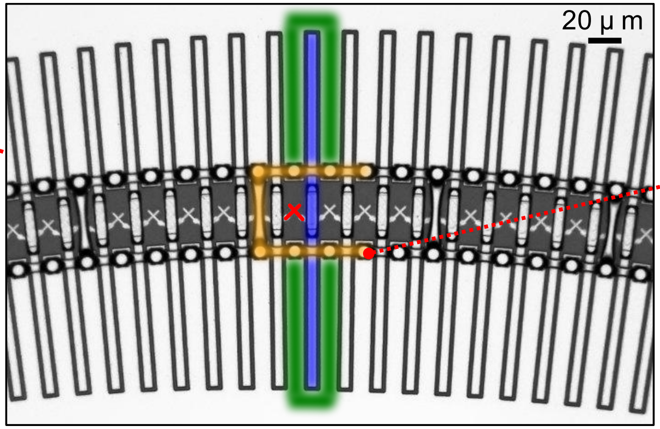
1. B. Eom *et al.*, *Nat. Phys.*, **8**, 623 (2012)
2. M. Malnou *et al.*, *PRX Quantum* **2**, 010302 (2021)
3. K. Peng *et al.*, *Proc. IEEE Int. Conf. Quant. Comput. Eng,* 2022, pp. 331–340

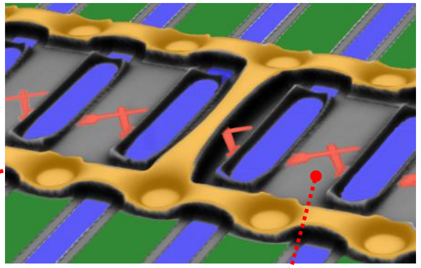
Coplanar JTWPA: Implementation and baseline transmission

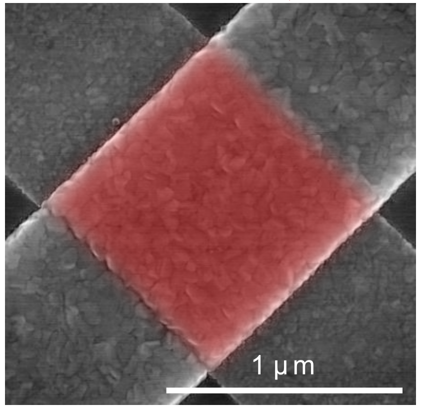
4WM JTWPA

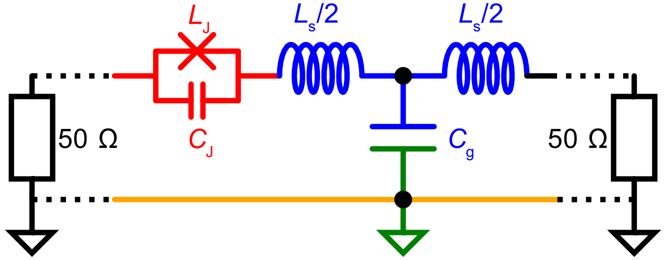
- All-aluminum conductor on silicon substrate
- Double-spiral layout
- 2400 unit cells, 20 um cell separation

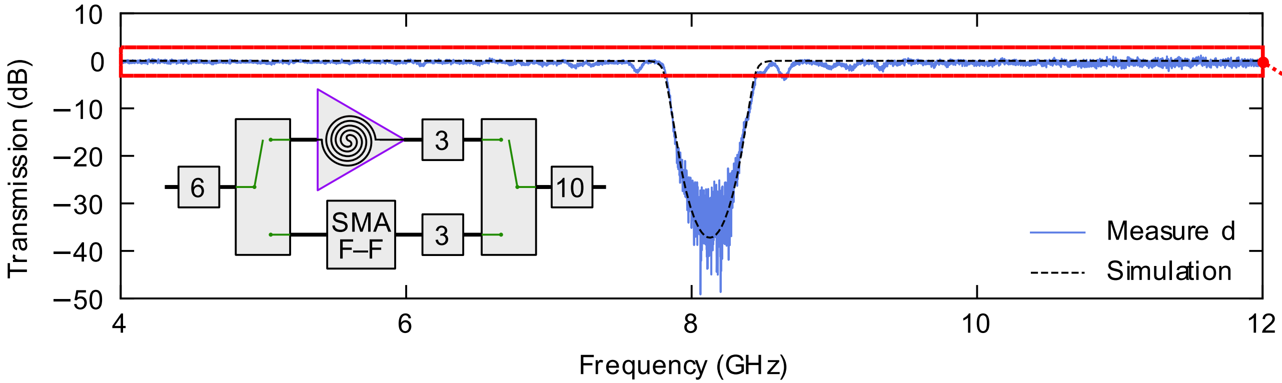


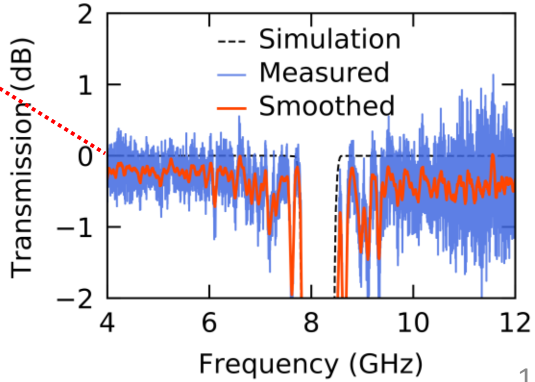












Recent work:

Phys. Rev. Applied **24**, 044081

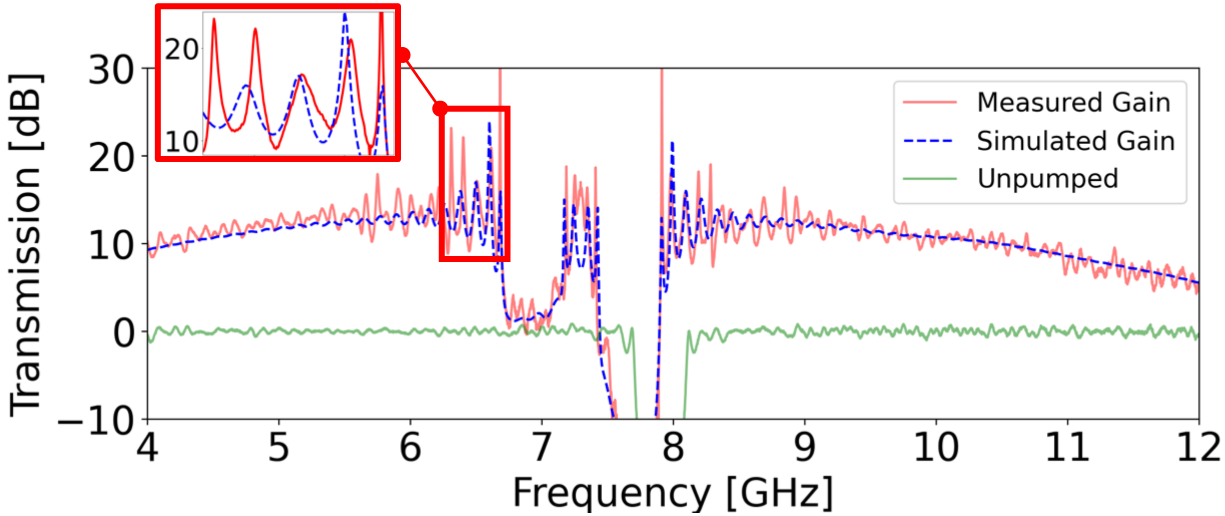
Our journey of developing JTWPAs at RIKEN

- Background, working principles of JTWPAs
- Periodic-modulation JTWPAs with windowed modulations
- Distributed-coupling resonant-phase-matching JTWPAs

Periodic-modulation JTWPAs with windowed modulations

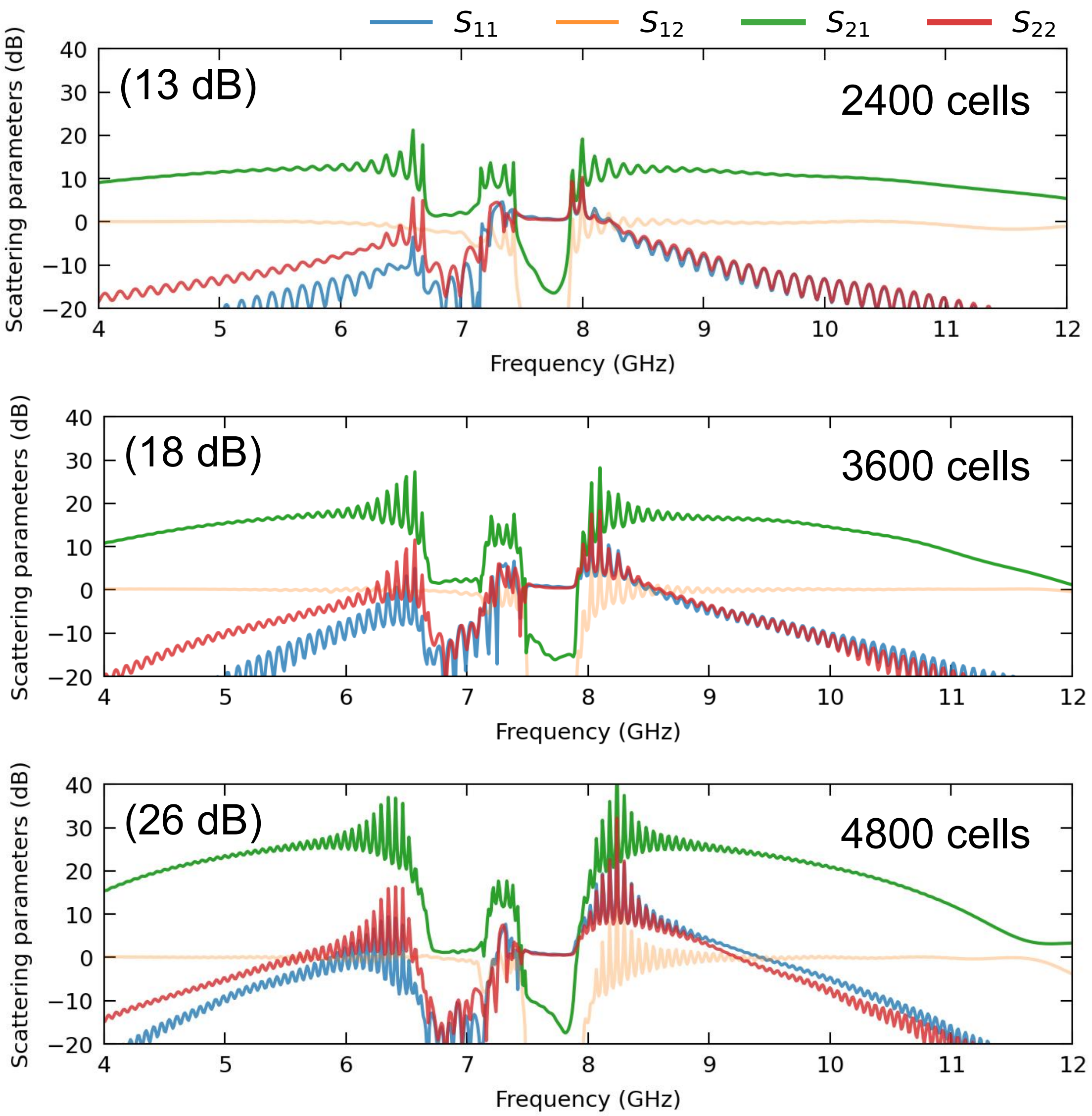
Periodic modulation: Gain and ripples

Gain curve of our first functional JTWPA (10-13 dB)



- Gain ripples near bandgap predicted by simulations
- Ripple amplitude can go above 5 dB, or even 10 dB next to the gap
- **What happens if we scale up the gain?**

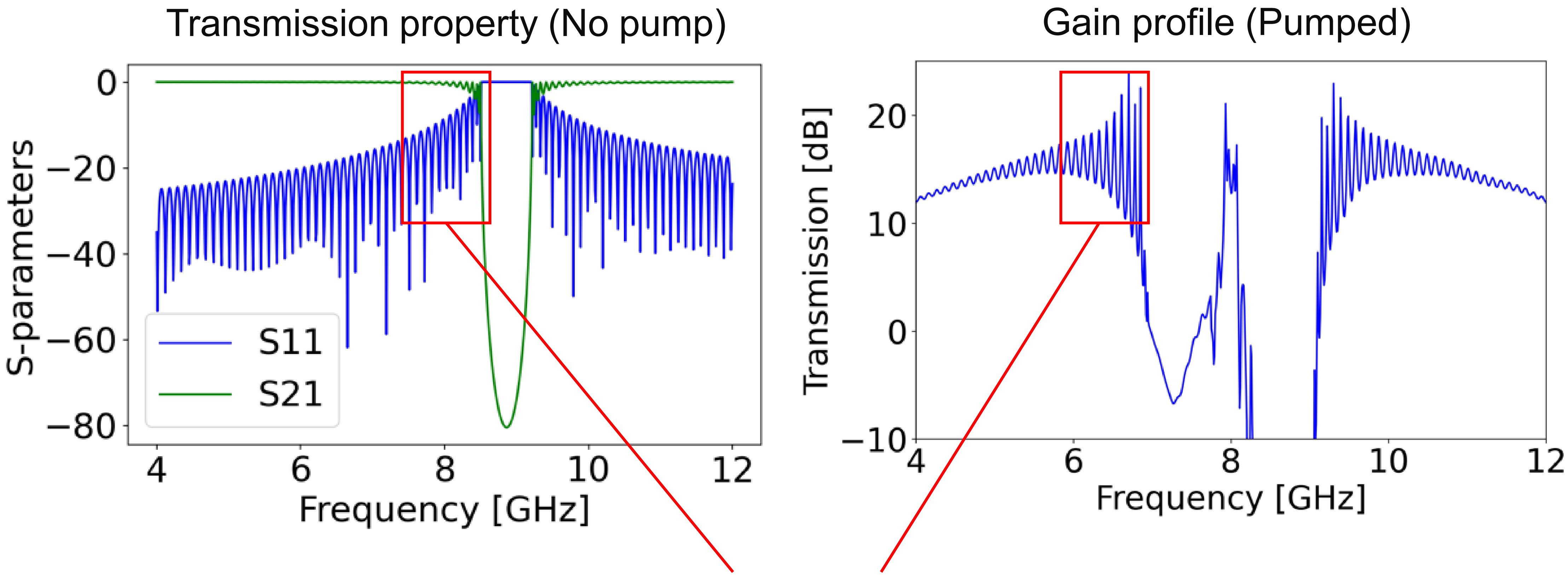
Simulating longer JTWPAs:



Simulation done using JosephsonCircuits (harmonic balance)

K. Peng *et al.*, *Proc. IEEE Int. Conf. Quantum Comput. Eng,* 2022, pp. 331–340

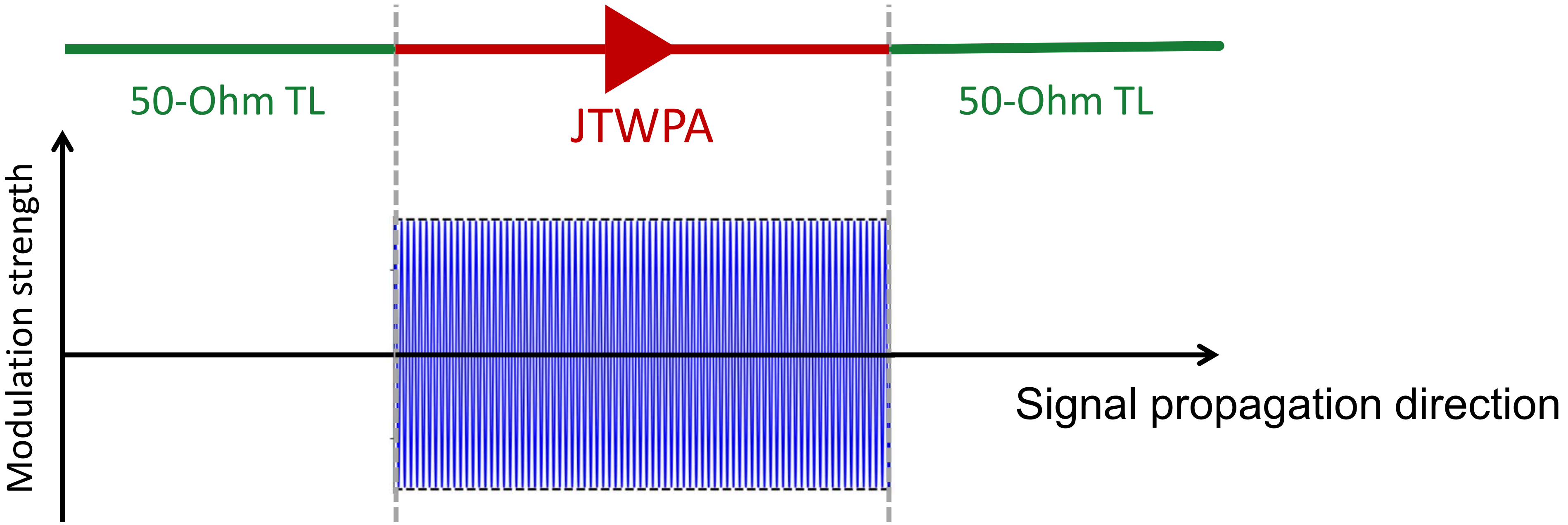
Periodic modulation: Source of gain ripples



- Gain and transmission/reflection ripples share similar periodicity
- A smoother transition near bandgap → a smoother gain profile?
- **Origin of transmission ripples?**

Periodic-modulation JTWPAs with windowed modulations

Periodic modulation: Origin of transmission ripples



- Periodic structures couples the forward and backward traveling waves
- With weak modulation, using coupled-mode theory, transmission is approximately

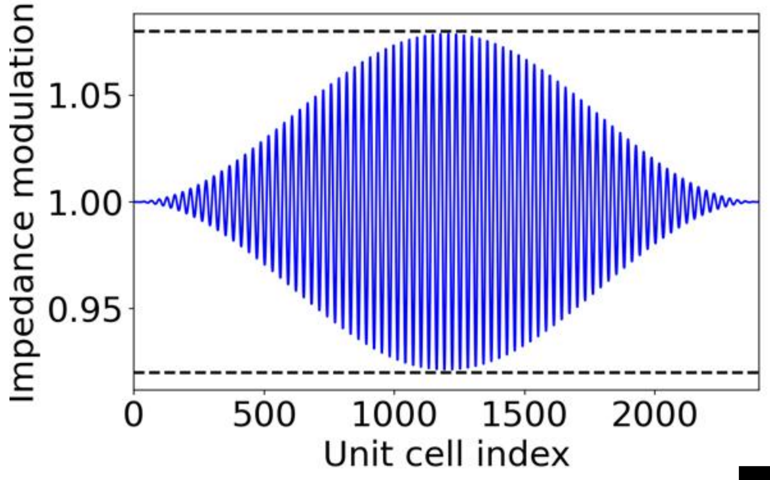
$$t \approx 1/\cosh\left(\kappa \left| \int_{-\infty}^{\infty} W(z) e^{j2\Delta_B z} dz \right| \right),$$

resembling a spatial Fourier transform of the window function.

