Multi-Chroic Dual-Polarization MKIDs

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https://doi.org/10.1007/s10909-018-2032-y

CrossMark

Development of Multi-chroic MKIDs for Next-Generation CMB Polarization Studies

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see also: Johnson, *et al.* (2016) *Proc. SPIE*, 9914, 99140X.

Overview of Multi-Chroic MKIDs

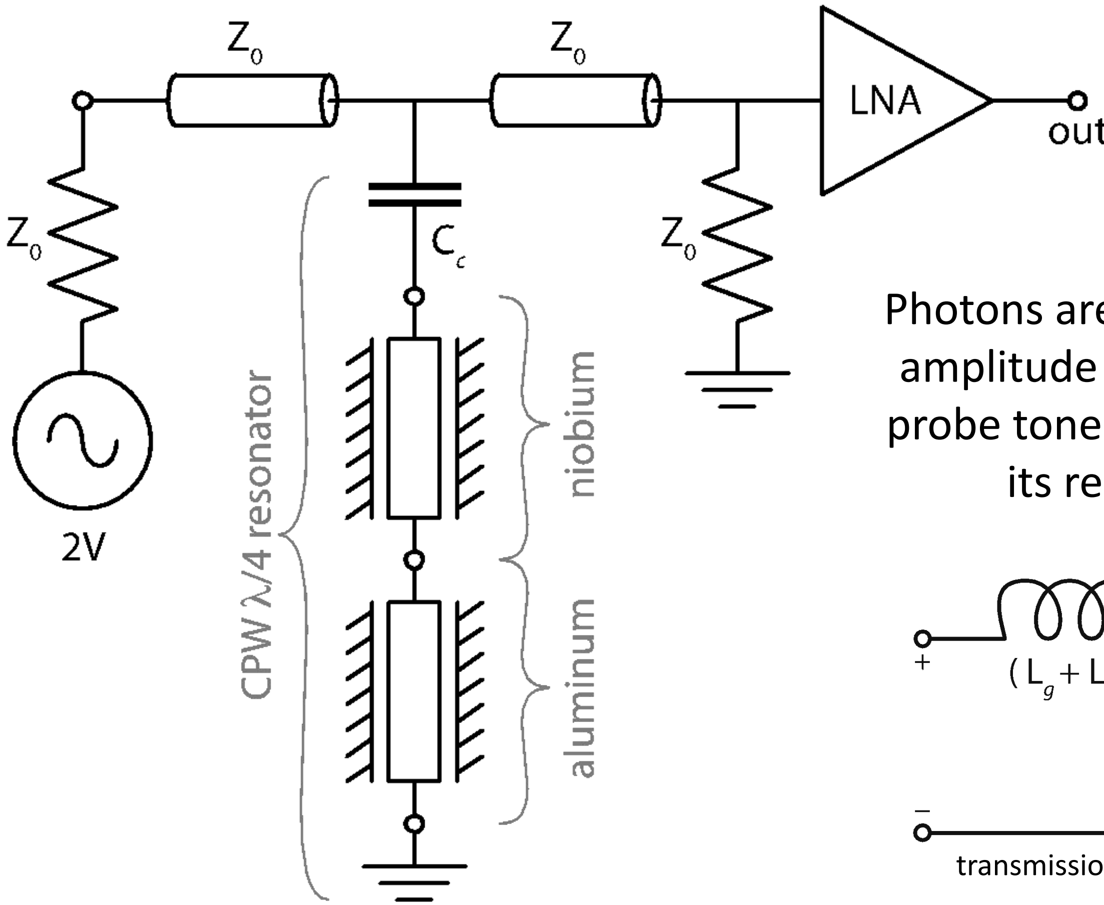
- We are developing scalable modular arrays of **horn-coupled, polarization-sensitive MKIDs** that are each sensitive to **two spectral bands between 125 and 280 GHz (150 GHz and 235 GHz)**.

- These MKID arrays are **tailored for future multi-kilo-pixel experiments** that will observe both the cosmic microwave background (CMB) and Galactic dust emission.

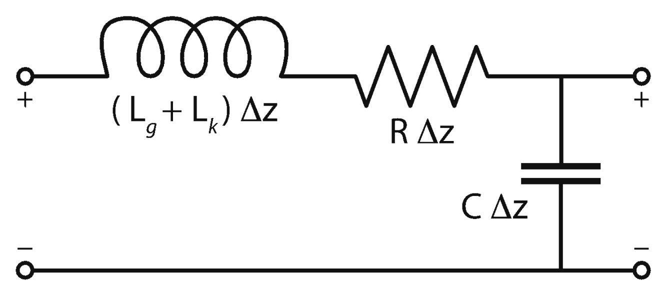
- Detector modules like these could be a strong candidate for **future CMB satellite mission and/or CMB-S4**.

- Our device **design builds from successful transition edge sensor (TES) bolometer architectures** that have been developed by the Truce Collaboration and demonstrated to work in receivers on the ACT and SPT telescopes.

Schematic for One CPW MKID



Photons are detected by measuring amplitude and phase changes in a probe tone driving the resonator at its resonant frequency.

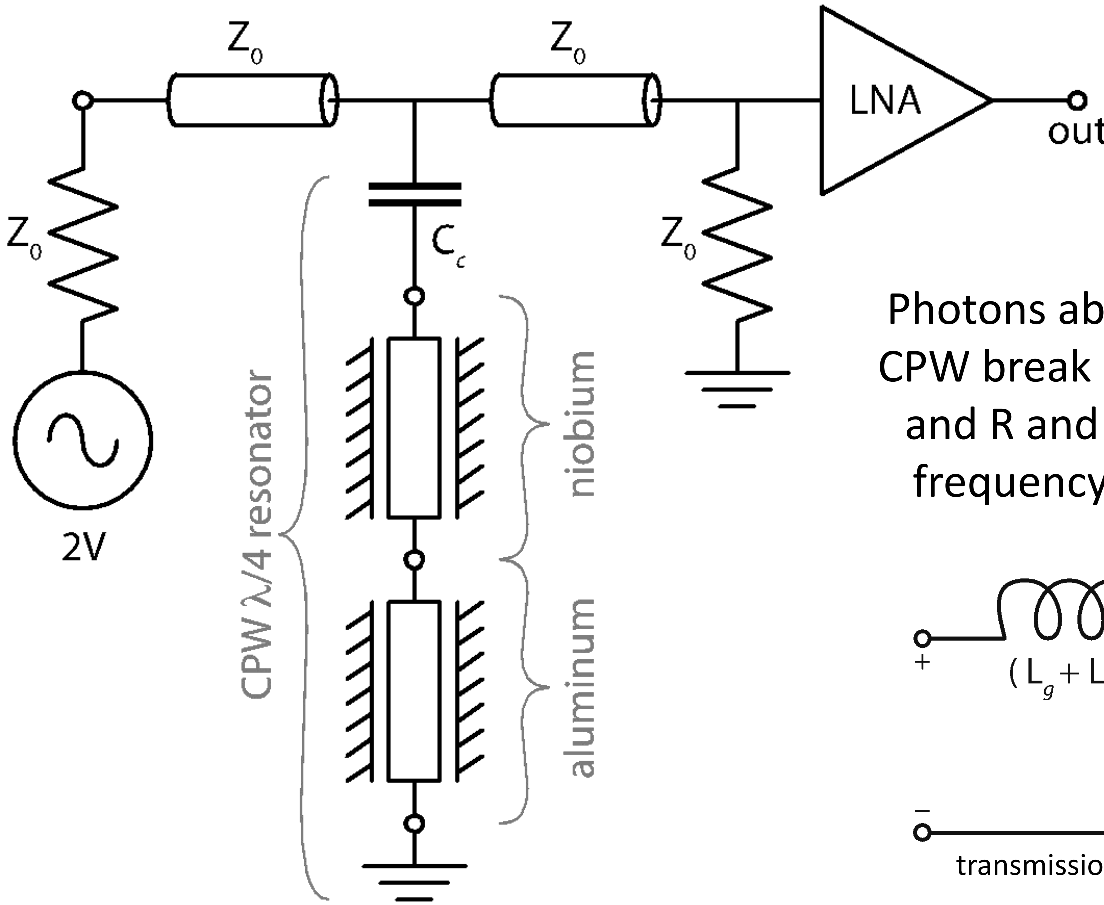


transmission line model for CPW element

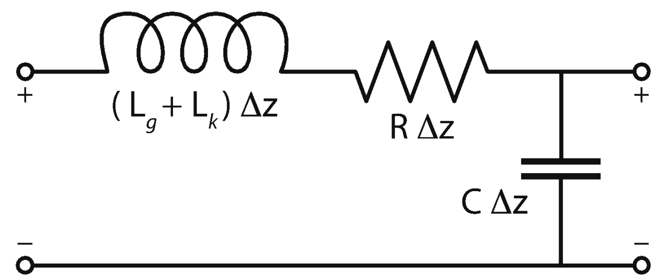
See for example, Day, *et al.* (2003) *Nature,* 425, 817-821.

Yates, *et al.* (2011) *APL*. 99, 7.

Schematic for One CPW MKID



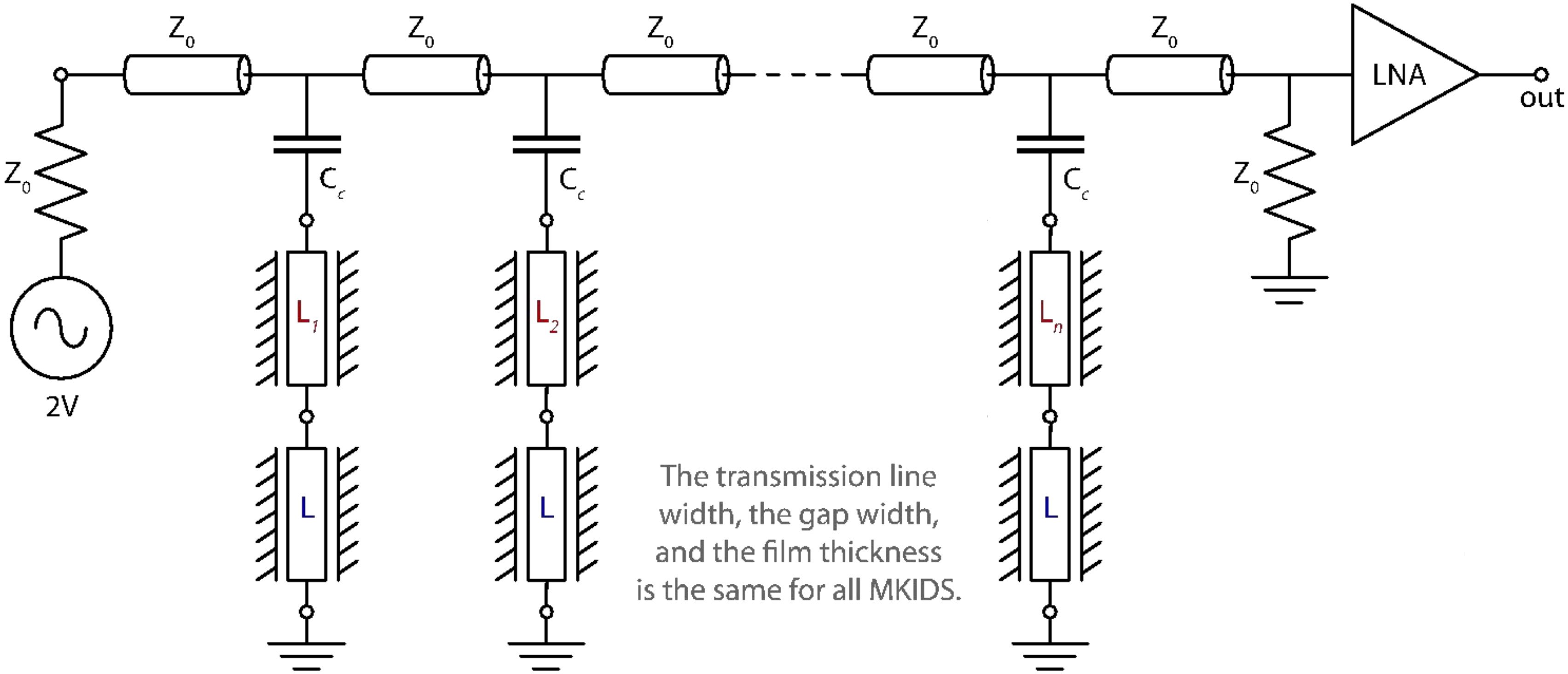
Photons absorbed in the aluminum CPW break Cooper pairs changing L_k and R and therefore the resonant frequency and the quality factor.



transmission line model for CPW element

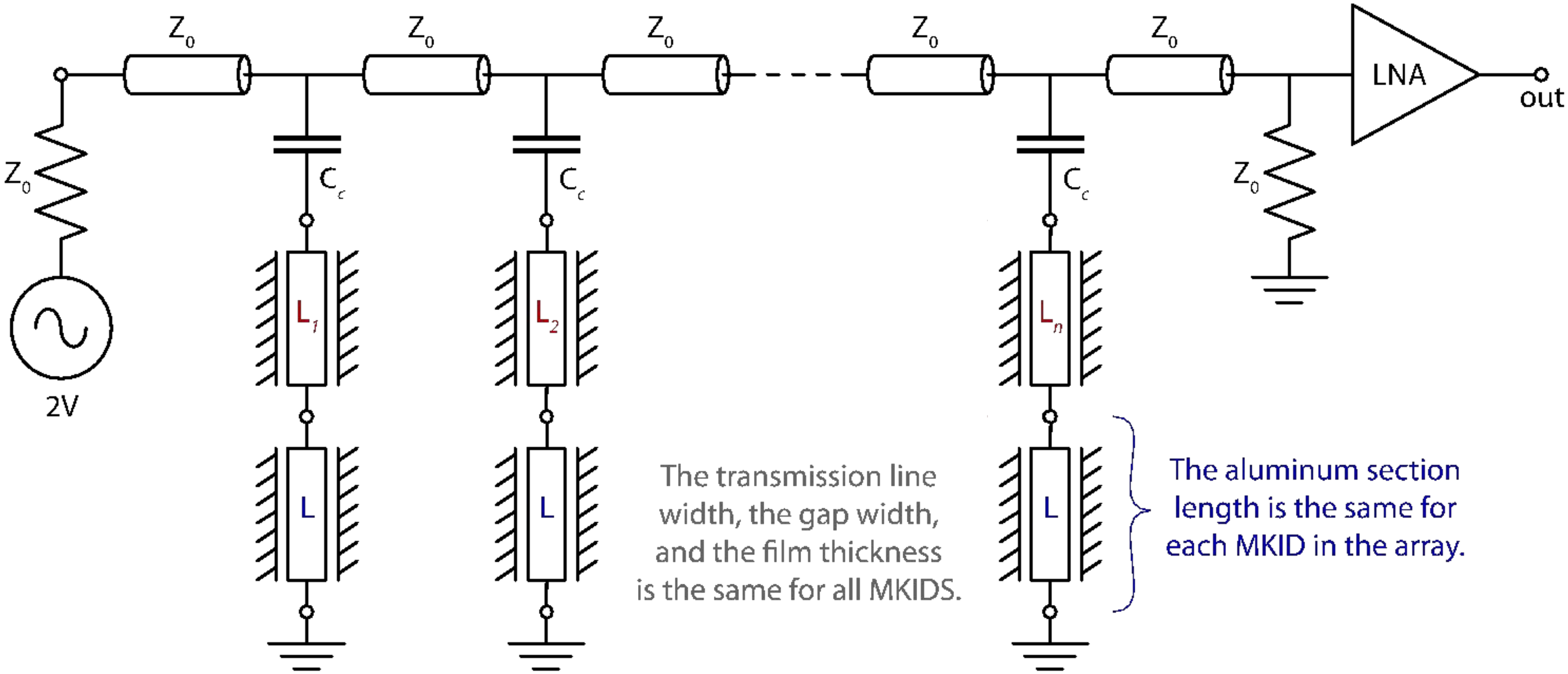
$$\nu_g = \frac{2\Delta}{h} \approx 74\ \mathrm{GHz} \times \frac{T_c}{1\ \mathrm{K}}$$

CPW MKID Multiplexing Strategy



Hundreds of detectors can be read out with a single pair of coaxial cables.

