Development of KIDs for CMB Polarization Studies

Brad Johnson
Assistant Professor
Columbia University

KID = kinetic inductance detector
MKID = microwave kinetic inductance detector
LEKID = lumped-element kinetic inductance detector

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Organization of Presentation

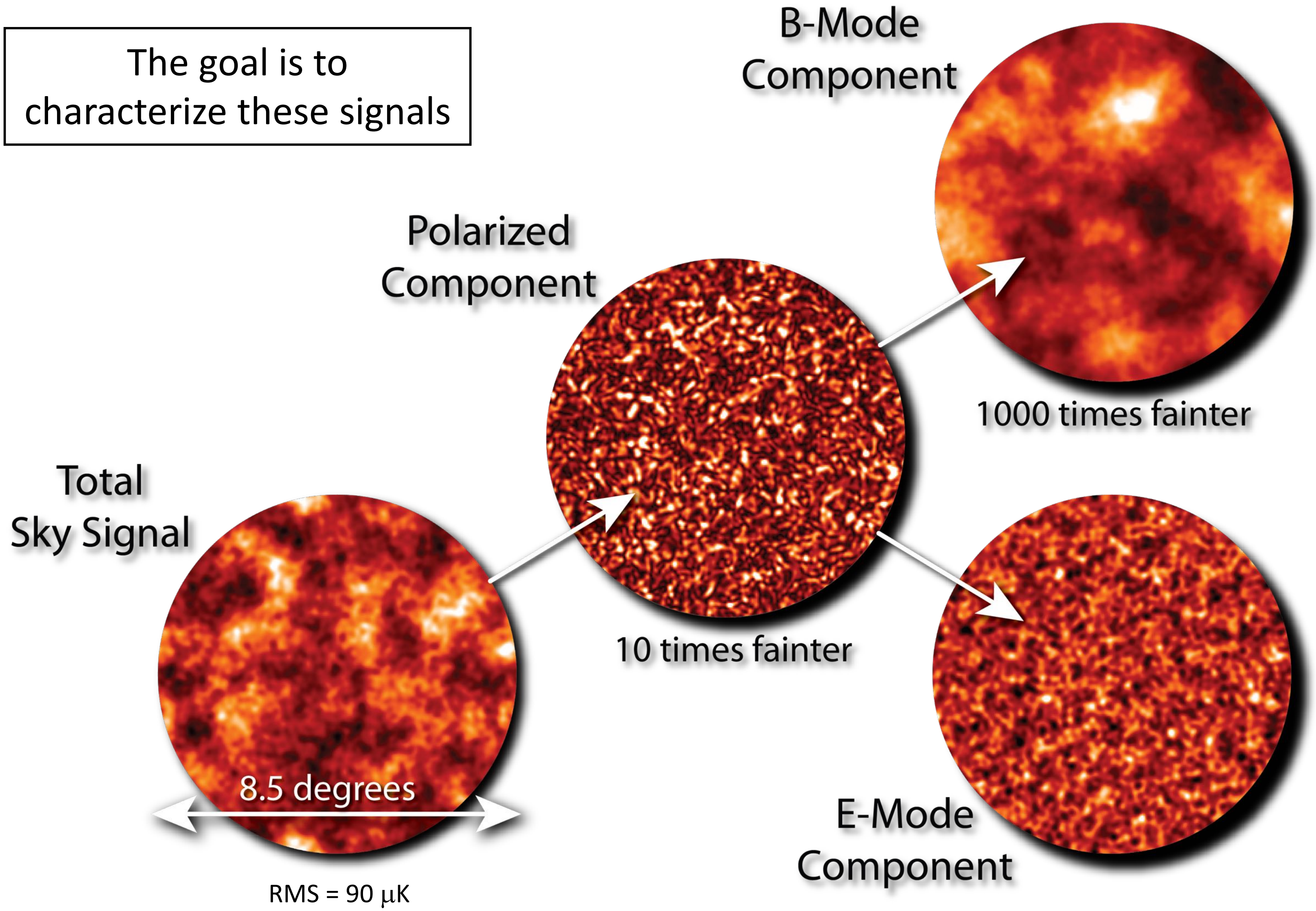
1) Overview of CMB Polarization Studies
2) "Single-Polarization" LEKIDs
3) Dual Polarization LEKIDs
4) Multi-Chroic Dual-Polarization MKIDs

KID = kinetic inductance detector
MKID = microwave kinetic inductance detector
LEKID = lumped-element kinetic inductance detector

1) Overview of CMB Polarization Studies

Scientific Goals of CMB Studies

The goal is to characterize these signals



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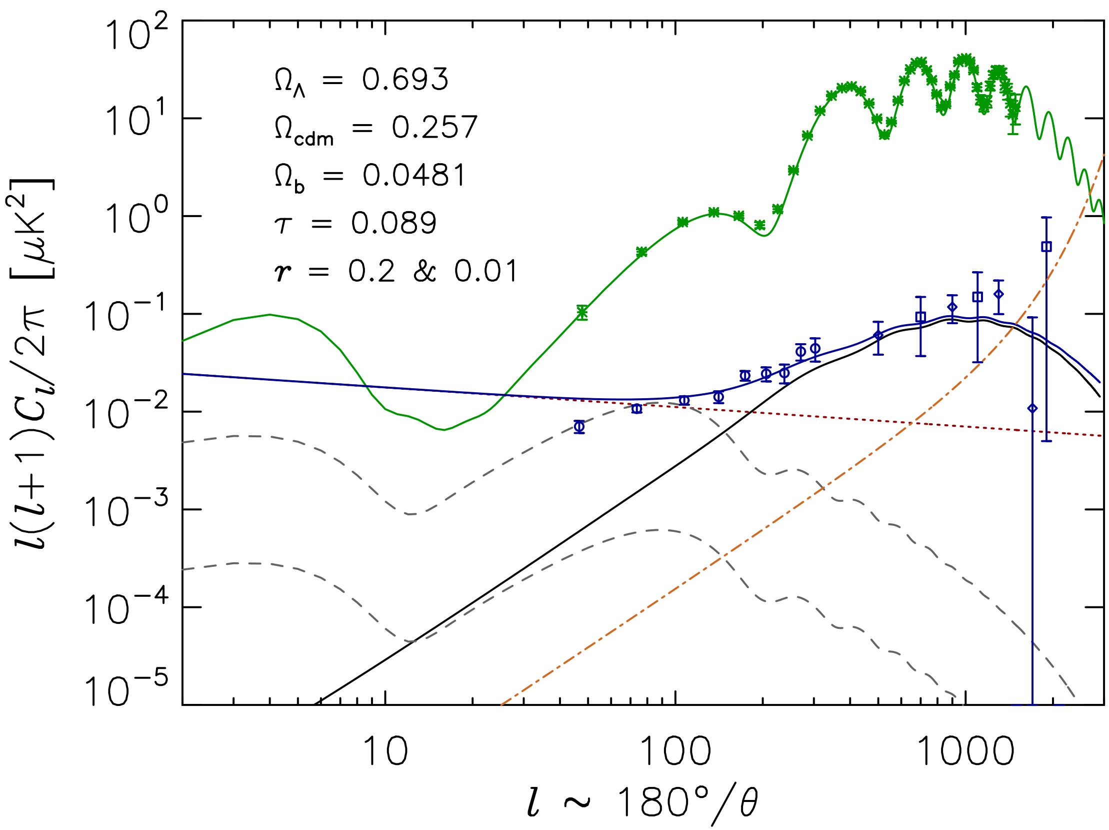
Scientific Goals of CMB Studies

1) Fainter signals require more detectors.



2) Galactic dust is important.

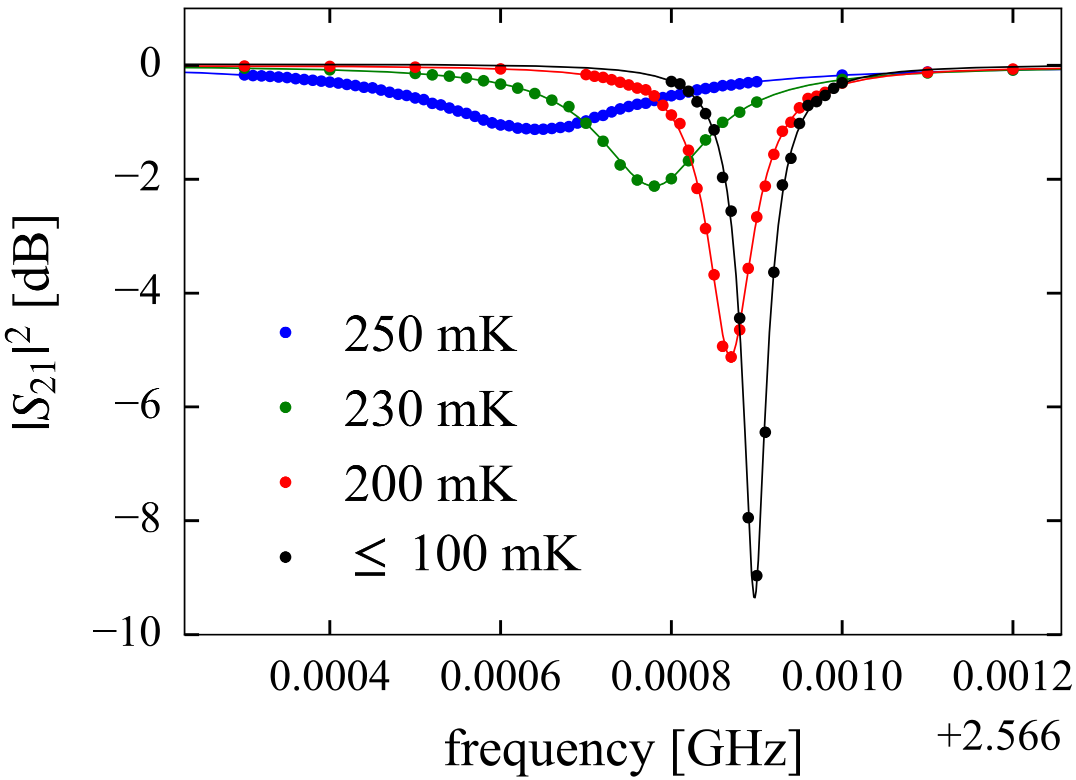
POLARBEAR, et al. (2014) *ApJ*, 794, 171.
Keisler, et al. (2015) *ApJ*, 807, 151.

B2K, et al. (2016) *PRL*, 116, 031302.
B2K and Planck, et al. (2015) *PRL*, 114, 101301.

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.

Resonances



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

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2) “Single-Polarization” LEKIDs

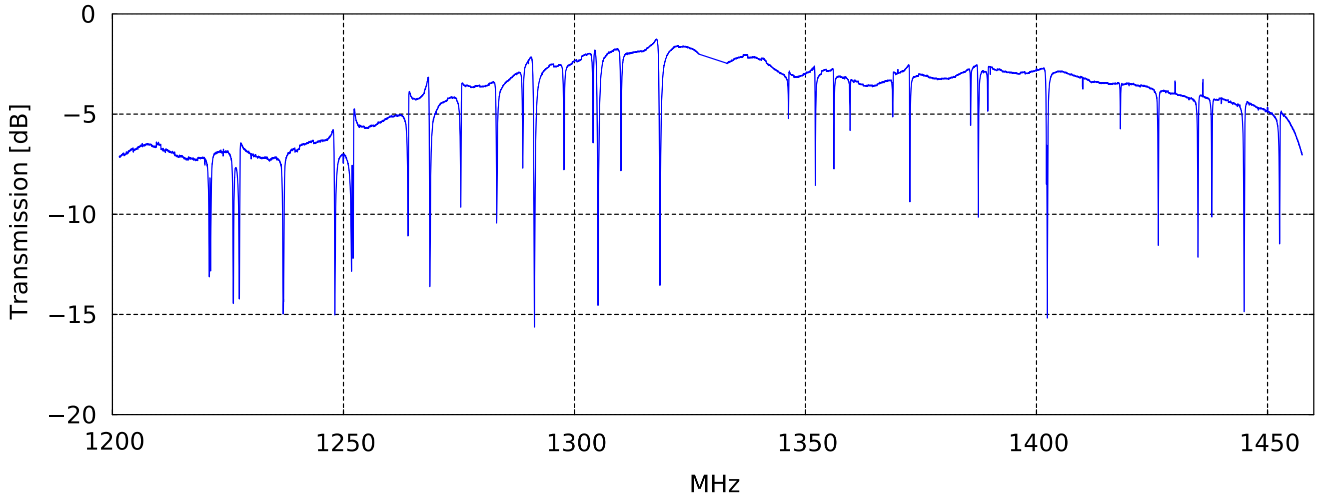
McCarrick et al. (2014) *RSI*, 85, 123117.

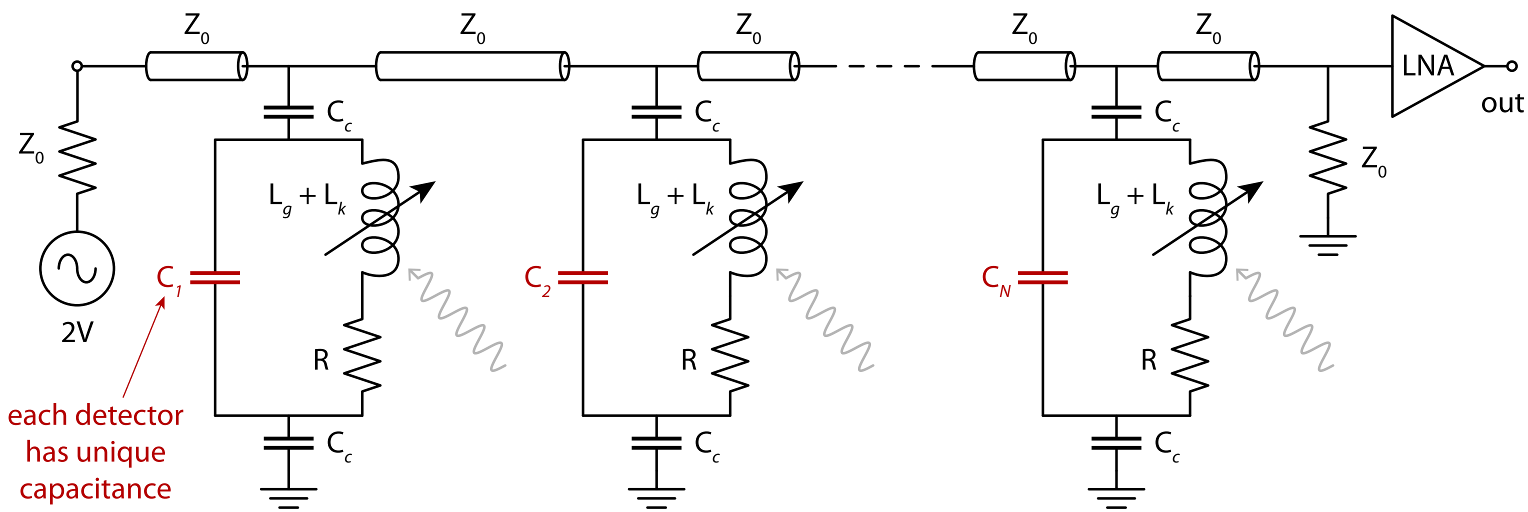
Flanigan et al. (2016) *APL*, 108, 083504.

Flanigan et al. (2016) *APL*, 109, 143503.

Jones et al. (2017) *APL*, 110, 222601.

