Kinetic Inductance Detectors for CMB Studies

Brad Johnson
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Organization of Presentation

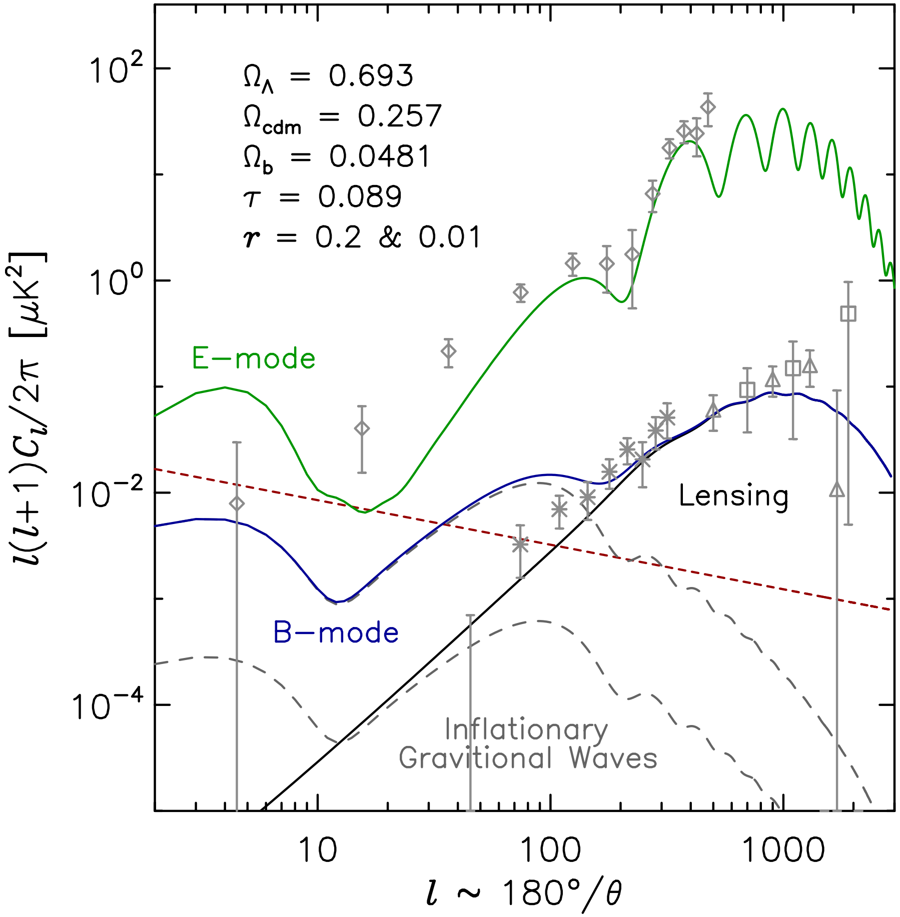
1) Status of CMB Studies
2) Overview of Kinetic Inductance Detectors
3) Lumped-Element Kinetic Inductance Detectors (LEKIDs)
4) Dual Polarization LEKIDs
5) Multi-Chroic Microwave Kinetic Inductance Detectors (MKIDs)

Emphasize the work of …

- Heather McCarrick (2nd year, NASA/NESSF fellow) -- LEKIDs
- Daniel Flanigan (5th year) – LEKID measurements, mulit-chroic MKIDs
- Max Abitbol (3rd year) – EBEX analysis, MKID readout
- Glenn Jones, Associate Research Scientist – MKIDs, CMB spectrometer, etc.

1) Status of CMB Studies

Where are we today with CMB studies?



Selected measurements from the following experiments show we need more sky coverage and sensitivity.

WMAP:

Bennett et al. (2013) *ApJS*, 208, 2.

POLARBEAR:

POLARBEAR Collaboration (2014) *ApJ*, 794, 2, 171

BICEP/Keck:

BICEP2/Keck Collaborations (2016) *PRL*, 116, 3

SPT-Pol:

Keisler et al. (2015) *ApJ*, 807, 2, 151.

B-mode Experiment Characteristics

1) Excellent Observation Site:

- *The atmosphere obscures the CMB. Measurements must be made from a high dry location or from space.*

2) High Sensitivity:

- ***Thousands of cryogenic detectors*** *cooled to sub-Kelvin temperatures AND long integration time are required to average down photon noise.*

3) Negligible Systematic Errors:

- *This requirement impacts everything from instrument design to observation strategy to data analysis algorithms.*

4) Large Sky Coverage:

- *CMB-S4 or 4th Generation Satellite mission*

5) Foreground Separation Capability:

- ***Observations in multiple spectral bands (multi-chroic detectors)***

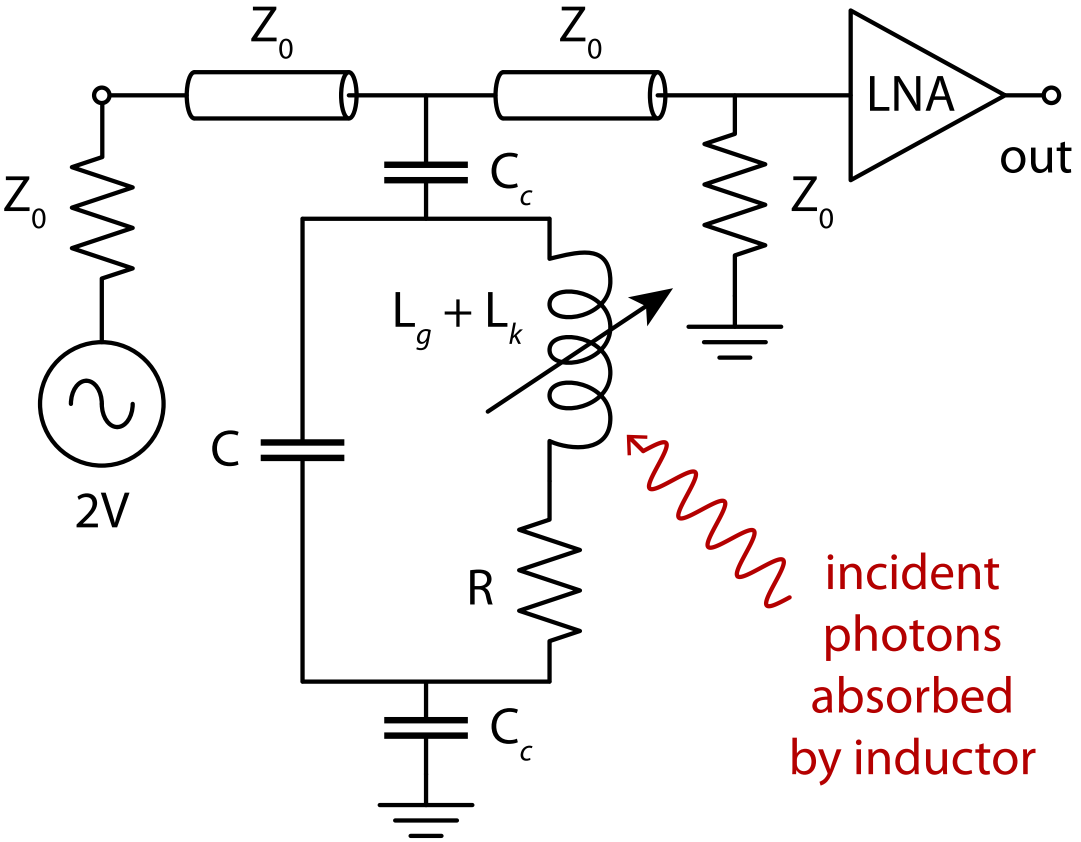
2) Overview of Kinetic Inductance Detectors

Why investigate MKIDs for CMB Studies?

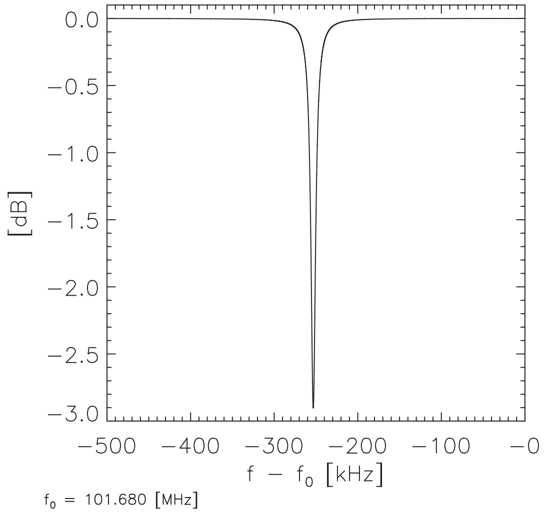
- **High multiplexing factors** make them particularly suitable for instruments with 10,000 or more detectors (CMB-S4, for example).
- No membranes are required and arrays can be made with a comparatively **small number of processing steps**. Fabrication in commercial foundries is possible.
- **Fast 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** (~20 watts) is commercially available. Required LNAs are available. Required firmware is open-source.

But is the sensitivity and 1/f noise suitable?

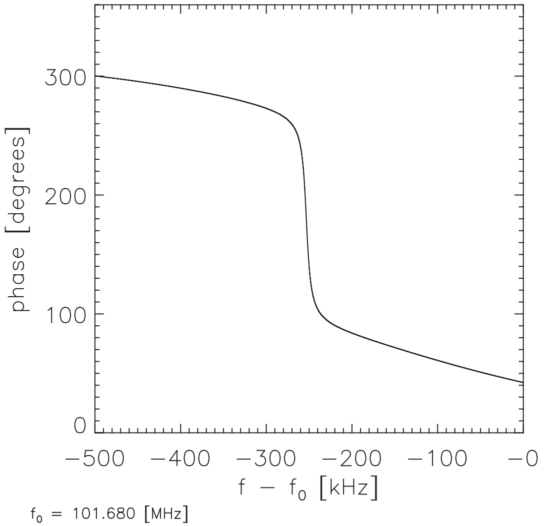
Circuit Schematic for One LEKID



incident photons absorbed by inductor



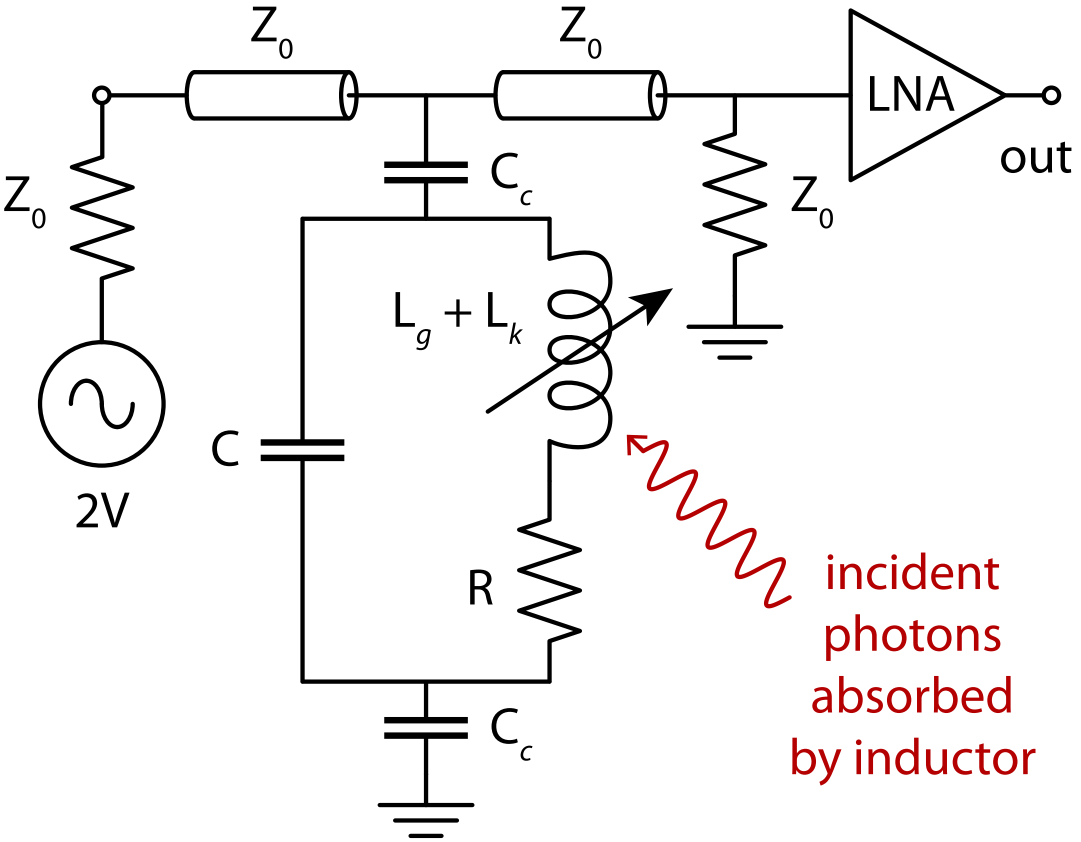
f_0 = 101.680 [MHz]



f_0 = 101.680 [MHz]

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

Circuit Schematic for One LEKID



incident
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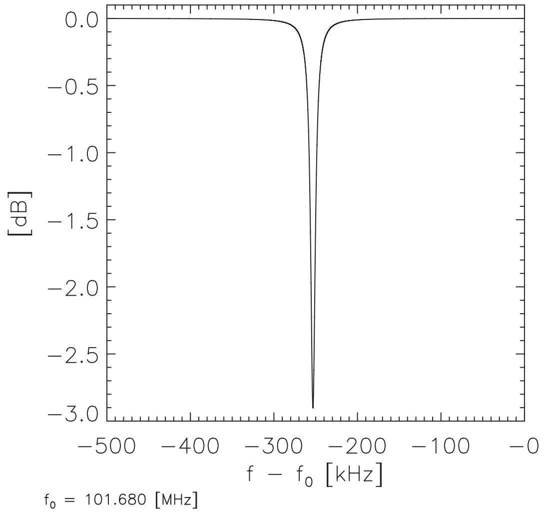
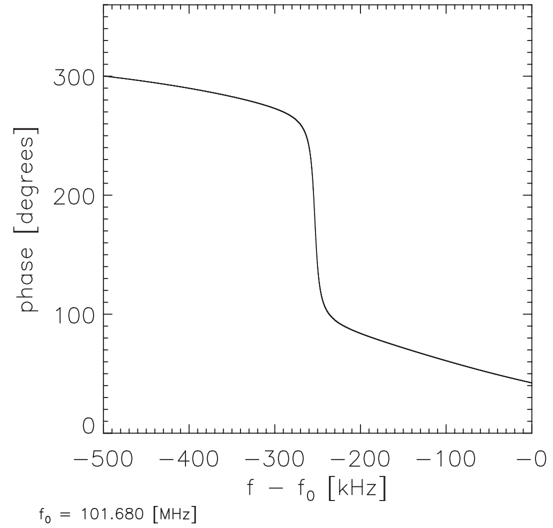
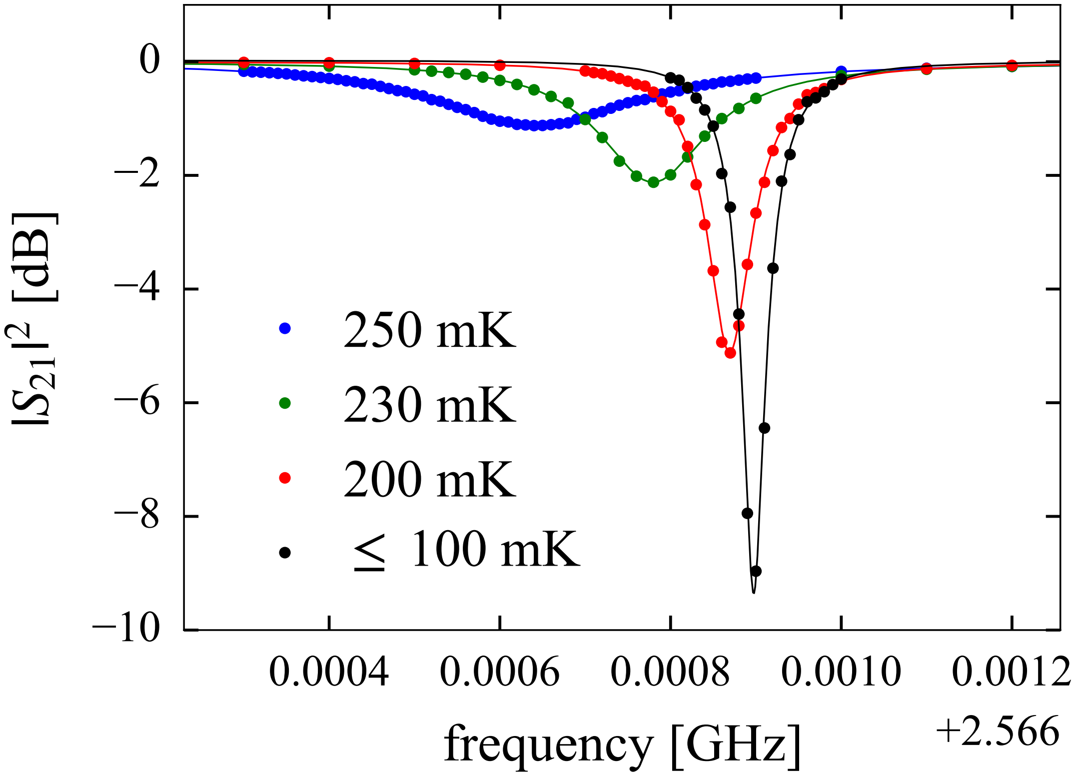




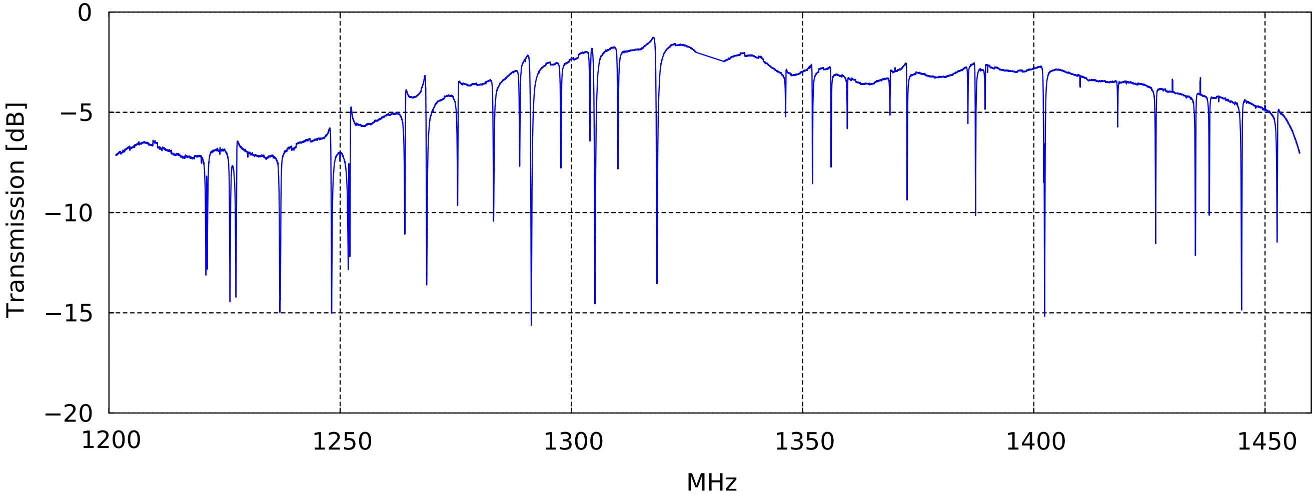
$$Z_L = R(n_{qp}) + j\omega[L_g + L_k(n_{qp})]$$

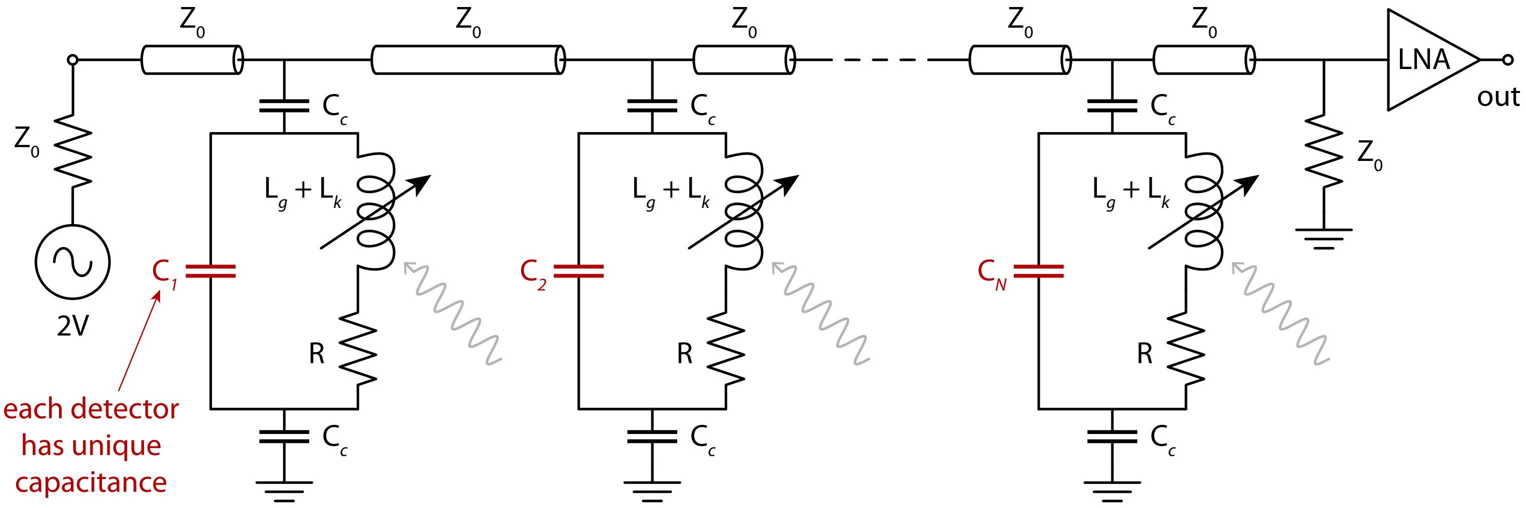
Resonances



$$S_{21} \approx 1 - \frac{Q_r}{Q_c}\frac{1}{1+2jQ_r x},\ x = \frac{f-f_r}{f_r},\ \frac{1}{Q_r} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

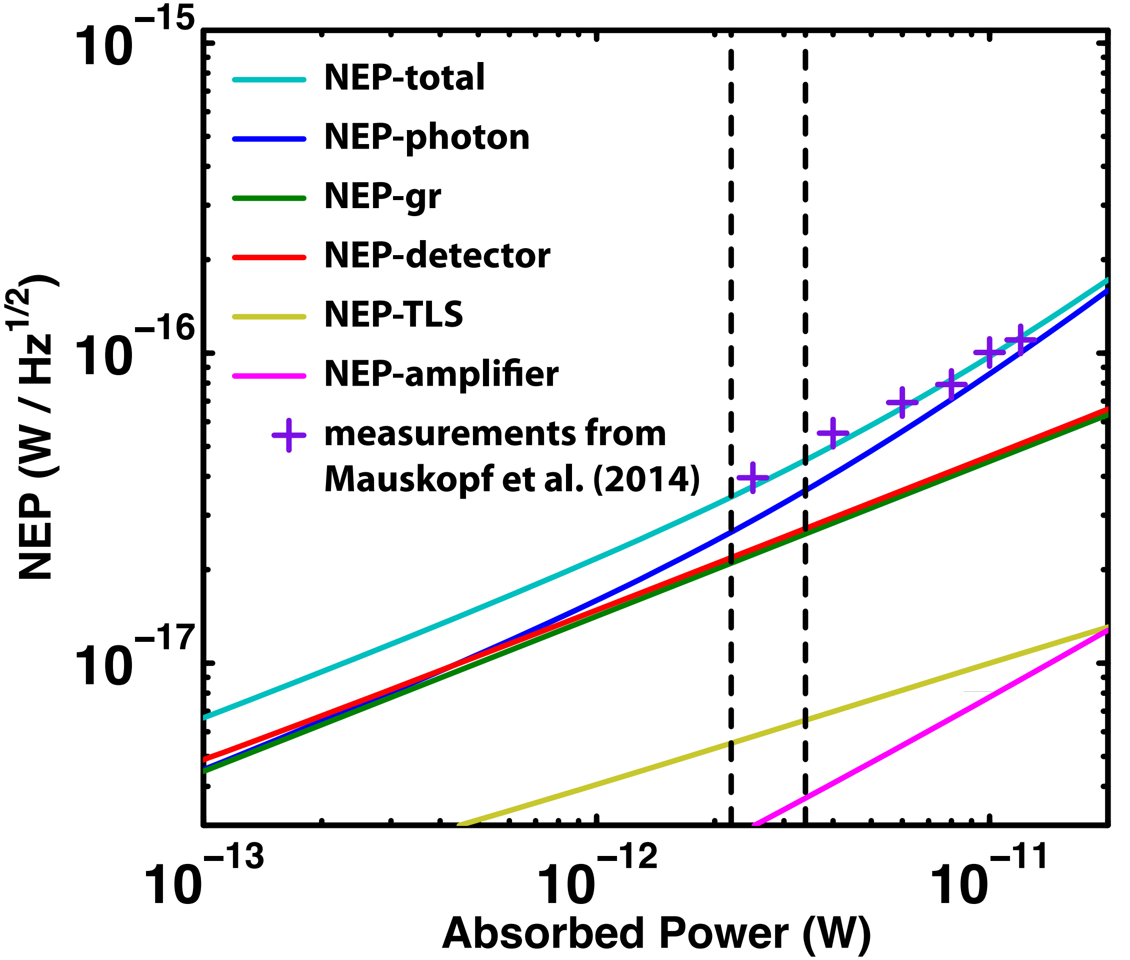
Resonances





each detector has unique capacitance

Noise Sources



2) Lumped-Element Kinetic Inductance Detectors (LEKIDs)

