Thermalization of Quantum Superconducting Devices

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Goal of this project: Decrease effective temperature of input microwave signals propagating to the quantum device.

Outline

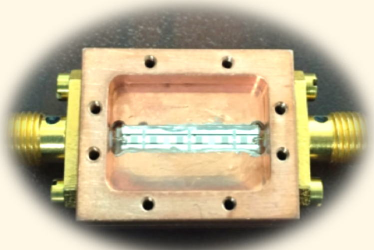
Introduction to Noise & Qubits

Superconducting Transmon Qubit & circuit QED

Problem: Hot attenuator

Cryogenic attenuator design & simulation

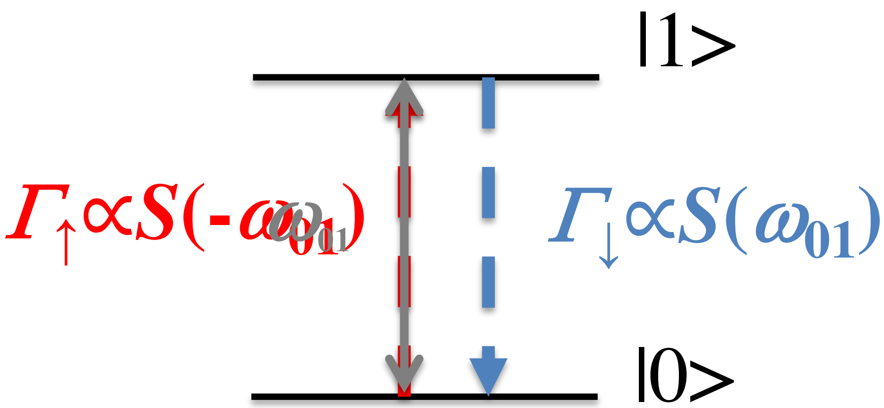
Attenuator



Measurements: Cold attenuator & cooling power

Conclusion and Future Work

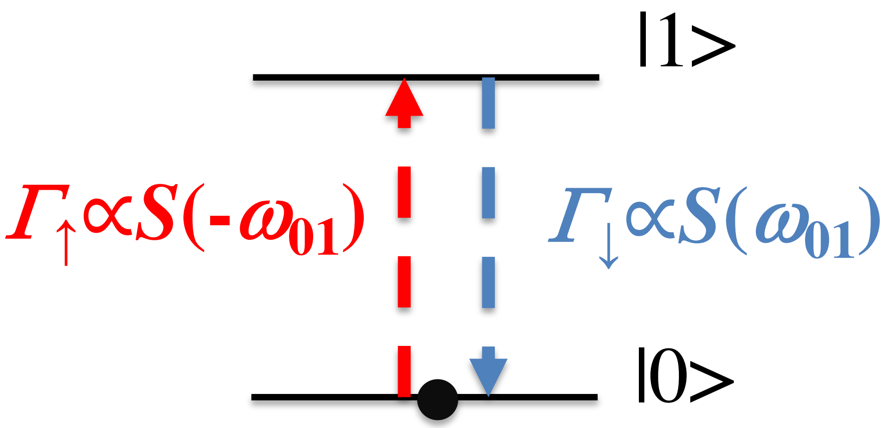
Influence of Noise on Qubits



Undriven steady state population: $P_{|0>} = \dfrac{\Gamma_{\downarrow}}{\Gamma_{\downarrow} + \Gamma_{\uparrow}}$

Decay rate: $T_1^{-1} \propto \Gamma_{\downarrow} + \Gamma_{\uparrow} \approx \Gamma_{\downarrow}$

Influence of Noise on Qubits



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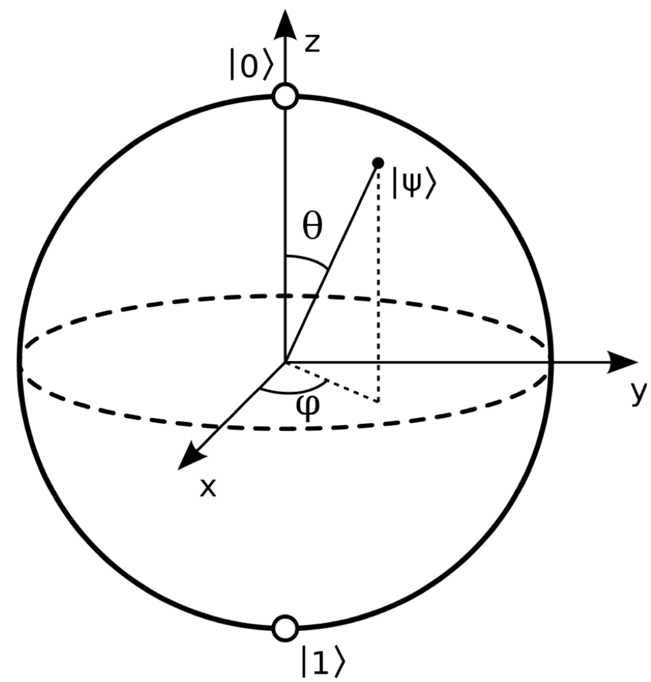
Decay rate: $T_1^{-1} \propto \Gamma_{\downarrow} + \Gamma_{\uparrow} \approx \Gamma_{\downarrow}$

$$\left|\Psi\right\rangle = Cos\left(\frac{\theta}{2}\right)\left|0\right\rangle + e^{i\varphi} Sin\left(\frac{\theta}{2}\right)\left|1\right\rangle$$

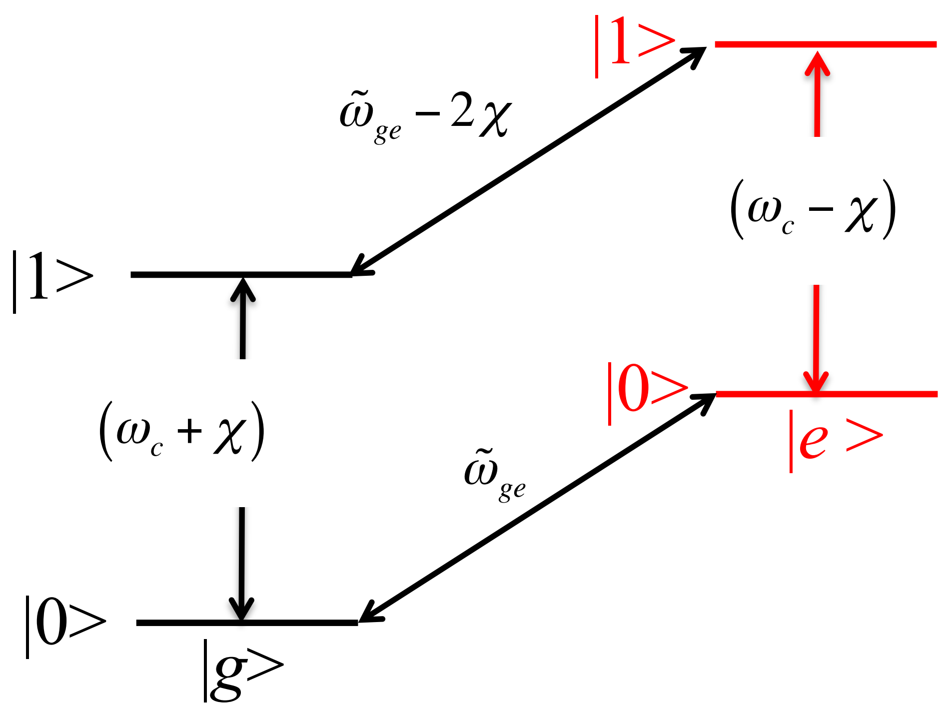
Laboratory frame: $\varphi = \varphi_o + \omega_{01} t$

Uncontrollable fluctuations in ω_{01} cause lost in control of φ or dephasing.