Multiplexing





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

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

H. McCarrick,[1,a)] D. Flanigan,[1] G. Jones,[1] B. R. Johnson,[1] P. Ade,[2] D. Araujo,[1] 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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[3]*Department of Physics, Arizona State University, Tempe, Arizona 85287, USA*
[4]*STAR Cryoelectronics, Santa Fe, New Mexico 87508, USA*
[5]*Jet Propulsion Laboratory, Caltech, Pasadena, California 91109, USA*
[6]*Department of Physics and School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, USA*
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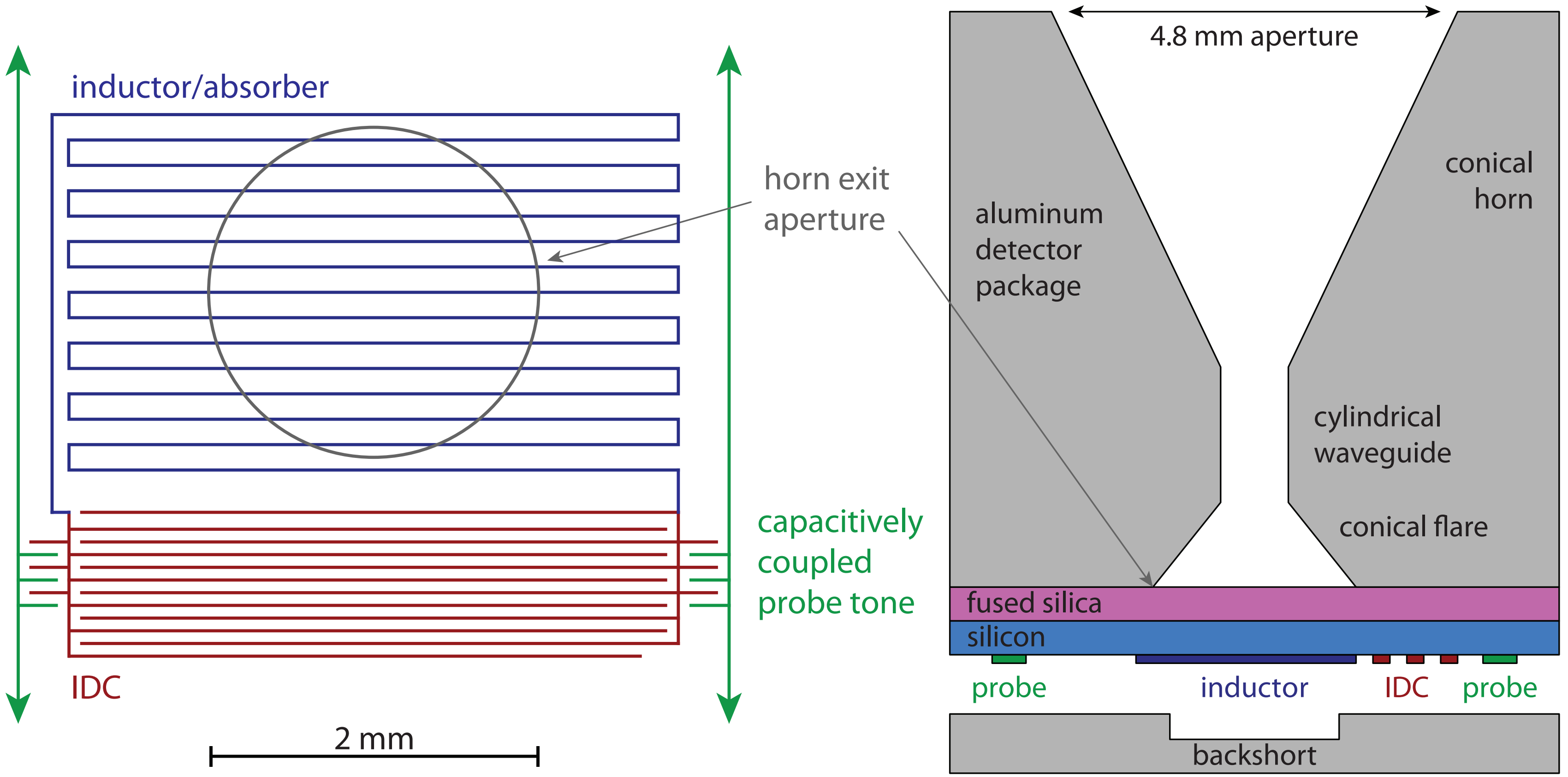
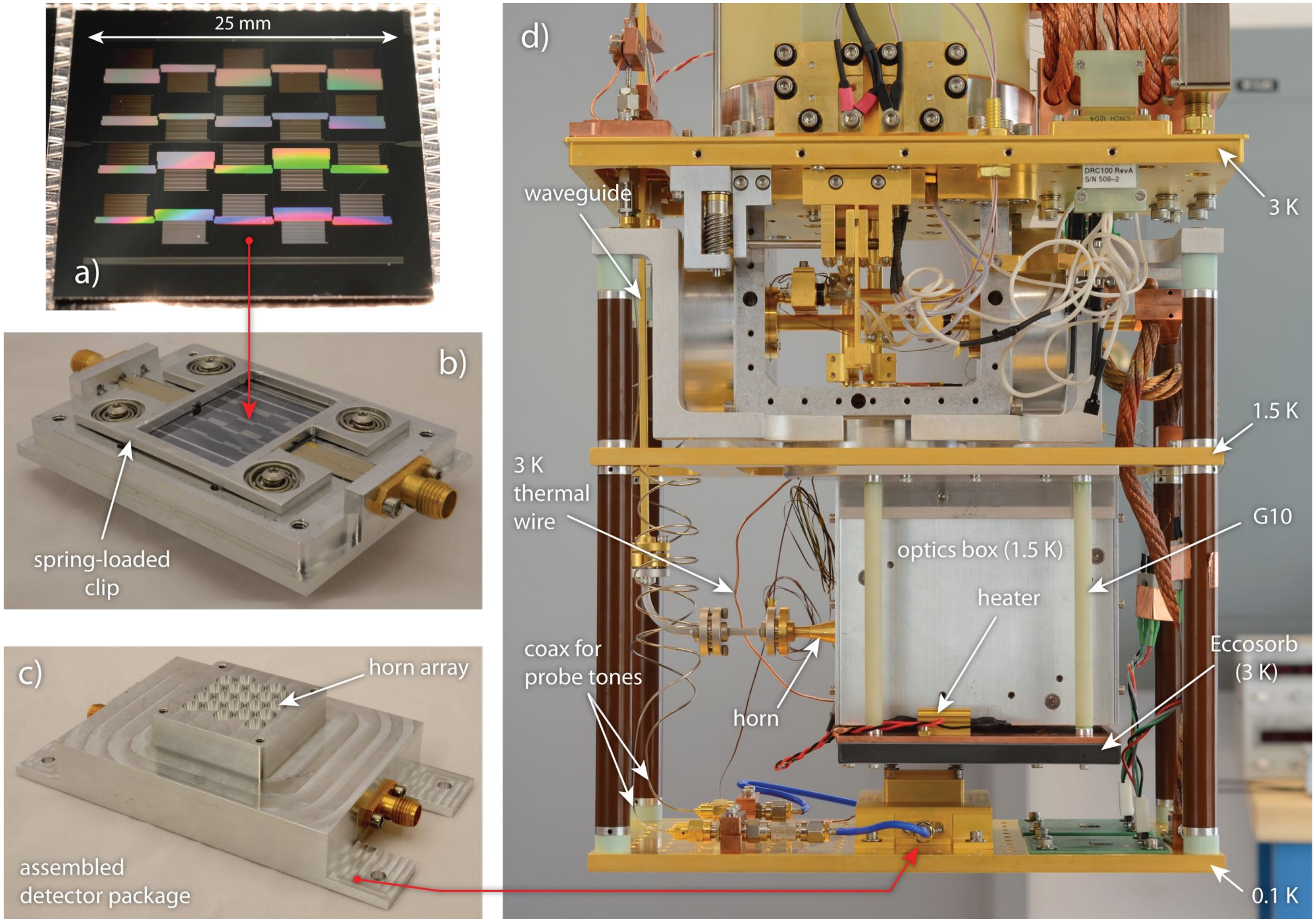
[8]*Department of Physics, Caltech, Pasadena, California 91125, USA*

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

“Single Polarization” Pixel Design



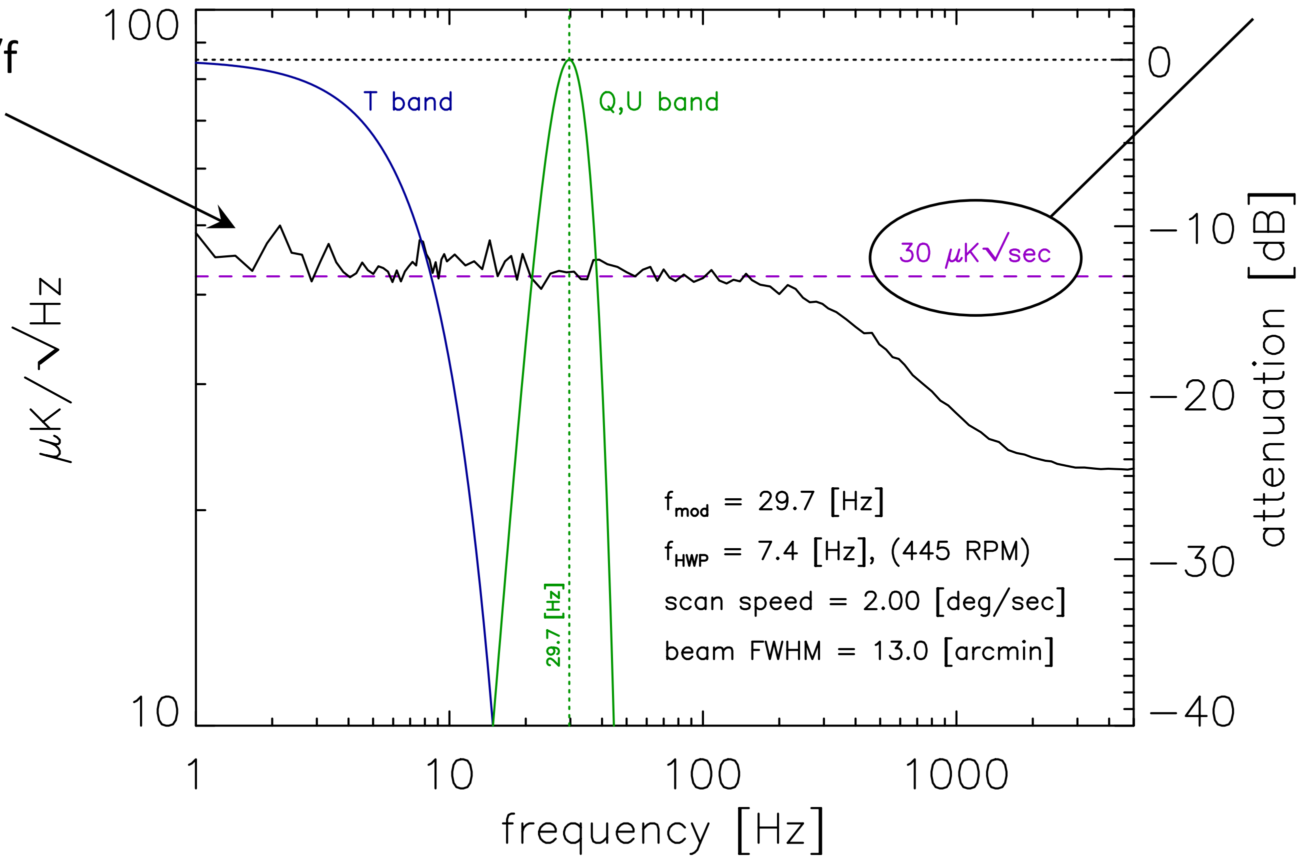
Optical Test Setup



Result: ***Measured*** LEKID Noise

1) low NET

2) low 1/f noise



150 GHz

3) lots of bandwidth

4 K beam-filling load

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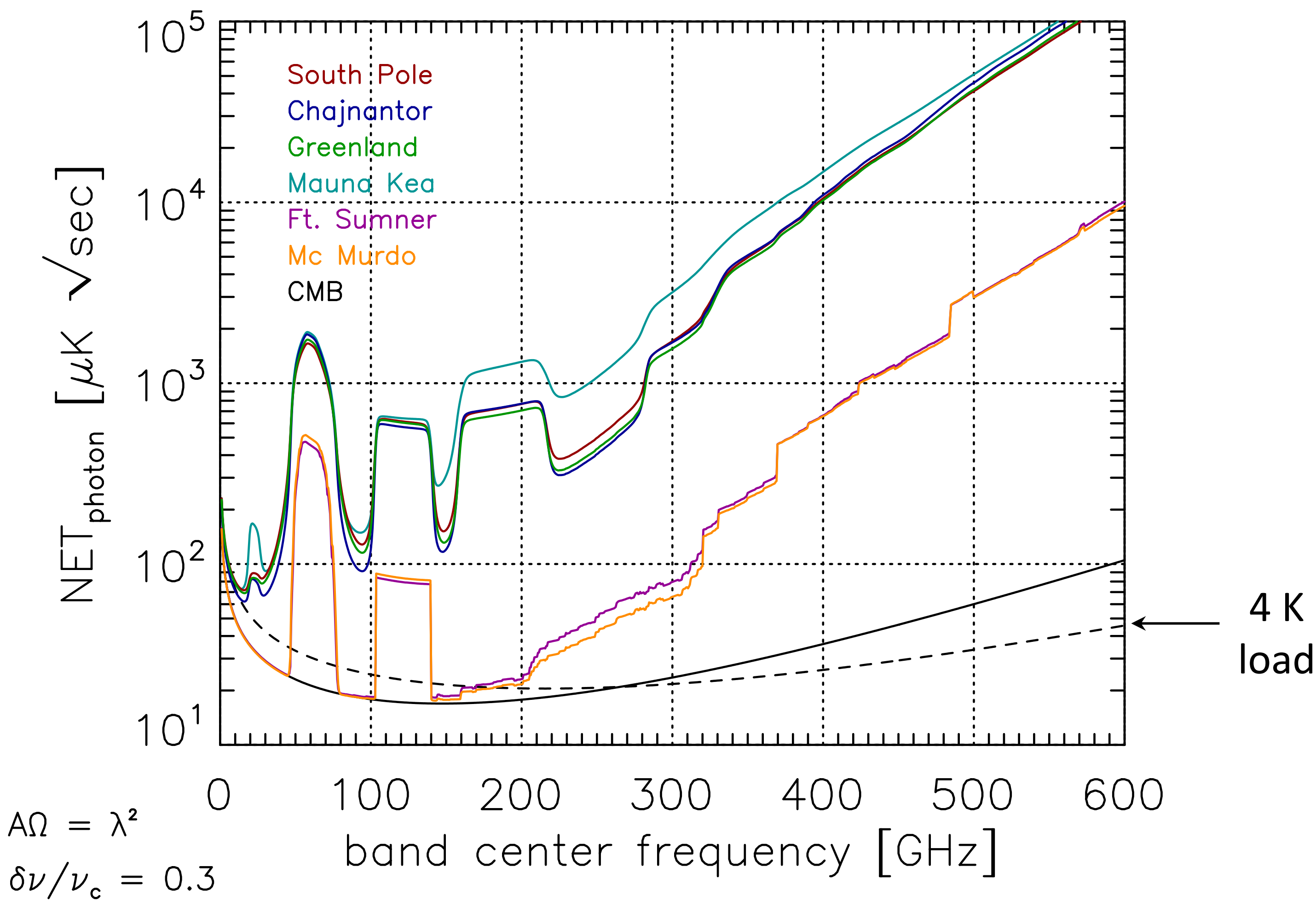
Interpreting the NET Result



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

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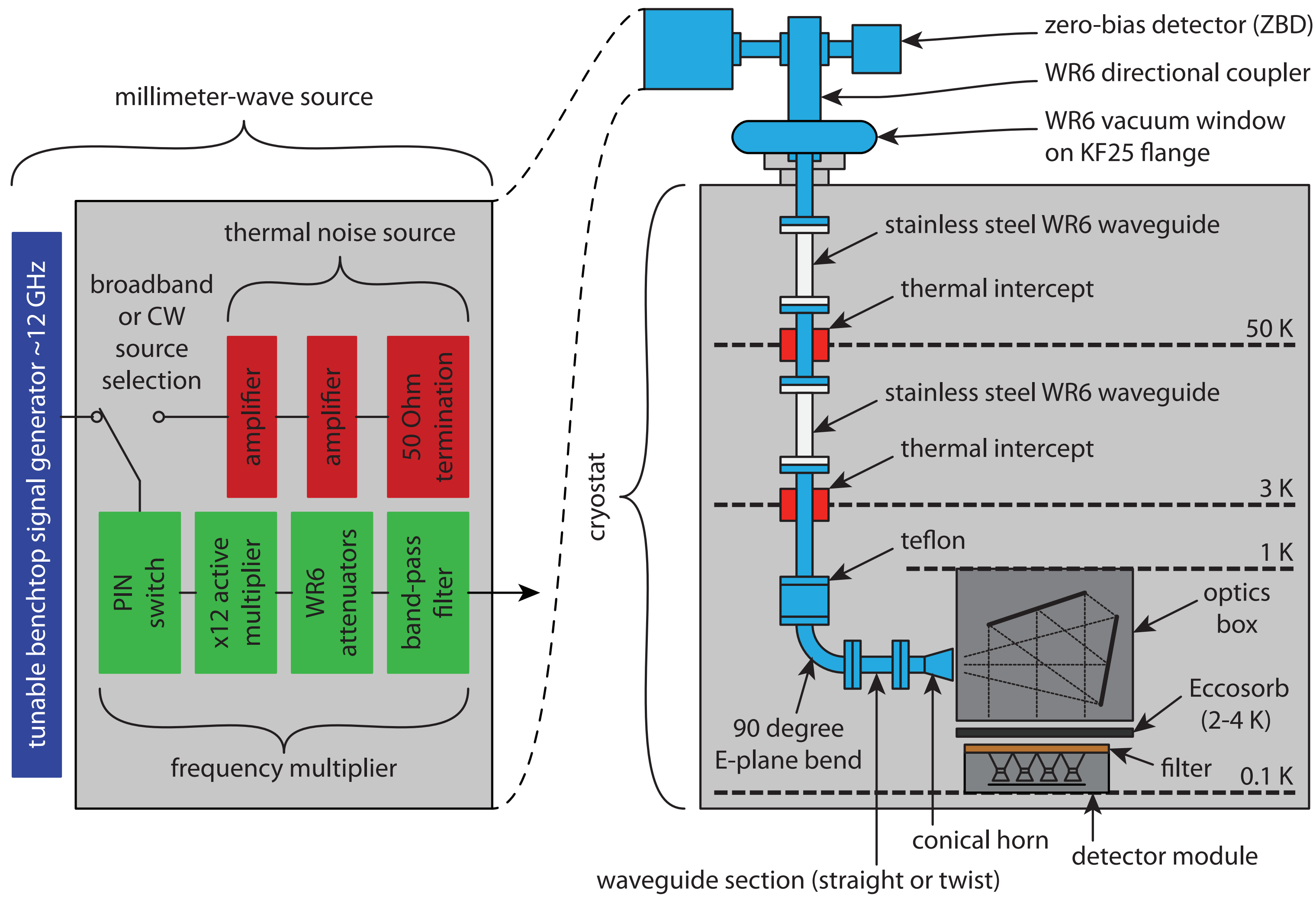
Project supported in part by a grant from the ***Research Initiatives for Science and Engineering*** program at Columbia.