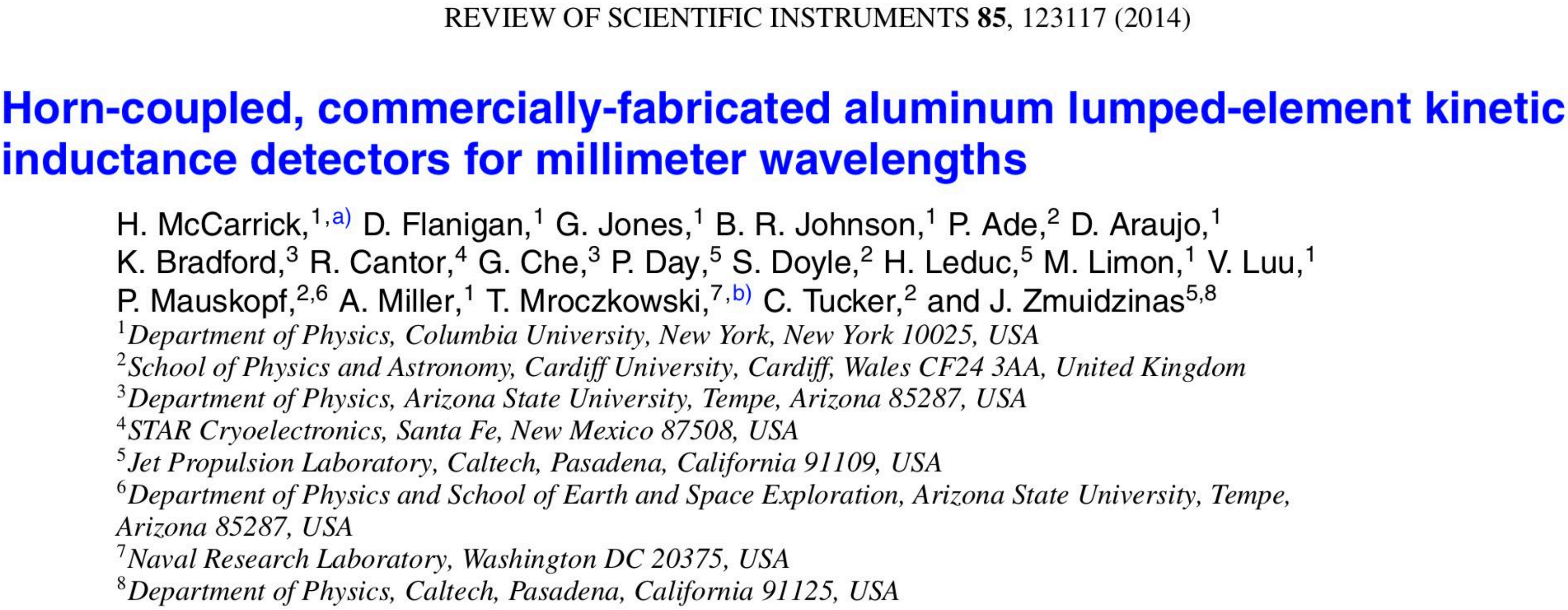
References:

McCarrick et al. (2014) *Review of Scientific Instruments*, 85, 123117.

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

McCarrick et al. (2015) *JLTP accepted*. (arXiv:1512.01847).

Jones et al. (2015) *ISSTT Proceedings*. P-16.



REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 123117 (2014)

Horn-coupled, commercially-fabricated aluminum lumped-element kinetic inductance detectors for millimeter wavelengths

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K. Bradford,[3] R. Cantor,[4] G. Che,[3] P. Day,[5] S. Doyle,[2] H. Leduc,[5] M. Limon,[1] V. Luu,[1]
P. Mauskopf,[2,6] A. Miller,[1] T. Mroczkowski,[7,b] C. Tucker,[2] and J. Zmuidzinas[5,8]
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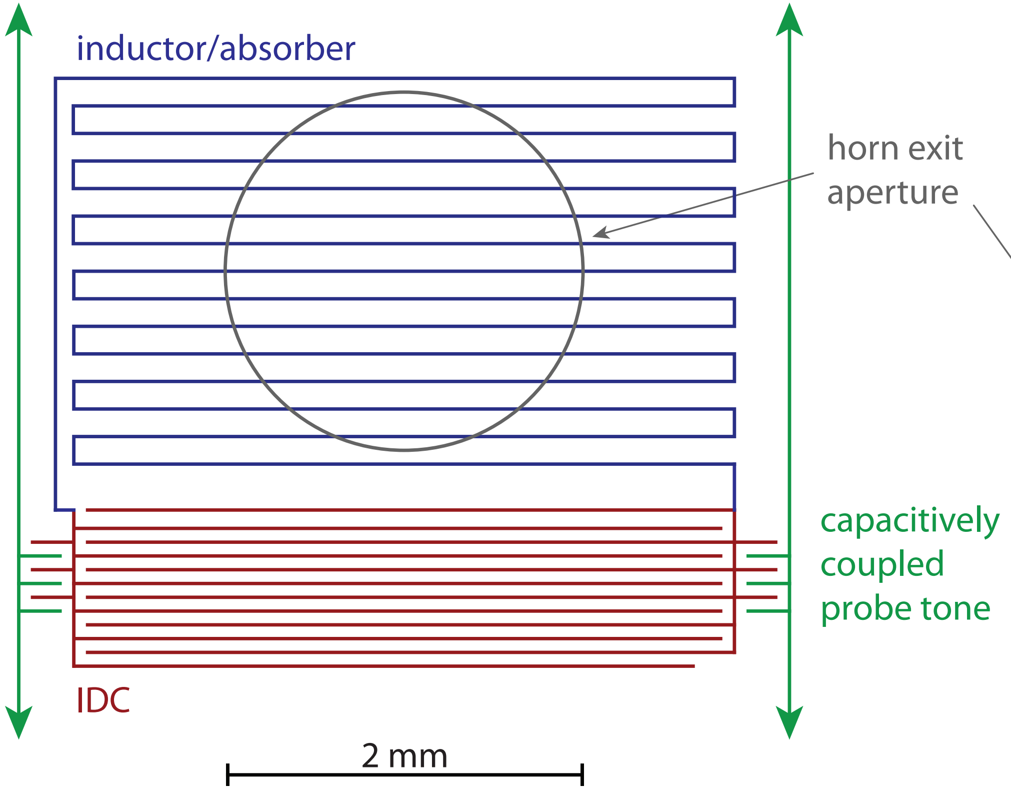
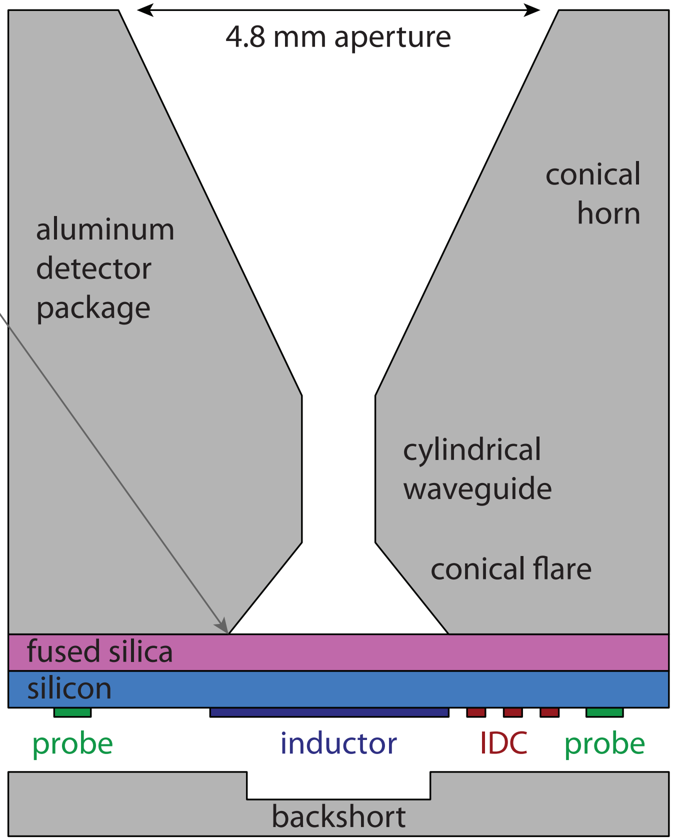
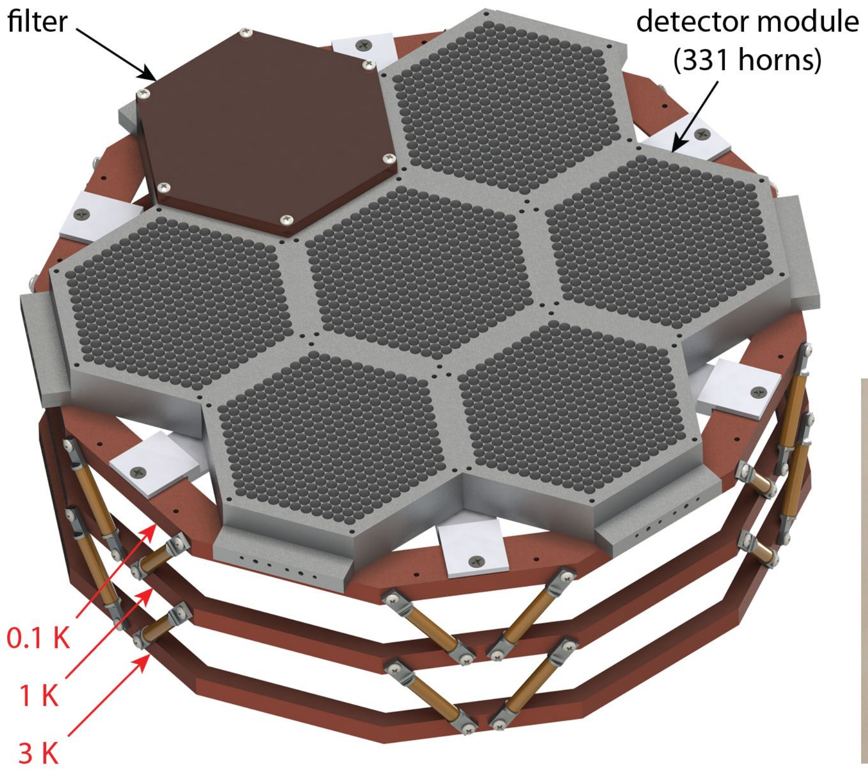
Project supported in part by a grant from the ***Research Initiatives for Science and Engineering*** program at Columbia.

“Single Polarization” Pixel Design

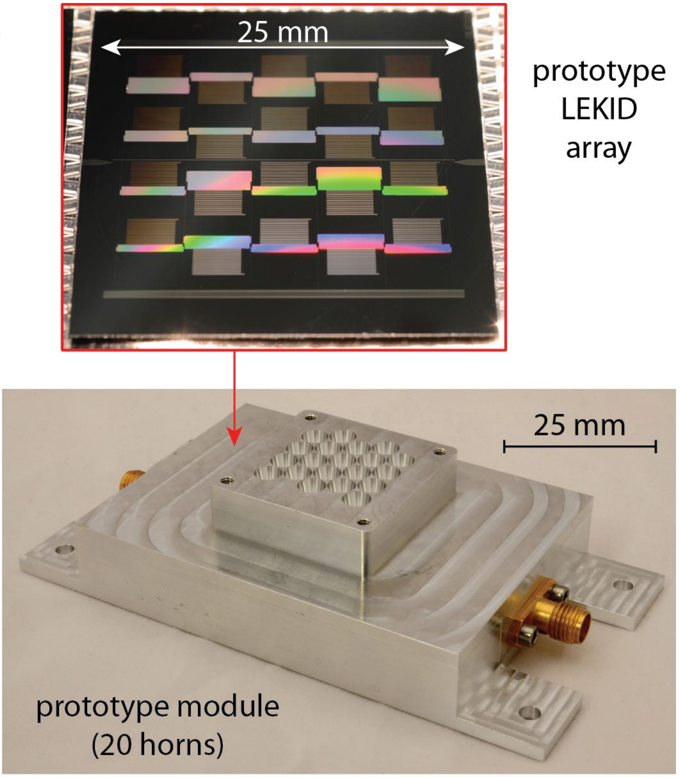




Ultimate Goal

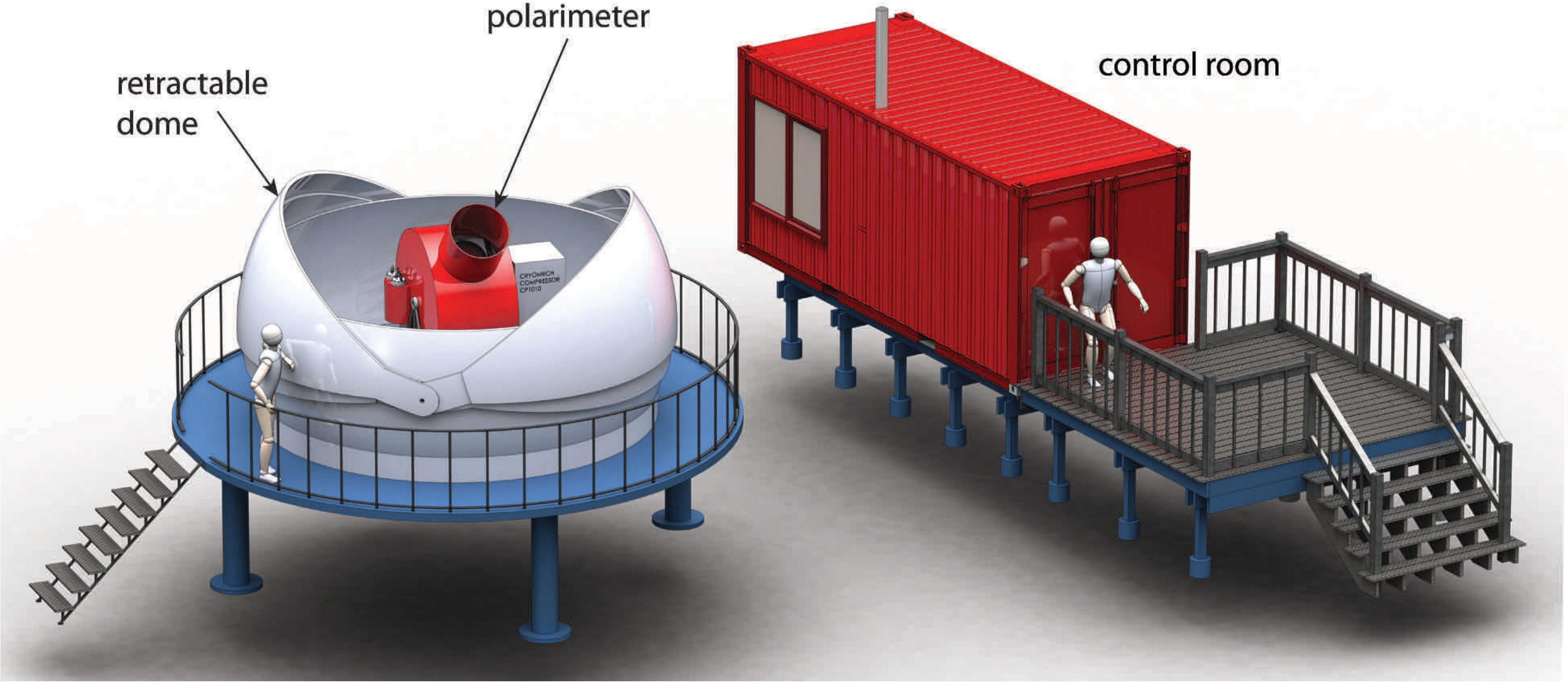


2317 horns/single-pol detectors
4634 dual-pol detectors
9268 multi-chroic detectors



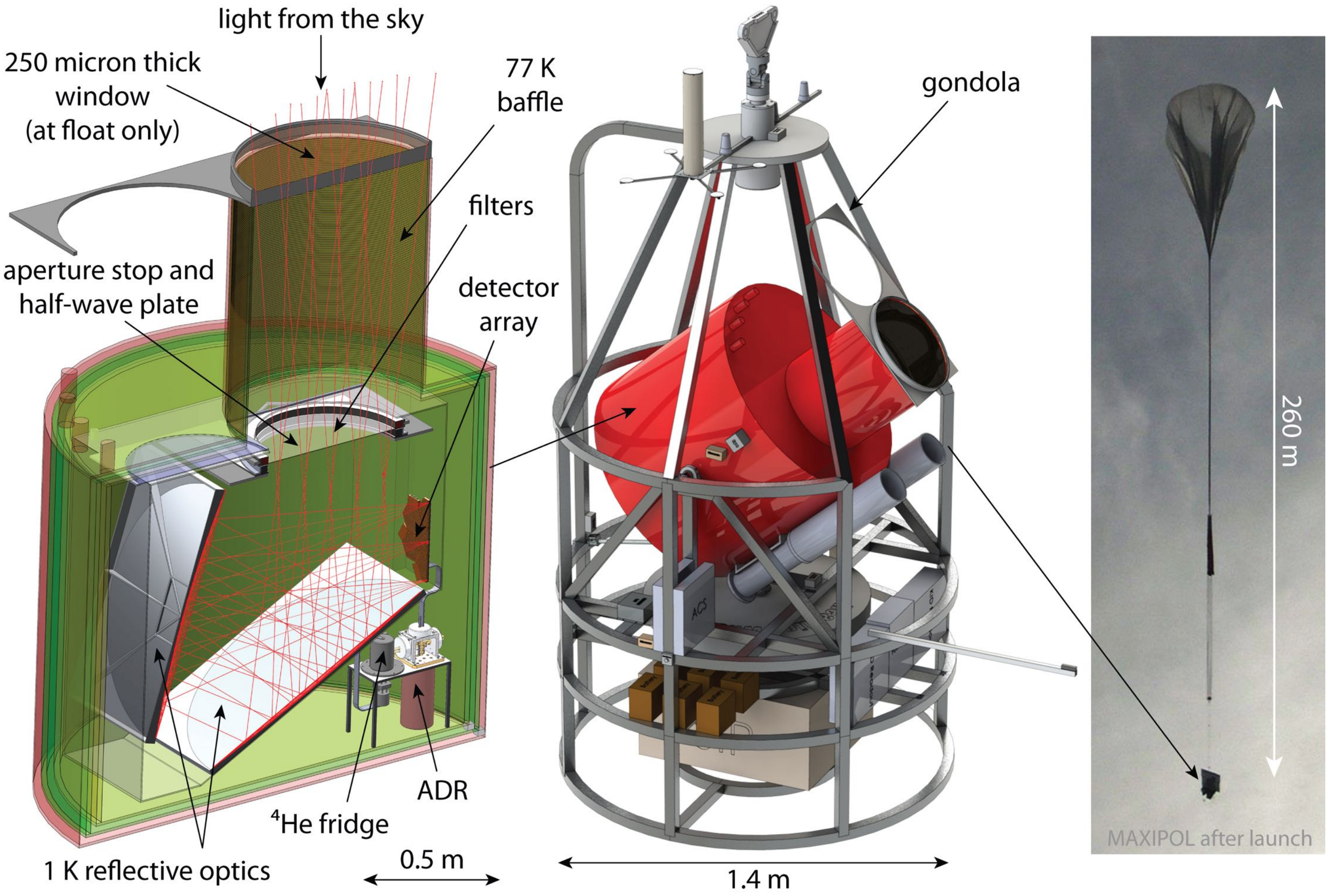
start with scalable, 20-element prototype module

The Greenland LEKID Polarimeter



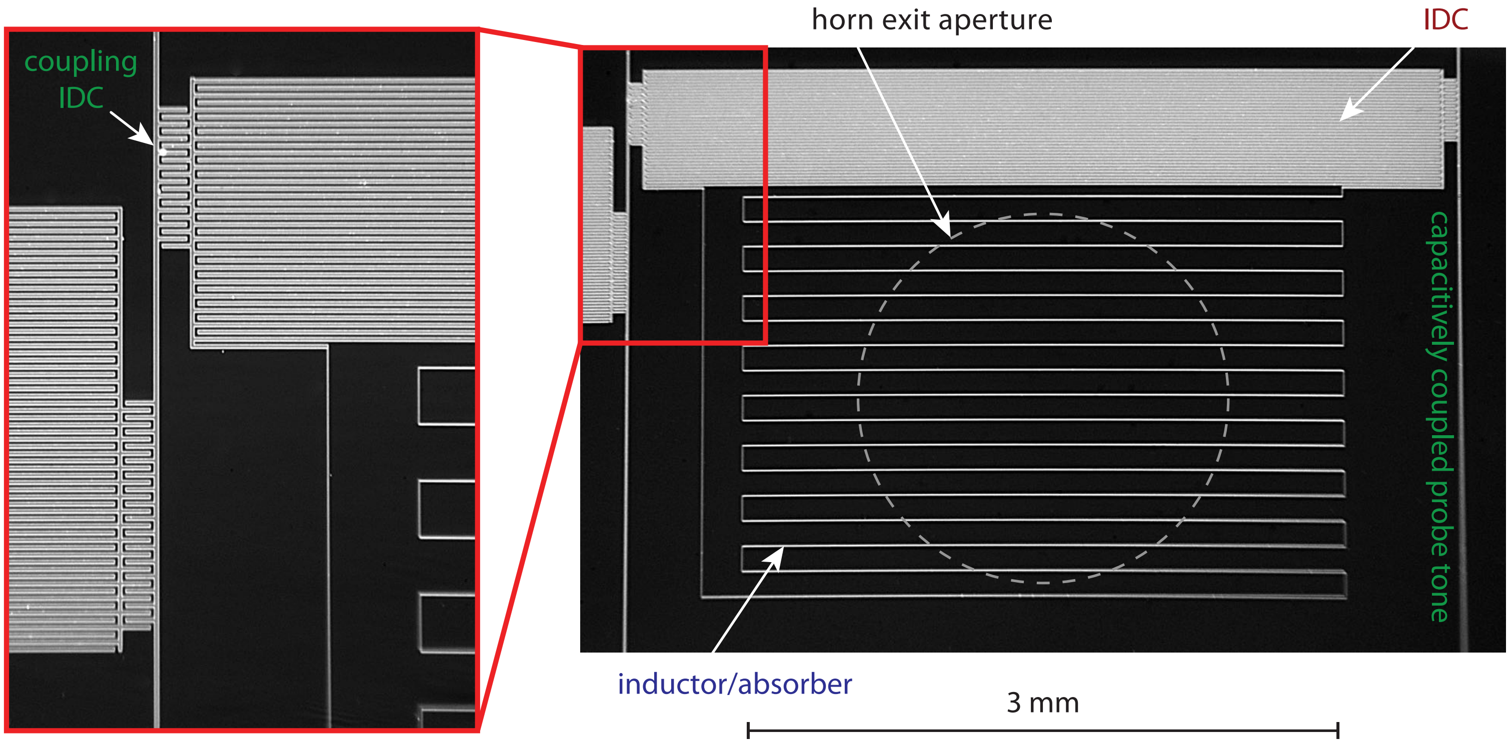
Araujo et al . (2014) *Proc. of SPIE*. Volume 9153, 91530W.