Periodic-modulation JTWPAs with windowed modulations

Windowed-modulation: Suppression of gain ripples

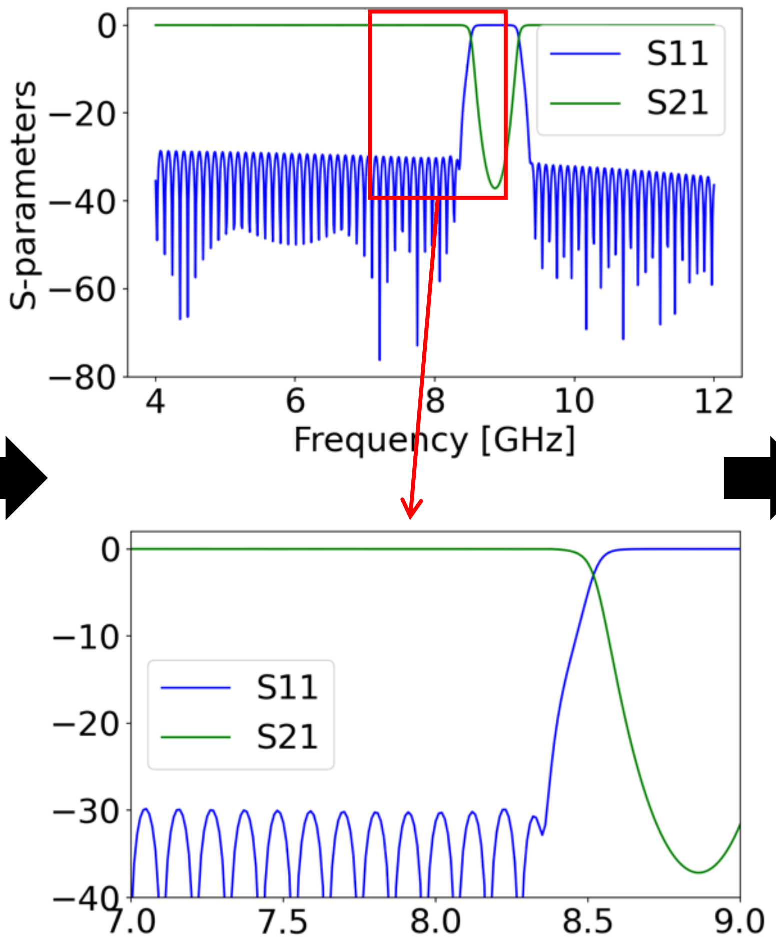
Modulation structure



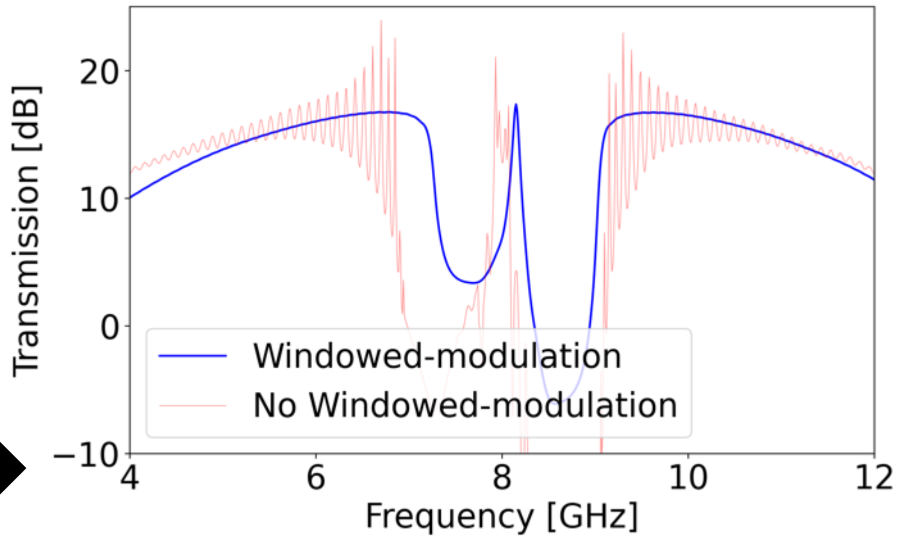
Applying a Hann window function on the modulation:

- Gradually increase then decrease the modulation strength along the waveguide

Transmission property



Gain profile

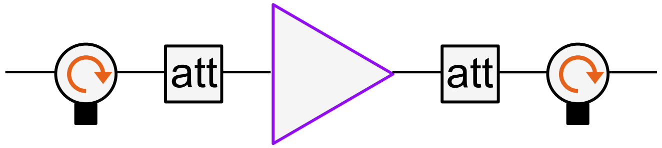


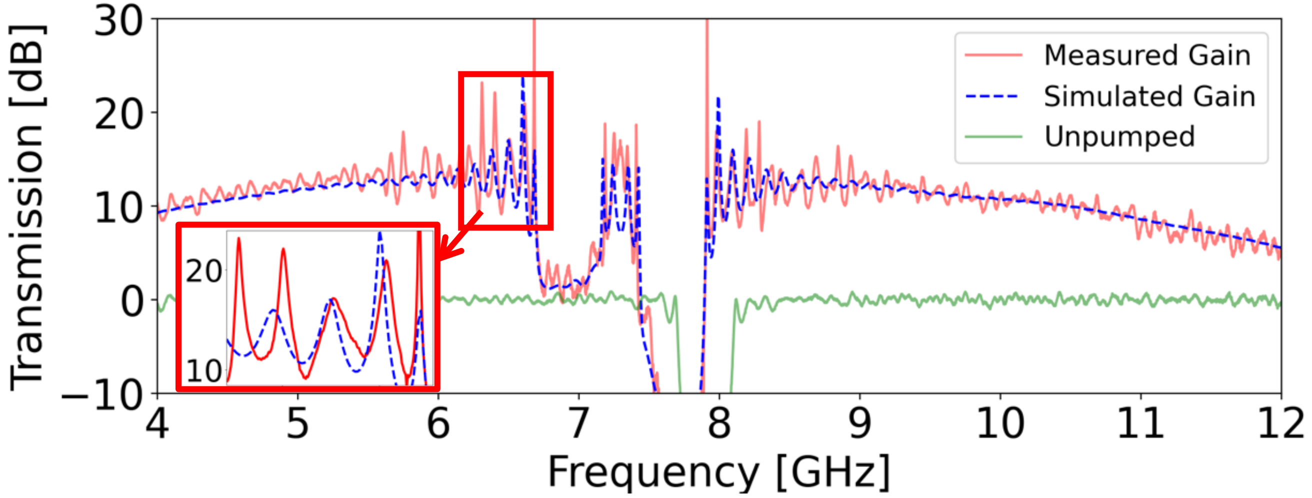
Gain ripple well suppressed

- No signs of gain ripples
- Enables the scale-up of gain with a longer waveguide based on periodic modulation schemes

Periodic-modulation JTWPAs with windowed modulations

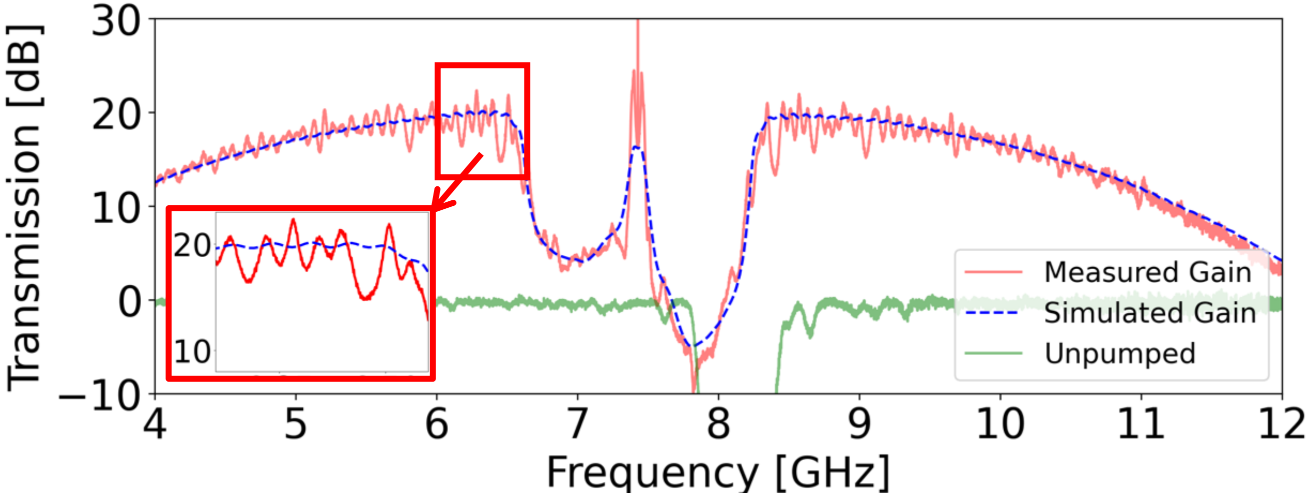
Windowed-modulation: Intrinsic gain ripples





boxcar sinusoidal modulation

- 10 – 13 dB gain only, significant gain ripples close to bandgap predicted by simulations
- Ripple amplitude can go above 5 dB, or even 10 dB next to the gap



Hann-windowed modulation

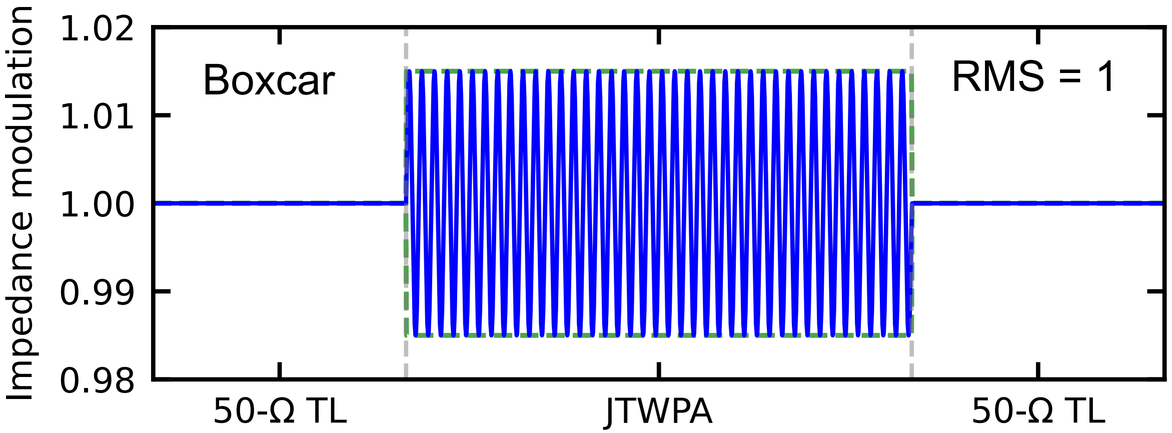
- 17 – 20 dB gain over 3.2 GHz bandwidth
- No strong gain ripples near bandgap
- Gain ripples typically within +/- 2 dB

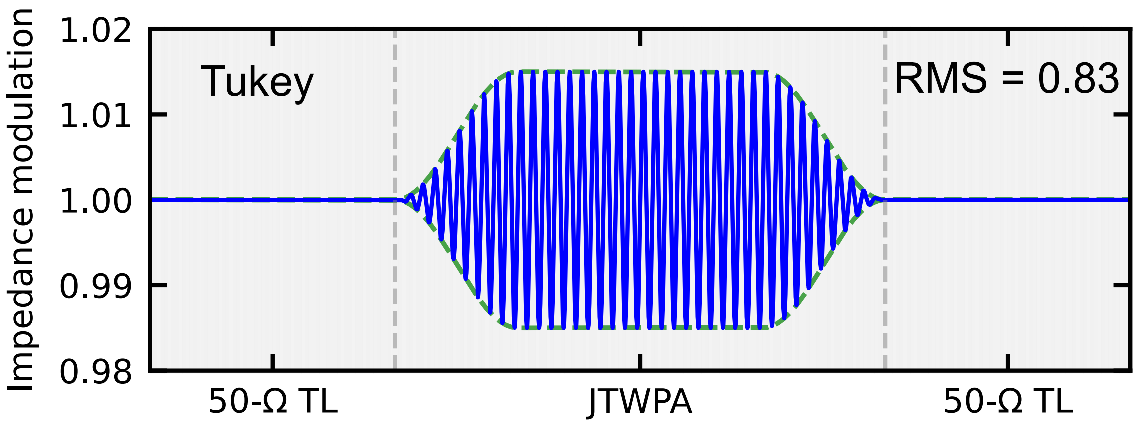
Periodic-modulation JTWPAs with windowed modulations

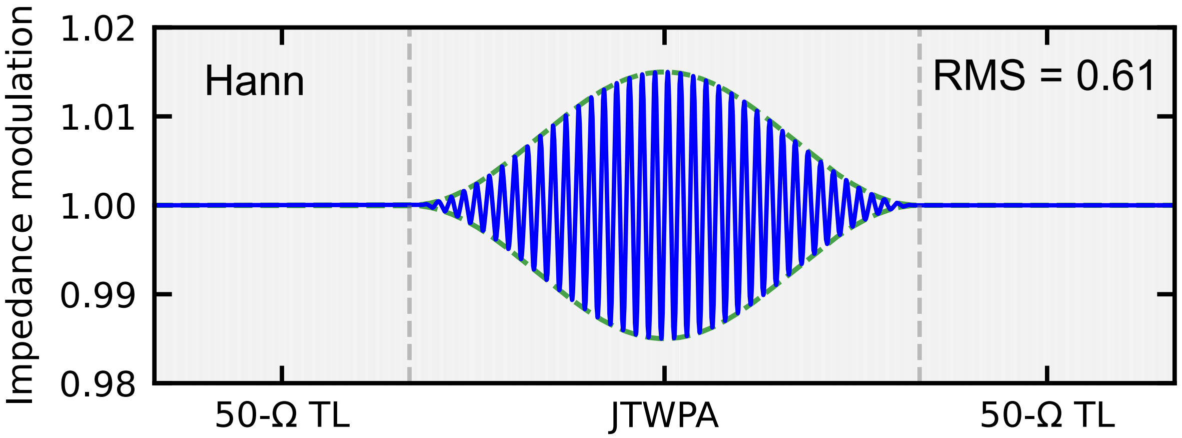
Windowed-modulation: Optimization

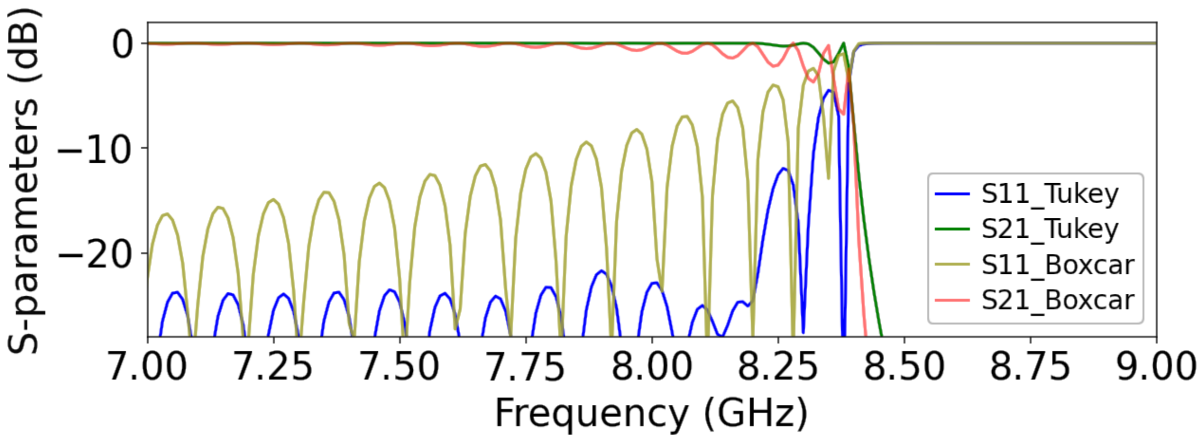
Windowing weakens the overall phase correction

Tukey window can be a balance between tapering and phase correction strength





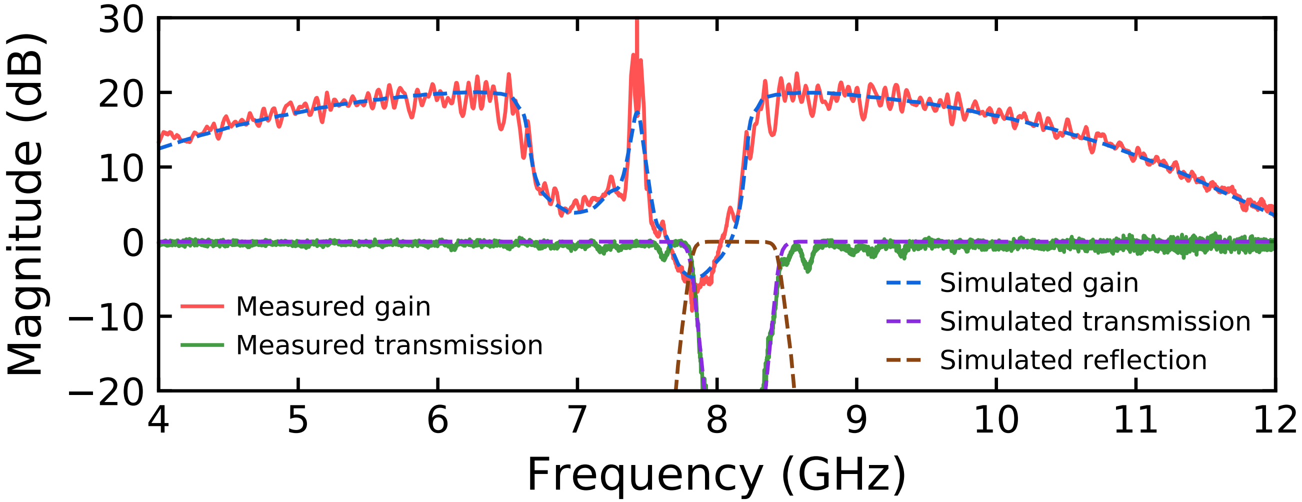




Periodic-modulation JTWPAs with windowed modulations

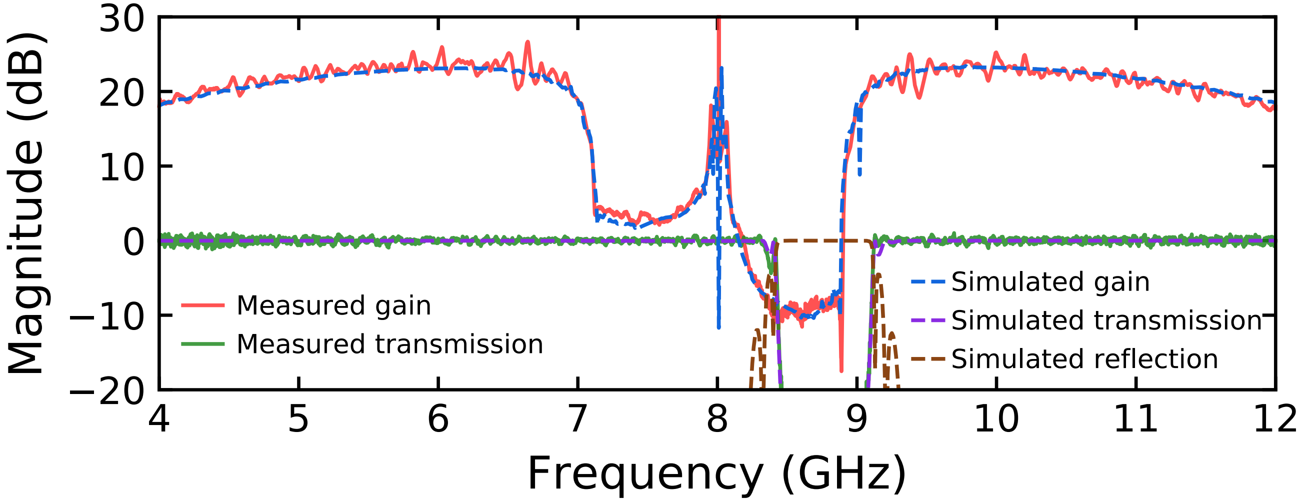
Windowed-modulation: Higher intrinsic gain from a Tukey-windowed JTWPA

Both JTWPAs contain ~ 2400 junctions, same 8% modulation strength



Hann-windowed JTWPA (L_J = 94 pH)