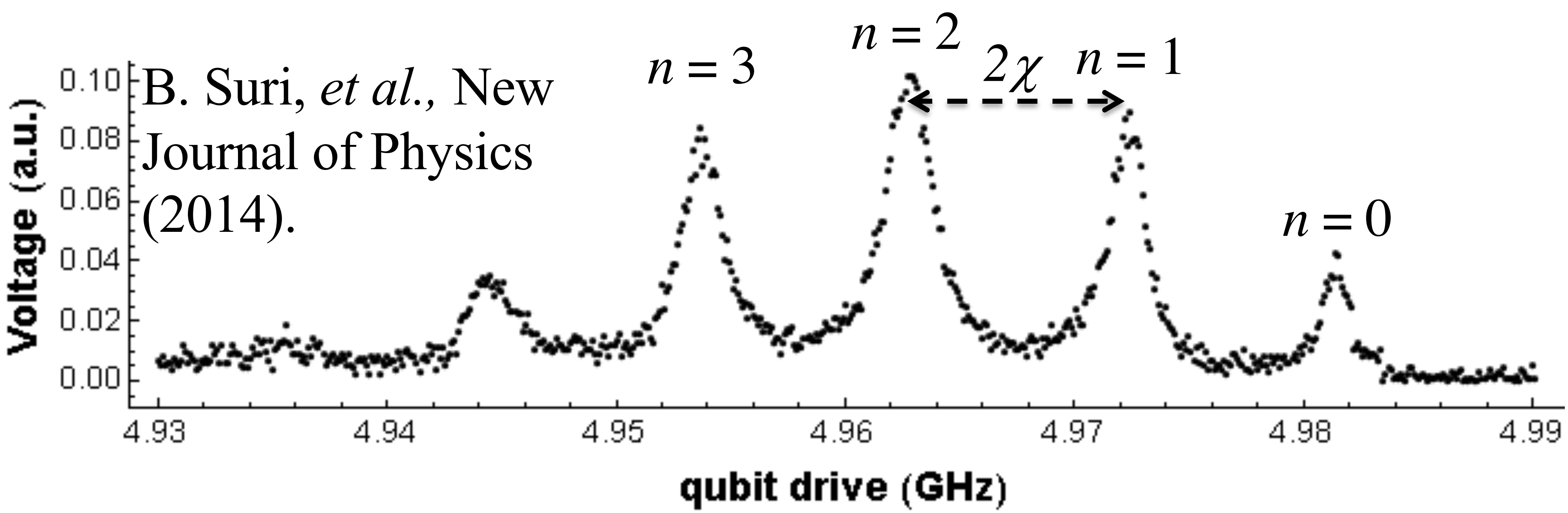
$$\frac{1}{T_2} = \frac{1}{2T_1} + \Gamma_{\varphi}$$



Cavity-Transmon Photon Ladder



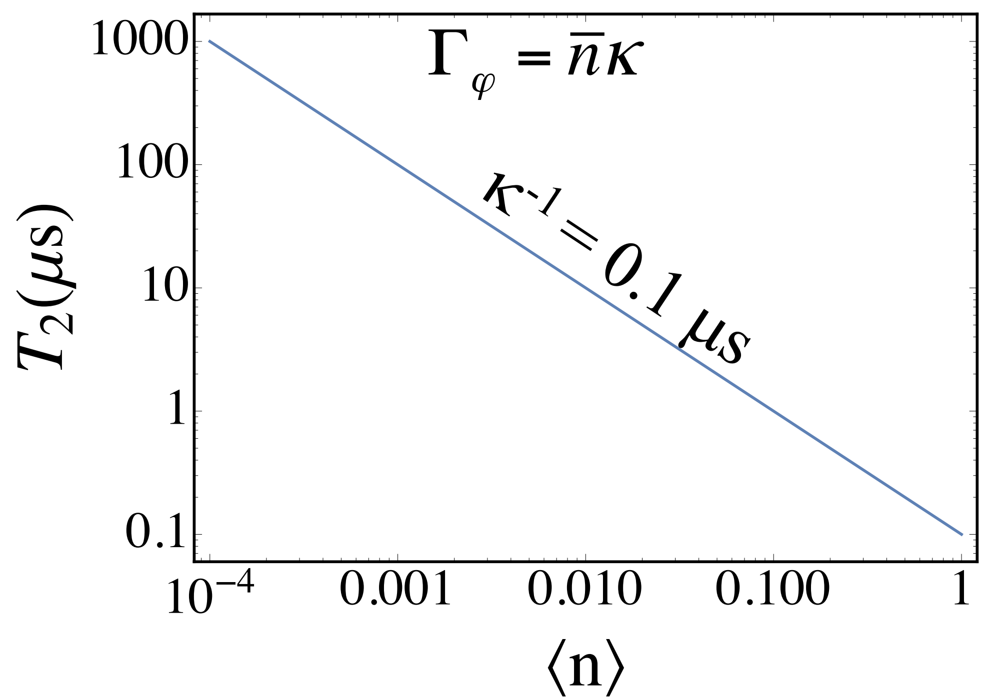
Fluctuations in |*n*> cause qubit dephasing.



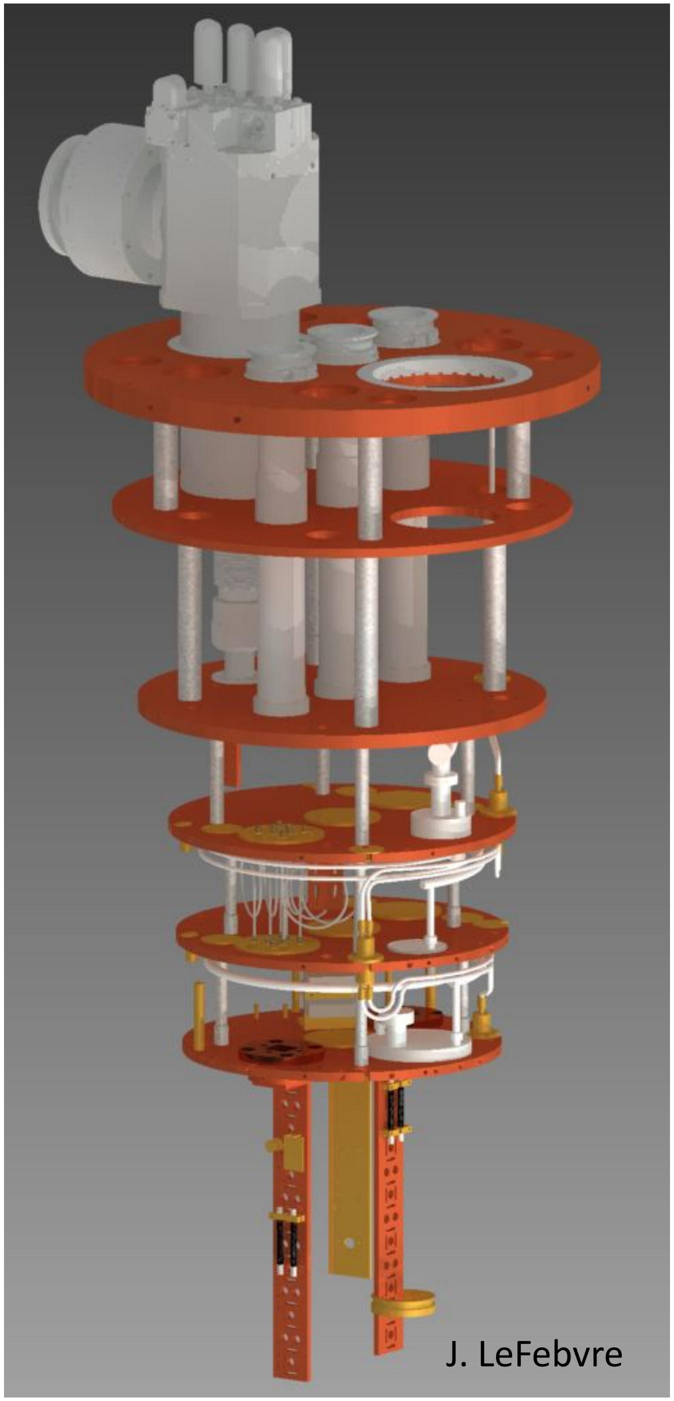
B. Suri, *et al.*, New Journal of Physics (2014).