Stratospheric Kinetic Inductance Polarimeter

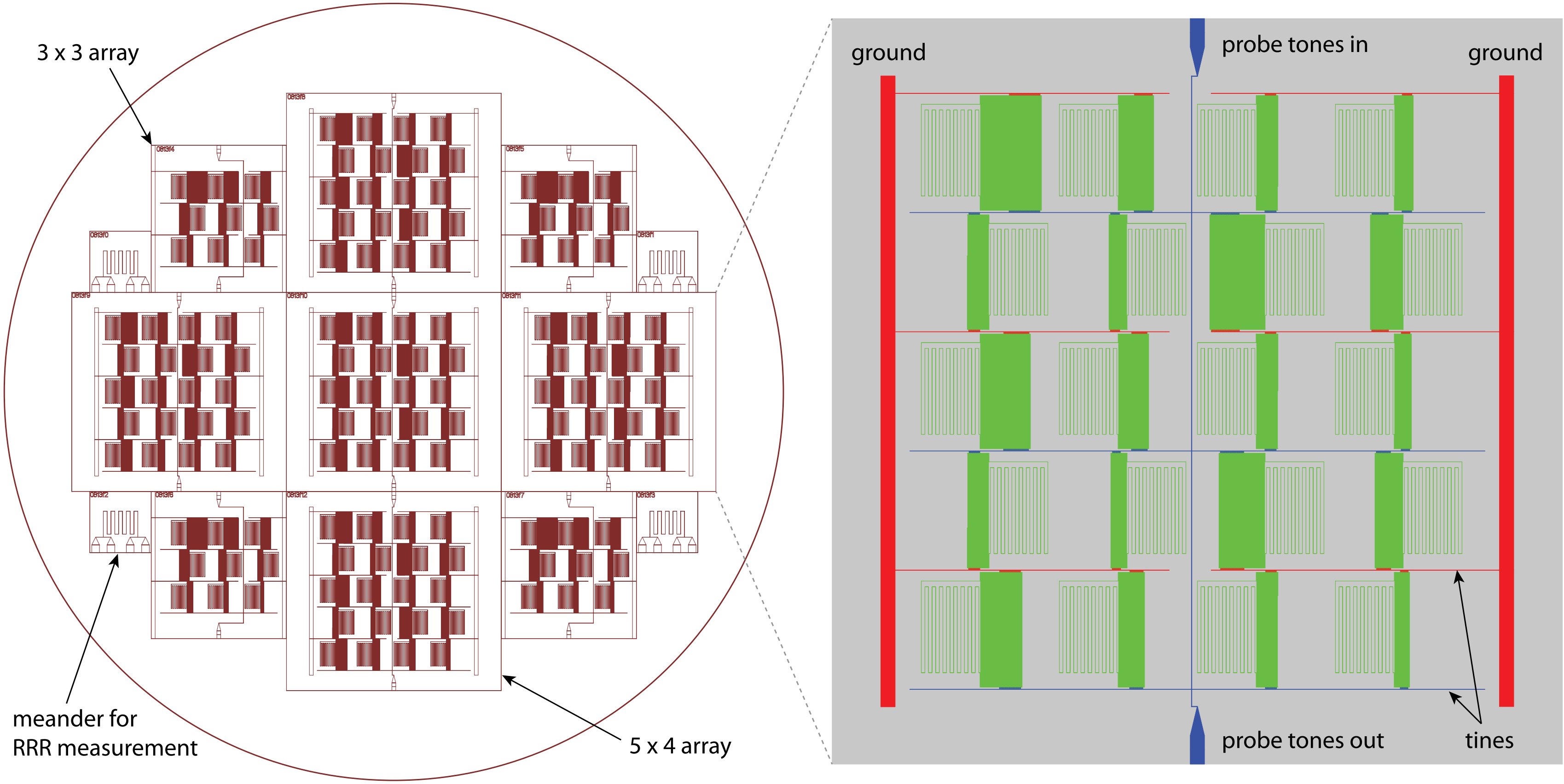


Johnson et al. (2014) *J. Low Temp. Phys*. Volume 176, Issue 5, p 741-748

Photomicrograph of Single LEKID



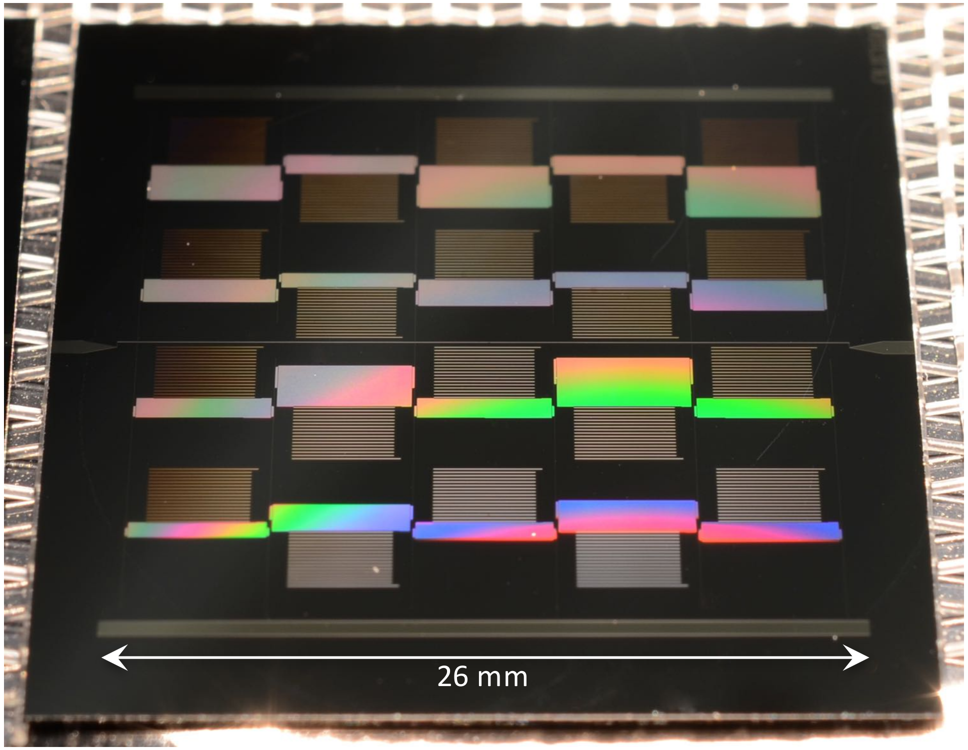
Prototype Array Design



prototype arrays made with contact lithography

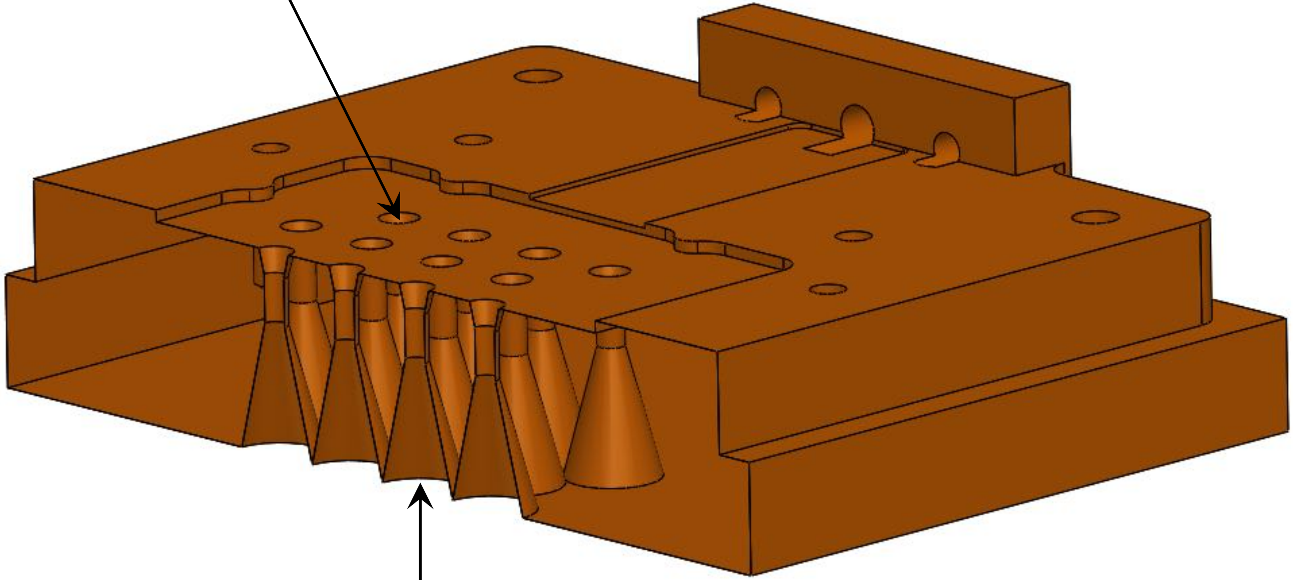
Photograph of Prototype Array

- Arrays fabricated on a 100 mm **float zone silicon** wafer 300 microns thick.
- Devices processed from one **aluminum film 20 nm thick**.
- **Contact lithography** used -- one mask required.
- **Commercially fabricated** at STAR Cryoelectronics (~$2k per wafer)
- Processing took ~1 week.
- Plan was to fabricate and test 1 wafer per month for two years.
- McCarrick et al. (2014) describes results from first wafer.



wafer yield > 90%

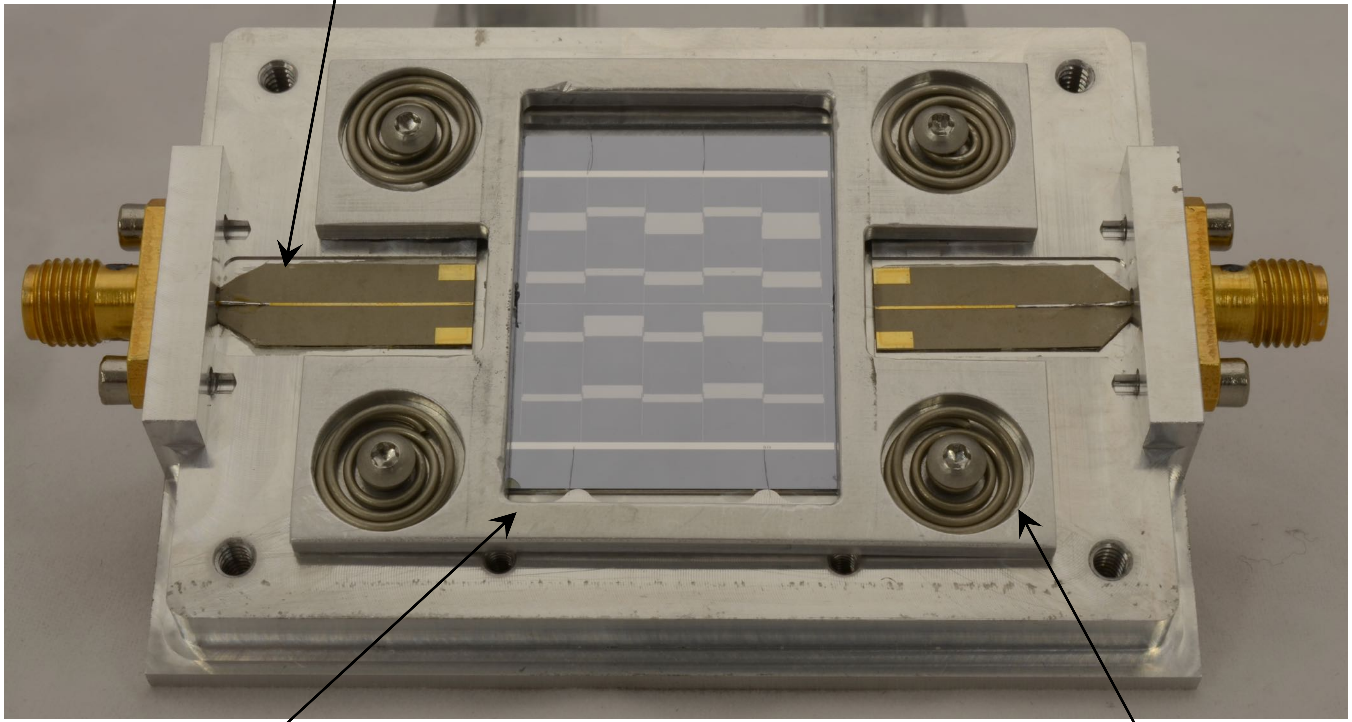
Cross Section of Detector Package



LEKIDs mounted at exit aperture

millimeter-wave light enters the horn

Prototype Array in Detector Package



Duroid boards connect probe tones to the array

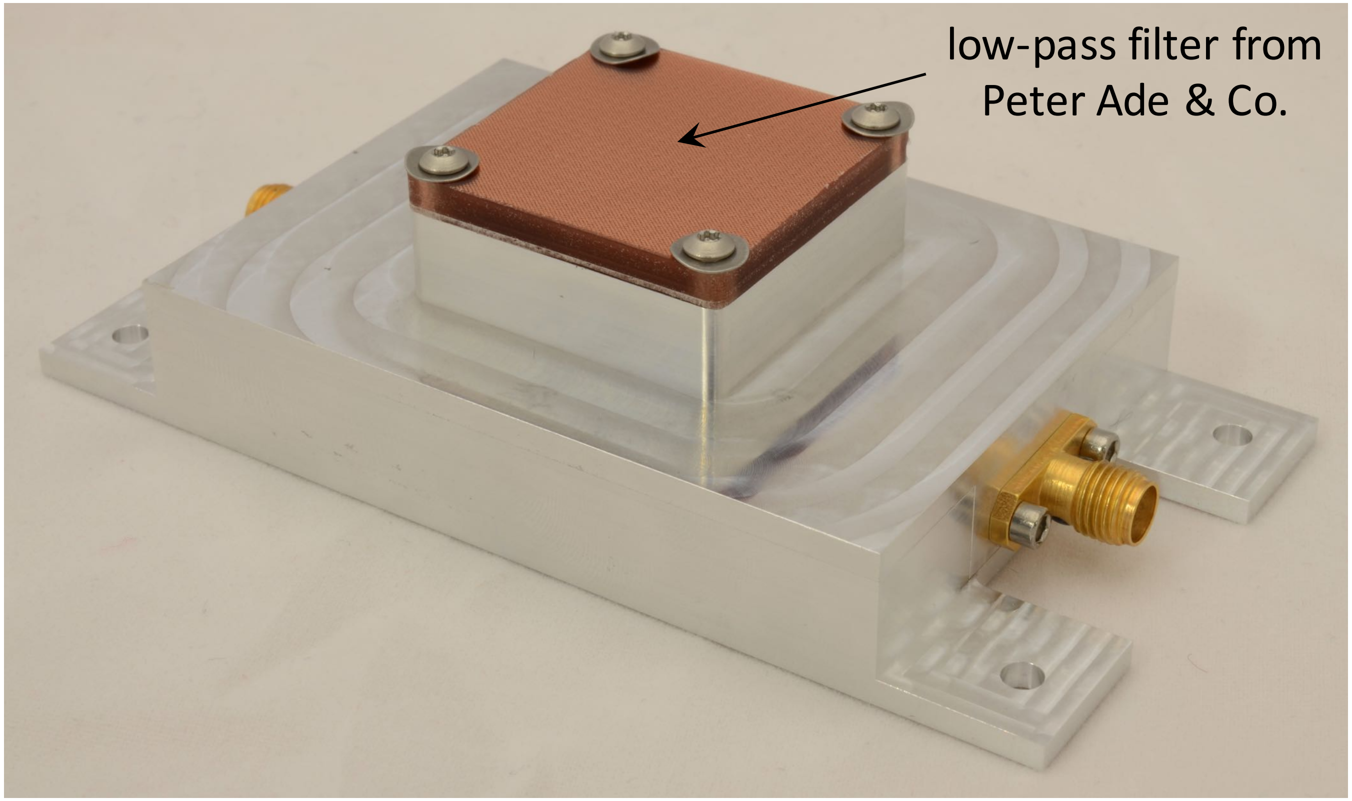
probe
comb
in

probe
comb
out

frame holds the chip in place

springs provide force and
improve thermal conductivity

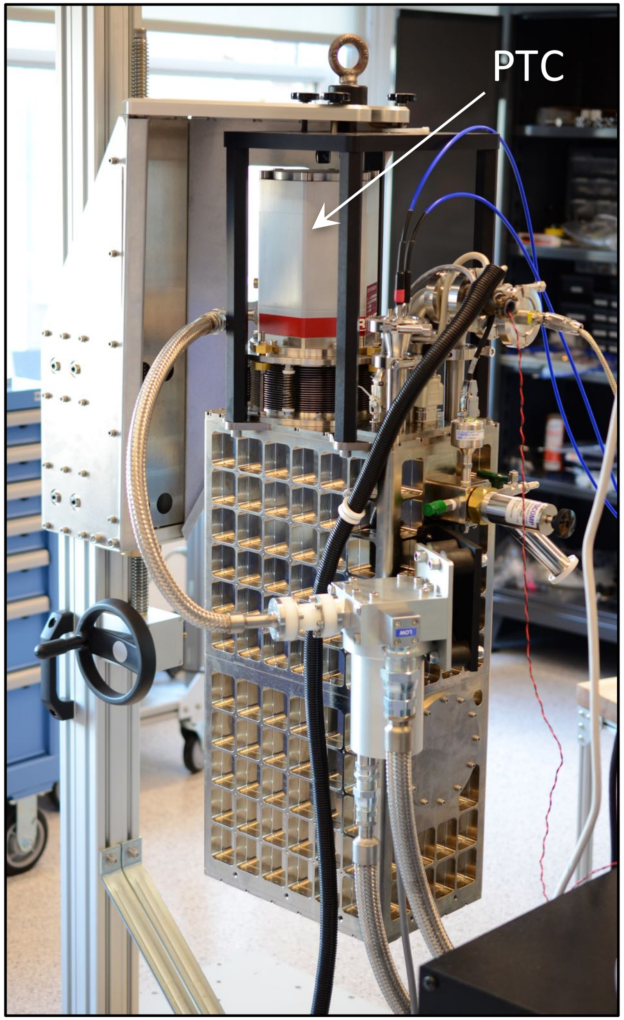
Prototype Array in Detector Package



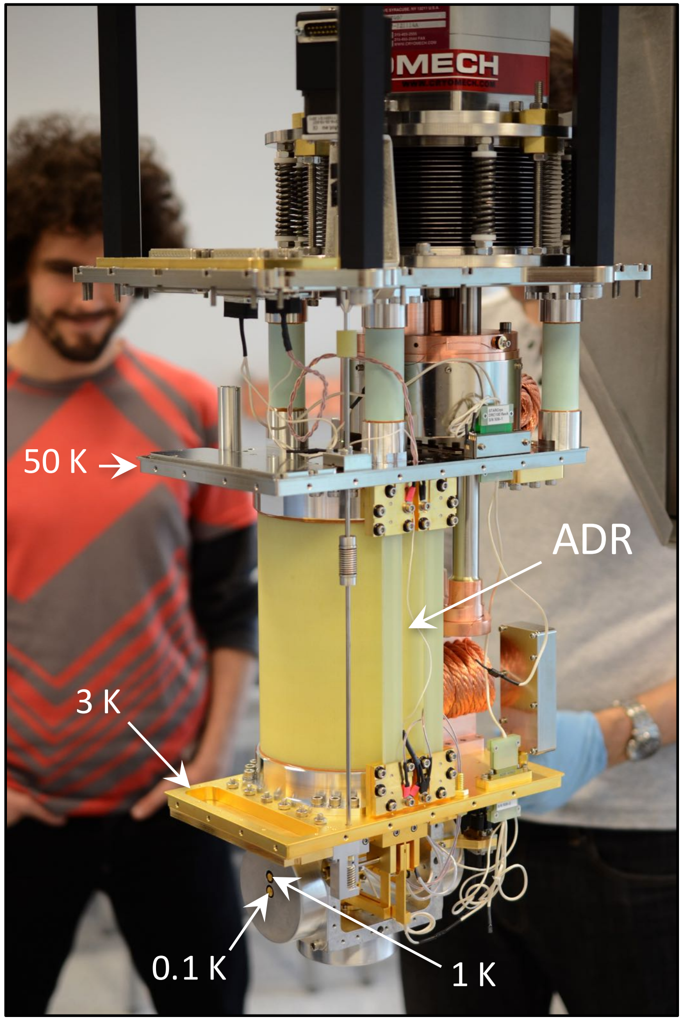
low-pass filter from
Peter Ade & Co.

