Development of Photon noise limited Kinetic Inductance Detector Array

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NIST

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Quantum Sensors Group, NIST Boulder

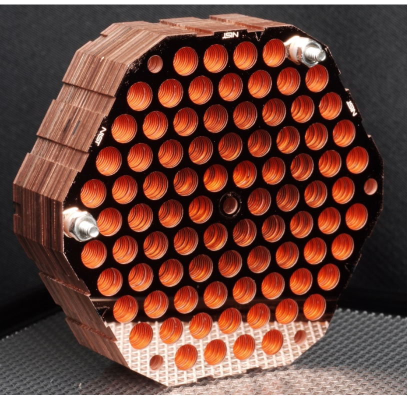
Group Leader: Joel Ullom

- **Long-wavelength Project** (TES and MKID): **Johannes Hubmayr (lead)**, **Jay Austermann**, Jim Beall, Dan Becker, Brad Dober, Shannon Duff, **Jiansong Gao**, Gene Hilton (fab lead), Jeff Van Lanen, Mike Link, Tammy Lucas, **Mike Vissers**, Sam Walker
- **Calorimeter project** (so far only TES…)

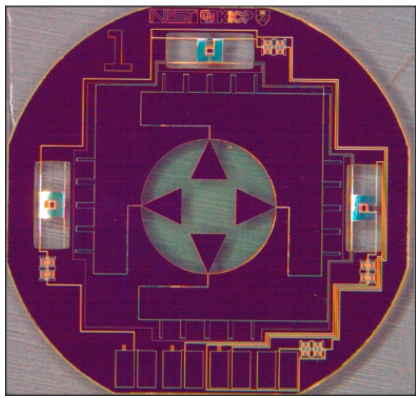
TES bolometer Development at NIST

- Wavelength range: CMB (30GHz to 300GHz)
- Basic approcach: Feedhorn-OMT coupled TES + microwave SQUID Mux
- Ongoing projects: AdvancedACT, SPIDER, Simons array, ALI-CPT

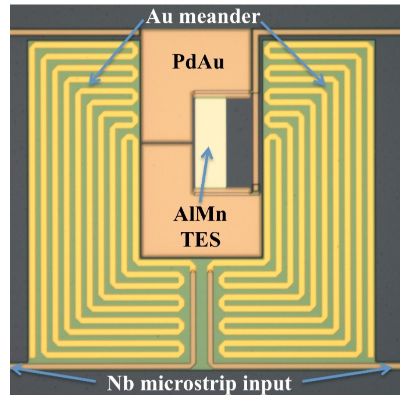
Si feedhorn



OMT mm-wave antenna

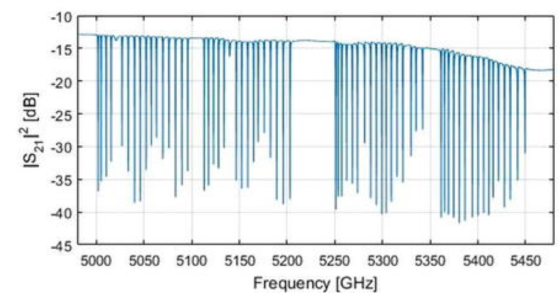


TES



SQUID Mux

Readout electronics



Reduce cost
=> DRIE to laser cutting?

Reduce complexity
⇒ X-over to X-under*

Reduce loss
⇒ SiO_2 to SiN

Uniformityrepeatability
⇒ MoCu to AlMn

Increase mux density
⇒ TDM to microwave
⇒ 32ch/mux*2 in 500MHz + ROACH2
⇒ 32 to 64, 128 ch/mux
⇒ ROACH to 4DSP (4GHz BW)