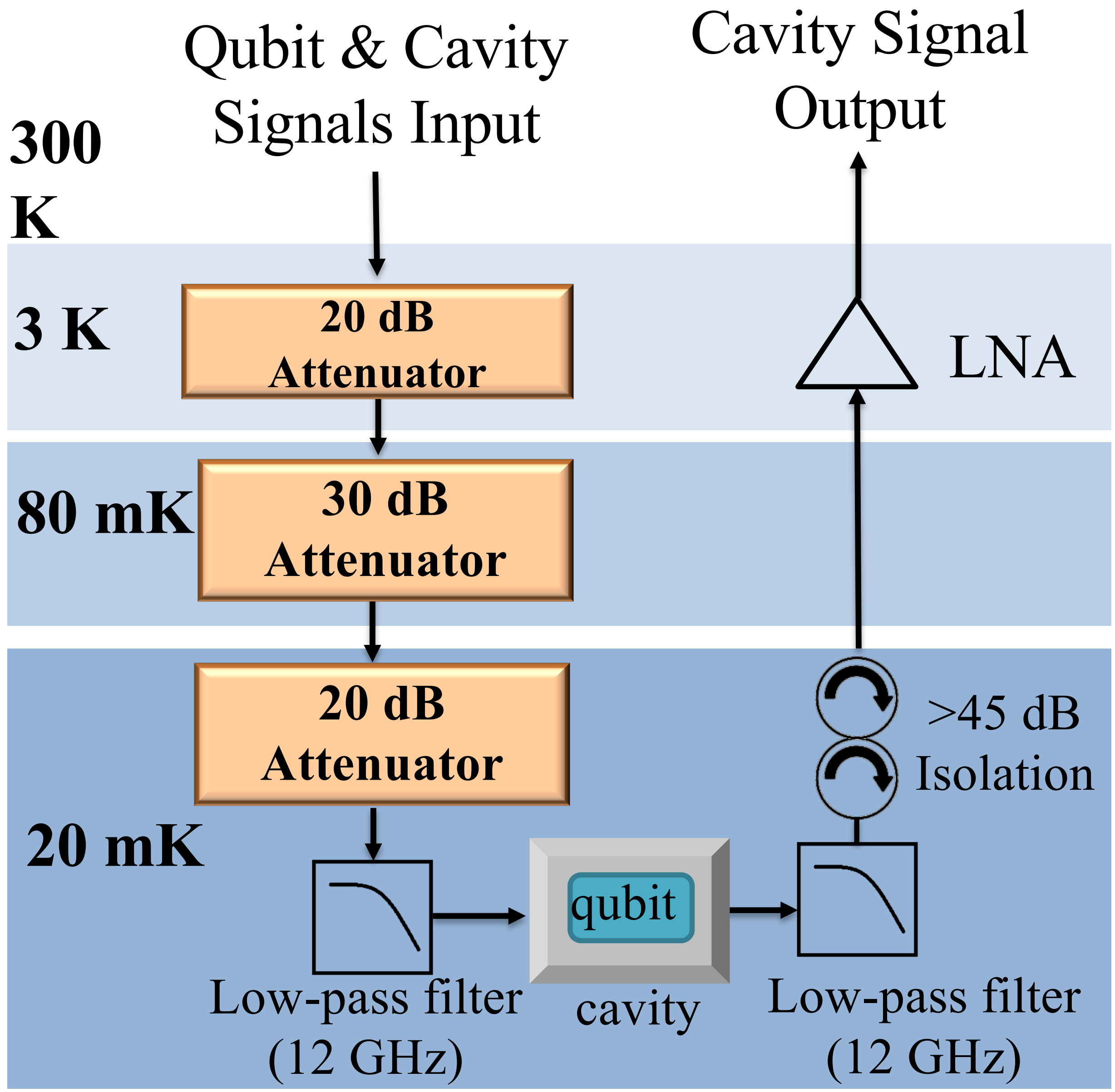
Cavity Dephasing Papers

1) A. Blais *et al.* *"Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation"* Phys. Rev. A (2004).
2) D. Schuster *et al.* "*AC-Stark shift and dephasing of a superconducting qubit strongly coupled to a cavity field* " Phys. Rev. Lett. (2005).
3) J. Gambetta *et al.* "*Qubit-photon interactions in a cavity: Measurement-induced dephasing and number splitting*" Phys. Rev. A (2006).
4) A. Clerk and D. Utami, "*Using a qubit to measure photon-number statistics of a driven thermal oscillator*" Phys. Rev. B (2007).
5) A. Sears *et al.* "*Photon shot noise dephasing in the strong-dispersive limit of circuit QED.*" Phys. Rev. B (2012).
6) F. Yan *et al.*, "*The flux qubit revisited to enhance coherence and reproducibility*" Nat. Commun. (2016).



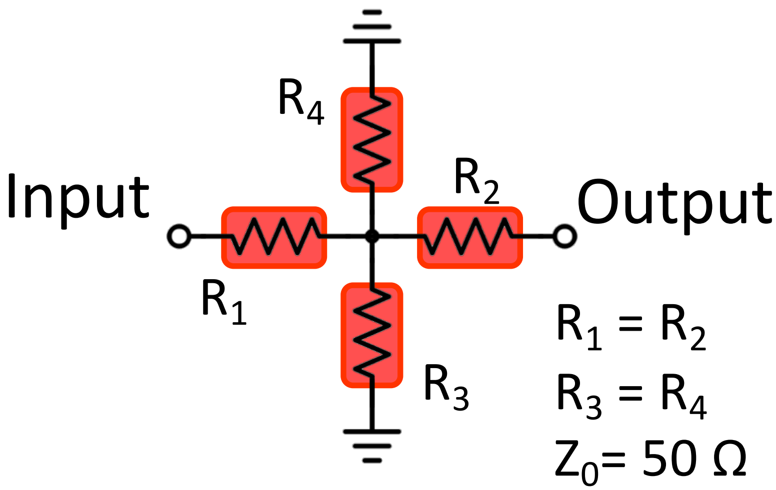
Passive Cooling: Dilution Refrigerator



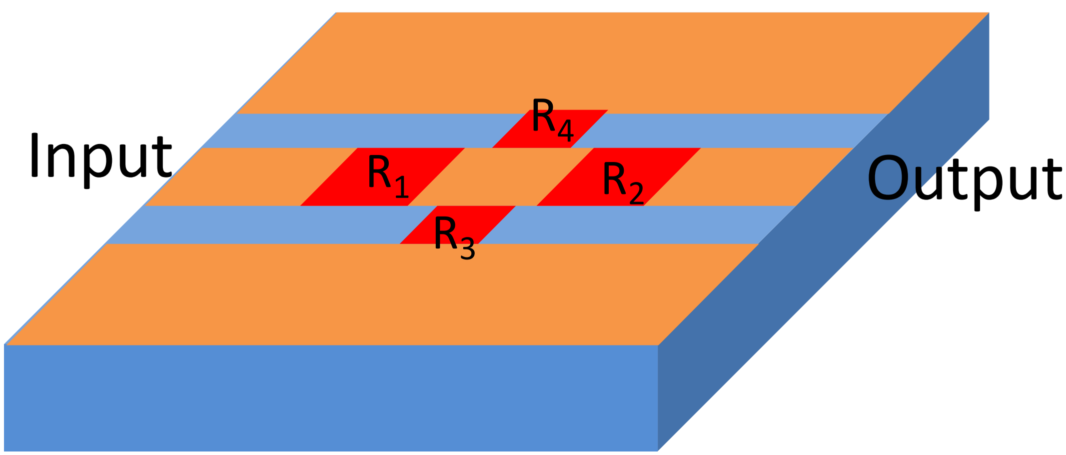


Materials & Circuit Schematic

T-Pad Attenuator Cell



Coplanar waveguide design



NiCr (80:20) – Resistors

•low-resistivity variation with temperature

Silver or Copper – Leads and Ground

•High thermal conductivity

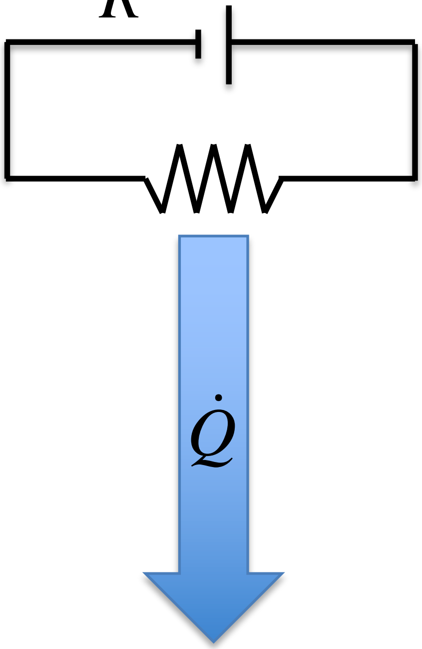
Quartz – Substrate

•High thermal conductivity

•Small relative permittivity

Heat Transfer at mK Temperatures

$$\frac{V^2}{R} = \dot{Q}$$



10 mK mixing chamber

<u>Obstacles to effective heat transfer</u>:

1. Decoupling of electrons from phonons:[1]

$$\dot{Q} = \Sigma\Omega\left(T_{e-}^5 - T_{ph,film}^5\right)$$

$\Sigma \sim 10^9$ Wm^{-3}K^{-5}

Ω: volume

[1] Roukes *et al*., PRL (1985) & Wellstood *et al*., PRB (1994).

