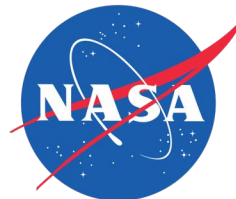


Development of Polarization Sensitive Multi-Chroic MKIDs for CMB Studies



Development of Polarization Sensitive Multi-Chroic MKIDs for CMB Studies

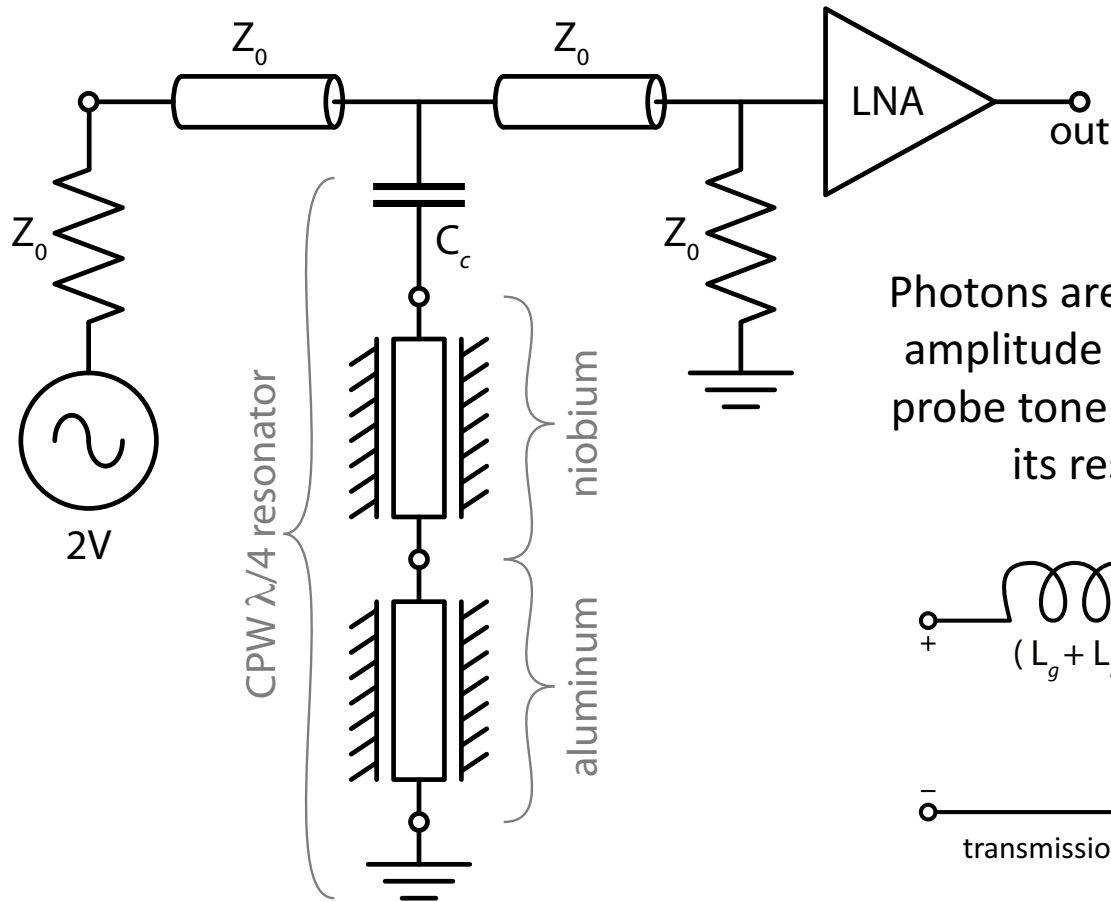
B. R. Johnson (PI), D. Flanigan, M. H. Abitbol, P. A. R. Ade, S. Bryan, H.-M. Cho, R. Datta, P. Day, S. Doyle, K. Irwin, G. Jones, S. Kernasovskiy, D. Li, P. Mauskopf, H. McCarrick, J. McMahon, A. Miller, G. Pisano, Y. Song, H. Surdi, C. Tucker

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

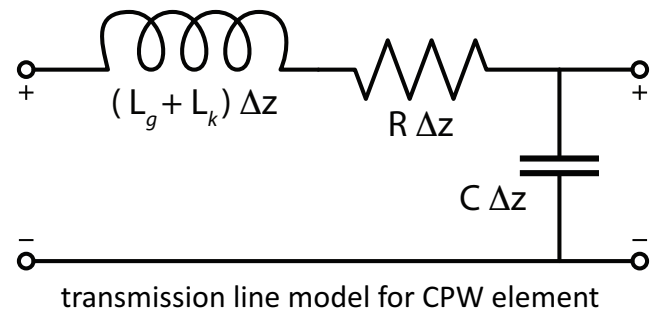
Overview

- 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.