6in fabrication

⇒ Increase BW
⇒ Multichroic

⇒ 6in integrated fabrication

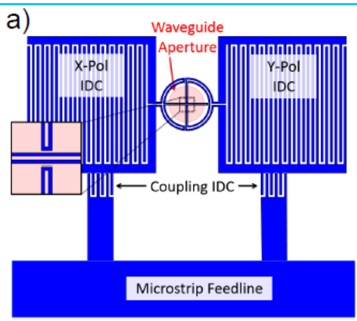
Tech. Lead; : Johannes Hubmayr

MKID Development at NIST

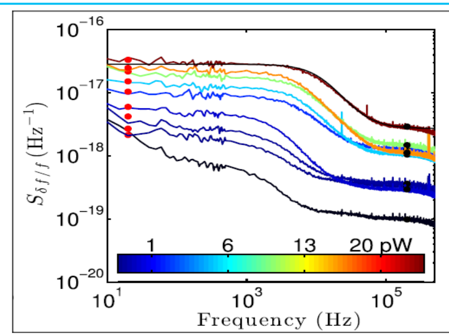
- Wavelength range: 150 GHz to 1.2THz; Ongoing projects: BLAST-TNG, TolTEC
- Basic MKID architecture: Feedhorn-coupled MKID polarimeters. Tech. Lead: Jiansong Gao
- Focus: **Sensitivity, optical coupling, large array fabrication**

Solved/accomplished during the project development of BLAST-TNG

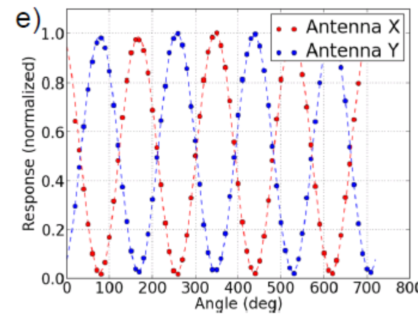
- TiN absorber coupled dual-polarization sensitive non-crossing MKID design



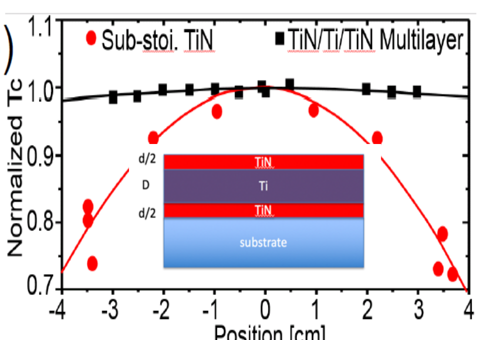
- Photon-noise limited sensitivity at >3Hz from 250 um to 1mm



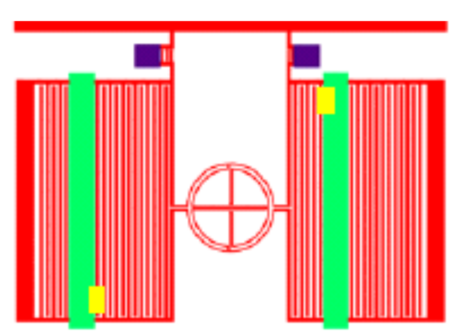
- cross-pol & inter-pixel crosstalk <2% , optical efficiency ~ 60%

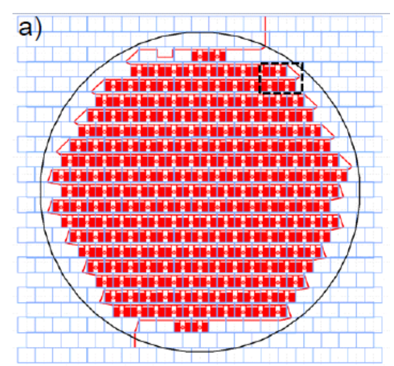


- Uniform and versatile TiN/Ti/TiN tri-layer and multi-layer (Tc, R, t tunable)



