Slides for CMB probe detectors

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Roger's 2¢

- TESes with TDM are the conservative option given SPIDER's success
- KIDs are maturing rapidly, but not safe right now. We should encourage development.
- HEMTs are not so compelling (to me). Large power dissipation at 20K.
- All optical coupling schemes could work.
- No one is really pushing readout to be low power or radiation hard. (SRON tried a little) This is a problem.

Technologies

- Detectors:
  - TESes
  - KIDs/TKIDs
  - mm-wave HEMTs
- Optical Coupling:
  - Horn direct
  - Horn/ustrip
  - Antenna array
  - lens
- Readout
  - SQUID FDM
  - SQUID TDM
  - u-wave SQUIDs
  - KIDs

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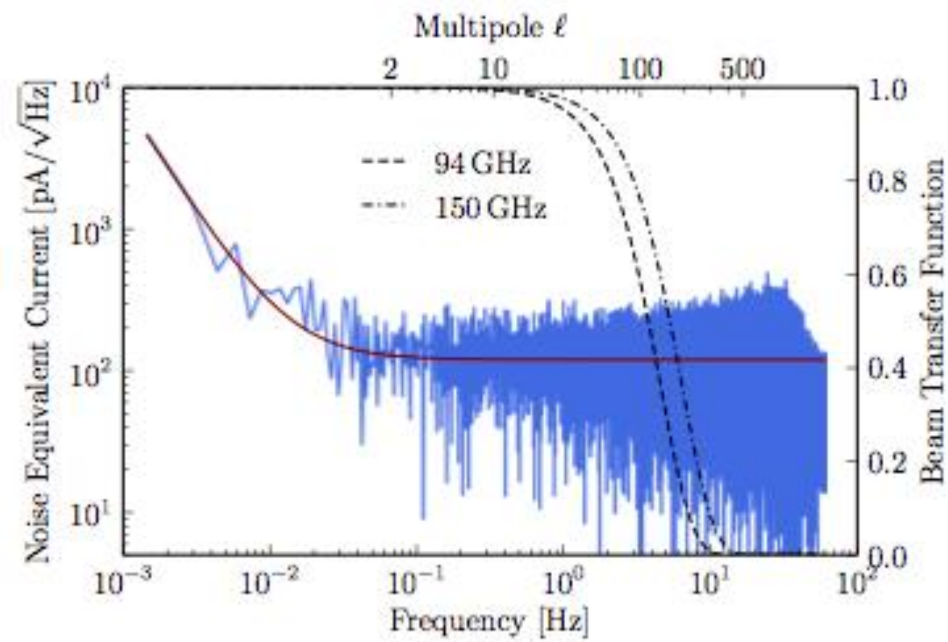
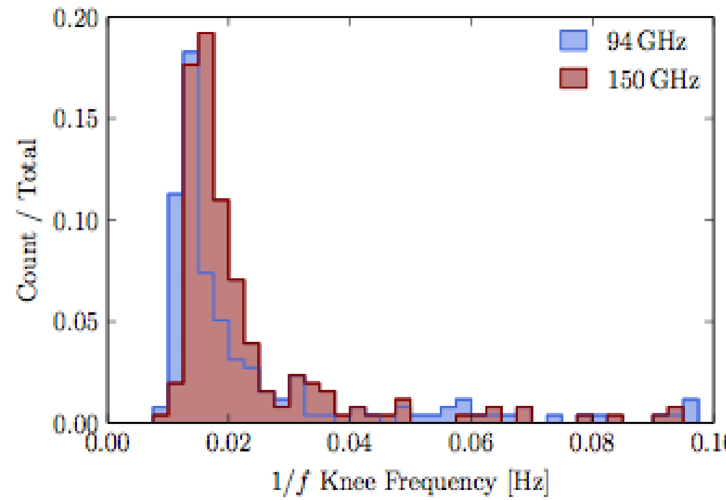
TESes

- TRL6 (90GHz & 150GHz, SPIDER)[1]
- Operating temperature: 250mK
- White noise:
  - ~25aW/√Hz for 95GHz optical band, stable to 0.02Hz
  - Can be extended to extreme frequencies 20GHz-1THz.
  - Noise at ~1aW/√Hz is challenging to achieve because legs are mechanically weak.

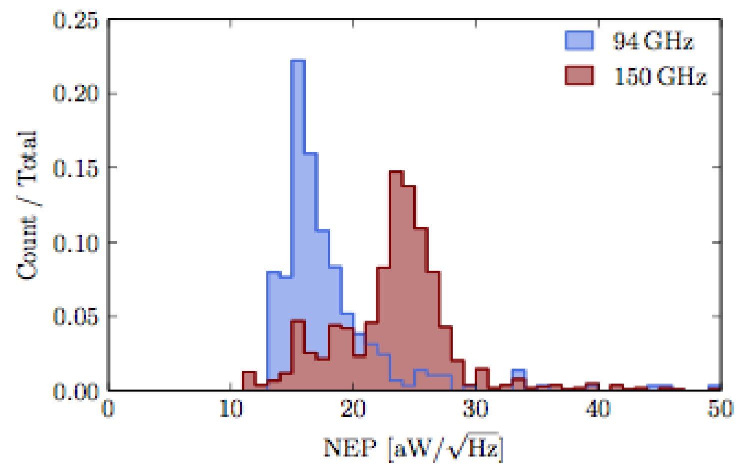
TESes



Multipole ℓ
2
10
100
500
94 GHz
150 GHz
Noise Equivalent Current [pA/$\sqrt{\text{Hz}}$]
Beam Transfer Function
Frequency [Hz]