Schematic of Experimental Setup



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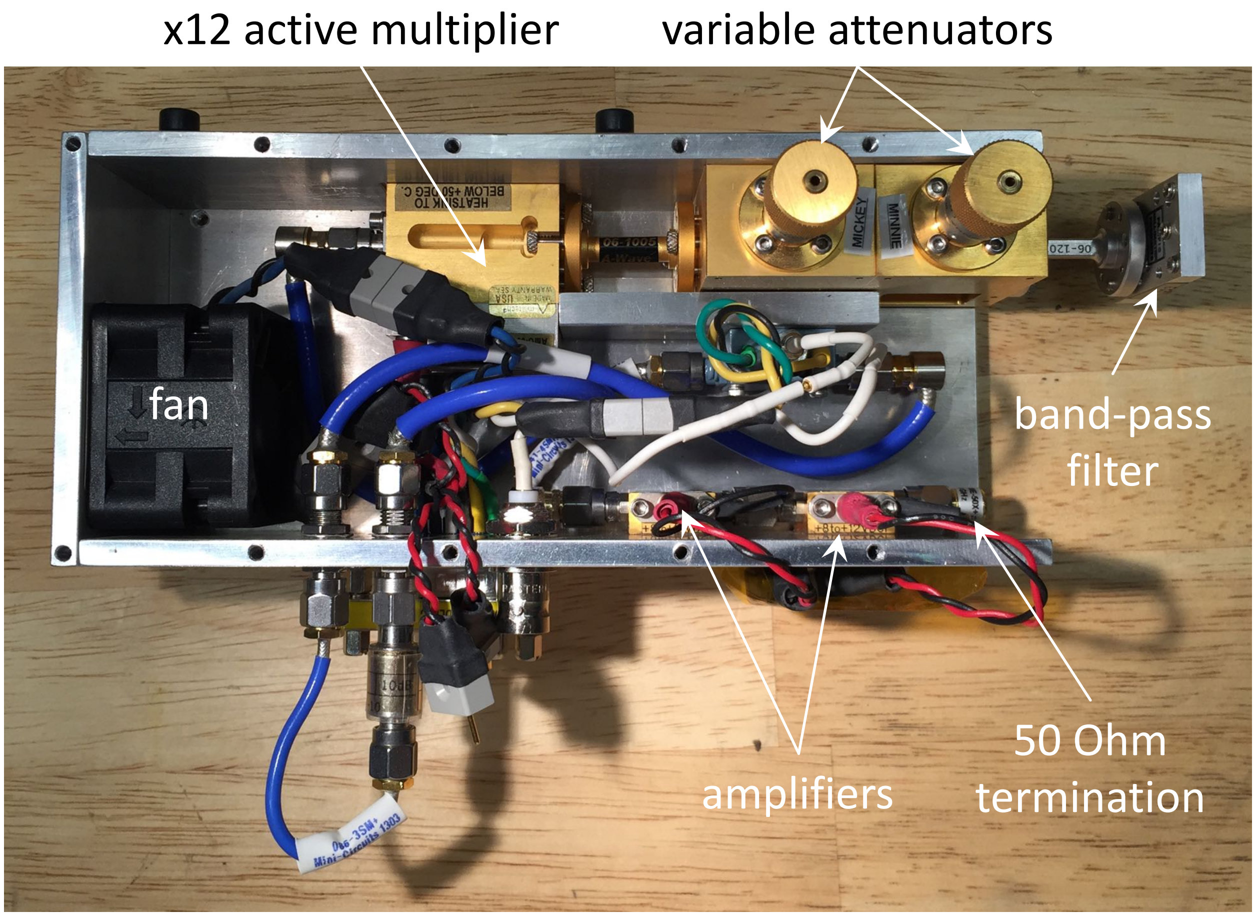
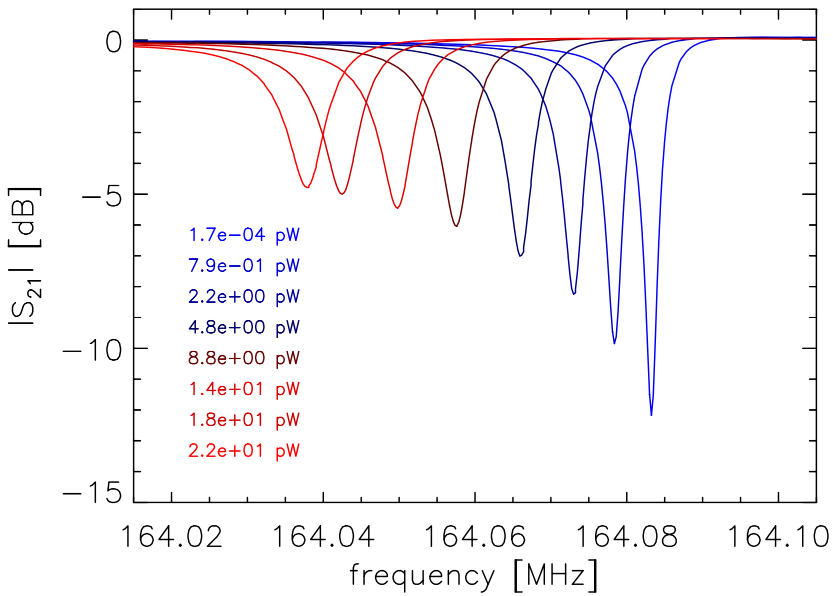
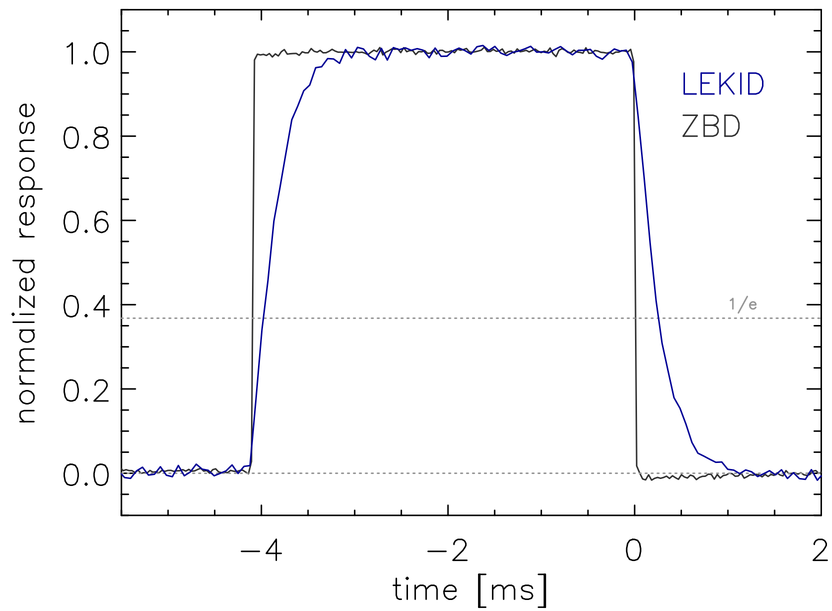
Millimeter-Wave Source



Other LEKID Measurements

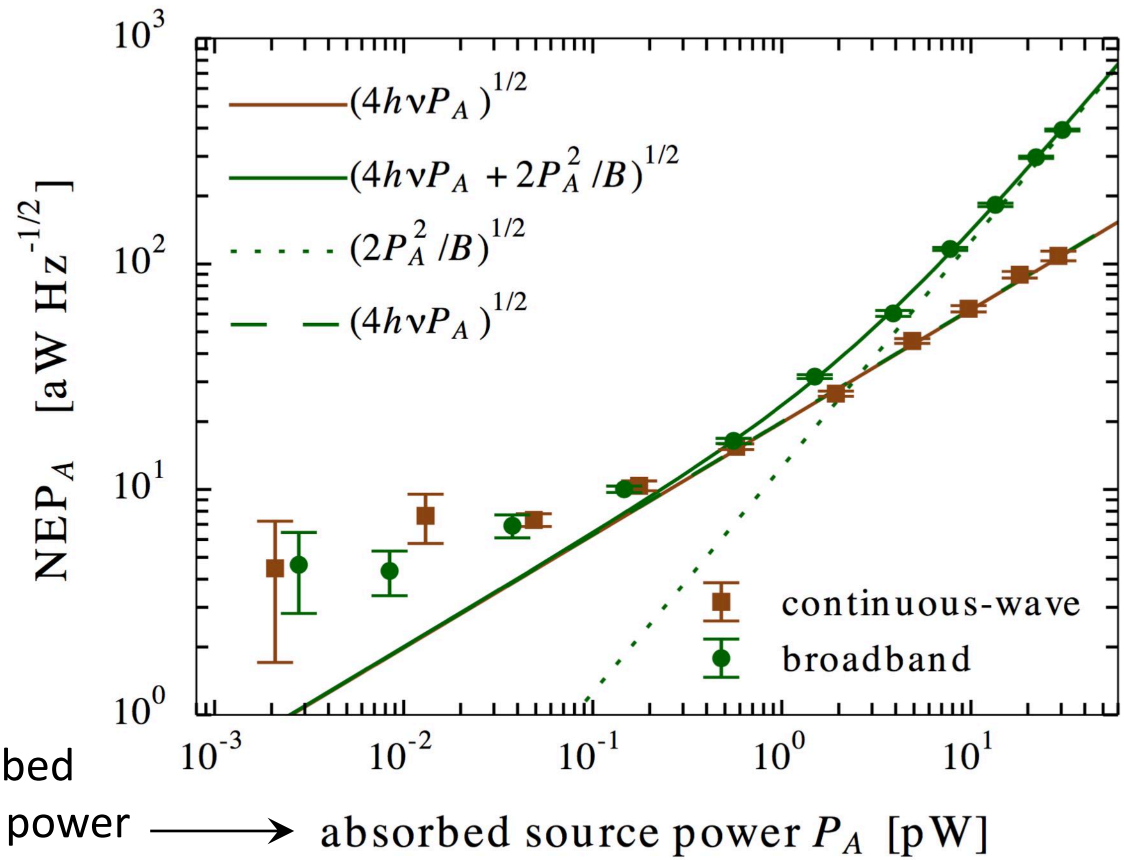


Measured S_{21} scattering parameter as a function of probe tone frequency for various millimeter-wave loadings. This plot shows that the LEKIDs work as expected. **As the millimeter-wave loading changes, the resonant frequency of the device changes**. The range of loading power used in this test spans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

Magnetic field dependence of the internal quality factor and noise performance of lumped-element kinetic inductance detectors

D. Flanigan,[1,a)] B. R. Johnson,[1] M. H. Abitbol,[1] S. Bryan,[2] R. Cantor,[3] P. Day,[4] G. Jones,[1] P. Mauskopf,[2,5,6] H. McCarrick,[1] A. Miller,[7] and J. Zmuidzinas[4,8]
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[3]*STAR Cryoelectronics, Santa Fe, New Mexico 87508, USA*
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[5]*Department of Physics, Arizona State University, Tempe, Arizona 85287, USA*
[6]*School of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, United Kingdom*
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(Received 31 August 2016; accepted 20 September 2016; published online 3 October 2016)

We present a technique for increasing the internal quality factor of kinetic inductance detectors (KIDs) by nulling ambient magnetic fields with a properly applied magnetic field. The KIDs used in this study are made from thin-film aluminum, they are mounted inside a light-tight package made from bulk aluminum, and they are operated near 150 mK. Since the thin-film aluminum has a slightly elevated critical temperature ($T_c = 1.4$ K), it therefore transitions before the package ($T_c = 1.2$ K), which also serves as a magnetic shield. On cooldown, ambient magnetic fields as small as approximately 30 μT can produce vortices in the thin-film aluminum as it transitions because the bulk aluminum package has not yet transitioned and therefore is not yet shielding. These vortices become trapped inside the aluminum package below 1.2 K and ultimately produce low internal quality factors in the thin-film superconducting resonators. We show that by controlling the strength of the magnetic field present when the thin film transitions, we can control the internal quality factor of the resonators. We also compare the noise performance with and without vortices present, and find no evidence for excess noise beyond the increase in amplifier noise, which is expected with increasing loss. [http://dx.doi.org/10.1063/1.4964119]

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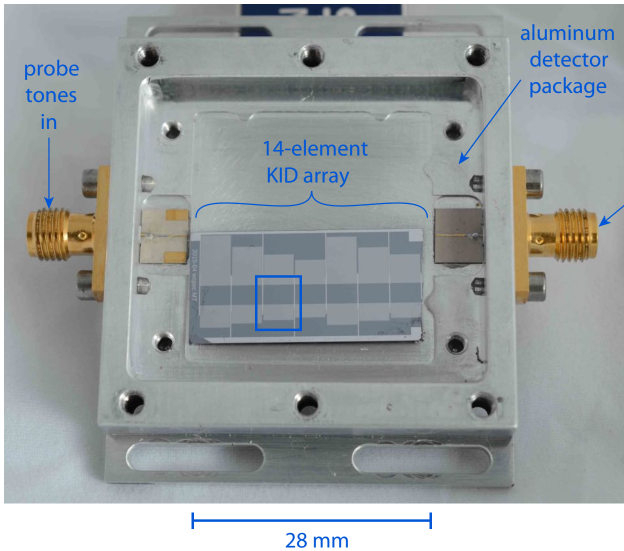
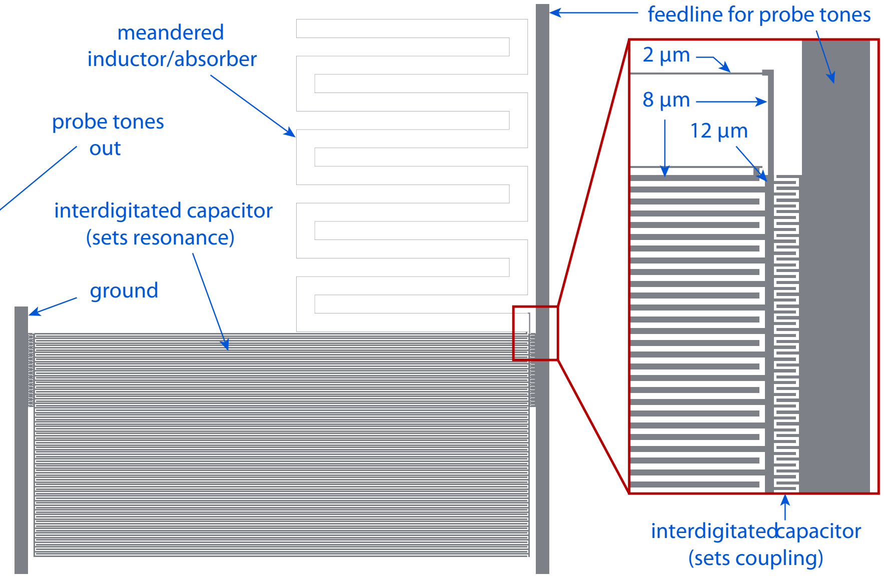
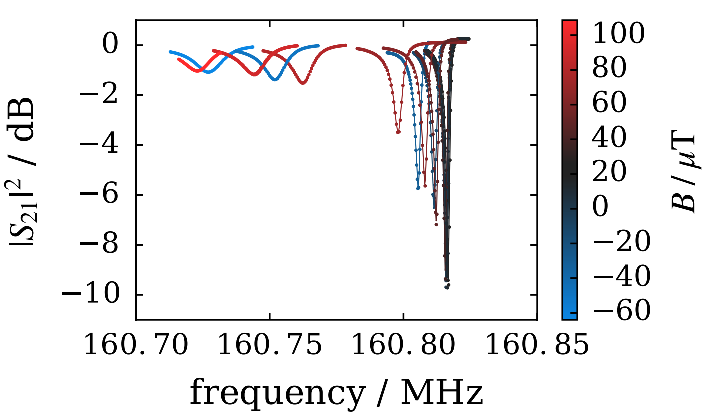
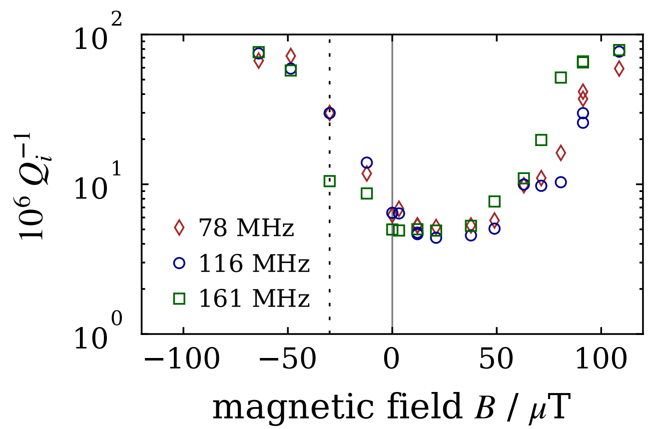
How do magnetic fields effect Q_i?









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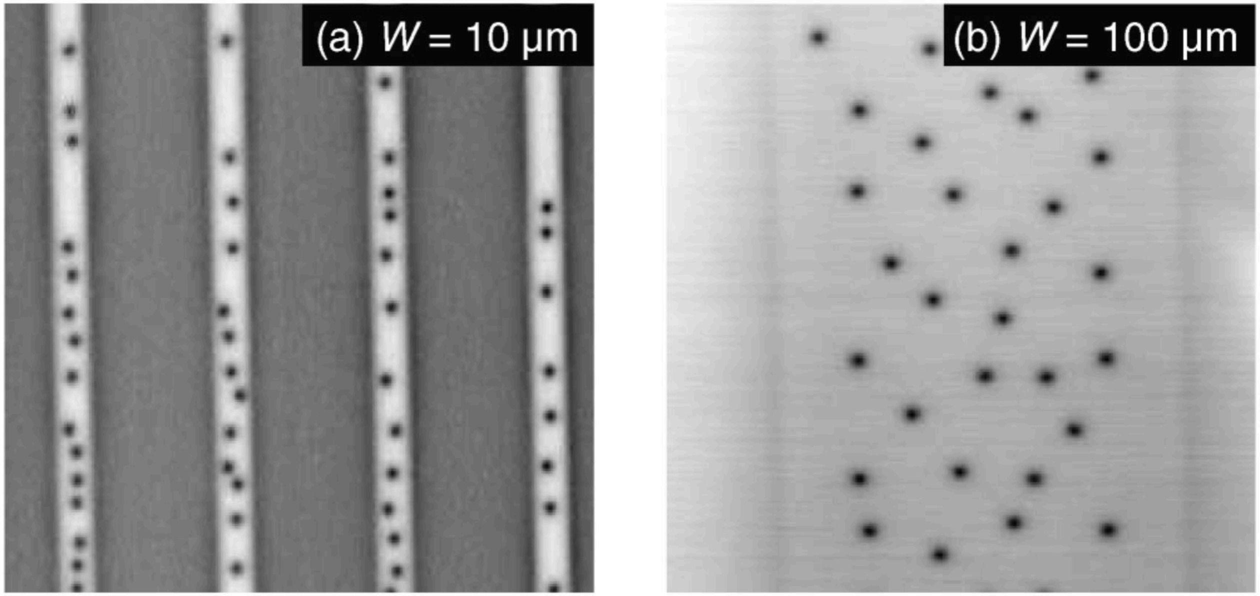

FIG. 2. (a) 10 μm strip after field cooling in 85 μT. The strips appear light because of the Meissner expulsion of the field, but many vortices (darker spots) are visible. (b) 100 μm strip after field cooling in 5.3 μT. Both images are 140 μT full scale, and about 145 μm wide.

Stan, Field & Martinis (2004) *PRL*, 92, 9.