- 17-20 dB gain over 3.2 GHz

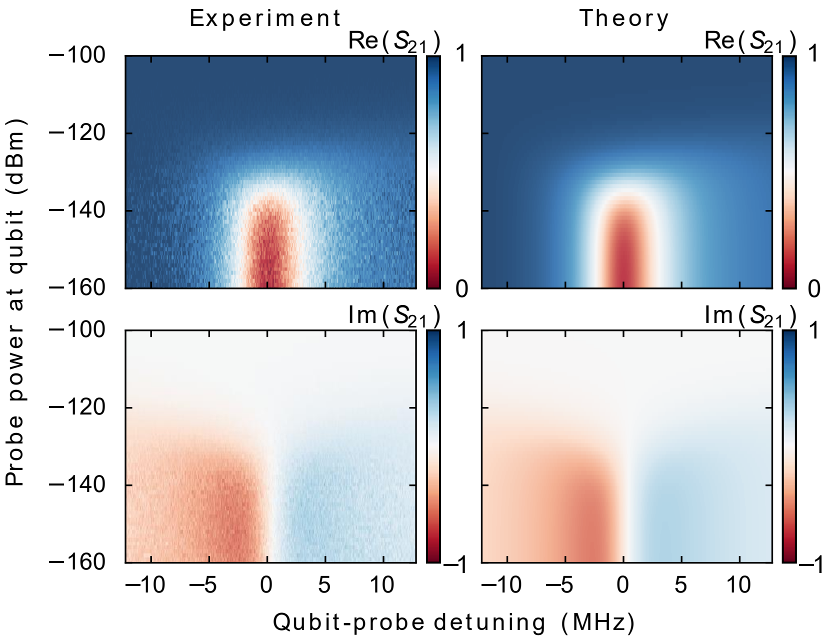


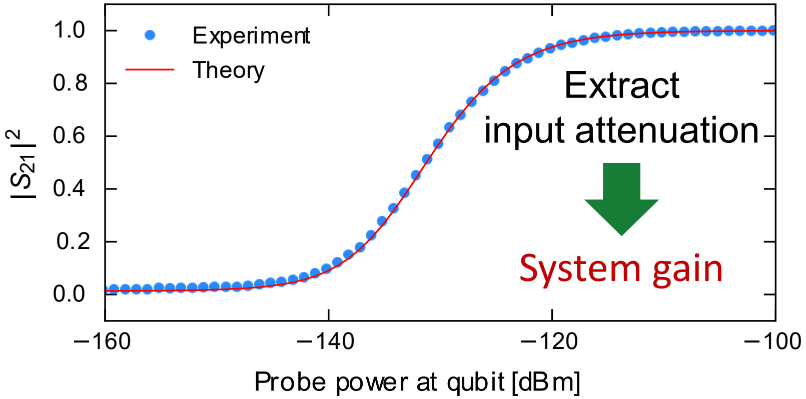
Tukey-windowed JTWPA (L_J = 78 pH)

- 20-23 dB gain over 5GHz
- Higher gain despite shorter electrical length
- Still maintain low intrinsic gain ripples (typically $\pm$ 2 dB)

Tukey-windowed JTWPA: System gain calibration (from JTWPA to RT analyser)

Measuring transmission through a qubit-coupled line [1]

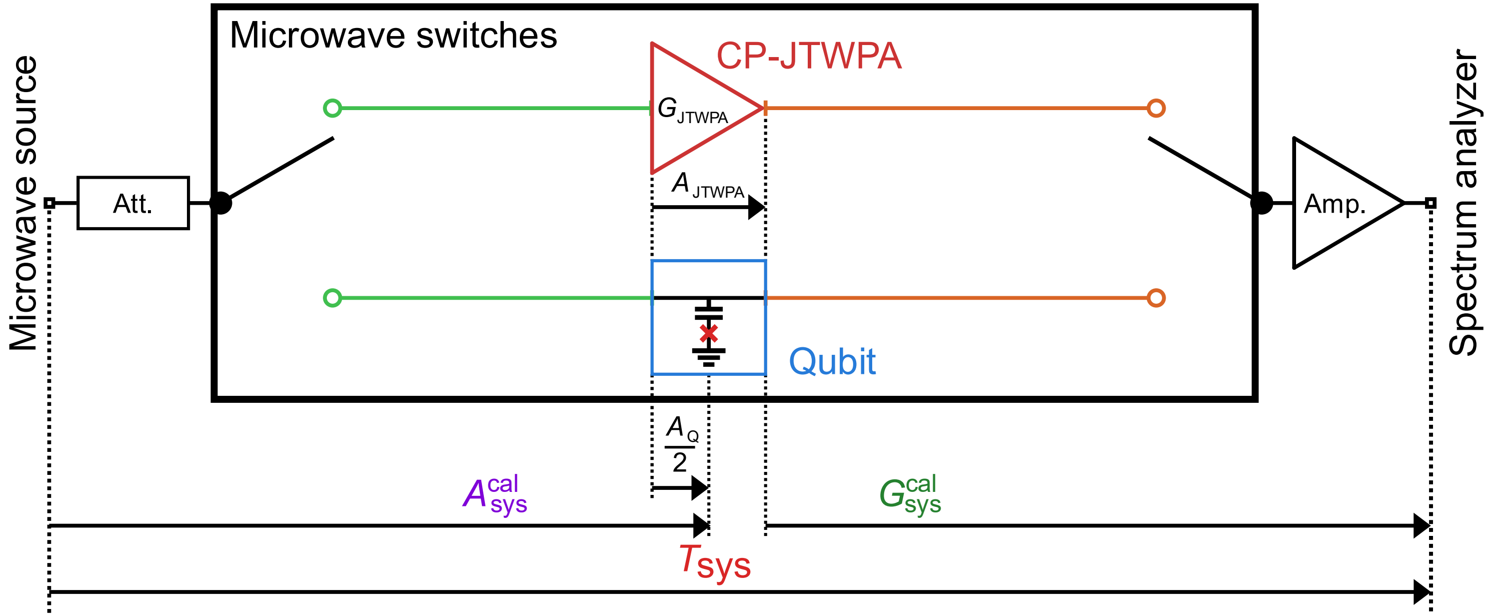




2D sweep of probe power and frequency for transmission t through qubit

- Fit by the expression: $t = 1 - e^{i\theta_F} \frac{\xi\Gamma_1}{2\Gamma_2} \frac{1-\frac{i\Delta}{\Gamma_2}}{1+\left(\frac{\Delta}{\Gamma_2}\right)^2+\frac{\Omega^2}{\Gamma_1\Gamma_2}}$, where $P = \hbar\omega_q\Omega^2/2\Gamma_1$
- Obtain the attenuation from RT source to qubit A_{sys}^{cal}

Measure system transmission T_{sys} → Obtain system gain G_{sys}^{cal} from JTWPA



[1] Kannan *et al.*, *Sci. Adv.* **6**, 41, (2020)

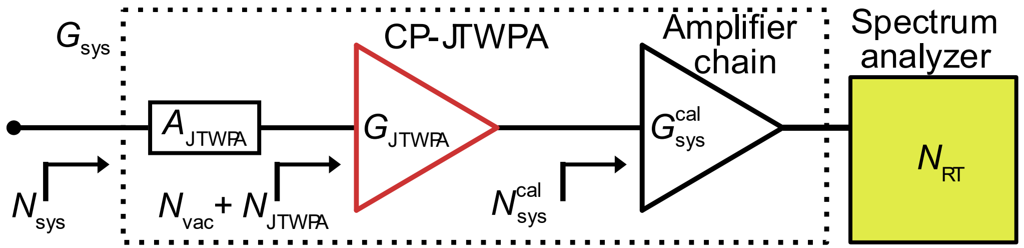
Periodic-modulation JTWPAs with windowed modulations

Tukey-windowed JTWPA: Added noise

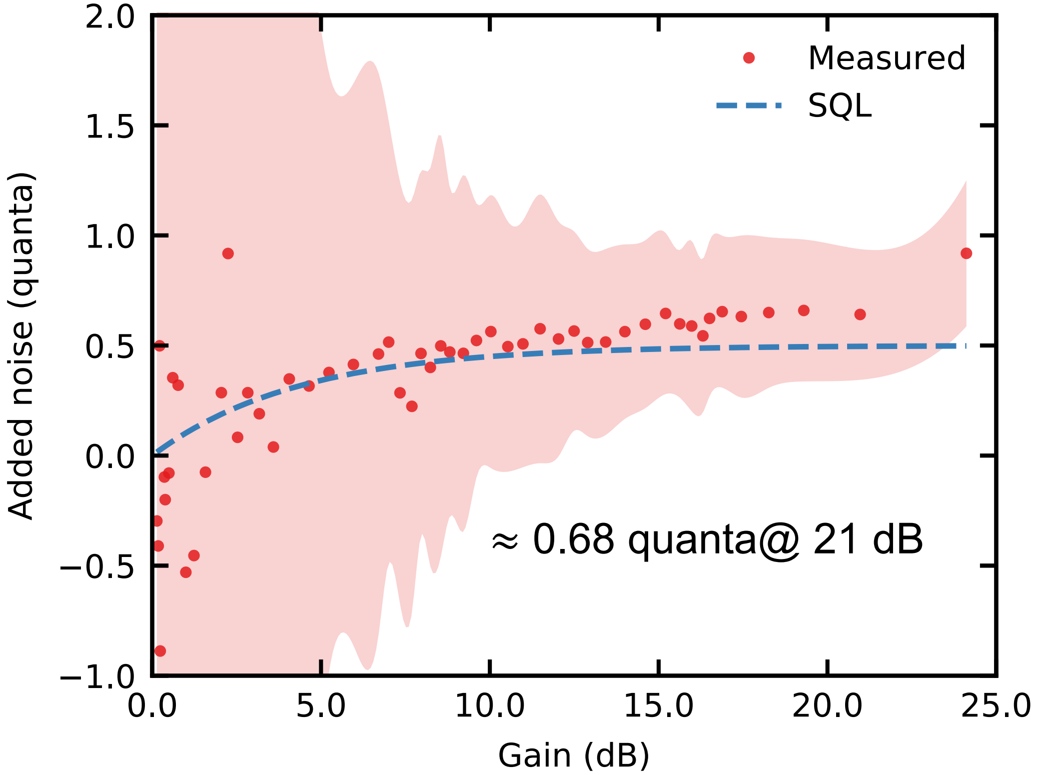
Measuring added noise by ON-OFF subtraction

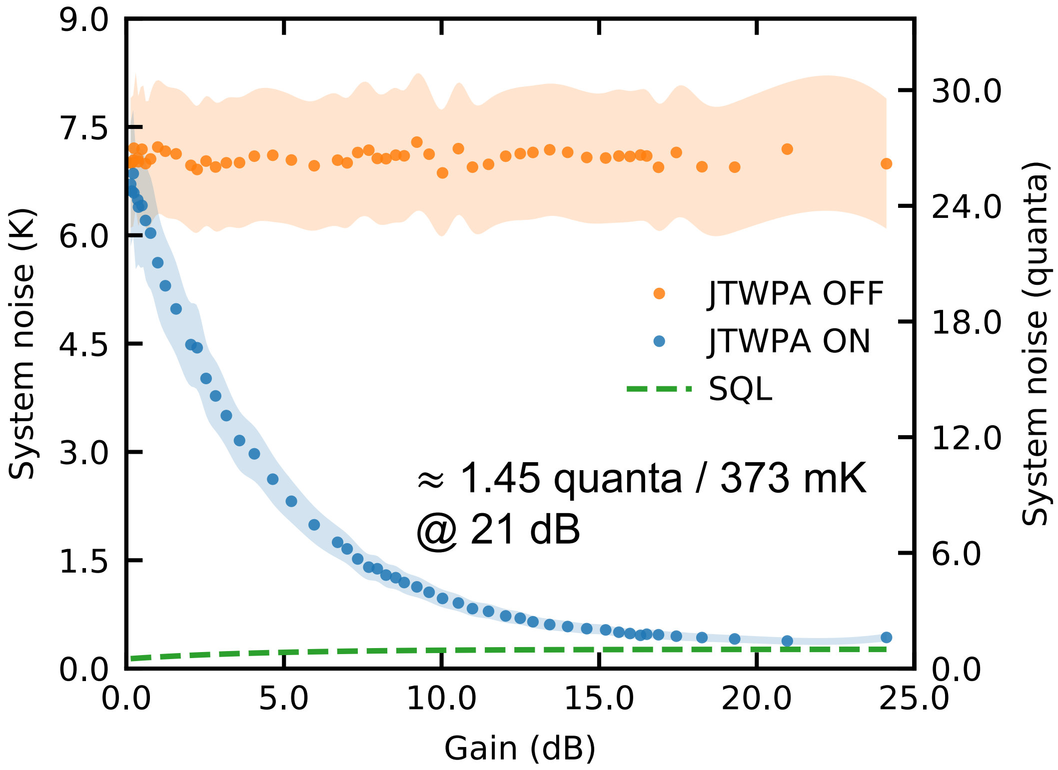
@ 5.56 GHz

$$N_J = \frac{(N_{RT}^{ON} - N_{RT}^{OFF})/G_{sys}^{cal}}{G_J} - N_{vac}\left(1 - \frac{1}{G_J}\right)$$



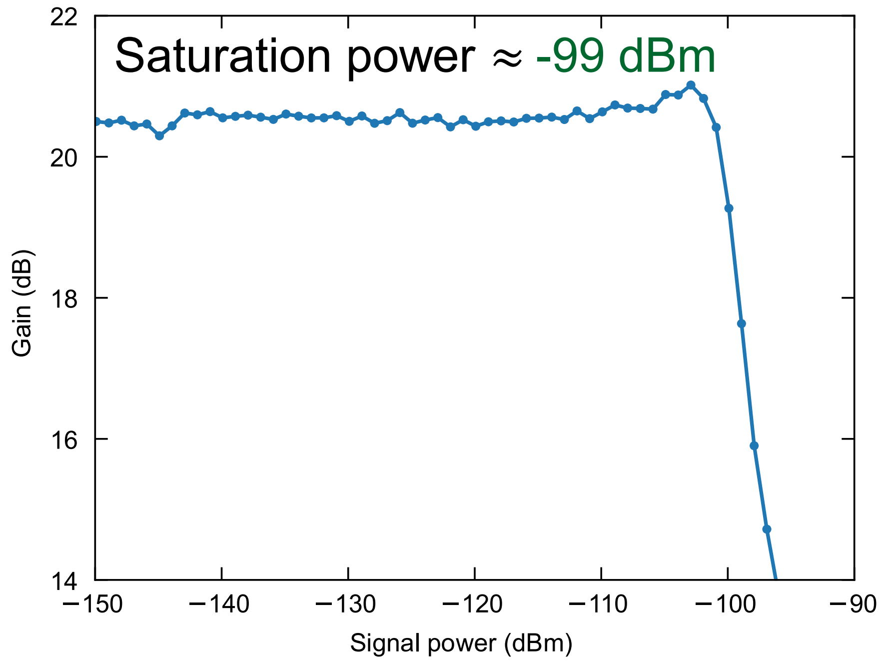
$$N_{sys}^{ON} = \frac{N_{RT}^{ON}}{G_{sys}} = \frac{A_{JTWPA} N_{RT}^{ON}}{G_J G_{sys}^{cal}}$$





Tukey-windowed JTWPA: Saturation power and conclusion

Saturation power



Conclusion on Periodic-modulation JTWPA

Demonstrated:

- Low-insertion-loss (< 1 dB) JTWPA line

Achieved with a Tukey-windowed JTWPA:

- 20-23 dB intrinsic gain over 5 GHz with low (< ±2 dB) intrinsic ripples
- Adding only 0.68 quanta of noise at 21-dB gain

Reference	Process	System noise (photons)	Gain (dB)	Bandwidth (GHz)	Saturation (dBm)	Pump power (dBm)
Macklin *et al.*	4WM	2	21.6	3	−99	−63
Planat *et al.*	4WM	3	18	2.3	−100	−70
Chang *et al.*	4WM	1.45	20	4.8	−99	−70

Q: Can we do even better?

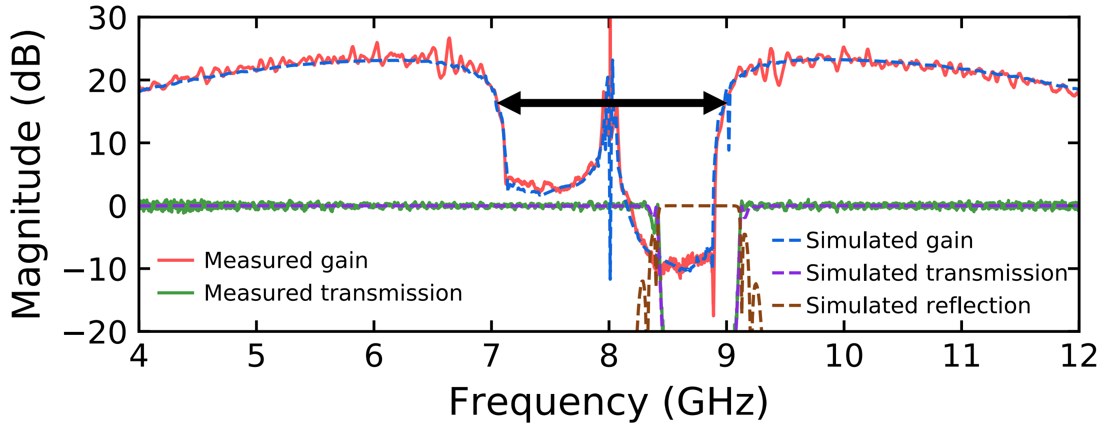
Bias-free JTWPAs

Our journey of developing JTWPAs at RIKEN

- Background, working principles of JTWPAs
- Periodic-modulation JTWPAs with windowed modulations
- Distributed-coupling resonant-phase-matching JTWPAs (dcRPM)

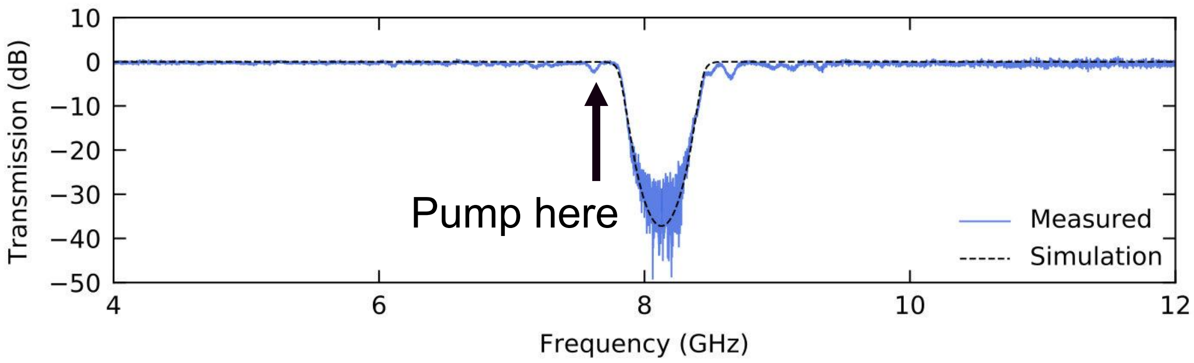
Periodic-modulation JTWPAs: Limitations

Large bandgap



- Modulation strength → Correction strength → Gap size
- 2 GHz gap with the Tukey-windowed JTWPA
- Consuming a significant amount of bandwidth