Heat Transfer at mK Temperatures

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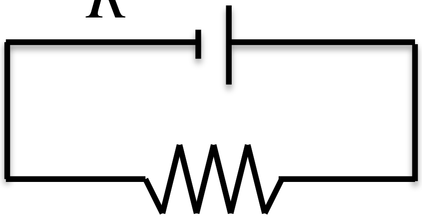

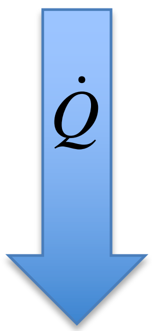

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Ω: volume

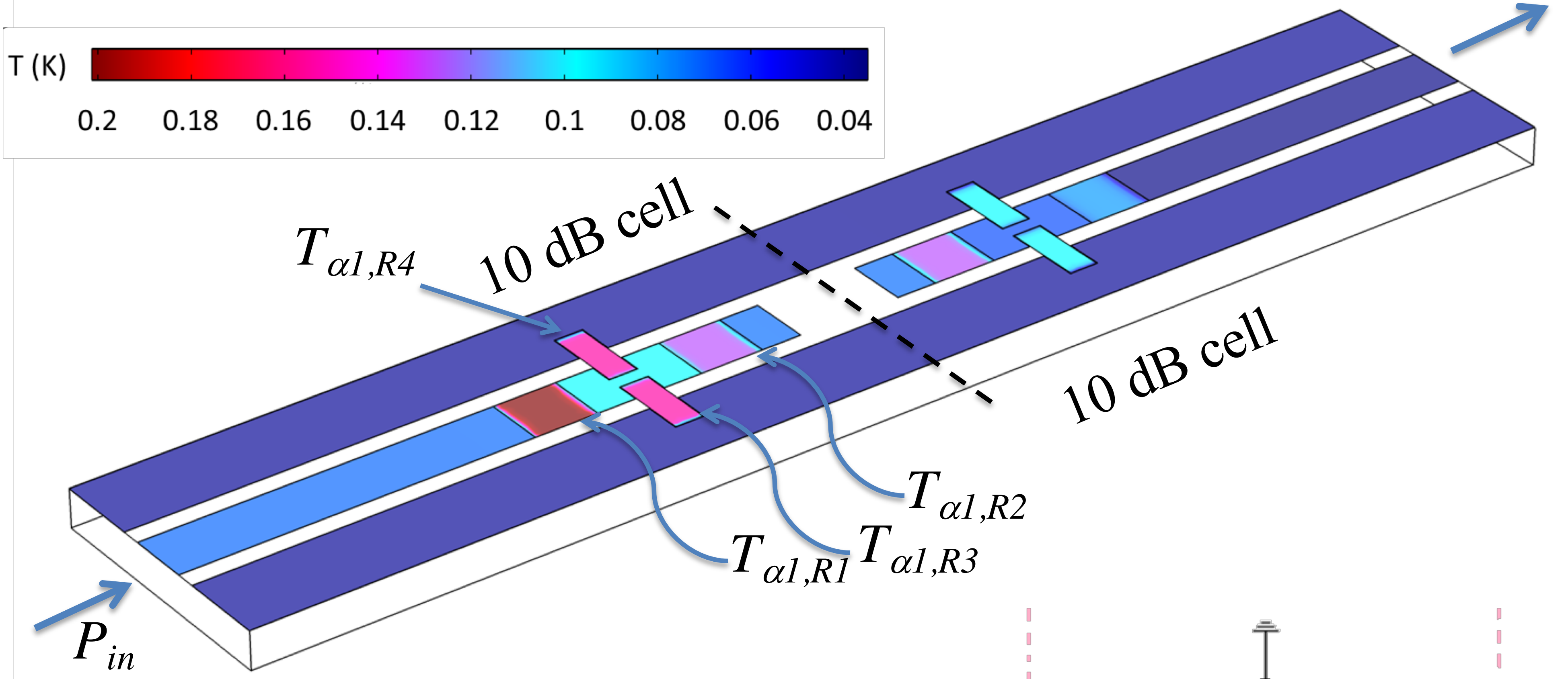
2. Kapitza boundary resistance interfaces:[2]
thin film/substrate, substrate/package,…

$$\dot{Q} = \sigma_{Kap} A\left(T_{ph,film}^4 - T_{ph,sub}^4\right)$$

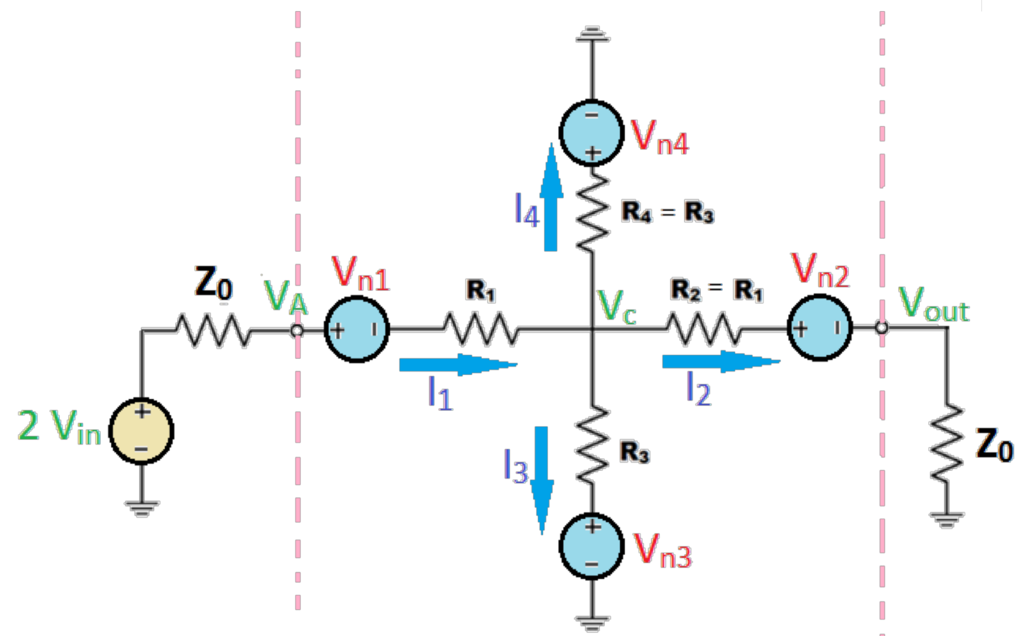
<u>Constraint:</u> Good microwave performance (flat transmission and small reflections) up to ~ 10 GHz.

[1] Roukes *et al*., PRL (1985) & Wellstood *et al*., PRB (1994).
[2] Peterson and Anderson, J. Low Temp. Phys. (1973).

Thermal Simulations

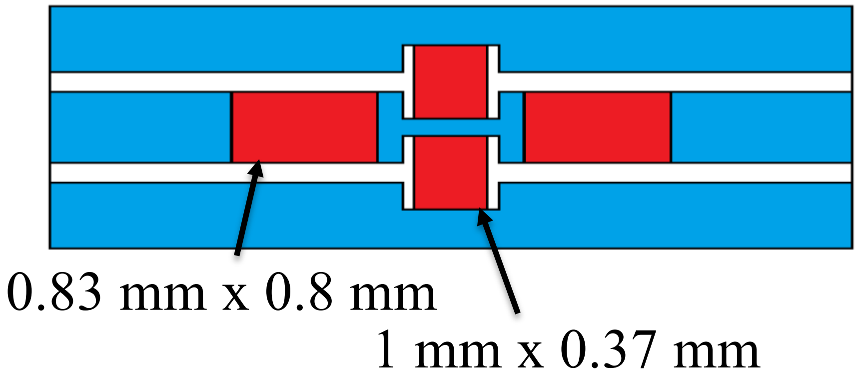


Estimate $S(f)$ from various $T_{\alpha i,Rj}$'s Johnson-Nyquist noise circuit model including the expected noise from previous stage.