High quality factor manganese-doped aluminum lumped-element kinetic inductance detectors sensitive to frequencies below 100 GHz

G. Jones,[1,a)] B. R. Johnson,[1] M. H. Abitbol,[1] P. A. R. Ade,[2] S. Bryan,[3] H.-M. Cho,[4] P. Day,[5] D. Flanigan,[1] K. D. Irwin,[6,4] D. Li,[4] P. Mauskopf,[3] H. McCarrick,[1] A. Miller,[7] Y. R. Song,[6] and C. Tucker[2]

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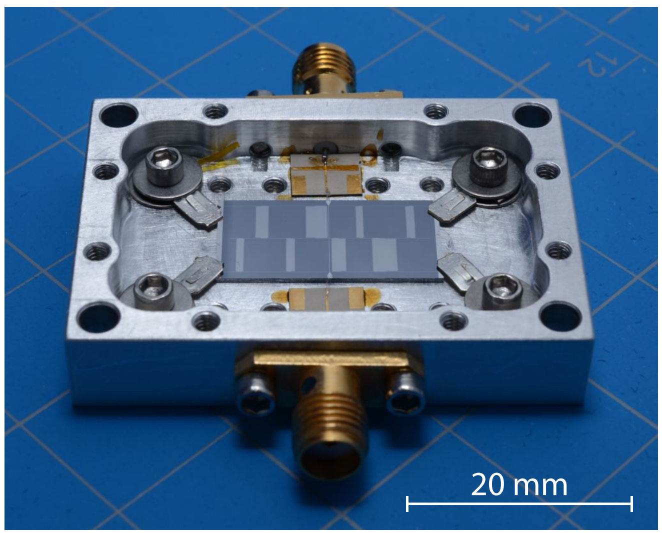
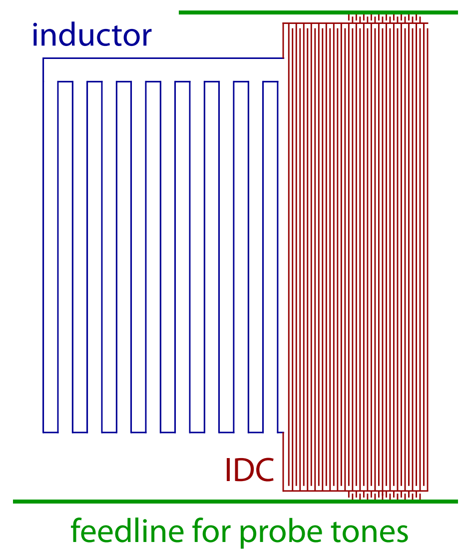
[7)] *Department of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089, USA*

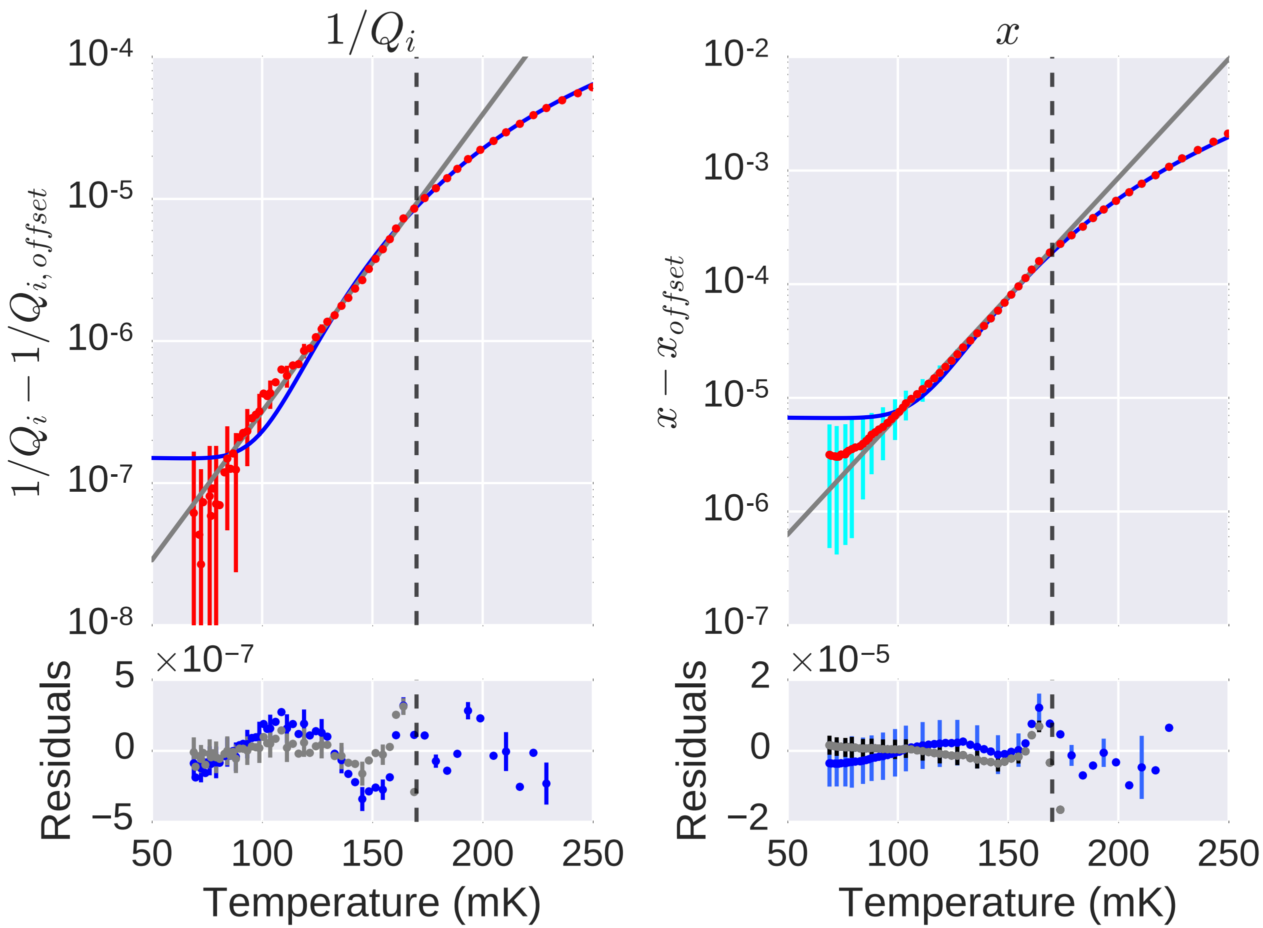
(Dated: 31 January 2017)





Jones et al. (2017) *APL*, 110, 222601.

High Q_i AlMn LEKIDs



Jones et al. (2017) *APL*, 110, 222601.

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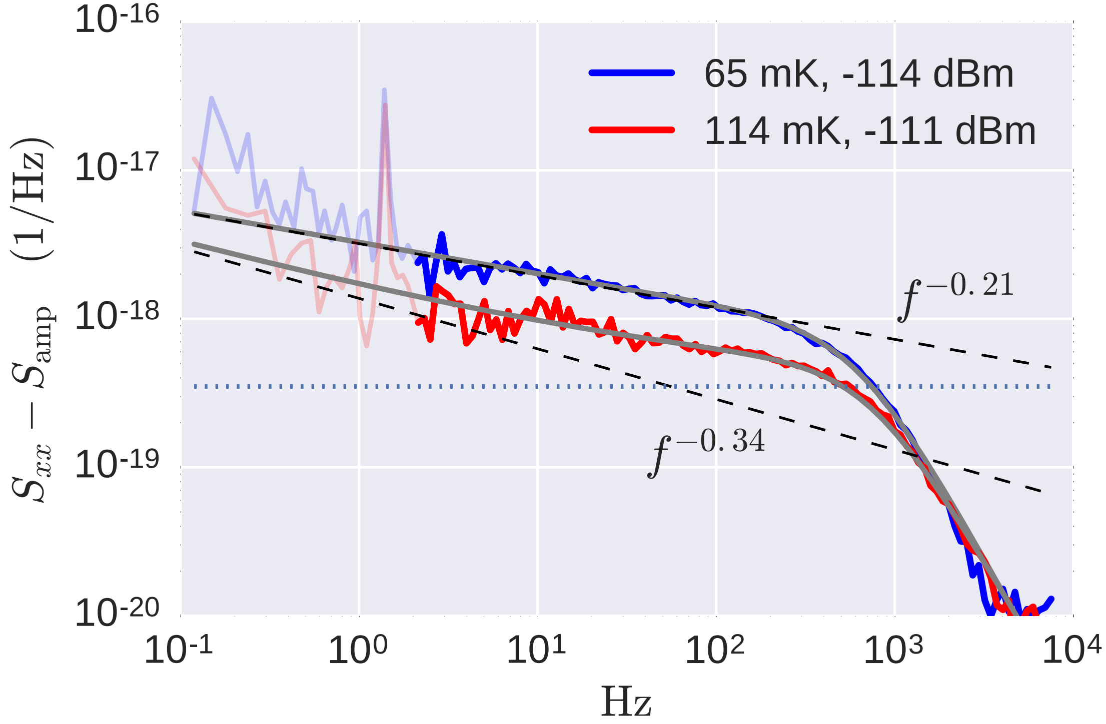
High Q_i AlMn LEKIDs



Jones et al. (2017) *APL*, 110, 222601.

3) Dual-Polarization LEKIDs

McCarrick et al. (2017) A&A, *in preparation*

McCarrick et al. (2016) *Proc. SPIE*, 9914, 99140O.

Bryan et al. (2015) *Proc. ISSTT*, T3-4.

Project supported in part by a ***RISE*** grant, ***ONR*** grant and ***NASA/NESSF***.

Development of dual-polarization LEKIDs for CMB observations

Heather McCarrick[a], Maximilian H. Abitbol[a], Peter A.R. Ade[e], Peter Barry[e], Sean Bryan[b], George Che[b], Peter Day[c], Simon Doyle[e], Daniel Flanigan[a], Bradley R. Johnson[a], Glenn Jones[a], Henry G. LeDuc[c], Michele Limon[a], Philip Mauskopf[b], Amber Miller[a], Carole Tucker[e], and Jonas Zmuidzinas[c,d]

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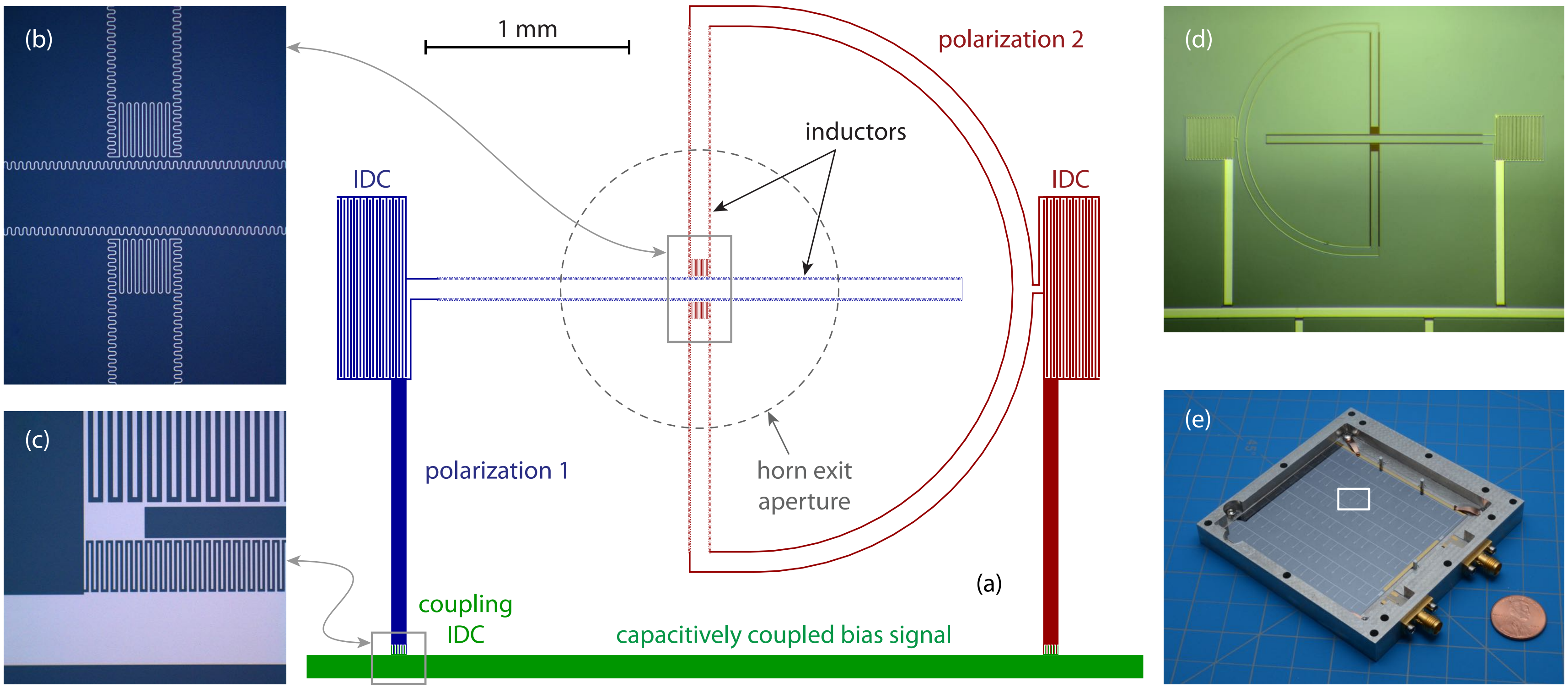
[e]School of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, UK

McCarrick et al. (2016) *Proc. SPIE,* 9914, 99140O.

Dual-Polarization LEKID Development



McCarrick et al. (2017) A&A, *in preparation*

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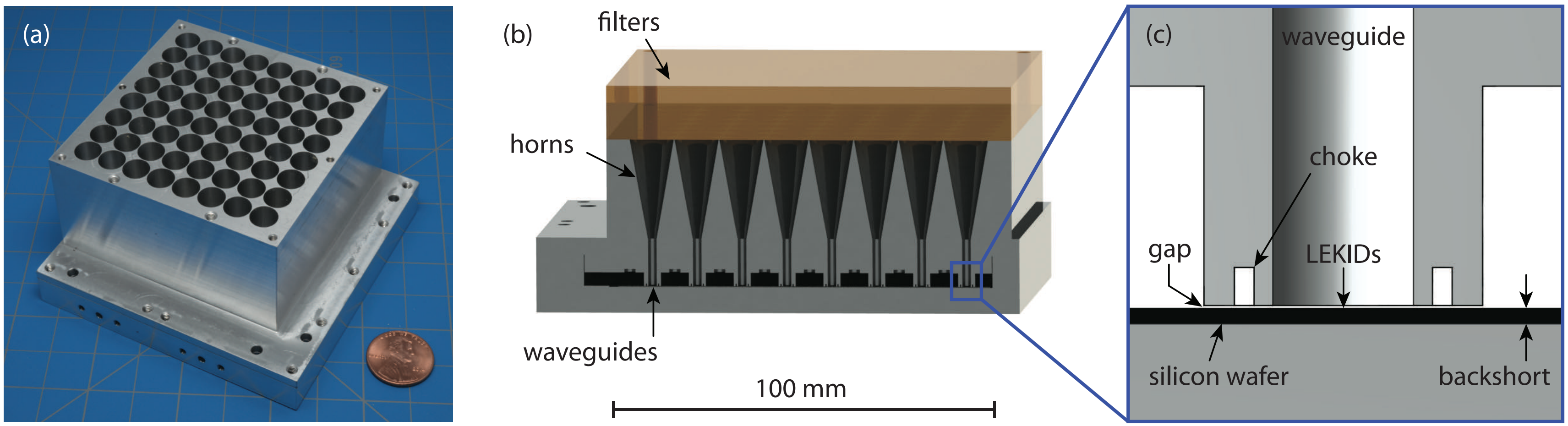
Bryan et al. (2015) *Proc. ISSTT*, T3-4.

Dual-Polarization LEKID Development



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McCarrick et al. (2016) *Proc. SPIE*, 9914, 99140O

Bryan et al. (2015) *Proc. ISSTT*, T3-4.