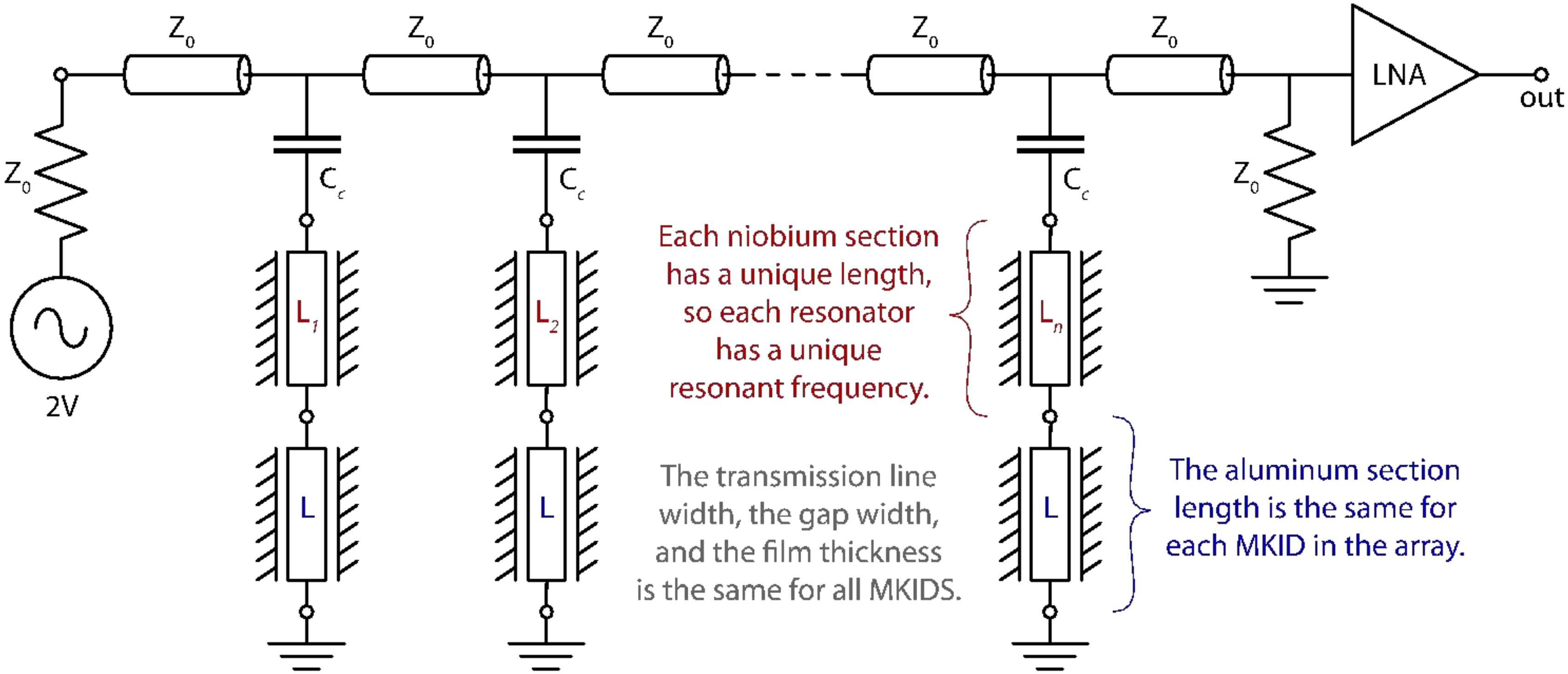
CPW MKID Multiplexing Strategy



The transmission line width, the gap width, and the film thickness is the same for all MKIDS.

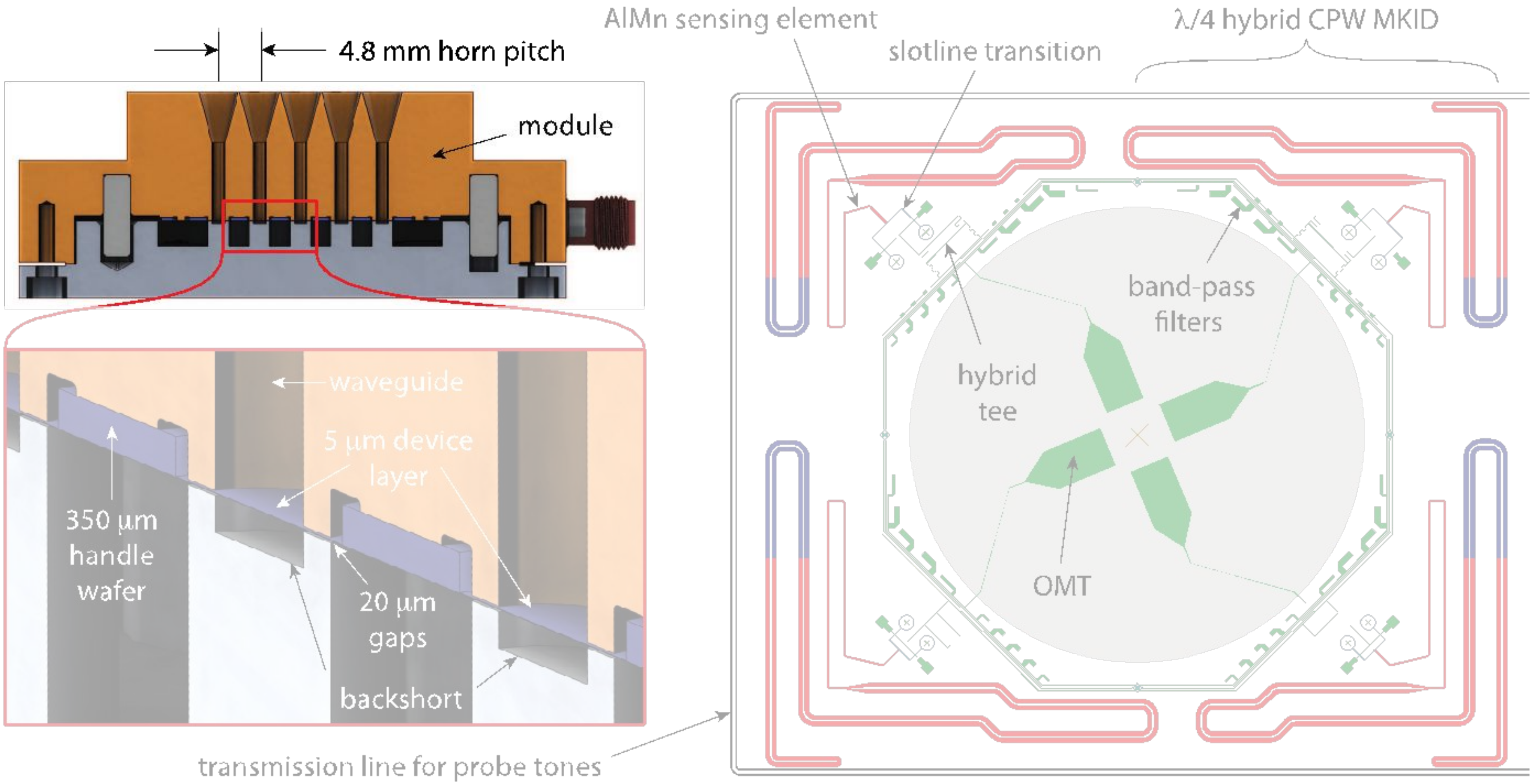
Hundreds of detectors can be read out with a single pair of coaxial cables.

CPW MKID Multiplexing Strategy



Hundreds of detectors can be read out with a single pair of coaxial cables.

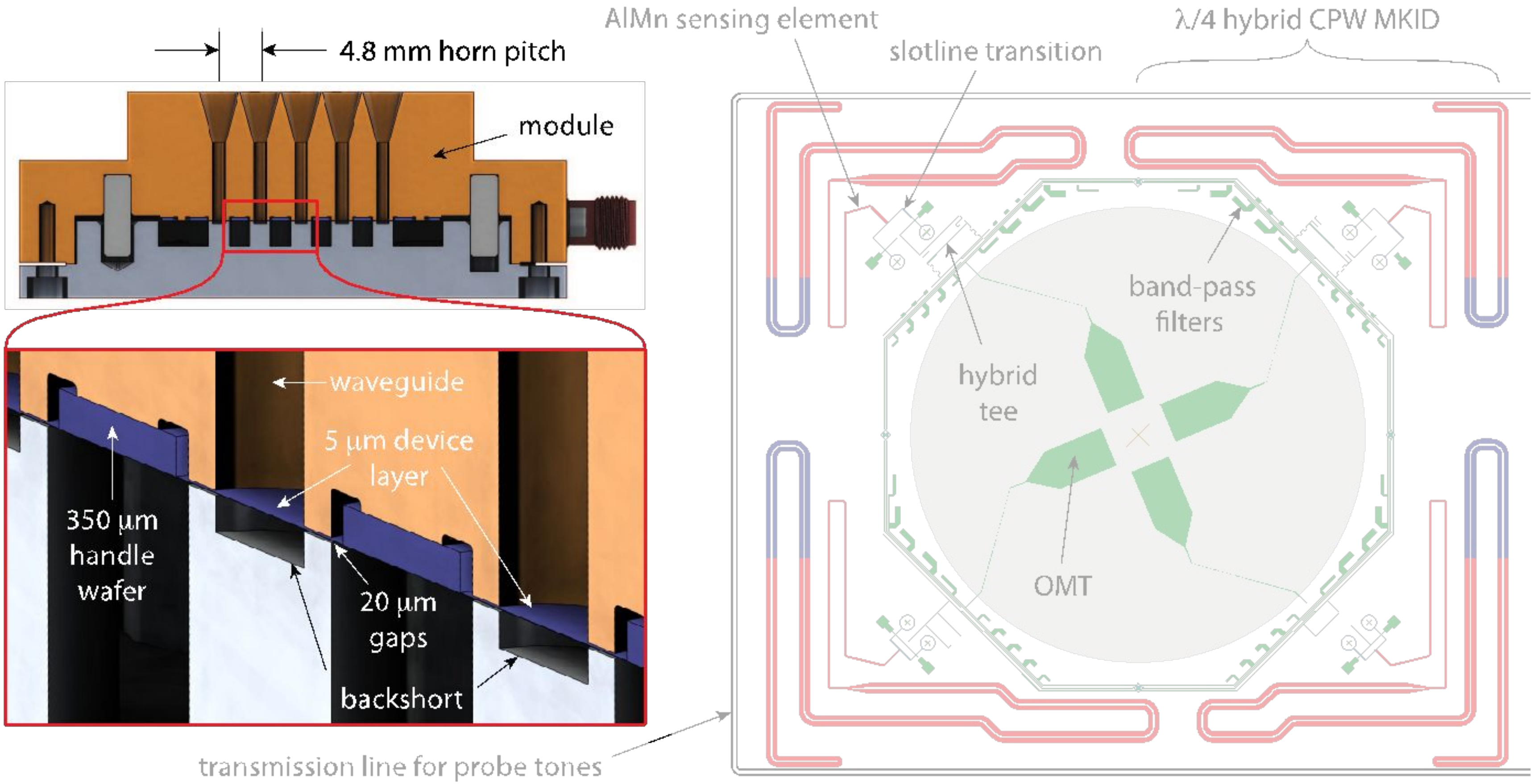
Development of Multi-Chroic MKIDs



MKID resonant frequencies around 3 GHz.

design based on: Datta, *et al.* (2014) *J. Low Temp. Phys.* 176, 670–676.

