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Optimizing MKIDs for Future Millimeter Wavelength Cosmological Surveys

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Dec 1, 2022

MKIDs as detectors

An example: sub-mm photometers for SPT4 camera

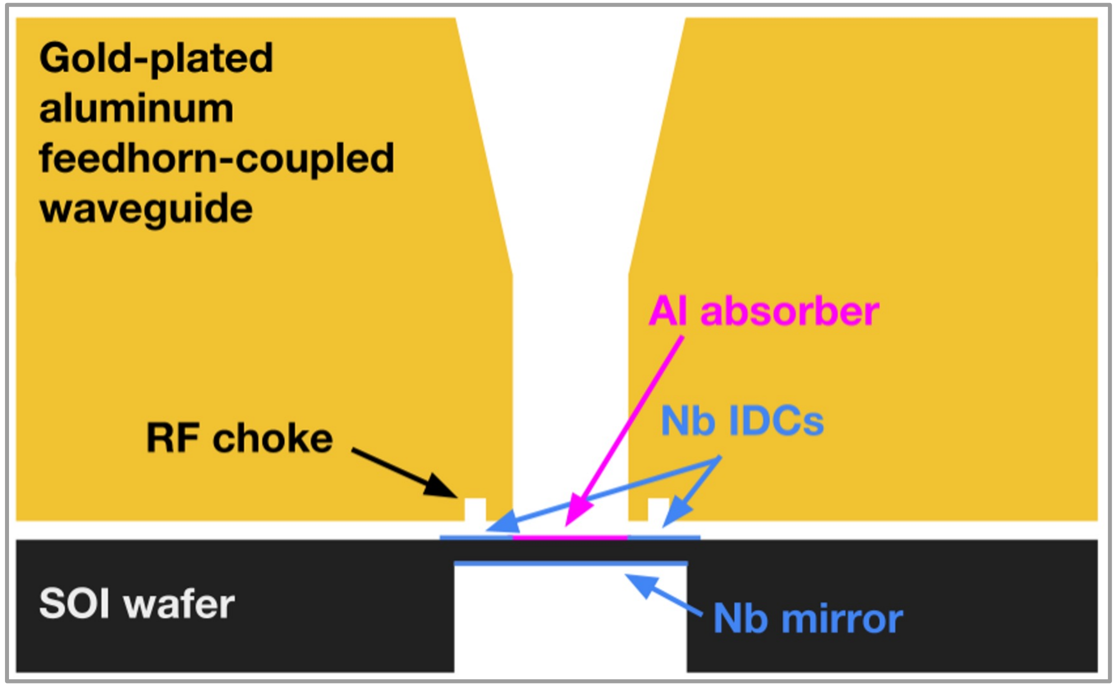
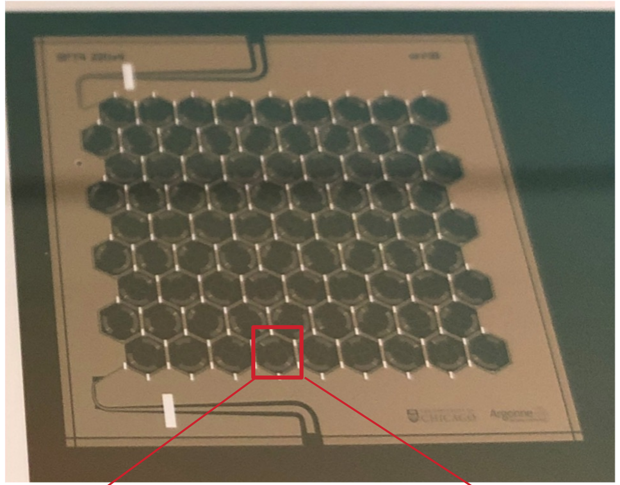


Figure from Dibert et al. ASC2022

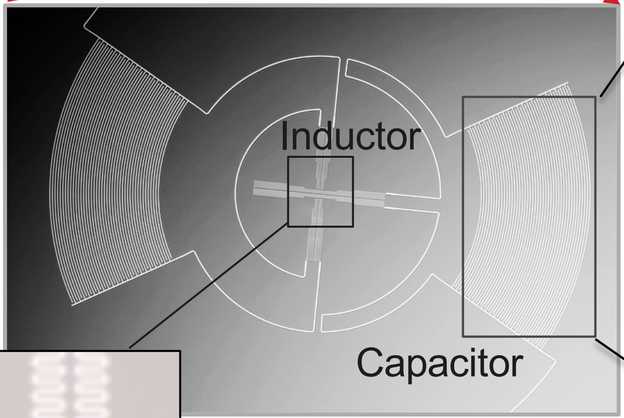
- The optical signal collected by the telescope is coupled to MKIDs detectors via feedhorns.
- The RF choke and Nb mirror enhances the optical coupling and reduce optical leakage.

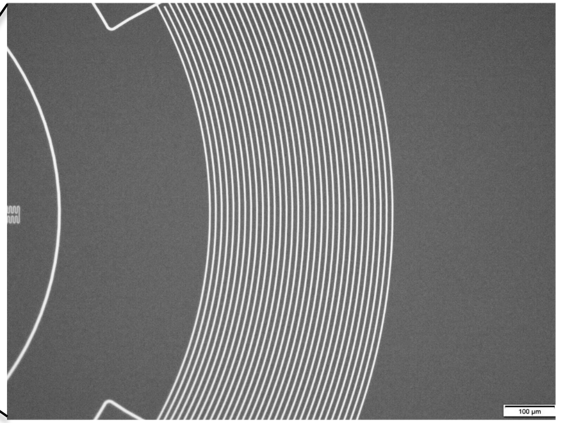


A fabricated detector array

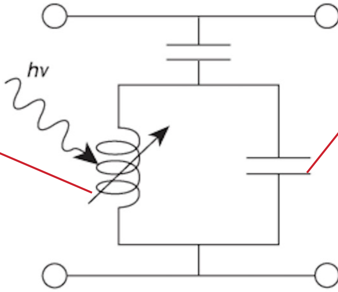
- One single readout line is coupled to multiple pixels, each of which contains two detectors at two polarizations.
- Each detector has an inductor and a capacitor, forming a resonant circuit.

Zoom in one pixel





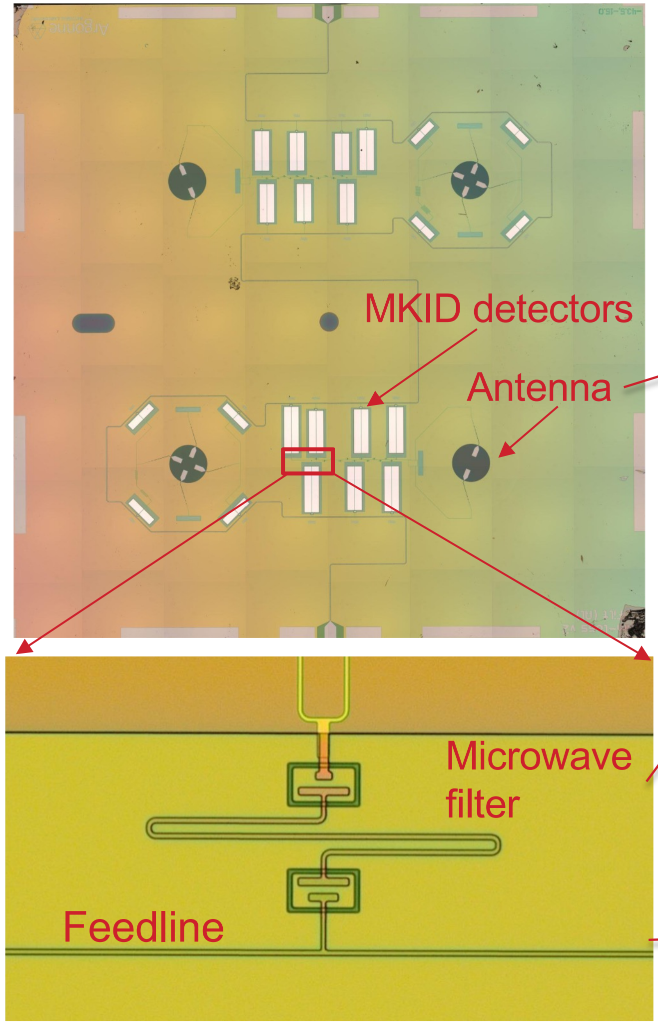
Capacitor structure with interdigitated fingers