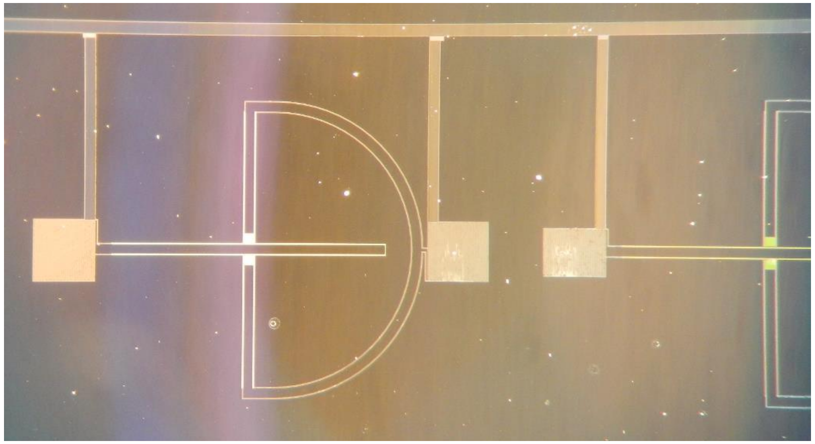


94 GHz
150 GHz
Count / Total
1/f Knee Frequency [Hz]

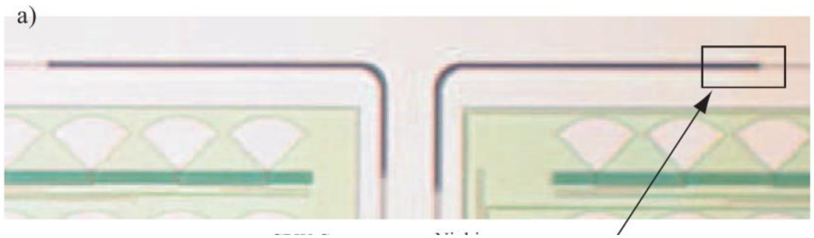


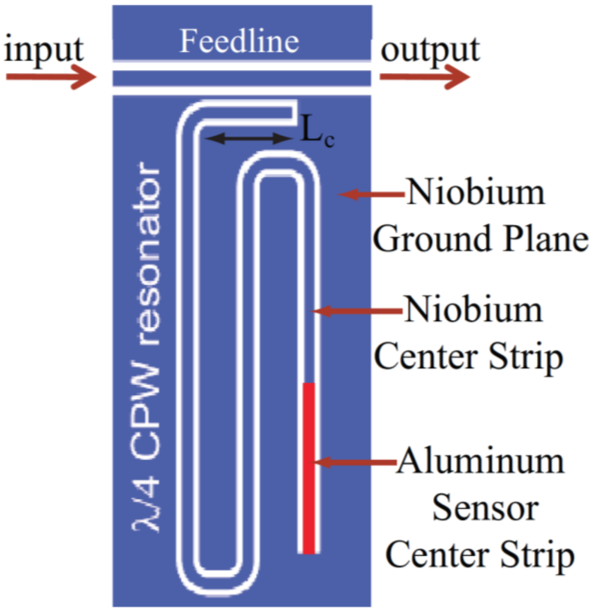
94 GHz
150 GHz
Count / Total
NEP [aW/$\sqrt{\text{Hz}}$]

KID Varieties

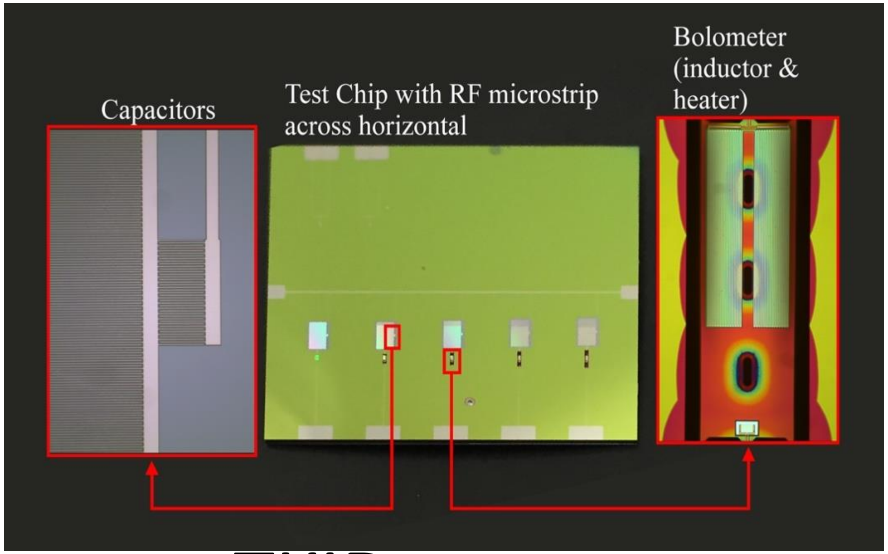


LEKID





MKID



TKID

LEKIDs

- LE= “lumped element”
- TRL 4-5.
- Operating temperature: 100mK
- NIKA2, IRAM Telescope, Pico Valeta (Andalusia) [2]
  - 150GHz optical band
  - 1.5 mK/√Hz white, stable to 1Hz in audio time-stream
- MAKO, Mauna Kea CSO
  - 350um, background limited
  - 850um, not background limited
- BLAST-TNG to fly 2018-19[3]. Lab demos suggest:
  - 1THz optical band
  - 2×10^{-16} W/√Hz under 14pW loading
- Columbia/ASU lab tests[4]
  - 150GHz optical band
  - 30μK√s per det white noise under 4K loading, stable to 1Hz
  - Many people don’t take this number seriously.
- Aluminum bandgap prevent KIDs from working below 100GHz
  - Need more exotic materials, e.g. TiN