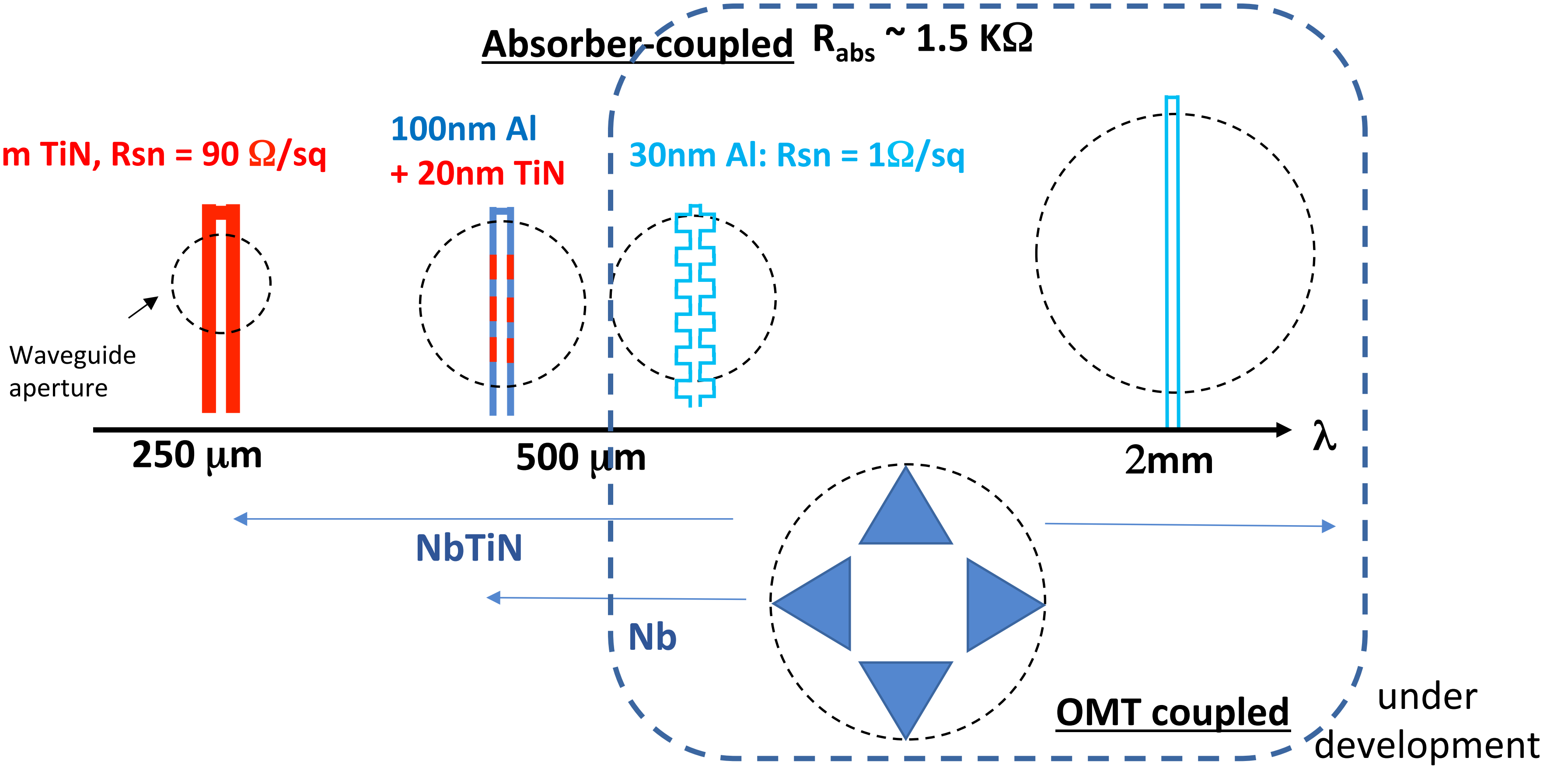
- Scalable and flexible "tile-and trim" fabrication process





Not solved and direction of future development

- Extend the wavelength coverage to 2mm (CMB)