Schematic for One CPW MKID

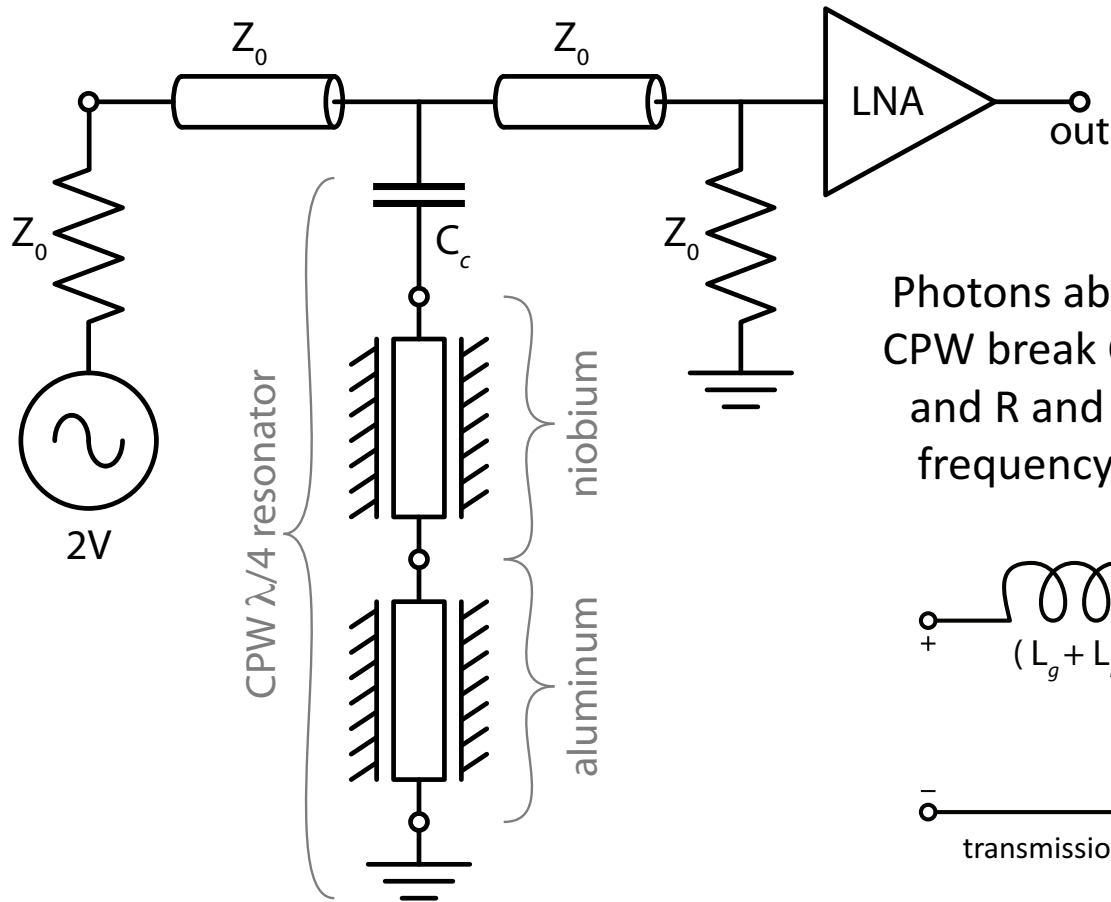


Photons are detected by measuring amplitude and phase changes in a probe tone driving the resonator at its resonant frequency.

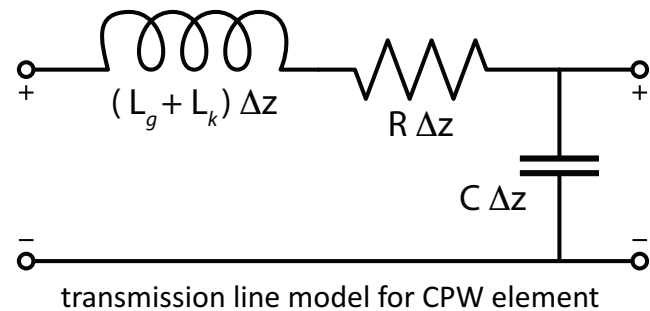


See for example, Day et al. (2003) *Nature* 425, 817-821
 Yates et al. (2011) *APL*. 99, 7