Pump frequency depends on junctions

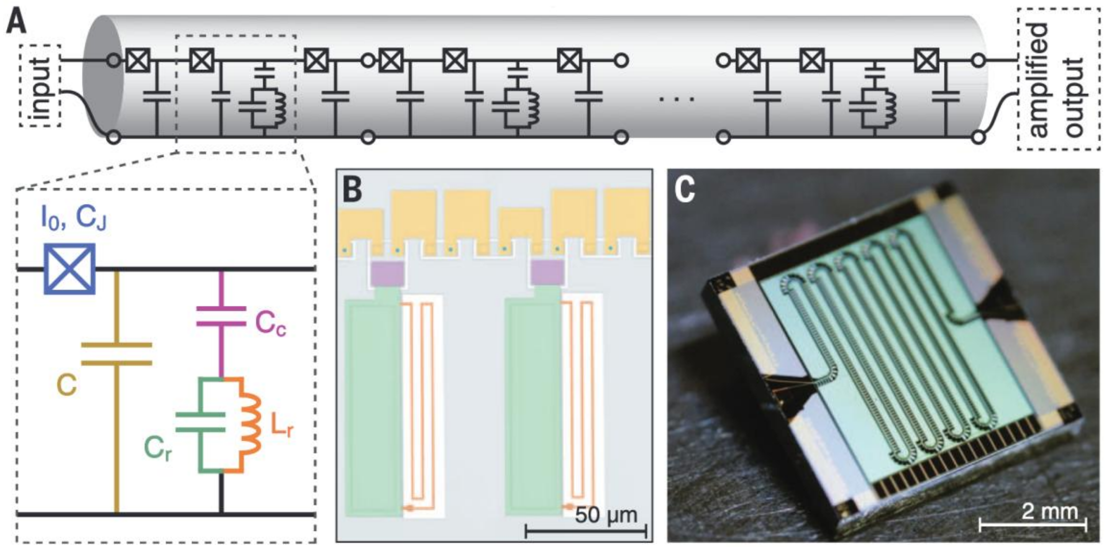


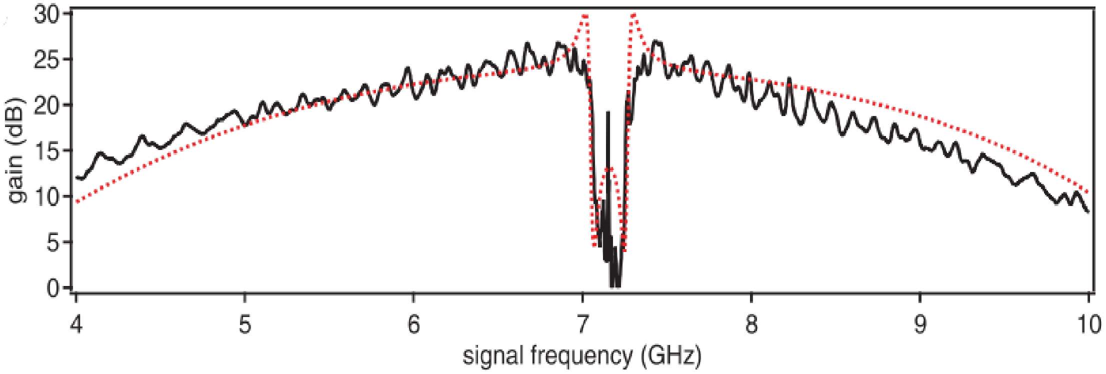
- Gap frequency varies with junction resistance
  A few-Ohm off → hundreds of MHz off
- Difficult to cascade two or more JTWPAs
  e.g. for use with reflectionless filters

RPM JTWPAs do not suffer from the above (without dc/flux bias)

Distributed-coupling resonant-phase-matching JTWPAs

Resonant-phase-matching[1] JTWPAs





Insert a band stop filter every few unit cells along the JTWPA line

→ create a very-sharp bandgap in transmission

Strong phase-matching, narrow bandgap

- Wide-band, high gain

Sensitive to resonator-frequency variation[3]

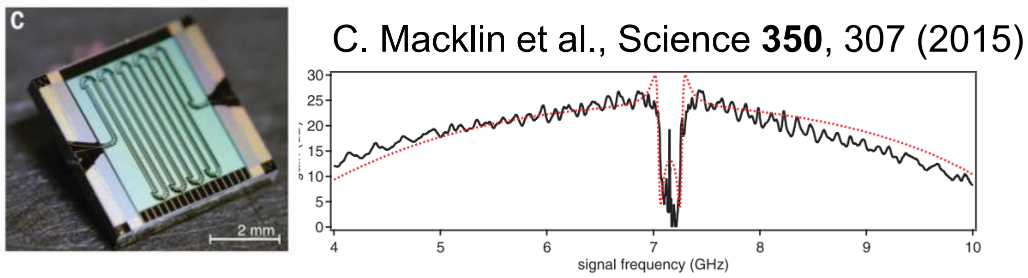
- Pump can be reflected by just one bad resonator
- Stringent fabrication requirement (with lumped-element resonators) → need less than 2% stdev

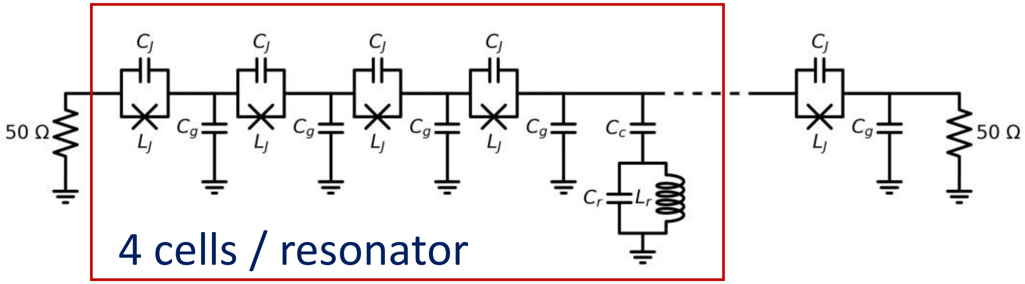
1. C. Macklin *et al.*, *Science* **350**, 6258 (2015) 3. C. Kissling *et al.*, *IEEE TAS*, **33**, 5 (2023)

RPM JTWPAs: Challenges in existing implementations

Lumped-element resonator

C. Macklin et al., Science **350**, 307 (2015)





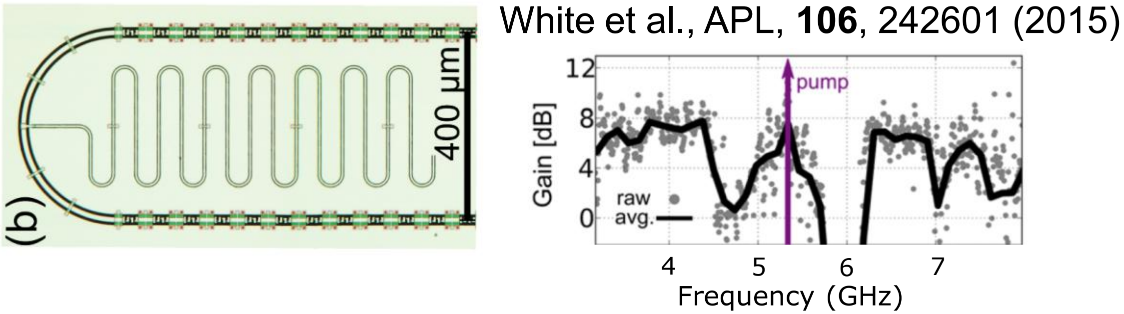
Pros: Dense phase correction → High and broadband gain

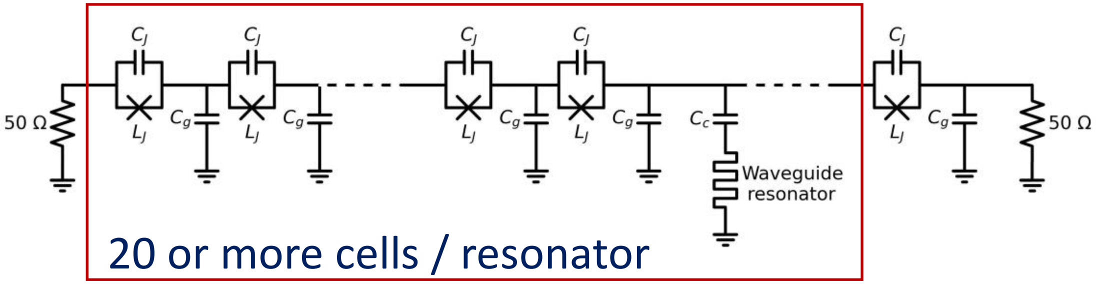
Cons: 2000 cells → 500 lumped resonators

Homogeneous lumped resonator is hard to achieve

Waveguide resonator

White et al., APL, **106**, 242601 (2015)





Pros: Homogenous resonant frequency is easy to achieve

Cons: Large footprint → sparse resonator placement

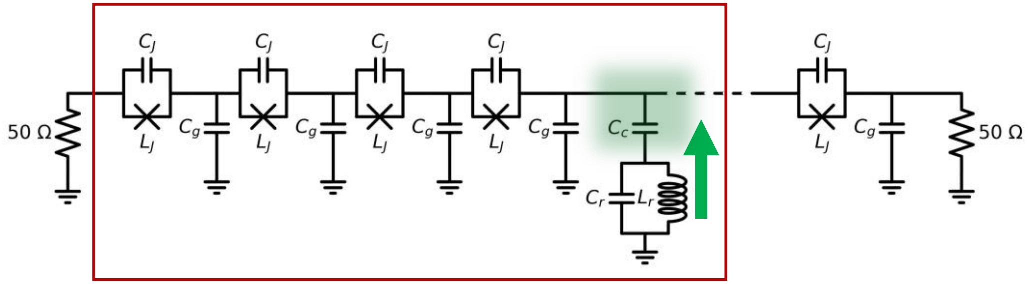
Weaker correction, reduced gain and bandwidth

Q: A design with high phase-correction density, while easy to fabricate?

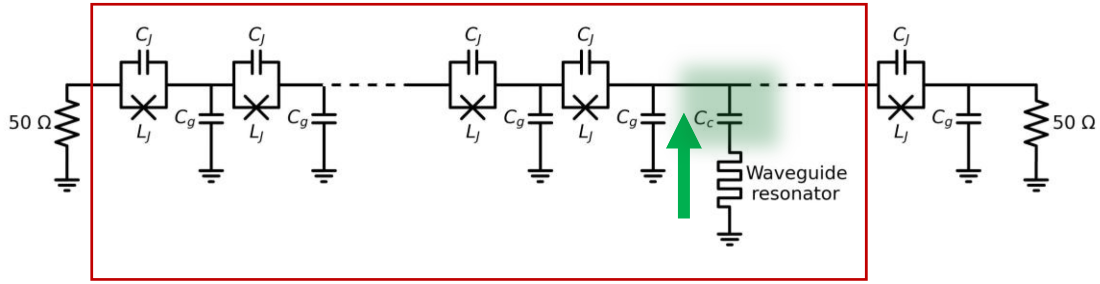
Distributed-coupling resonant-phase-matching JTWPAs

dcRPM JTWPAs: Distributed coupling of one waveguide-resonator to multiple cells

Lumped-element RPM

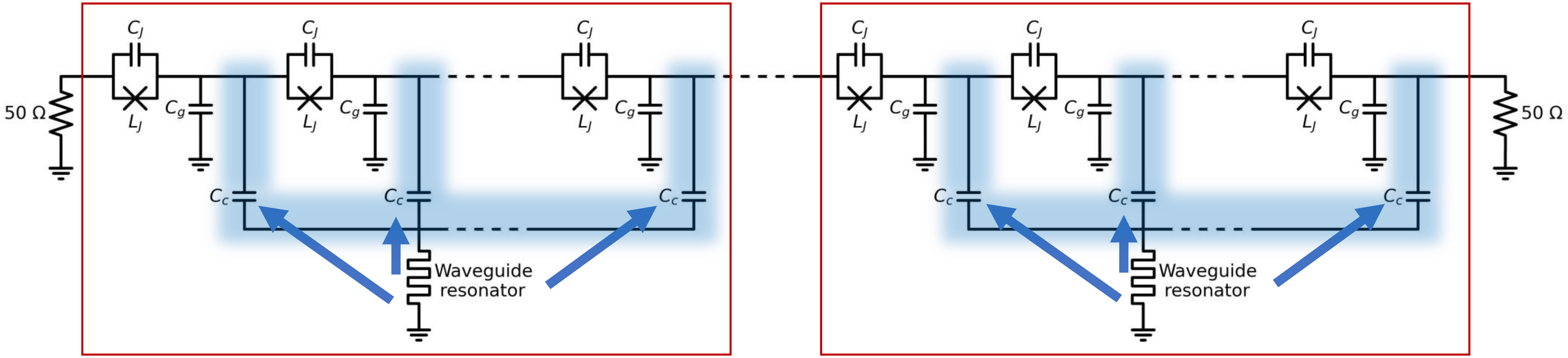


Waveguide RPM



Both schemes capacitively couple one resonator to a single node

Distributed-coupling RPM (dcRPM)

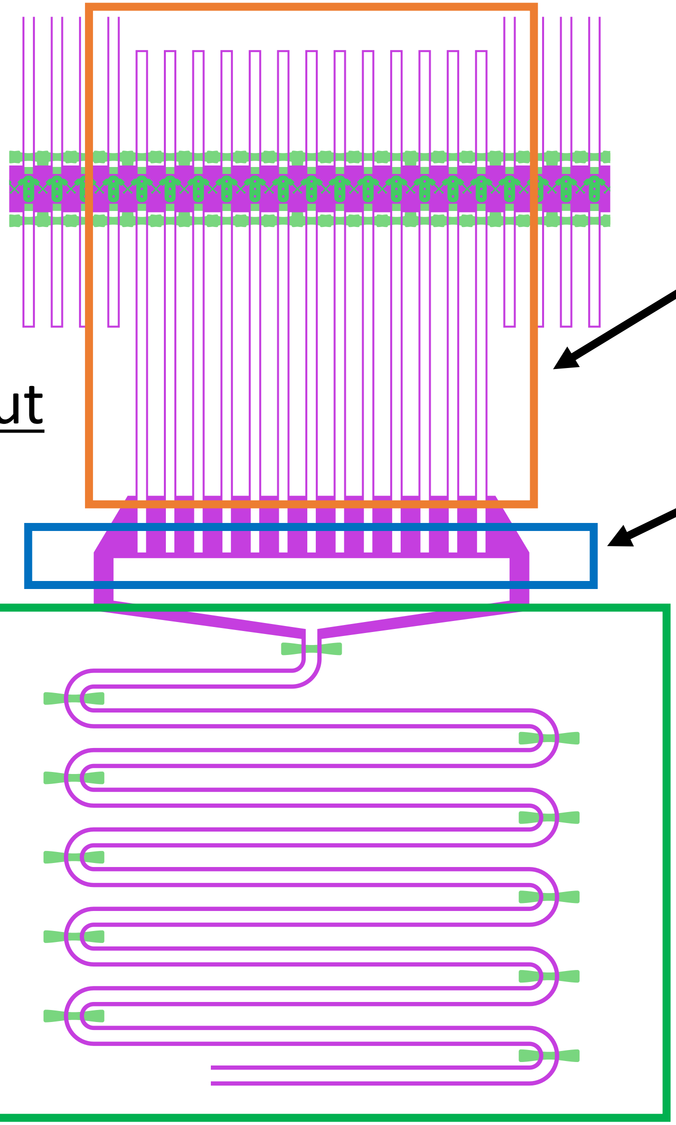


Couple one resonator capacitively to multiple nodes → Phase correct every node

Distributed-coupling resonant-phase-matching JTWPAs

dcRPM JTWPAs: Architecture

Layout



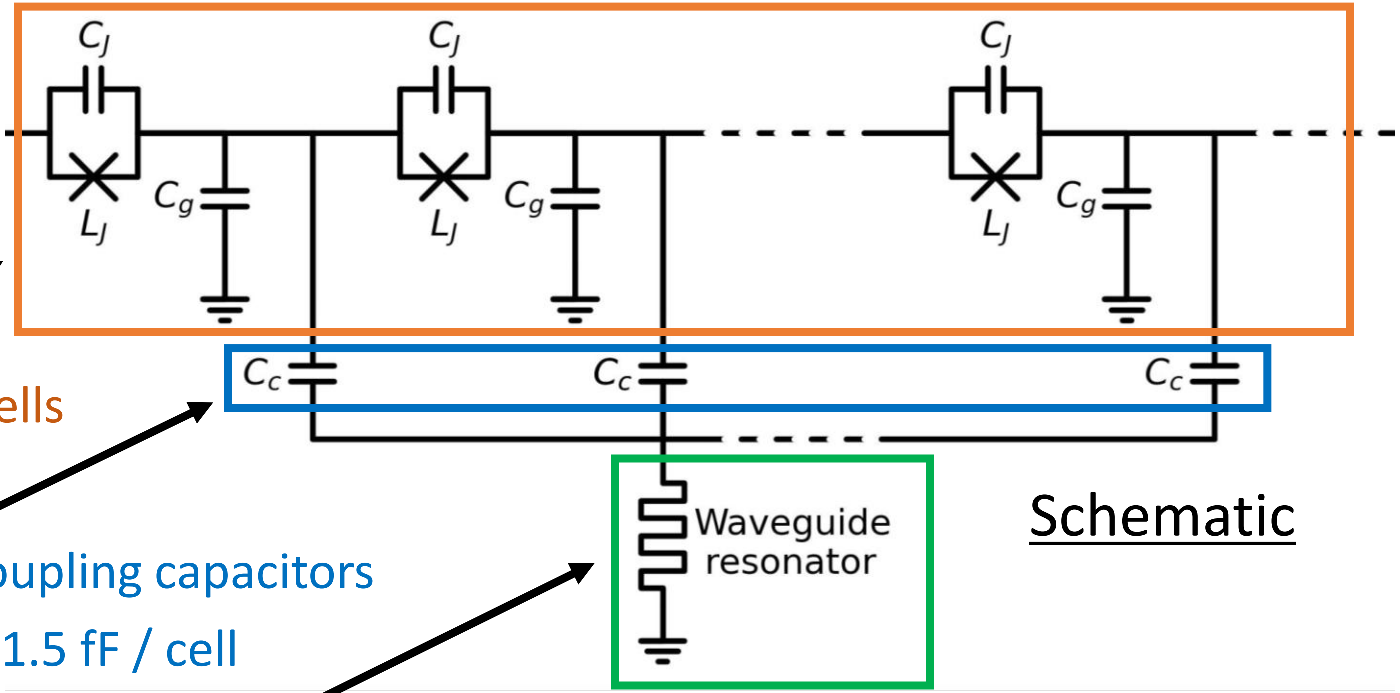
13 unit cells

Coupling capacitors

- 1.5 fF / cell

Phase-matching resonators

- $\lambda/4$ resonator
- Coupled to 13 cells



Schematic

Advantages of this implementation

Dense phase correction with fewer resonators

- Only 144 resonators for 1872 cells

Compatible with waveguide resonators

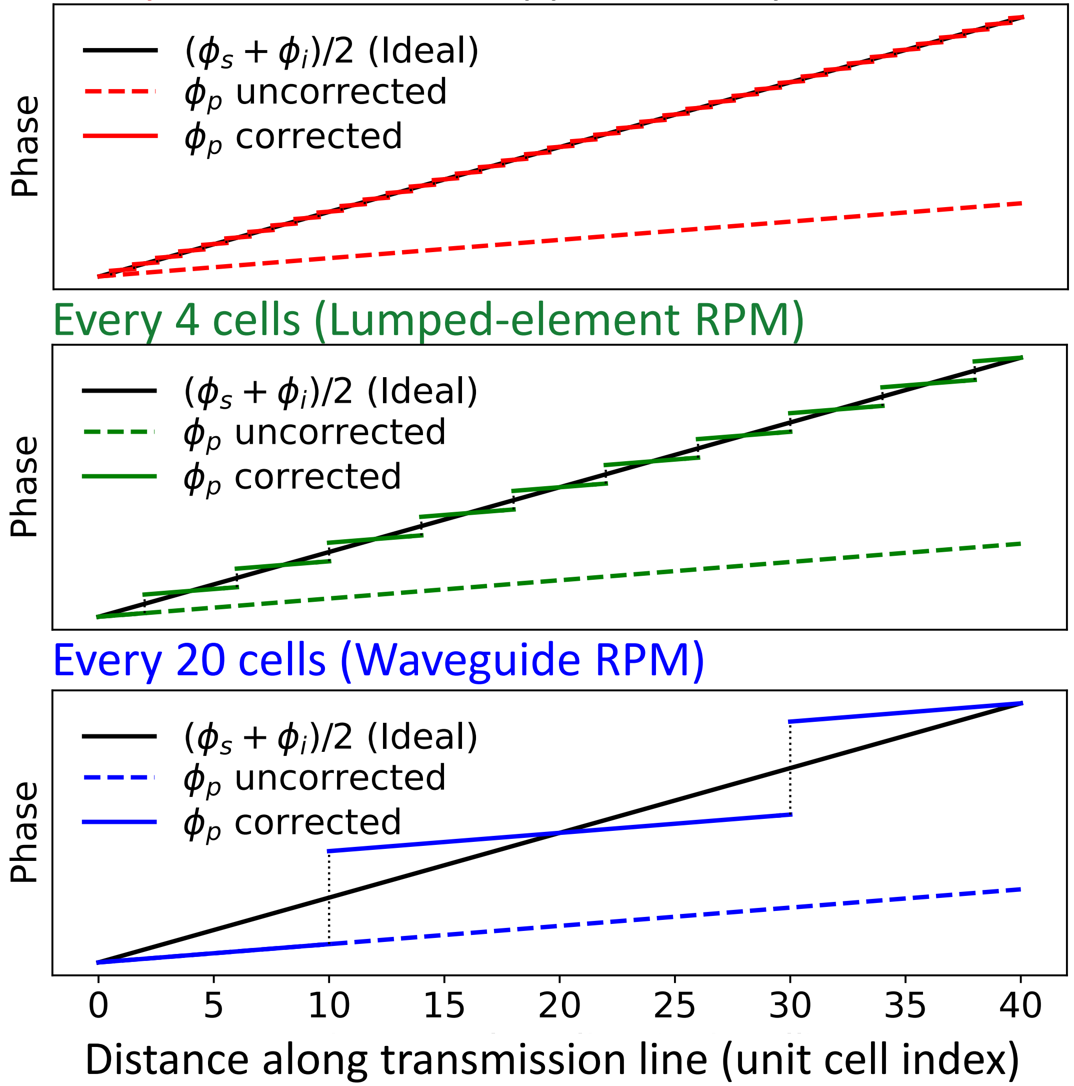
- Homogeneous resonant frequency
- Footprint no longer a limitation for correction-node density

dcRPM JTWPAs: Phase-correction density along the JTWPA line

Every 1 cell (dcRPM) (approximately)