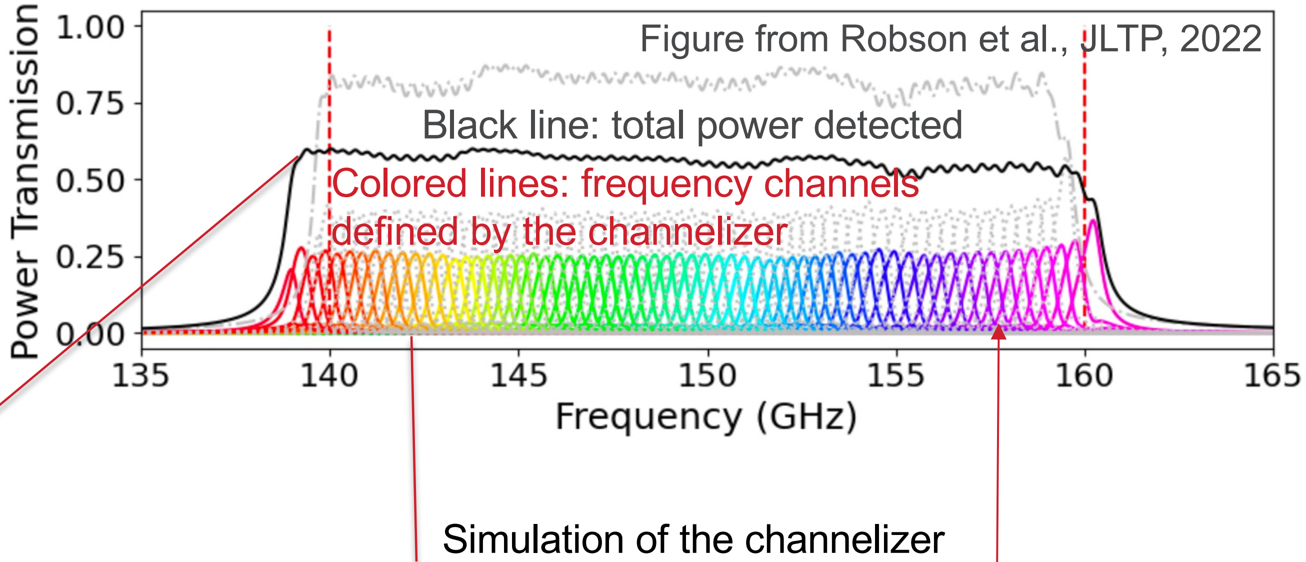


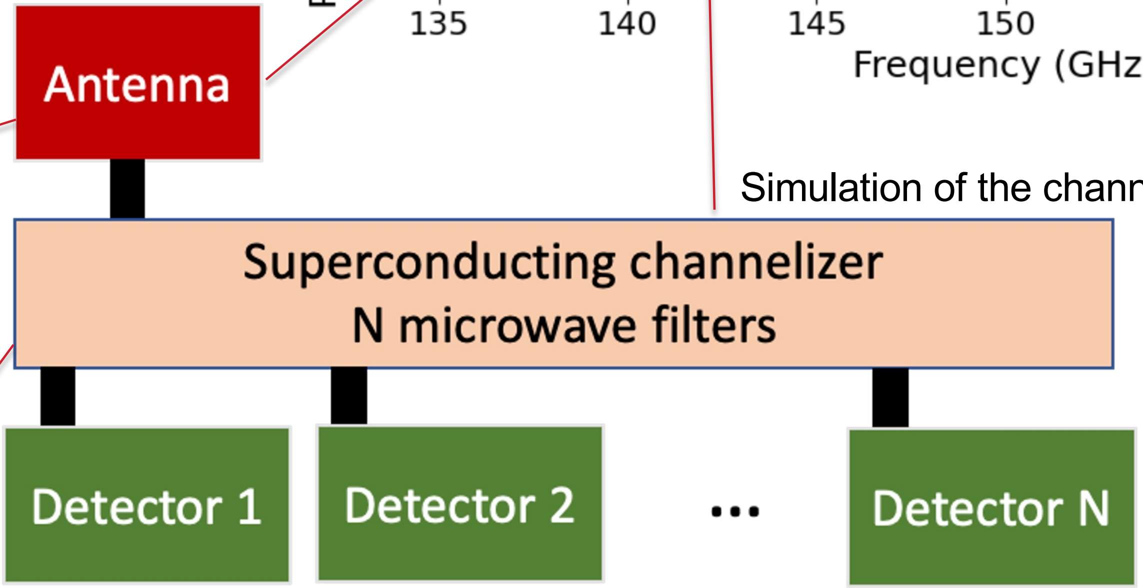
The inductor is below the feedhorn and also serves as the optical signal absorber

MKIDs-based spectrometers

Prototype spectrometer by ANL, for SPT-SLIM (see Adam's talk)





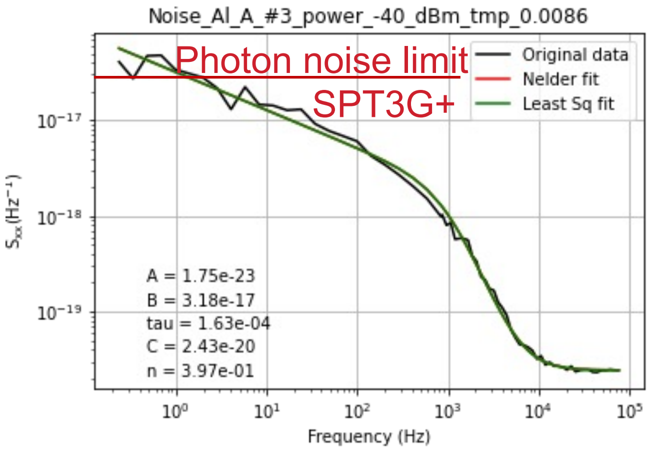


Each **microwave filter** defines a **frequency channel (one colored line)**
Repeat N times to get N channels

Optimization goals

- Detector noise optimization
  - Reduce the TLS noise by tuning the geometry of the capacitors.
  - Tune the GR noise by changing the detector volume.
  - Understand the dependence on power and temperature.
  - Noise vs. different materials (Al, Nb, AlMn with different Mn doping levels).
- Expand the frequency range with different Tc materials
- Improve the optical efficiency and spectral resolution
  - Both are limited by loss in dielectric materials
  - A new device was designed to measure dielectric loss
  - A few promising dielectrics candidates
- Detector integration
  - Galvanic contact between Al and Nb
  - Integration to larger detector arrays

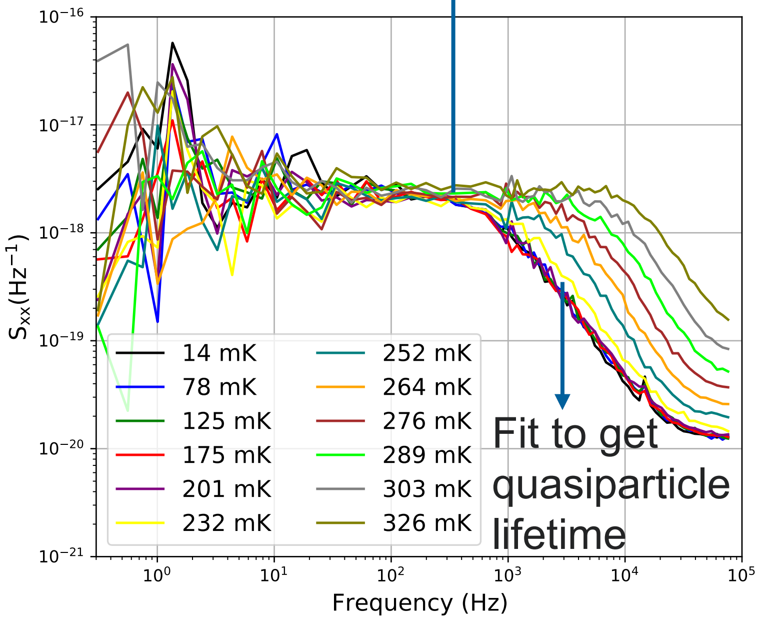
Noise optimization



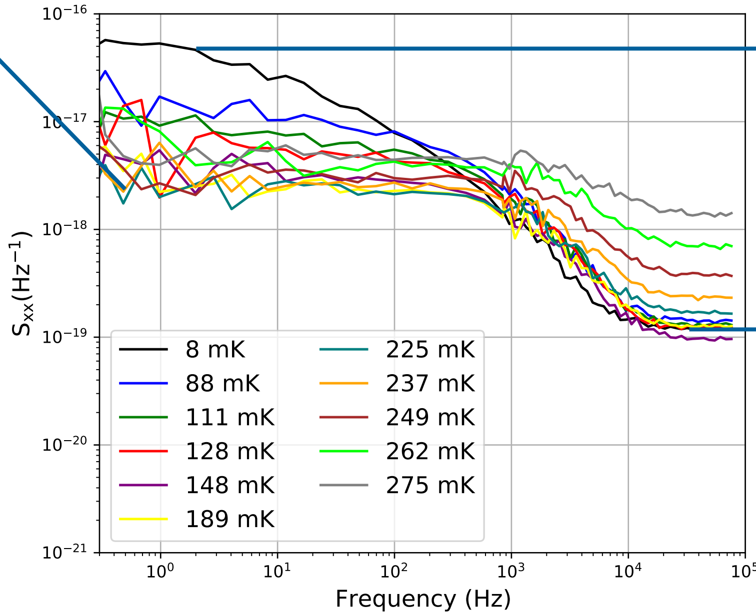
$$S_{xx}(f) = \left(\frac{A + Bf^{-n}}{1 + (2\pi f \tau)^2} + C \right)$$