Schematic for One CPW MKID

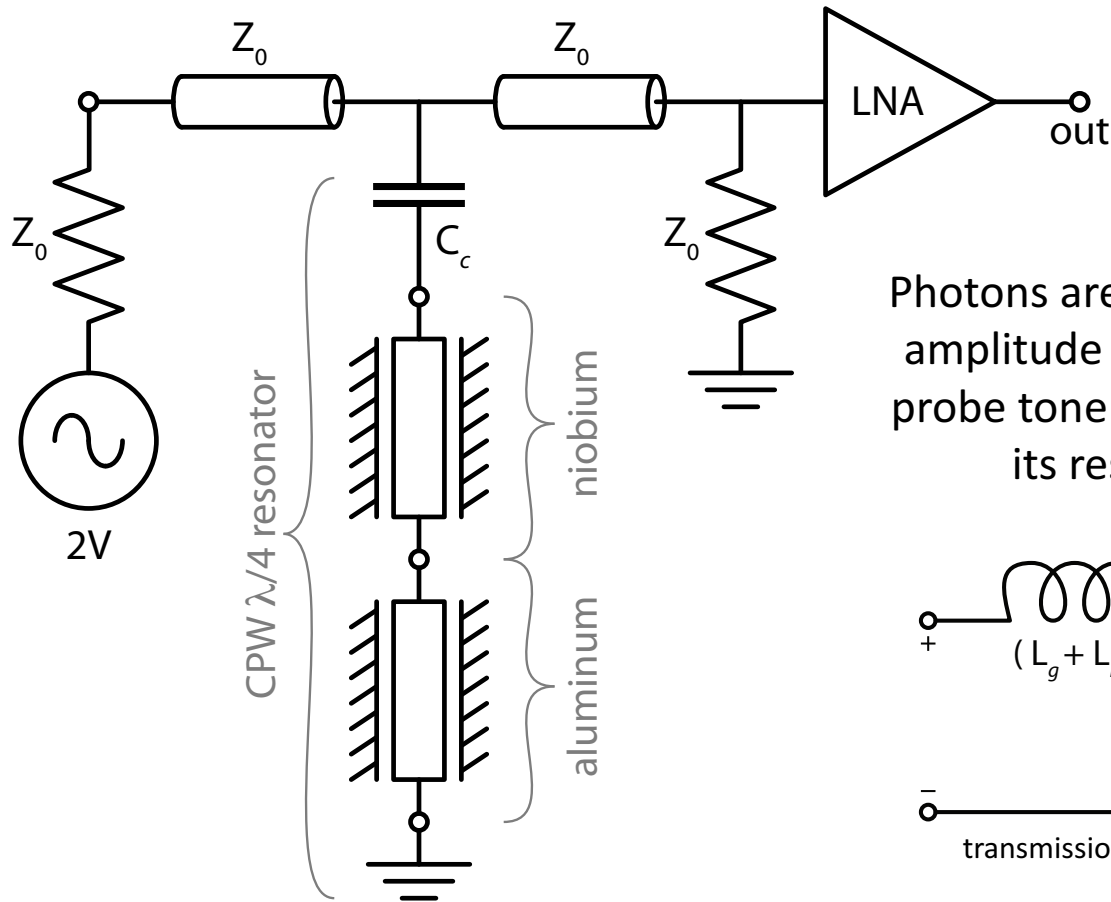


Photons absorbed in the aluminum CPW break Cooper pairs changing L_k and R and therefore the resonant frequency and the quality factor.

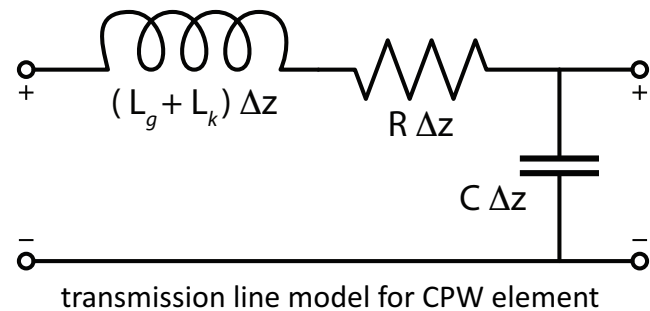


$$\nu_g = \frac{2\Delta}{h} \approx 74 \text{ GHz} \times \frac{T_c}{1 \text{ K}}$$