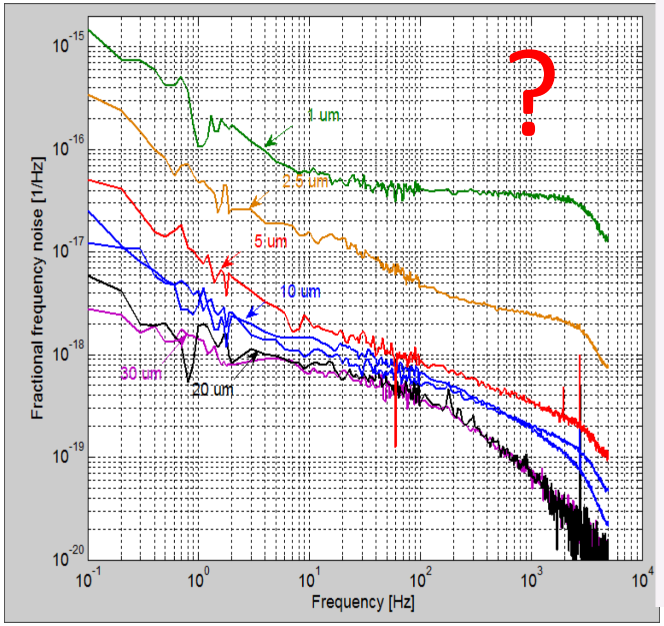


- OMT-coupled MKID
  - **multichroic** operations
  - Better optical efficiency and cross-pol control
  - Direct replaceable of OMT-TES arrays
  - Ease of design due to separation of mm-wave and microwave circuits

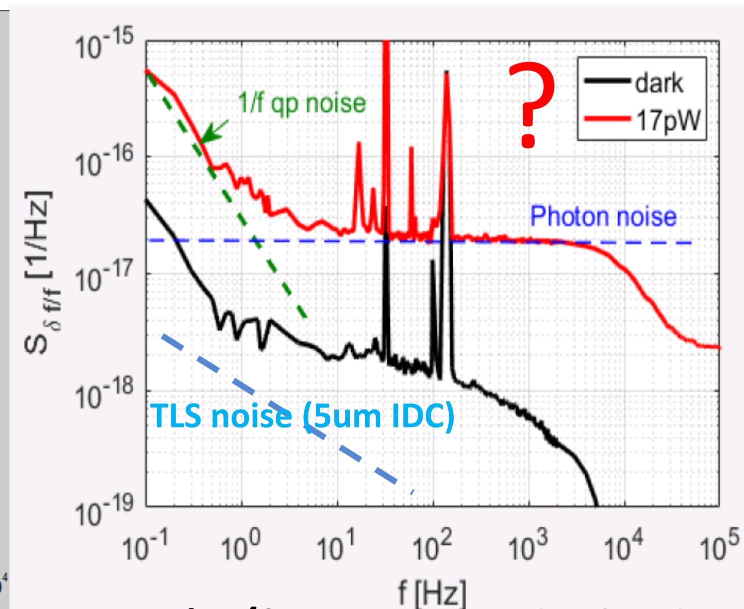
➢ Extend the photon-noise limited performance down to 0.1 Hz