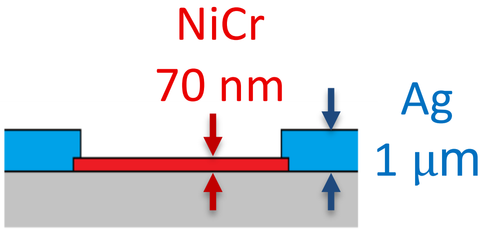


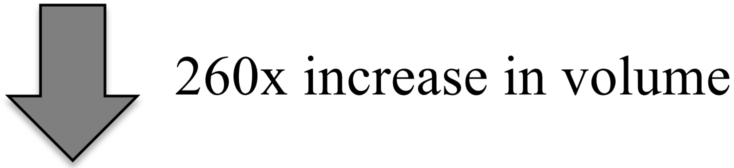
10 dB Attenuator Cell Designs

Attenuator cell v1†

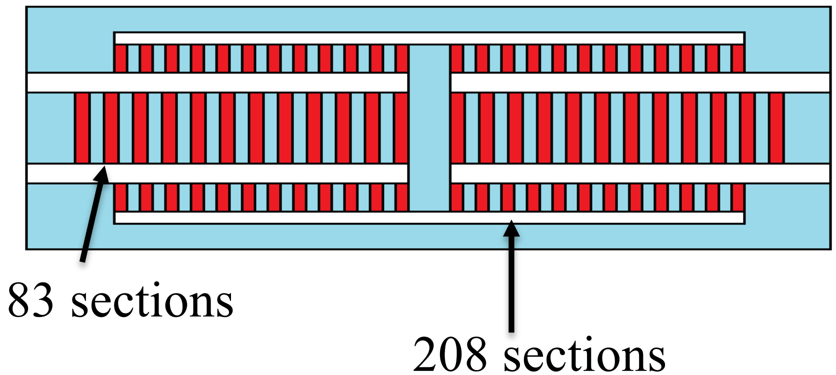


cross-sectional view

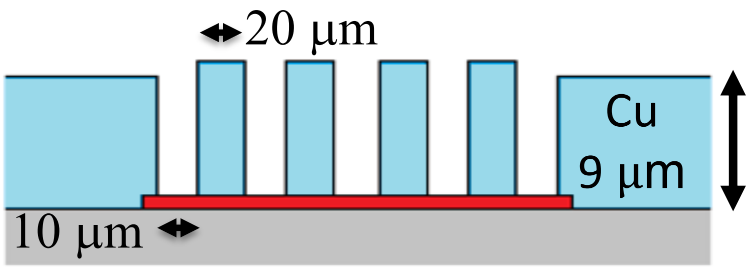




Attenuator cell v3

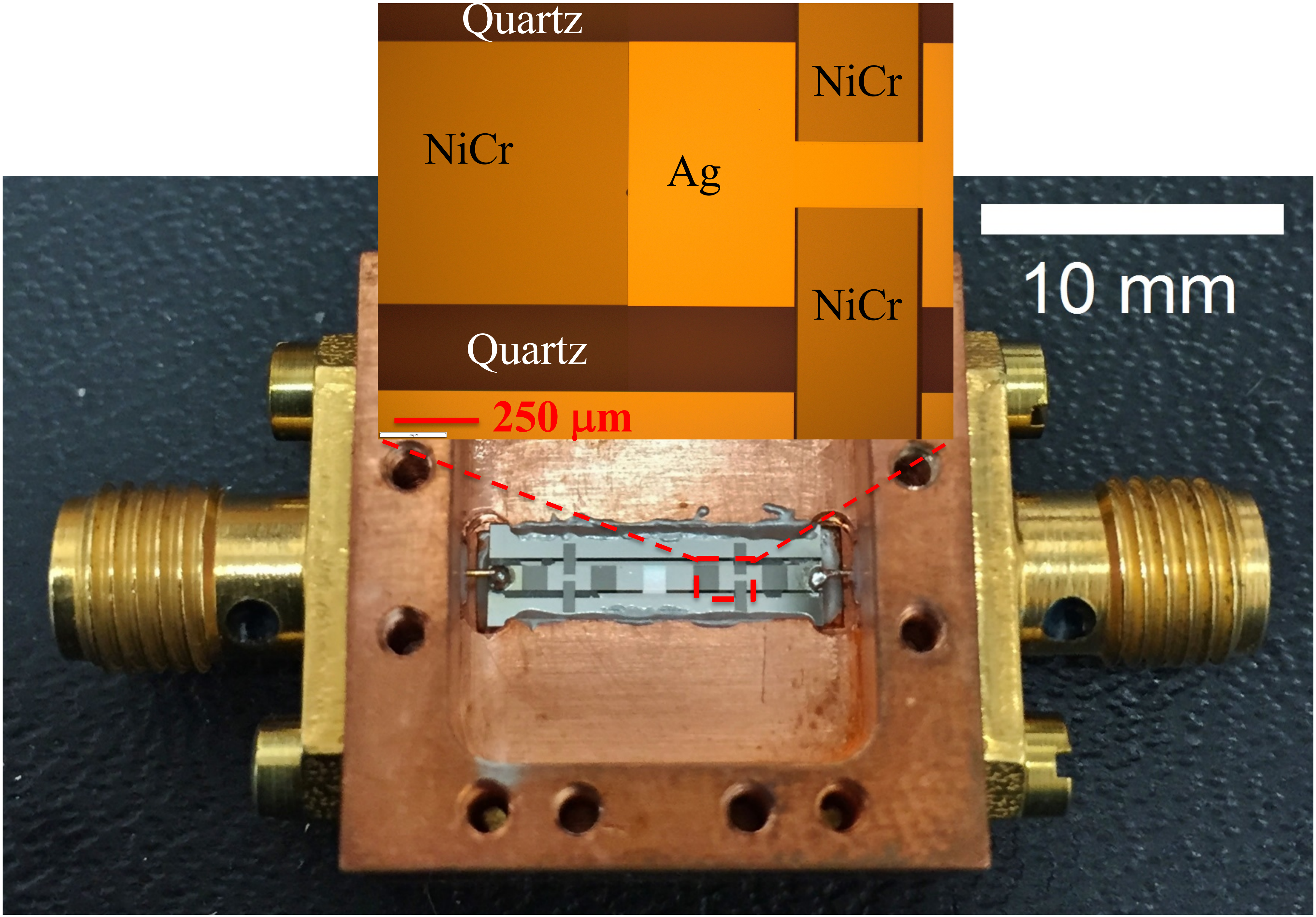