Development of Multi-Chroic MKIDs



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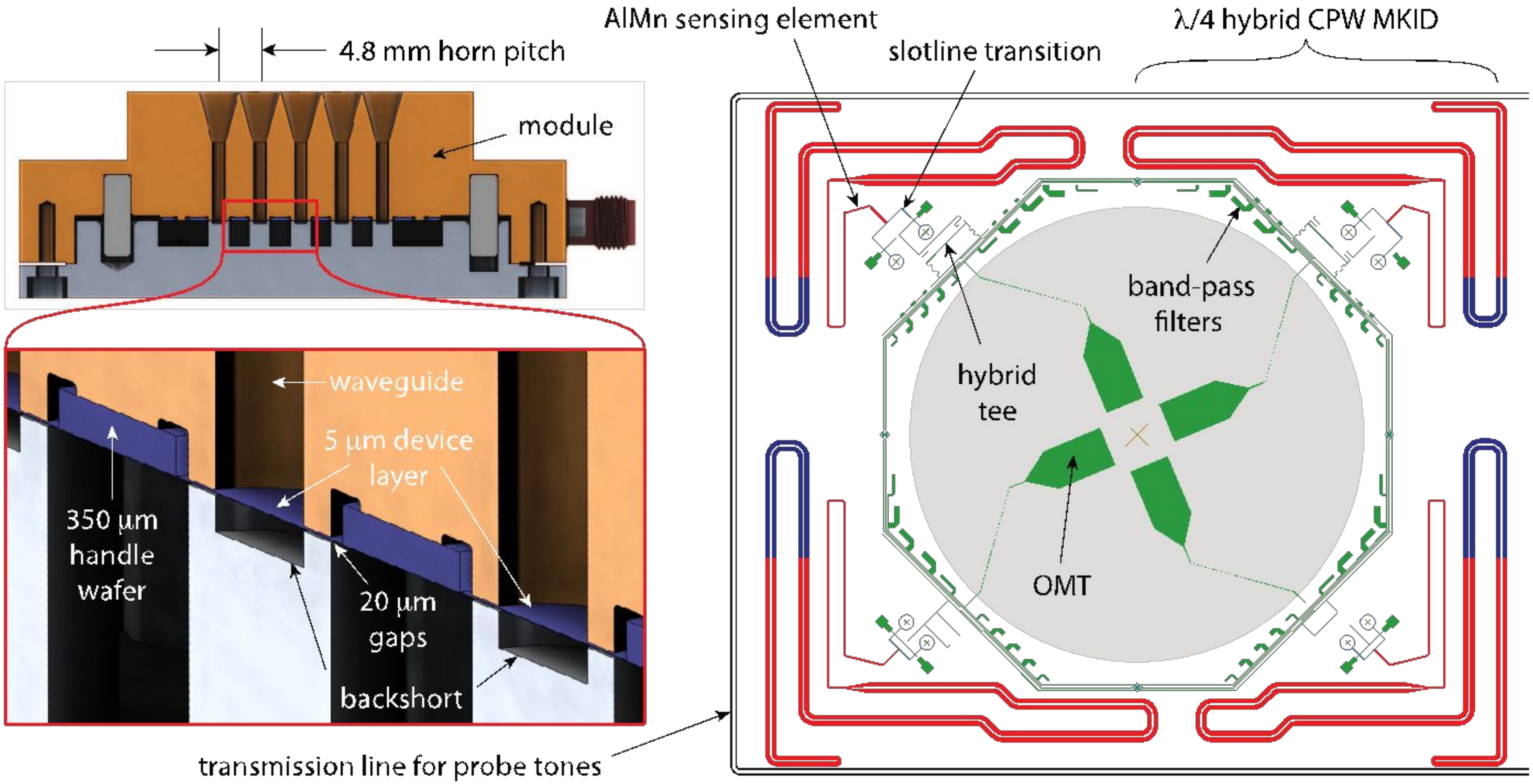
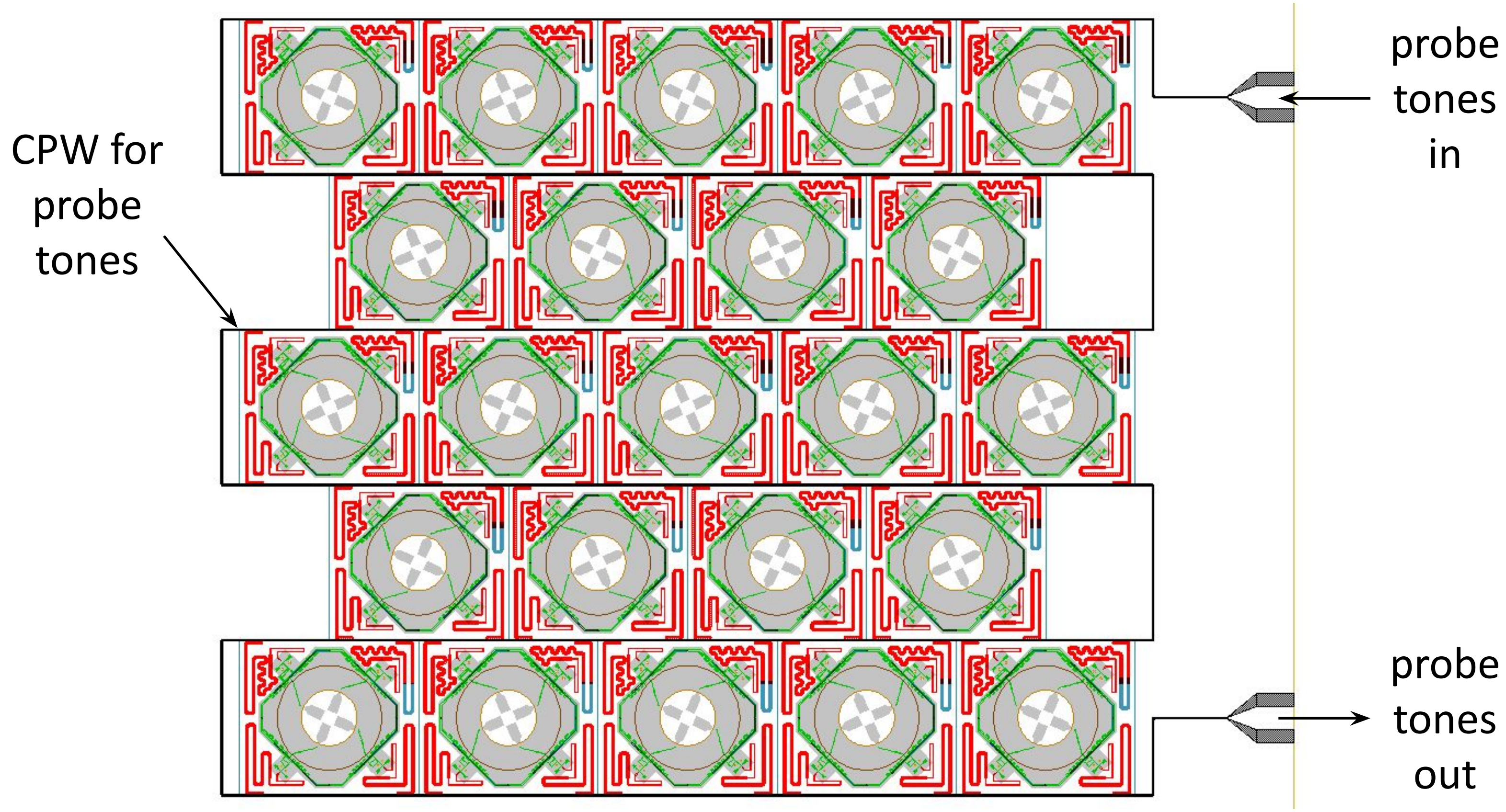
Development of Multi-Chroic MKIDs



MKID resonant frequencies around 3 GHz.

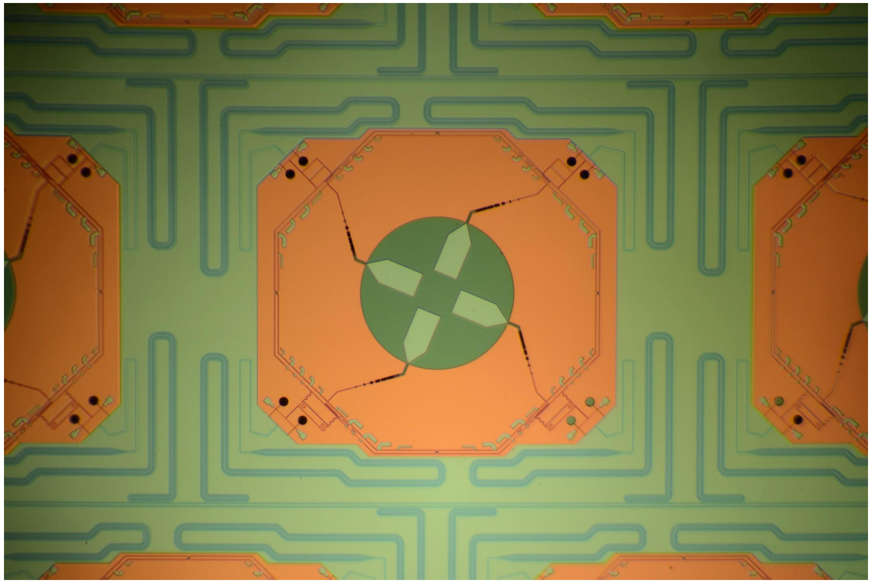
design based on: Datta, *et al.* (2014) *J. Low Temp. Phys.* 176, 670–676.