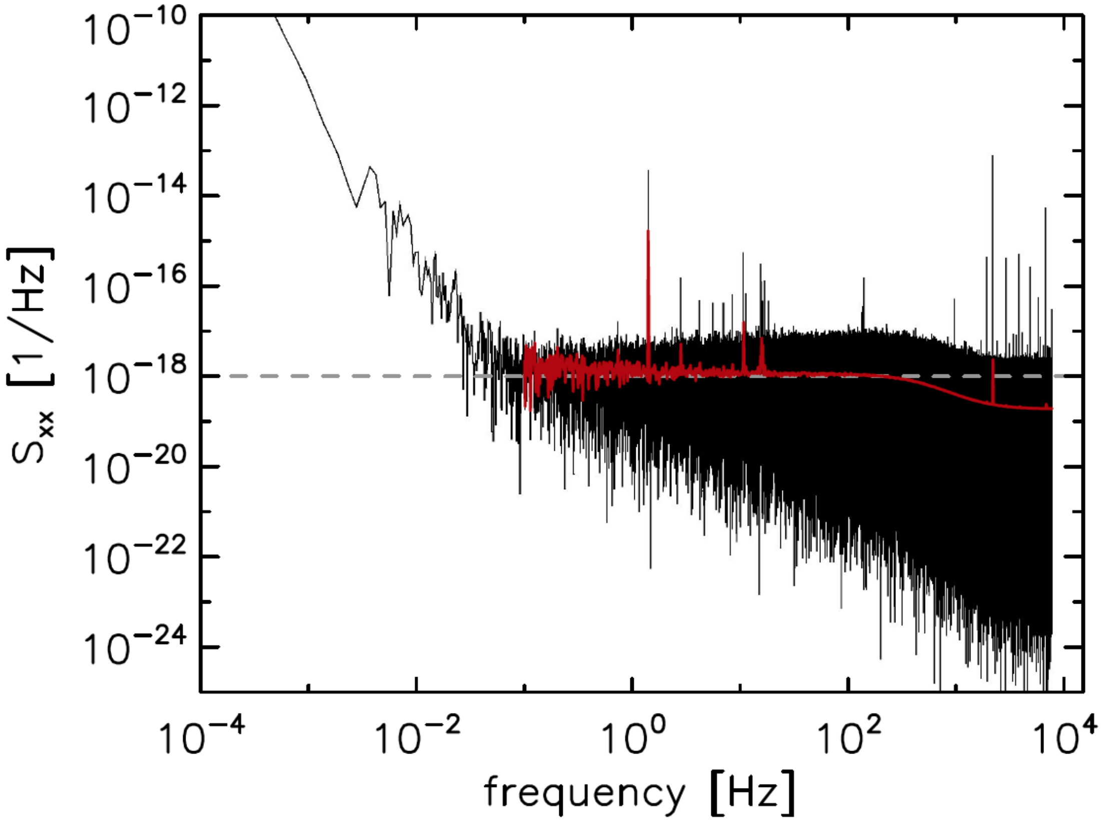
MKIDs & TKIDs

- M= “microwave” (1-10GHz)
- MUSIC (150-300GHz) deployed to CSO, not background limited.
- TLS is a problem at these frequencies. Readout becomes power-hungry
- So TRL 4ish?

- T=“thermal.” A bolometer with a KID thermometer
- More expensive to fabricate, but avoid nasty engineering/test challenges
- Only lab demos, so TRL 3

LEKIDs

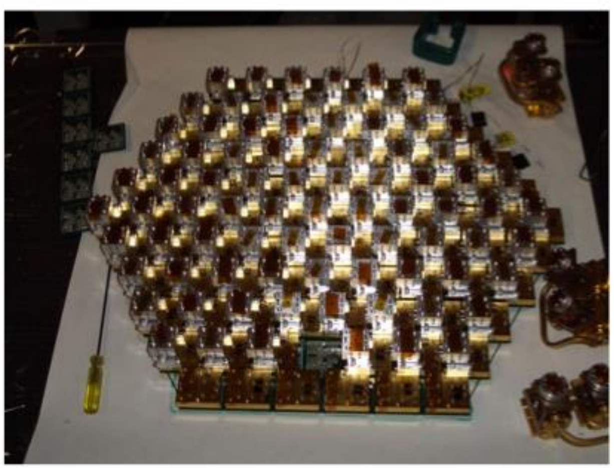
- A flattering noise spectrum, from Johnson group at Columbia, unpublished.

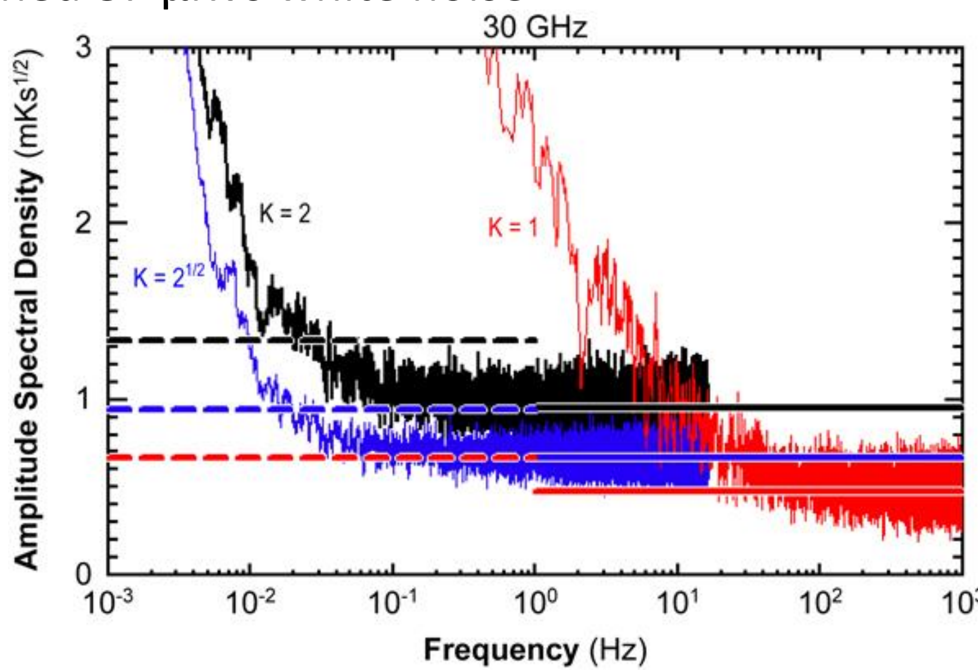


- Calibrated using very bright sources to ensure photon-limited performance

HEMTs

- TRL 9.
- Demonstrated in Planck and QUIET [5].
- Operating temperature: 20K
- NET is not background limited above ~90GHz in space
- Cryo stage Power dissipation in HUSIR ~1W/feed![6]
- QUIET (Atacama)[7]:
  - Q-band: 17 element, combined 69 μK√s white noise
  - W-band: 84 element, combined 87 μK√s white noise