Cu electroplating

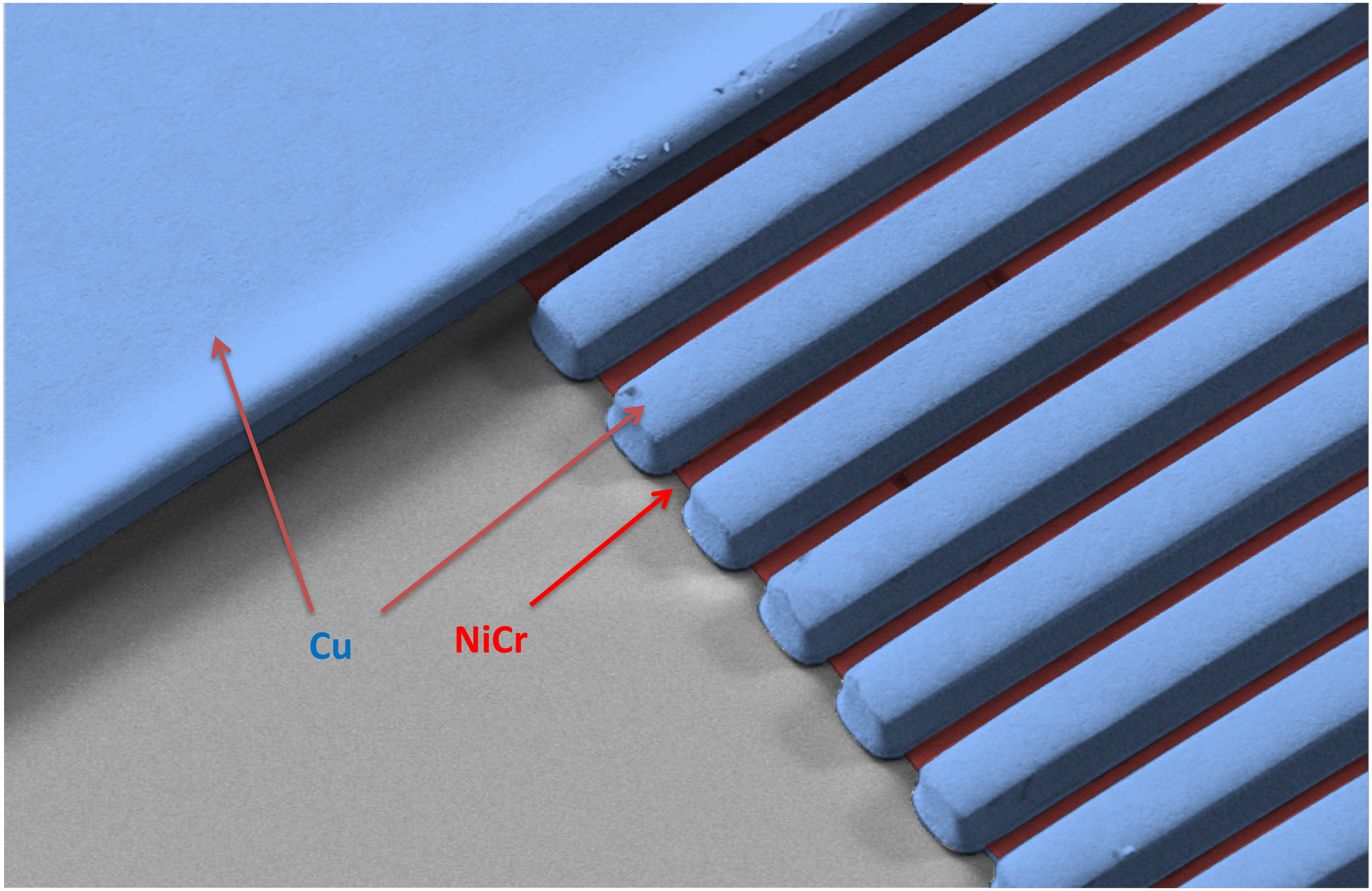


micro-heatsinks

Attenuator Device v1

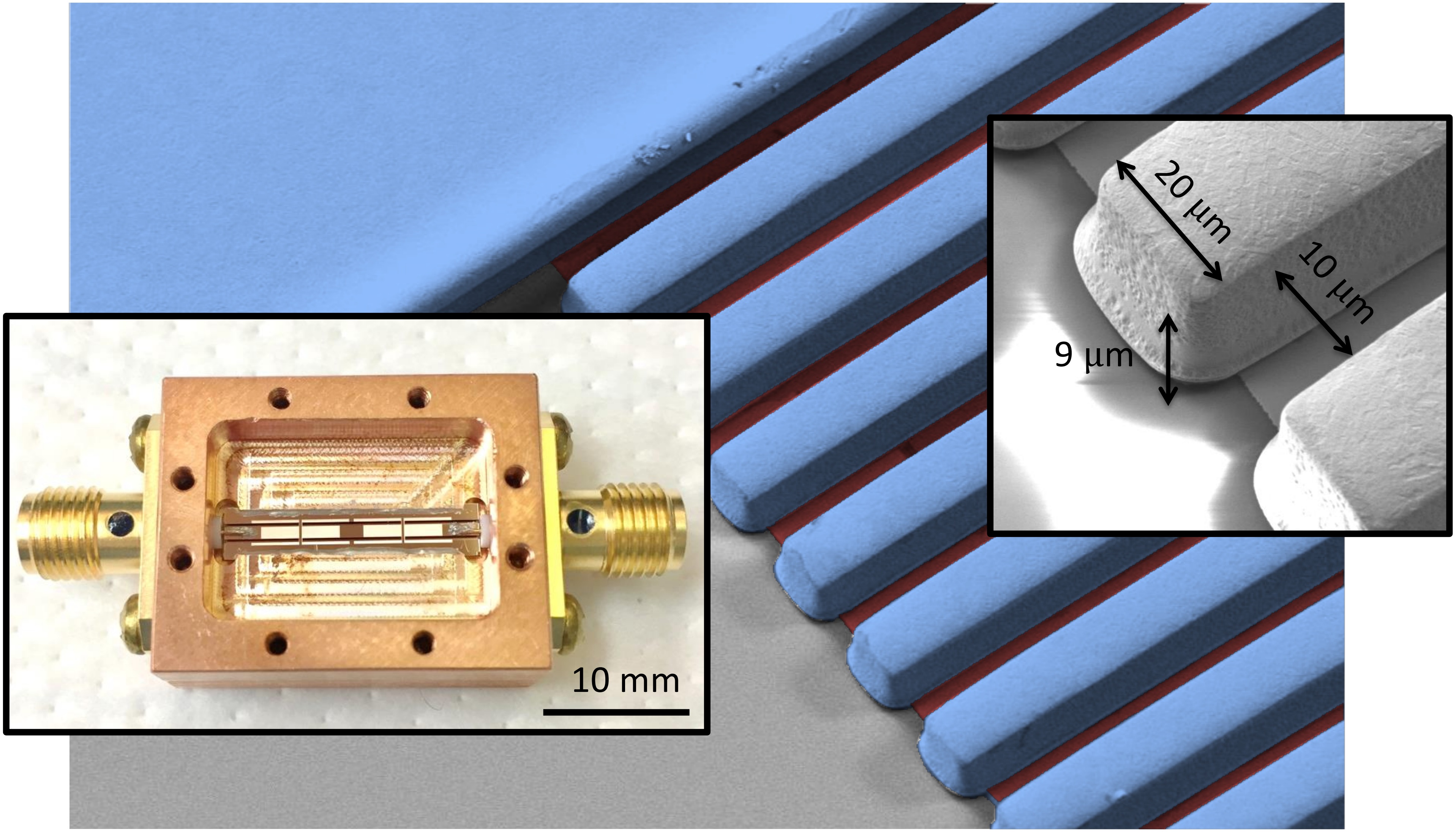


Cryogenic Attenuator v3



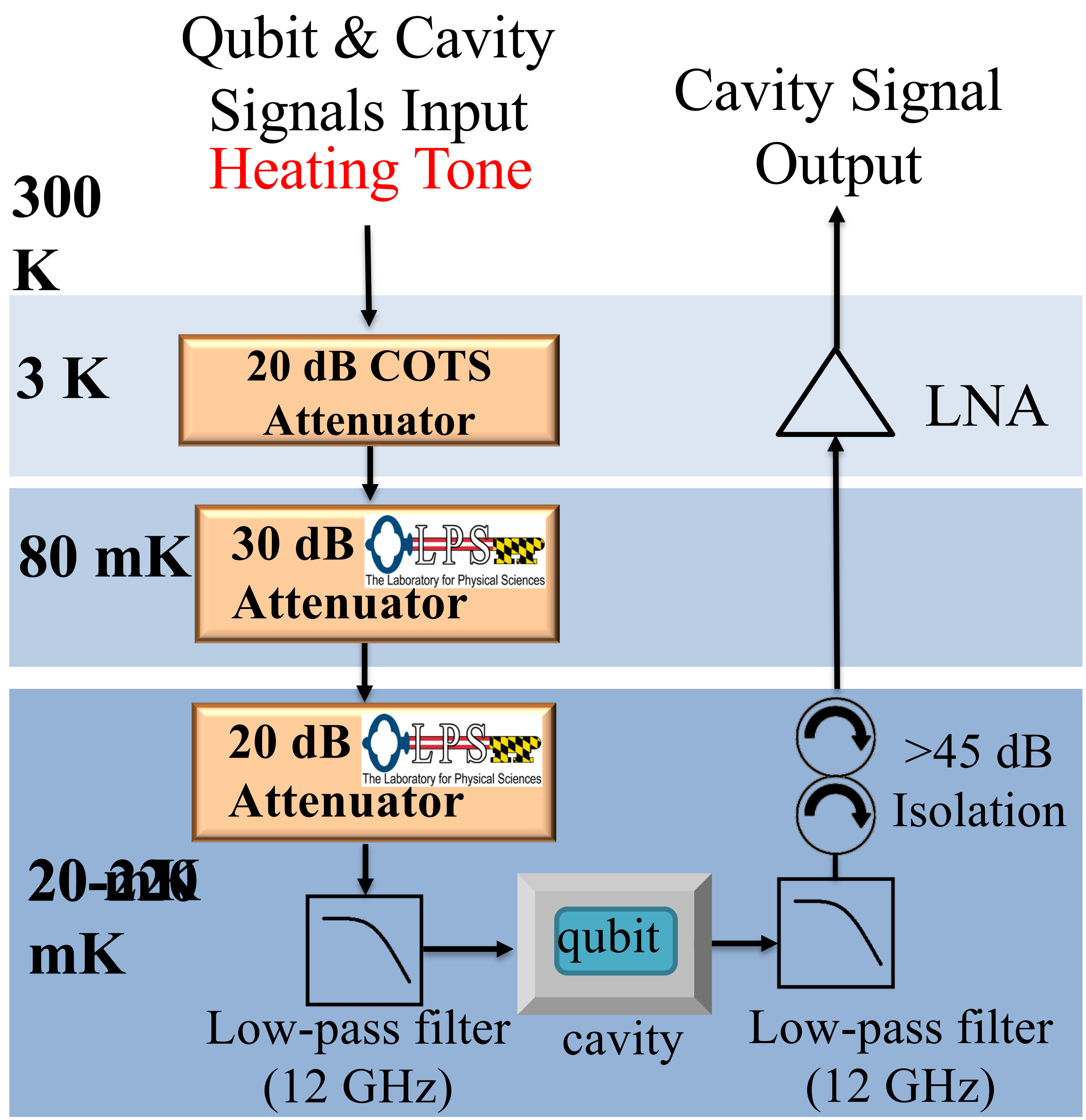
Thanks to Warren Berk for assistance in electroplating Cu.