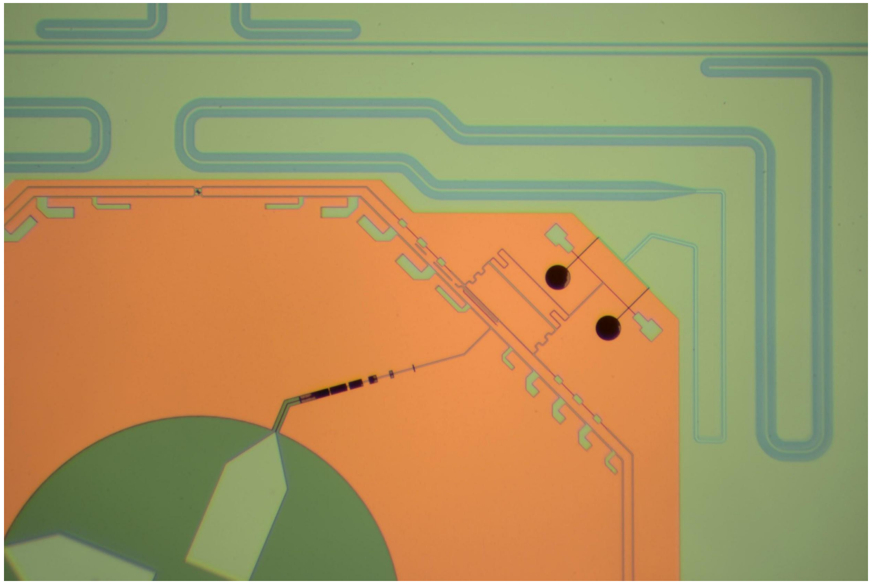
Layout of Prototype Array



23 elements in the array → 92 MKIDs

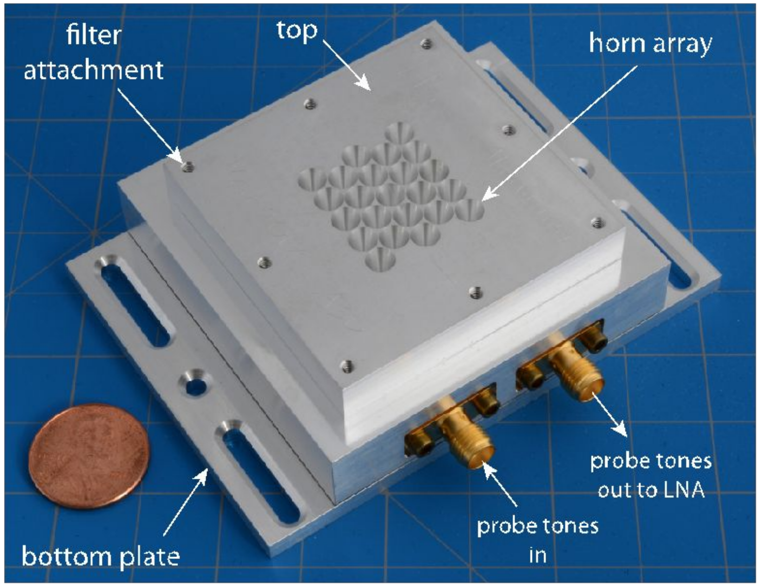
Photographs of Engineering Array

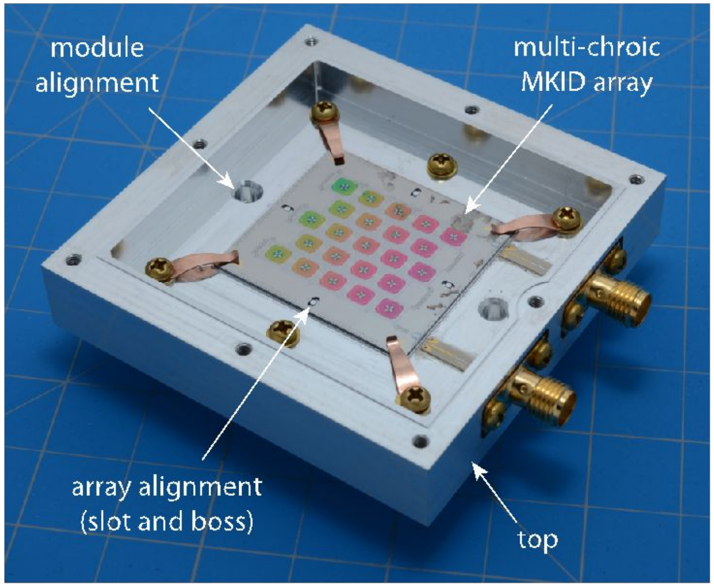




Fabricated at Stanford

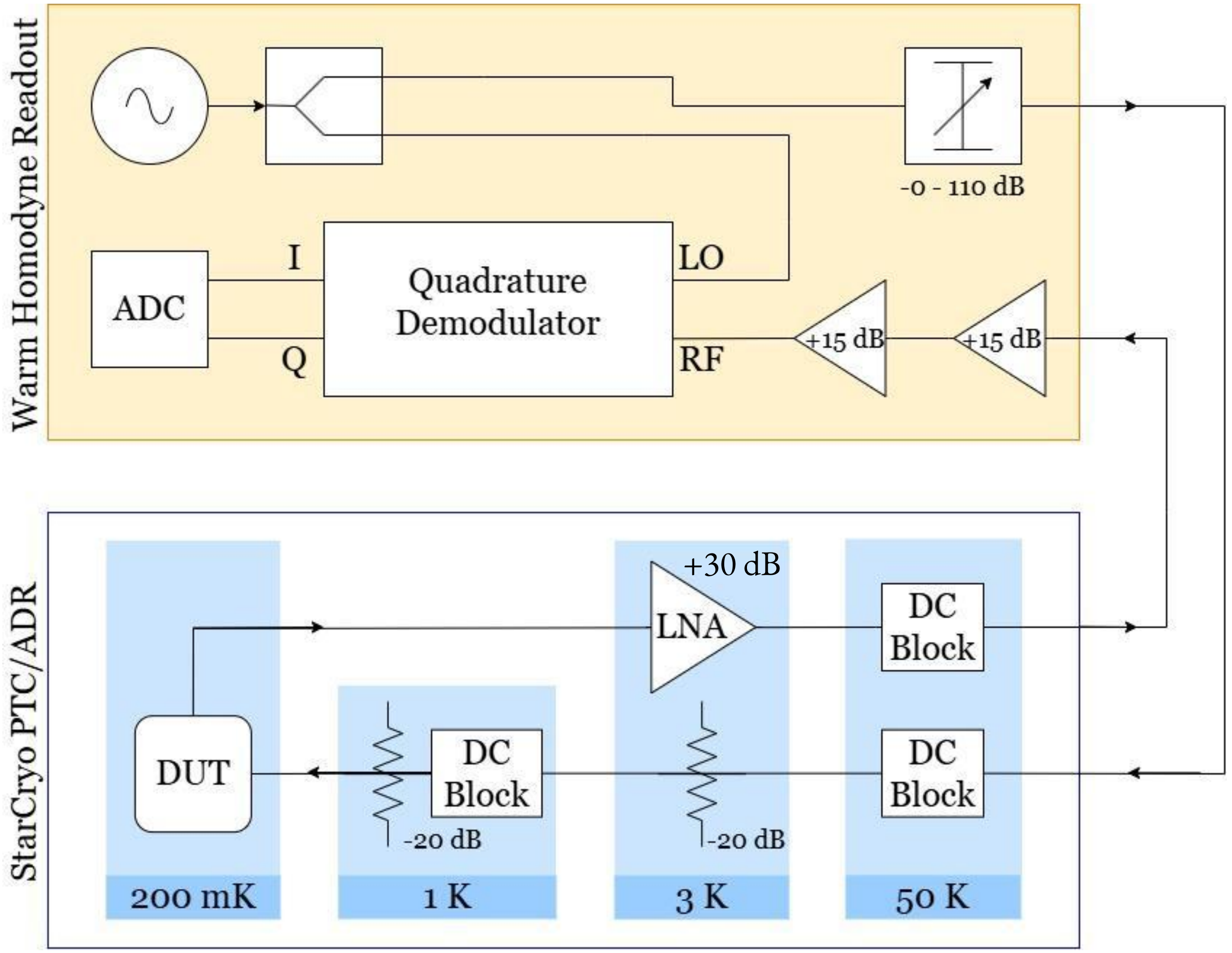
First Complete Prototype Array





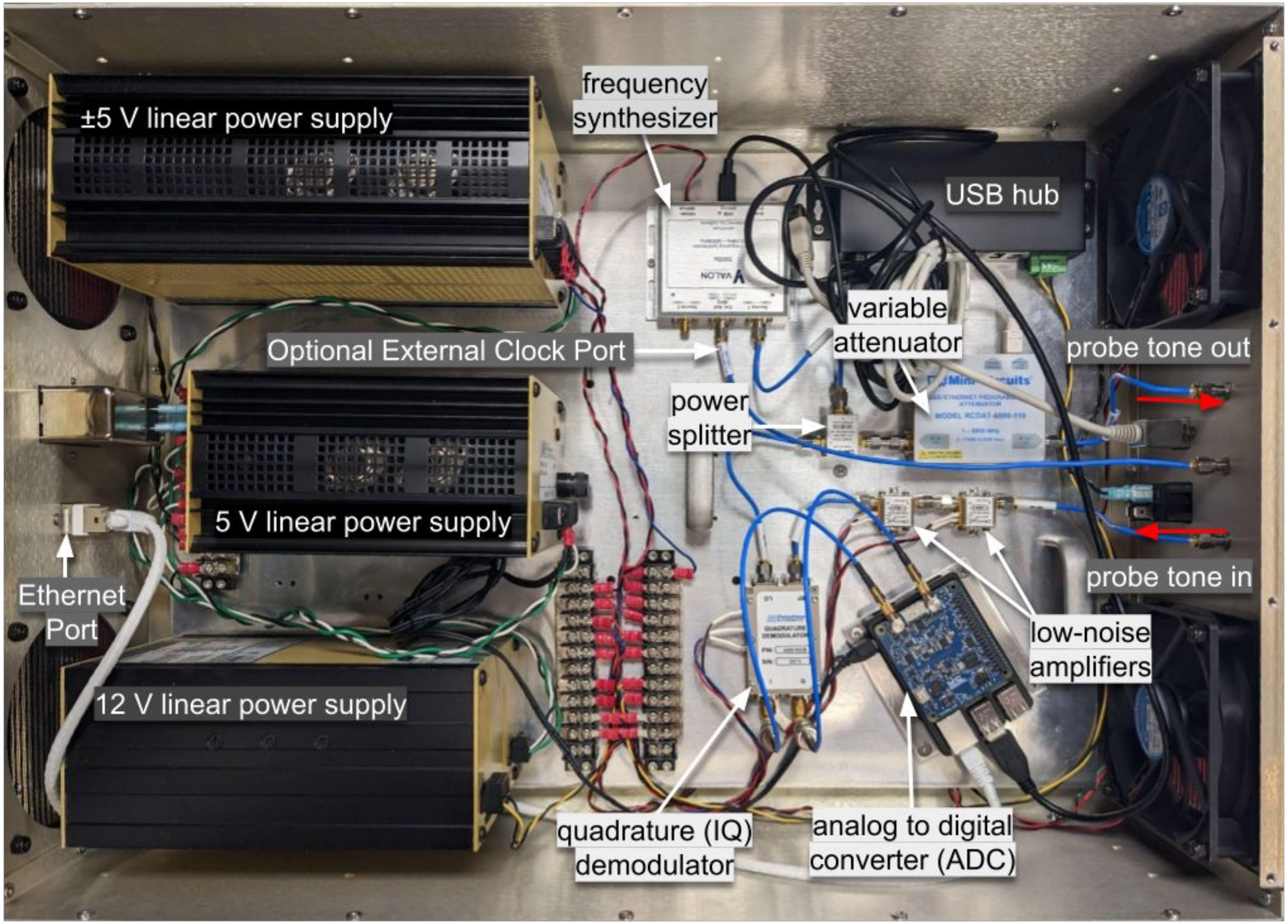
fabricated on silicon-on-insulator (SOI) wafer
Johnson, *et al.* (2018) *J. Low Temp. Phys.*, 193, 3-4, 103-112.

Experimental System: Readout Chain



Note: This design requires a vacuum feedthrough with just two SMA connectors and two pins for LNA bias.

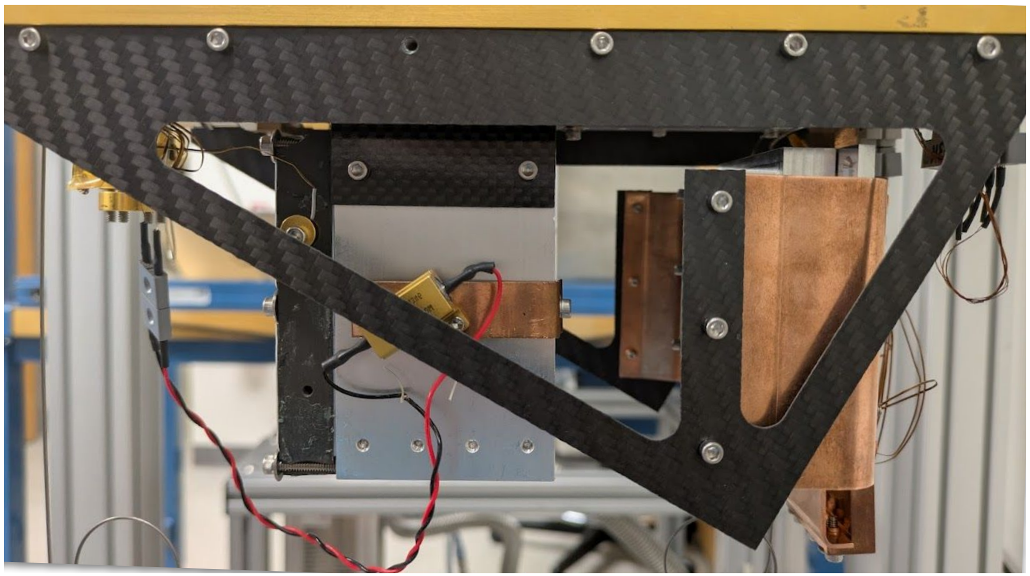
Experimental System: Homodyne Readout Photograph



See Shroyer, *et al.* (2022) *Proc. SPIE.*

Experimental System: Cryogenic Testbed Configuration

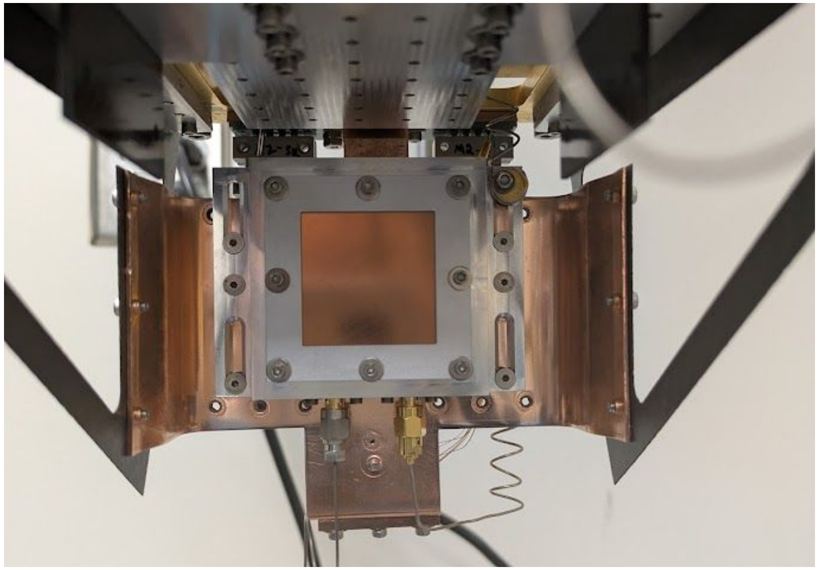
Side View



Beam-filling 4K cold load

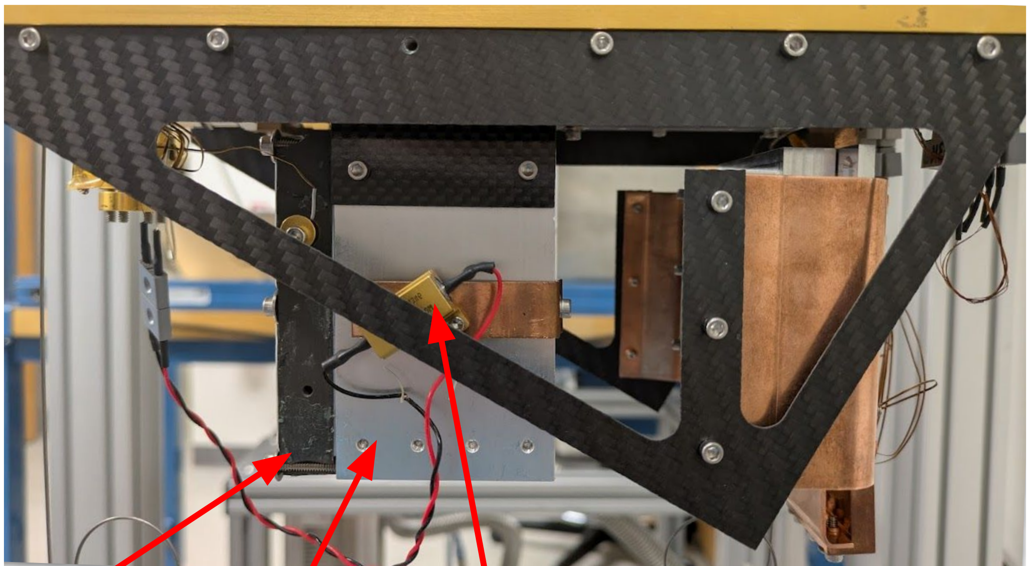
Cu Bracket: 200 mK test stage

Front View (cold load removed)



Experimental System:
Cryogenic Testbed Configuration

Side View



AR-coated eccosorb slab

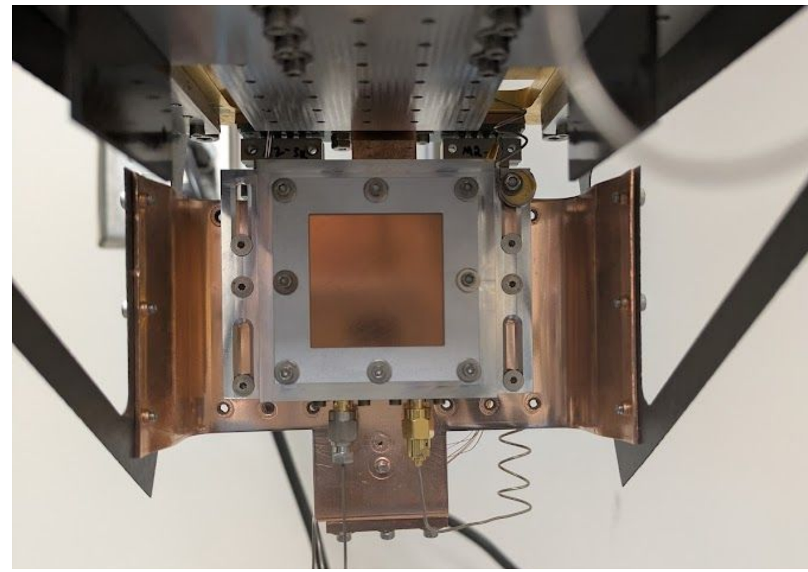
aluminum baffle

heater

Cu Bracket: 200 mK test stage

beam-filling cold load (suspended from 3K stage)

Front View (Blackbody removed)



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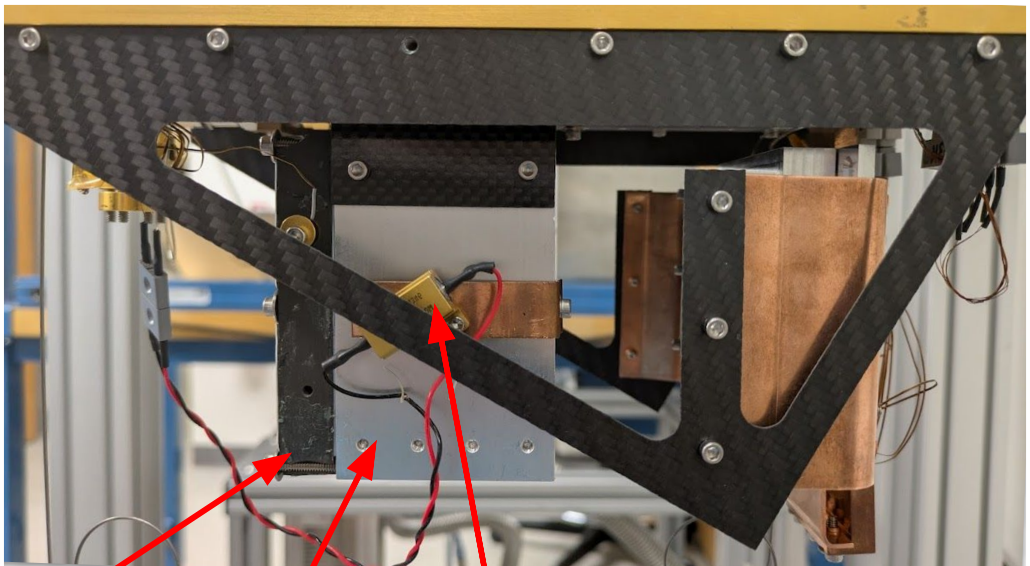


AR-coated eccosorb slab

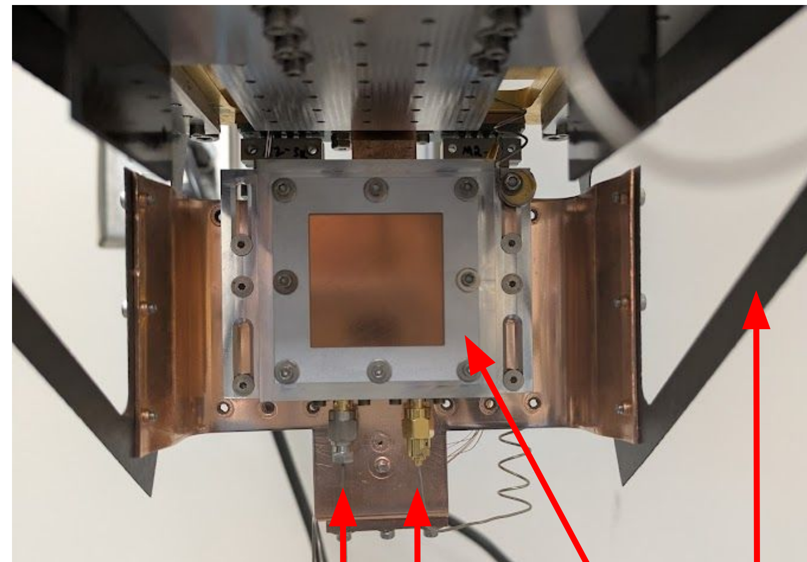
aluminum baffle

heater

Cu Bracket:
200 mK test stage

Blackbody Source
(suspended from 3K stage)

Front View (Blackbody removed)