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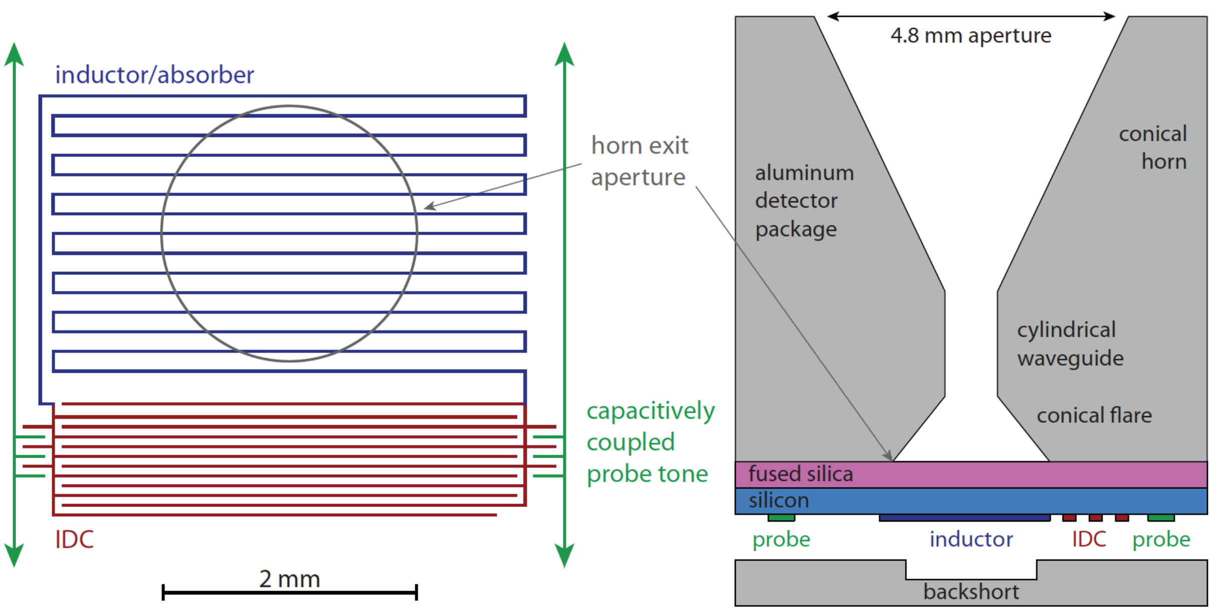
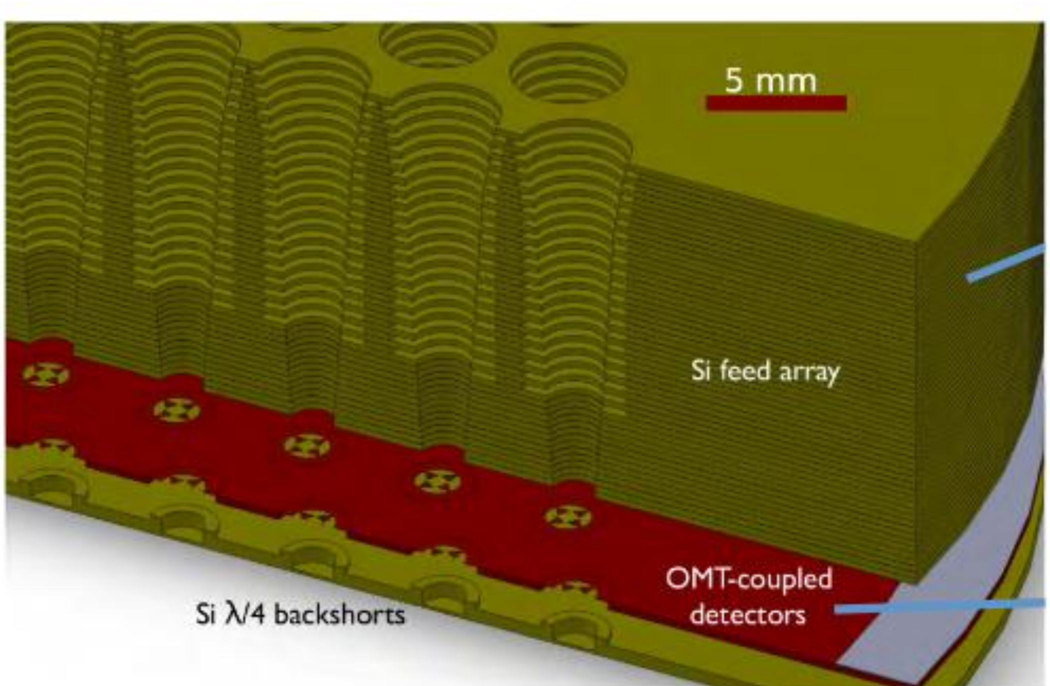
Horn, direct coupling