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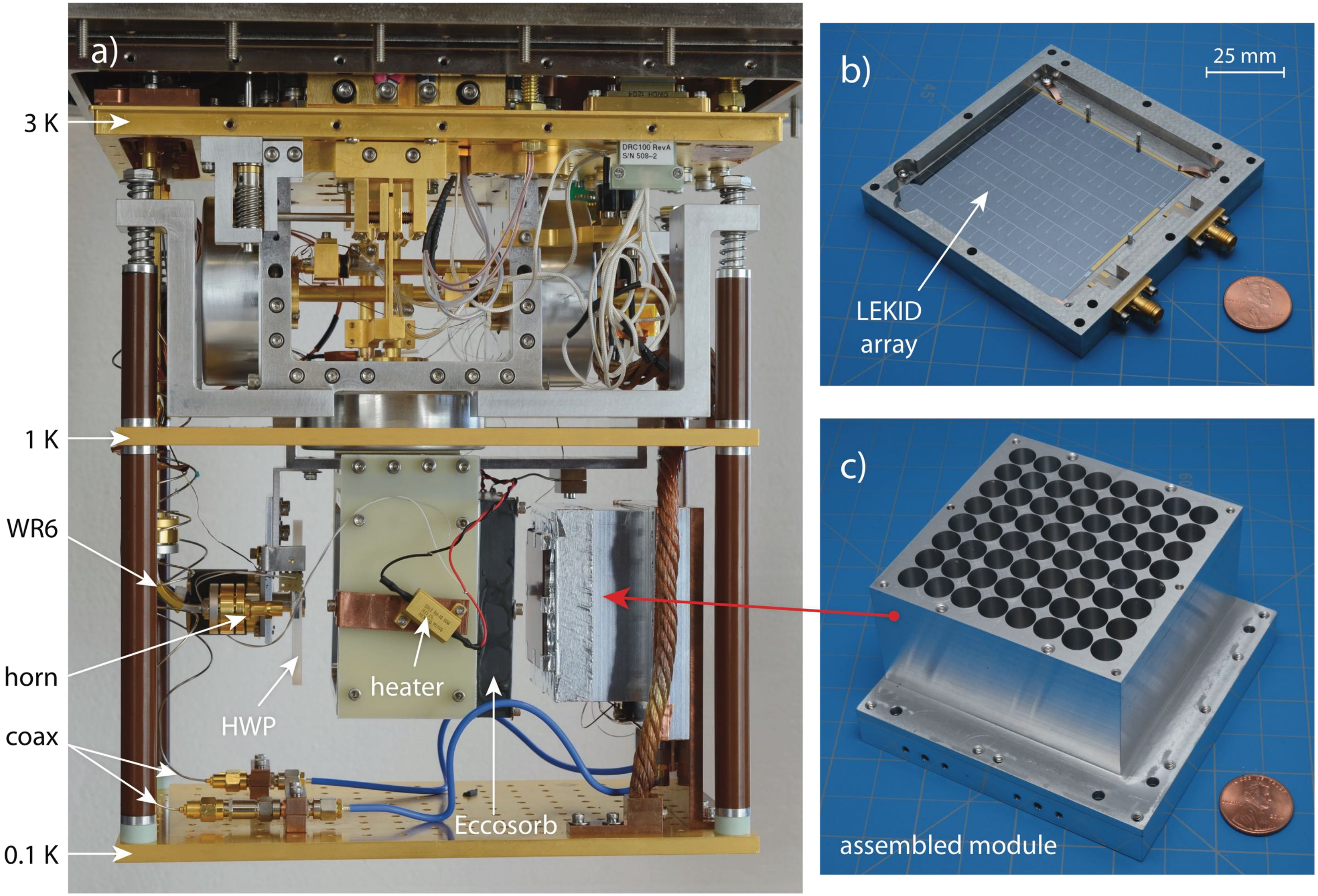
Test Setup with Half-Wave Plate



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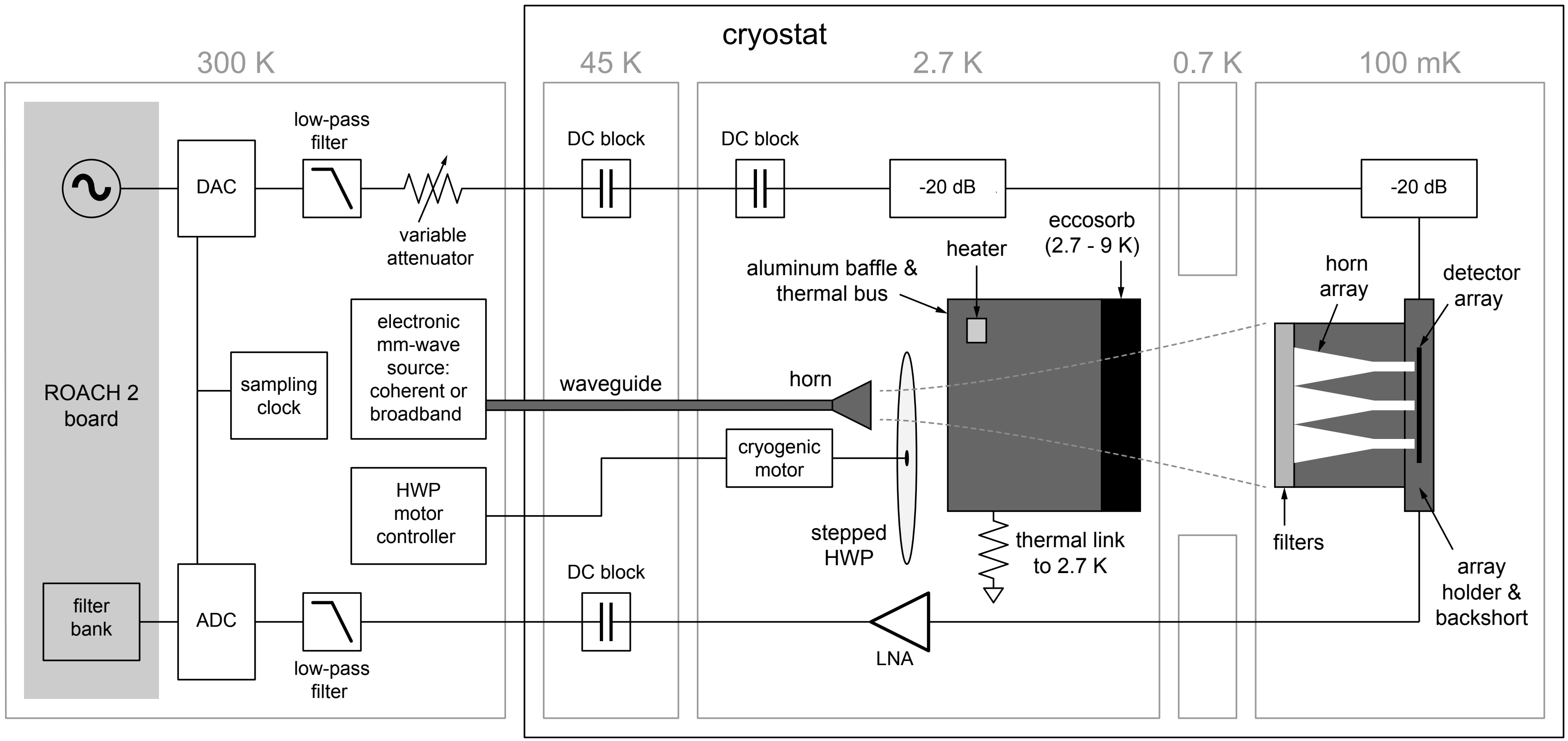
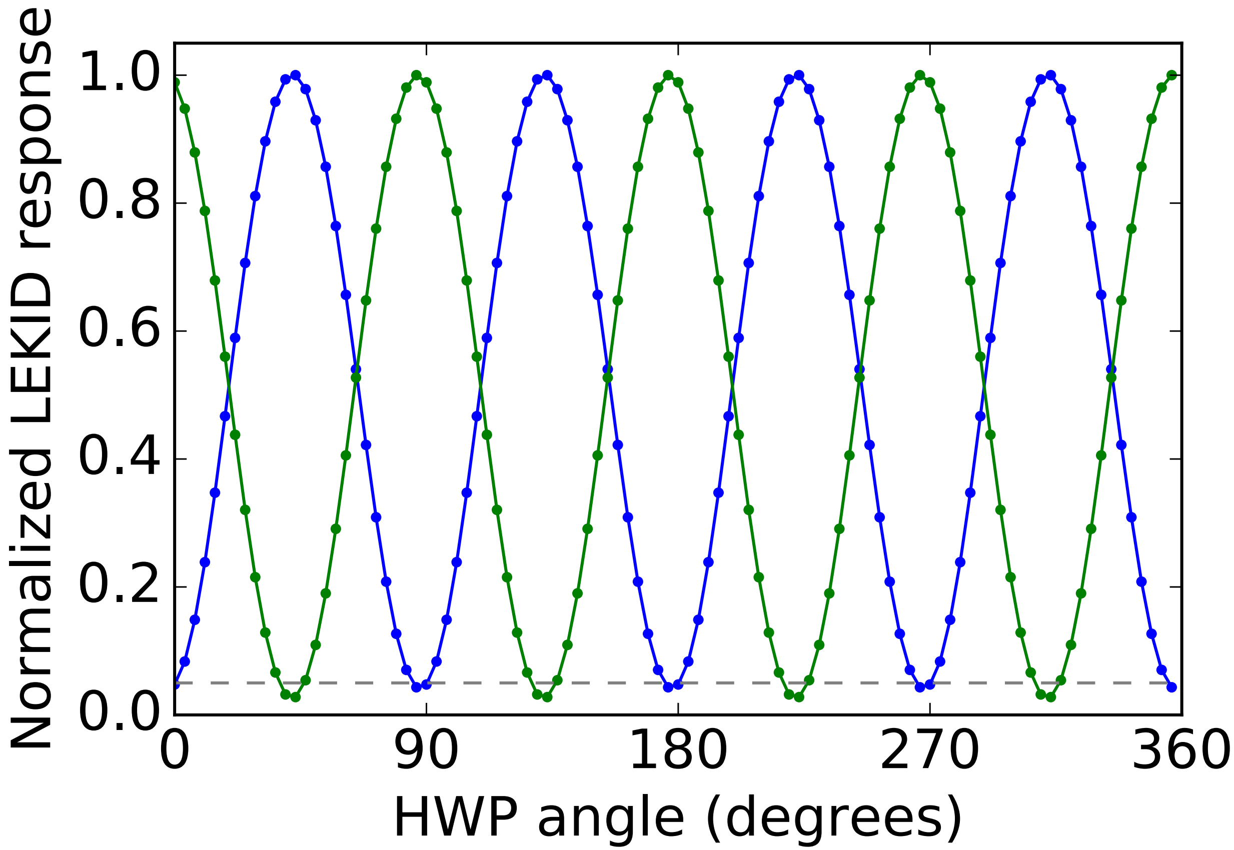
Test Setup with Half-Wave Plate

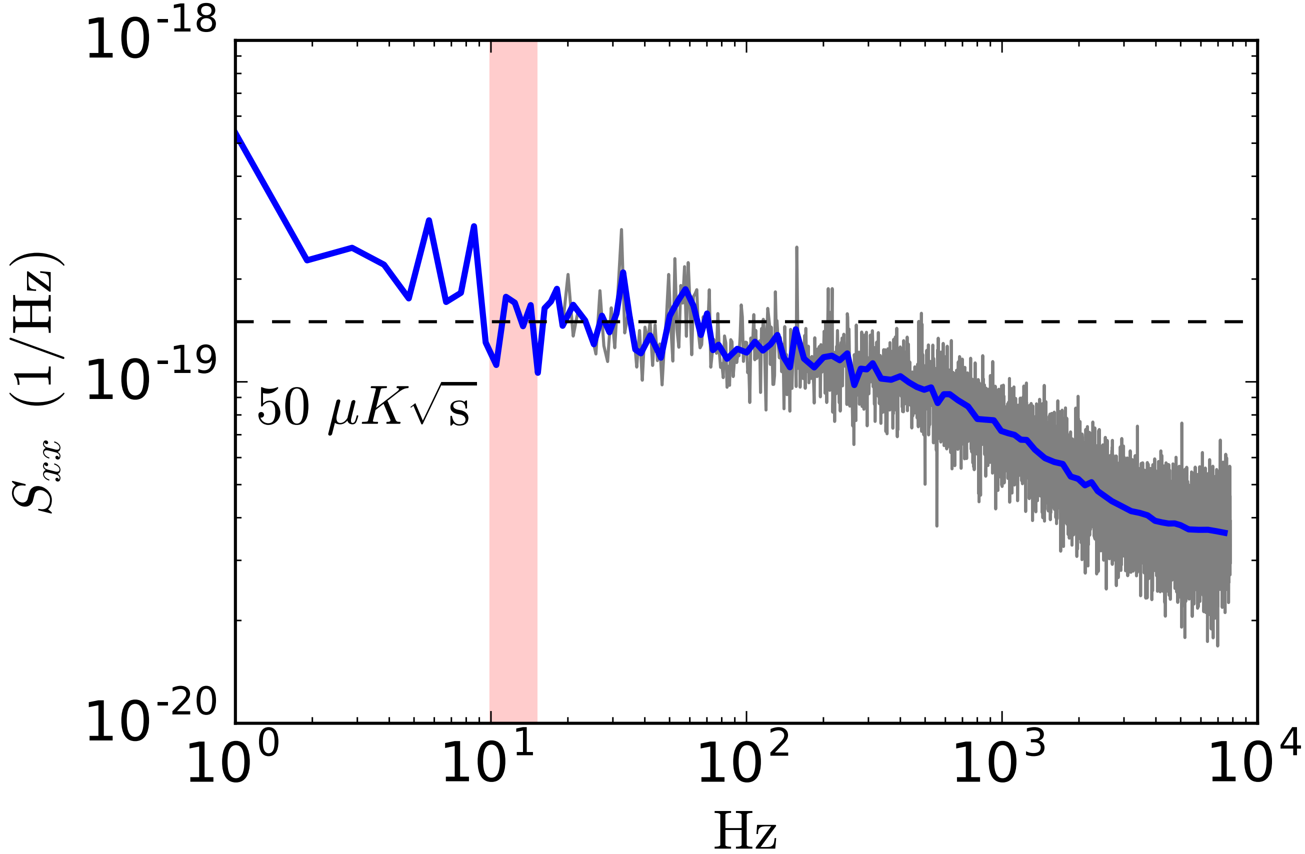


Measured Polarization Response



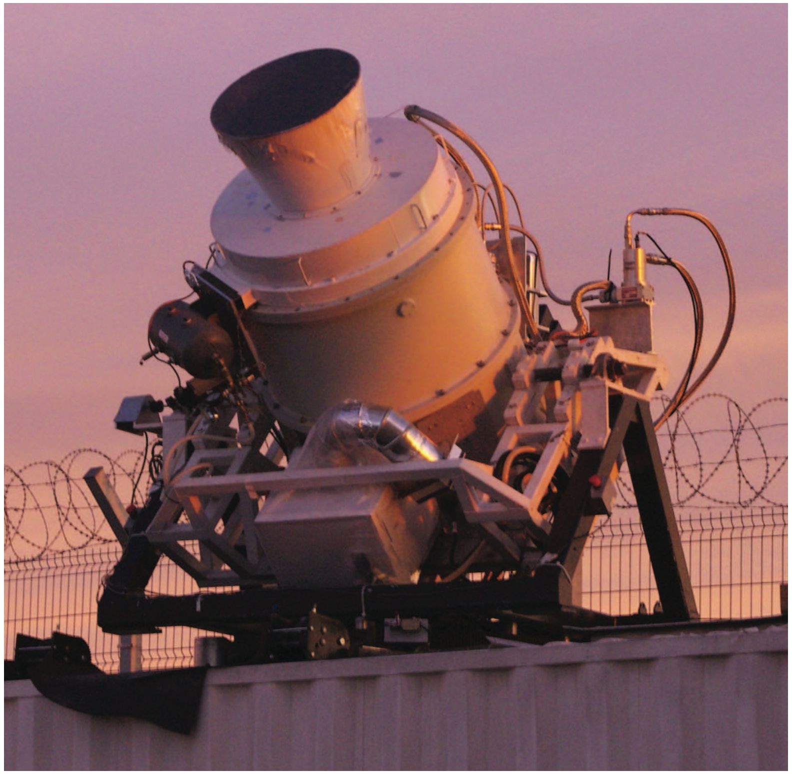
McCarrick et al. (2017) A&A, *in preparation*

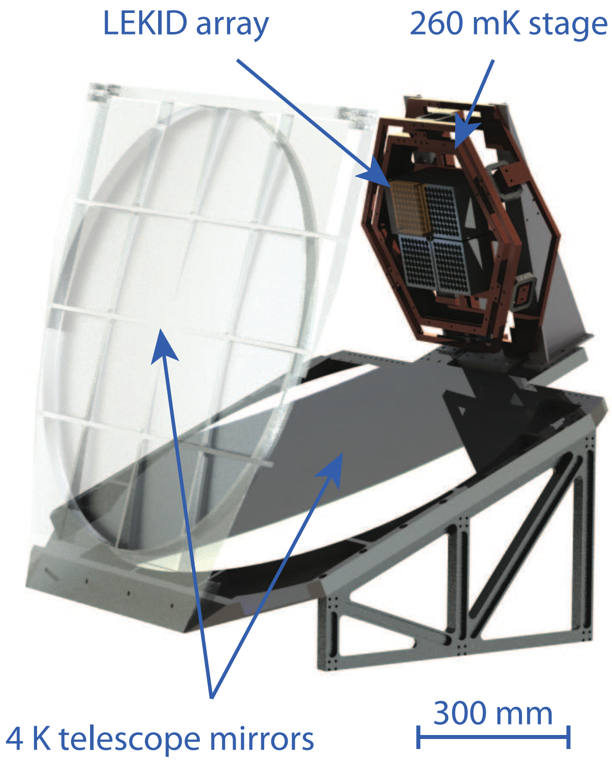
Measured Noise



McCarrick et al. (2017) A&A, *in preparation*

Dual-Polarization LEKIDs in ABS





New collaboration with Tom Essinger-Hileman, Suzanne Staggs, and Lyman Page.

ABS receiver is now at Columbia.

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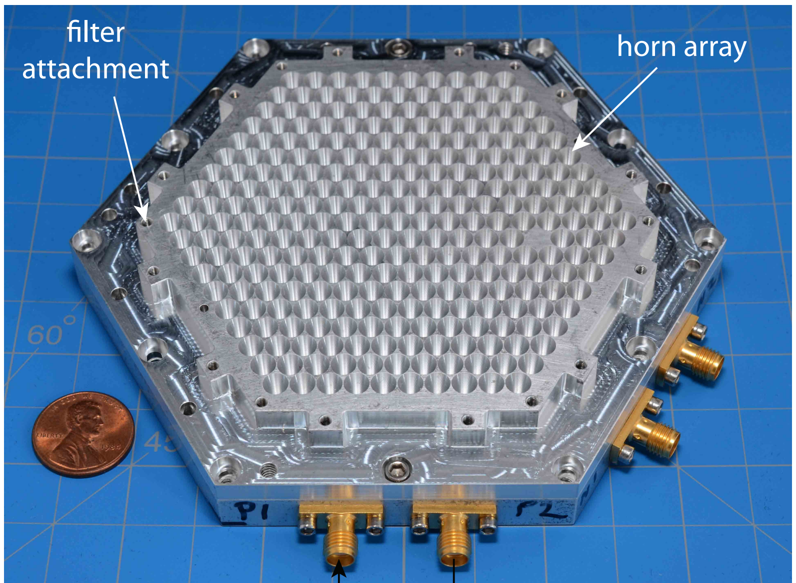
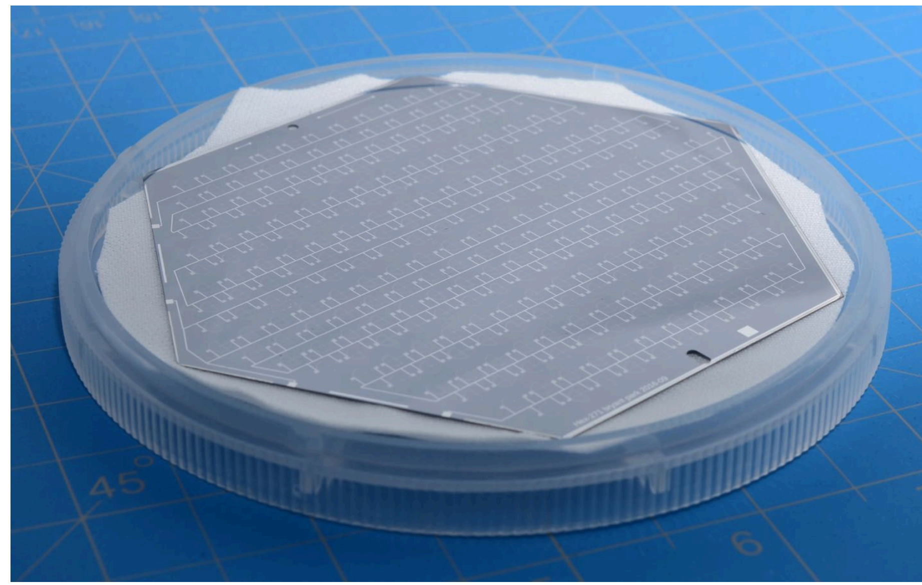
Scaled-Up Array Modules

prototype module (271 horns)



probe tones in

probe tones out to LNA



Arrays fabricated at JPL and BNL.