Schematic for One CPW MKID

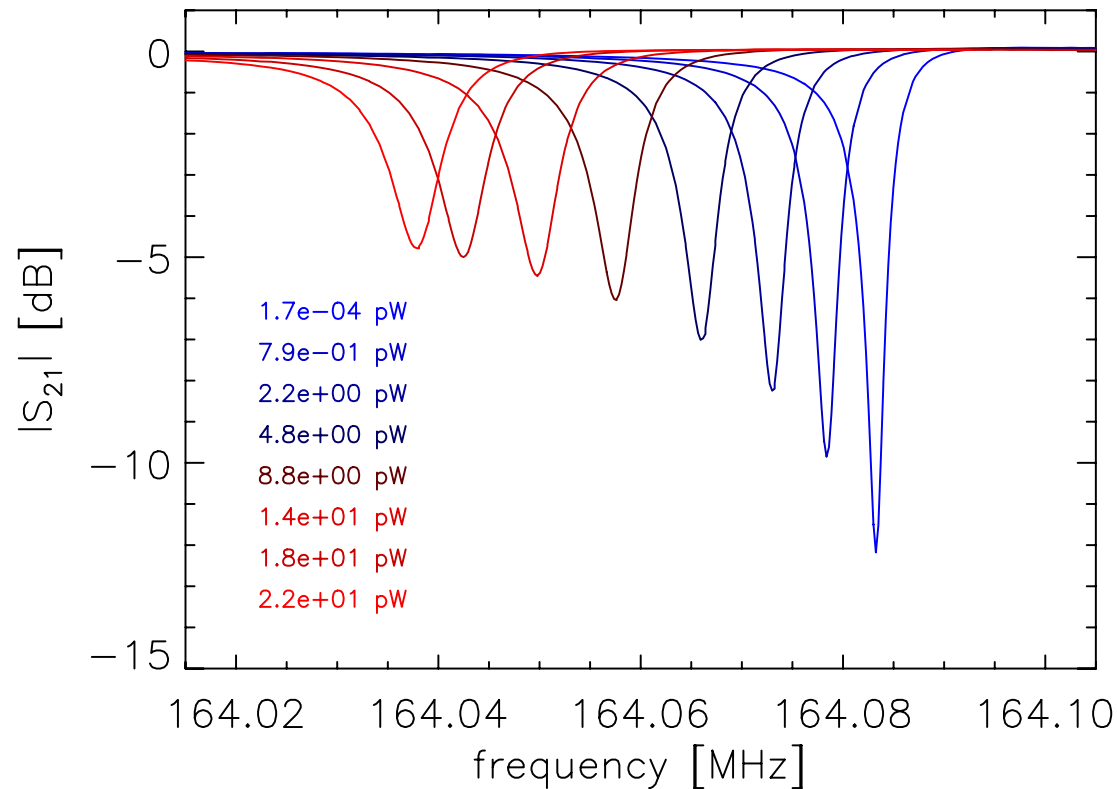


Photons are detected by measuring amplitude and phase changes in a probe tone driving the resonator at its resonant frequency.



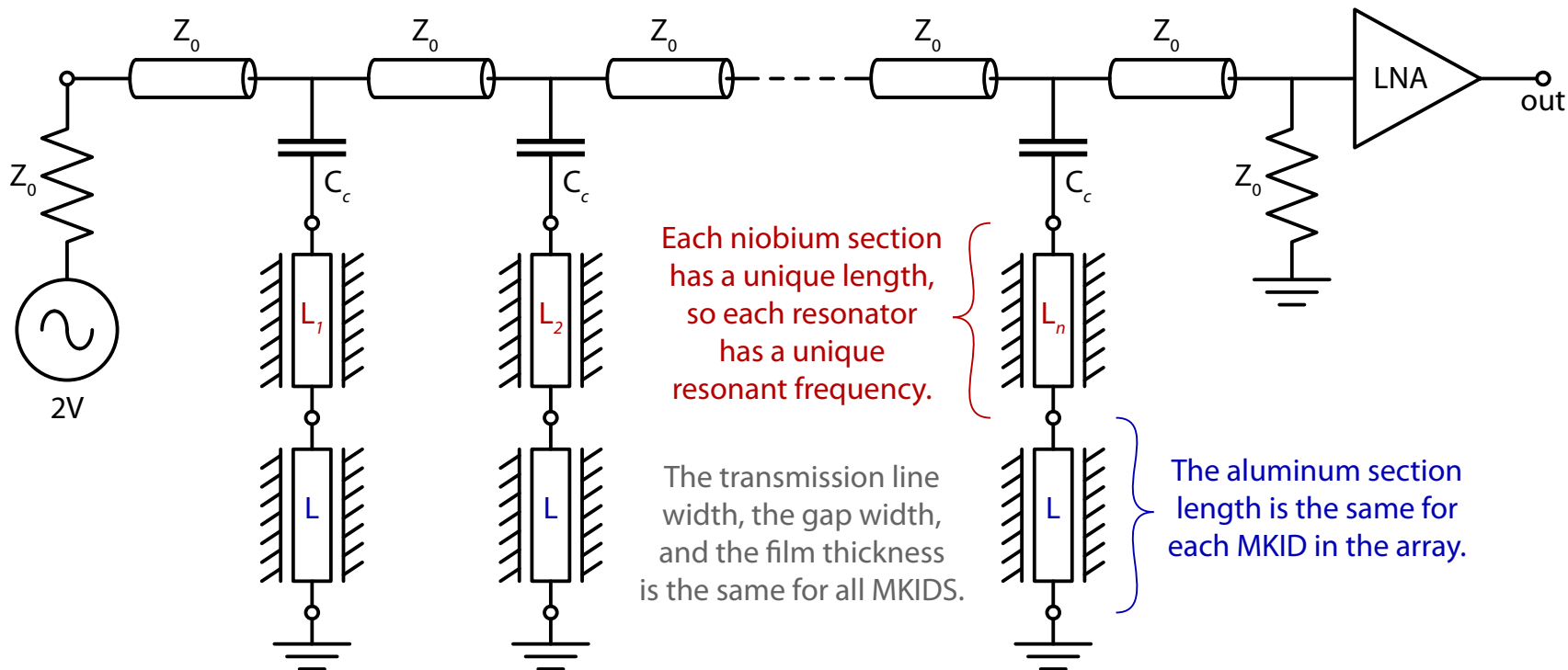
$$\nu_g = \frac{2\Delta}{h} \approx 74 \text{ GHz} \times \frac{T_c}{1 \text{ K}}$$