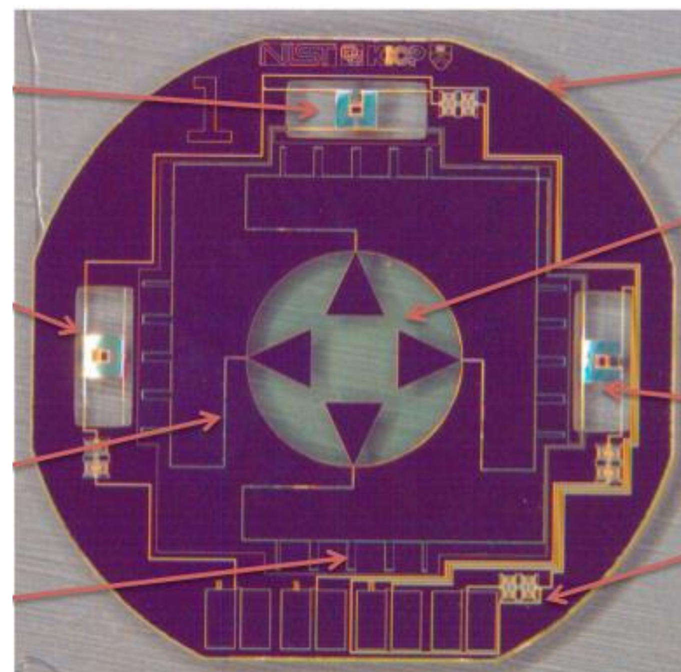
- TRL 9. Used in Planck, SPT-SZ, NIKA, ColumbiaASU-KIDs [8]
- Only one color per detector. Dual pol can be tricky
- For bolometers, must release large surface area.
- No microstrip loss challenges



Horn,microstrip

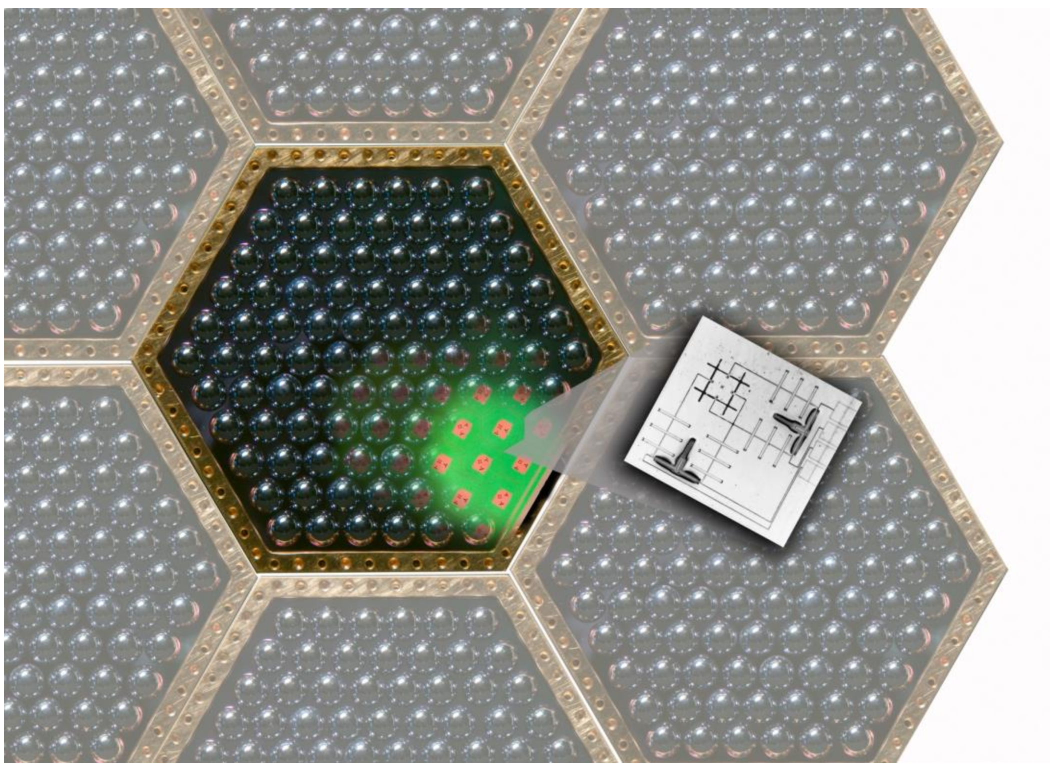
- Couple from WG modes to OMT, to CPW, to microstrip [9]
- NIST centered collaborations
- TRL 5. Used in ACTpol, ABS & SPTpol. Will fly in SPIDER 2019-20
- Broadband: Have deployed 90/150GHz channels
- Highly symmetric beams
- Platelet or mandrel formed