Three components in the model fit.

Generation-recombination (GR) noise, with a flat shelf and rolling off time constant



A detector's noise vs. stage temperature measured at -95 dBm



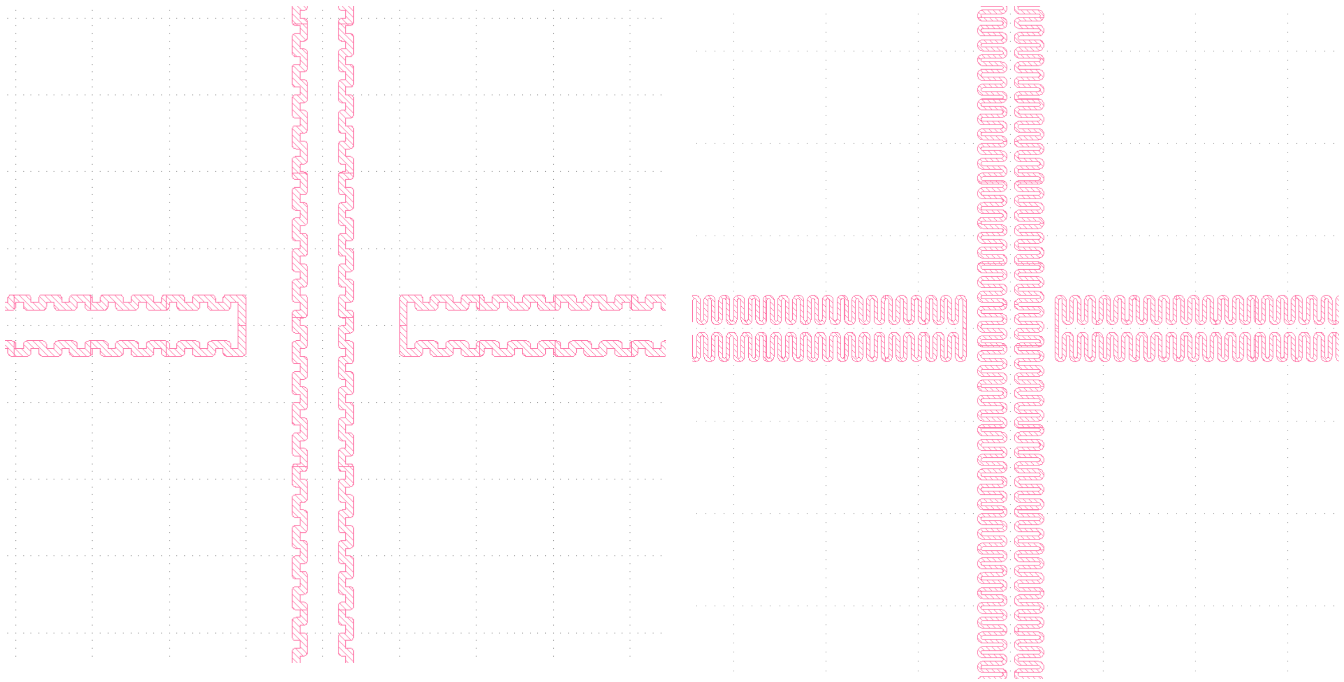
A detector's noise vs. stage temperature measured at -110 dBm

At lower driving power, we have more **1/f noise** coming from **the two-level system** (dipole of the tunneling states can coupling to electric field).

White noise increases vs. temperature.

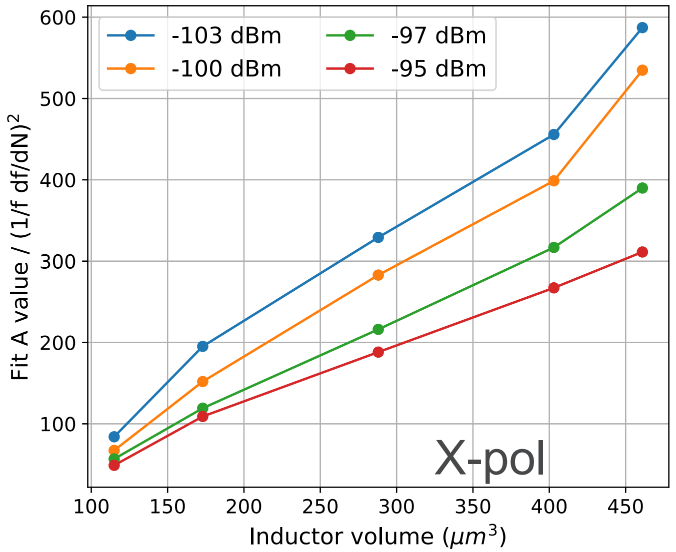
Detector fractional frequency noise

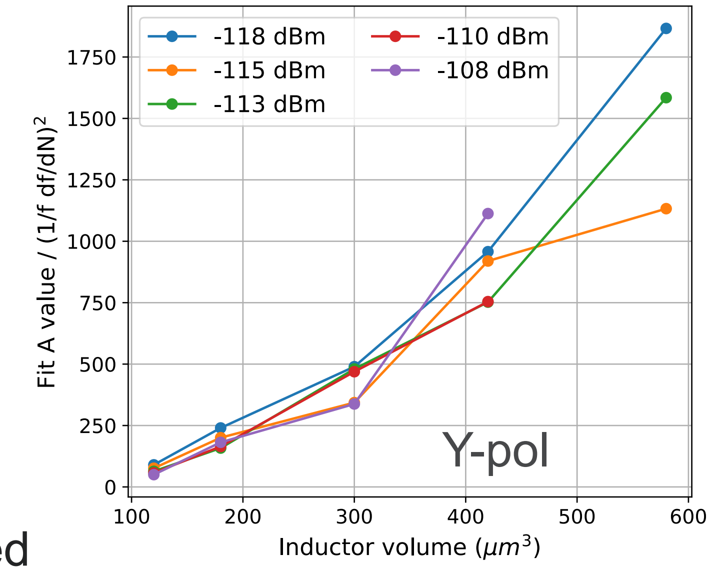
Tune the generation-recombination noise



Inductor volume: 173 μm^3

Inductor volume: 460 μm^3



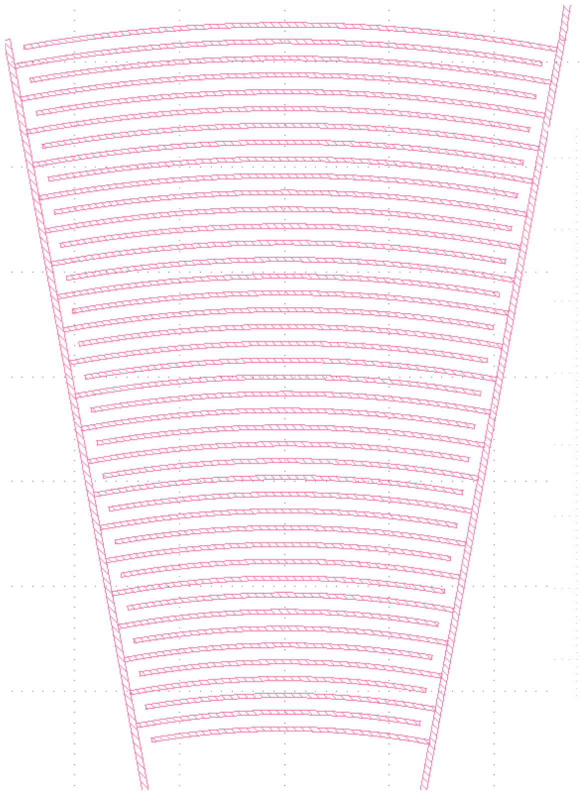


- A represents the GR noise level
- $A = 4 n_{qp} V_L \tau \left(dx / dN_{qp} \right)^2$, where $x = df/f$
- To reduce the GR noise, we can reduce the detector volume