Probe tone out, in

detector module

CF suspension from 1K stage

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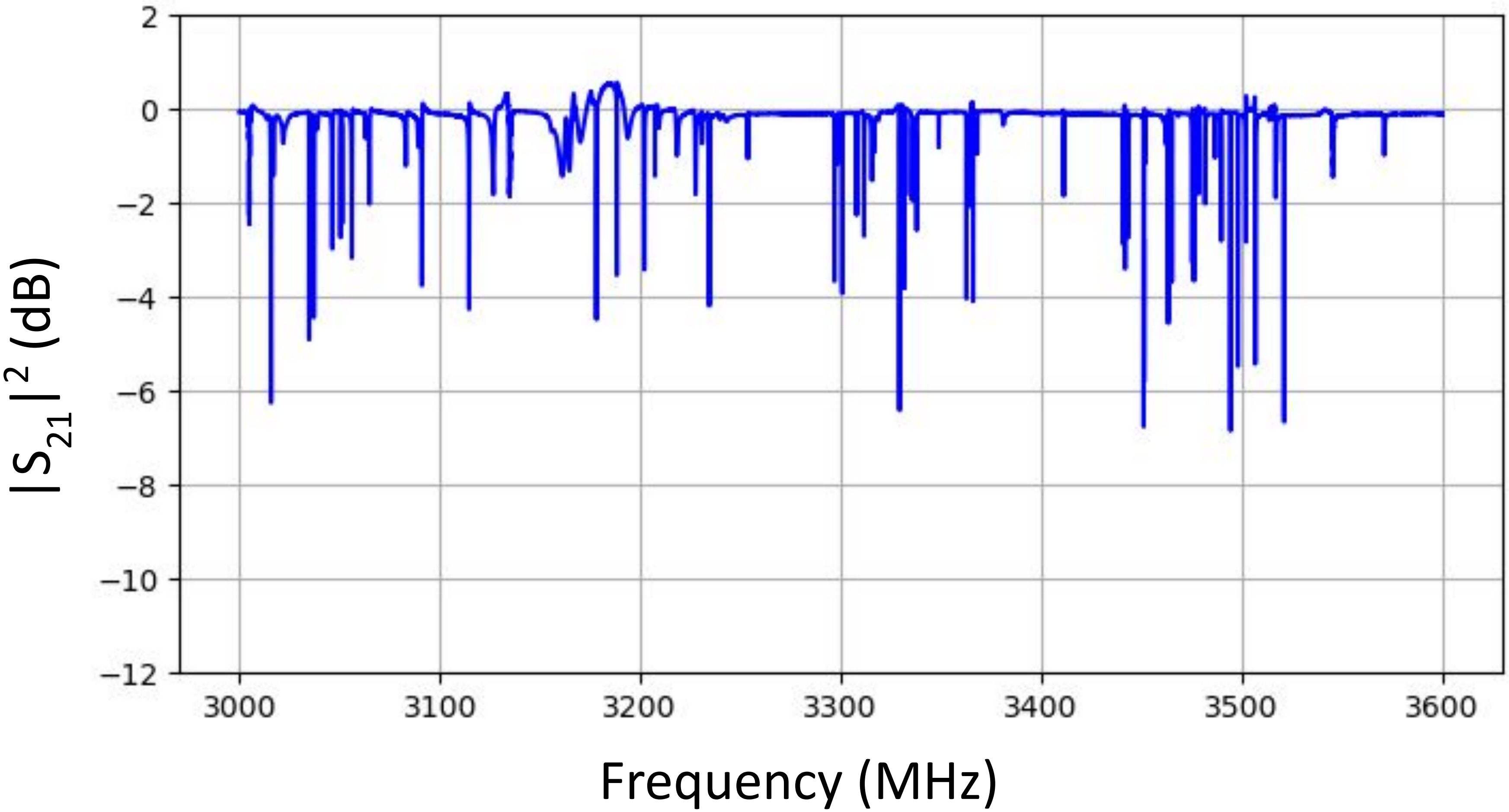
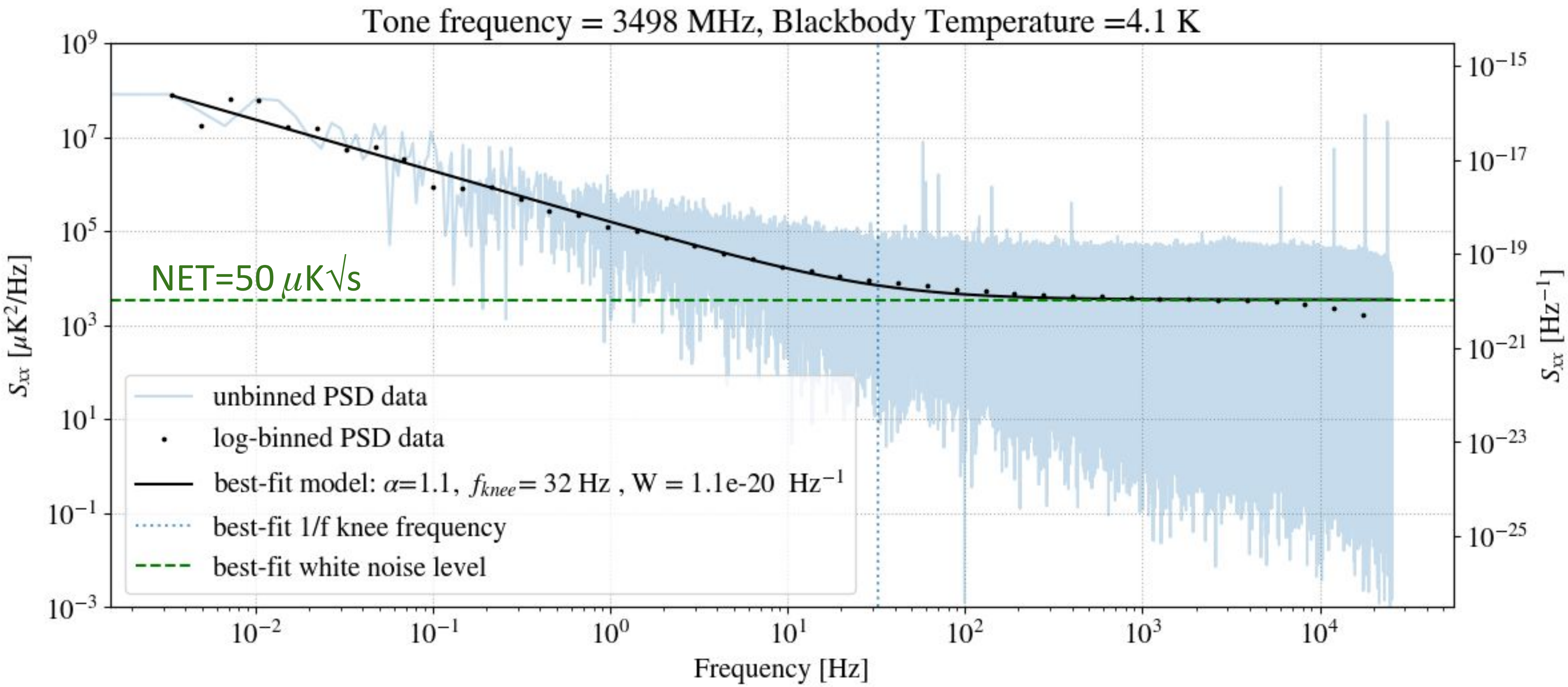
Results: S21 transmission spectrum



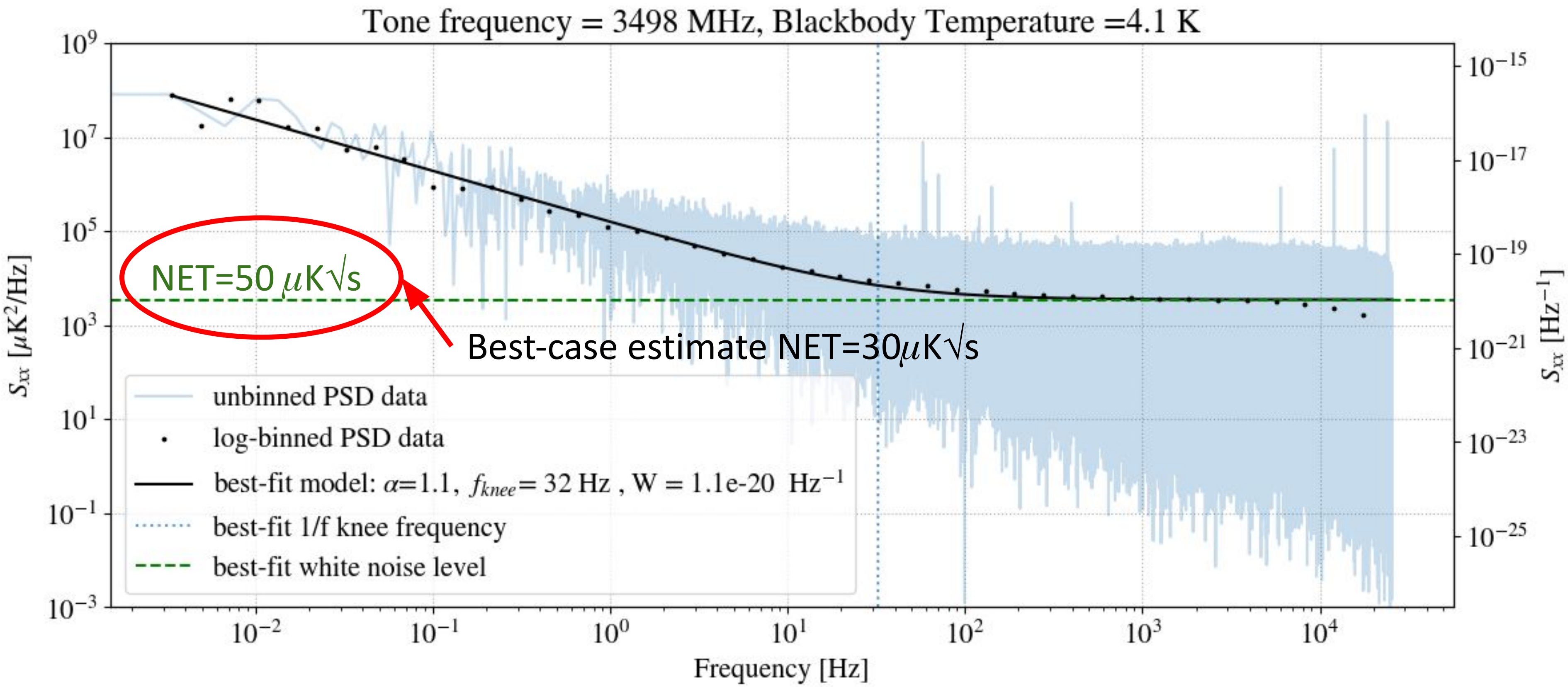
- "dark" measurement with Al tape over horns
- frequency resolution = 25 kHz
- T_{mod}=200 mK
- **yield ~= 80%**

Main Result: Measured Noise Spectrum



- perform S21 sweep and fit to resonator model
- collect 5 minutes of TOD, convert from I,Q to fractional frequency shift (x) and loss ($1/Q_i$)
- Calculate the PSD of x, S_{xx} [Hz^{-1}] and fit noise spectrum $S_{xx}=W(1+(f_k/f)^{\alpha})$
- Calculate NET = $(W/2)^{1/2}(dx/dT)^{-1}$

Main Result: Measured Noise Spectrum



- perform S21 sweep and fit to resonator model
- collect 5 minutes of TOD, convert from I,Q to fractional frequency shift (*x*) and loss ($1/Q_i$)
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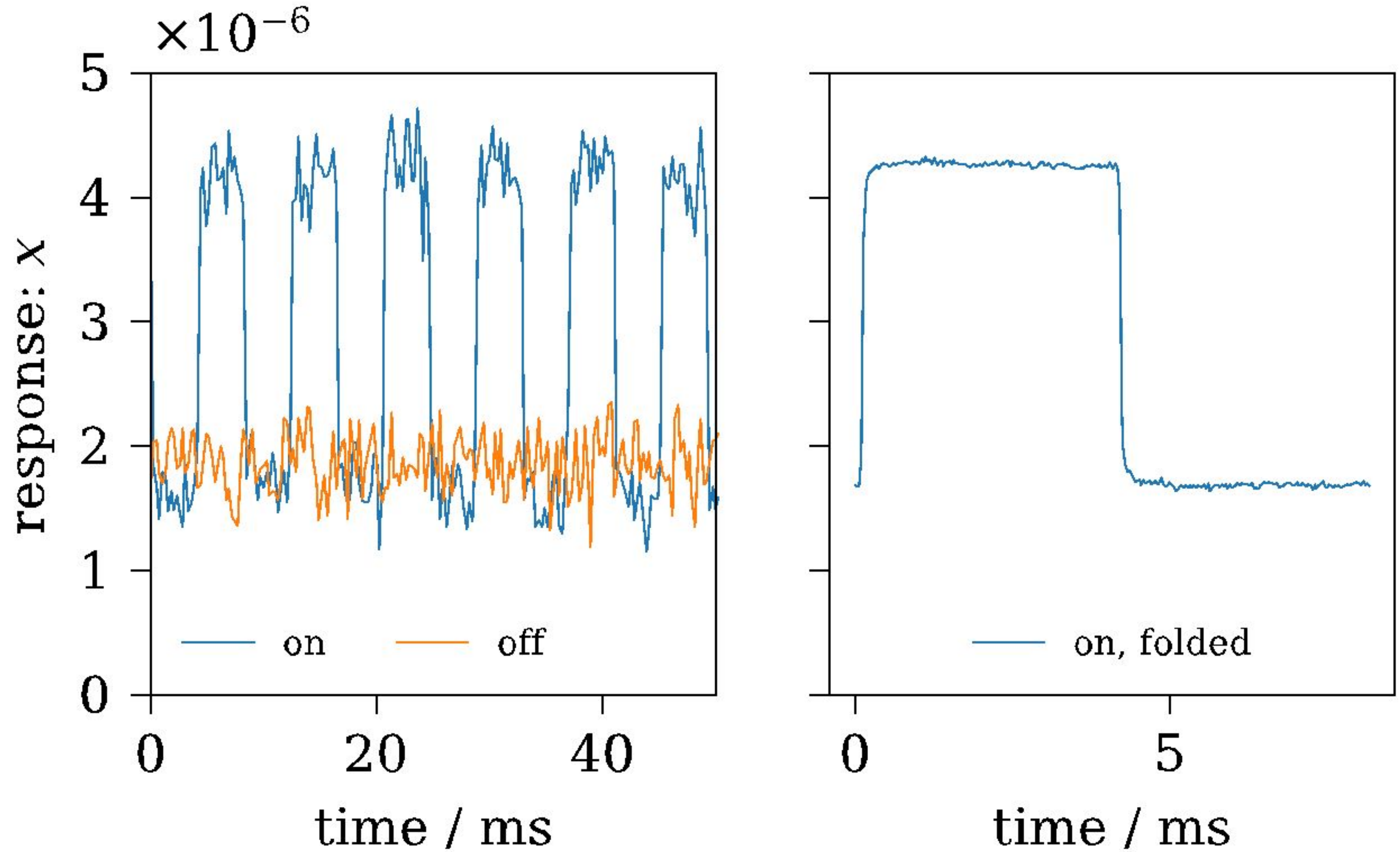
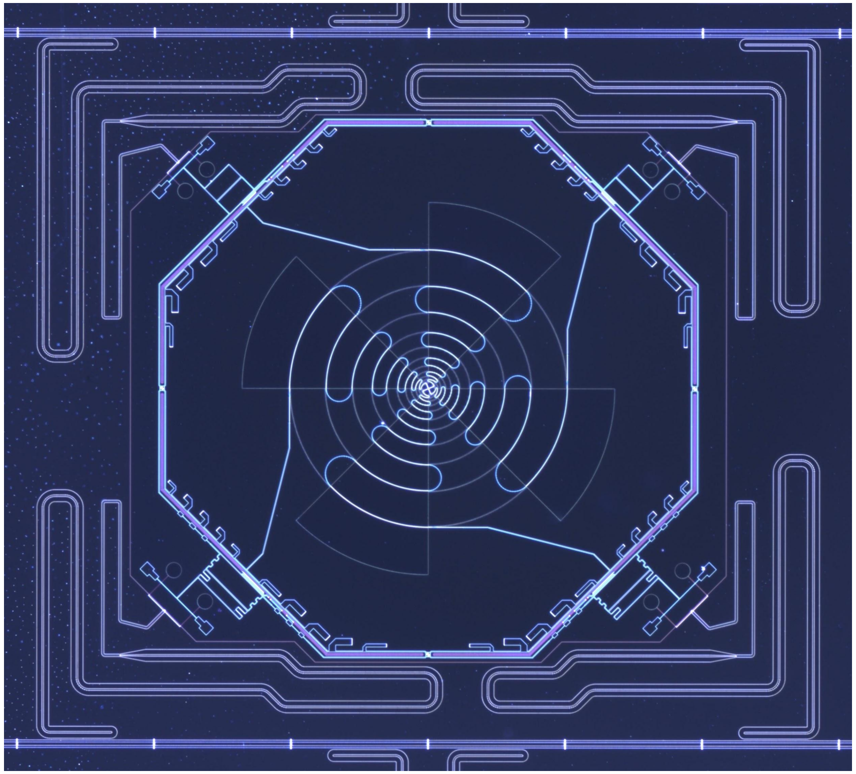
Future Work: MKID response to mm-wave pulse