NIST

TiN MKID for BLAST-TNG

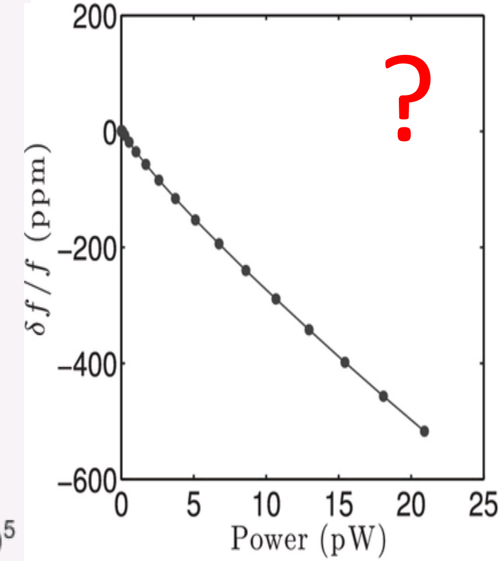


Dark inductor noise ~ w^{-2}

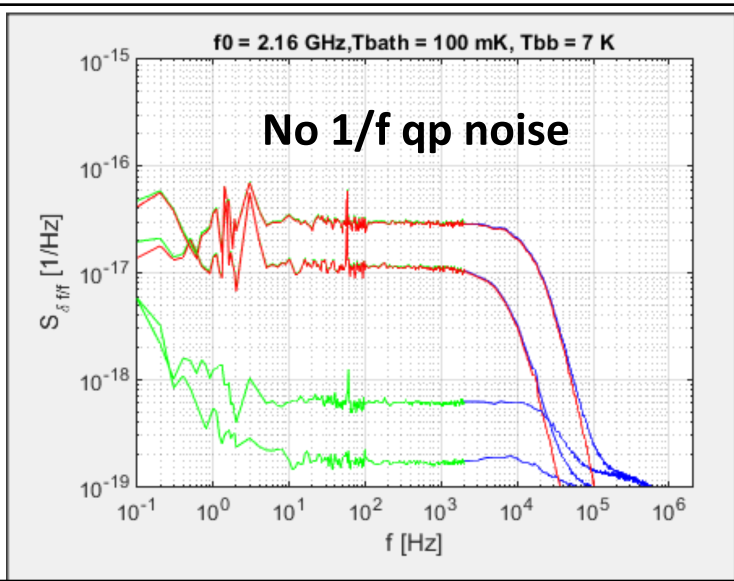


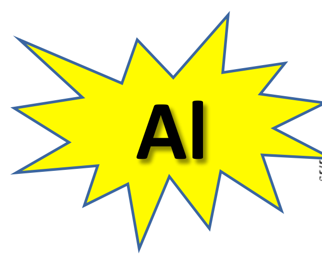
1) 1/f QP noise under load

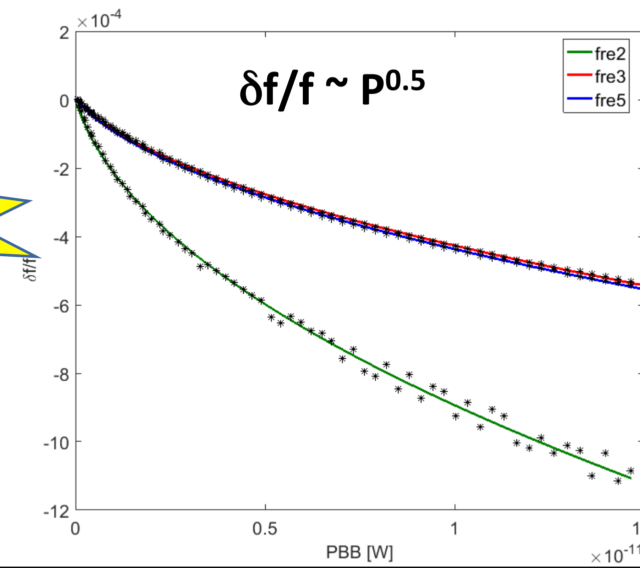
2) Dark inductance noise



δf/f ~ P



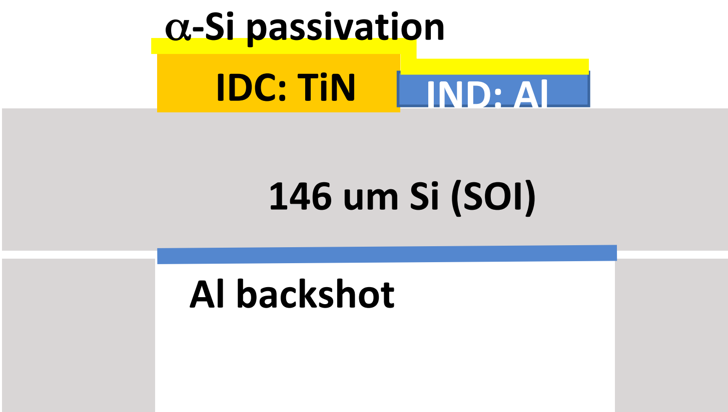


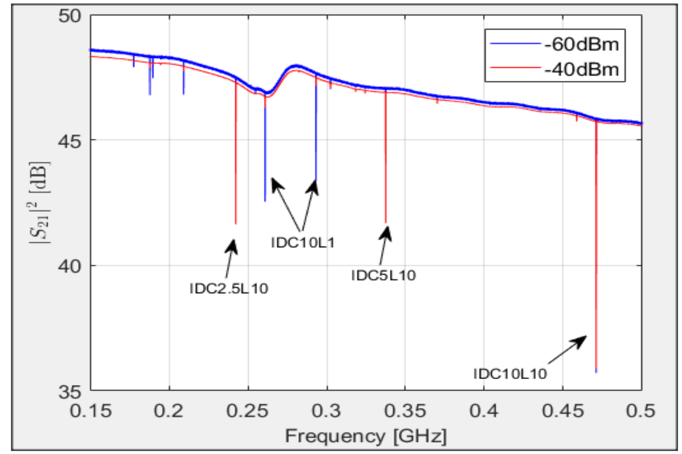