Resonances



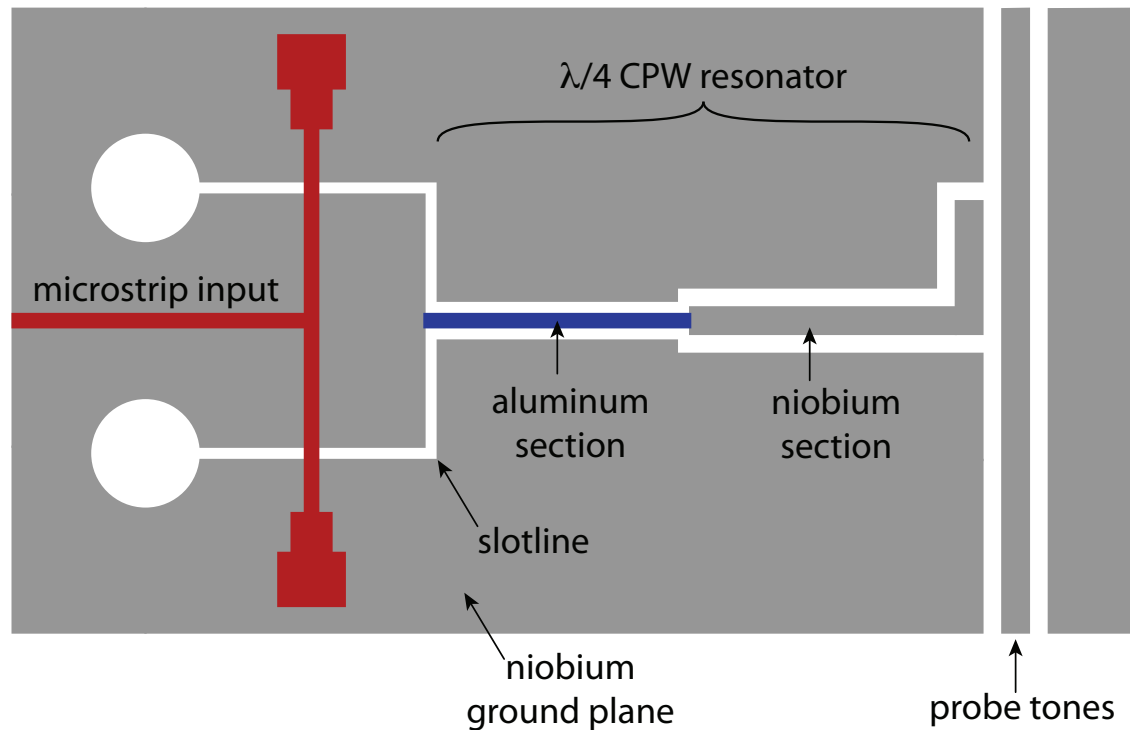
$$S_{21} \approx 1 - \frac{Q_r}{Q_c} \frac{1}{1 + j2Q_r x}, \quad x = \frac{f_r - f}{f_r}, \quad \frac{1}{Q_r} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