STAR Cryo DRC-102 ADR Cryostat

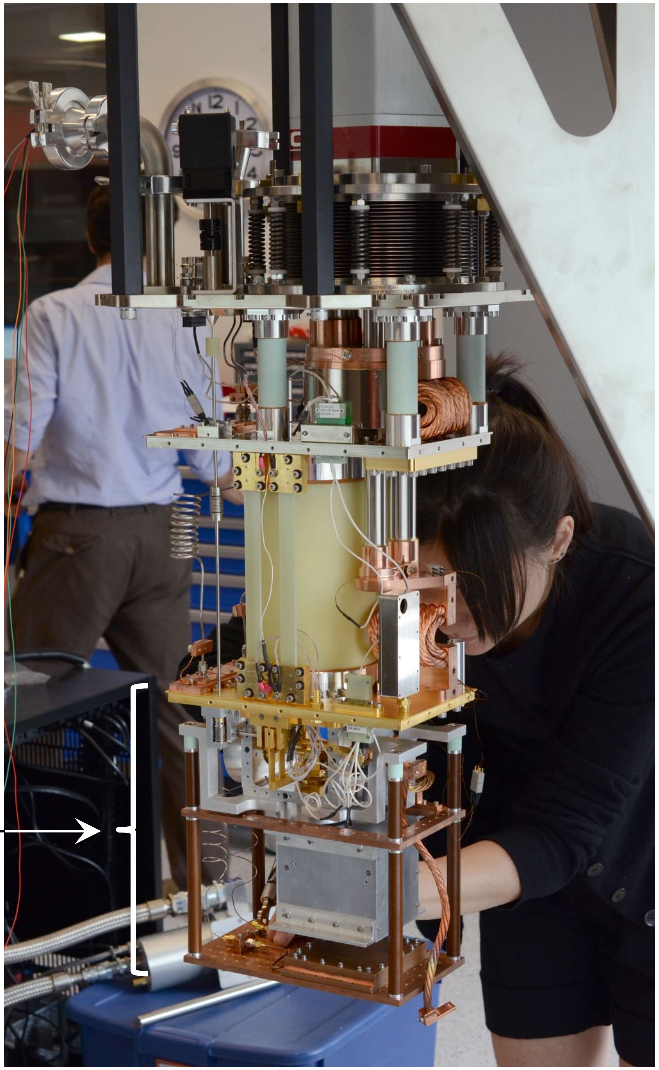
fully assembled



vacuum jacket, radiation shields off

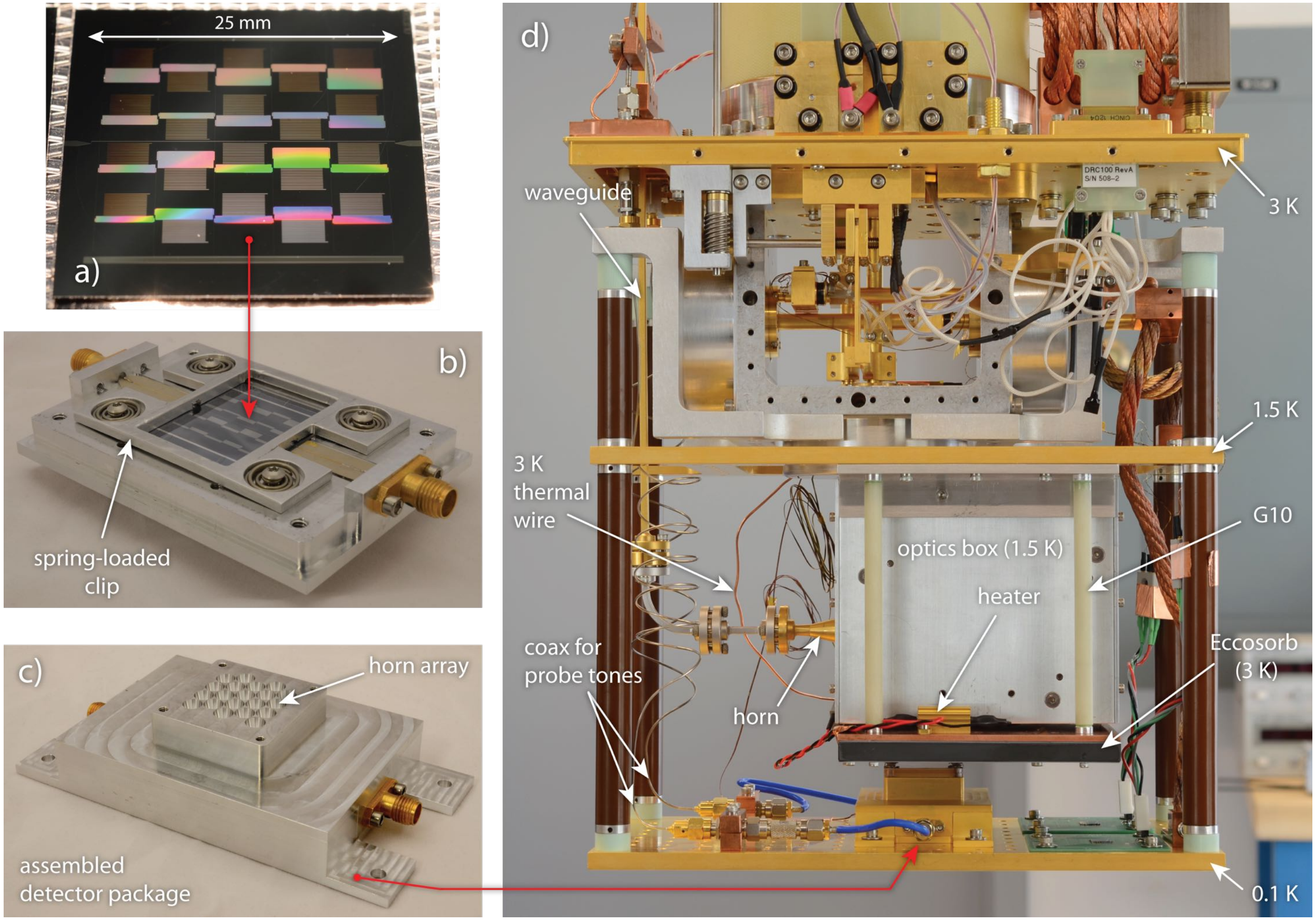


STAR Cryo DRC-102 ADR Cryostat

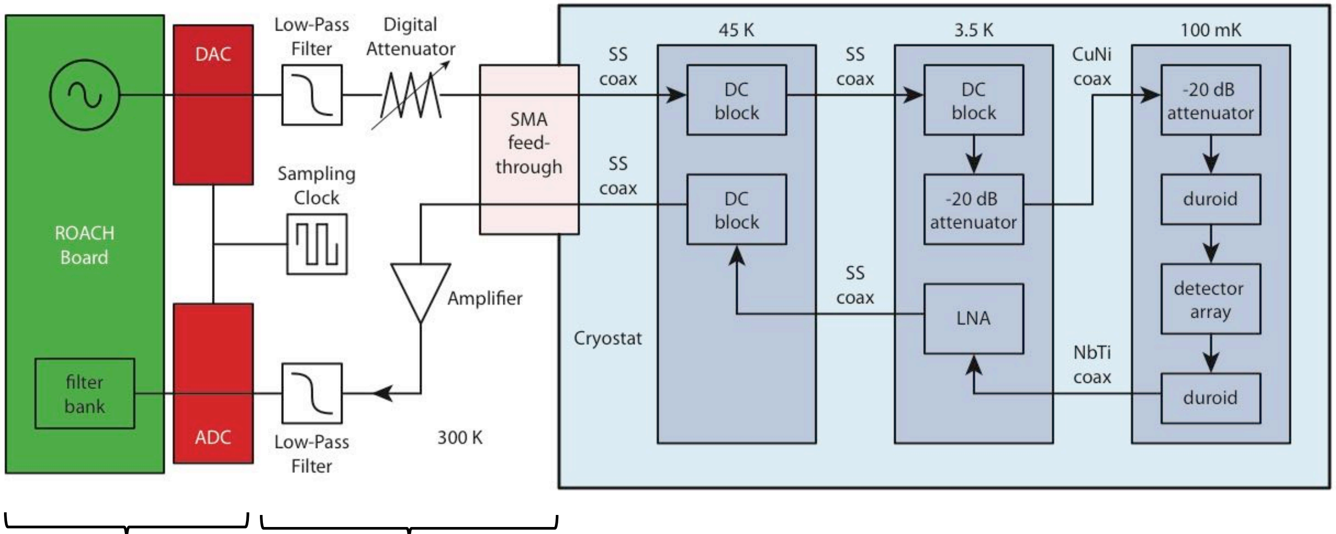


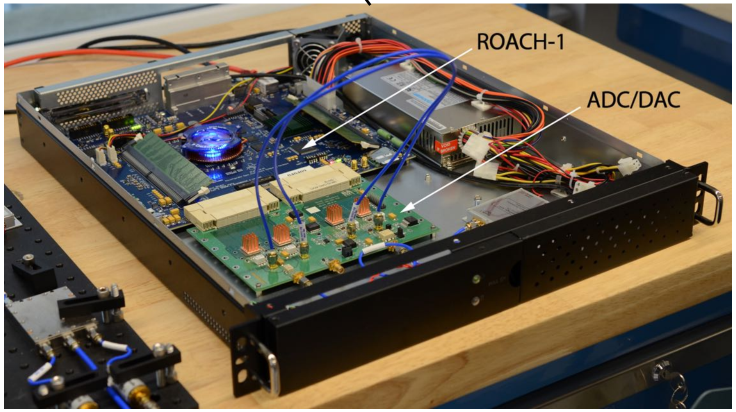
optical
test
setup

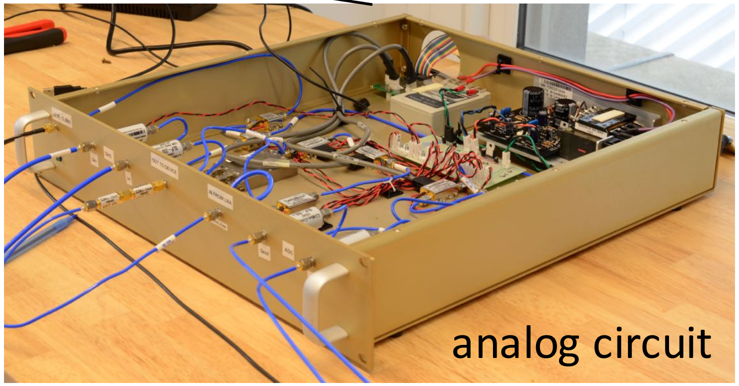
Optical Test Setup



Commercially Available Readout Hardware

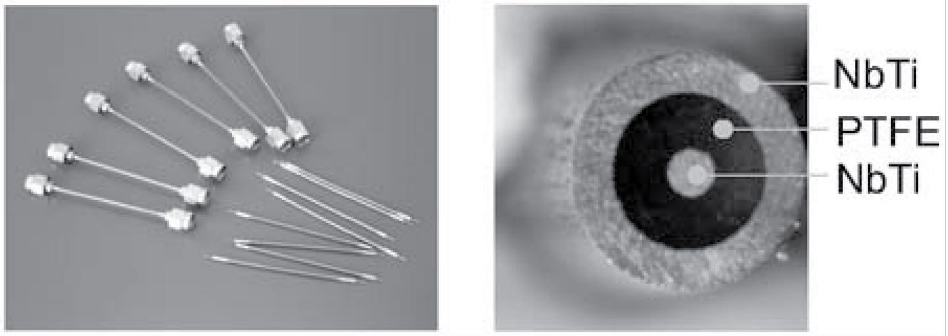


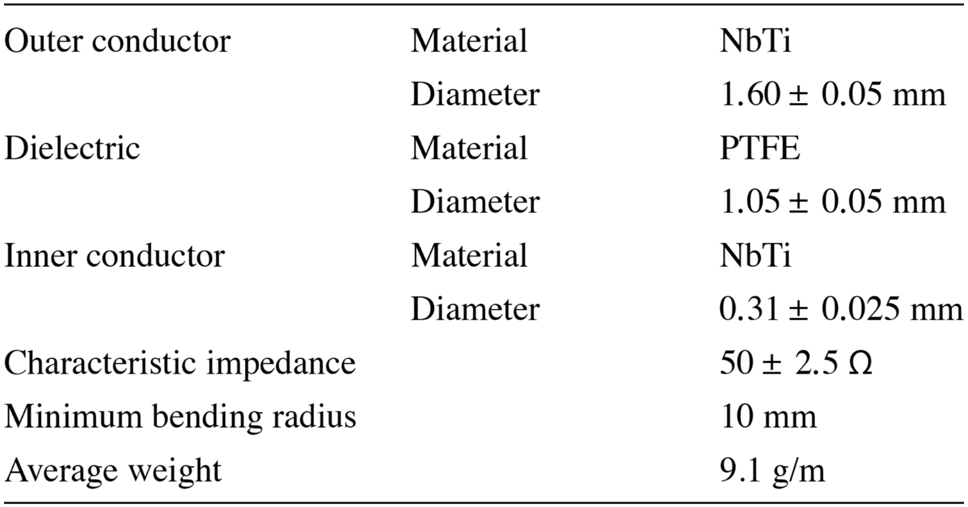




Readout Hardware: Cryogenic Coax

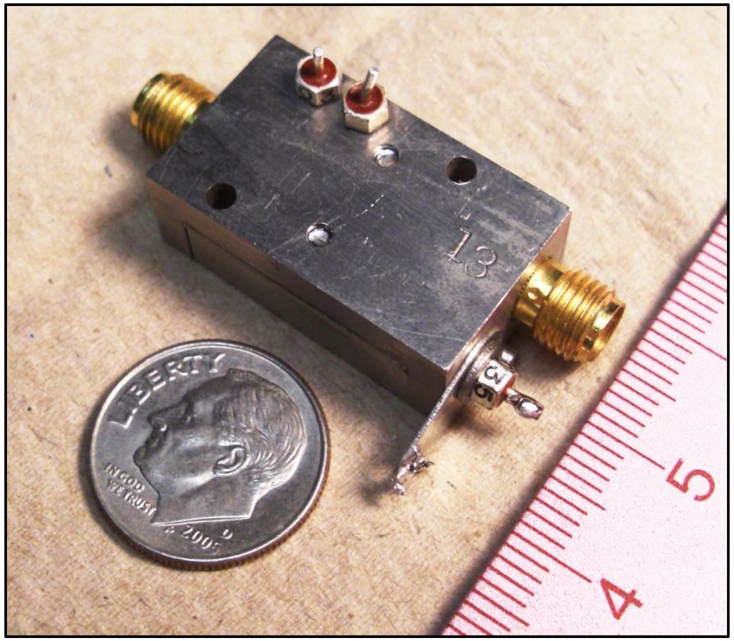
- Used for connections from 4 K to 0.1 K.
- Commercially available from Coax Co. in Japan. http://www.coax.co.jp/
- Cupronickel also works, and it is cheaper.
- Both coax technologies have been demonstrated at Columbia.

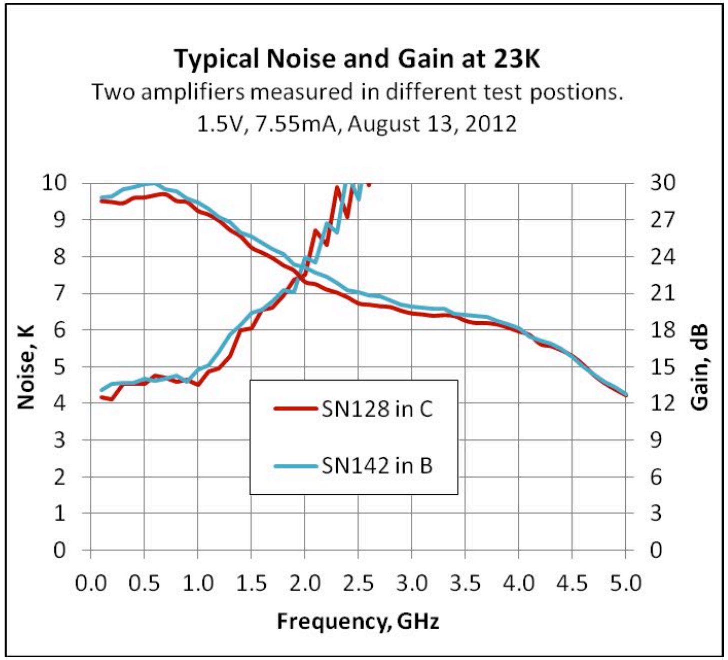




Outer conductor	Material	NbTi
	Diameter	1.60 ± 0.05 mm
Dielectric	Material	PTFE
	Diameter	1.05 ± 0.05 mm
Inner conductor	Material	NbTi
	Diameter	0.31 ± 0.025 mm
Characteristic impedance		50 ± 2.5 Ω
Minimum bending radius		10 mm
Average weight		9.1 g/m

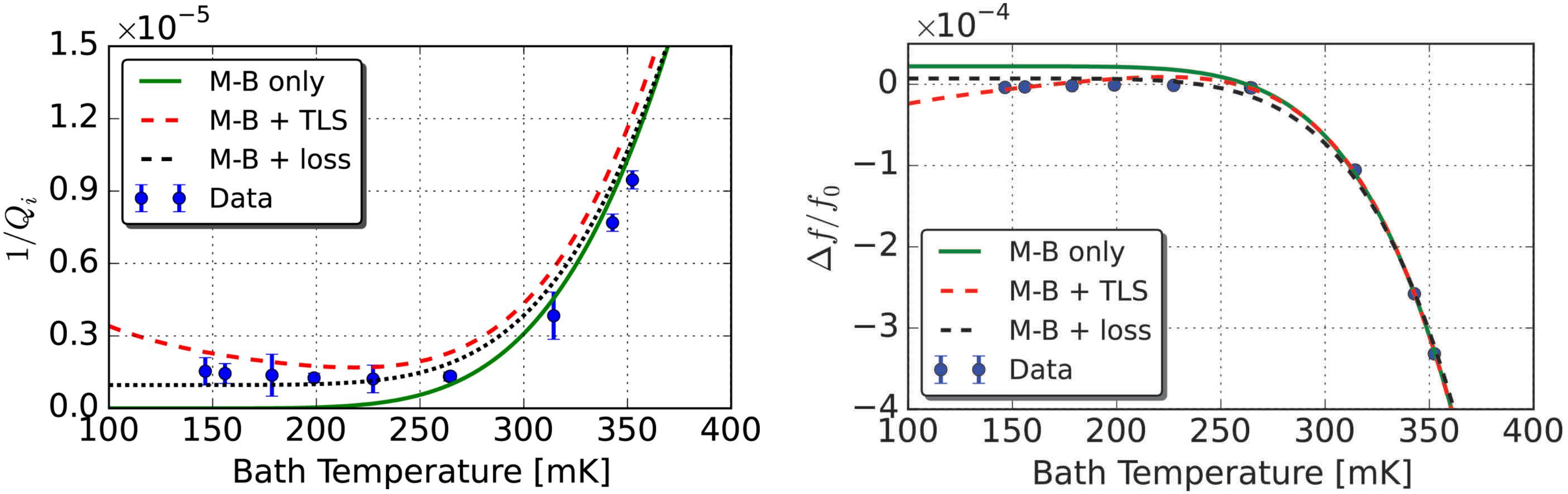
Cryogenic SiGe Low-Noise Amplifier





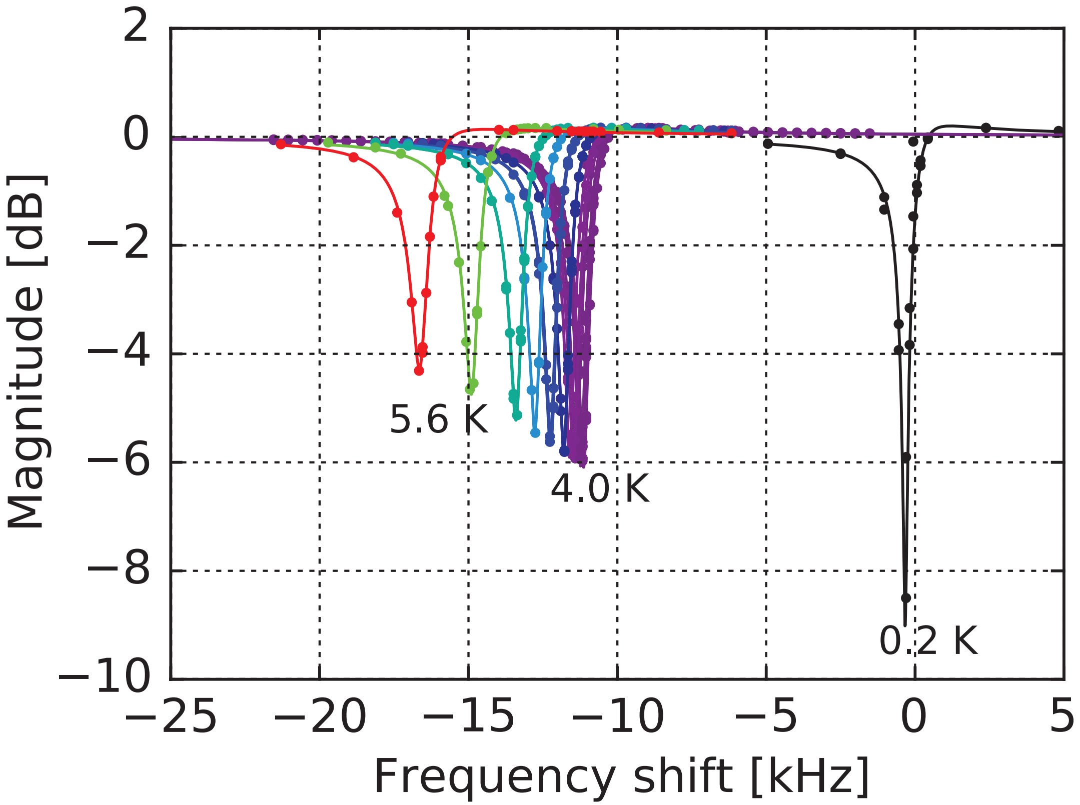
Parameter	@1.5V, 7.5mA Bias	@2.5V, 22mA Bias
Noise Temperature	< 5K	< 4K
Gain = -20 log|S21|	29 +/- 1.5 dB	34 +/- 2 dB
IRL = -20 log|S11|	> 10	> 10
ORL = -20log|S22|	> 15	> 13
Gain Compression, Output P1dB	-14 dBm	-4 dBm

Do the resonantors perform as expected?



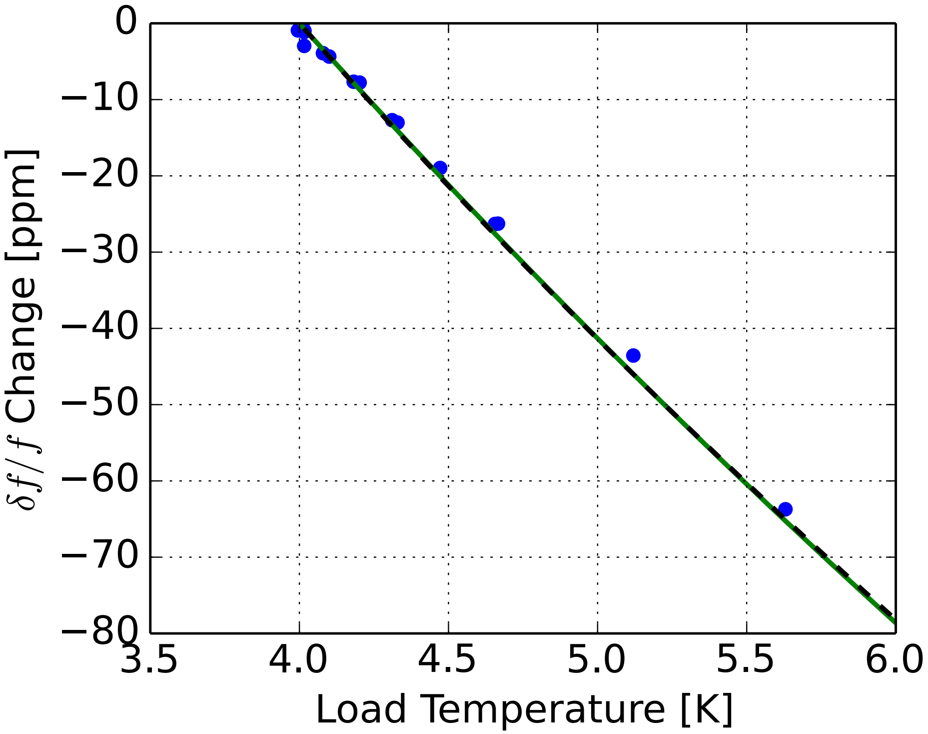
Bath temperature sweeps for a single resonator. The resonant frequency at 200 mK is 86.31195 MHz, and the probe power used was −111 dBm. The plot on the left shows the inverse internal quality factor, and the plot on the right shows measurements of the fractional frequency change. Joint fits to the data for three models are plotted: Mattis-Bardeen theory alone (solid green), M-B with temperature-dependent TLS loss (dashed red), and M-B with a fixed loss term (dotted black) .

Measured Resonances



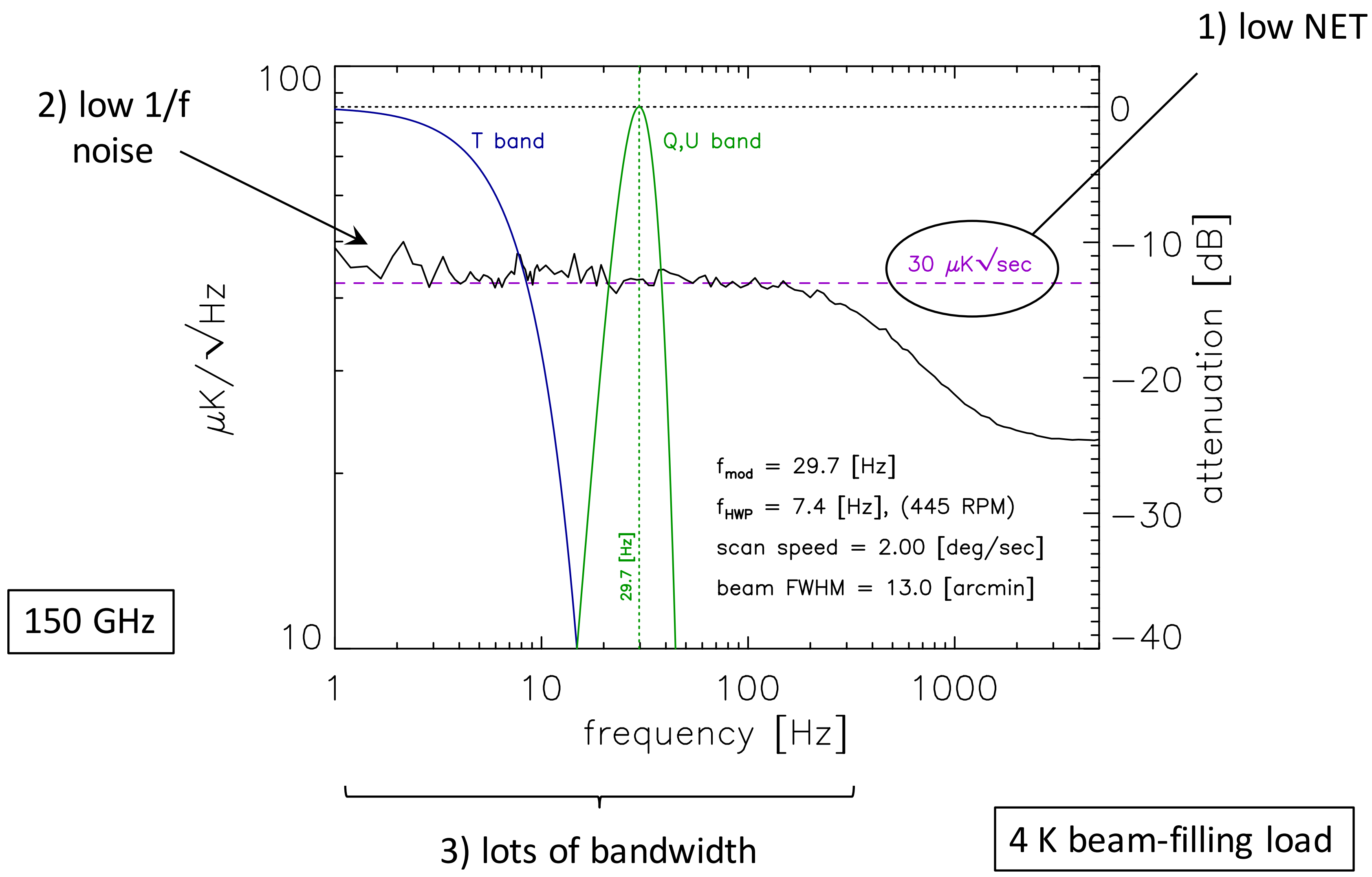
Resonance sweeps of a single resonator with changing optical load. The dots are measured points and the lines are fits. The resonant frequency at 200 mK is 86.31195 MHz. For these measurements the bath temperature was 200 mK. The measurement labeled 0.2 K was taken a the dark configuration.