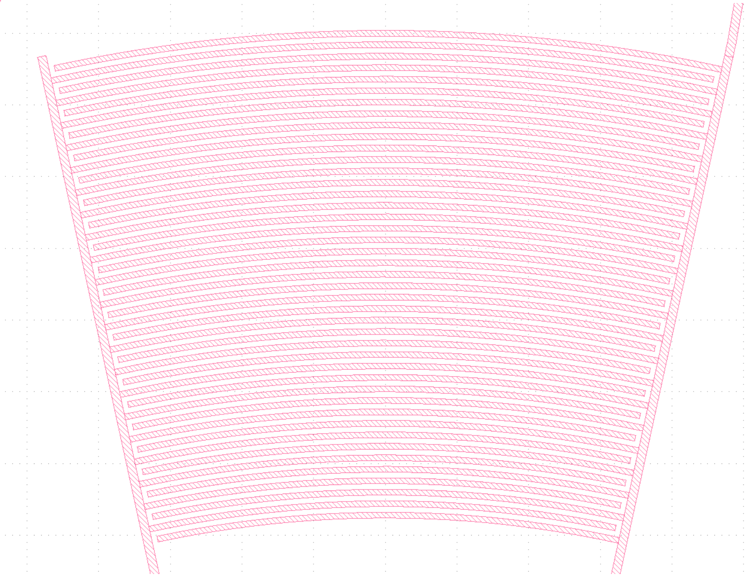
Pan et al, ASC 2022, submitted

Tune the TLS noise

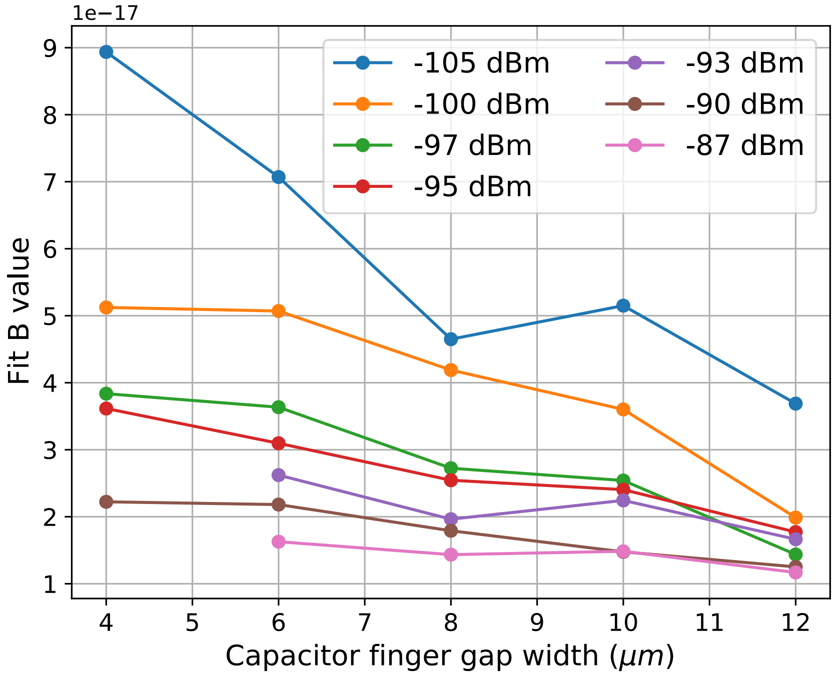
- We tune the TLS by changing the gap between interdigitated capacitor fingers.
- The idea is less of the electric field will couple to the dipole states in amorphous solids with a larger capacitor gap.
- Below is a plot for Al-based resonators, and we found similar trends for Nb-based resonators



Capacitor gap: 12 μm



Capacitor gap: 4 μm

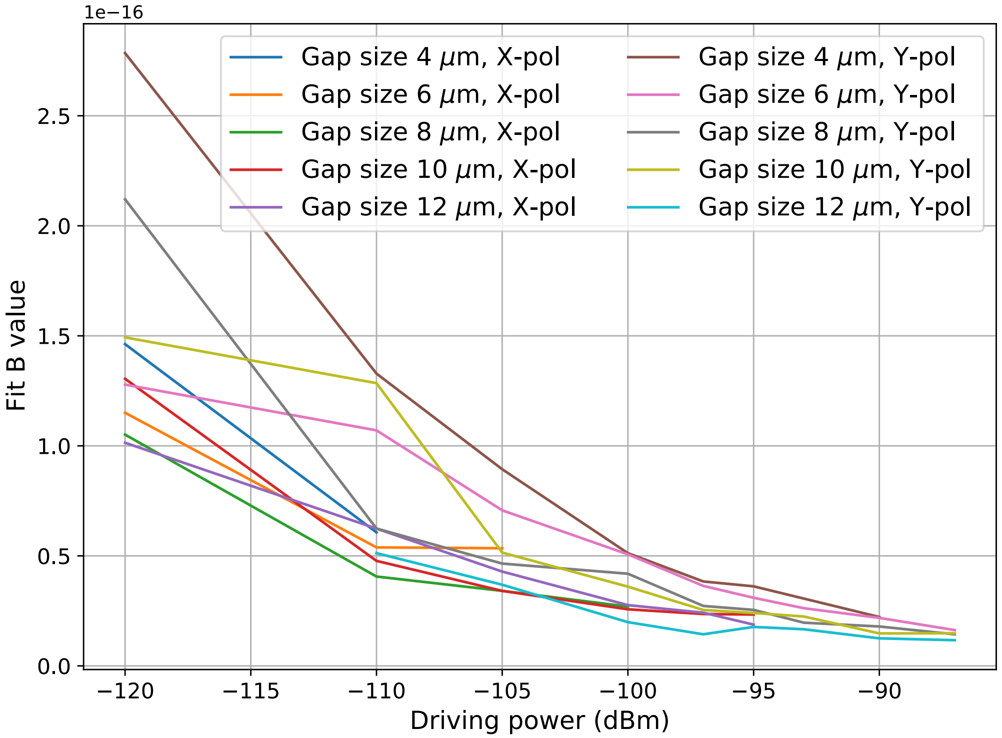


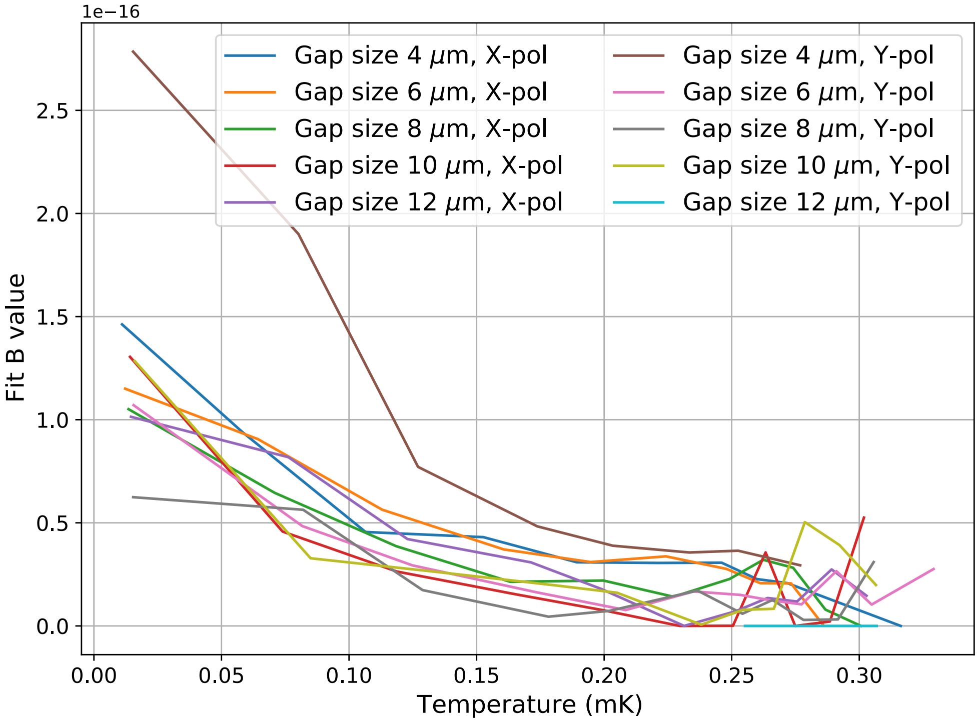
Measurement for Al resonators

$$S_{xx}(f) = \left(\frac{A + Bf^{-n}}{1 + (2\pi f \tau)^2} + C \right)$$

Pan et al, ASC 2022, submitted

TLS noise vs. temperature and power





- TLS noise can be suppressed by increasing the measurement power and operating temperature, which can saturate the TLS states.