Cryogenic Attenuator v3

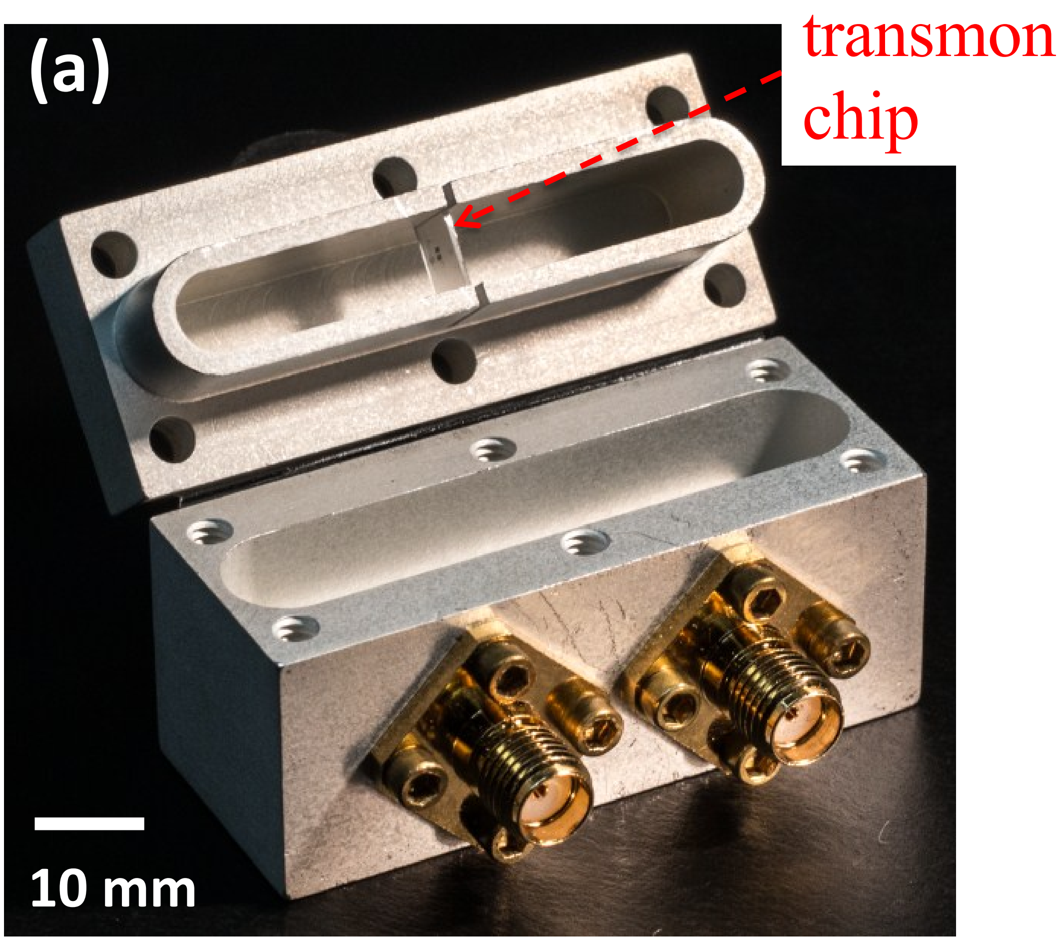


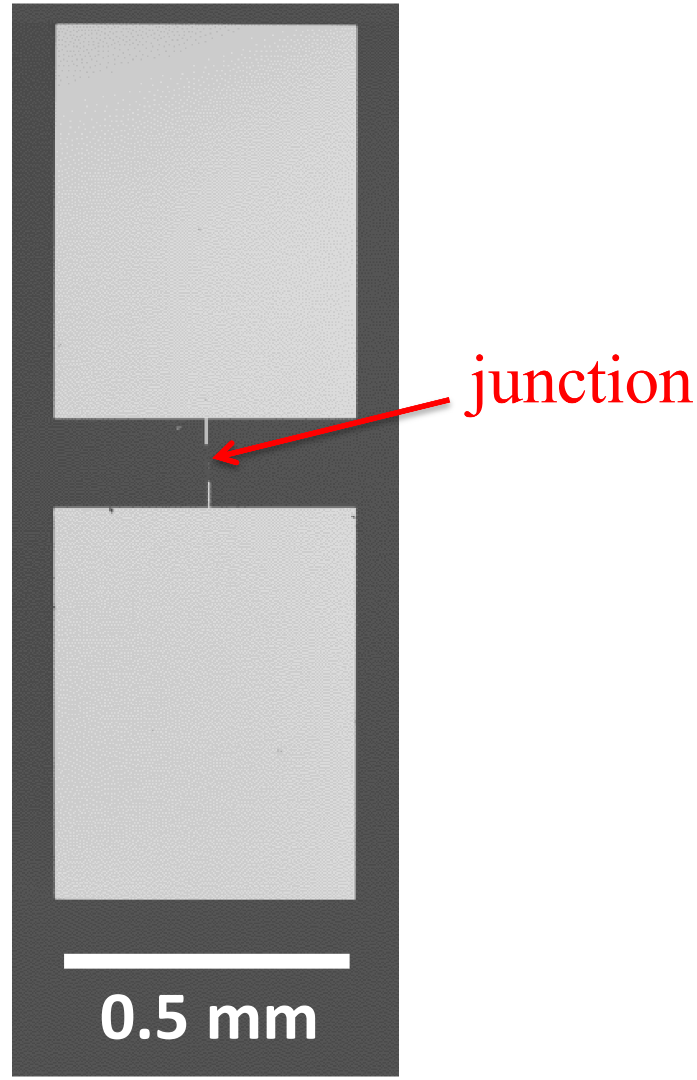
Bandwidth of device: DC-10 GHz

Attenuator Placement



3D Transmon Parameters

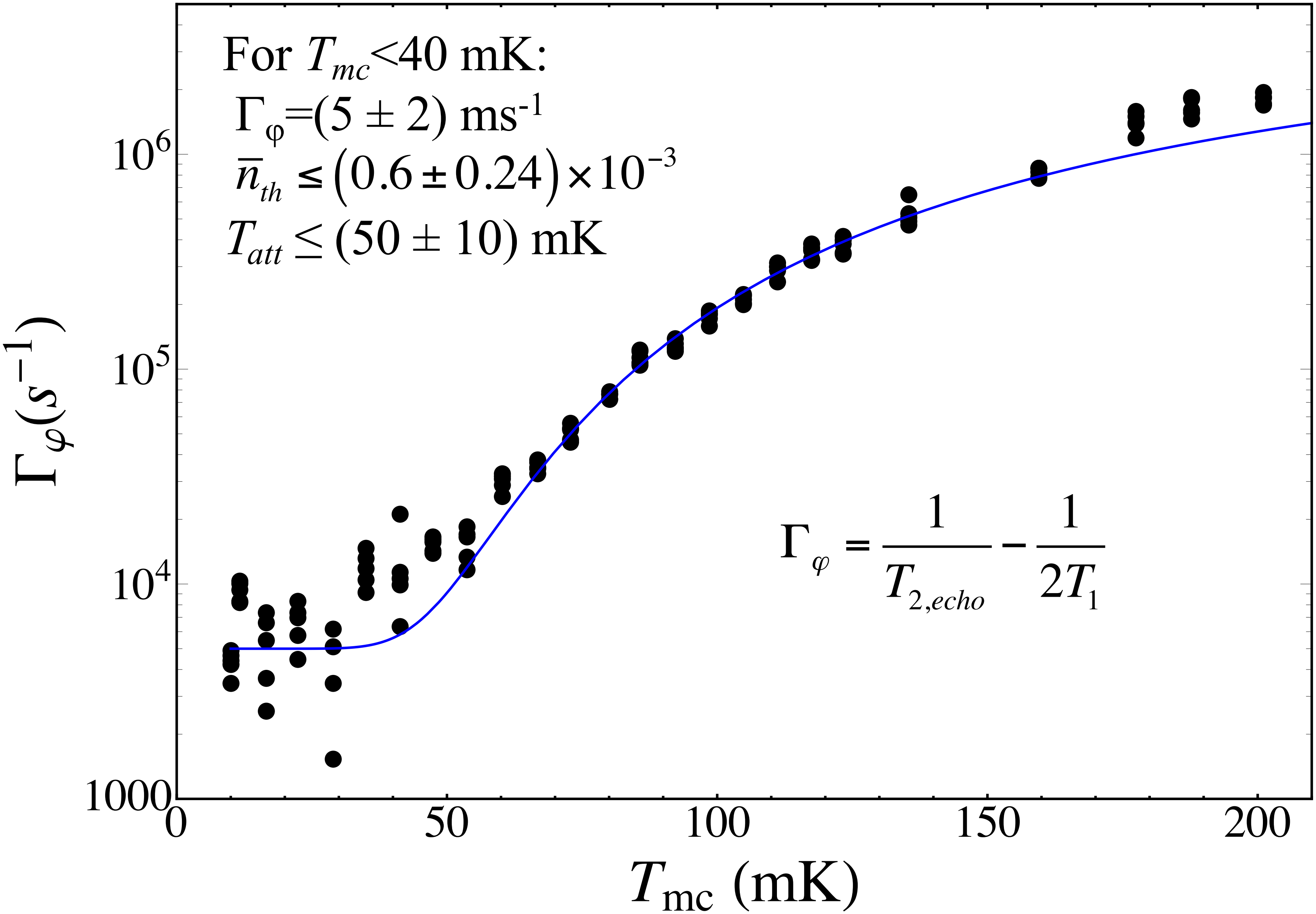




	Aluminum Cavity				$\chi/2\pi$ (MHz)	Qubit			Read-out Mechanism
	f_{cav} (GHz)	Q_{in}	Q_{out}	$\kappa/2\pi$ (μs^{-1})		f_{01} (GHz)	T_1 (μs)	E_c/h (MHz)	
Att-1	7.9	3,700	$\sim 10^5$	1.4	-5	6.55	~8	190	High-power
Att-3	7.96	18,000	79,000	0.8	-0.34	3.67	14	220	High & low-power with TWPA