Measured LEKID Responsivity

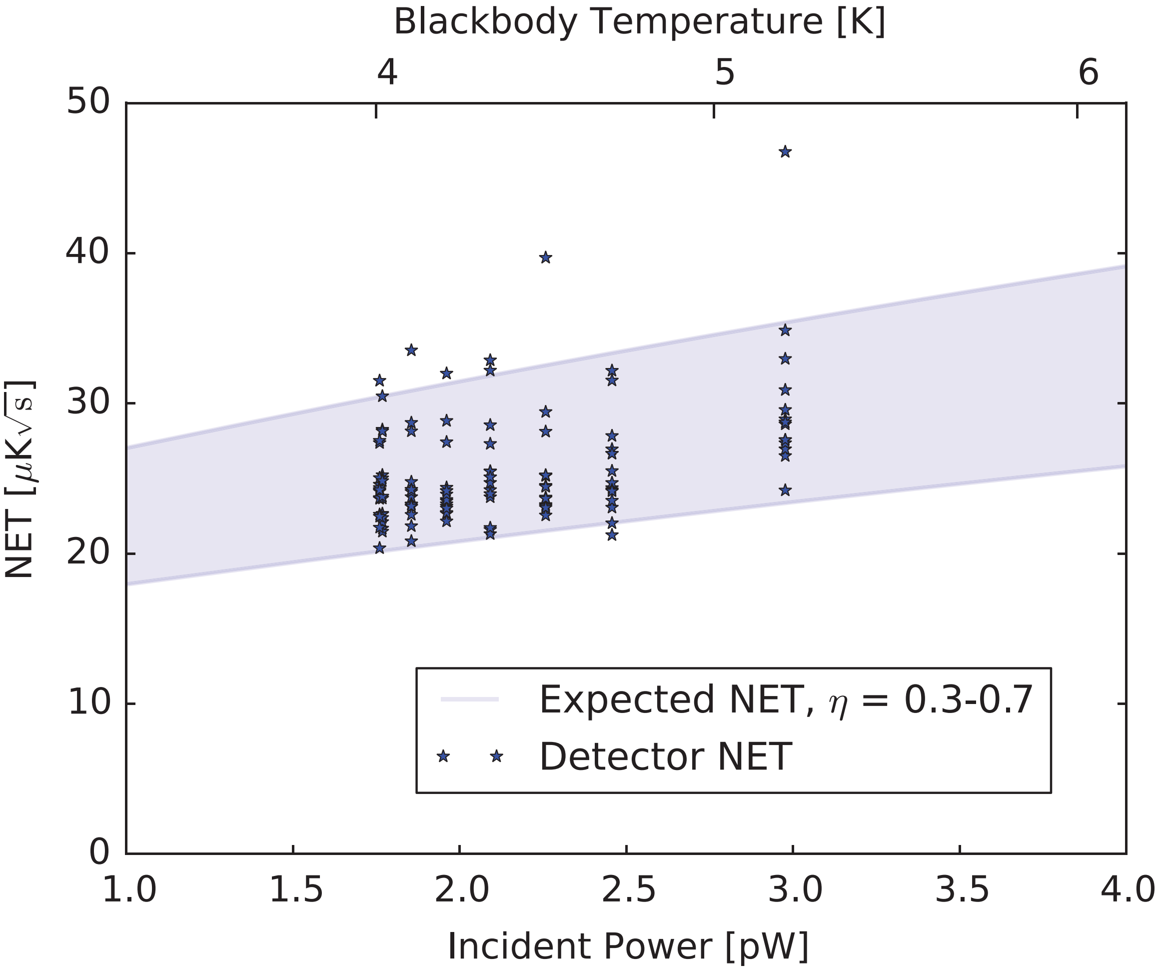


The measured frequency response has a slope of approximately **40 ppm/K**. This fractional responsivity is seen consistently across all resonators. The solid green line shows the expected response.

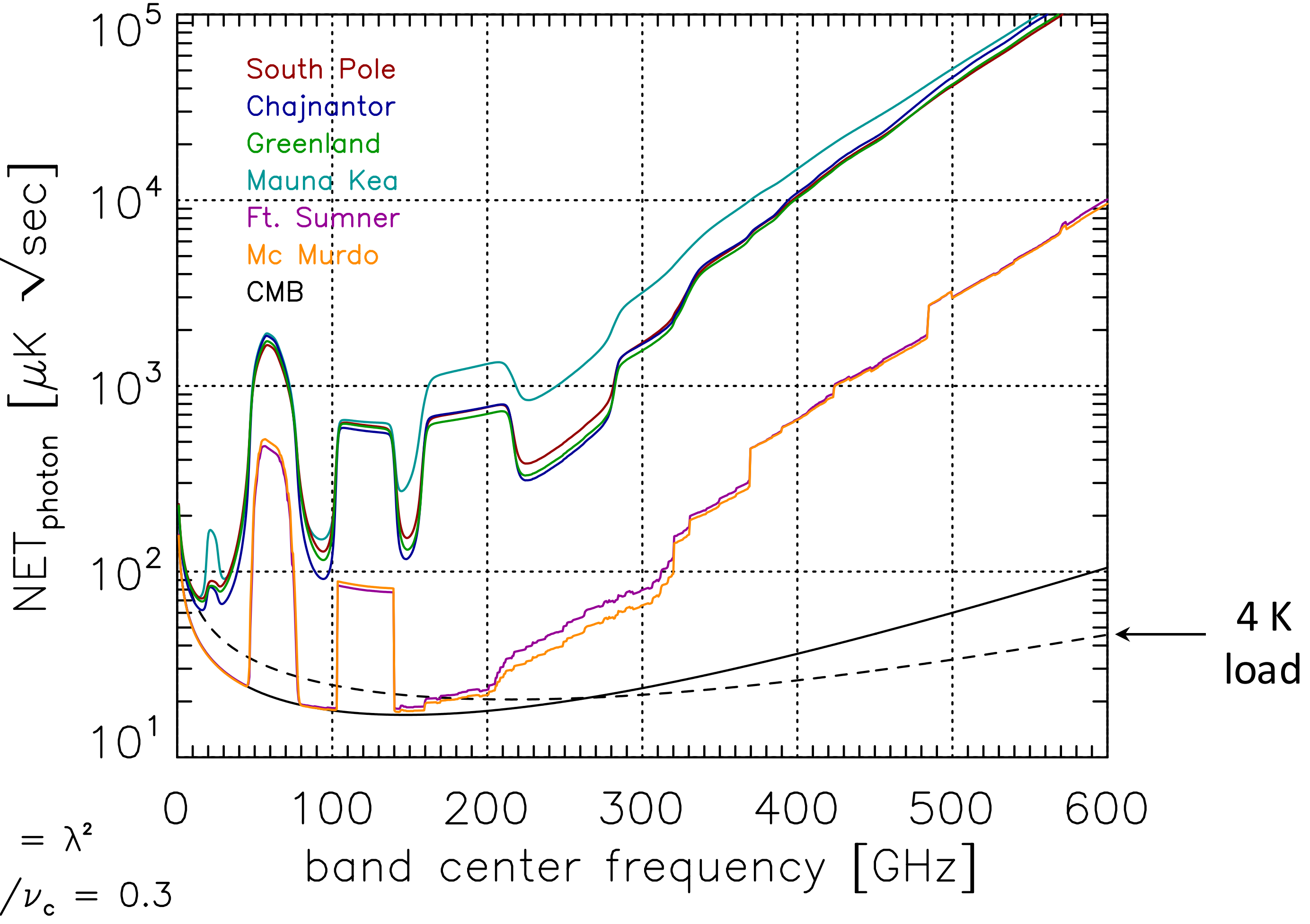
Result: ***Measured*** LEKID Noise

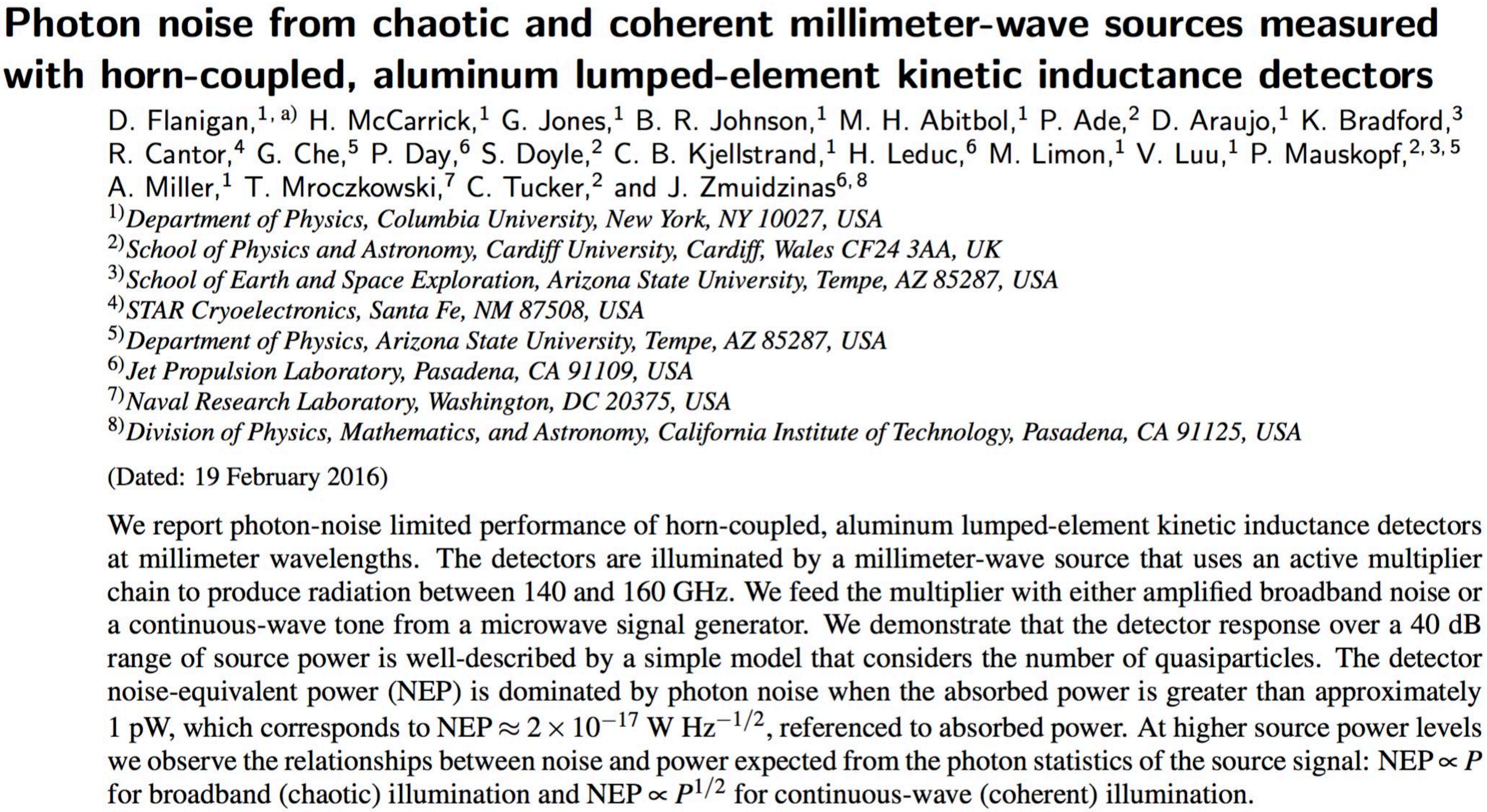


Measured Detector Noise



Interpreting the NET Result





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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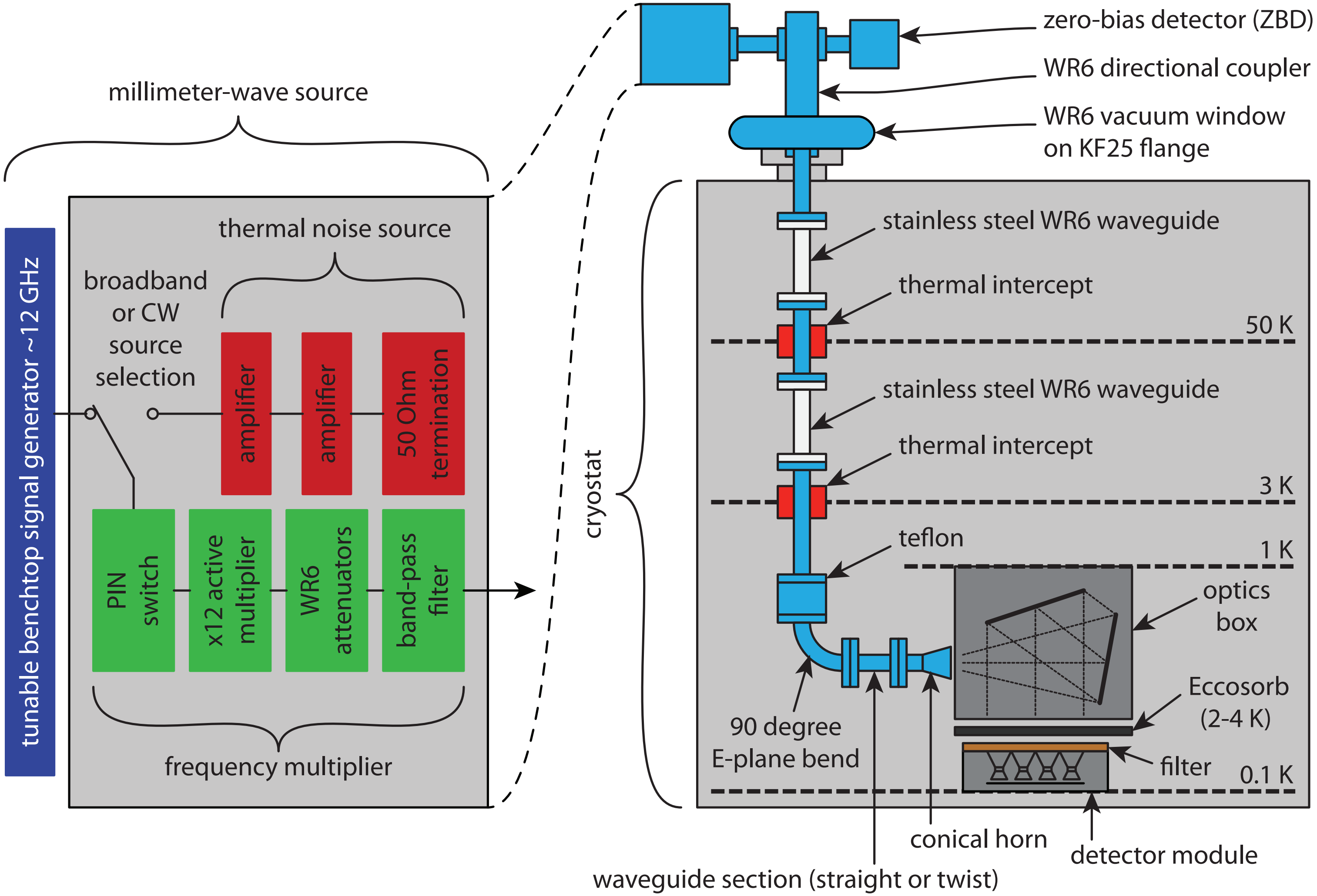
(Dated: 19 February 2016)

We report photon-noise limited performance of horn-coupled, aluminum lumped-element kinetic inductance detectors at millimeter wavelengths. The detectors are illuminated by a millimeter-wave source that uses an active multiplier chain to produce radiation between 140 and 160 GHz. We feed the multiplier with either amplified broadband noise or a continuous-wave tone from a microwave signal generator. We demonstrate that the detector response over a 40 dB range of source power is well-described by a simple model that considers the number of quasiparticles. The detector noise-equivalent power (NEP) is dominated by photon noise when the absorbed power is greater than approximately 1 pW, which corresponds to $\mathrm{NEP} \approx 2 \times 10^{-17}\ \mathrm{W\ Hz^{-1/2}}$, referenced to absorbed power. At higher source power levels we observe the relationships between noise and power expected from the photon statistics of the source signal: $\mathrm{NEP} \propto P$ for broadband (chaotic) illumination and $\mathrm{NEP} \propto P^{1/2}$ for continuous-wave (coherent) illumination.

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

Schematic of Experimental Setup



millimeter-wave source

tunable benchtop signal generator ~12 GHz

thermal noise source

broadband or CW source selection

amplifier

amplifier

50 Ohm termination

PIN switch

x12 active multiplier

WR6 attenuators

band-pass filter

frequency multiplier

cryostat

zero-bias detector (ZBD)

WR6 directional coupler

WR6 vacuum window on KF25 flange

stainless steel WR6 waveguide

thermal intercept

50 K

stainless steel WR6 waveguide

thermal intercept

3 K

teflon

1 K

optics box

Eccosorb (2-4 K)

filter

0.1 K

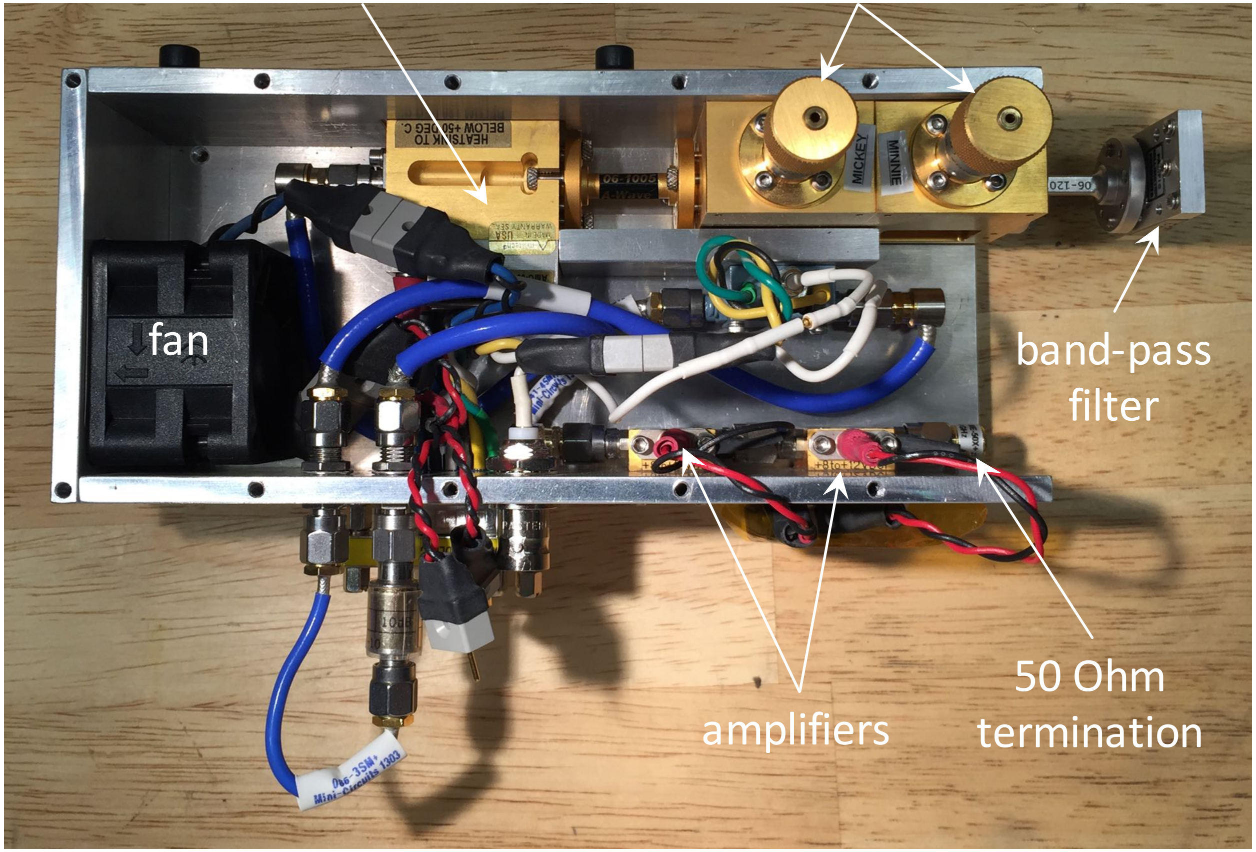
90 degree E-plane bend

conical horn

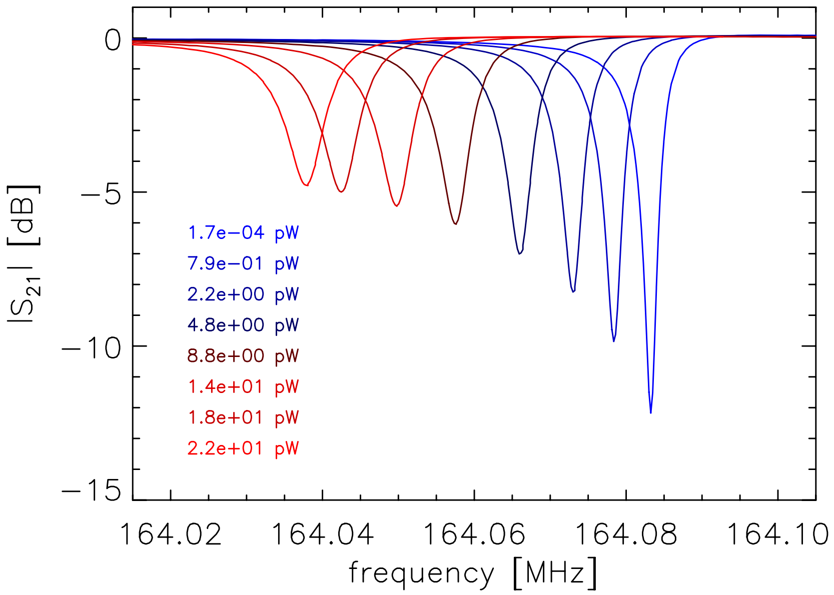
detector module

waveguide section (straight or twist)

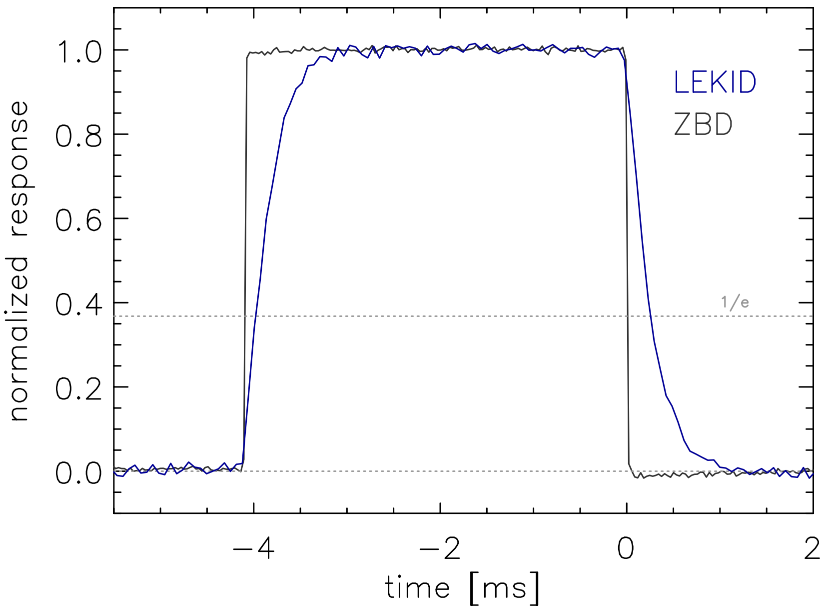
Millimeter-Wave Source



Other LEKID Measurements

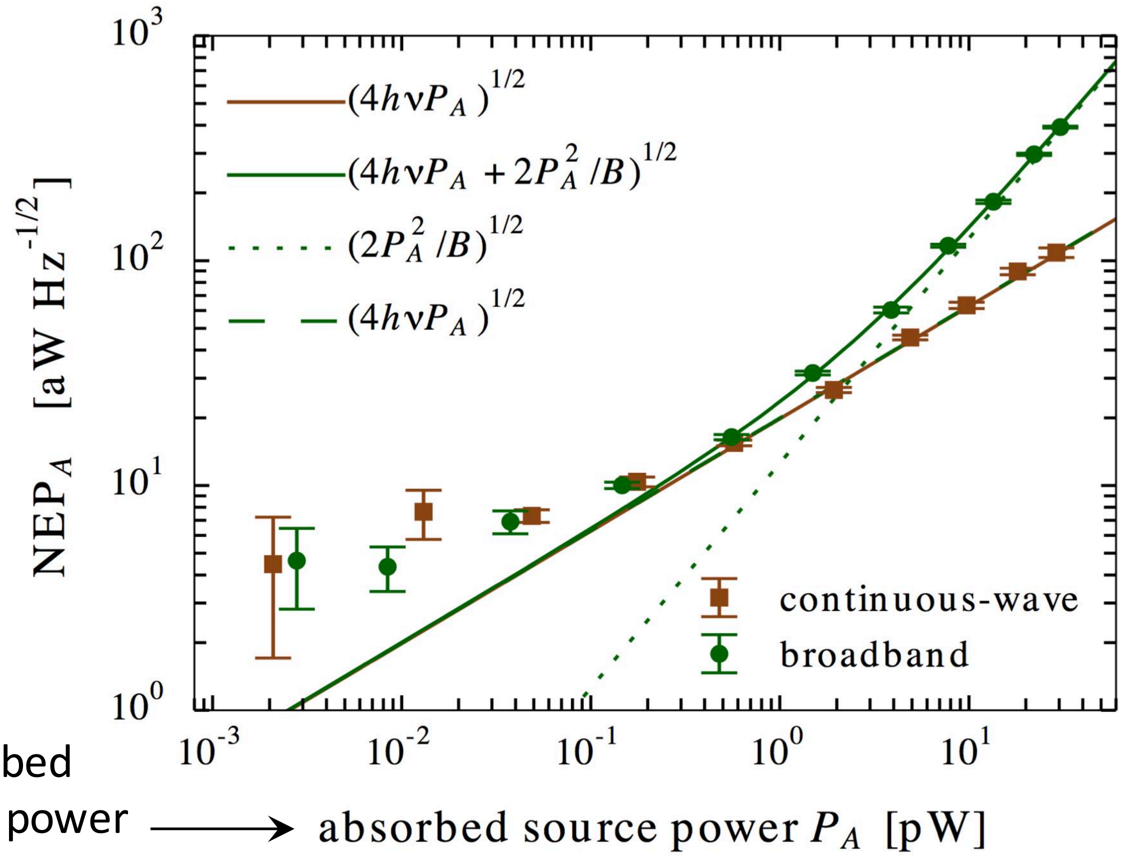


Measured S_{21} scattering parameter as a function of probe tone frequency for various millimeter-wave loadings. This plot shows that the LEKIDs work as expected. **As the millimeter-wave loading changes, the resonant frequency of the device changes**. The range of loading power used in this test spans 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**.