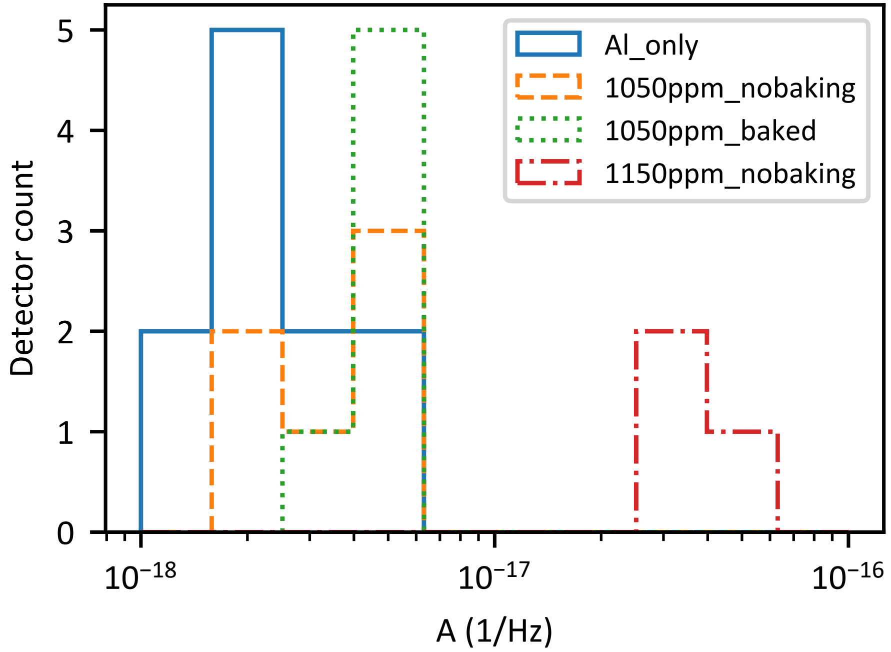
$$S_{\delta f_r / f_r} \propto |\vec{E}|^{-1} f^{-1/2} \, T^{\beta} \, \tanh(h\, f_r / 2\, k_B\, T)$$

Pan et al, ASC 2022, submitted

AlMn resonators

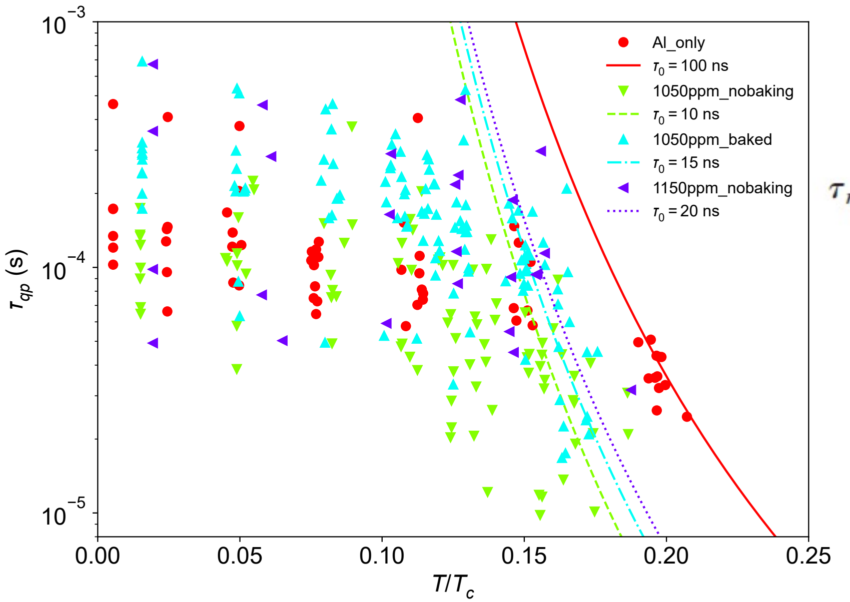
- AlMn resonators with 0, 1050, and 1150 ppm Manganese doping.
  - Superconducting transition temperatures:
    - Aluminum (1.1K)
    - 1050ppm (0.73K)
    - 1050ppm with 180C 10min baking (0.78K)
    - 1150ppm (0.61K).
  - Bifurcation power is lower with doping; the quality factor is slightly lower.
- Questions:
  - How does the GR noise level depend on Manganese concentration and baking conditions?
  - How does the roll-off time constant change as a function of doping?

AlMn noise results



GR Noise Level in S_{xx}

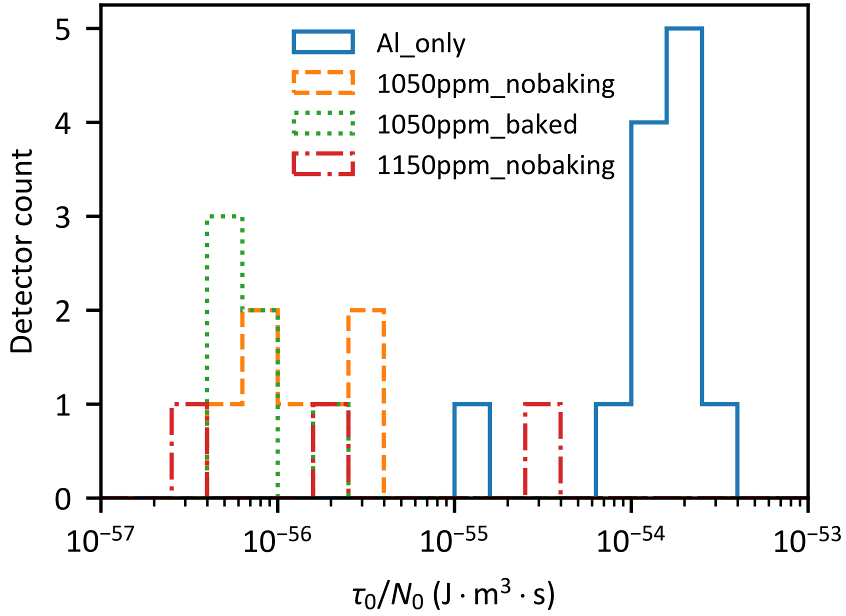
GR noise is worse with Mn doping



τ_{qp} vs Reduced temperature

$$\tau_r = \frac{\tau_0}{\sqrt{\pi}}\left(\frac{k_B T_c}{2\Delta}\right)^{5/2}\sqrt{\frac{T_c}{T}}e^{\Delta/k_B T} = \frac{\tau_0}{n_{qp}}\frac{N_0(k_B T_c)^3}{2\Delta^2}$$