Multiplexing the Array



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

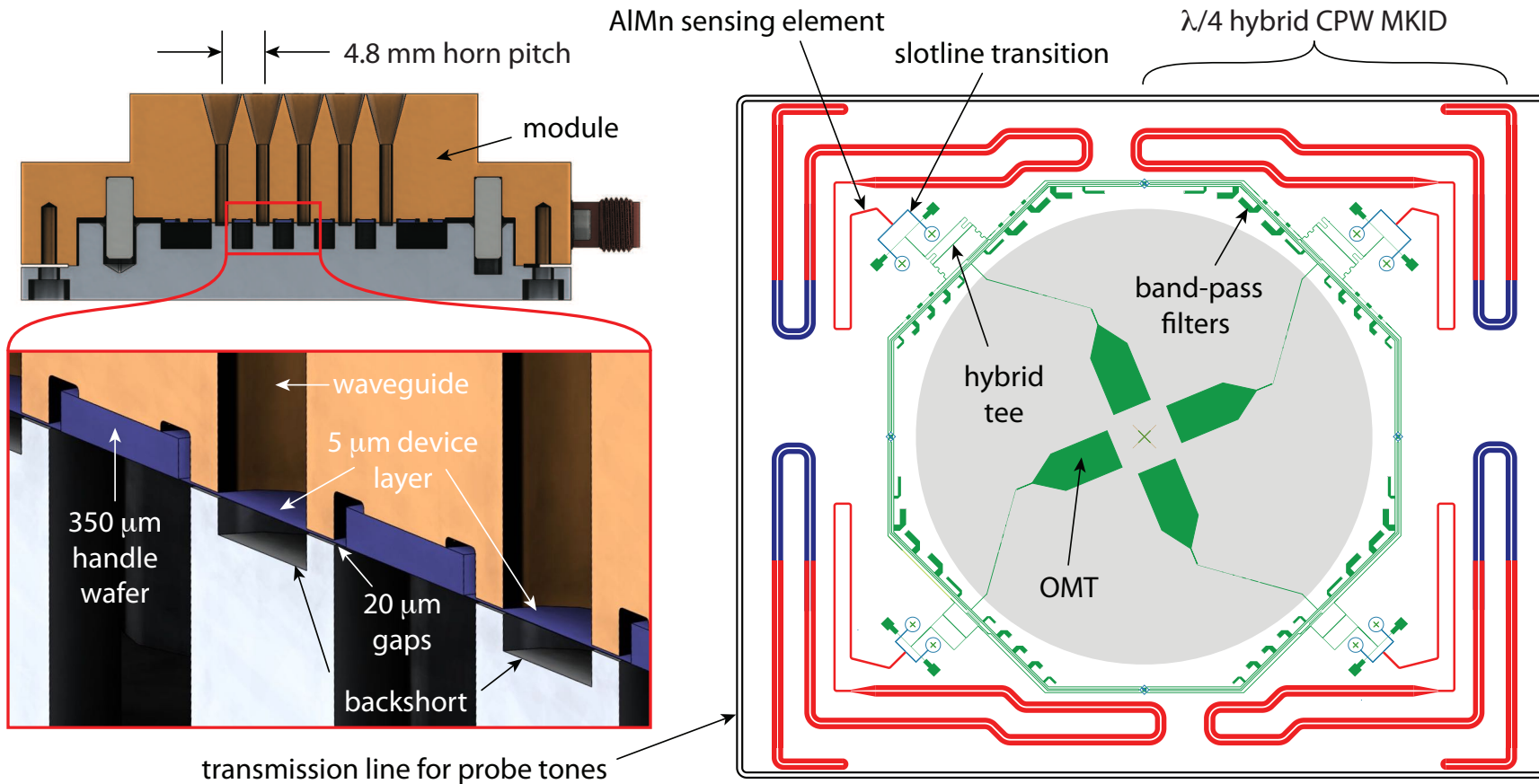
Microstrip-to-CPW MKID Coupling Schematic



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.

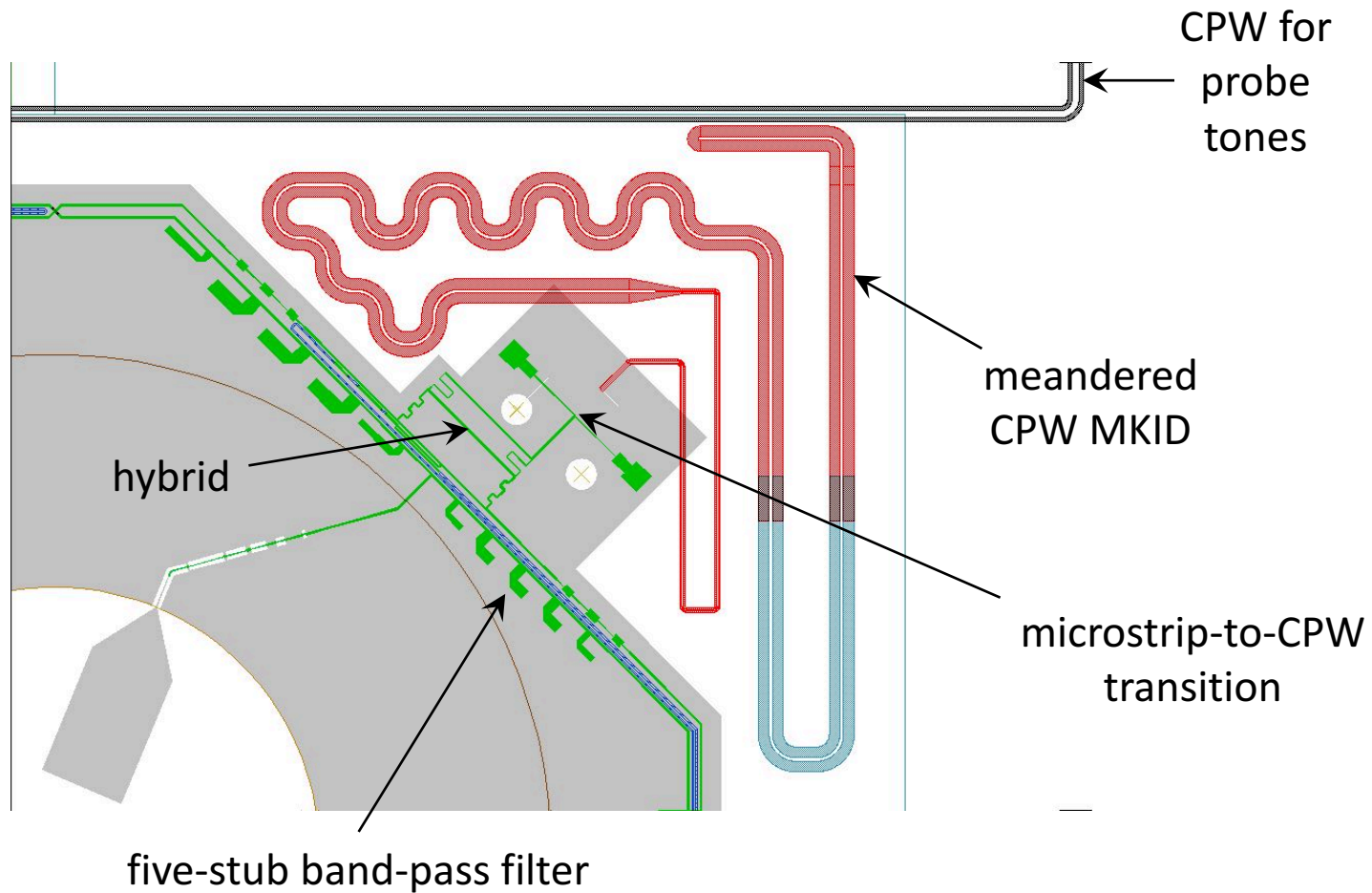
Johnson et al. (2016) *Proc. SPIE*, 9914, 99140X