Measured Photon Noise

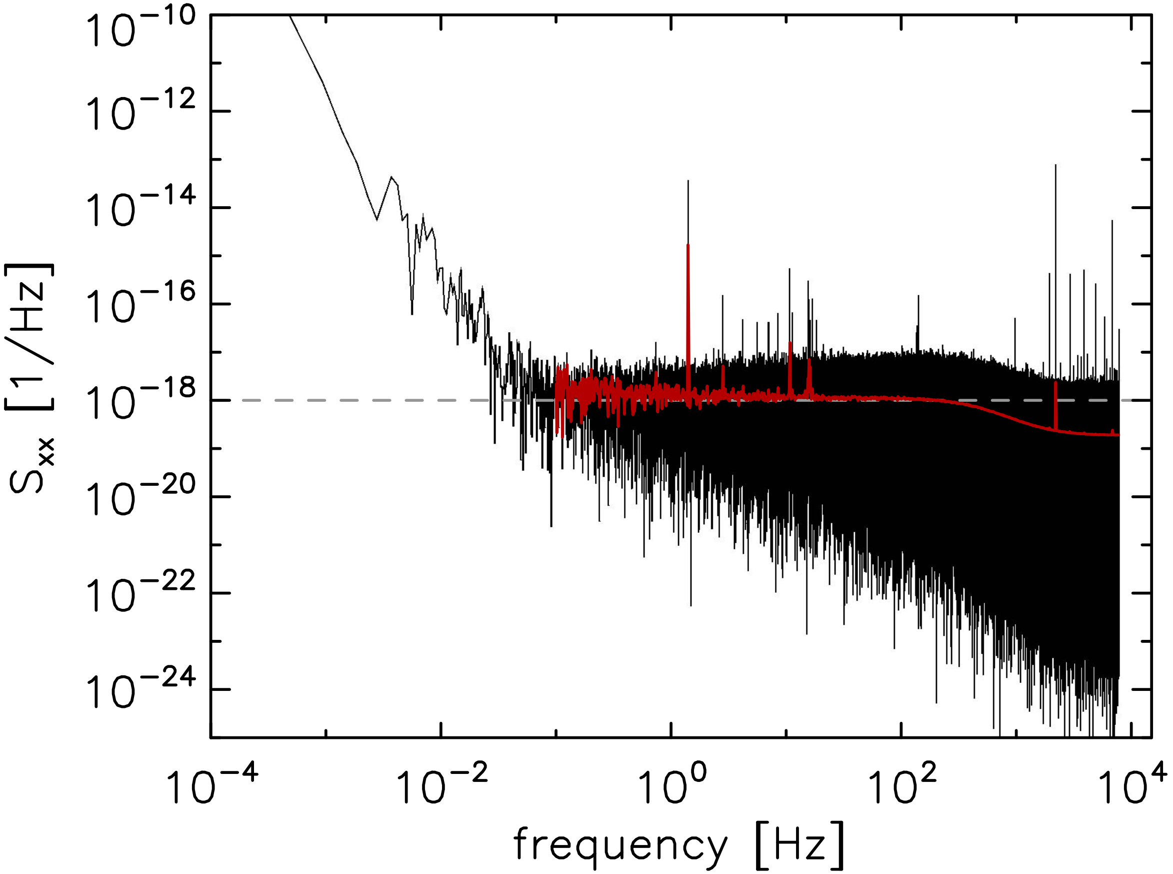


detecting
photon noise
and able to
differentiate
between
shot and wave
noise above
~1 pW

absorbed
incident power
from our source →

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

Low-Frequency Noise Properties



3) Dual-Polarization LEKIDs

P. Ade, S. Bryan, G. Che, P. Day, S. Doyle, D. Flanigan, B. R. Johnson,
G. Jones, P. Mauskopf, H. McCarrick, A. Miller, C. Tucker, J. Zmuidzinas

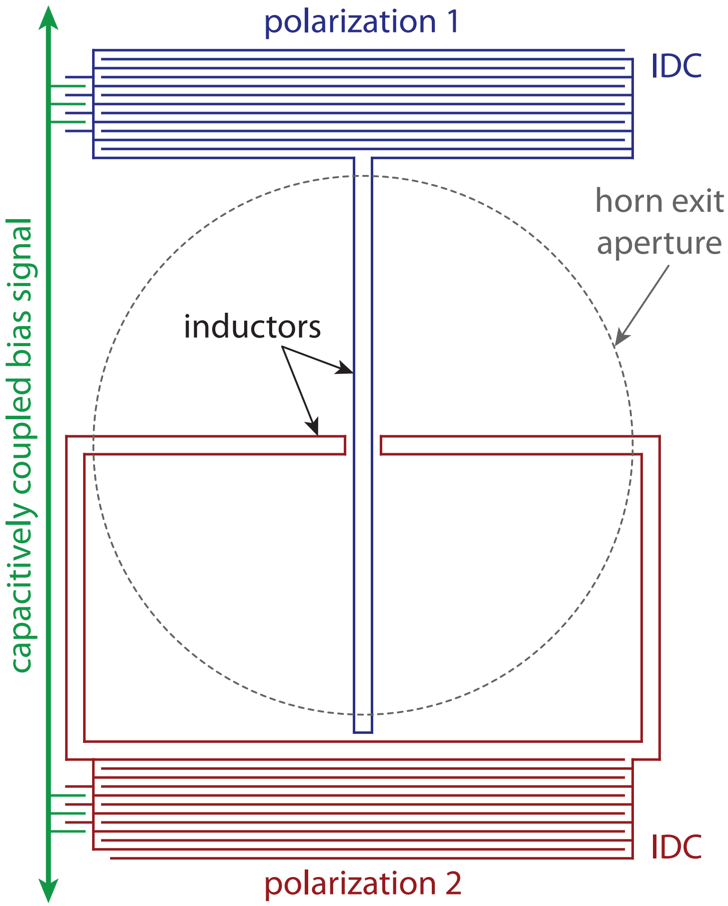
References:

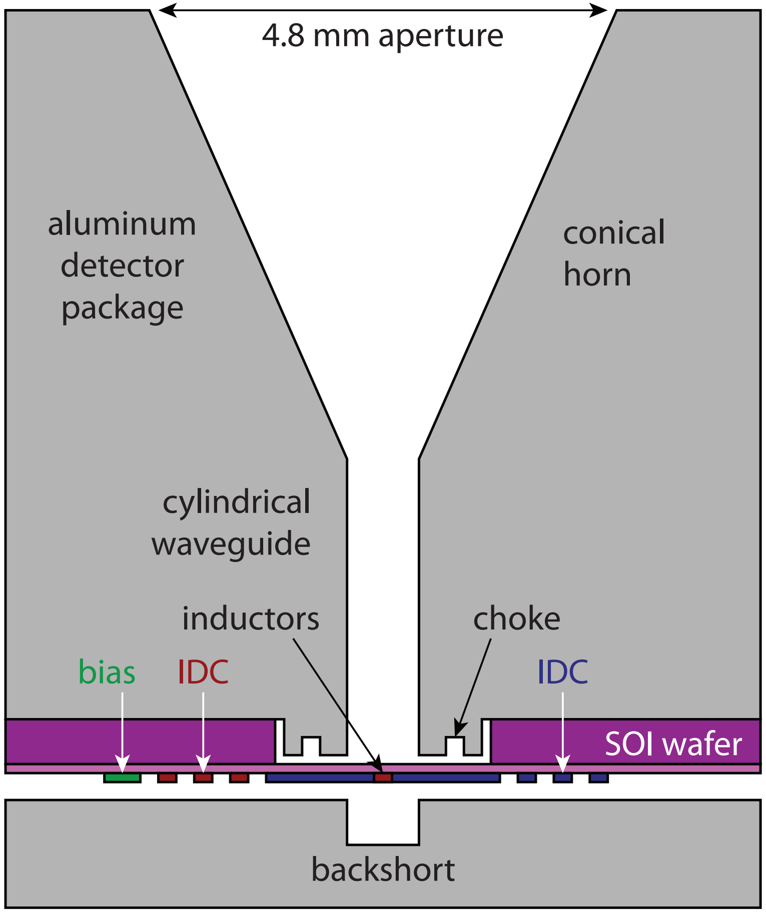
Bryan et al. (2015) *ISSTT Proceedings*, arXiv:1503.04684.

Galitzki, N., et al. (2014) *Journal of Astronomical Instrumentation*, Vol. 3, No. 2, 1440001.

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

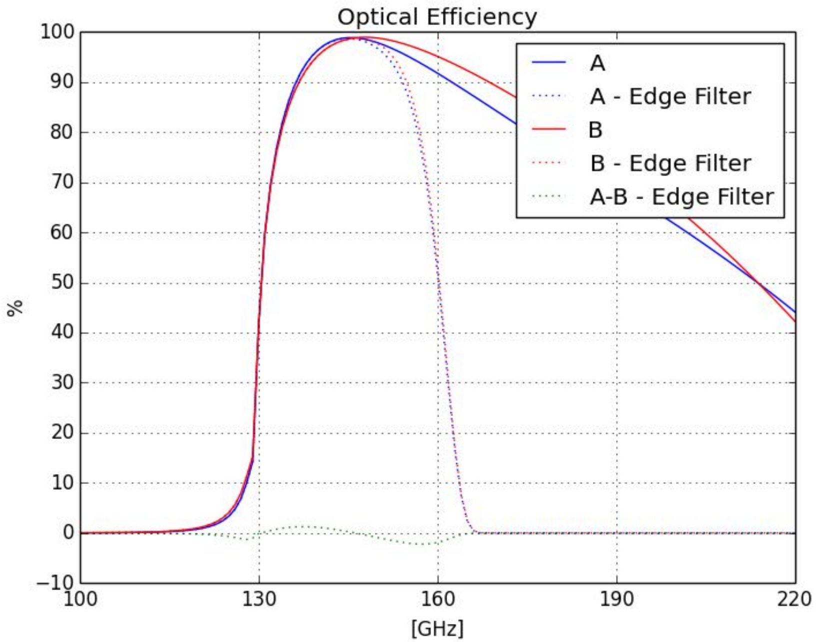
Dual-Polarization Pixel Design

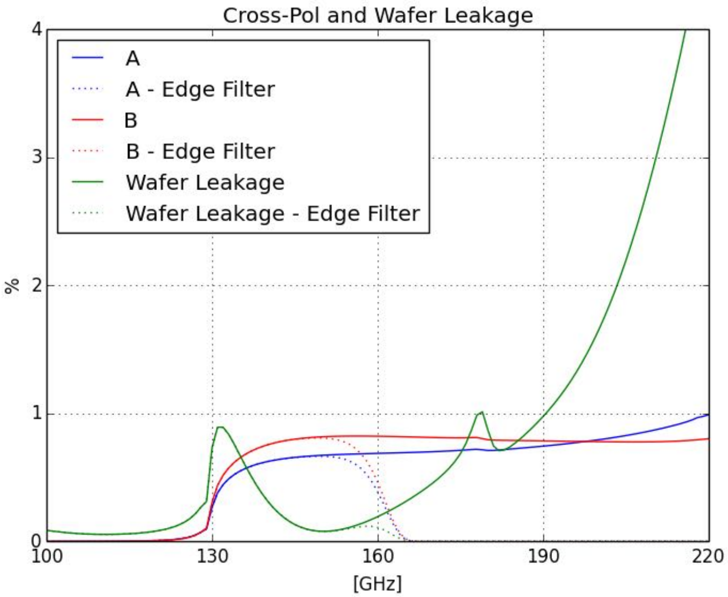




Dual-Polarization Pixel Design

HFSS Simulations



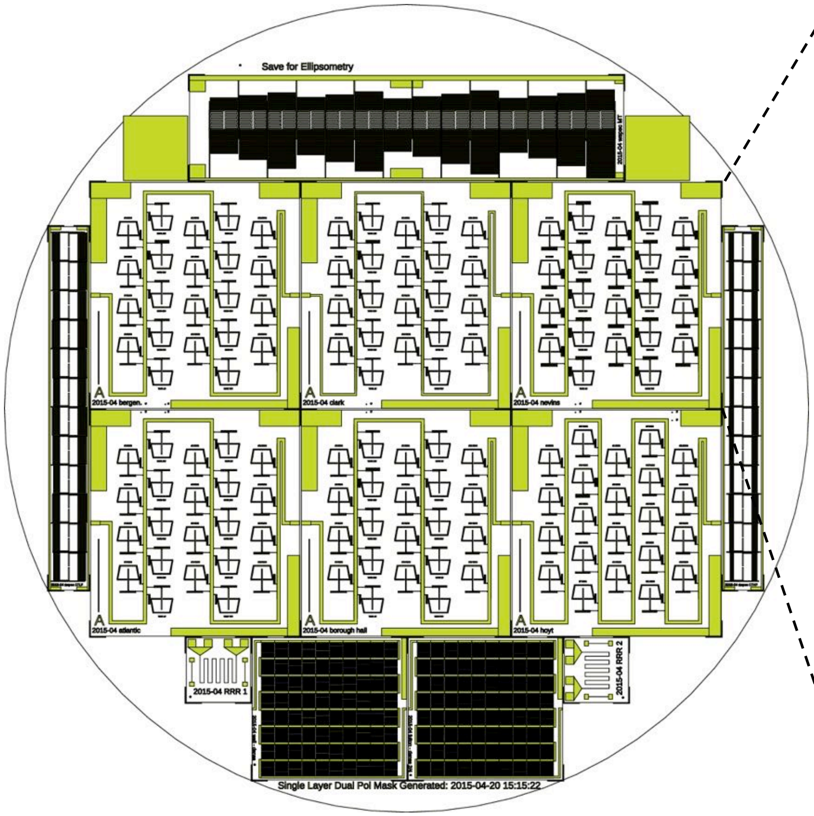


The two polarizations are matched to within ~2%

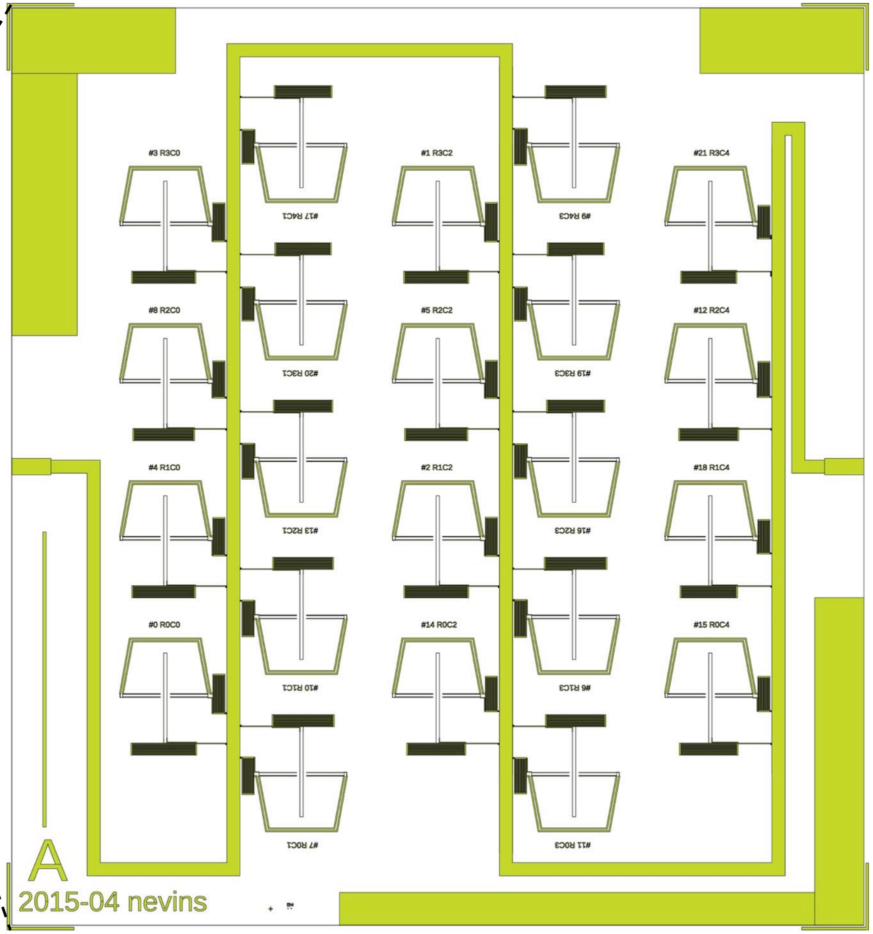
Cross-pol and leakage below 1 %

Bryan et al. (2015) *ISSTT Proceedings*, arXiv:1503.04684.

Dual-Polarization Pixel Status

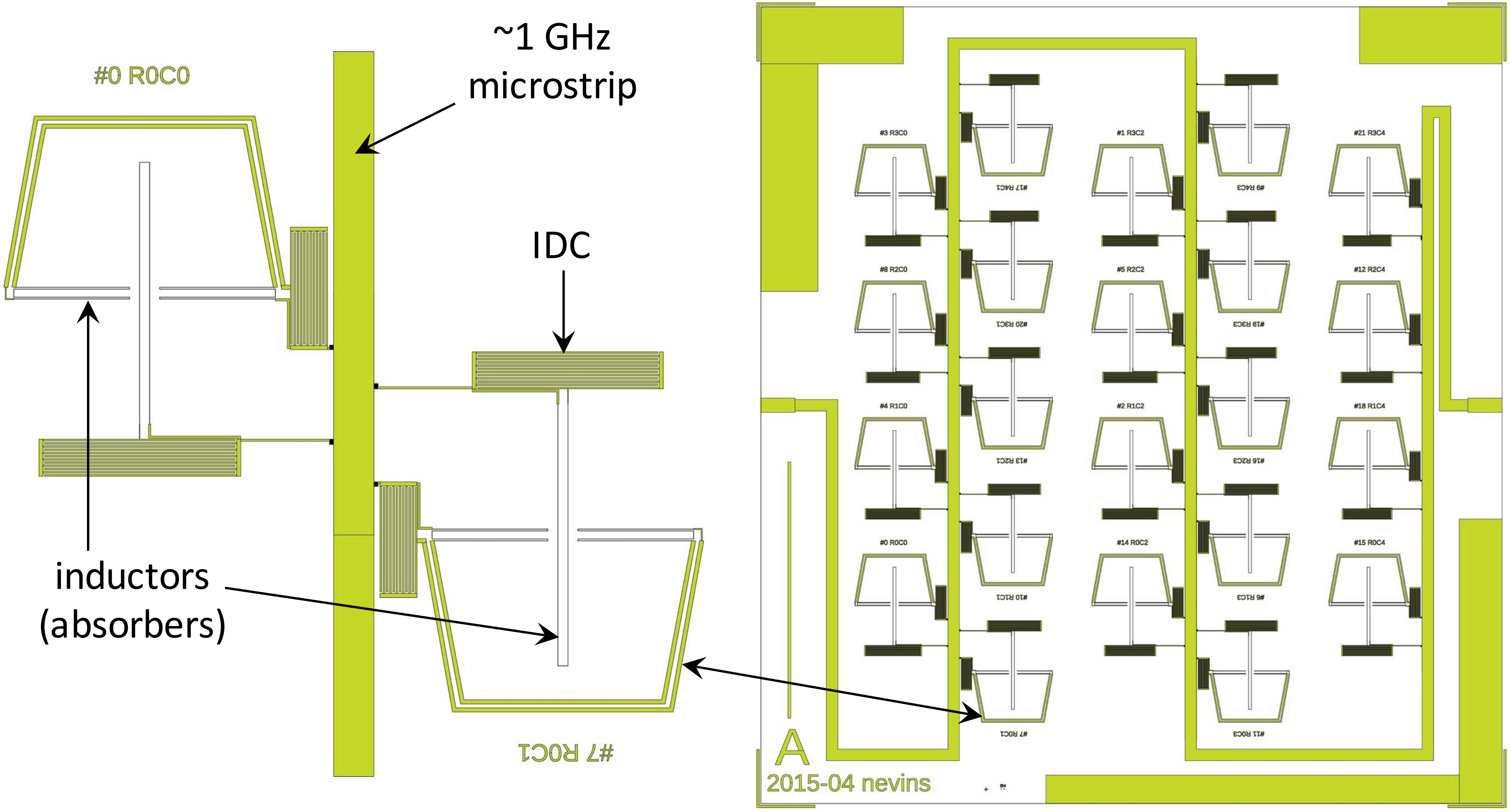


prototype array wafer layout



one 20-element prototype array

Dual-Polarization Pixel Status



~1 GHz microstrip

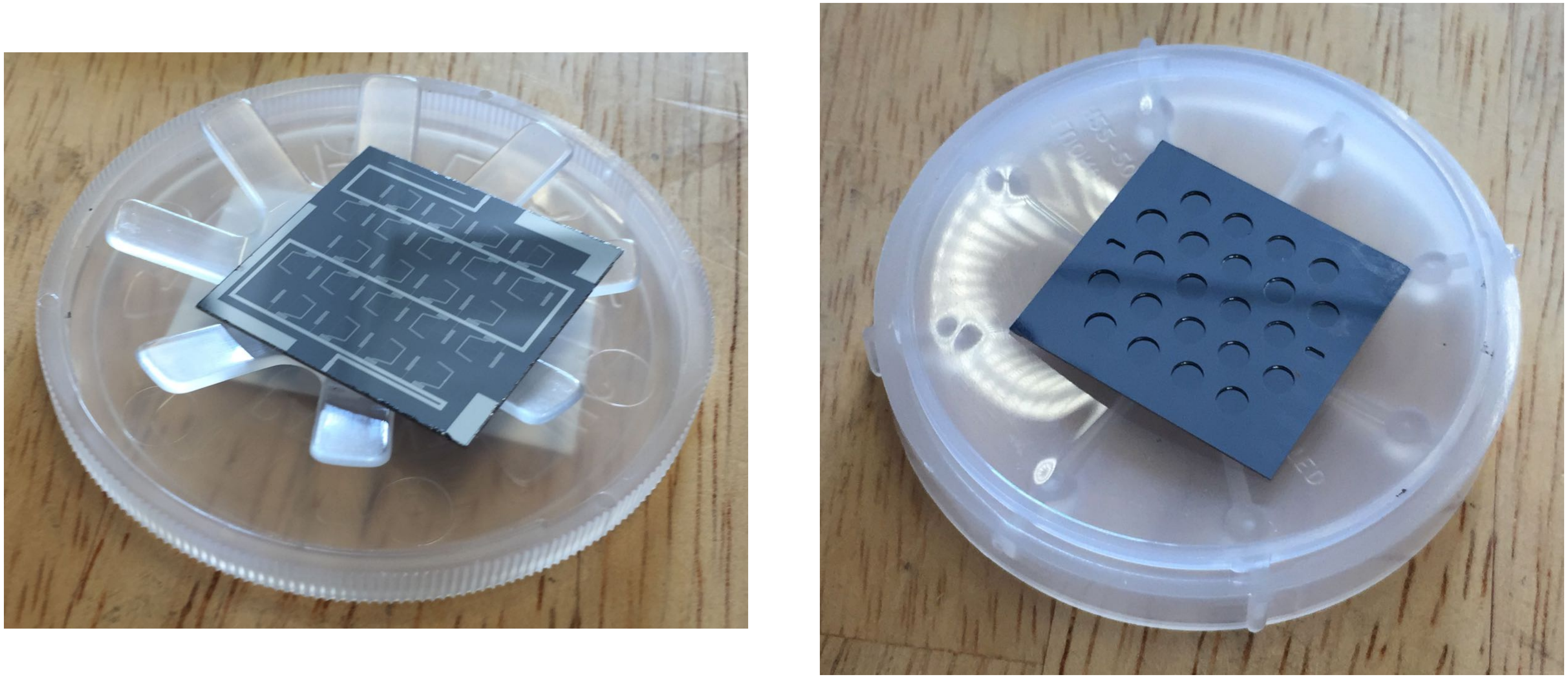
IDC

inductors (absorbers)