271 horns, 542 LEKIDs per module

4) Polarization Sensitive Multi-Chroic MKIDs

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

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Polarization Sensitive Multi-Chroic MKIDs

Bradley R. Johnson[a], Daniel Flanigan[a], Maximilian H. Abitbol[a], Peter A. R. Ade[b], Sean Bryan[c], Hsiao-Mei Cho[g], Rahul Datta[e], Peter Day[f], Simon Doyle[b], Kent Irwin[d,g], Glenn Jones[a], Sarah Kernasovskiy[d], Dale Li[g], Phil Mauskopf[c], Heather McCarrick[a], Jeff McMahon[e], Amber Miller[a], Giampaolo Pisano[b], Yanru Song[d], Harshad Surdi[c], and Carole Tucker[b]

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[d]Department of Physics, Stanford University, Stanford, CA, 94305-4085, USA;
[e]Department of Physics, University of Michigan, Ann Arbor, MI, 48103, USA;
[f]NASA, Jet Propulsion Lab, Pasadena, CA, 91109, USA;
[g]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

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

Overview

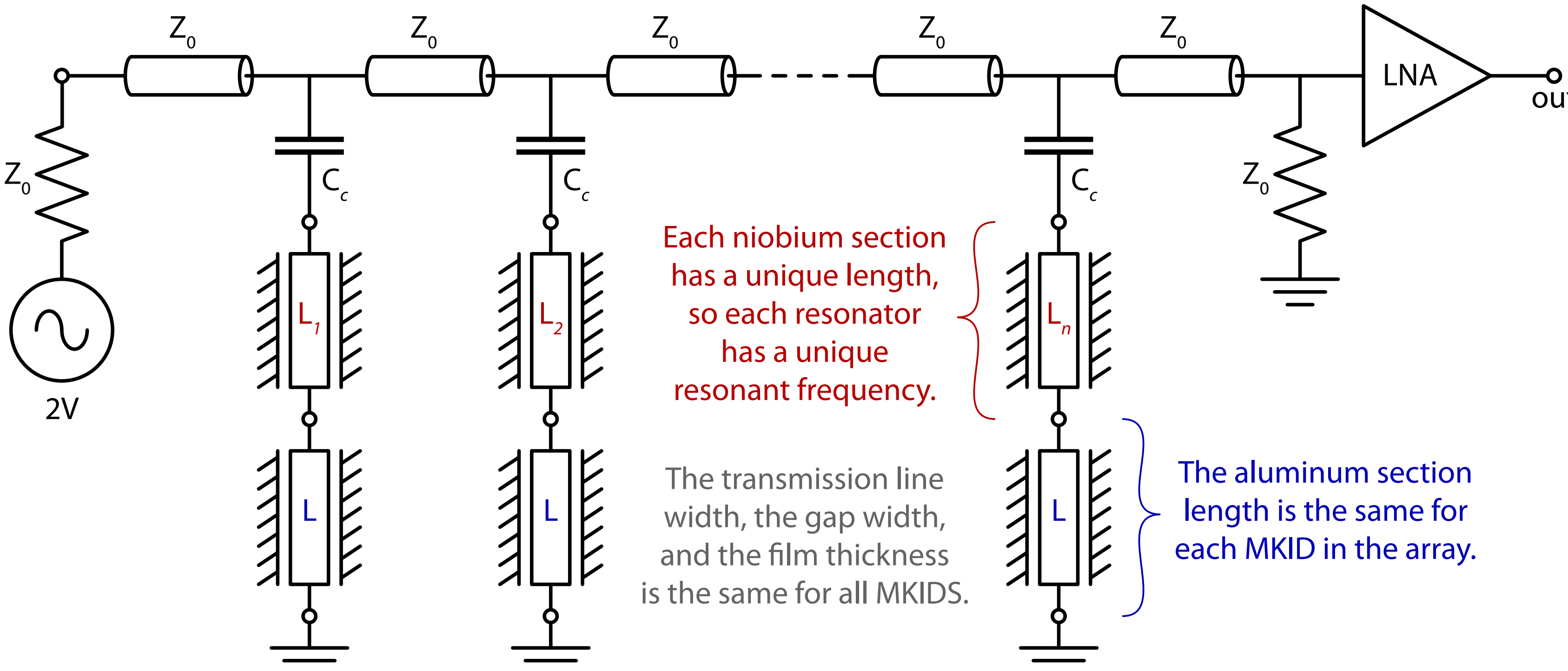
- We are developing scalable modular arrays of **horn-coupled, polarization-sensitive MKIDs** that are each sensitive to **two spectral bands between 125 and 280 GHz**.

- 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 a **future CMB satellite mission and/or CMB-S4**.

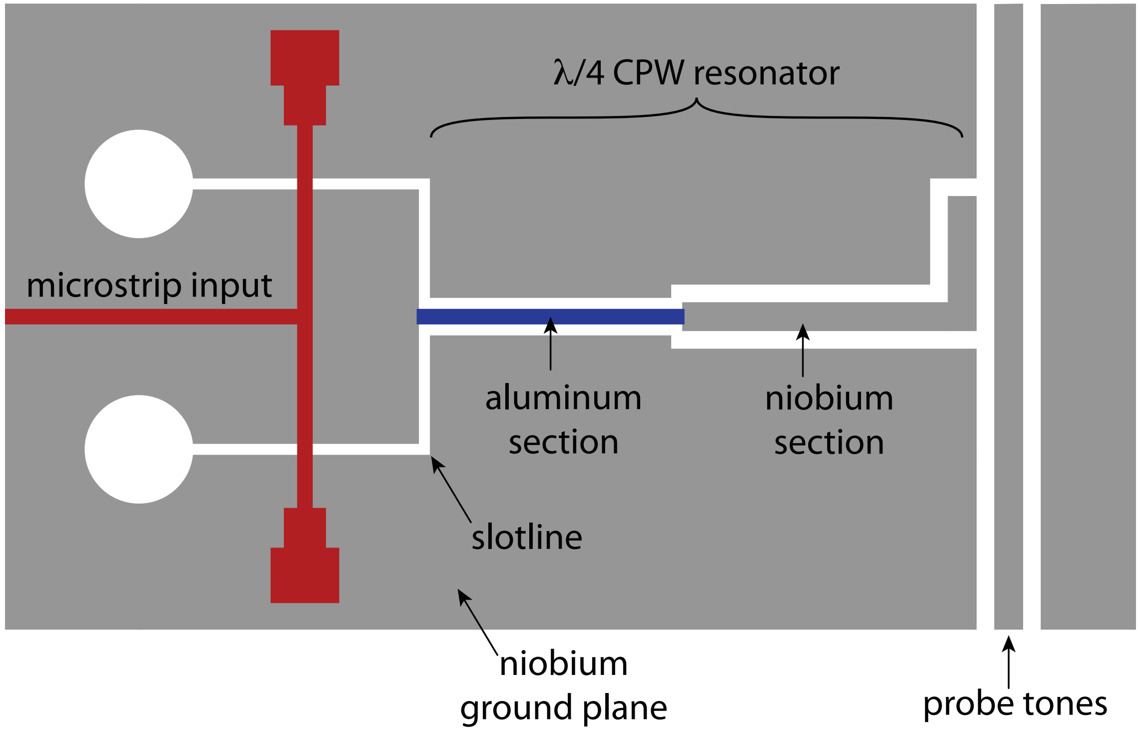
- Our device **design builds from successful transition edge sensor (TES) bolometer architectures** that have been developed by the Truce Collaboration and demonstrated to work in receivers on the ACT and SPT telescopes.

Multiplexing the Array



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

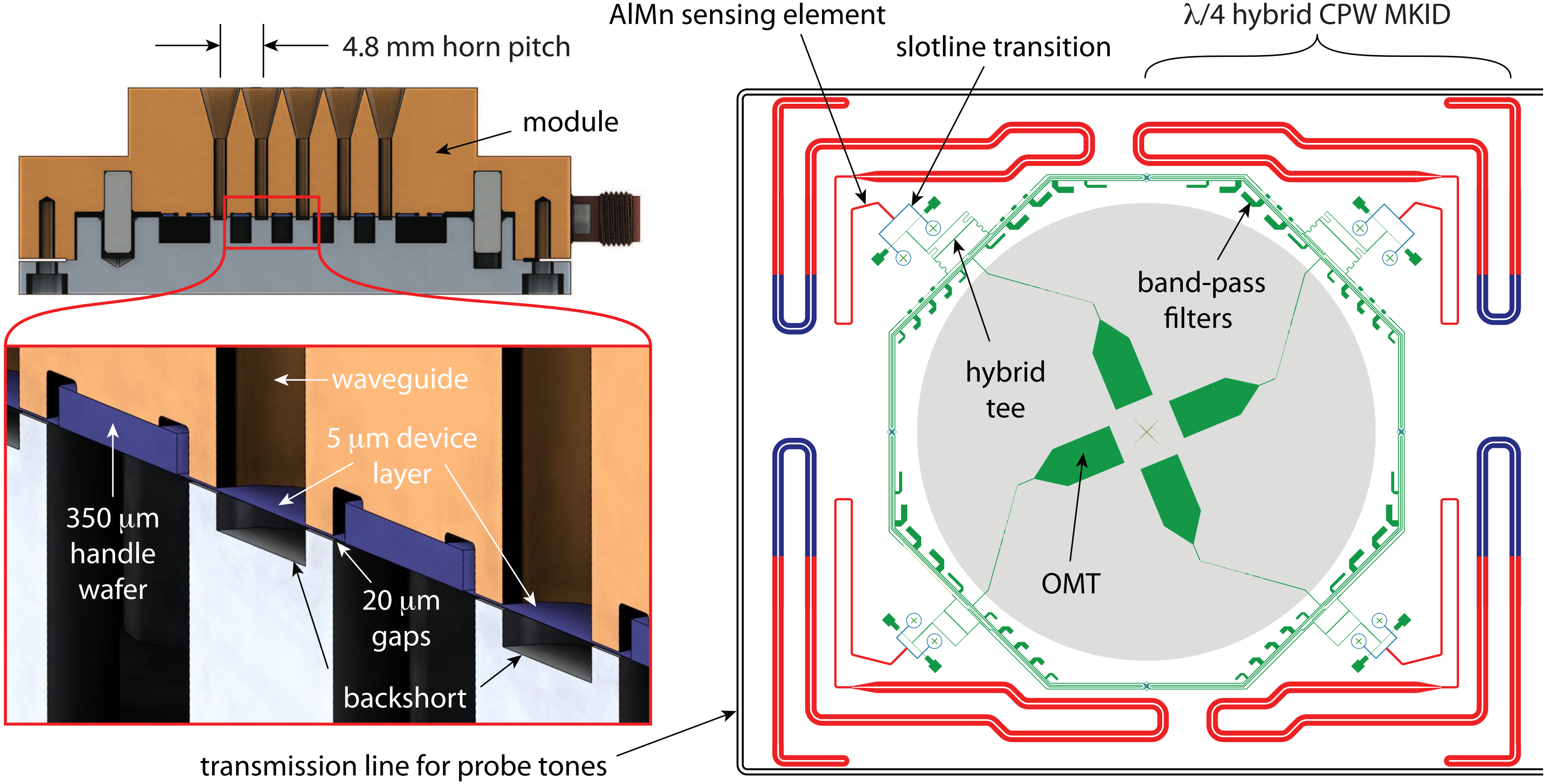
Microstrip-to-CPW MKID Coupling Schematic



Surdi, H. (2016) "*Applications of Kinetic Inductance: Parametric Amplifier & Phase Shifter, 2DEG Coupled Co-planar Structures & Microstrip to Slotline Transition at RF Frequencies*." Dissertation at ASU.

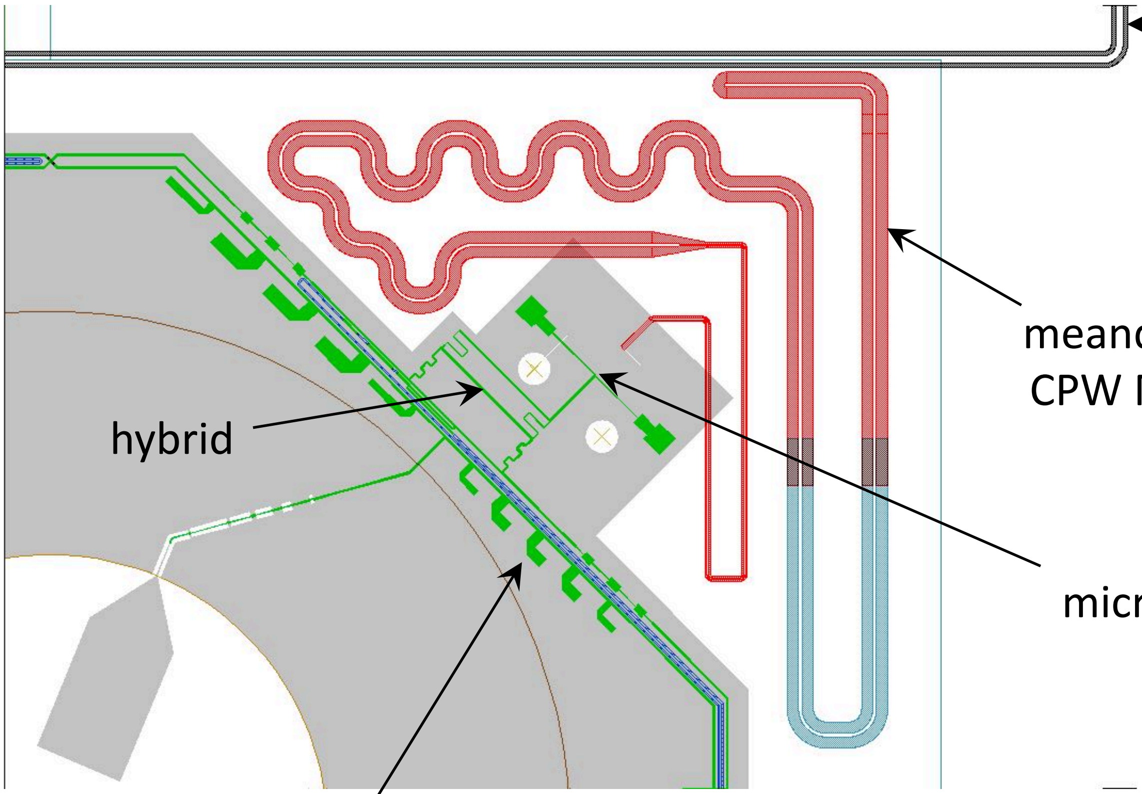
Johnson et al. (2016) *Proc. SPIE*, 9914, 99140X

Development of Multi-Chroic MKIDs



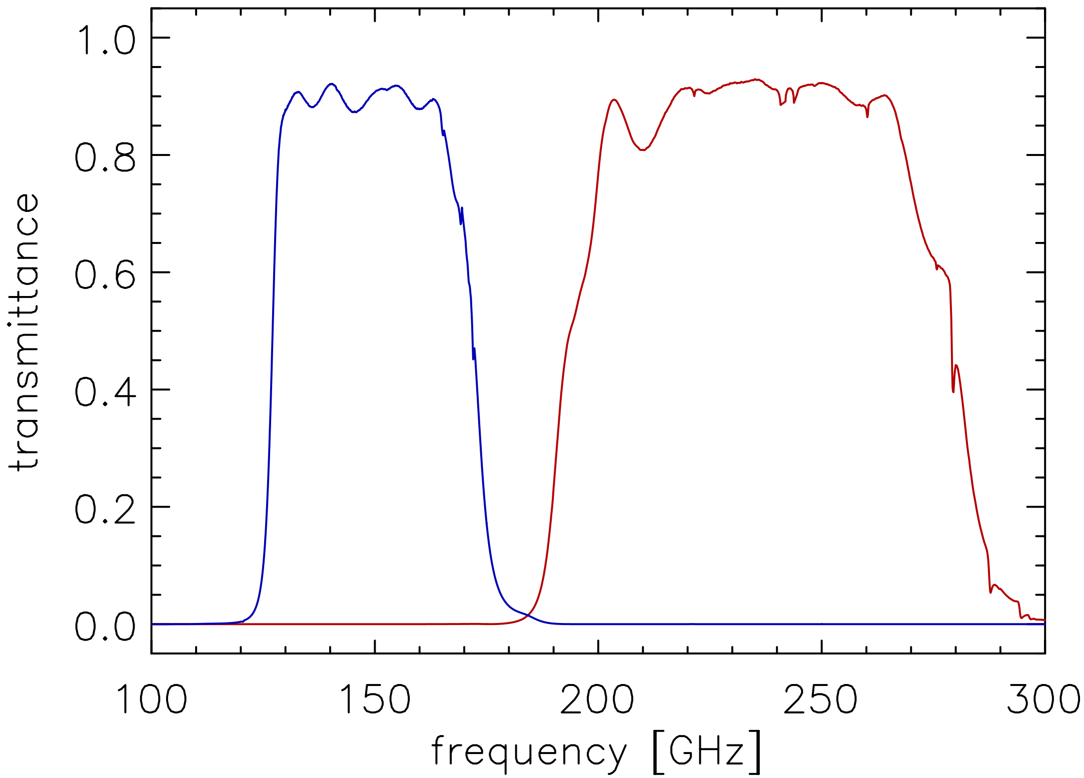
based on: Datta et al. (2014) *J. Low Temp. Phys.* 176, 670–676