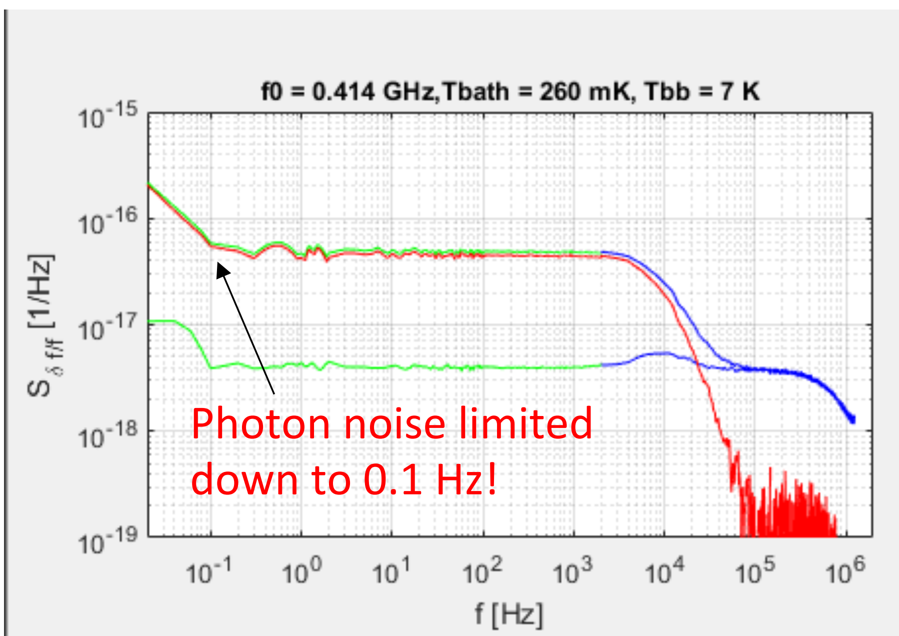
New solution: TiN/Al hybrid MKID

NEW

- Why hybrid? (1 yr of work to come to these conclusions)
  - TLS noise from Al IDC is 10 times higher than made from TiN
  - Al devices turn to degrade over time likely due to oxidation
  - Stoichiometric TiN (Tc ~4.5K) blocks Al (Tc~1.4 K) QPs from diffusion into IDC