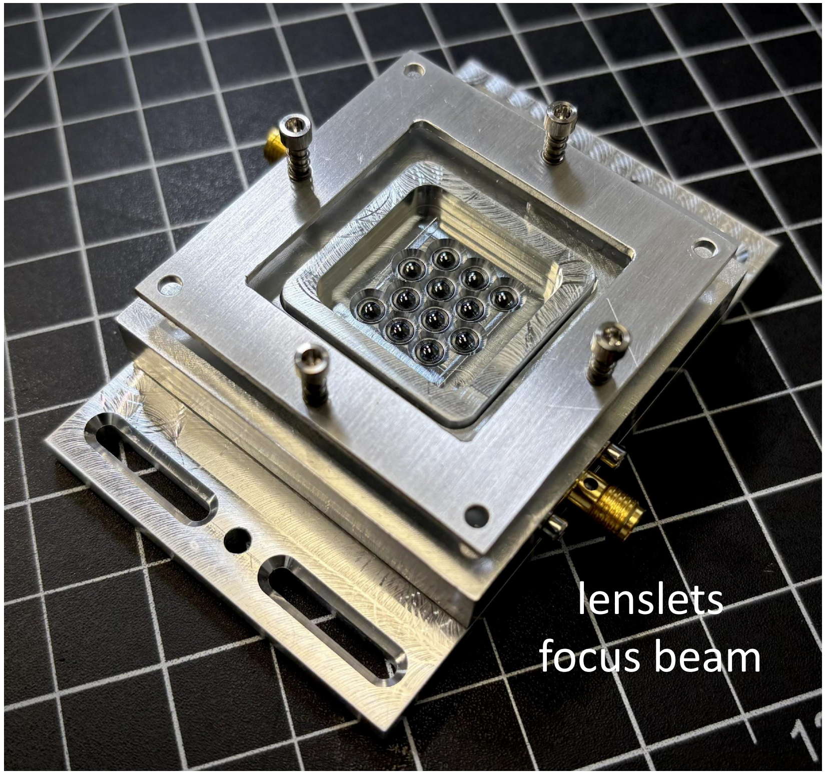
Result for earlier prototype; new array will be tested this summer.
Johnson, *et al.* (2018) *J. Low Temp. Phys.*, 193, 3-4, 103-112.

Future Work: Antenna-Coupled Multi-Chroic MKIDs

one array element fabricated at NIST



12-element module at UVA



Advertisement slide. Testing results soon ...

Project supported by series of grants from ***NSF/ATI***.

Backup Slides

Why investigate KIDs for CMB Studies?

- **High multiplexing factors** make them particularly suitable for instruments with 10,000 or more detectors (CMB-S4, for example).
- Comparatively **small number of wires** needed to sub-kelvin stage, and no additional sub-kelvin multiplexing circuitry is needed (**no SQUIDs**).
- **No delicate membranes are required** and arrays can be made with a comparatively small number of processing steps. **Some architectures have been fabricated in commercial foundries**.
- **Fast time constants** (~100 μs) provide a lot of bandwidth for modulation schemes – like half-wave plate modulation – and they help with cosmic ray hits.
- **Low power consumption readout** (< 50 watts per comb) is commercially available. Required LNAs are available. Required firmware is open-source.
- Some TES bolometer architectures are hard to make with < 1 pW saturation power, and MKIDs might actually be more straightforward.

Wafer Stack-up (Flanigan Dissertation)

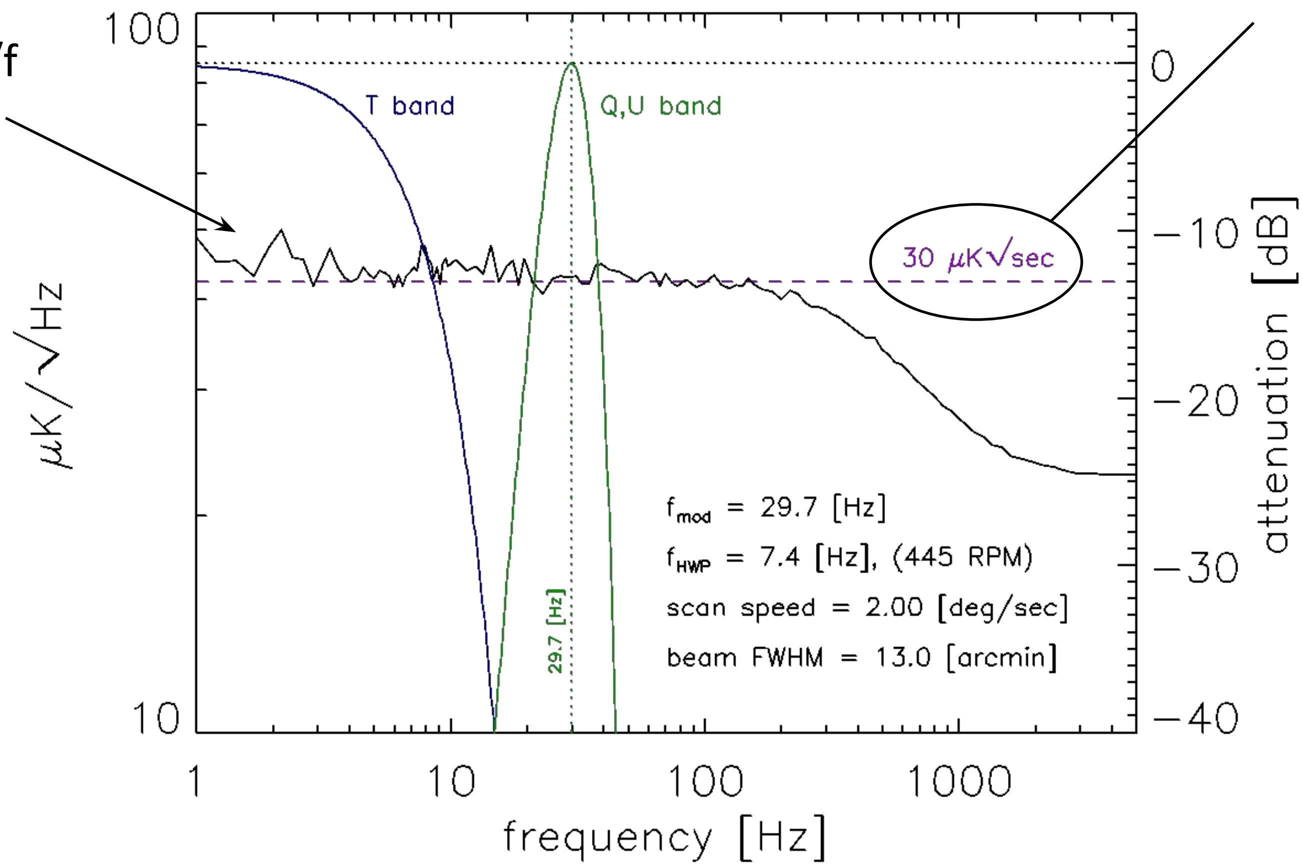
Table 6.1: The stack-up for the first multichroic detector array on a SOI wafer. The direction of light propagation is from the bottom of the table to the top. Because the thick silicon handle wafer and silicon oxide layer are etched away from under the OMTs, the light first encounters the thin silicon device layer. HTO: hot thermal oxide.

Material	Thickness/μm	Notes
Al	bulk	lid with back-shorts
vacuum	varies	from metal on wafer to package bulk metal
Au	0.1	180° tee termination and heat sink wirebond pads
Nb	0.4	microstrip: filters, hybrids, coupler; feedline cross-overs
SiN_x	0.35	not present above the resonators or feedline
Nb	0.2	ground plane: resonators, feedline, OMTs
Al	0.04	ground plane and KID active region
Si (intrinsic ⟨100⟩)	5	resistivity $> 10^4\,\Omega$ cm, float-zone; thickness ±0.5 μm
SiO_2 (wet HTO)	0.5	thickness ±5%
Si (P / boron ⟨100⟩)	350	resistivity 1 Ω cm to 10 Ω cm; thickness ±5 μm
Al	bulk	holder with feedhorns and circular waveguides

Main Result: Measured LEKID Noise

1) low NET

2) low 1/f noise

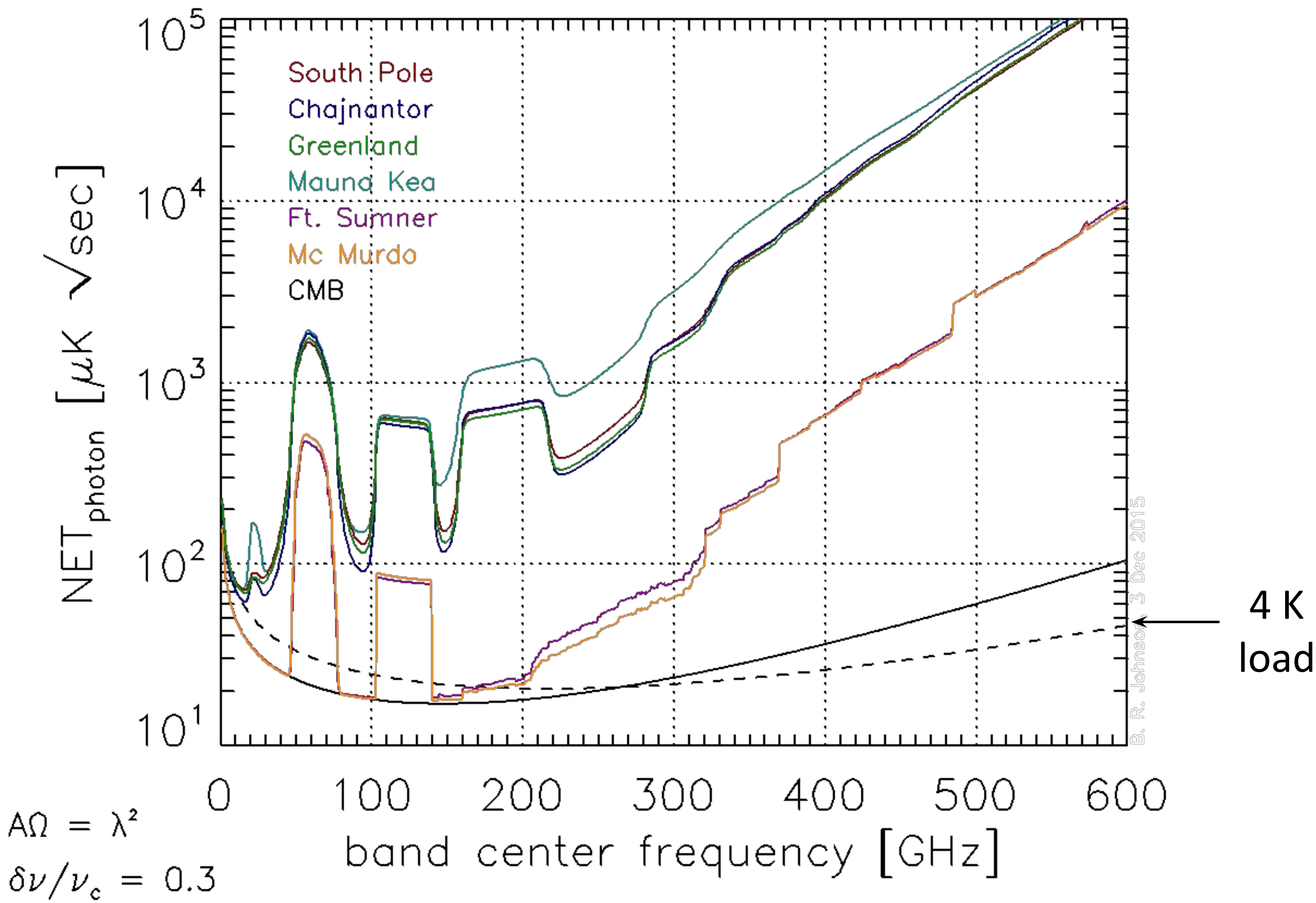


150 GHz

3) lots of bandwidth

4 K beam-filling load

Interpreting the NET Result



APPLIED PHYSICS LETTERS **108**, 083504 (2016)

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Photon noise from chaotic and coherent millimeter-wave sources measured with horn-coupled, aluminum lumped-element kinetic inductance detectors

D. Flanigan,[1,a)] H. McCarrick,[1] G. Jones,[1] B. R. Johnson,[1] M. H. Abitbol,[1] P. Ade,[2] D. Araujo,[1] K. Bradford,[3] R. Cantor,[4] G. Che,[5] P. Day,[6] S. Doyle,[2] C. B. Kjellstrand,[1] H. Leduc,[6] M. Limon,[1] V. Luu,[1] P. Mauskopf,[2,3,5] A. Miller,[1] T. Mroczkowski,[7] C. Tucker,[2] and J. Zmuidzinas[6,8]