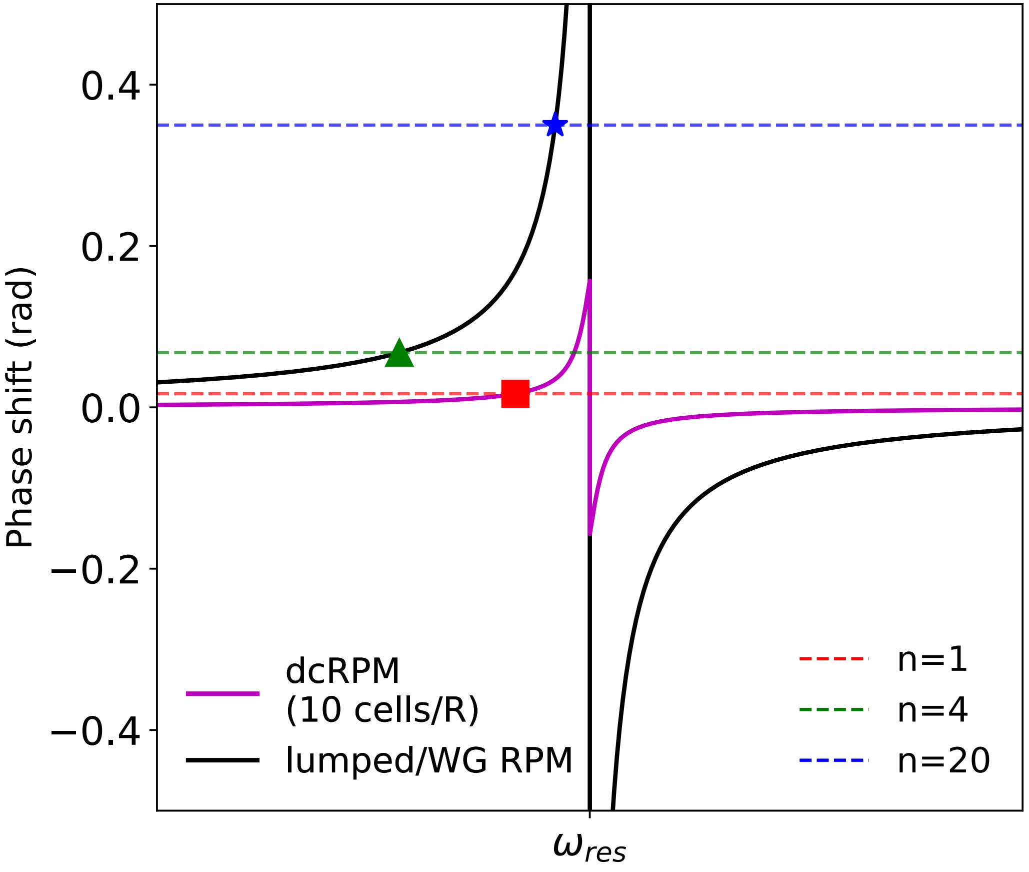
Every 4 cells (Lumped-element RPM)

Every 20 cells (Waveguide RPM)



High phase-correction density

- Resonator phase shift (π) spreads over the cells
- Denser phase correction → small reset needed

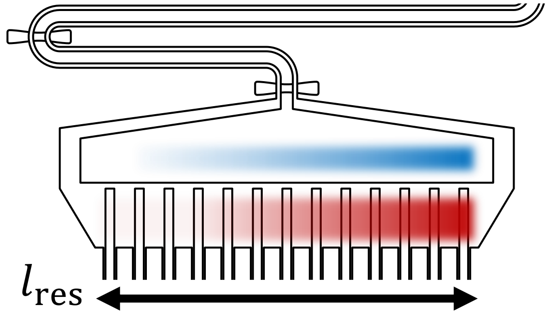


dcRPM JTWPAs: Built-in rejection of higher-harmonic modes

$$\kappa_{\mathrm{ext}}(\omega) \approx \frac{\omega^2 C_c^2 Z_0}{2C_r} \times \left[\mathrm{sinc}\left(\frac{\omega l_{\mathrm{res}}}{2v_p}\right)\right]^2$$

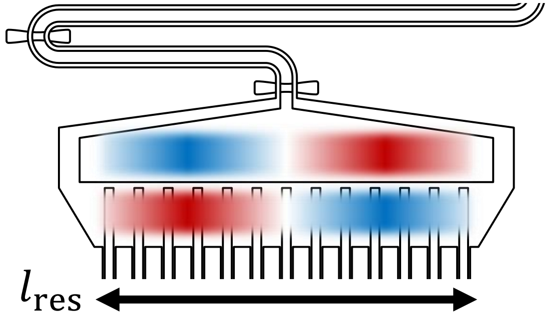
For low-frequency propagating waves:

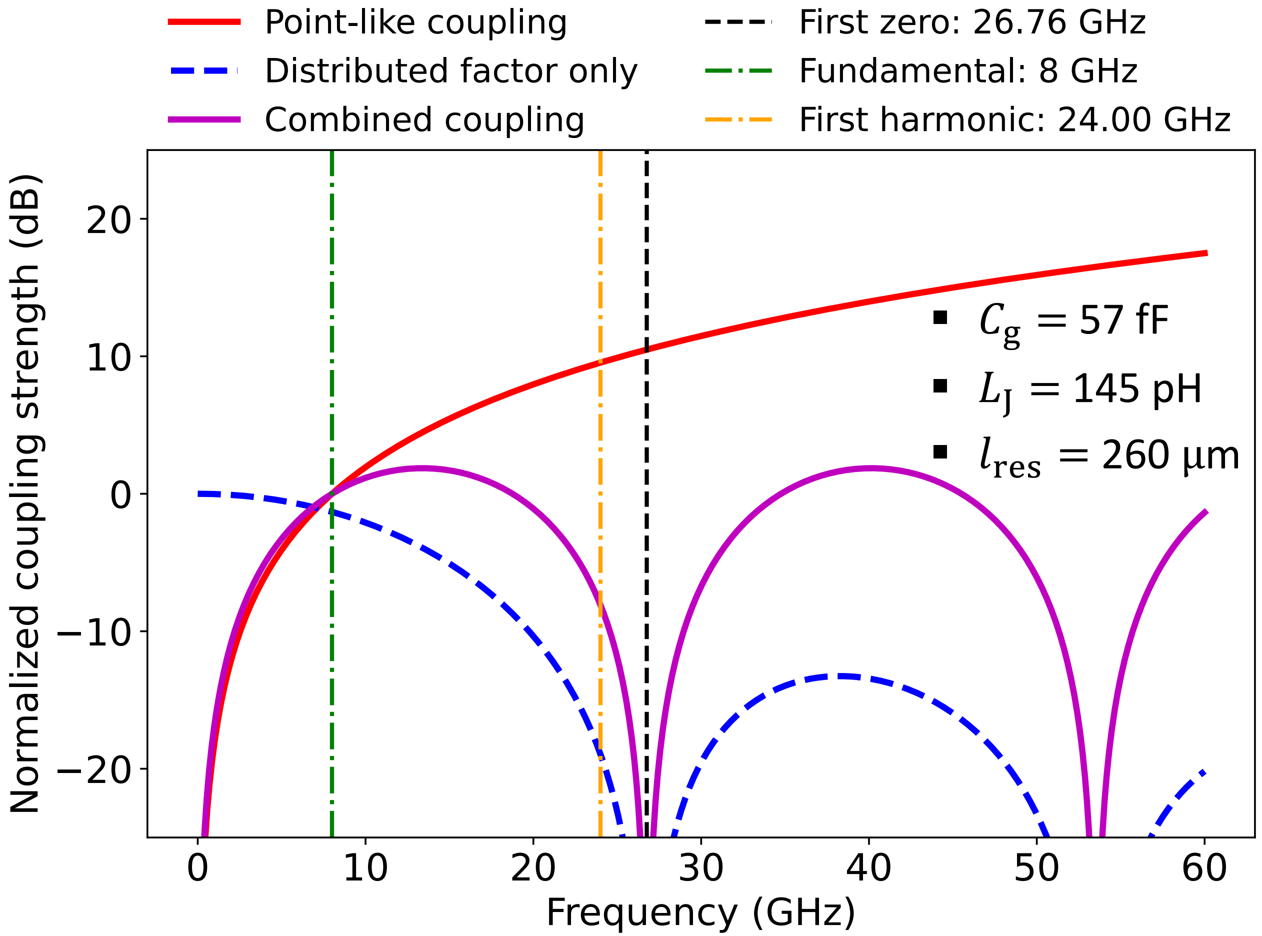
- Point-like coupling
- Overlapping cells induce a net voltage over l_{res}



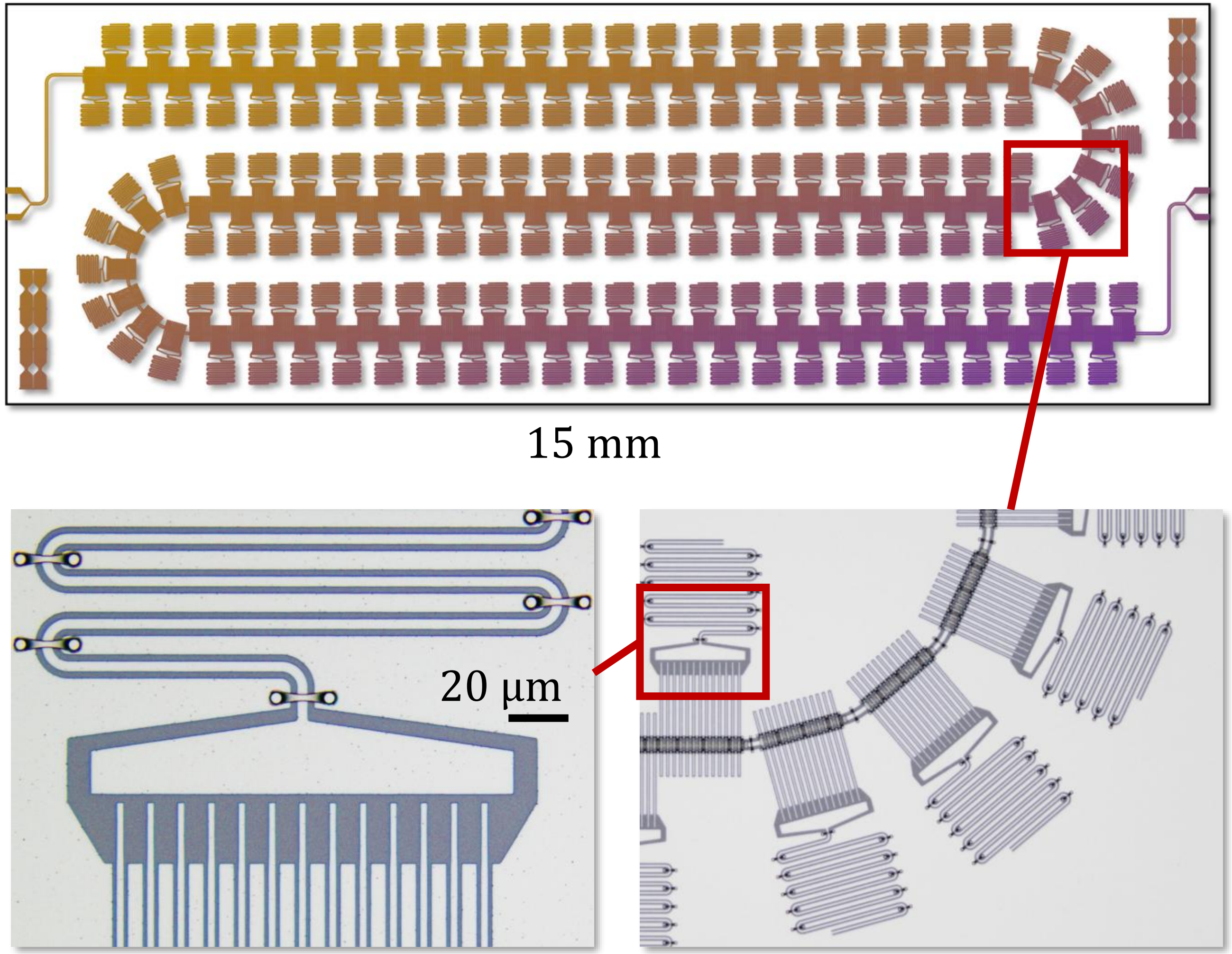
For higher-frequency propagating waves:

- When $l_{\mathrm{res}} \approx \lambda$, coupling becomes less efficient
- Coupling is cancelled when $\lambda = m \times l_{\mathrm{res}}$



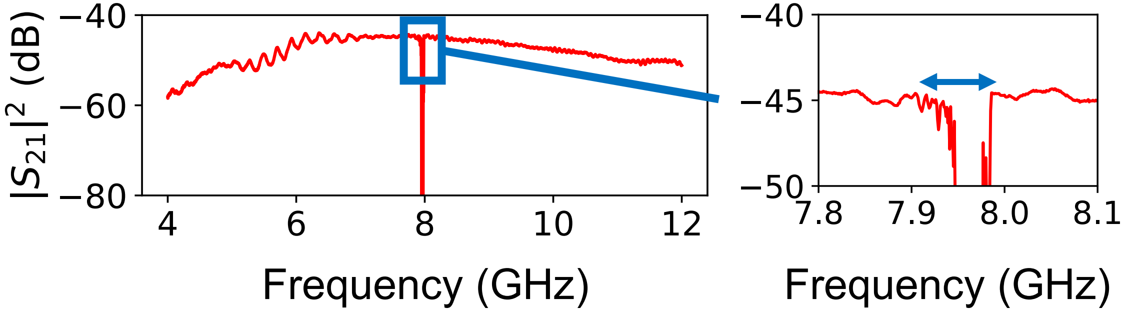


dcRPM JTWPAs: Device 2 – 1872 cells



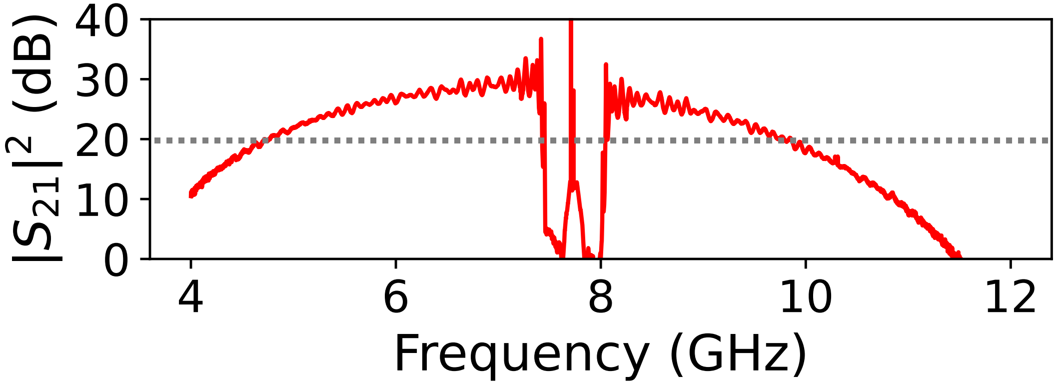
- 13 cells / R → 144 resonators

Baseline

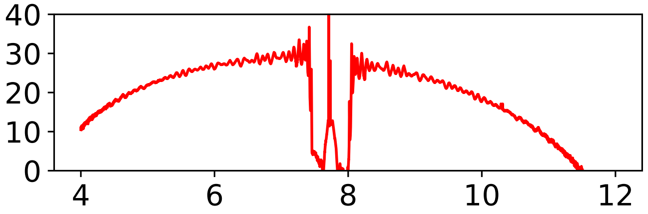


Intrinsic gain (On – Off)

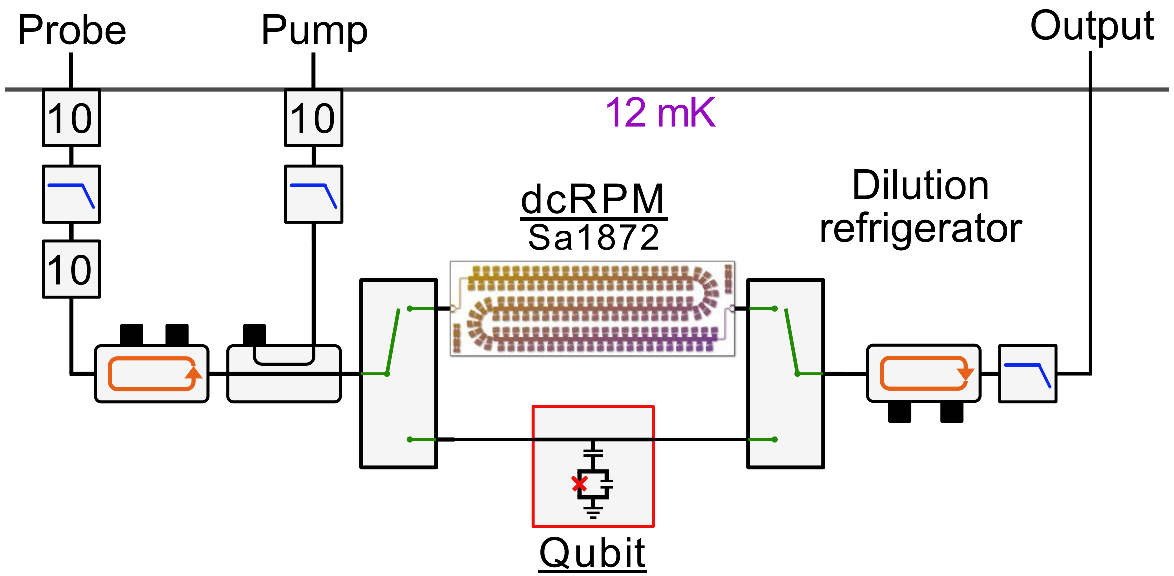
- 4.7 to 7.4 GHz: 20 to 29 dB
- 26 to 29 dB over 2 GHz