τ_0 reduces with Mn doping



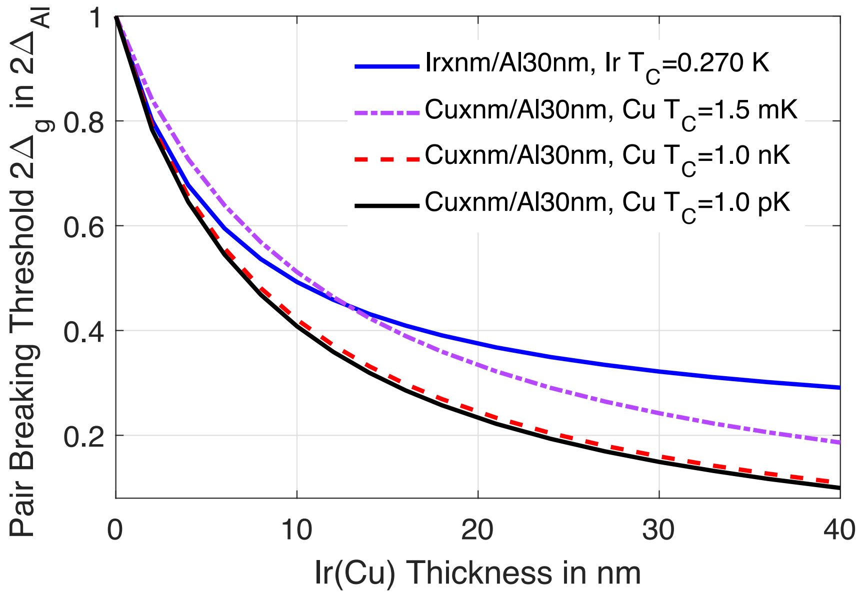
Relate to density of states

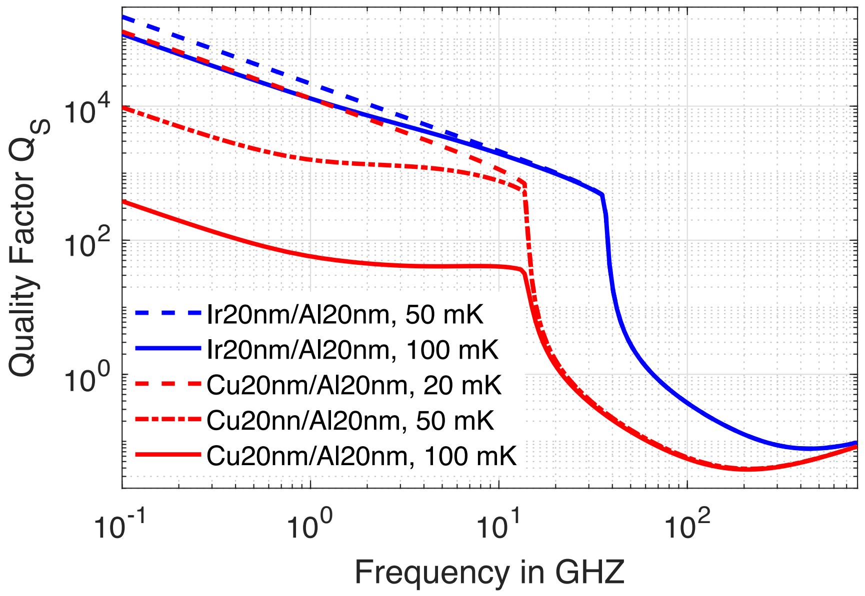
We can also constrain the density of states (at the Fermi level) N_0 using the GR noise level and the time constant data if we assume a BCS model

Pan et al, ASC 2022, submitted

Another way to lower the Tc – metal bilayer

- The density of states can be calculated for a metal bilayer using Usadel equations.
- Here Ir/Al and Cu/Al bilayers are considered.
- The pair-breaking energy can be tuned by layer thickness (left plot)
- When $\Delta_g < 0.3\Delta_{Al}$, a KID needs to be operated at a low temperature (10 mK) and with low readout frequencies (<2.0 GHz) for a large quality factor (right plot)

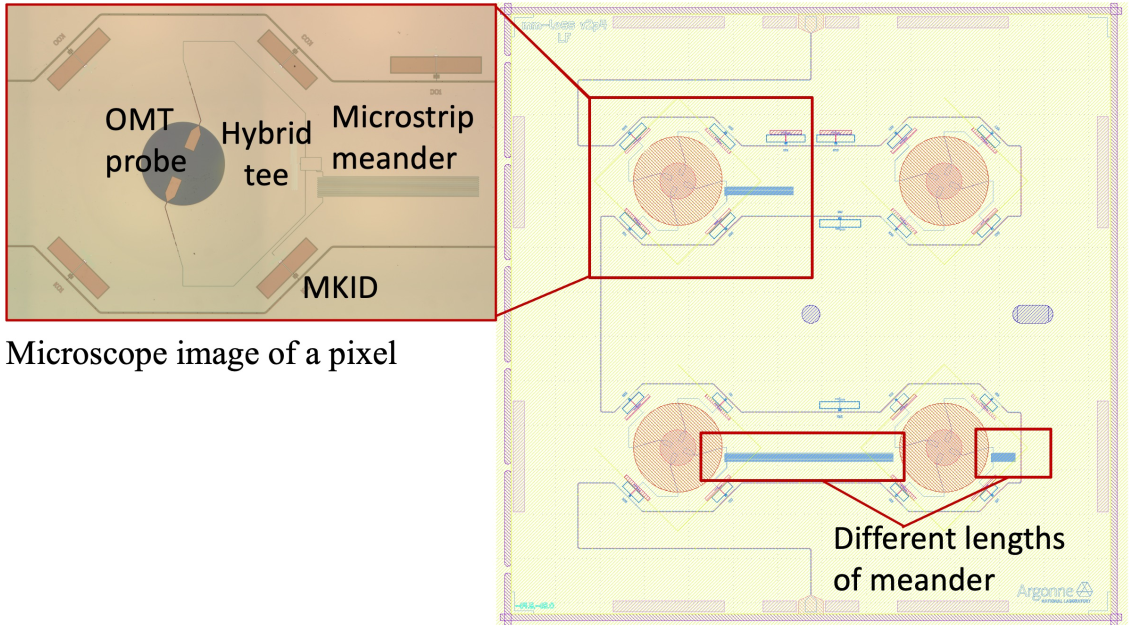




Wang et al, ASC 2022, submitted

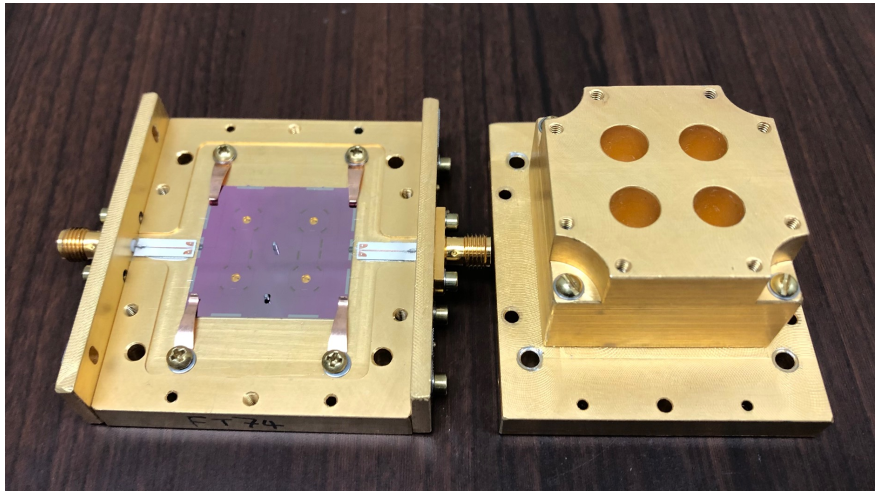
Dielectrics Optimization – Methodology

- **Status of dielectrics loss measurement**
  - Previous measurements **mostly focused on a few GHz**
  - NIST's mm-wave loss is ~**3 times worse than a few GHz**
  - **Mm-wave is where our detectors operate**: we need more data there
- **We have *three* methods to constrain dielectrics loss from mm-wave to cm-wave using the same device**
  - Measure the quality factor Q_i, the **loss** $\sim \mathbf{1/Q_i}$ in the low power limit (~ 1 GHz)
  - Fit resonator frequency vs. temp. to **two-level system (TLS) model** (~ 1 GHz)
  - Compare optical responses through **different lengths of microstrip line** (~ 150 and 220 GHz)



Microscope image of a pixel

Device design mask



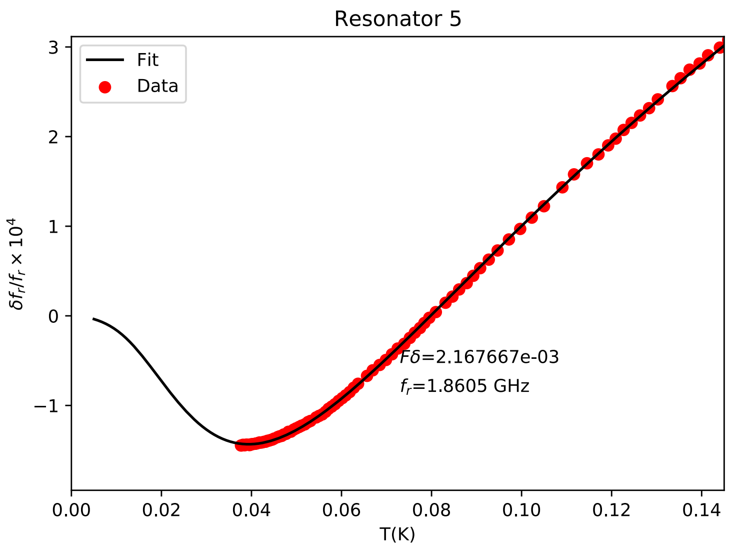
Pan et al, ASC 2022, submitted

Dielectrics Measurement Results for Conventional SiNx

- **Method 1 (1 GHz)**: Assuming a phenomenological model with a density of states uniform in logarithm space, we can model resonator frequency's dependence on temperature, loss tangent δ, and the dielectrics filling factor F