two representative detector pairs

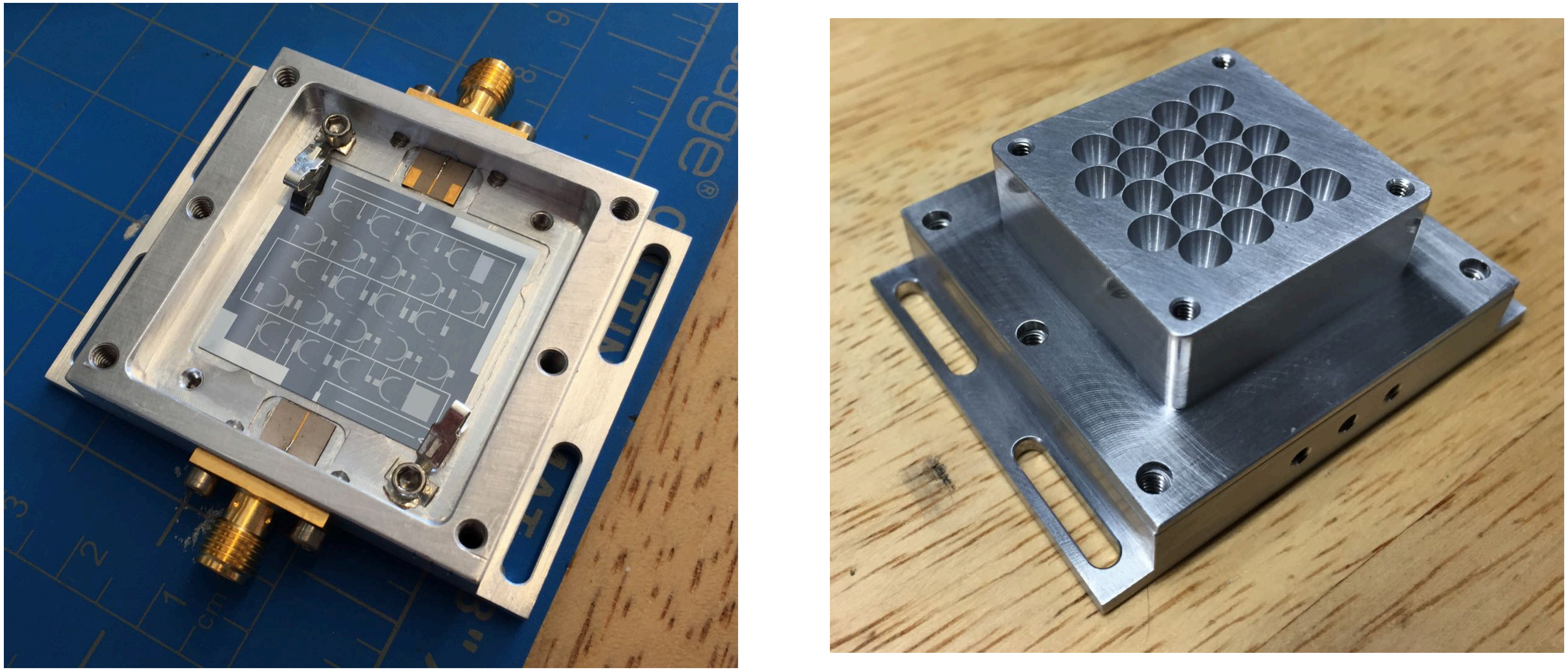
one 20-element prototype array

Dual-Polarization LEKIDs



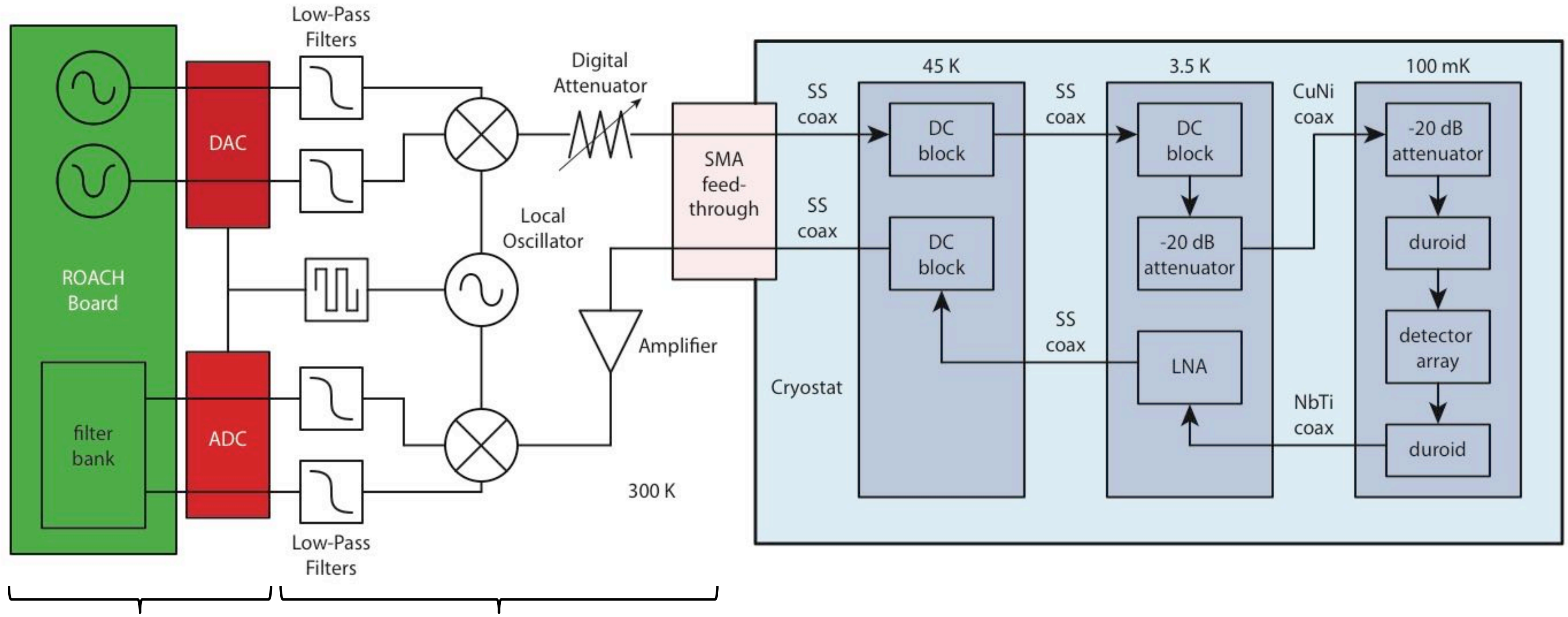
devices fabricated at NASA/JPL

Dual-Polarization LEKIDs



devices fabricated at NASA/JPL

Readout Hardware: Schematic



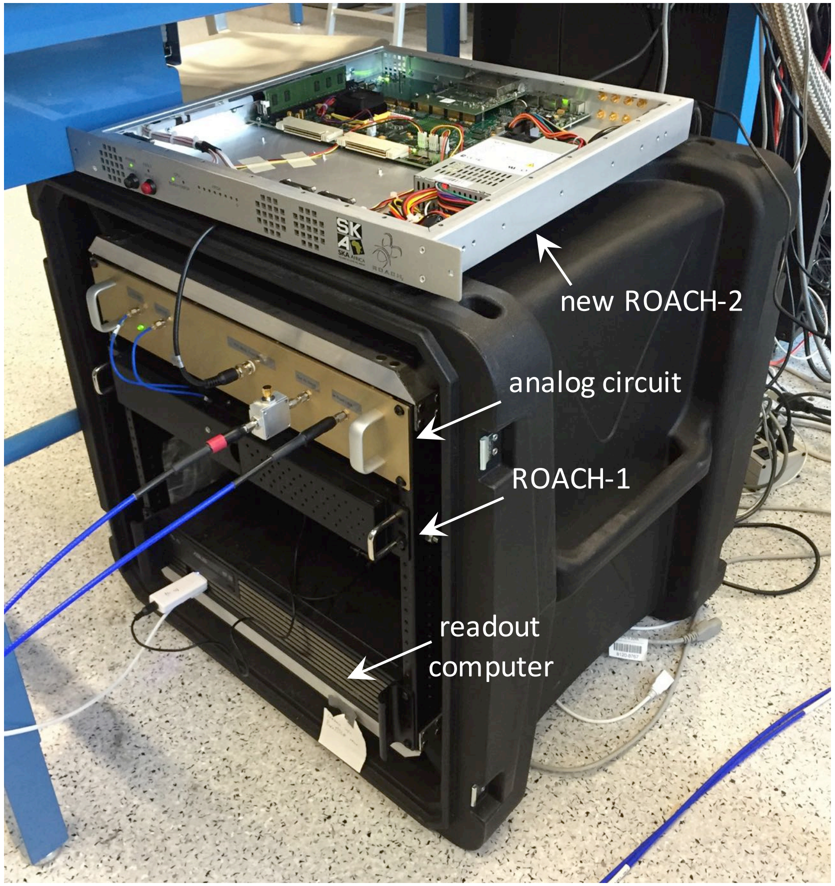
ROACH and ADC/DAC

analog circuit

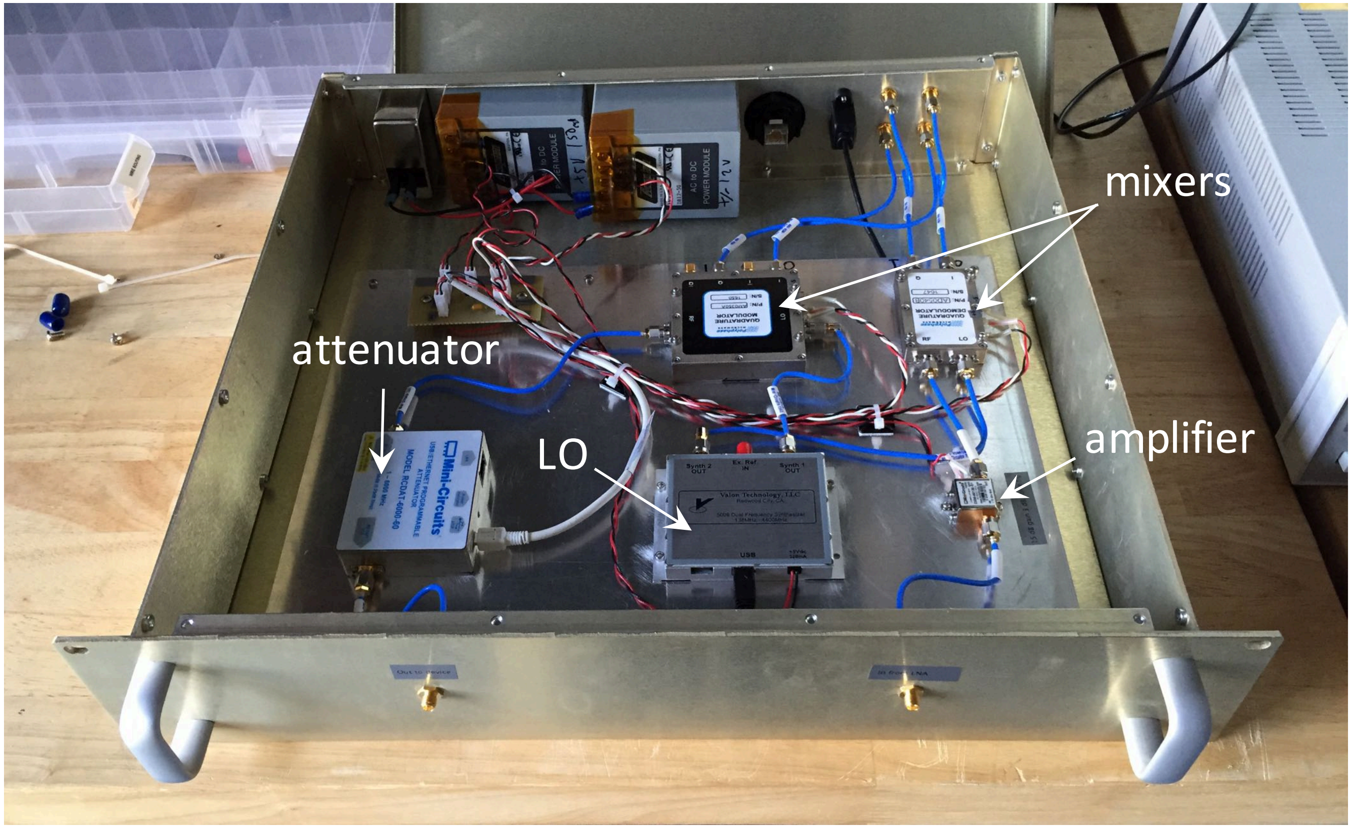
Note: This design requires a vacuum feedthrough with just two SMA connectors and two pins for LNA bias.

Readout Development Work

- ROACH 1 readout and data reduction software working in the lab, currently optimized for detector testing, rather than observations.
- Currently working on upgrading to ROACH 2, which will offer improved performance for large numbers of resonators.
- Need to develop and adapt software from lab measurements to observations on the sky.

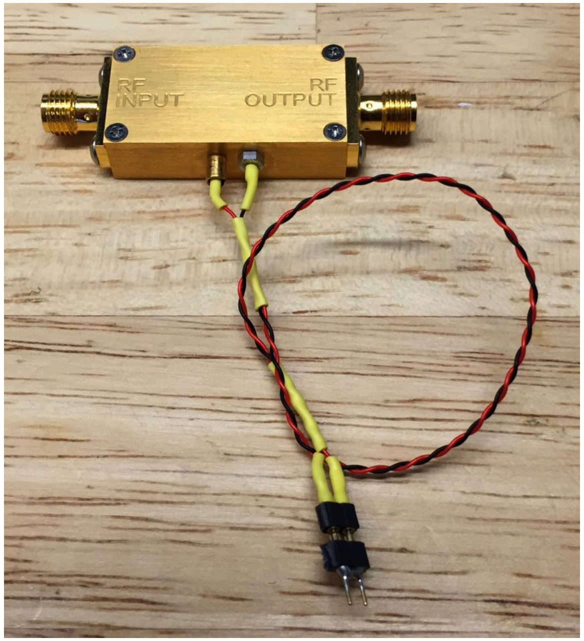


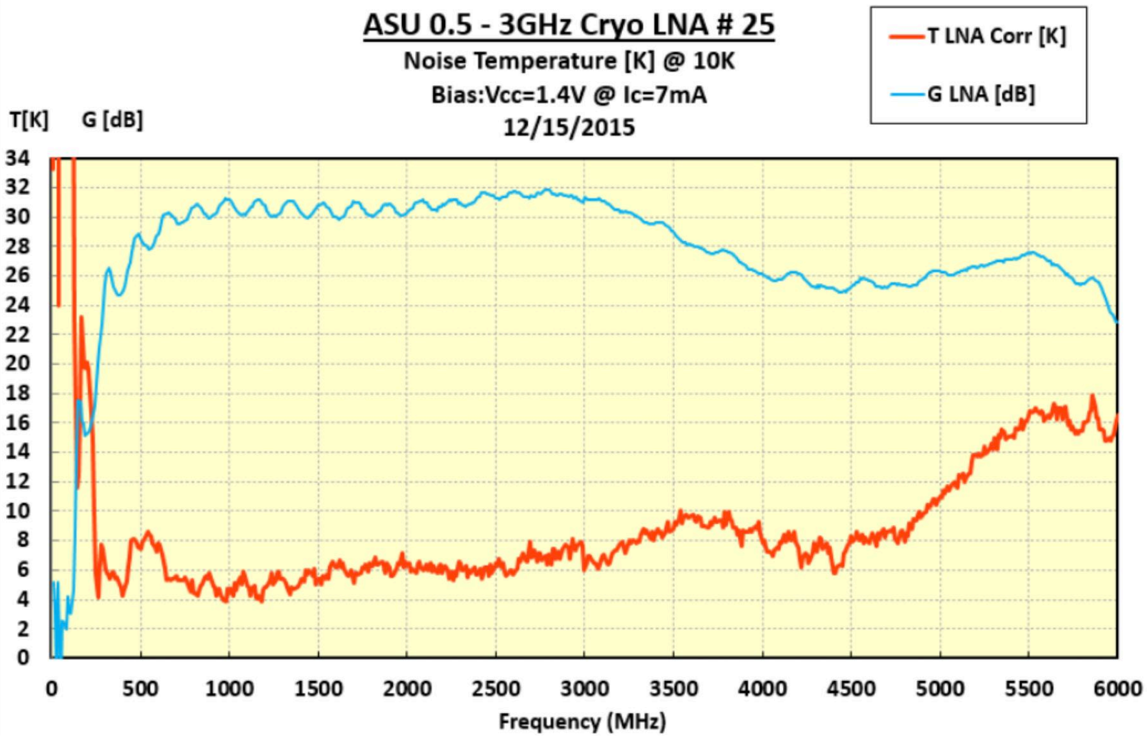
Readout Development Work



Readout Development Work

SiGe LNA from ASU





more bandwidth allows higher frequency resonators

4) Multi-Chroic MKIDs

P. Ade, S. Bryan, G. Che, S. Cho, R. Datta, P. Day,
S. Doyle, D. Flanigan, K. Irwin, **B. R. Johnson (PI)**,
G. Jones, S. Kernasovskiy, D. Li, P. Mauskopf, H. McCarrick,
J. McMahon, A. Miller, G. Pisano, H. Surdi, C. Tucker

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

Our Work Based on ACT-Pol Devices

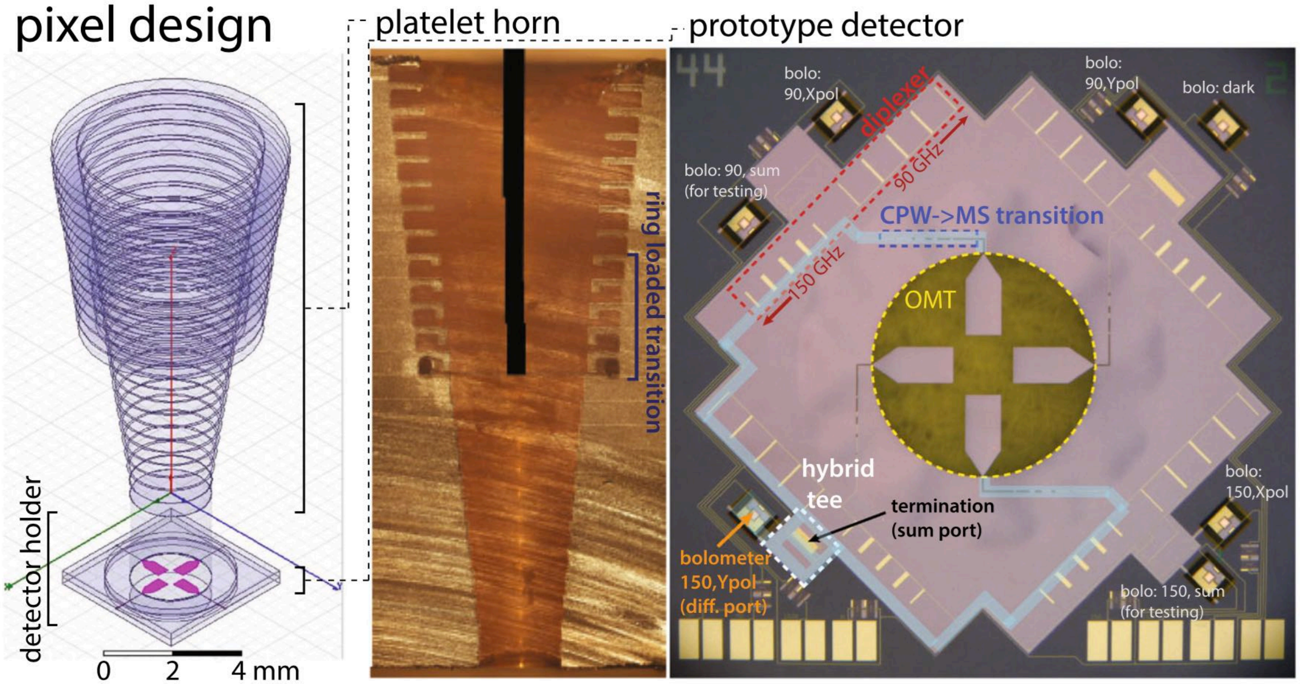
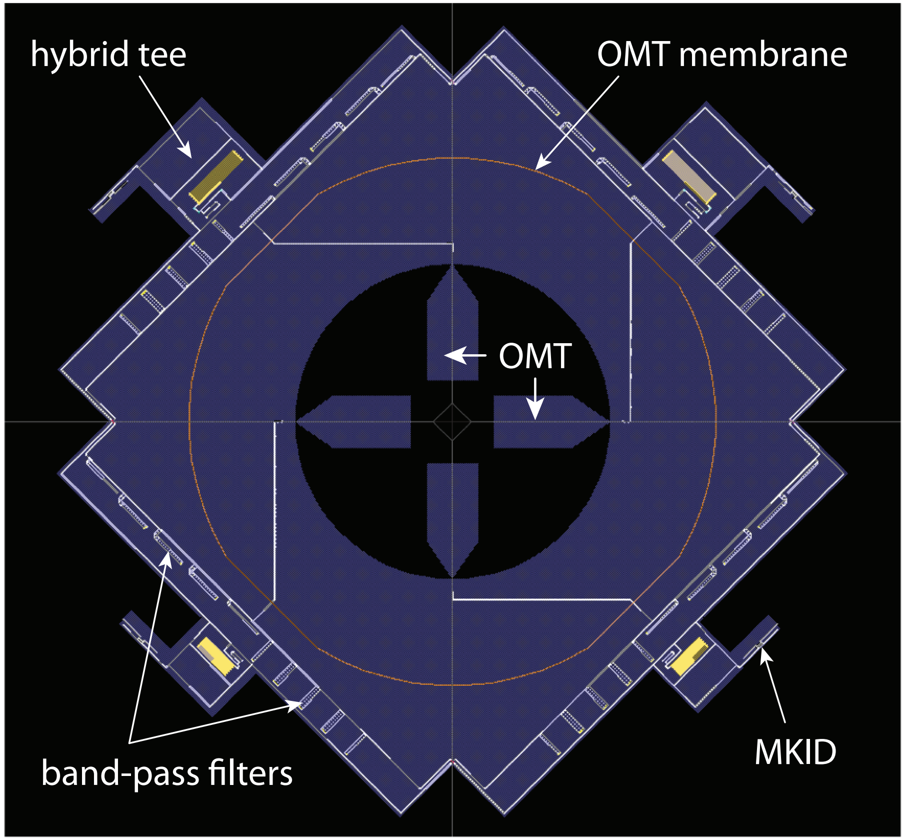
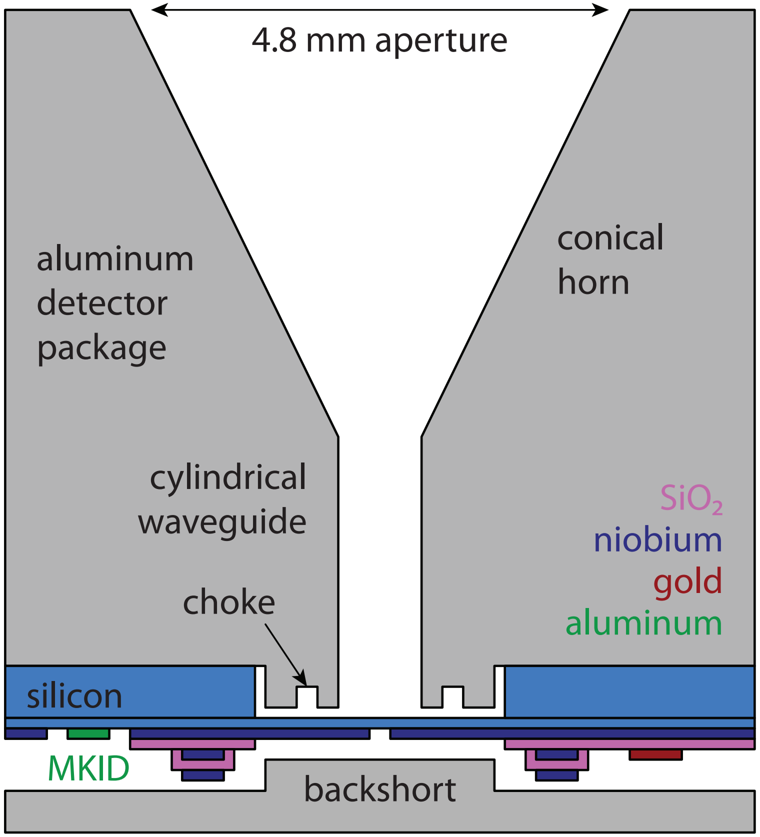


Fig. 1 *Left* design of a single horn coupled multichroic polarimeter with labels on the major components. *Center* a photograph of a cross-section of a broad-band ring-loaded corrugated feed horn fabricated by gold plating a stack of etched silicon platelets. *Right* a photograph of a prototype 90/150 multichroic detector with the major components labeled. A description of these components is in the text. For clarity, the path light follows to reach the bolometer corresponding to Y polarization in the 150 GHz band has been highlighted (Color figure online)