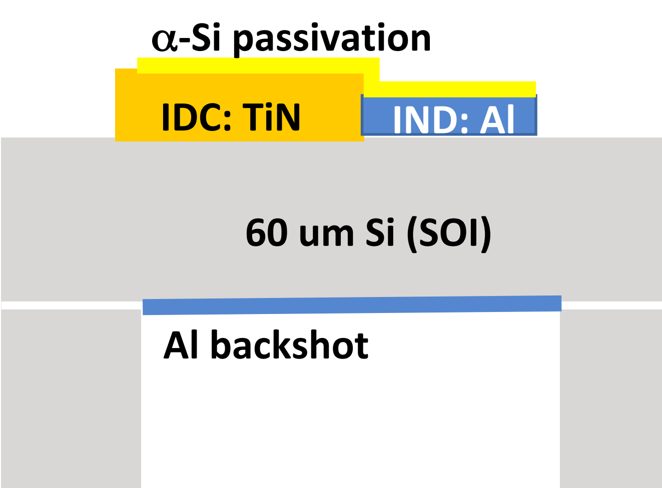


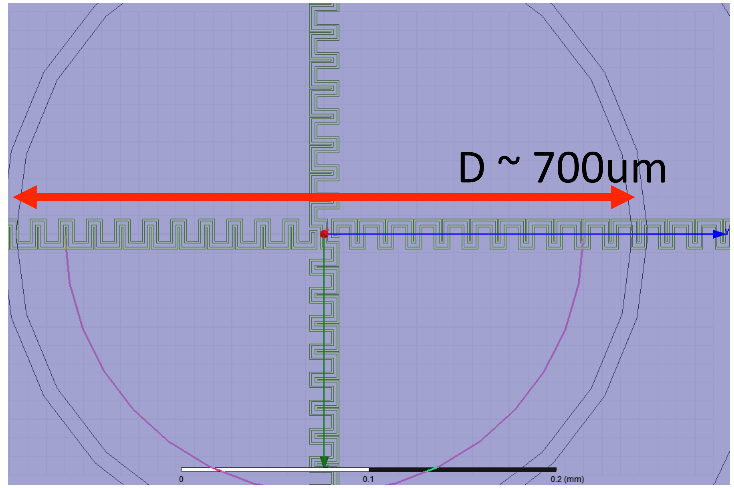


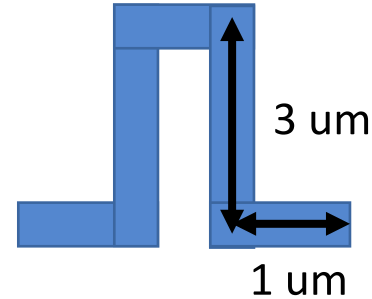


- IDC: thick TiN, Tc ~ 4.5K, w = g = 5, 10um
- Ind: 30nm sputtered Al, Tc ~ 1.4K
- Ind: w=1um, l = 2000um (*2), Rn =1 Ω/sq
- Tbath = 250mK (reduce TLS)
- $Q_{i,dark}$ = 800 k, f0 = 200 - 500 MHz
- $Q_{i,opt}$ ~ 20k -40k

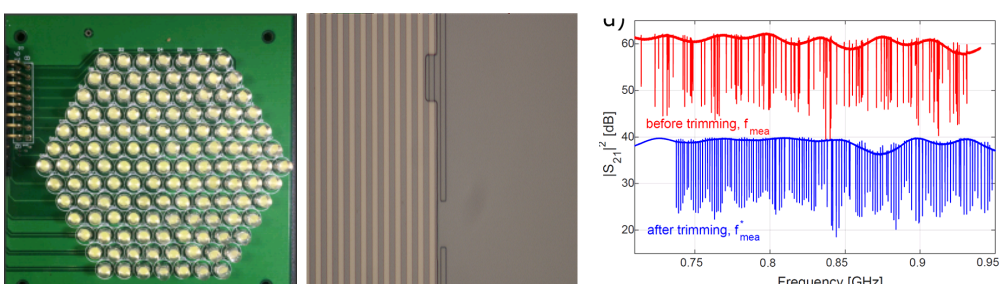
TiN/Al hybrid MKID for 850um band design concept