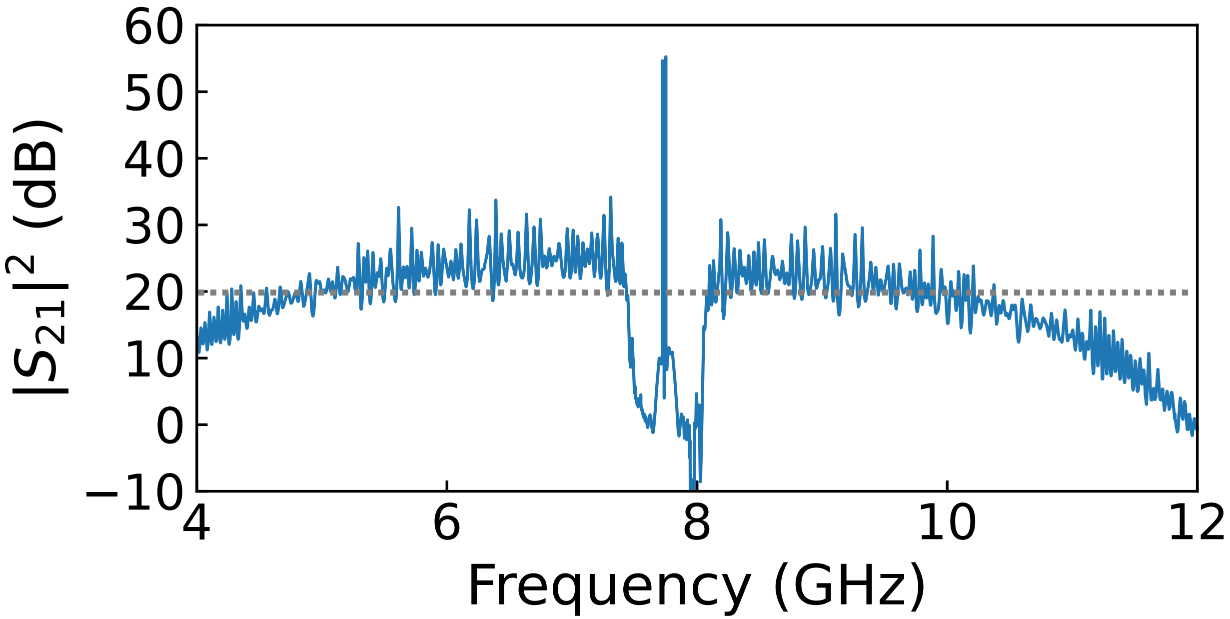


dcRPM JTWPAs: Device 2 – 1872 cells



A practical qubit-readout circuit



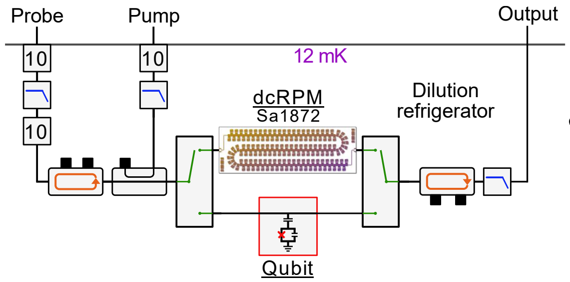


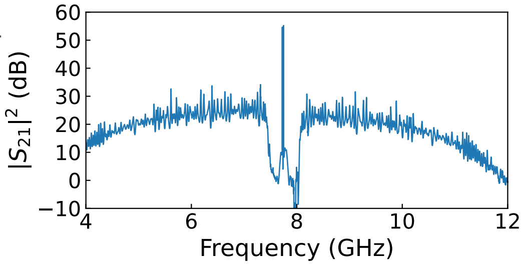
- No added attenuation between input/output circulators
- Pump coupled through directional coupler

- > 20-dB gain over 4.2 GHz (5 – 7.3 // 8.1 – 10)
- Gain ripples (± 5 dB) from background impedance mismatches

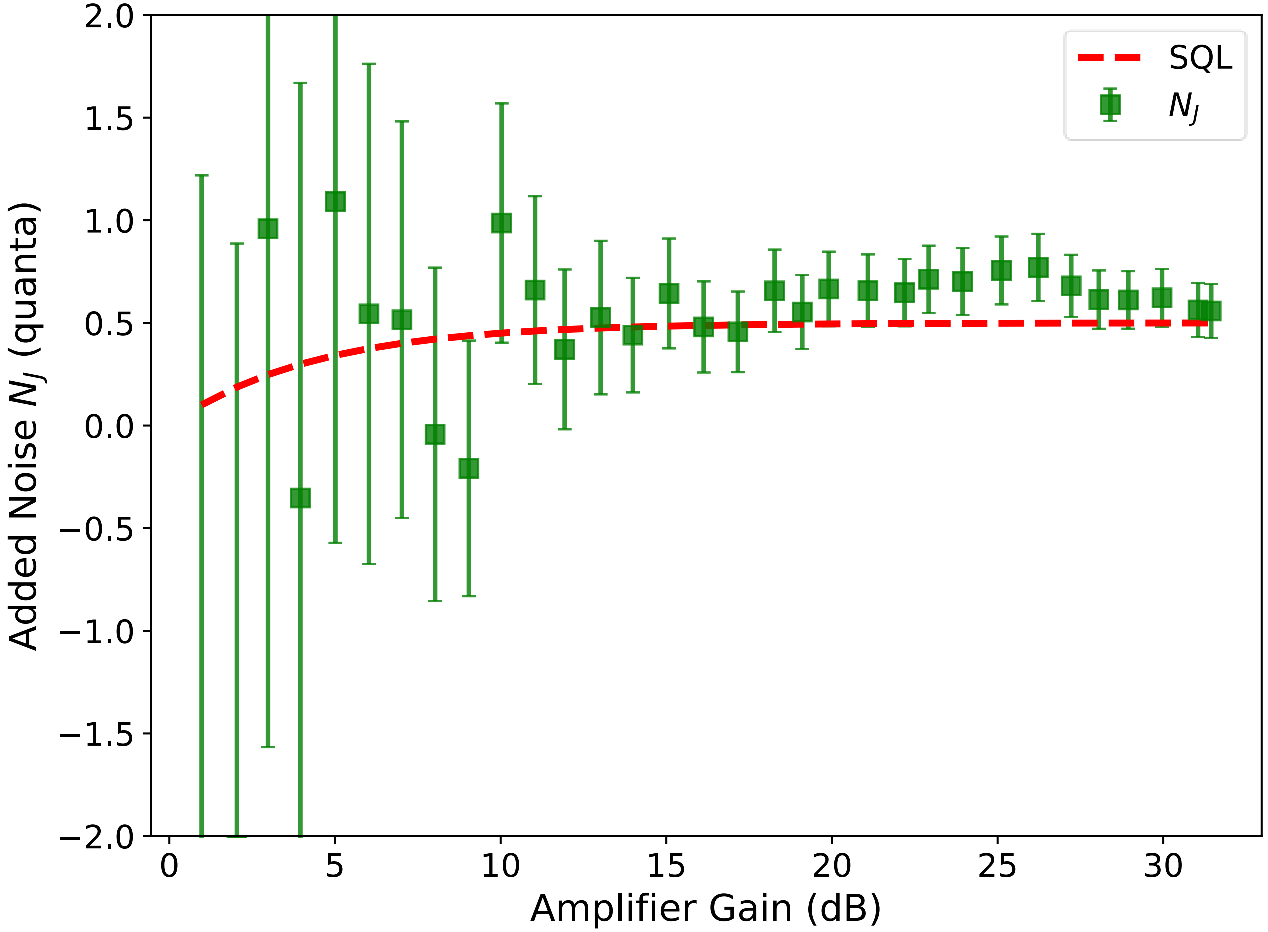
Distributed-coupling resonant-phase-matching JTWPAs

dcRPM JTWPAs: Device 2 – 1872 cells





Noise performance (@ 5.563 GHz)

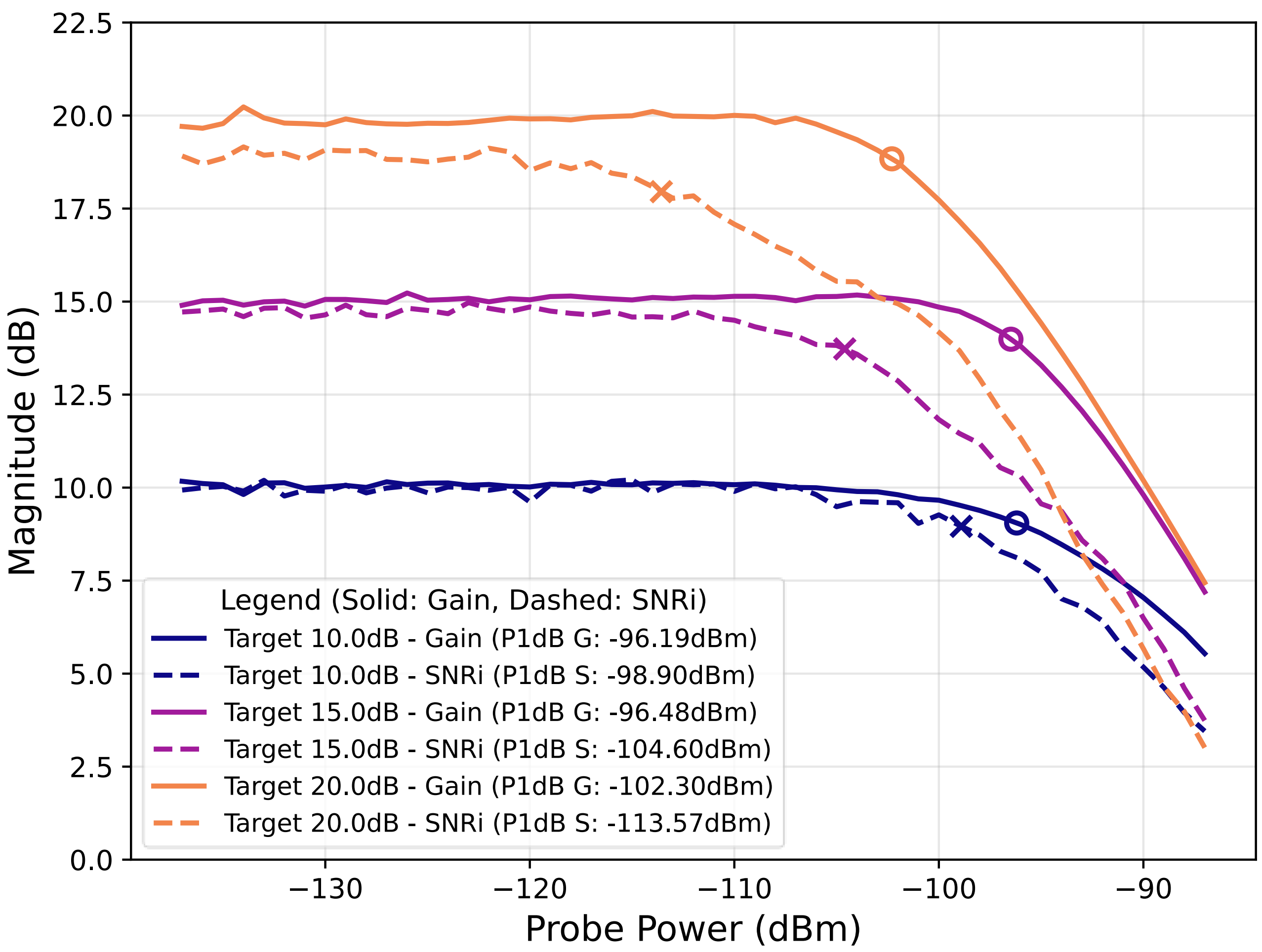


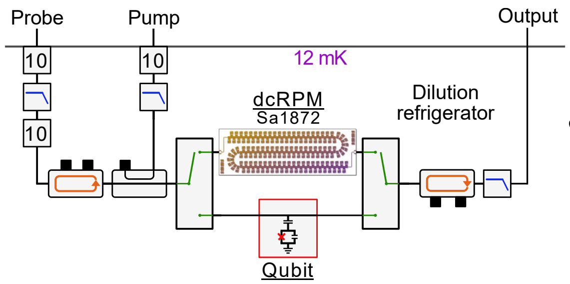
≈ 0.68 quanta over 20 – 24 dB gain

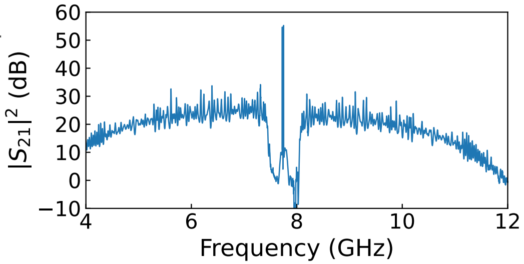
Distributed-coupling resonant-phase-matching JTWPAs

dcRPM JTWPAs: Device 2 – 1872 cells

Gain and SNR improvement saturation (@ 5.563 GHz)







@ 20-dB gain

- Gain saturates at -102 dBm
- SNRi saturates at -114 dBm, 12 dB lower comparing to gain

This gap may be closed by implementing Floquet-mode engineering[1]

*High SNRi as we only used HEMT in the output line, no RT amps

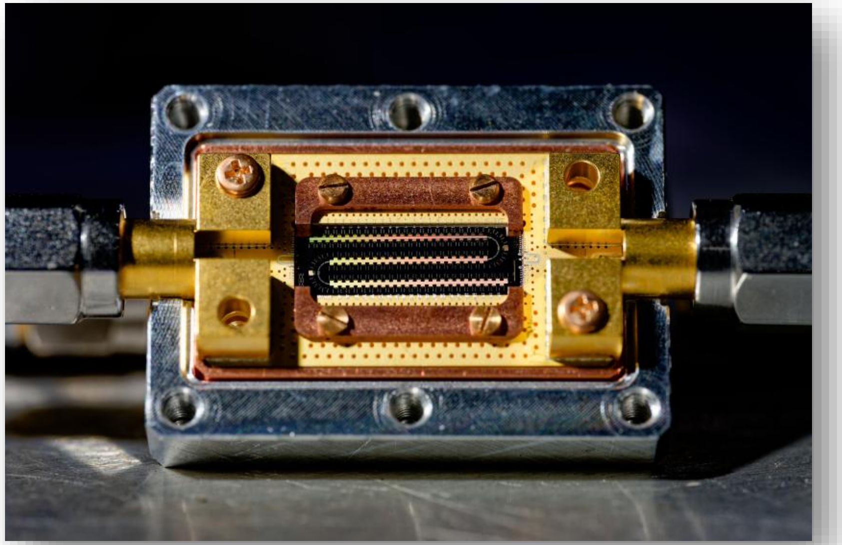
1. J. Wang *et al.*, *arXiv:2503.11812v2* (2025)

Conclusion on distributed-coupling RPM JTWPAs

dcRPM design makes fabrication easier without compromising performance

- > 20-dB gain over 4.2 GHz in a realistic qubit-readout circuit
- Reaching an added noise of 0.68 quanta, within 0.2 quanta from the SQL
- Saturation power at -102 dBm (SNRi at -114 dBm)

Package designed by Yu Zhou from Fujitsu



Reference	Process	System noise (photons)	Gain (dB)	Bandwidth (GHz)	Saturation (dBm)	Pump power (dBm)
Macklin *et al.*	4WM	2	21.6	3	−99	−63
Planat *et al.*	4WM	3	18	2.3	−100	−70
Chang *et al.*	4WM	1.45	20	4.8	−99	−70
This work	4WM	≈ 1.4	23	4.2	−102	≈ −72

A long way to go

From none to one ✅, from one to many?

Current fabrication recipe has a limited throughput (6 device in two weeks)

- Problem: Systematic variation in R_{N} of junctions evaporated over a wafer[2]
- To-try: Computational lithography to compensate for the offset in R_{N}

Making JTWPA more resilient and non-reciprocal

Poor impedance matching reduces achievable gain, and increases gain ripples

To-try:

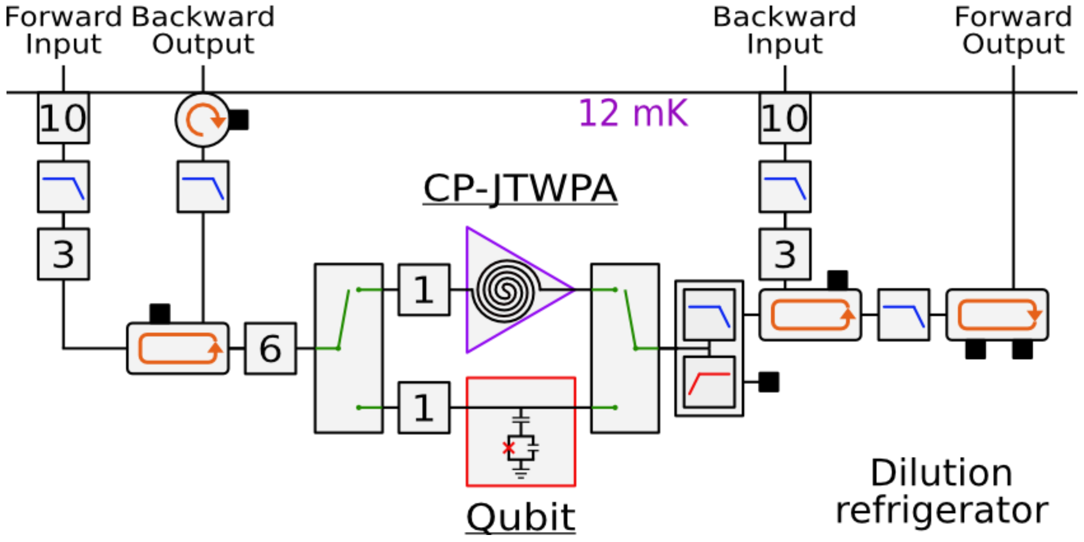
- Using reflectionless filters to introduce non-reciprocality[1] and prevent oscillations of signal waves through the JTWPA

1. C. Kow *et al.*, *arXiv:2505.04059* (2025) 2. T. Takahashi *et al.*, *Jpn. J. Appl. Phys.* 62 SC1002 (2023)

Appendices

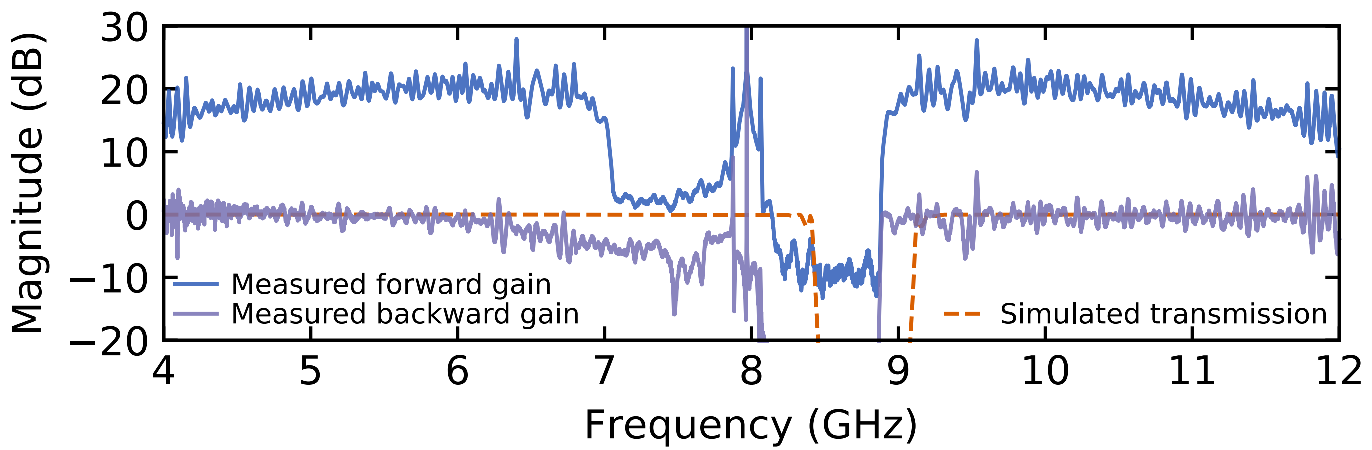
Periodic-modulation JTWPAs with windowed modulations