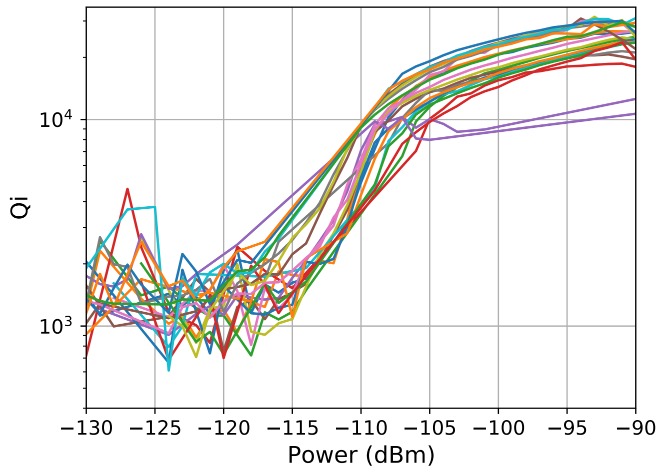
$$\frac{f(T)-f_0}{f_0} = \frac{F\delta^0_{\mathrm{TLS}}}{\pi}\left[\mathrm{Re}\Psi\left(\frac{1}{2}-\frac{\hbar f_0}{jk_BT}\right)-\log\frac{\hbar f_0}{k_BT}\right]$$

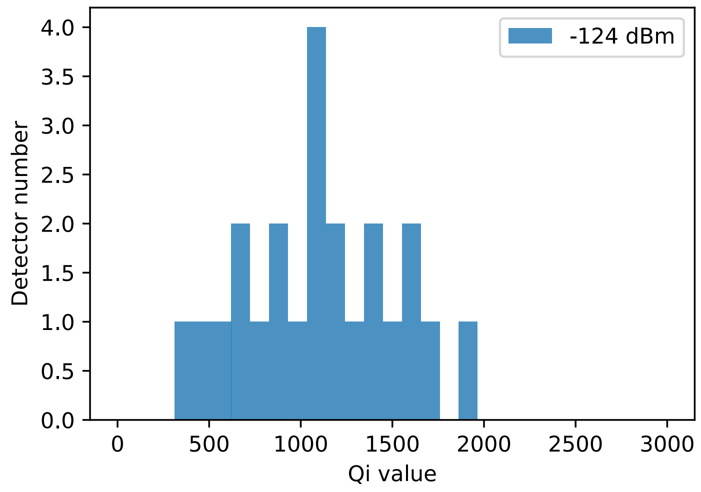
- **$F\delta$ at the 2e-3 level**. The statistical error within each chip is within 1e-4.



Pan et al, ASC 2022, submitted

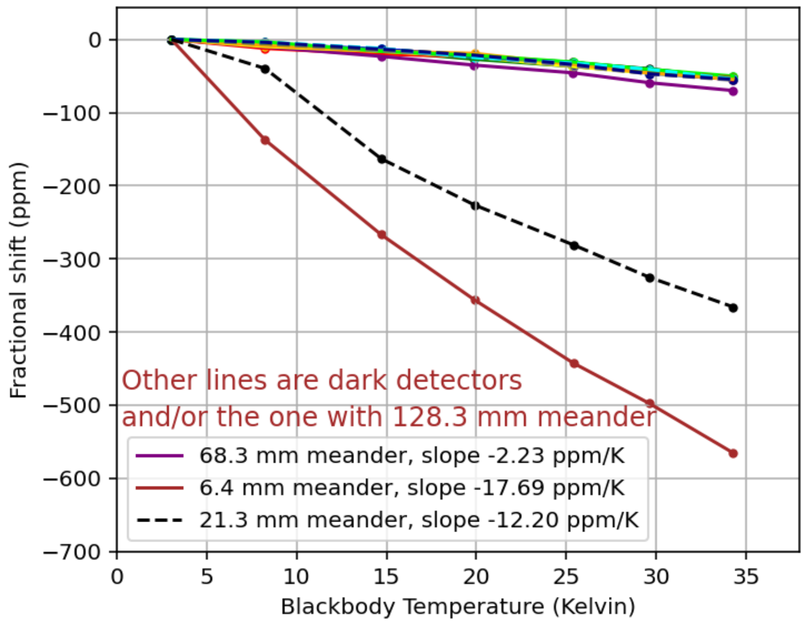
- **Method 2 (1 GHz)**: $Q_i \sim 1/\delta$ in the low-power limit.
- The internal quality factors of our resonators are limited by the TLS loss.
- TLS can be saturated by a higher power, resulting in a higher Q_i at higher power, so we need the power sufficiently low for this method.
- Q_i asymptote to ~1000 in the low power limit. However, our data is noisier when the power is < -120 dBm.
- We can constrain **δ ≳1e-3** from Q_i measurement. Note that this is a lower limit because our S/N reduces at lower power.





Dielectrics Measurement Results

- **Method 3 (150 GHz): compare optical efficiency for detectors coupled through different lengths of microstrip lines**
- The left plot below shows the detectors' frequency shift vs. cold load temperature. We have four optical detectors coupled to 6.4, 21.3, 68.3, and 128.3mm meanders.
- The inferred dielectrics loss is $\mathbf{\tan\delta \sim 4e\text{-}3}$**, about a factor of two higher than the loss at 1 GHz (for conventional SiNx)**



Pan et al, ASC 2022, submitted

We have more dielectrics with measurements at 1GHz

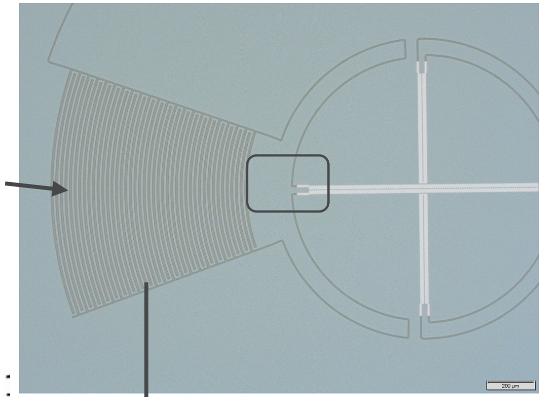
Material	Method	Deposition parameters	Refractive index	Stress	Tan delta
SiO2	MS	250C 4h, 4.6sccm O2 25sccm Ar	1.46	-314 MPa	10E-3
SiO2	IBAD MS	RT 1h, 8sccm O2, 20sccm Ar	1.58	-311 MPa	8E-4
a-Si	IBAD MS	RT 1h, 20sccm	4.1	-705 MPa	5E-4
SiNx (Si rich)	IBAD MS	RT 1h, 6sccm N2, 20sccm Ar	2.4	-1575 MPa	8E-4
SiNx	IBAD MS	RT 1h, 17sccm N2, 20sccm Ar	1.98	-1702 MPa	1E-3
SiNx (Si rich)	PCVD	100C 1h	2.38	-792 MPa	2E-4
SiNx	PCVD	100C 1h	..	..	1.1E-3

Marharyta Lisovenko et al., ASC 2022, submitted

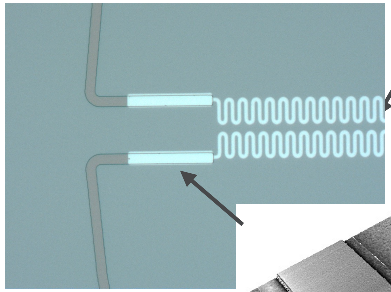
Detector Integration – galvanic contact

- We can cap Nb layer with NbN before depositing the next metal layer to avoid oxidization and enhance galvanic contact.
- Control of the nitrogen flow can tune the NbN Tc from 10.5 to 14.5K.
- The NbN film surface is smooth within 7 nm.
- The achieved resonator internal quality factor Q is around 700K (low loss).