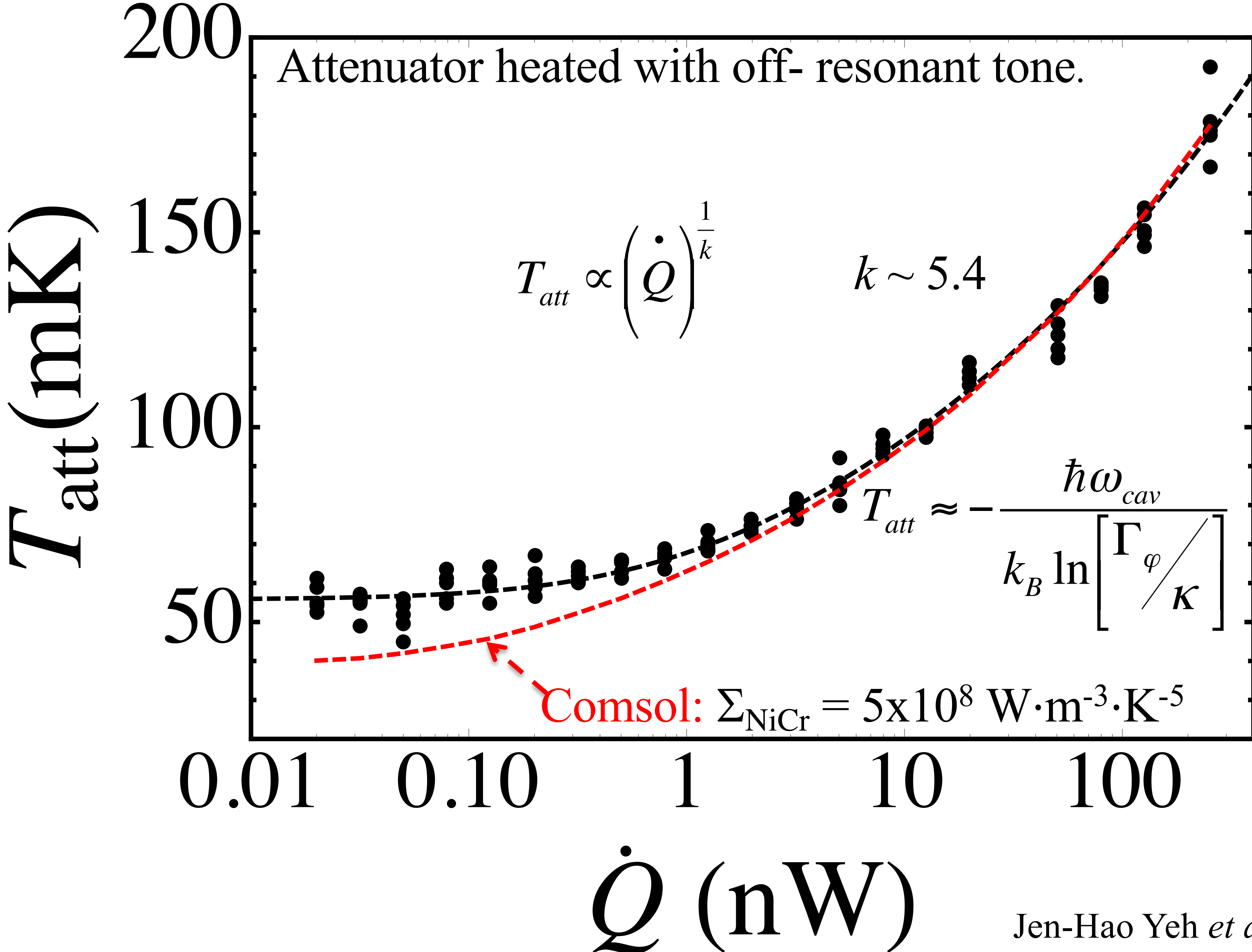
Thanks to G. Calusine, W. Oliver and staff at Lincoln for TWPA.

Dephasing versus Temperature



Jen-Hao Yeh *et al*,
J. Appl. Phys. (2017).

Dissipated Power Dependence



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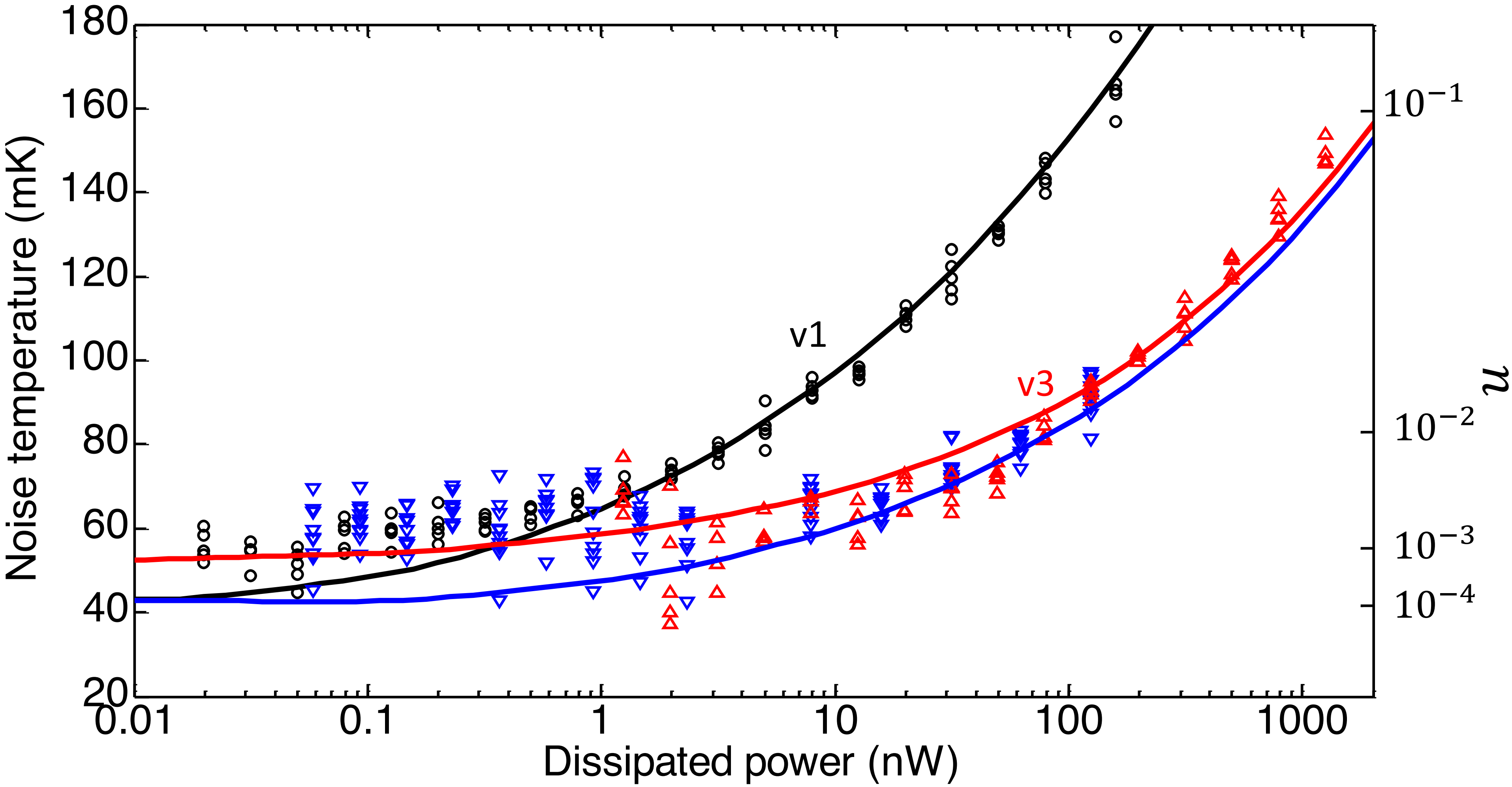
Dissipated Power Dependence



Conclusions

- Coherence of cQED devices very sensitive probe of cavity microwave photons (n ~0.001)
- Fabricated and accessed attenuators designed to work below 100mK:

$$\bar{n} \leq 8 \times 10^{-4}$$

$T_{att} \leq 60$ mK (up to 2x improvement)

$\dot{Q} = T_e^n$ (v1: n ~5.4, 30 nW $\rightarrow$ T_e ~120 mK)
(v3: n ~4.4, 400 nW $\rightarrow$ T_e ~120 mK)
(XMA: n~4.8, 10 nW $\rightarrow$ T_e ~120 mK)

v1: Jen-Hao Yeh *et al.*, J. Appl. Phys. (2017).
v3: Jen-Hao Yeh *et al.*, arXiv: 1810.07722.