Tukey-windowed JTWPA: Noise and backward gain calibration circuit



- Input-side attenuation: 7 dB
- Output-side attenuation: ~ 1 dB
- In parallel with a qubit-coupled line for power calibration
- Allow for measuring added noise, saturation power and backward gain

Gain profile under imperfect impedance matching



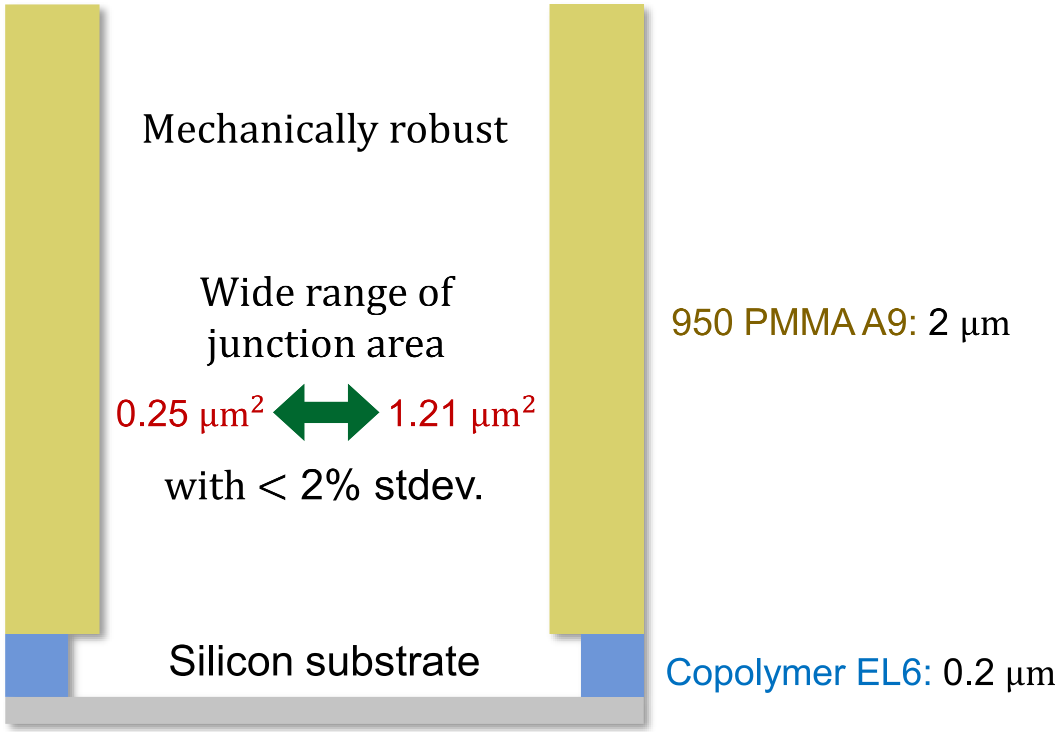
- Gain ripples become stronger, reaching ± 5 dB
- Near zero to negative backward gain is observed over the 4 – 7 GHz range
- Noise calibration done at 5.563 GHz

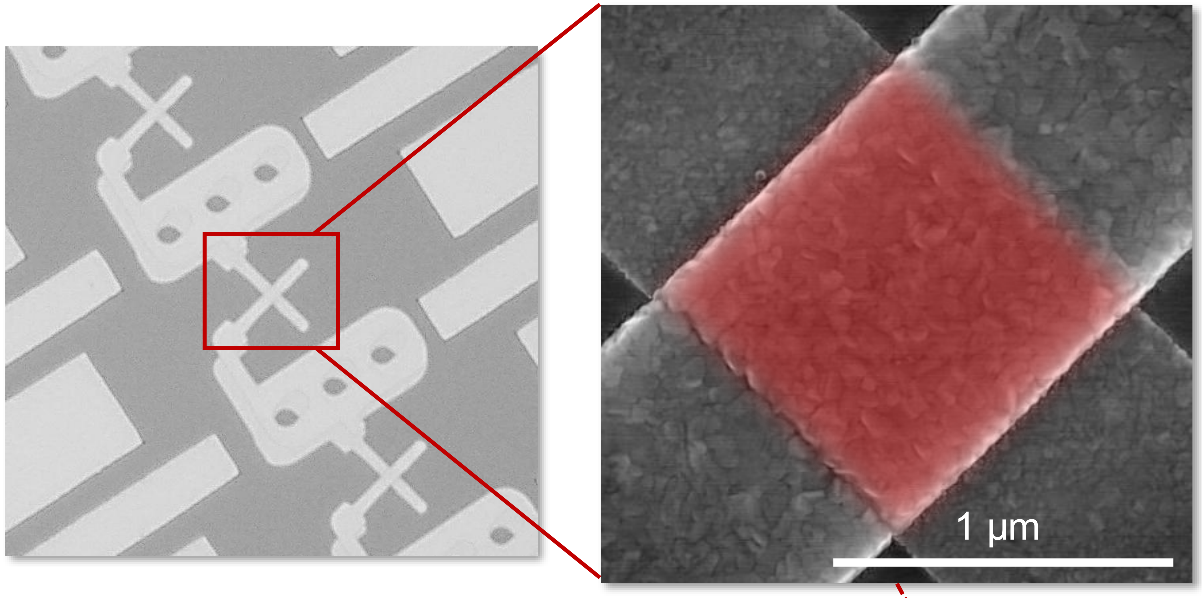
Coplanar JTWPA: Design challenge 1

Reliable junction fabrication

- High yield (99.99% JJ yield → 80% device yield)
- High uniformity (< 2% for low gain ripple/reflection[1])

Large cross-type junction





Resistance tests on a 5-by-5 mm chip area, 10 test junctions per design

Electrode width (um)	0.3	0.5	0.7	0.9	1	1.1
Area (um^2)	0.09	0.25	0.49	0.81	1	1.21
Average resistance (Ω)	1340	447	225	139	116	98.2
stdev (Ω)	30.2	7.29	2.53	1.03	0.576	0.419
stdev %	2.25	1.63	1.12	0.739	0.498	0.426
Area x Resistance (um^2-Ω)	121	112	110	113	116	119

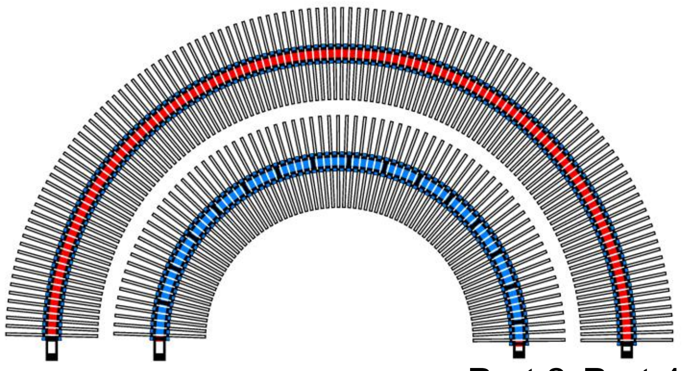
1. K. Peng *et al.*, *PRX QUANTUM* **3**, 020306 (2022)

Coplanar JTWPA: Design challenge 2

Slotline modes and ground current routing

Can be mitigated by adding airbridges across different ground planes

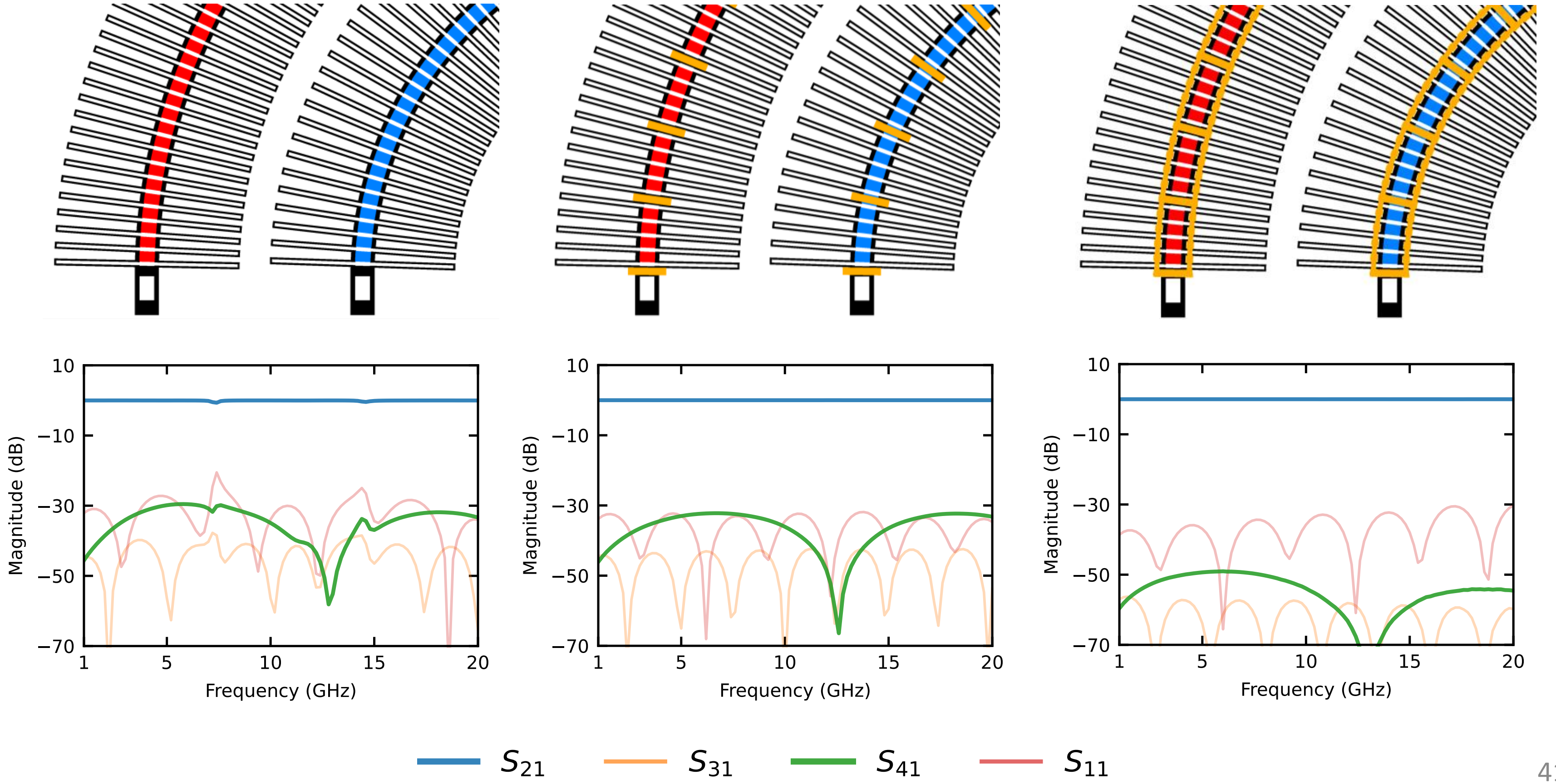
- FEM crosstalk simulation



Simulating the coupling between two adjacent arcs different in length

- High density (every 5 cells) cross-GND and cross-stub airbridges are desired

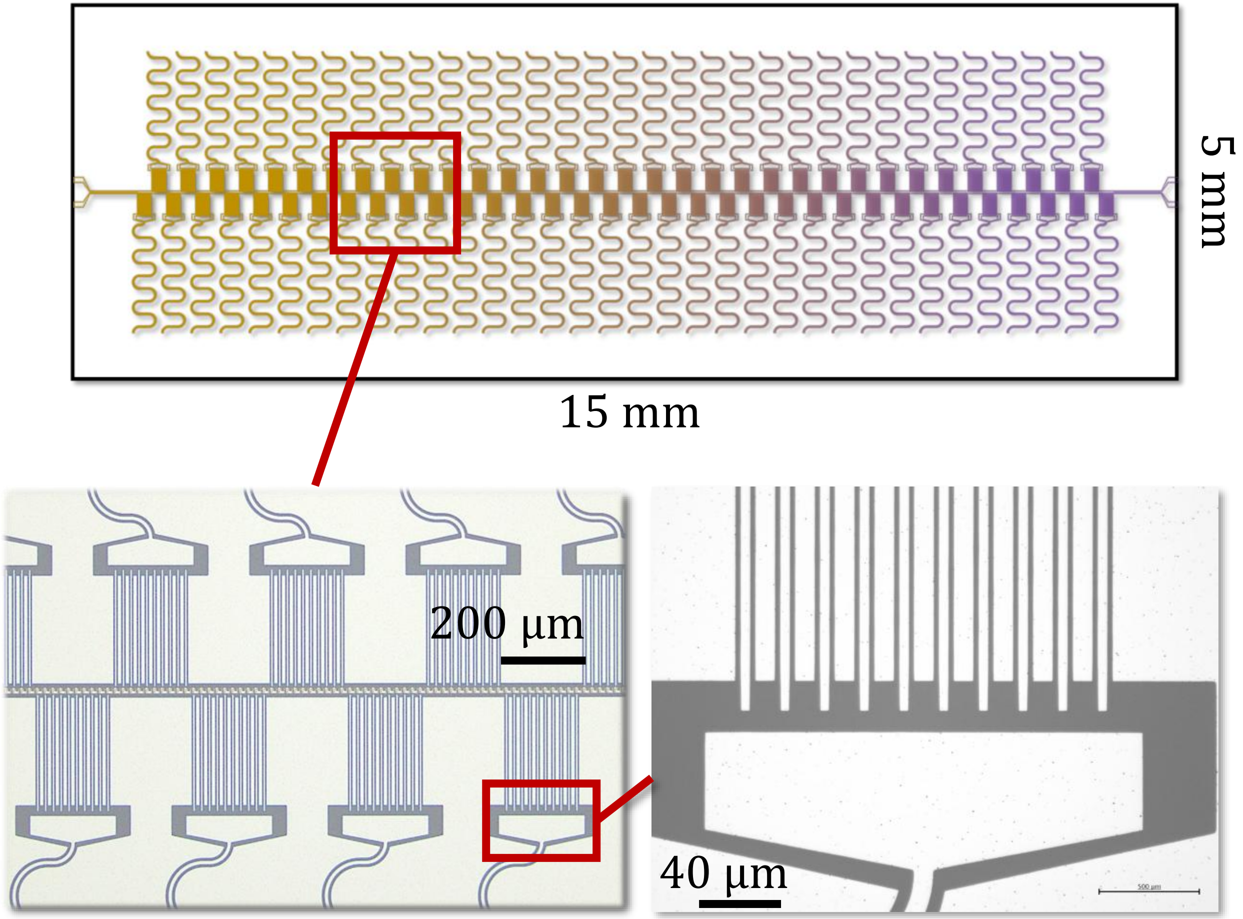
- No airbridge at all
- Cross-GND airbridges
- Cross-GND + Cross-stub airbridges



Distributed-coupling resonant-phase-matching JTWPAs

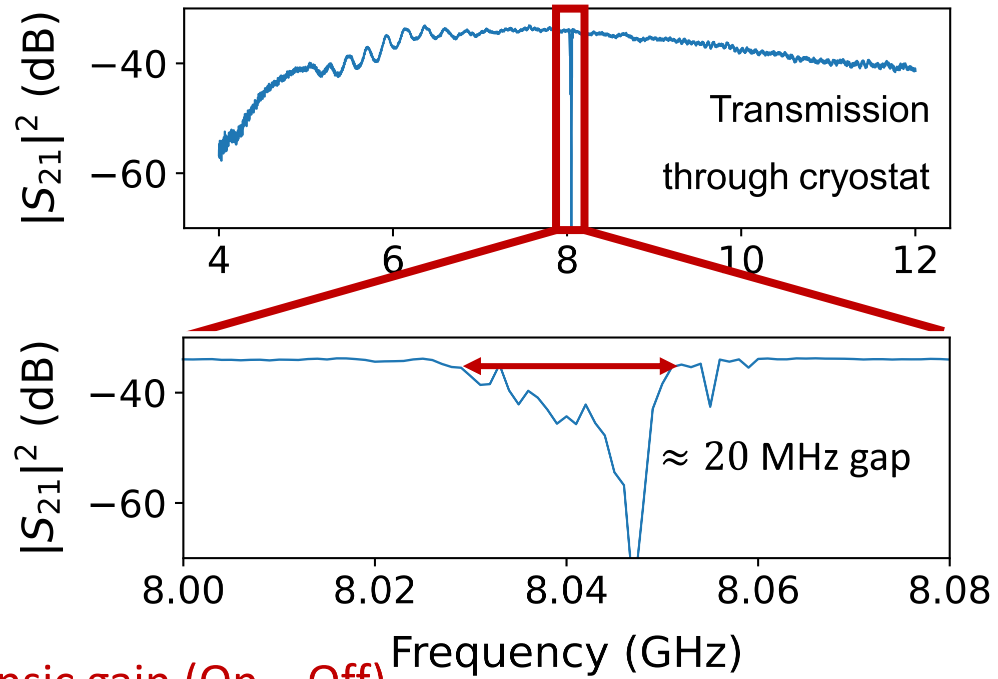
dcRPM JTWPAs: Device 1 – 670 cells

Designed by Shintaro Ae

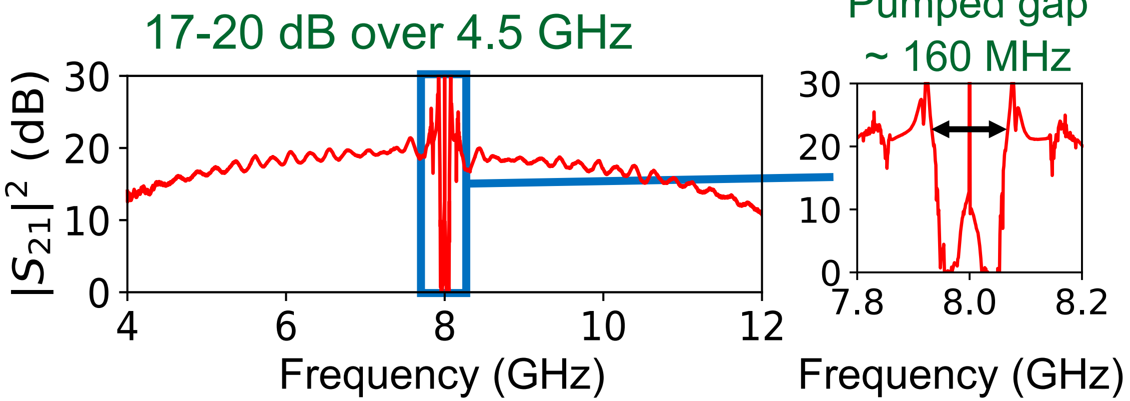


- 10 cells / R → 67 resonators

Baseline



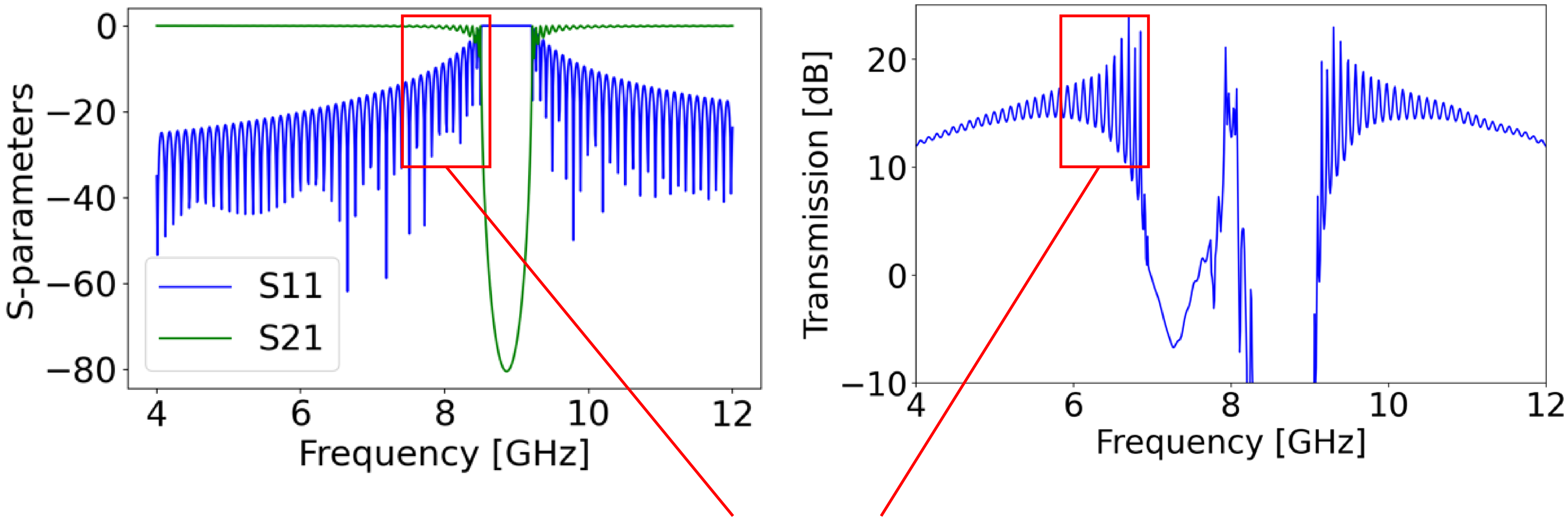
Intrinsic gain (On – Off)