Development of Multi-Chroic MKIDs



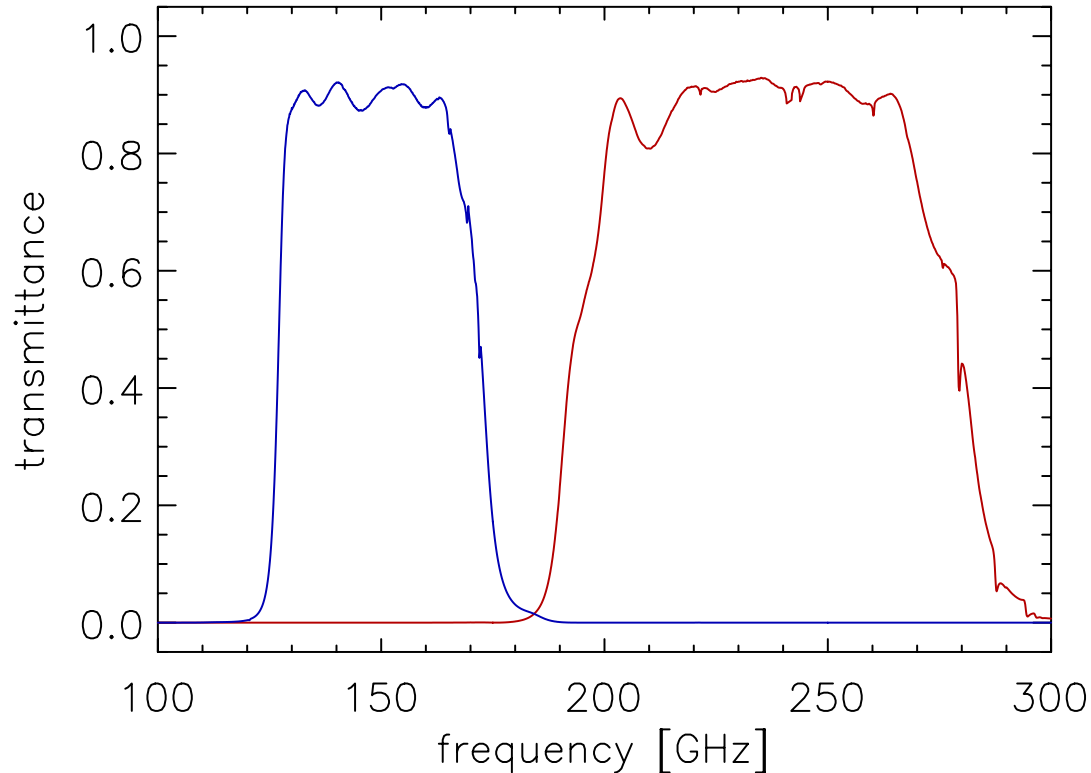
based on: Datta et al. (2014) *J. Low Temp. Phys.* 176, 670–676