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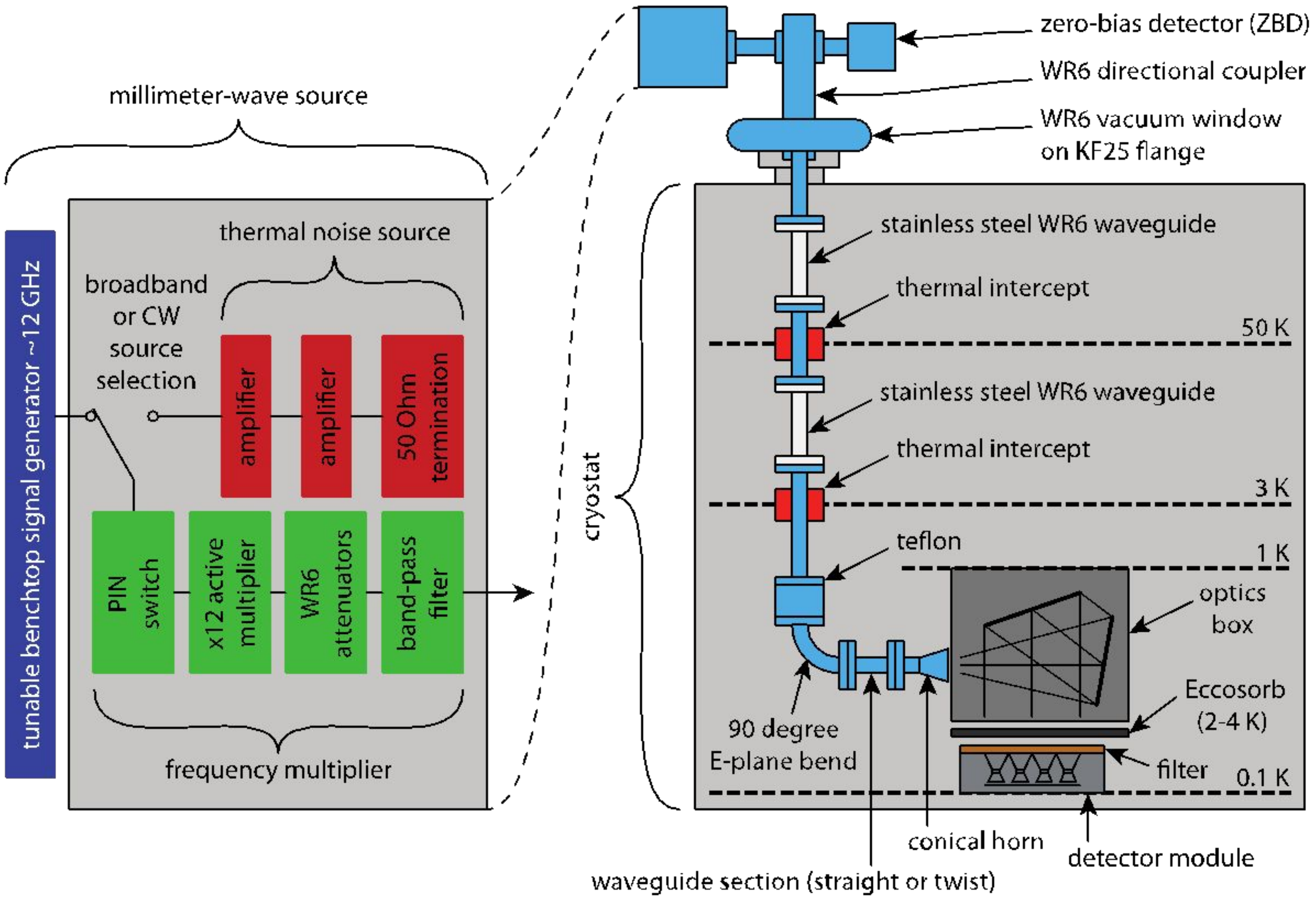
Project supported in part by a grant from the ***Research Initiatives for Science and Engineering*** program at Columbia.

Schematic of Experimental Setup



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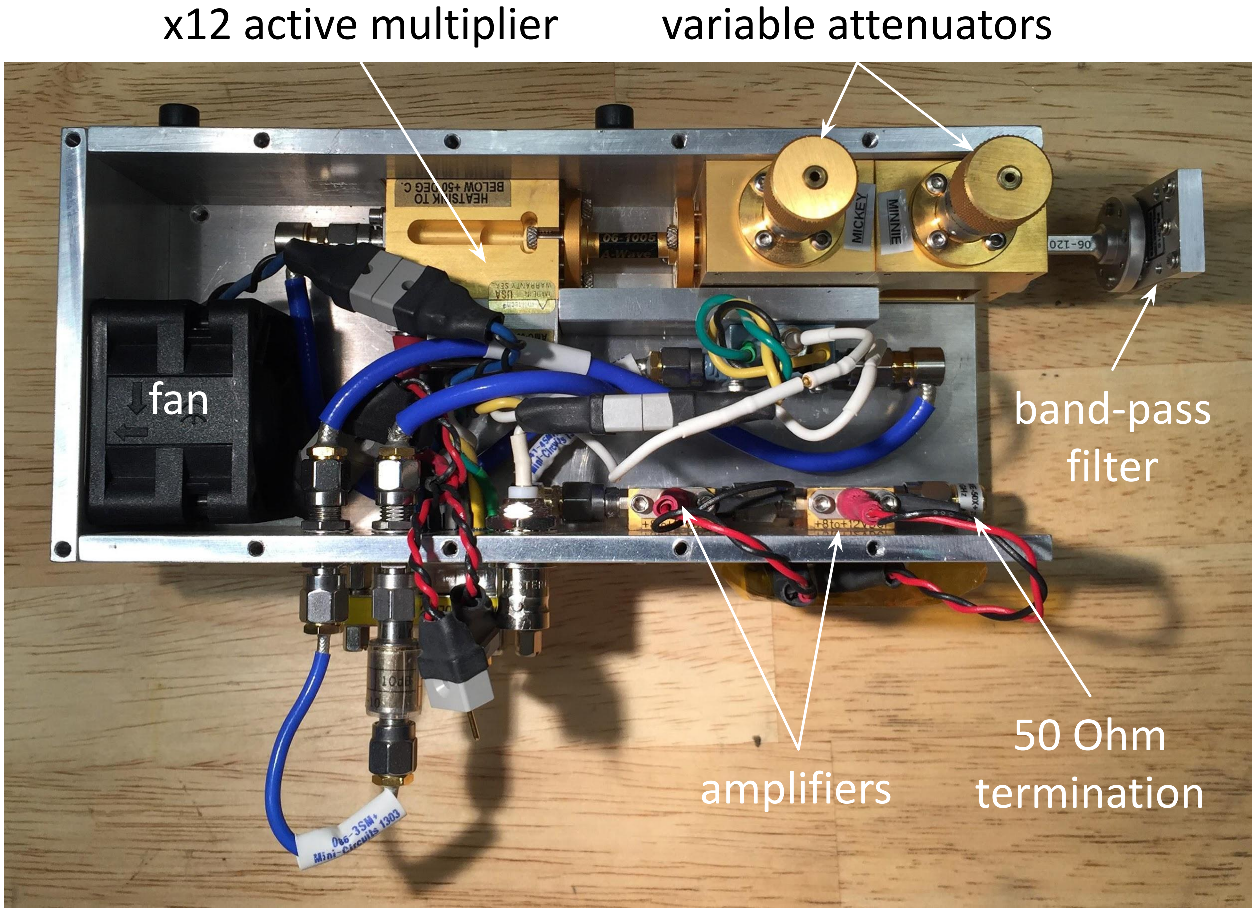
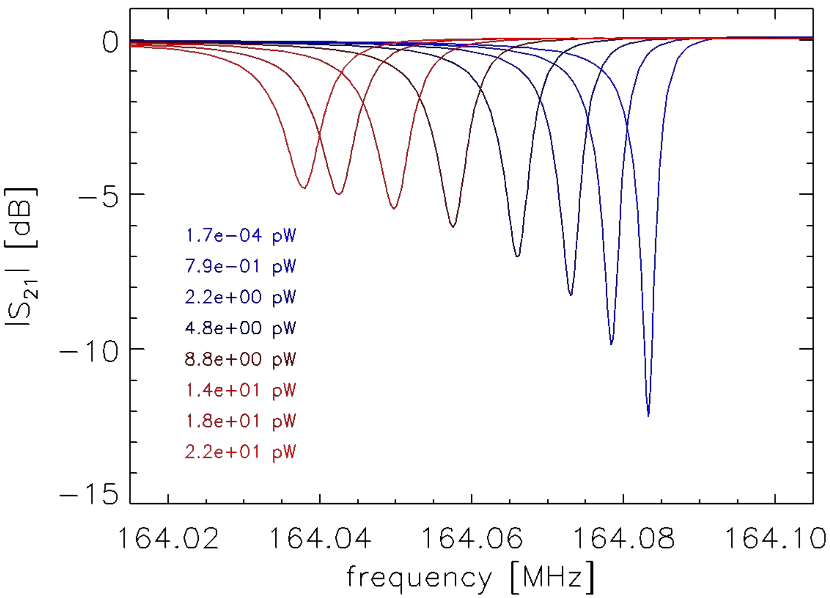
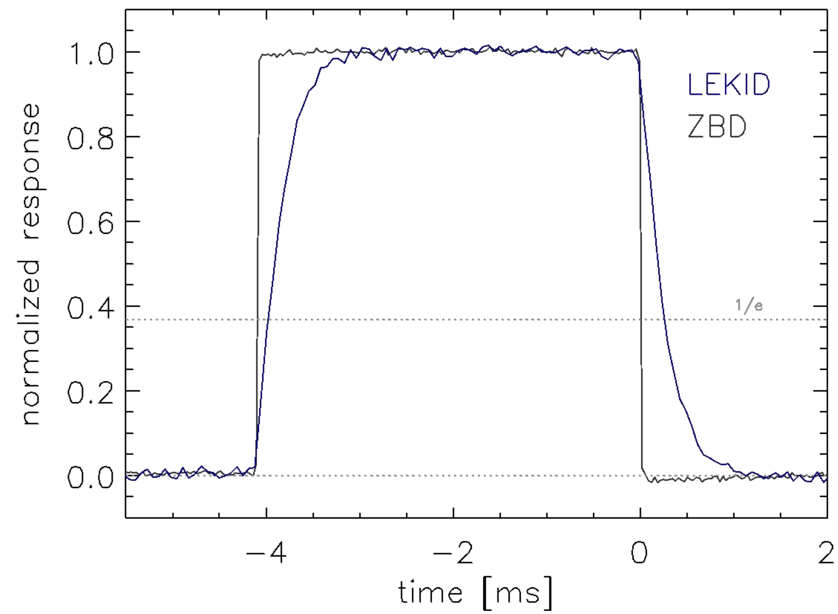
Millimeter-Wave Source



LEKID Measurements

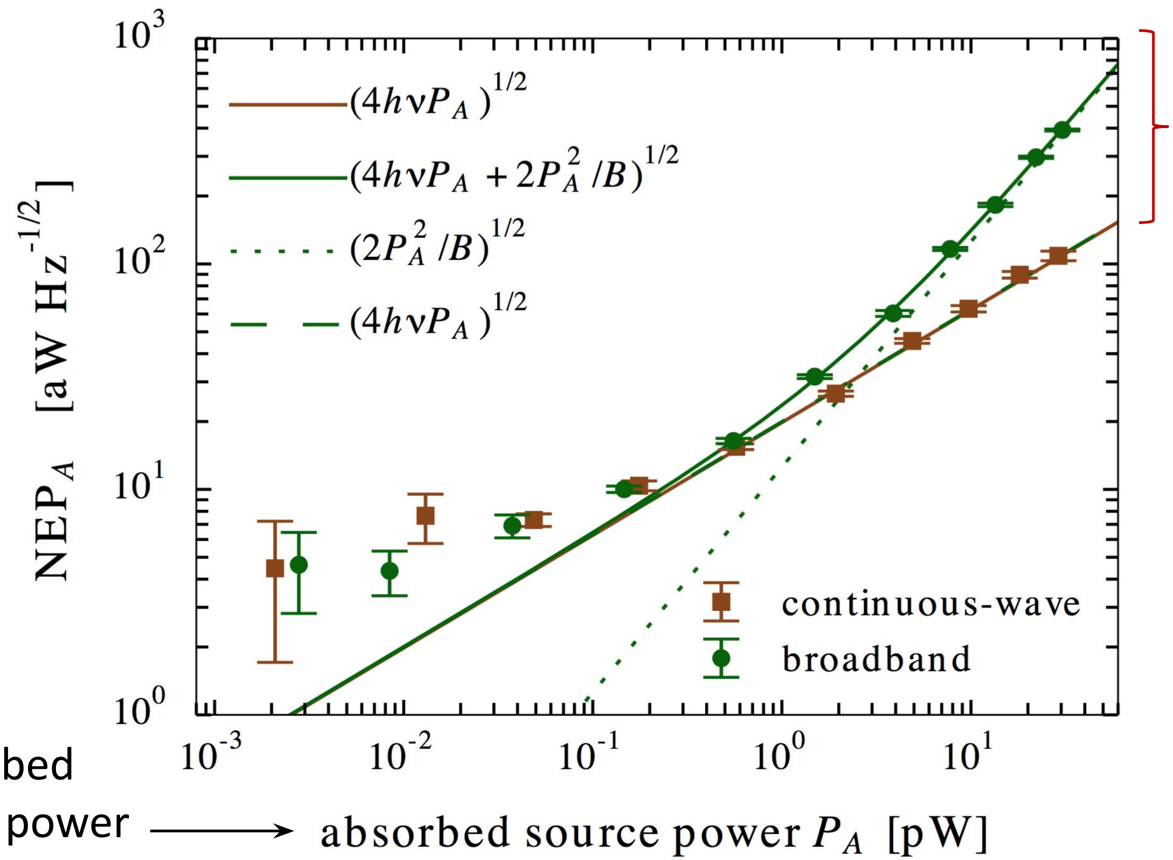


Measured S_{21} scattering parameter as a function of probe tone frequency for various millimeter-wave loadings. This plot shows that the LEKIDs work as expected. **As the millimeter-wave loading changes, the resonant frequency of the device changes**. The range of loading power used in this test spans the range expected in space-based, balloon-borne and ground-based experiments, so these detectors should work for any application.



LEKID response to a pulse of millimeter-wave radiation. The response from a faster and much less sensitive zero-bias detector (ZBD) is also plotted for comparison. The ZBD response shows that our millimeter-wave source is pulsed with microsecond time resolution and the comparison reveals that **the 1/e detector time constant for our LEKIDs is less than 500 microseconds**.