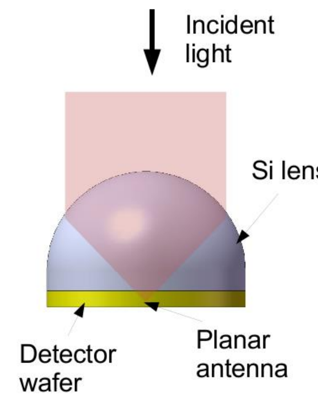




Lens coupled

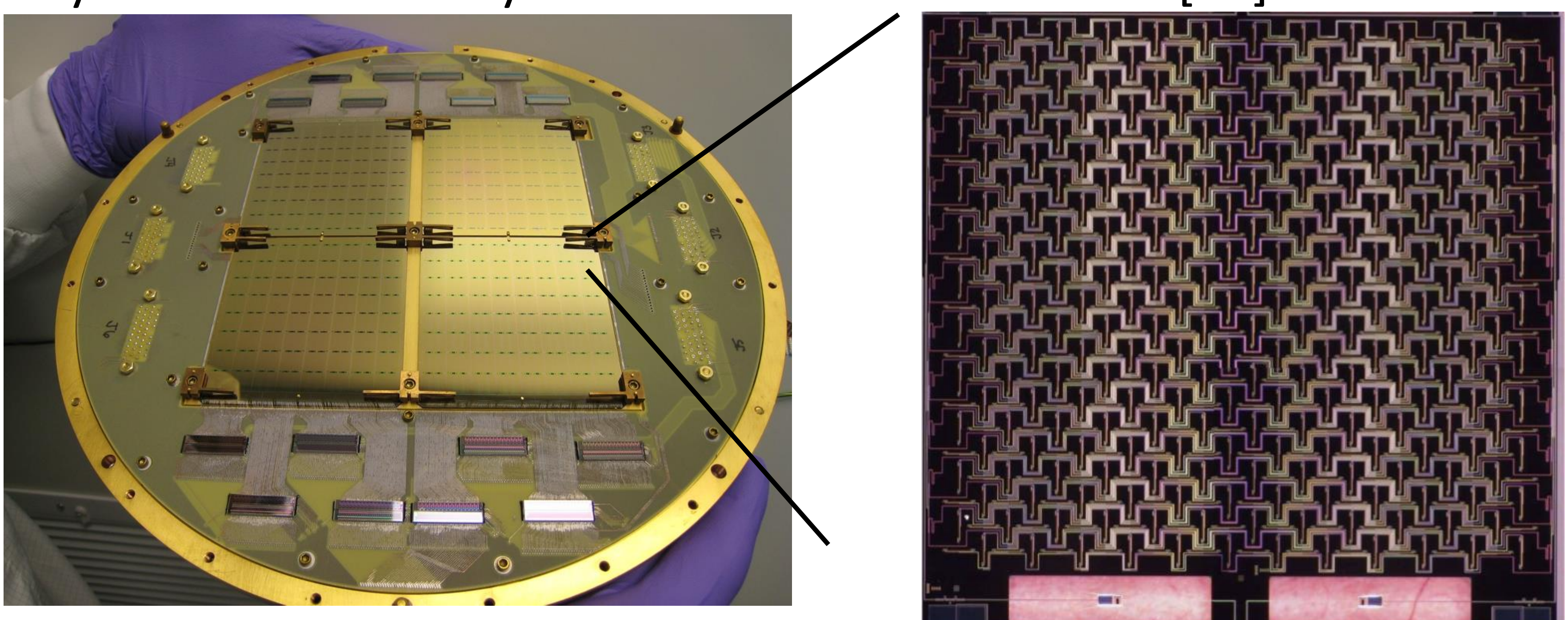
- Use small dual slot antennas, or sinuous antennas [10]
- Berkeley centered collaborations
- TRL 5. Used in Polarbear/Simon's Array and SPT-3G
- Broadband: Have deployed 90/150/220GHz channels
- Wonky beams! Need to see serious systematics studies.





Antenna Array coupled

- Use antenna arrays for beam synthesis [1]
- Caltech/JPL centered collaborations
- TRL 6. Used in BICEP/Keck Array and SPIDER
- Broadband under slow development; not scientifically motivated in BICEP program
- Beams less wonky than sinuous, not as pure as horns, but systematics certainly controlled to r~0.001 levels [12]



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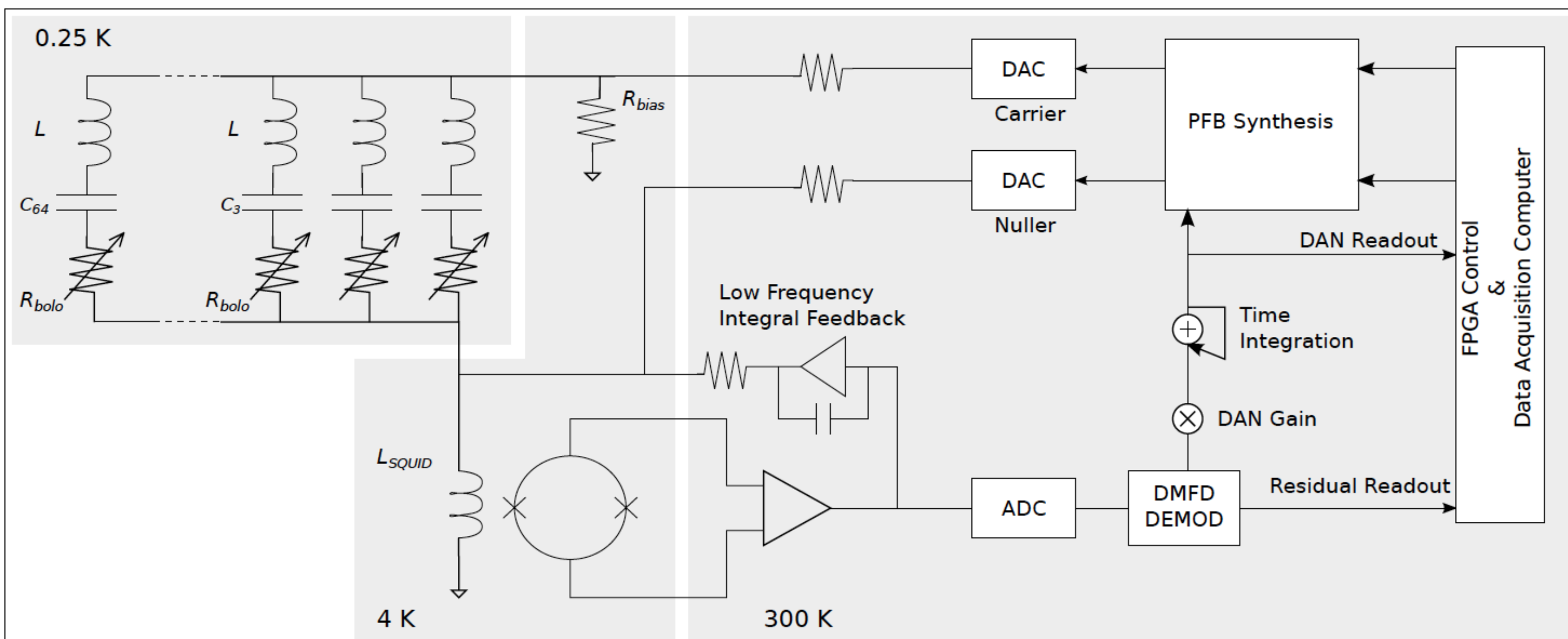
SQUID FDM[12]

- AC biased and summed TESes.
- Used in Polarbear, EBEX, SPT. Baseline for LiteBIRD (TRL 5-6)
- Uses only one SQUID (SSA) per bolo comb.
- All detectors continuously sampled. No aliasing.
- Active nulling. Account for phase delays in lines.
- In personal communications, McGill people occasionally suggest low-f noise issues!