Periodic-modulation JTWPAs with windowed modulations

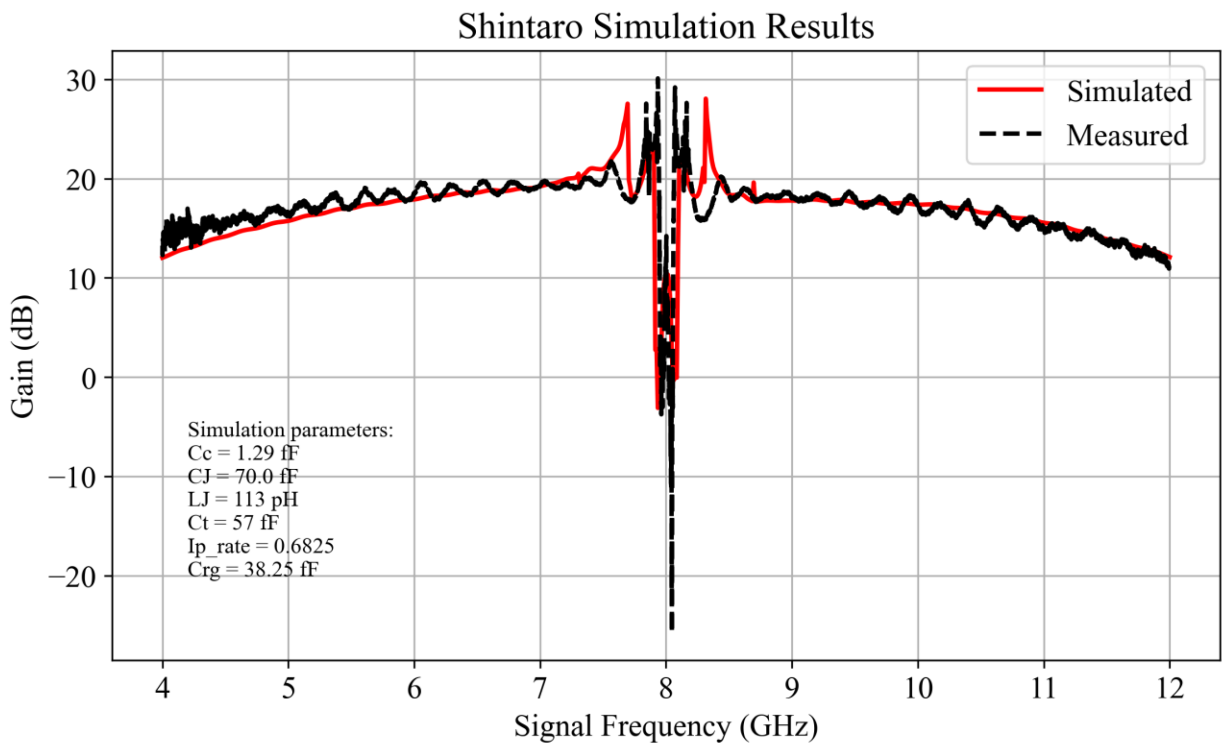
Periodic modulation: Source of gain ripples

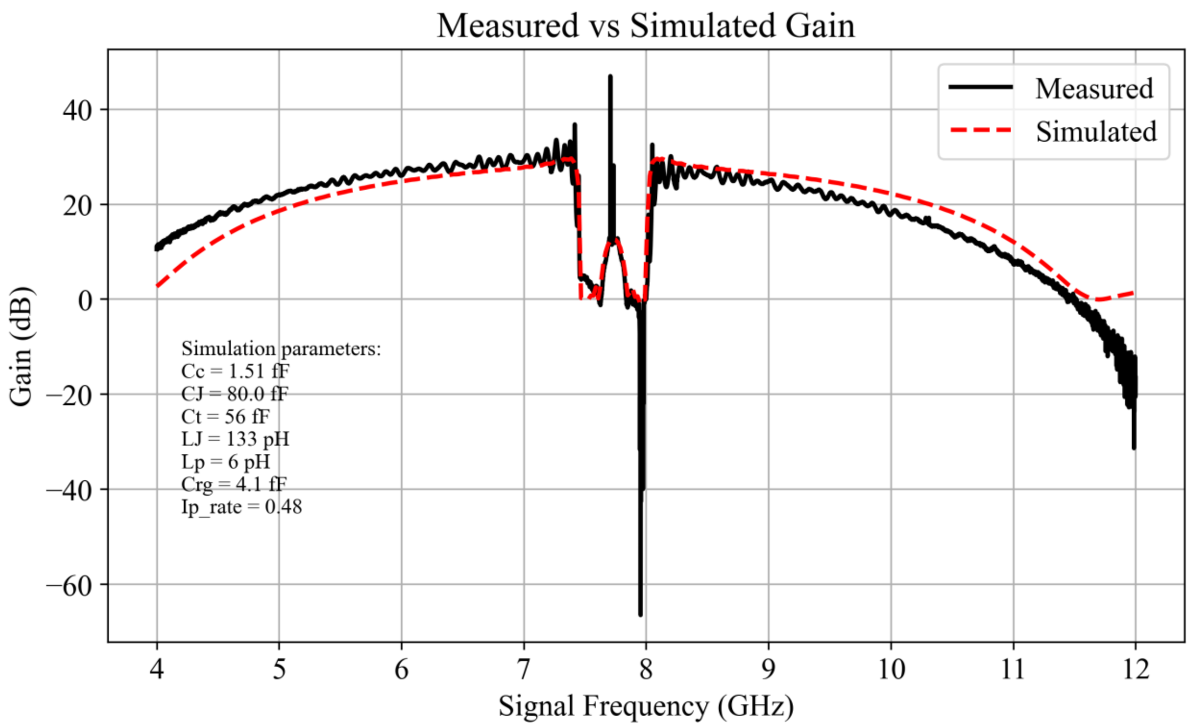
Transmission property (No pump) | Gain profile (Pumped)



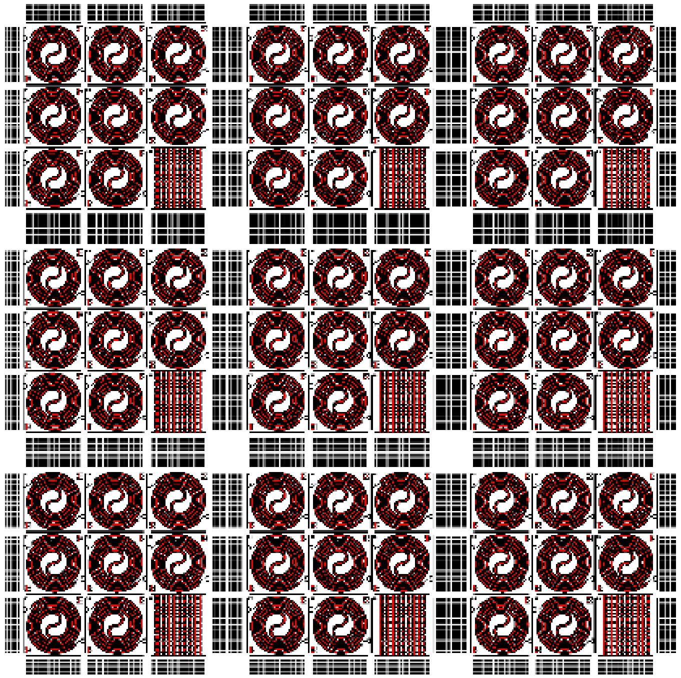
- Gain and transmission/reflection ripples share similar periodicity
- A smoother transition near bandgap → a smoother gain profile?
- **Origin of transmission ripples?**

Distributed-coupling resonant-phase-matching JTWPAs

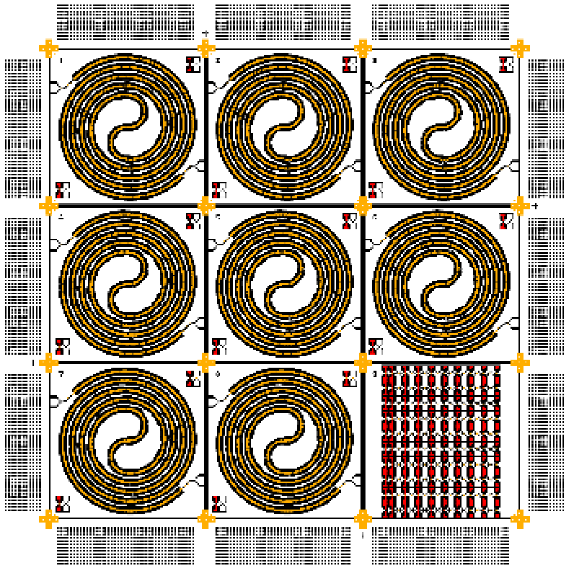




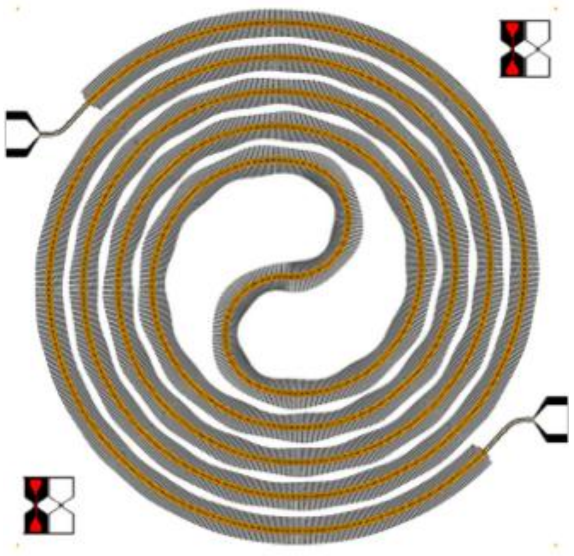
JTWPA: Current recipe (same for CP-JTWPAs and dcRPM JTWPAs)



Scribing a wafer into 9 blocks (after ebeam dev.)



Dicing a block into chips



On a wafer: ~ 4 days

Operations	Days	Check
Wafer cleaning + Al. depos.	1	
UV litho. + Al. etching	1	Optical
Ebeam litho. + scribing	2	Optical

On 1-2 blocks: ~ 5 - 6 days

Operations	Days	Check
Tuning oxid. + Junc. depos. Liftoff + measurement	2-3	Optical + Resistance
Airbridge + dice + clean	3	Optical

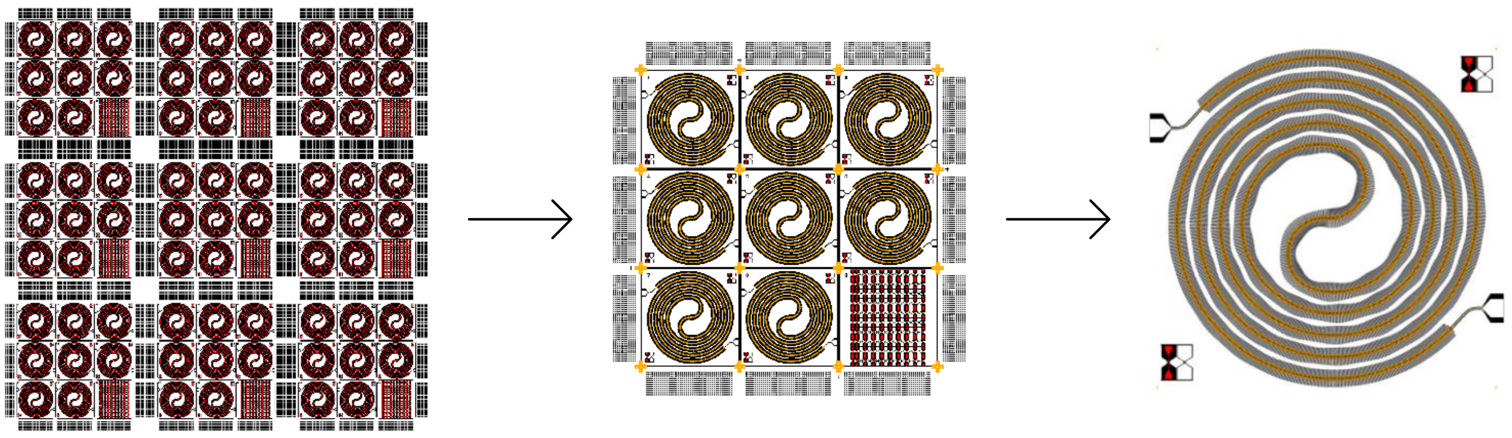
On the 9-18 chips: ~ 2 days

Operations	Days	Check
Meas each chip	1	Optical + Resistance
Packaging	1	

→ Maximum: 18 CP-JTWPAs or 6 dcRPM-JTWPAs in 11-12 days. Room temp. yield ~ 50%. Cold yield ~ 30%

JTWPA: Current recipe (same for CP-JTWPAs and dcRPM JTWPAs)

Limitations of current recipe



<u>Low throughput</u>

- Evaporating junctions block-by-block
- Airbridge and dicing steps must then be done on a block

<u>Difficulty in measuring chip resistance</u>

- Junctions are deposited after the circuit pattern, measurable only after airbridge and dicing into chip
  Cannot be done via the auto-prober. Manual probing is slow, higher chance in damaging chips in the process

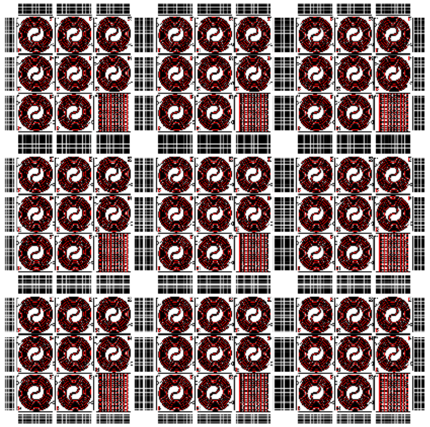
<u>Hard to screen good devices at room temperature</u>

- Input-to-output port resistance ≪ expected series resistance of the junction array
  e.g. GP5B8C2 (Tukey CP-JTWPA) gave 13.6 kOhm, while it should have been 2400*80 = 192 kOhm
  This is due to the circuit pattern is shorting out the otherwise high background resistance of the silicon substrate

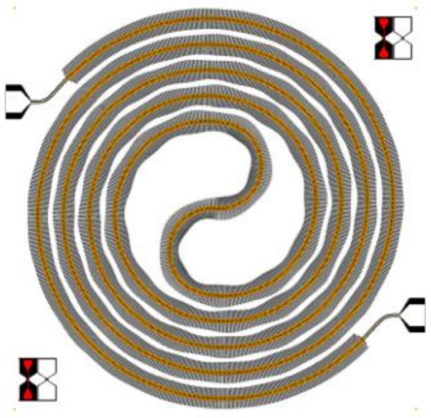
JTWPA: New (planned) recipe for better throughput

On a wafer: ~ 10-11 days

Operations	Days	Check
Wafer clean + Ebeam litho.	2	Optical
Tuning oxid. + Junc. depos. Liftoff + 1st meas. & screen	2-3	Optical + Resistance
UV litho. for junc. protection	1	Optical
(Wafer cleaning +) Al. depos.	1	
UV litho. for circuit + Al. etching	1	Optical
Airbridge + 2nd meas. & screen	2	Optical + Resistance
Laser dicing	1	



Dicing a wafer into chips



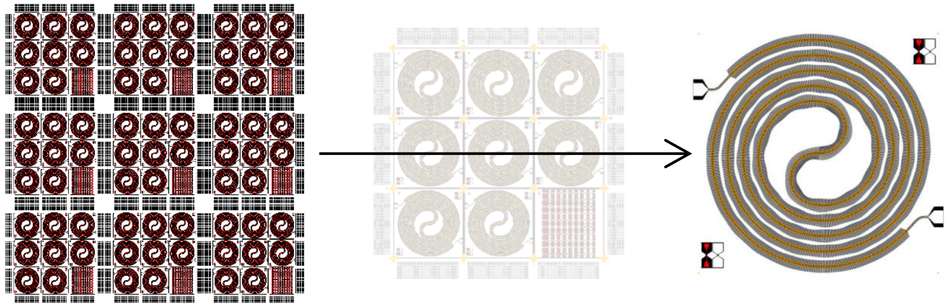
On the chips: ~ 1 days

Operations	Days	Check
Packaging	1	

→ Maximum: 81 CP-JTWPAs or 27 dcRPM-JTWPAs in 11-12 days. Room temp. yield ~ 50%. Cold yield ~ 30%

Number of chip can be even more by further utilizing spaces on a wafer (possibly 13*9 = 117 chips for CP-JTWPAs)

JTWPA: New (planned) recipe for better throughput



With the new recipe

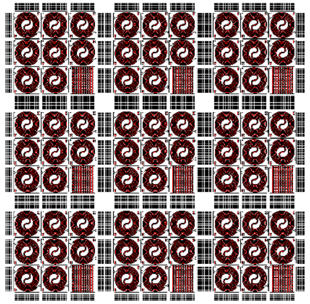
High throughput

- 5 to 10 times more chips over the turn-around time (12 days)
- No more block-wise operations
- All steps are done on a wafer level until dicing to finished chips

Easier to measure chip resistance along the process

- Auto-prober can be used to check the chips at two stages
  - 1st : After junction deposition, check for individual-junction resistance and input-to-output port resistance
    Without the circuit pattern but only junction, we can get a more accurate measurement closer to the series resistance of the full junction array → Allow a better first round screening by removing outliners
  - 2nd : After the airbridge process and right before dicing
    While resistance will drop a lot, we can still check if the patterns for outliners are consistent. There might be more variations due to e.g. short of circuit patterns. This might allow us to further narrow down working chips

JTWPA: New (planned) recipe for better throughput



Challenges in implementing new recipes

Need to make sure junction resistance is systematically consistent over a wafer

- Due to use of shadow evaporation and Mahattan pattern, a constant-size ebeam mask of junctions will likely result in differences in resistance, depending on where the junctions are
- To solve this, the current plan is to do a reverse mapping of the systematic variation (computational lithography) by compensating for the difference using the variation itself when doing the ebeam lithography

❑ This is assuming the variation is very systematic and is reproducible across vacuum cycles of Plassys 2

Junction aging/deterioration over subsequent fabrication steps

- As the junction deposition is now the first step, the junctions will see a couple thermal cycles (100C – 140C) in the following UV lithography step, with the highest being the airbridge reflowing process (140C).
- We will need to check if this degrade the junction quality. Unlike qubit, we don’t need to worry too much if the junction has a bit more loss, but JTWPAs are vulnerable to variations – the degradation cannot be an increase in variation. (systematic increase in overall junction resistance is fine and was always observed to be 5 (80C) to 13 (120C) %, depending on the lift off Remover 104 temperature