Main Result: Measured Photon Noise

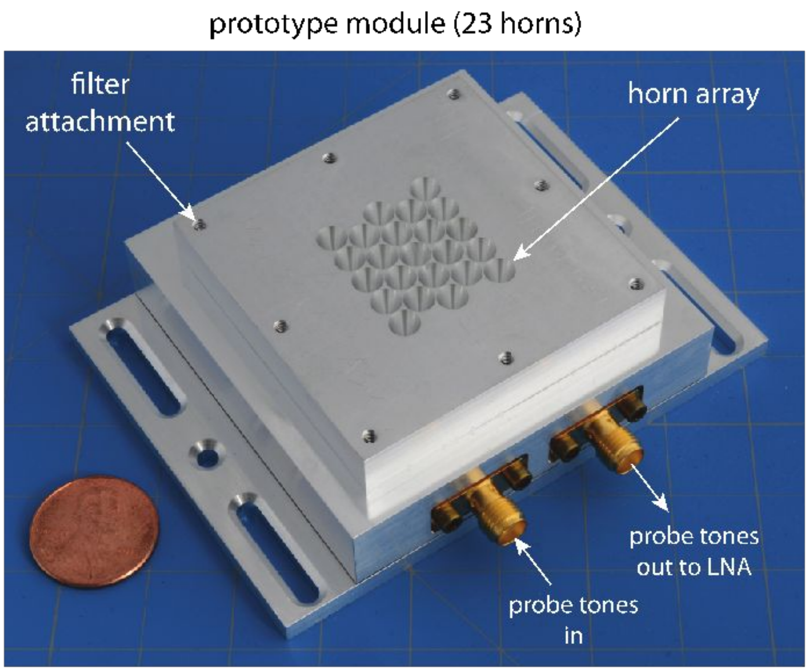


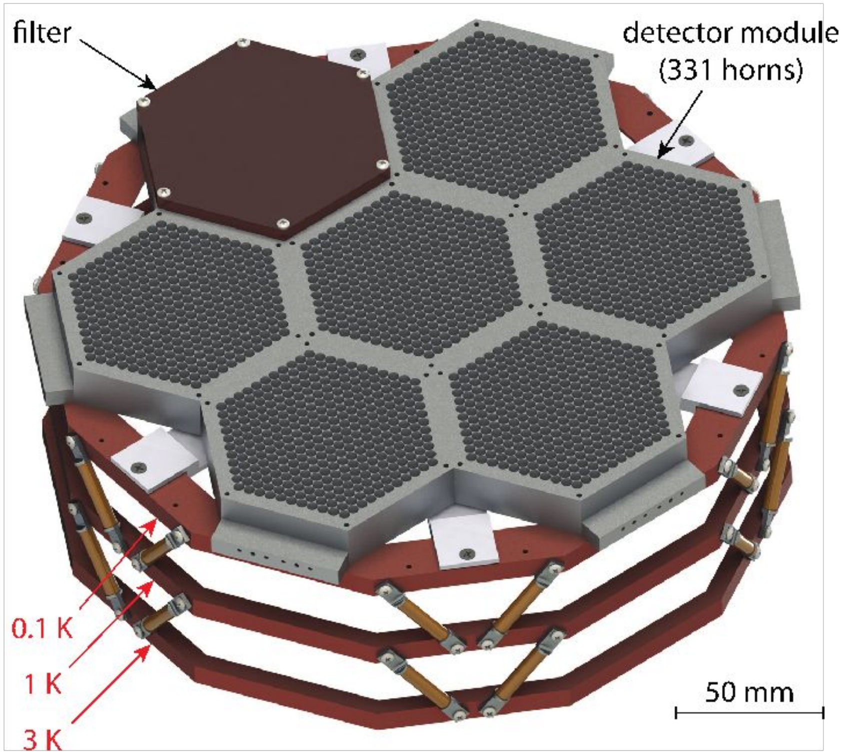
detecting photon noise and able to differentiate between shot and wave noise above ~1 pW

absorbed incident power from our source →

Flanigan, *et al.* (2016) *Appl. Phys. Lett.*, 108, 083504.

Goal: Multi-Chroic MKID Array

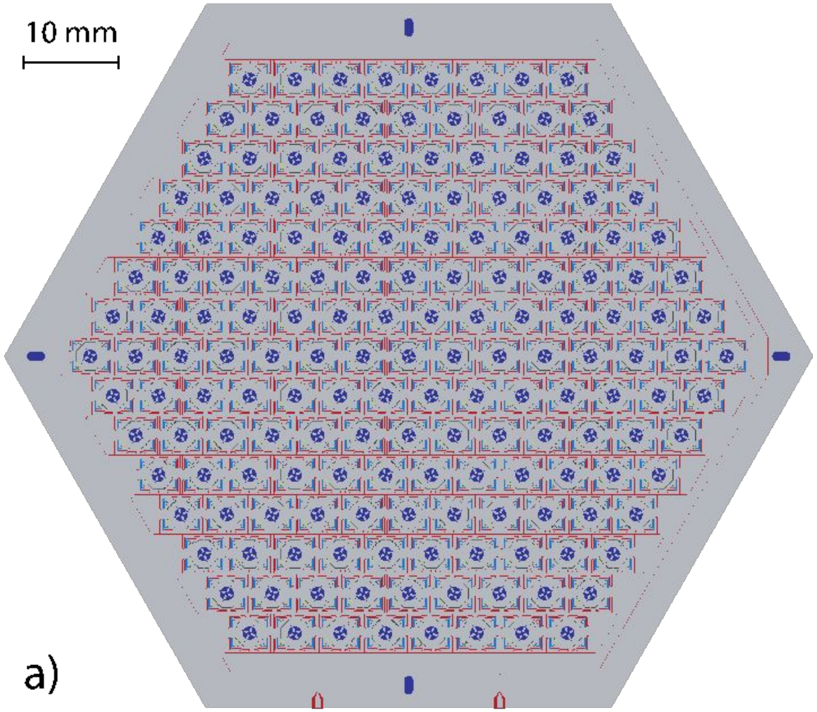


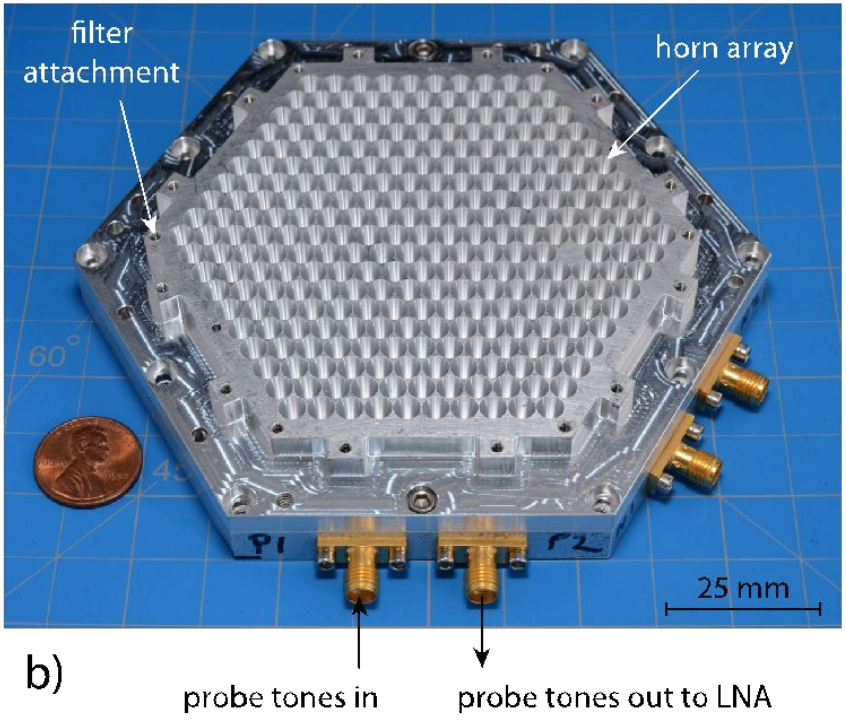


start with scalable, 23-element prototype module …

… scale up to 2317 horns or **9268 detectors**

Ongoing: Scale up the Prototype Module





Project supported by a grant from ***NSF/ATI***.

Paths Forward for KIDs

near-term projects:

1) CCAT-Prime
1) Simons Observatory
1) New receiver for Green Bank Telescope
1) new balloon-borne project (IDS) …

long-term projects:

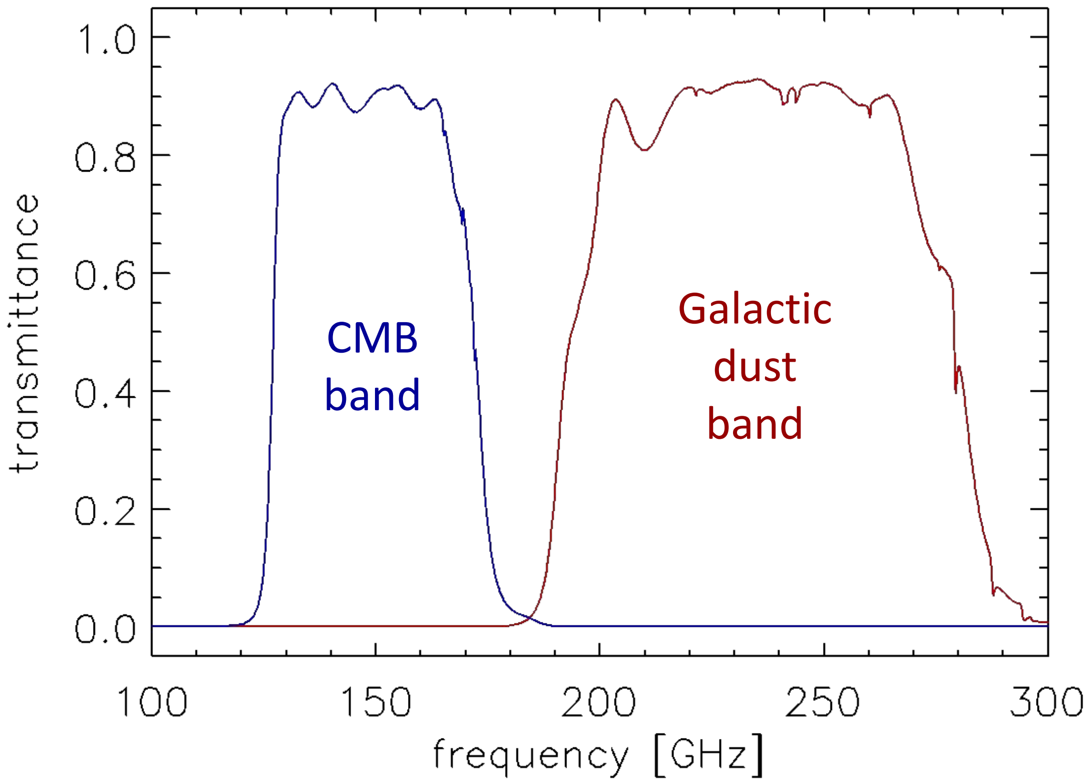
1) "CMB Stage 4" (CMB-S4)
1) 4th generation satellite mission (PICO)

"CMB Stage-4" (CMB-S4)

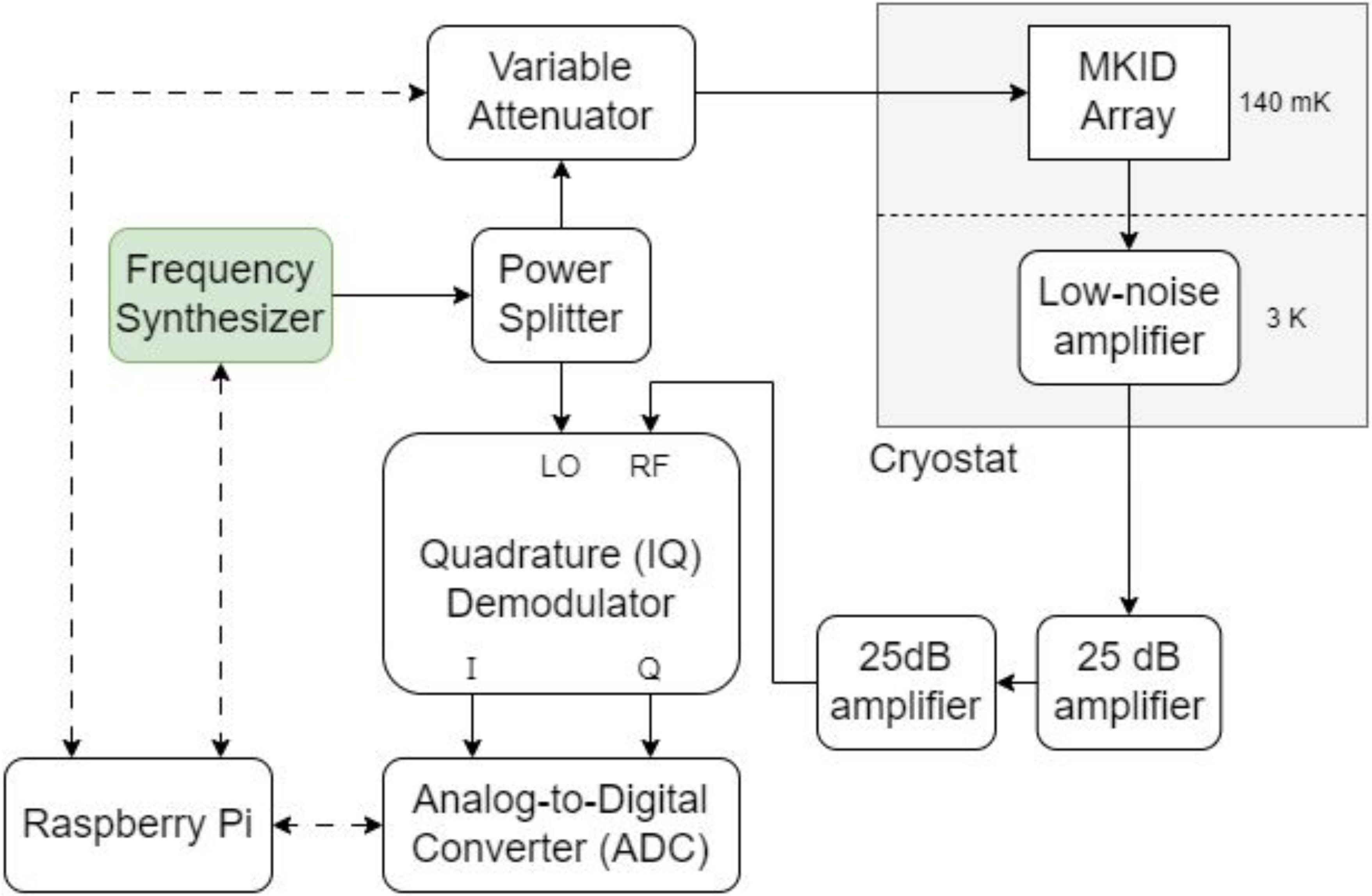
- Designed to be "The definitive ground-based CMB experiment"
- Sensitivity limited by ~500,000 photon-noise limited detectors.
- Primarily funded by the Department of Energy (DOE) and NSF
- Scientific goals:
    - *test inflation*
    - *determine the number and masses of the neutrinos*
    - *constrain possible new light relic particles*
    - *provide precise constraints on the nature of dark energy*
    - *test general relativity on large scales*
- Collaboration is forming now. Designed to be a community-wide project.
- Instrument(s) and observation sites are not yet defined.
- Observations should begin in 2027.

CMB-S4 Technology Book, First Edition: arXiv:1706.02464
CMB-S4 Science Book, First Edition: arXiv:1610.02743

Simulated Spectral Bands



HFSS/Sonnet simulation results show the expected **absorption efficiency is approximately 90%** taking into account all of the elements in the circuit except the OMT probes.


Variable Attenuator
MKID Array
140 mK
Frequency Synthesizer
Power Splitter
Low-noise amplifier
3 K
LO
RF
Cryostat
Quadrature (IQ) Demodulator
I
Q
25dB amplifier
25 dB amplifier
Raspberry Pi
Analog-to-Digital Converter (ADC)