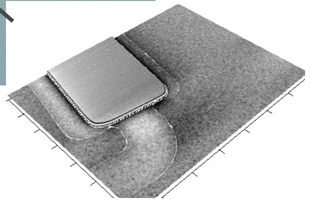
MKID resonator



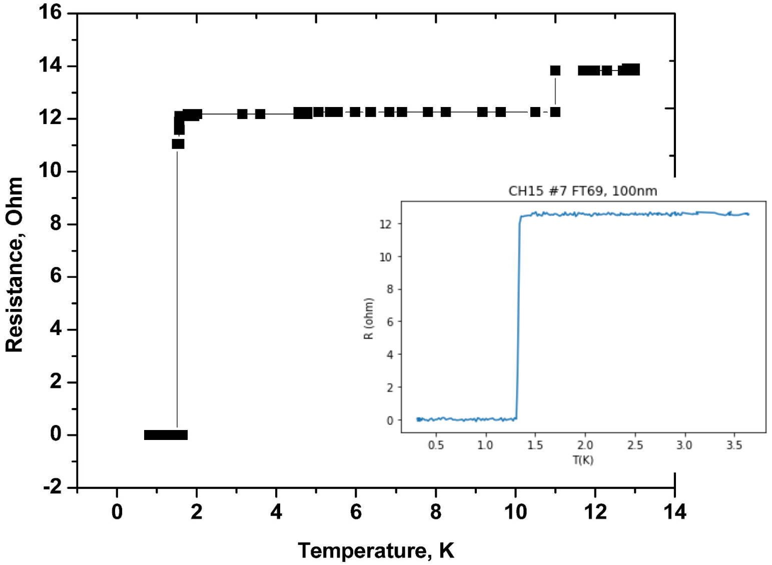
Nb170nm+NbN 30nm
Interdigitated capacitor



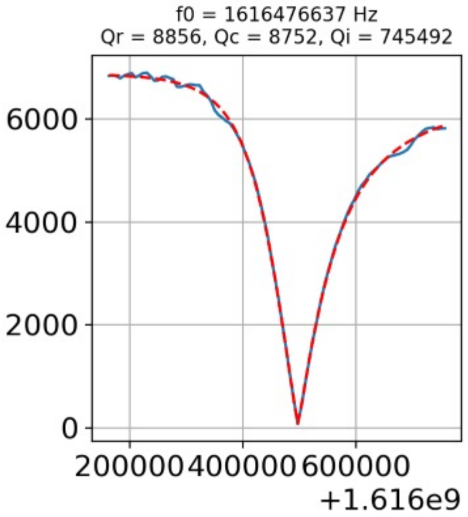
Al 30nm
inductor



AFM image



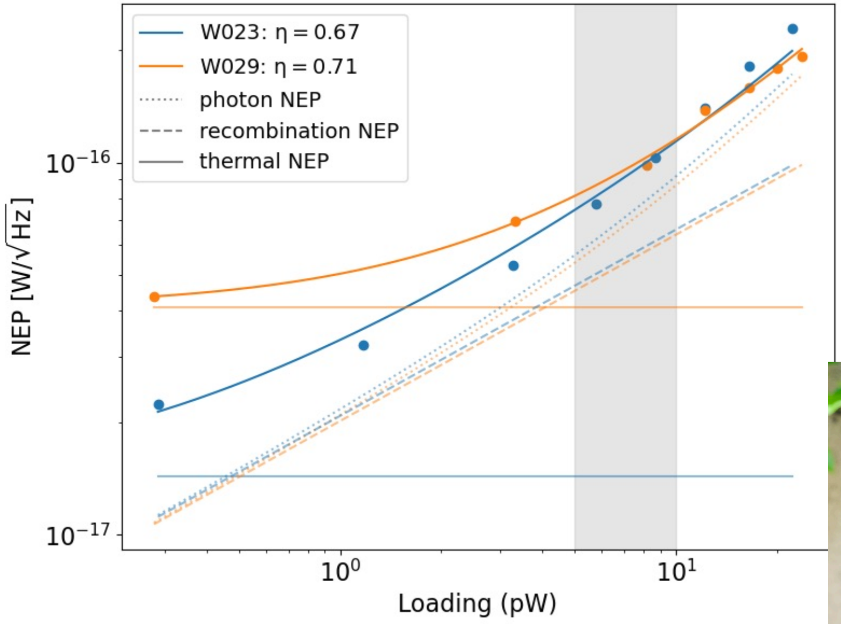
Superconducting transitions for NbN and Al



Yefremenko et al., ASC 2022

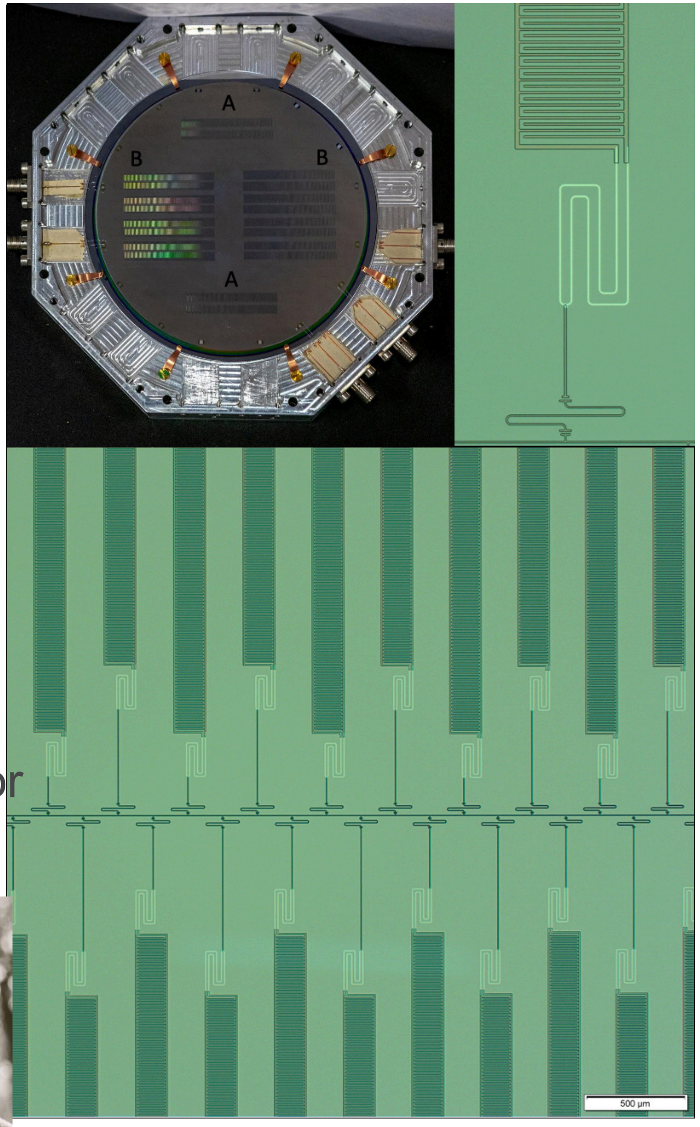
Integrated Detectors and Performance

Top left: picture of a 63-pixel photometer array for SPT-3G+. The quality factor is ~ 4.8e5.



Bottom left: optical efficiency fit for SPT-3G+ detectors, ~70%

Dibert et al, ASC 2022, submitted



Right: prototype spectrometer array for SPT-SLIM

Cecil et al, ASC 2022, submitted

Summary

- This talk summarizes the MKIDs optimization efforts targeting next-generation photometers (SPT-3G+) and spectrometers (SPT-SLIM).
- We validated a few knobs to tune detector noise and studied the dependence on materials
  - GR noise: tune by volume
  - TLS noise: tune by detector capacitor geometry, temperature, and power
  - AlMn resonators: doping with Mn increases the GR noise and reduces τ_0
- Two ways to tune detector Tc: doping with Mn or using metal bilayer
- Dielectrics optimization
  - One single test structure to measure dielectric loss from mm-wave to cm-wave
  - Mm-wave loss seems ~ x2 worse than at cm-wave
  - Promising dielectric: Si-rich SiNx (conformal film quality, low deposition temp, loss ~ 8e-4)
- Detector integration
  - NbN cap on Nb helps establish stable galvanic contact with subsequent metal layers
  - Prototype photometer arrays for SPT-3G+ showed high optical efficiency
  - A prototype spectrometer array for SPT-SLIM was fabricated