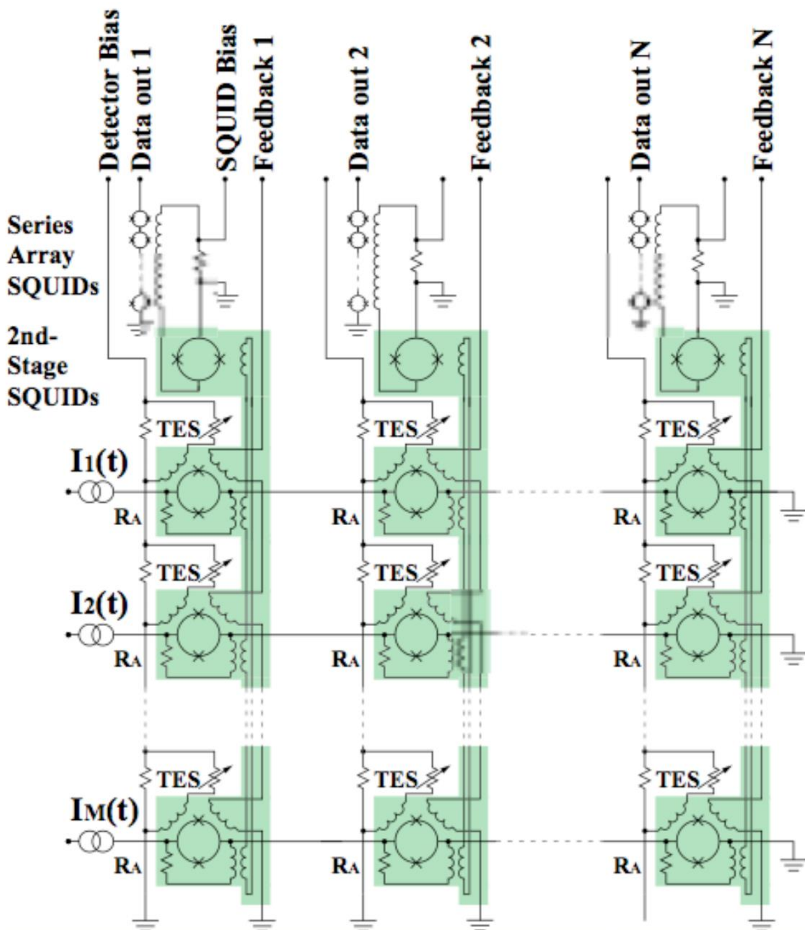


SQUID FDM

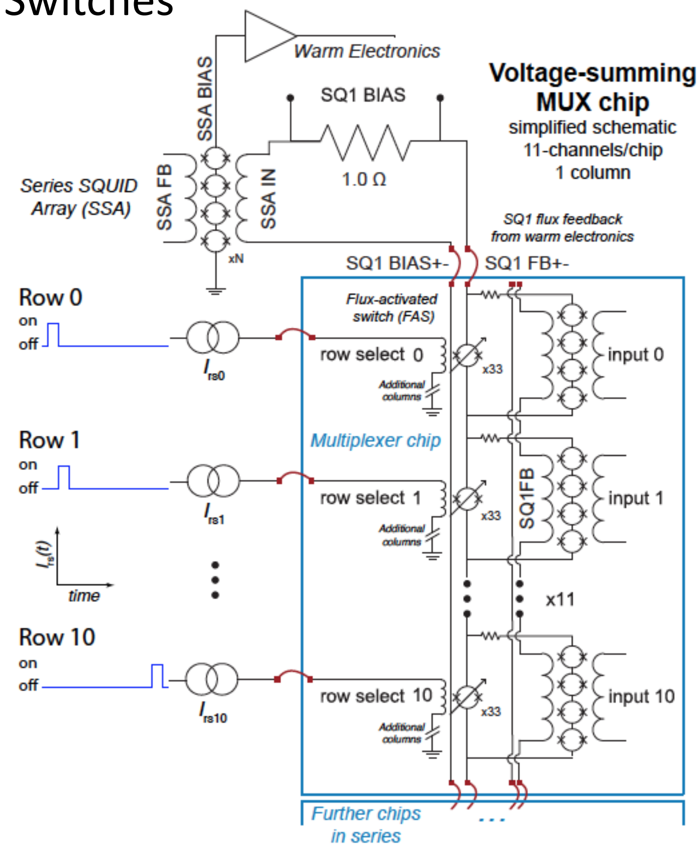
- Achieved MUX factors: 68 in SPT-3G
- Crosstalk from neighboring tones in PB1: 1%.
- Warm electronics power: McGill “ICE” no more than 7.8W/comb (68 tones ea., in SPT3G)
- Cryogenic Power dissipation:
  - UC: no power consumption (no SQUIDs)
  - 4K SSA: no more than 1uW/comb (of ~68 tones)

SQUID TDM [13]