Array Element Details



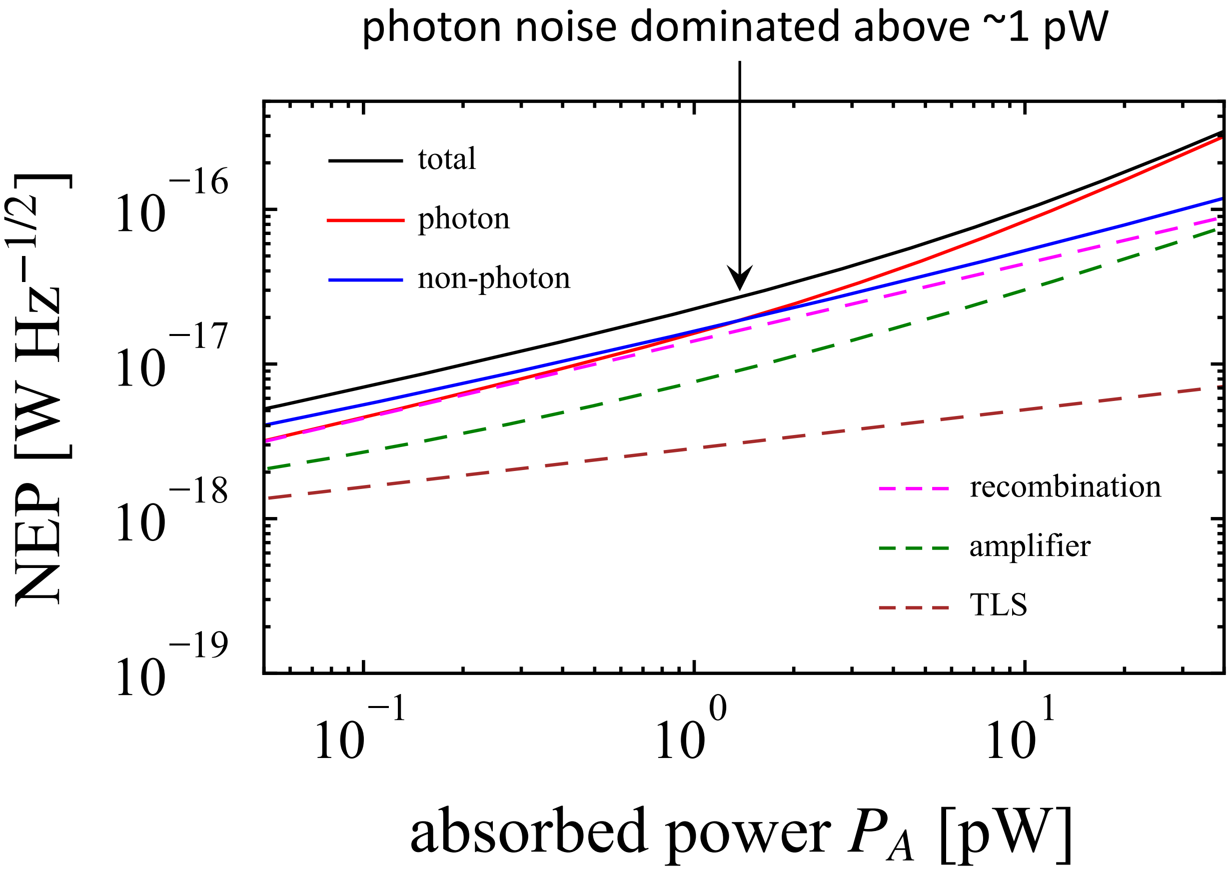
MKID resonant frequencies around 3 GHz

Simulated Spectral Bands



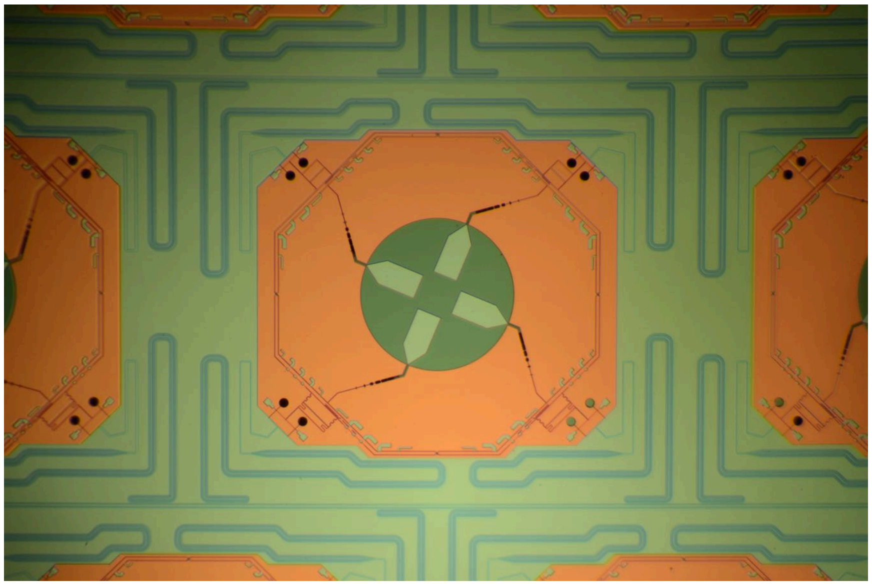
HFSS/Sonnet simulation results show the expected absorption efficiency is approximately 90% taking into account all of the elements in the circuit except the OMT probes.

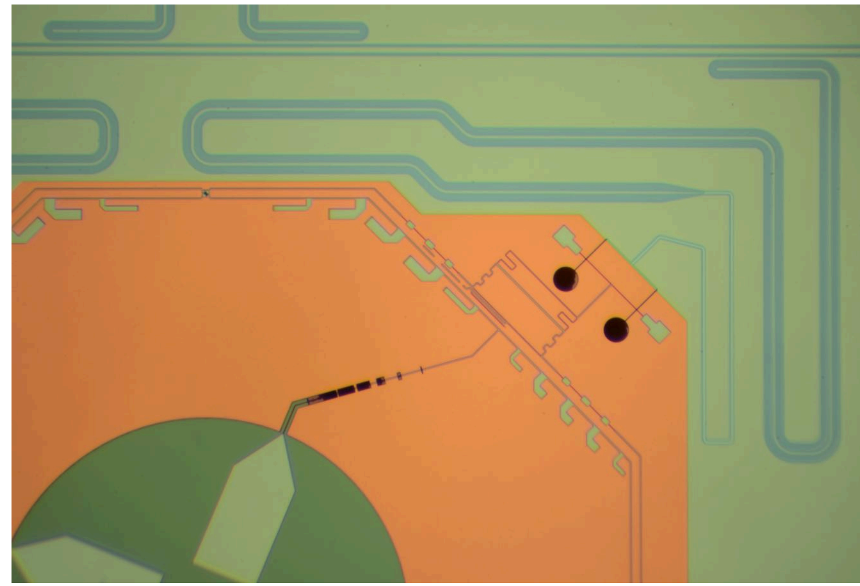
Noise Sources and Expected NEP @ 150 GHz



We have **plans to fabricate aluminum manganese sensors**, which will make the MKIDs photon-noise dominated at lower absorbed power levels.

Photographs of First Devices

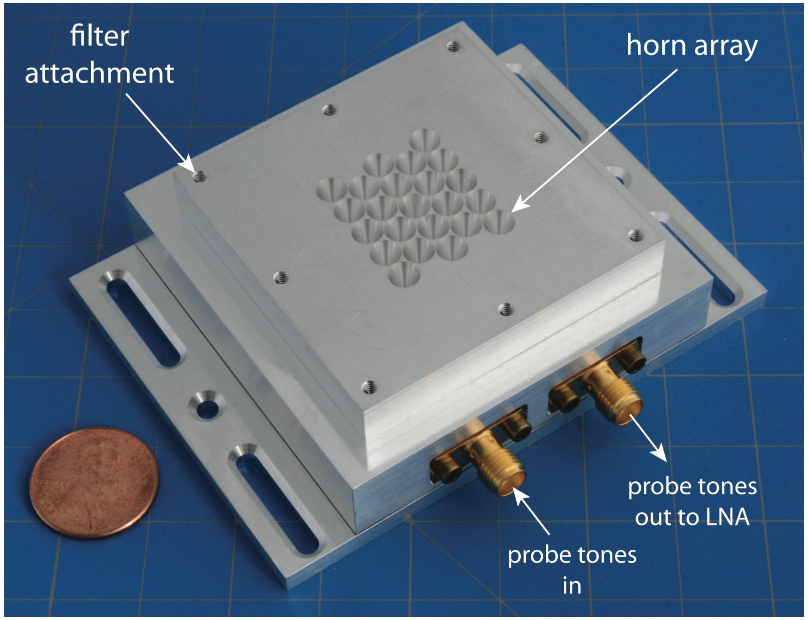


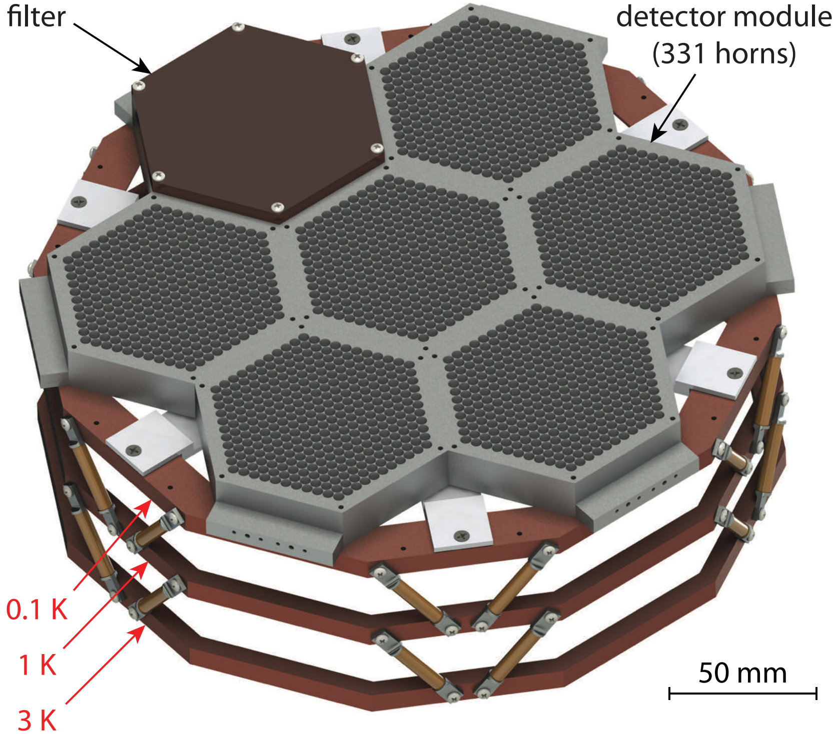


Fabricated at Stanford

Multi-Chroic MKID Array Goal

prototype module (23 horns)



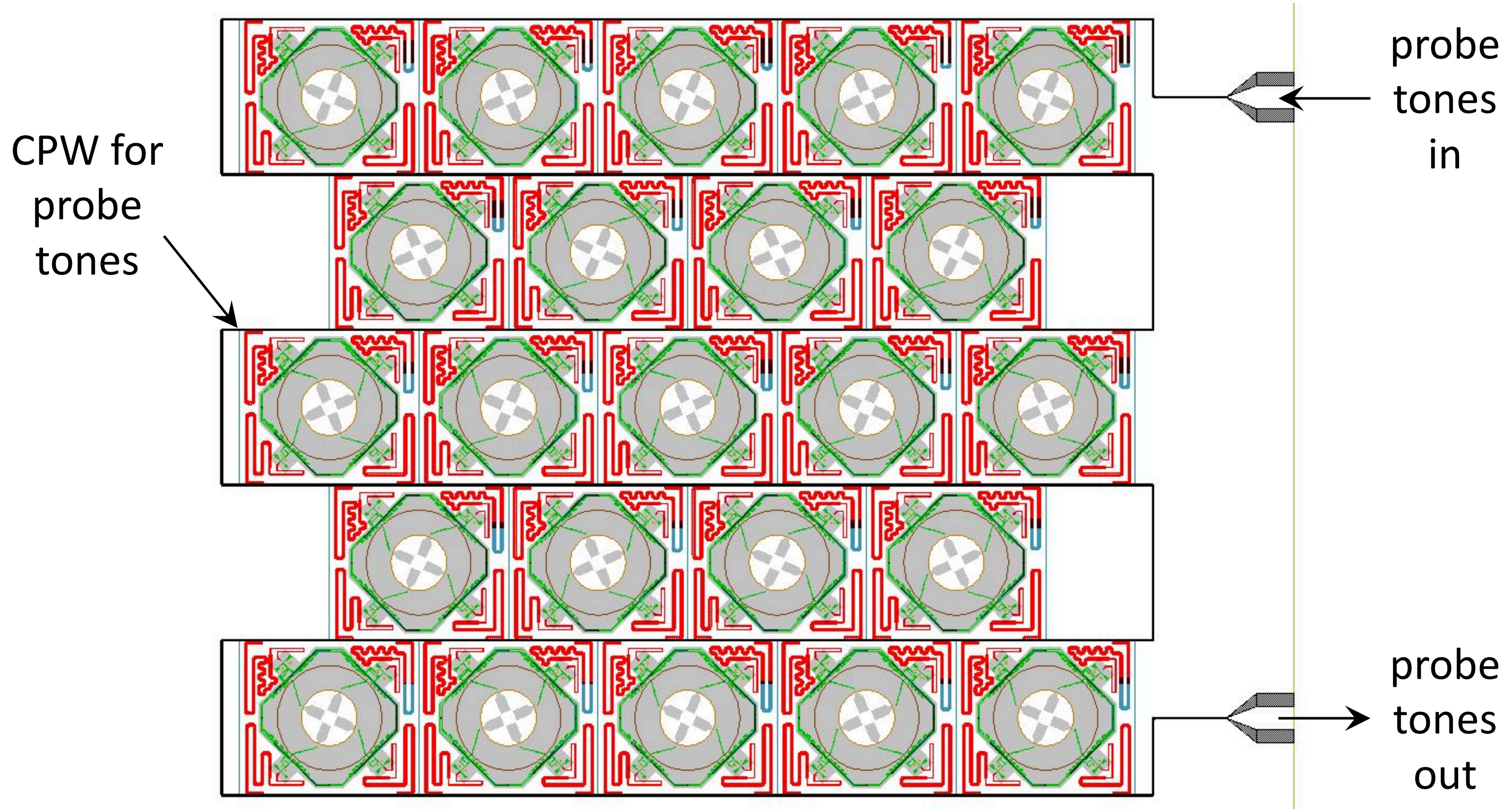


start with scalable, 23-element prototype module …

… scale up to 2317 horns or 9268 detectors

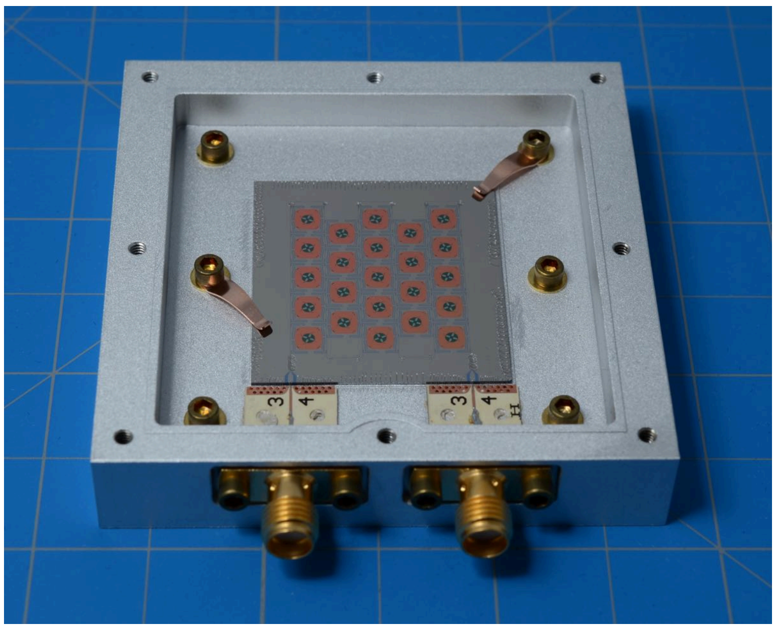
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Layout of Prototype Array