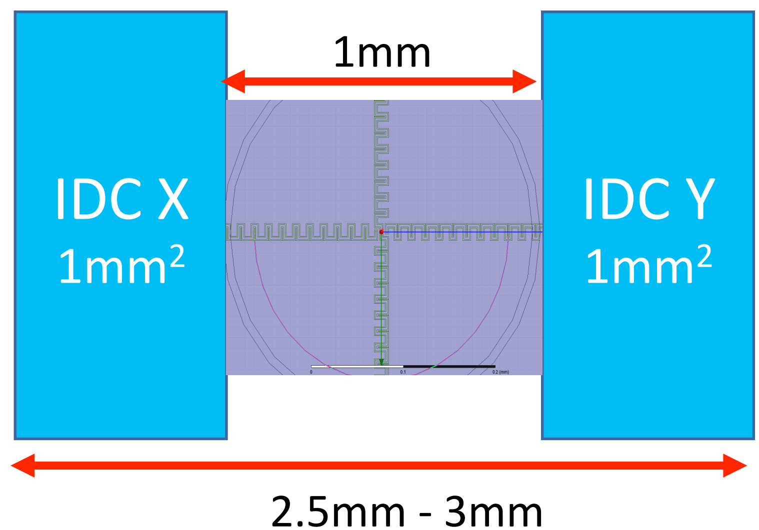




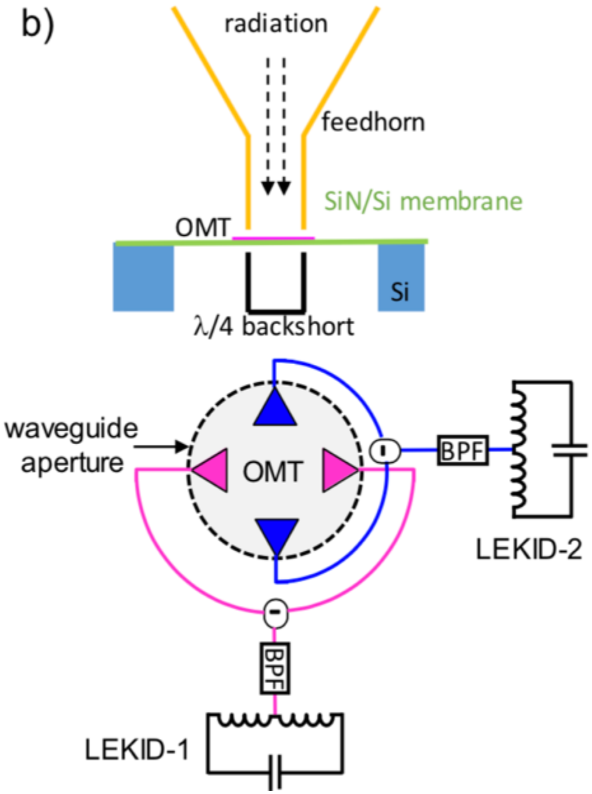
- IDC: thick TiN, Tc ~ 4.5K, w = g = 2.5 or 5um, area 1mm*1mm
- Ind: 30nm sputtered Al, Tc ~ 1.4K
- Ind: w=1um, l = 2800um (*2) meandered, R_{abs} ~ 1.4 kΩ (R_n = 1 Ω/sq)
- Tbath = 150mK - 250mK
- $Q_{i,dark}$ = 800k, f0 = 500 MHz – 1 GHz
- P_{opt} = 5pW, $Q_{i,opt}$ ~ 20k -40k, Q ~ 10k -20k

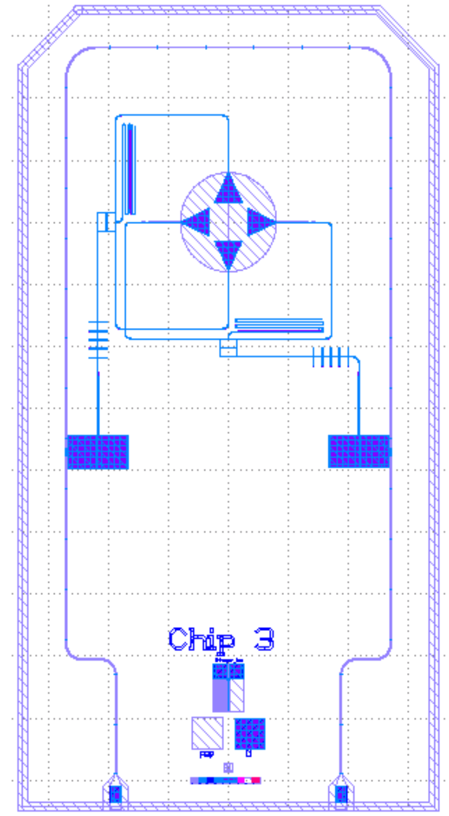


Post-measurement lithographic correction
=> address the non-uniformity of Al wet etch



OMT-coupled MKIDs





- OMT very mature from TES-based implementation
- Keep all mm-wave components on chip identical to TES version, only replace TES with MKIDs, to reduce development work
- Use low-TLS amorphous Si instead of SiN

Coming next year, stay tuned!

Conclusion

- Large format (1000s of pixels on 6-in wafer) feedhorn-coupled MKID arrays based on TiN and hybrid TiN/Al absorbers on SOI wafers developed at NIST are becoming mature in terms of sensitivity, optical performance, fabrication and readout.
- For **single-band** polarimeter/total power detection applications **above 120GHz,** MKIDs are the first choice, with much simpler fabrication, operation and lower cost than TES.
- For **multichroic** applications and **CMB-Pol** applications in 100GHz – 300GHz, OMT-coupled MKIDs are the proper solution which we are actively working on.
- Lower Tc superconductor that Al is needed from CMB applications below 90GHz.

JCMT 850um MKID array

- Pixel development: both TiN version (BLAST, Toltec) and new TiN/Al version (~6 mo)
- Select the best of the two and start array development (~6 mo)

Fist "fully working" and the greatest MKID array of all time!

Collaborations and guest researchers are very welcome.