Old 3-stage SQUID design

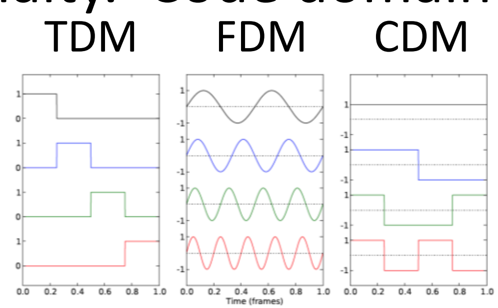


New 2-stage SSA+ Flux Activated Switches



SQUID TDM

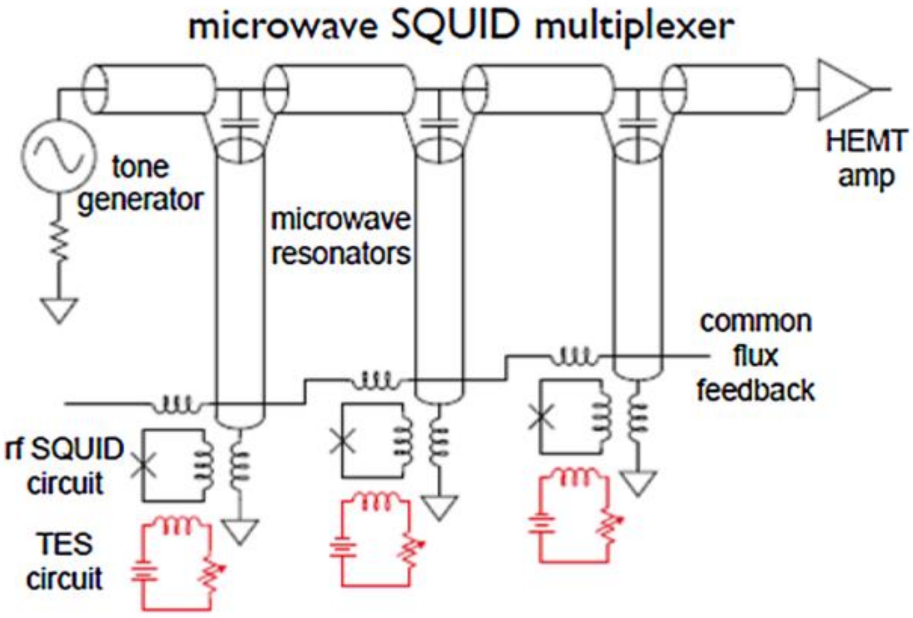
- ACT, CLASS, BICEP/Keck, SPIDER (TRL 6)
- MUX factor 64/col achieved in ACT. Claim 128 is possible.
- Demonstrated 0.01Hz stability in SPIDER
- Inductive Crosstalk: 0.25% btwn adjacent rows in a col for TDM (f/ B2 beam maps). Finite recovery time not a problem for MUX 32 (and, I presume, 64).
- \sqrt(N) aliasing noise penalty. Code domain MUX could alleviate this [14]

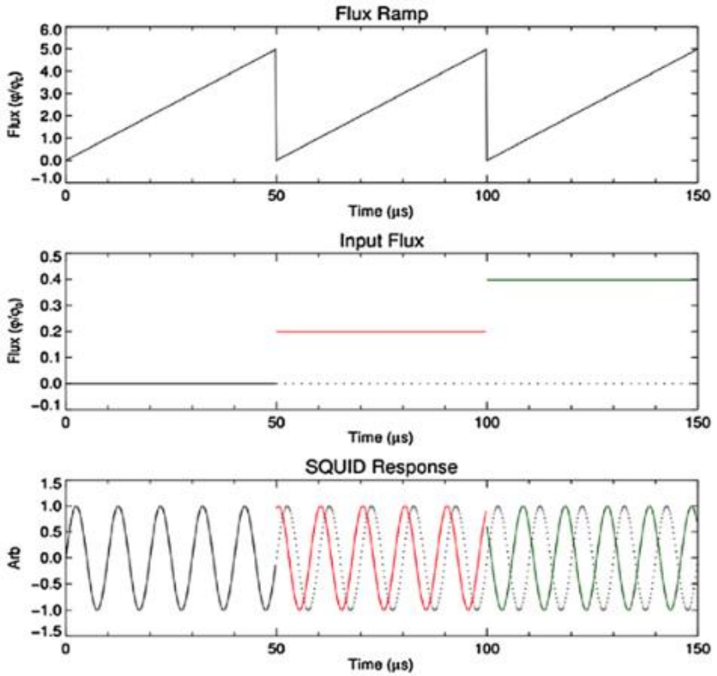


- Cryogenic power dissipation of NIST SQUIDs:
  - UC: 2nW/col
  - 4K SSA: 20nW/col
- Warm Power Consumption in UBC MCE: 2.7W/col (MUX factor 64)

Microwave MUX

- Demo in MUSTANG, various DOE x-ray cameras (TRL 4)





- TES currents couple to SQUID, which couples to resonator termination. So TESes can "act like" KIDs.
- Linearize with flux ramping [16].
- Ramping acts like a chop, supresses TLS noise (or other low freq noise)

Microwave MUX/KID Readout

TES/ uMUX:

- System noise: 17pA/rtHz (subdominant to photons for stage4 atmosphere) above 1Hz
- 32 tones/comb demonstrated. Could be hundreds in future.
- UC power load: 10pW/channel
- Cross-talk: 0.1% claims made.

KIDs:

- negligible power dissipation at UC.
- 1000 tones/comb.

Both:

- 4K power load: 5-10mW from an LNA.
- ROACH2/SRON readout: 50-100W, but depends on channel count. Still young technology
- NIKA-2 & MAKO each had 400 tones/rf-line.

References

1. BICEP/SPIDER detectors: arXiv1502.00619
2. NIKA2 KIDs: arXiv1601.02774
3. BLAST-TNG KIDs: arXiv1603.02963
4. ColumbiaASU KIDs: arXiv1510.06609
5. Planck LFI: http://planck.caltech.edu/lfi.html
6. HUSIR detectors: *www.nrao.edu/meetings/isstt/papers/2007/2007131134.pdf*
7. QUIET Paper: arXiv1207.5562
8. Direct Coupling: arXiv1603.02963
9. Horn coupling: arXiv1510.07797
10. Lens coupling: arXiv1302.0325
11. BICEP Beam systematics: arXiv:1502.00608
12. Digital fMUX: arXiv1407.3161
13. TDM MUX: DOI [10.1007/s10909-015-1373-z](10.1007/s10909-015-1373-z)
14. Seminal CDM TES paper: arXiv1110.1608
15. McGill ICE electronics; arXiv1608.06262
16. Flux Ramping: doi:10.1007/s10909-012-0518-6