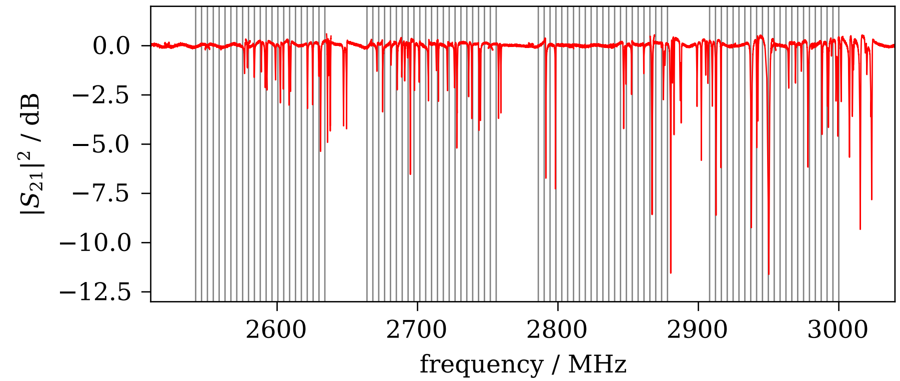


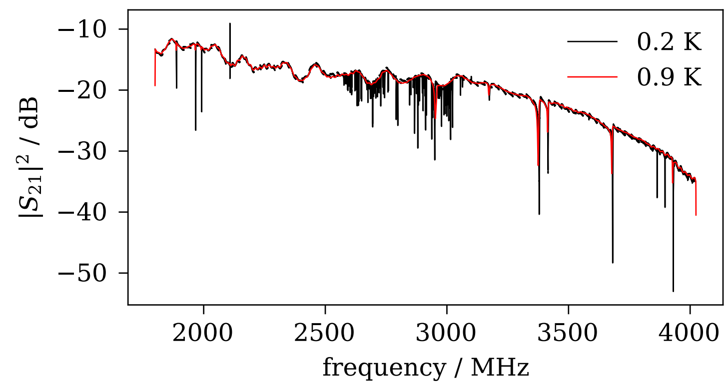
23 elements in the array

Development of Multi-Chroic MKIDs

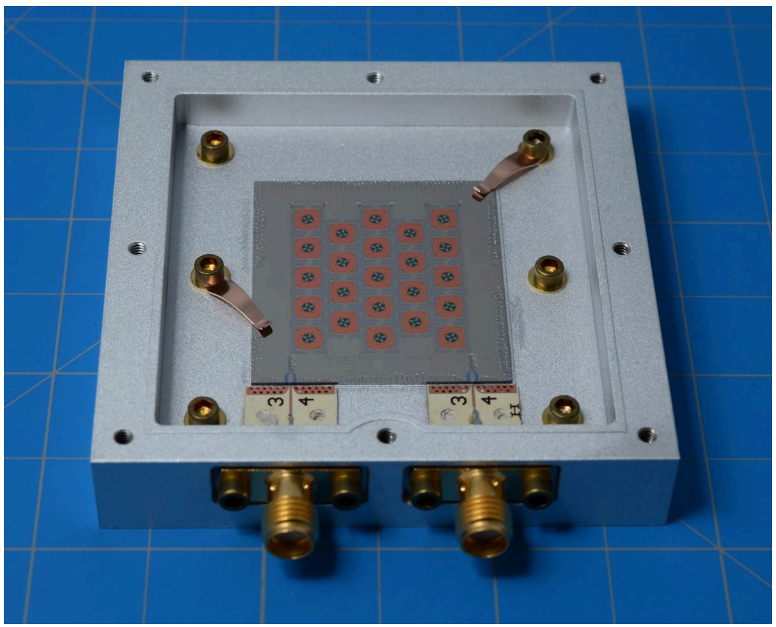


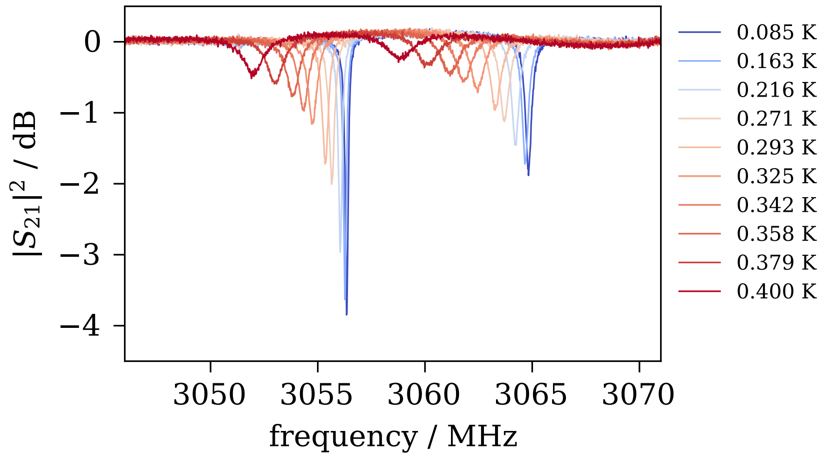
92 of 92 resonators found

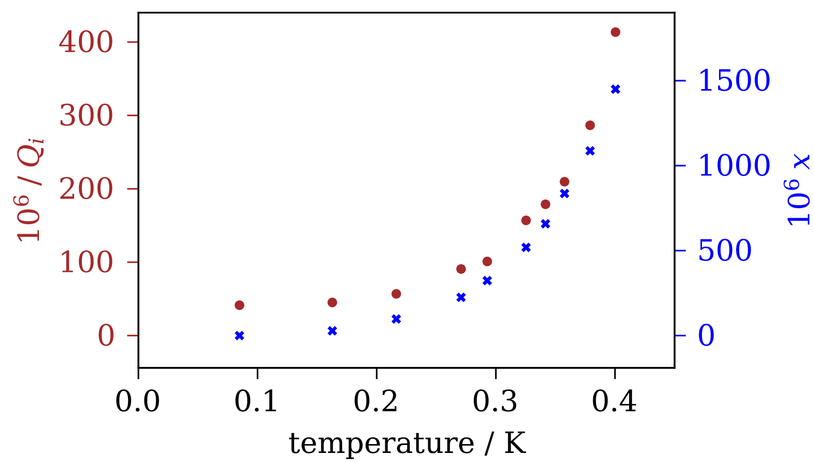




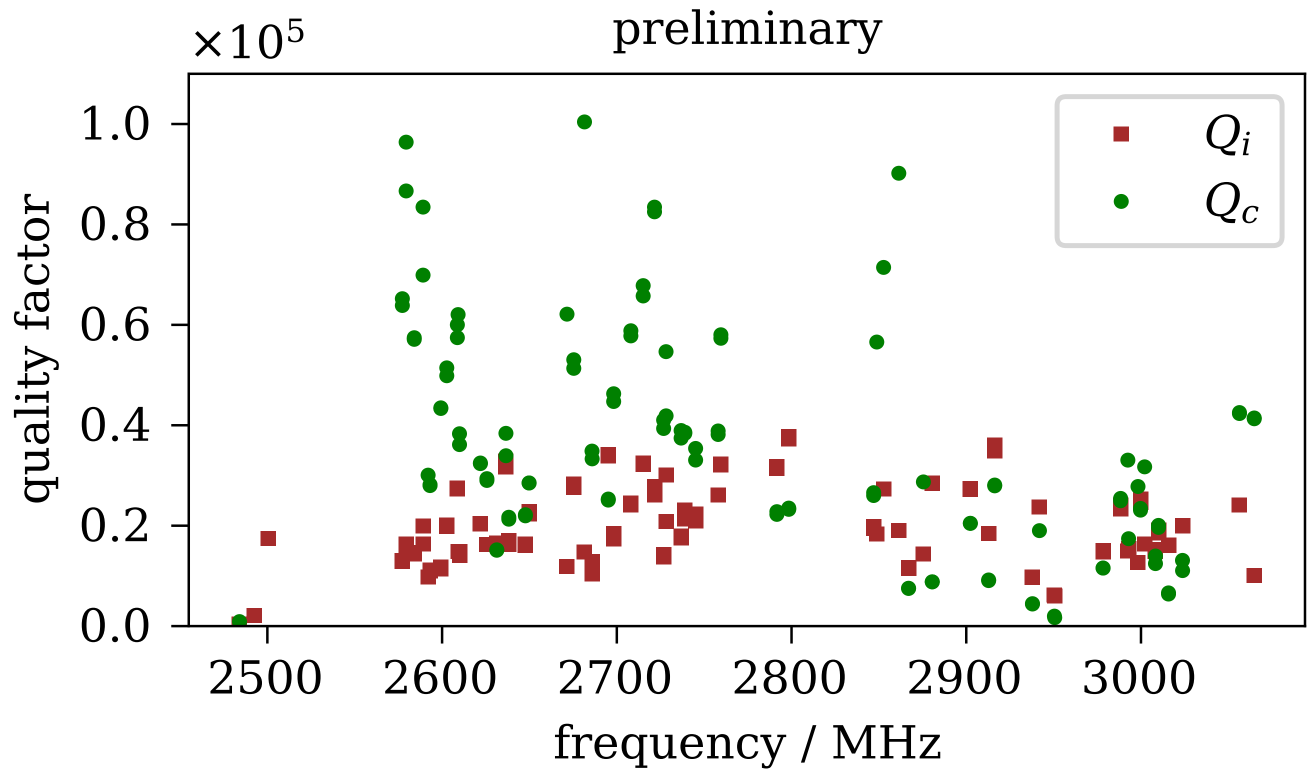
Development of Multi-Chroic MKIDs



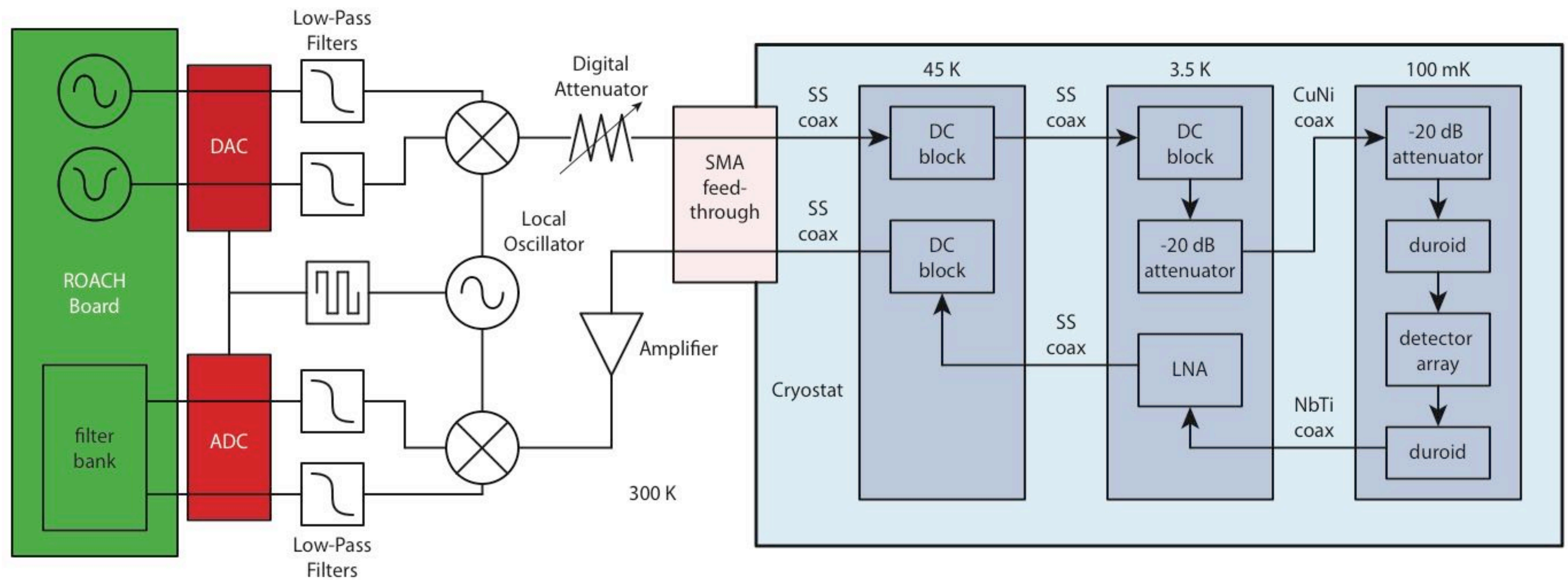




Development of Multi-Chroic MKIDs



Schematic of Readout System

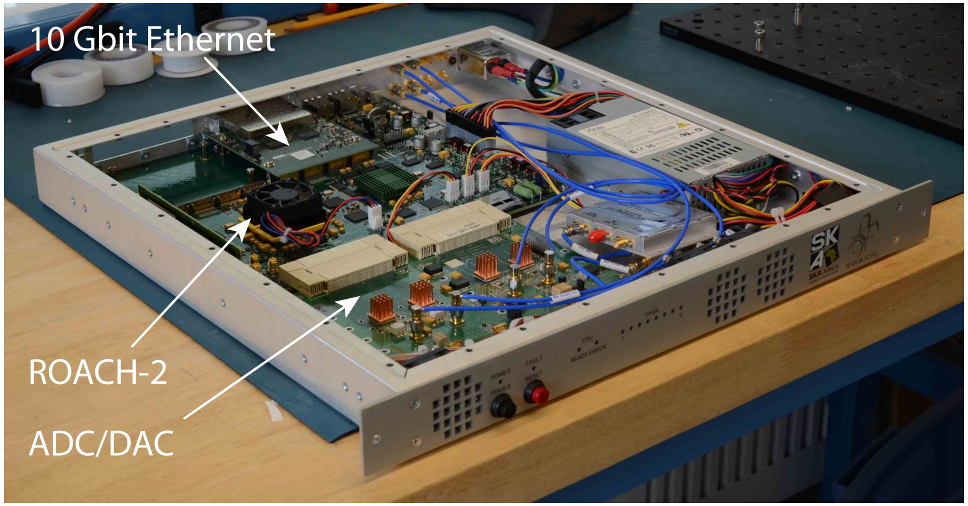


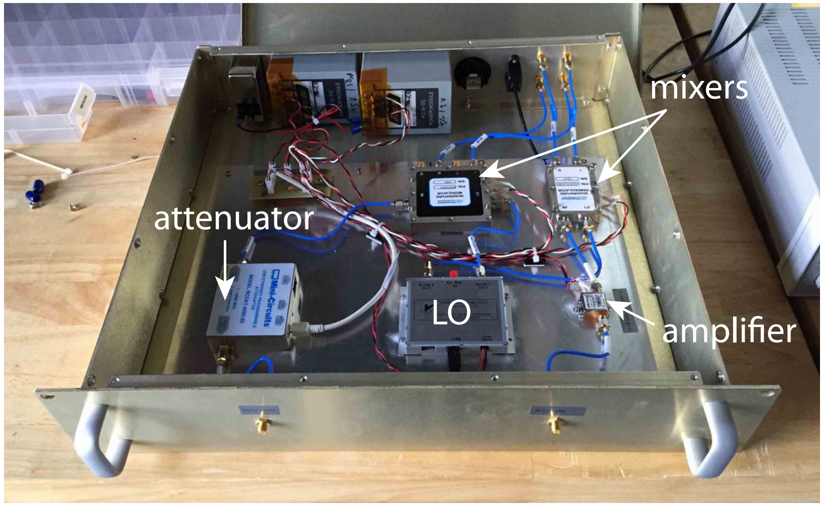
ROACH and ADC/DAC

analog circuit

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

ROACH-2, ADC/DAC, and Analog Circuit

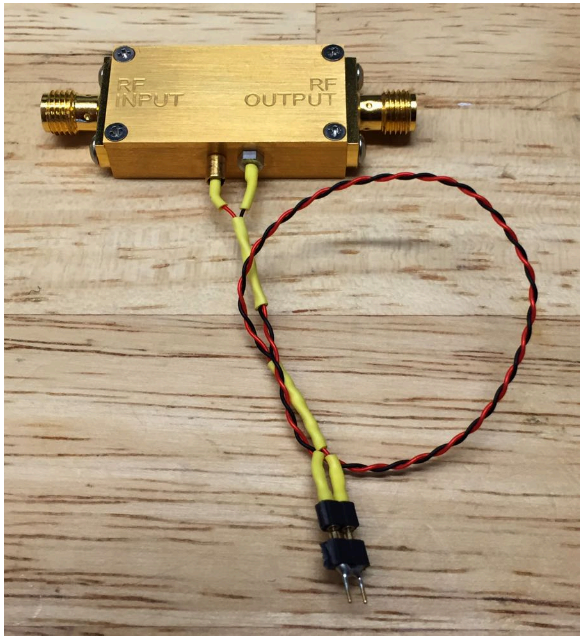


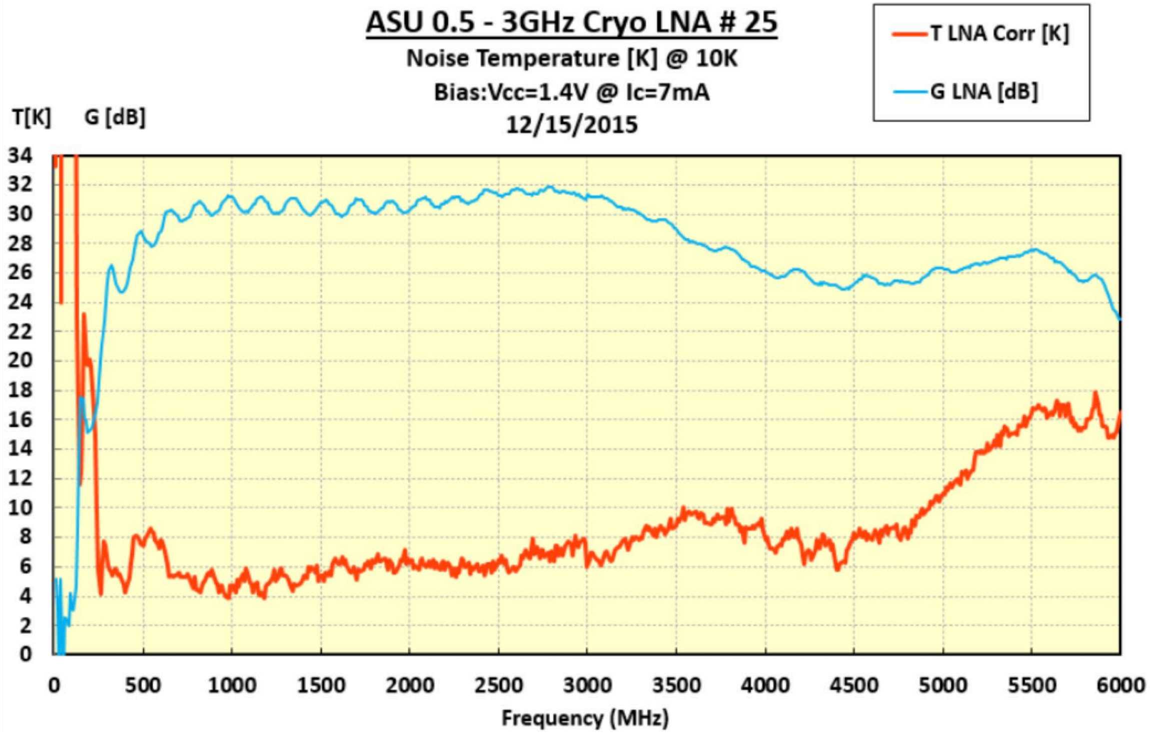


Analog signal conditioning system based around Polyphase Microwave quadrature modulators and demodulators is used to convert the baseband signals generated and analyzed by the ROACH-2 to the target ~3 GHz readout band.

SiGe LNA from ASU

SiGe LNA from ASU





resonant frequencies around 3 GHz

Summary

MKIDs have characteristics that could be useful for CMB studies:

- high multiplexing factors
- no SQUIDs
- no delicate membranes
- Fast time constants
- Low power consumption readout
- Some architectures have been fabricated in commercial foundries.

We are developing three different KID varieties:

- “single-polarization” LEKIDs
- dual-polarization LEKIDs
- multi-chroic dual-polarization MKIDs (supported by NSF/ATI)

ROACH-2-based readout system has been developed.

Measured noise properties look promising.

We are developing a dual-polarization LEKID array for ABS for on-sky testing.