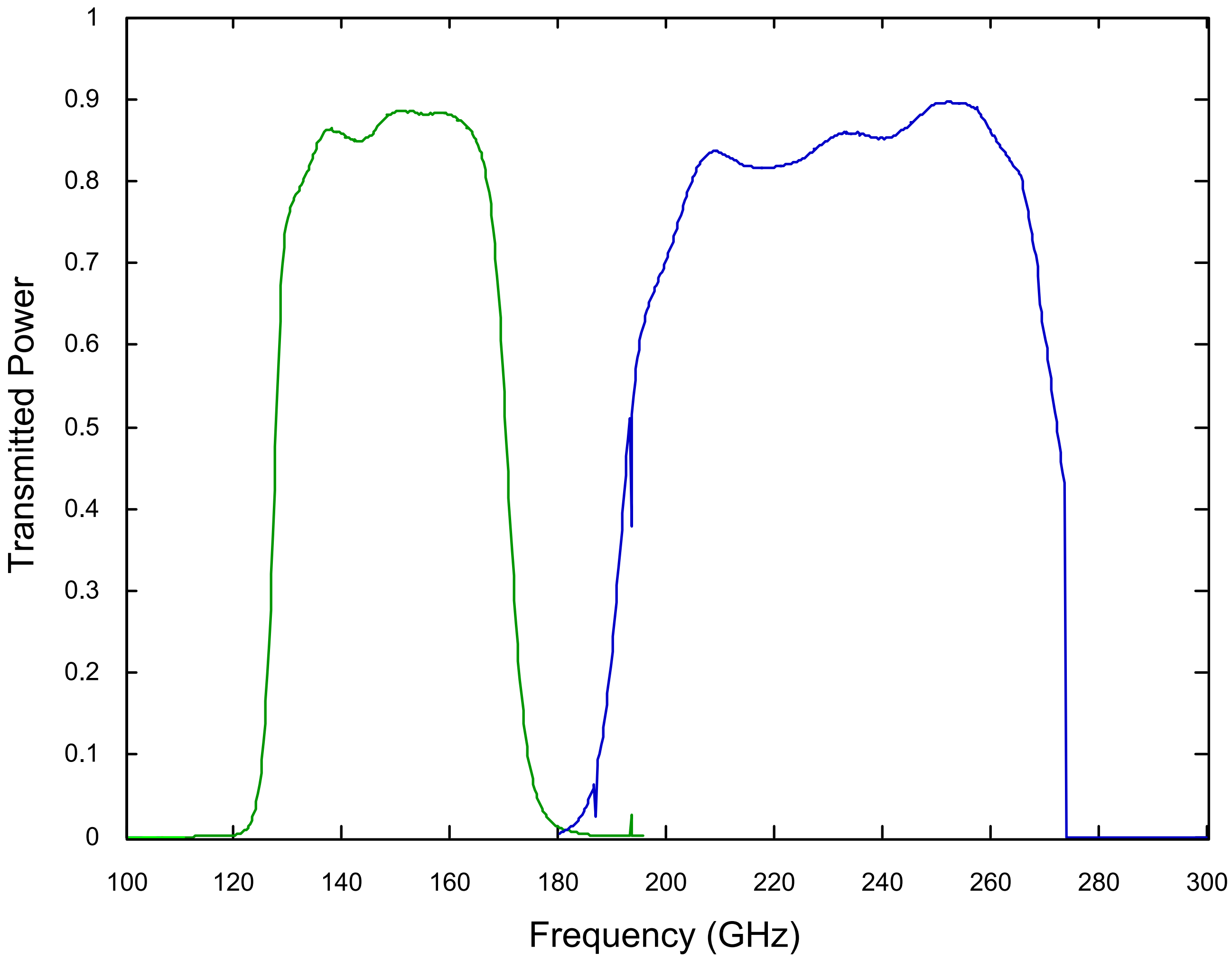
Datta et al. (2014) J. Low Temp. Phys. 176, 670–676

Schematic of an Array Element

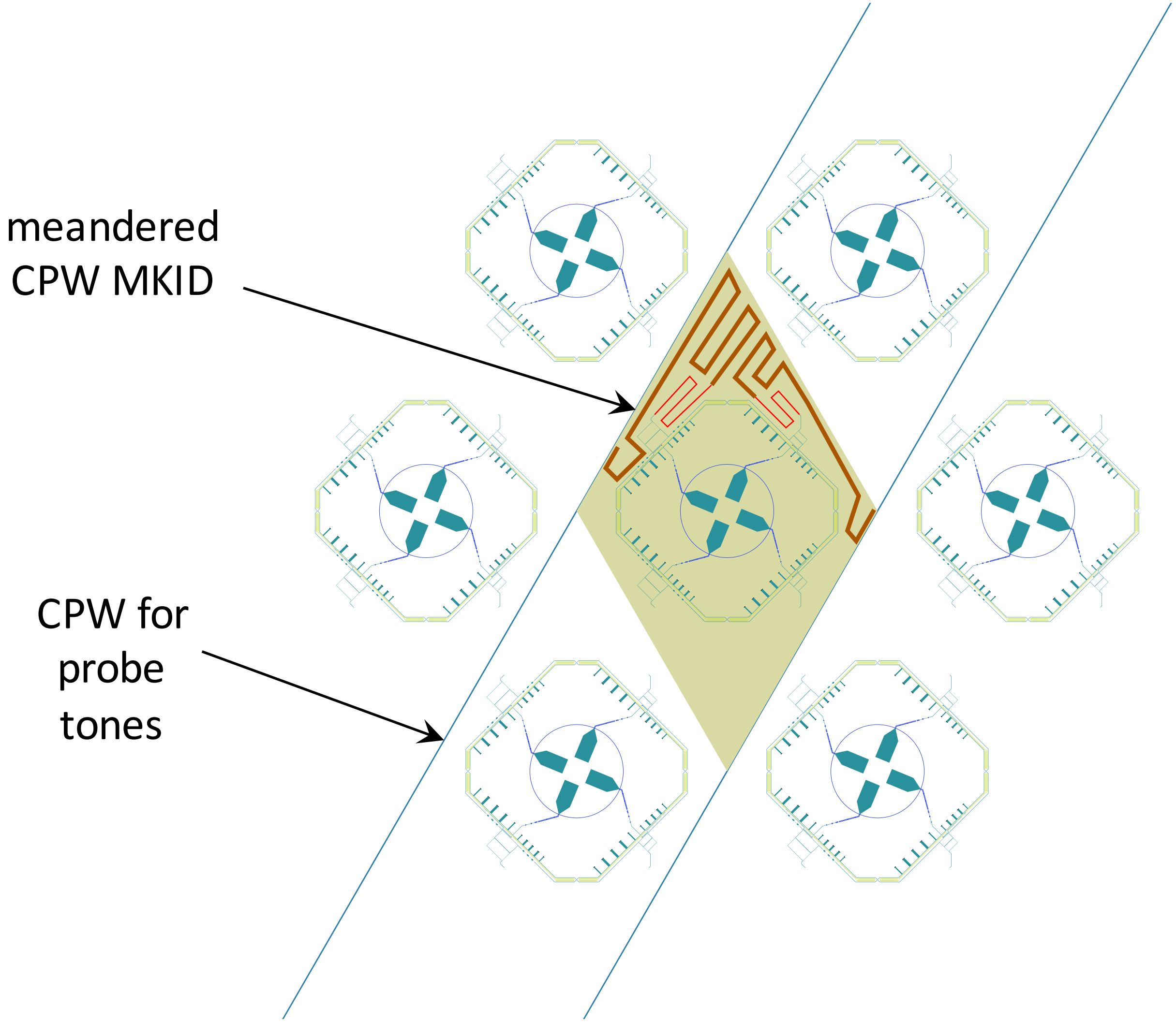




Simulated Spectral Bands



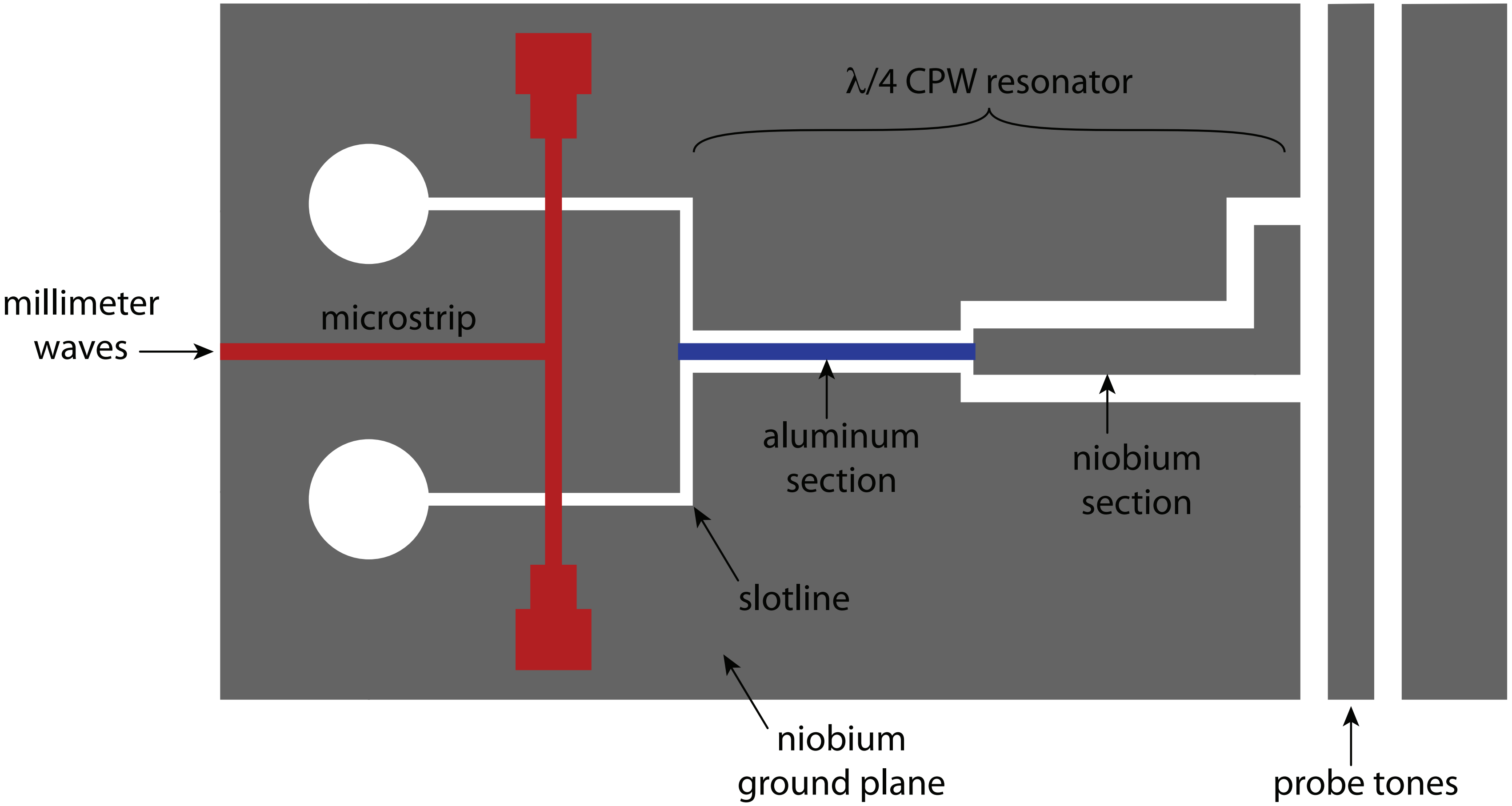
Multi-Chroic MKID Array Layout



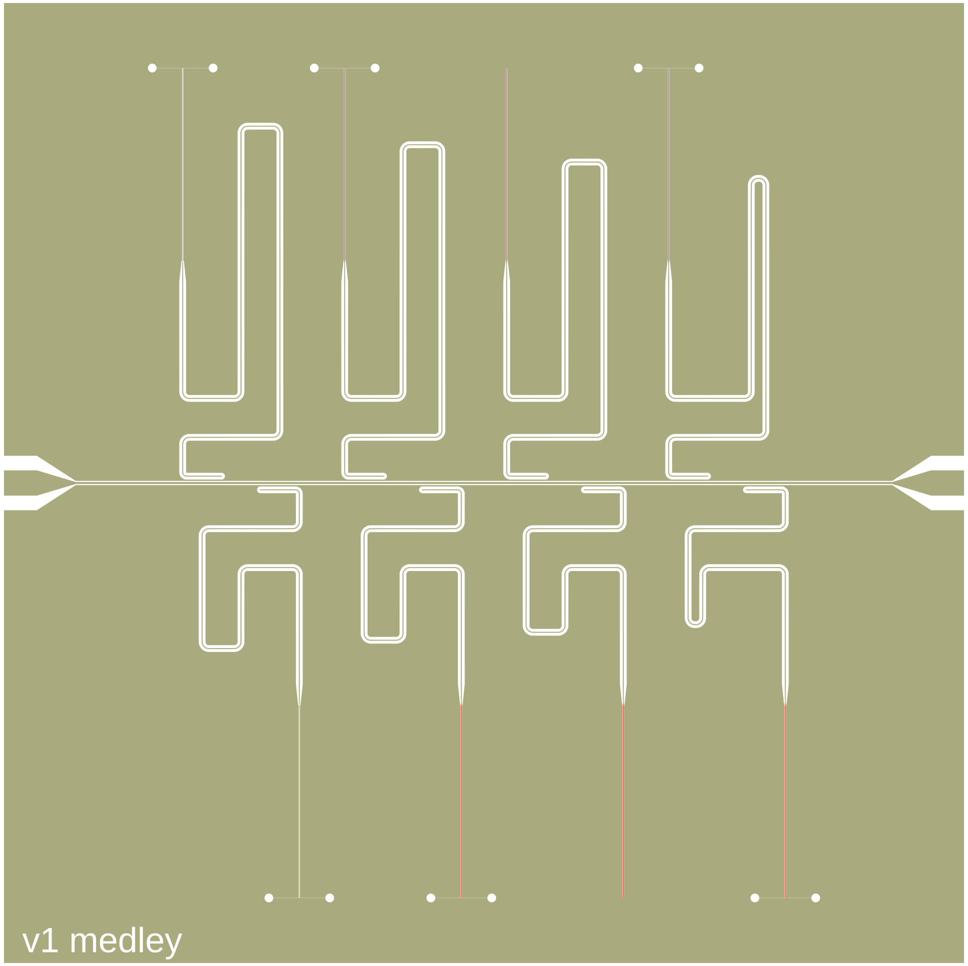
meandered
CPW MKID

CPW for
probe
tones

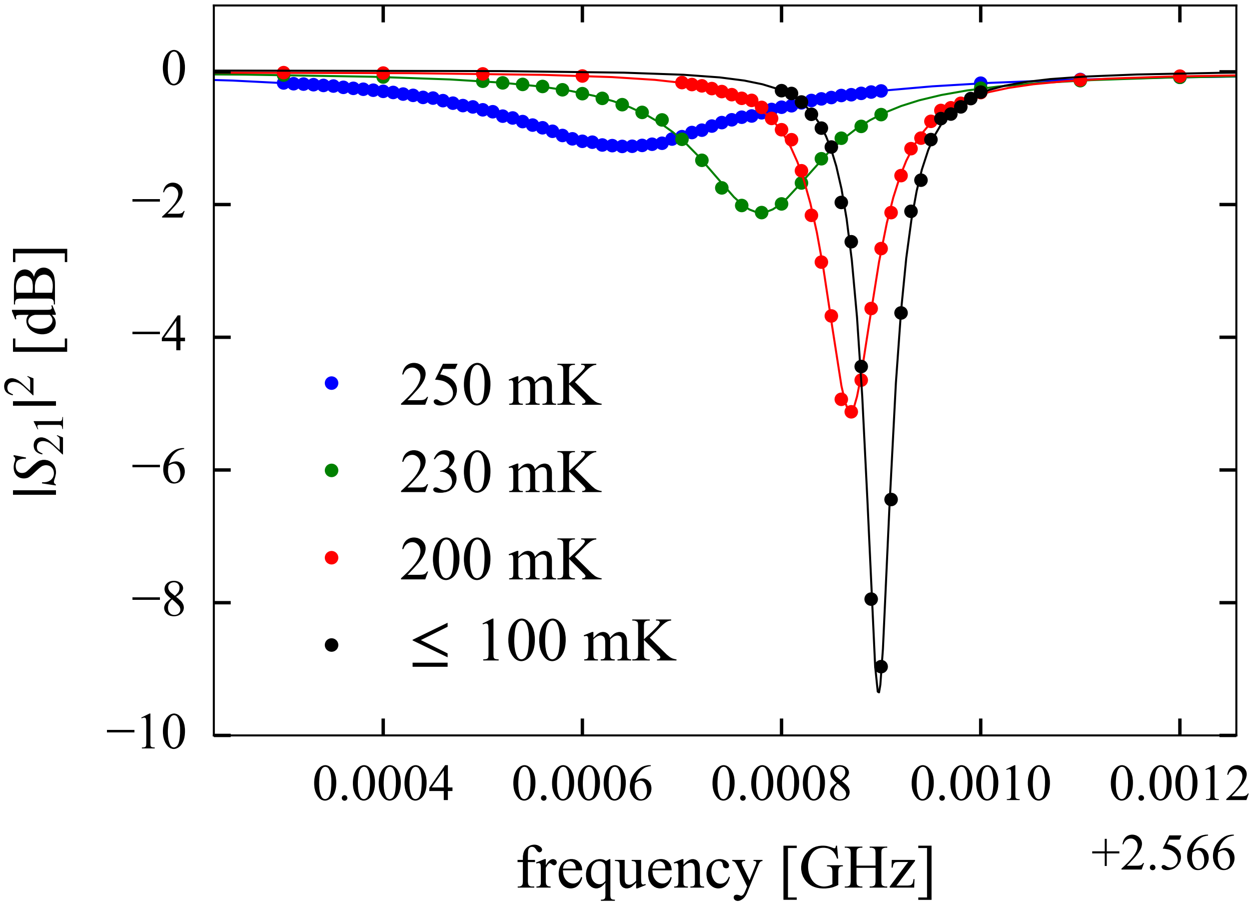
MKID Coupling Schematic



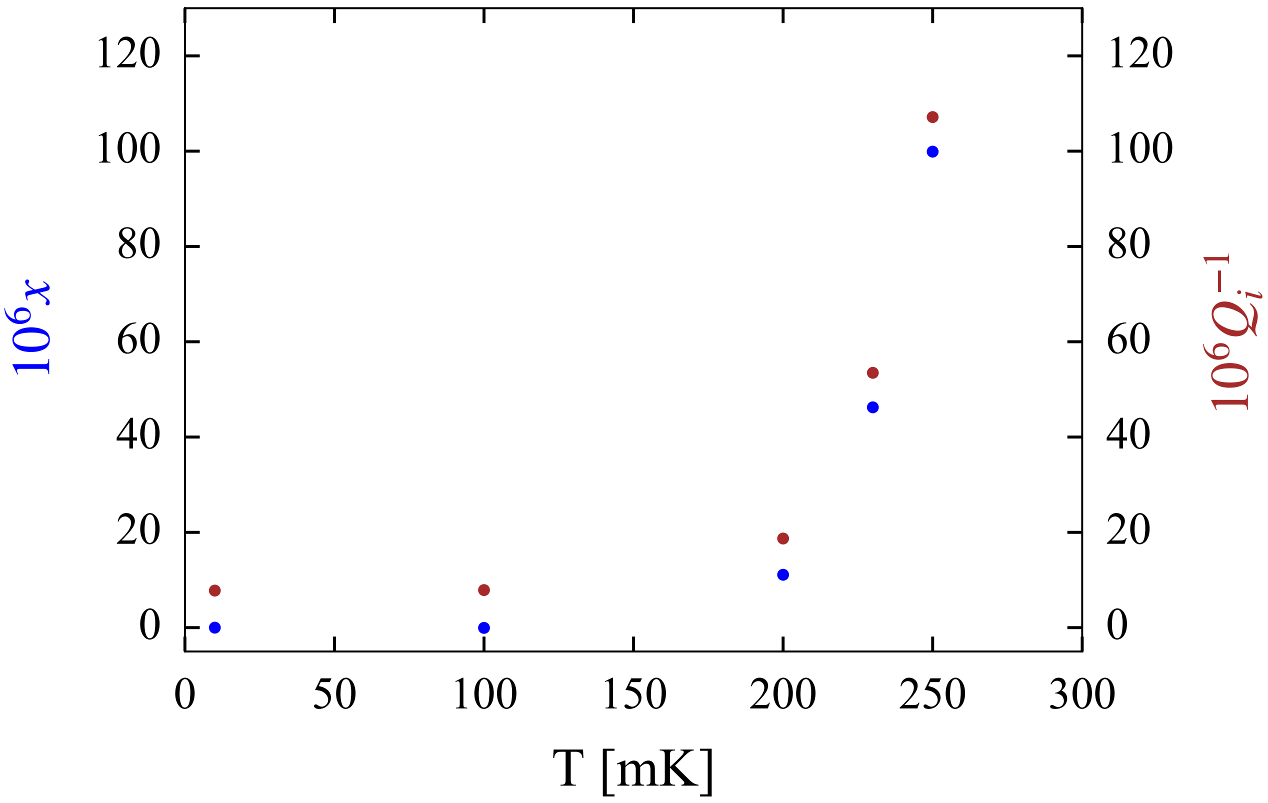
Prototype Devices



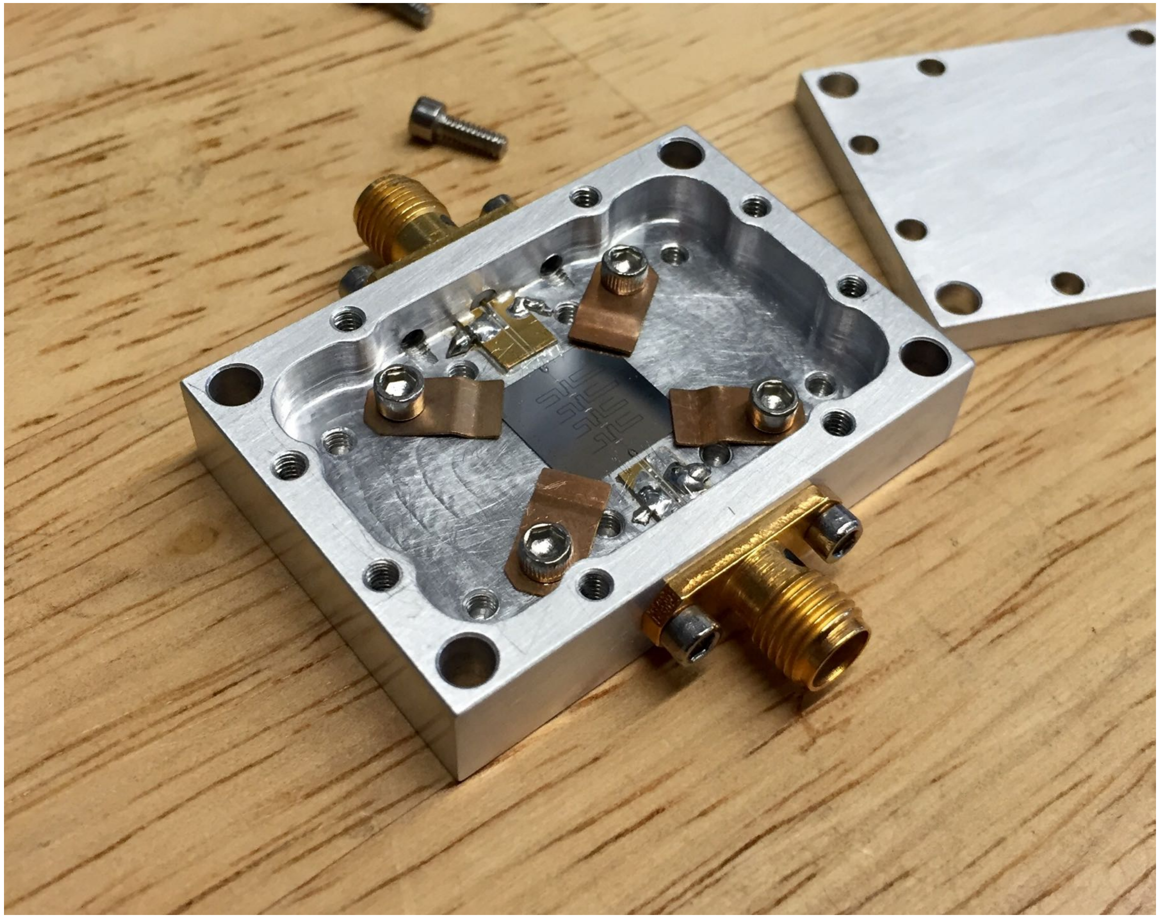
Simulated Performance of Resonators



Simulated Performance of Resonators



Prototype Devices



Summary

- We are developing three kinds of kinetic inductance detectors: LEKIDs, Dual-Polarization LEKIDs, and Multi-Chroic MKIDs.

- Our LEKIDs and the Dual-Polarization LEKIDs can be fabricated in industry (new).

- Measurements show competitive sensitivity.

- Multiplexing factor of 44 has been demonstrated by our group with prototype devices, though existing hardware should straightforwardly support hundreds.

- Working on on-sky demonstration.

- Data from first Multi-Chroic devices should be in hand this summer.