Array Element Details



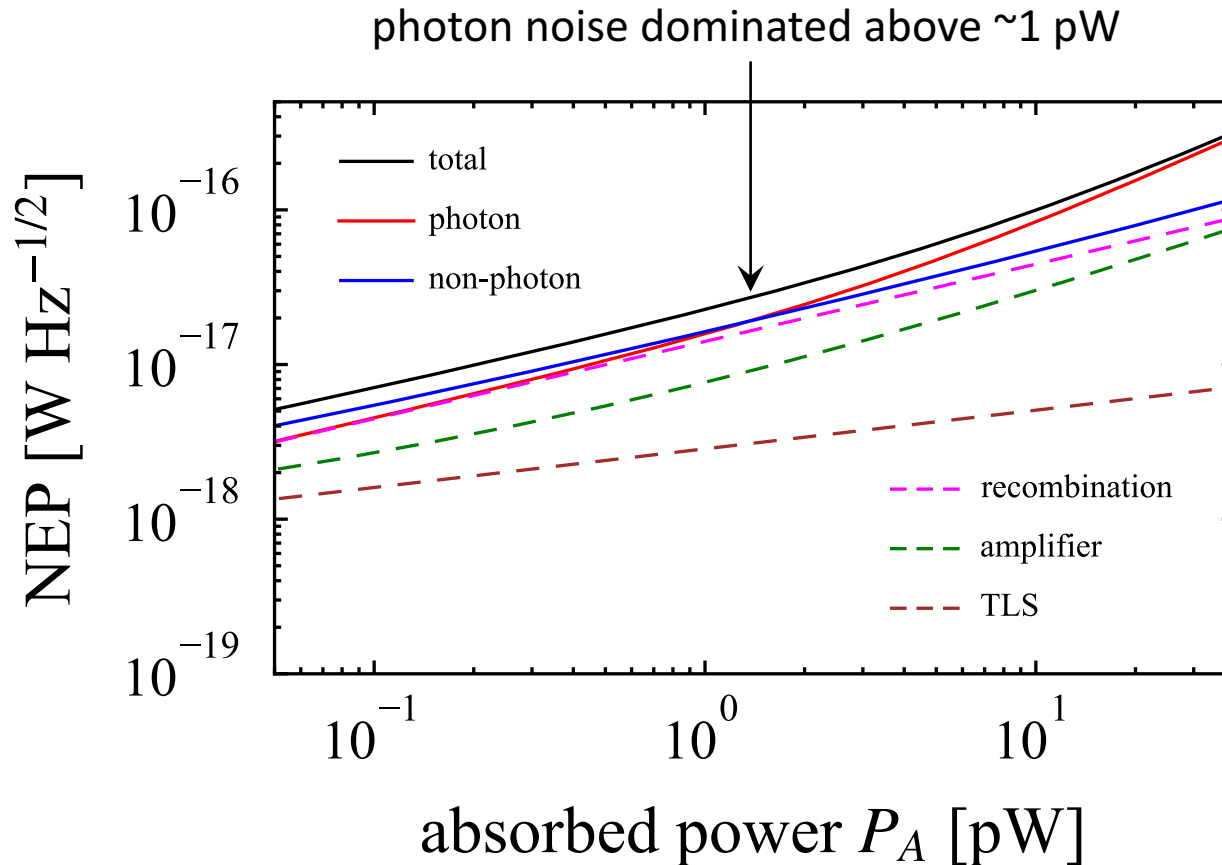
MKID resonant frequencies around 3 GHz

Simulated Spectral Bands



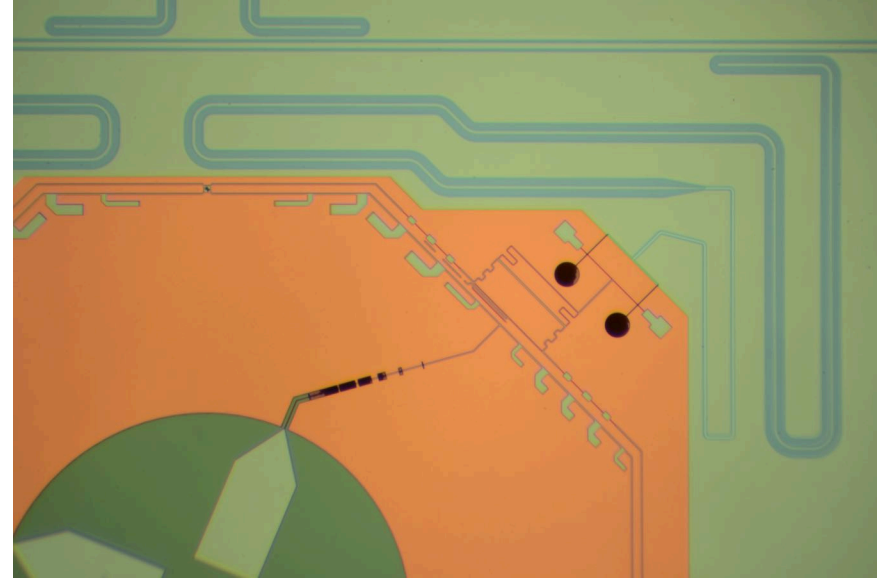
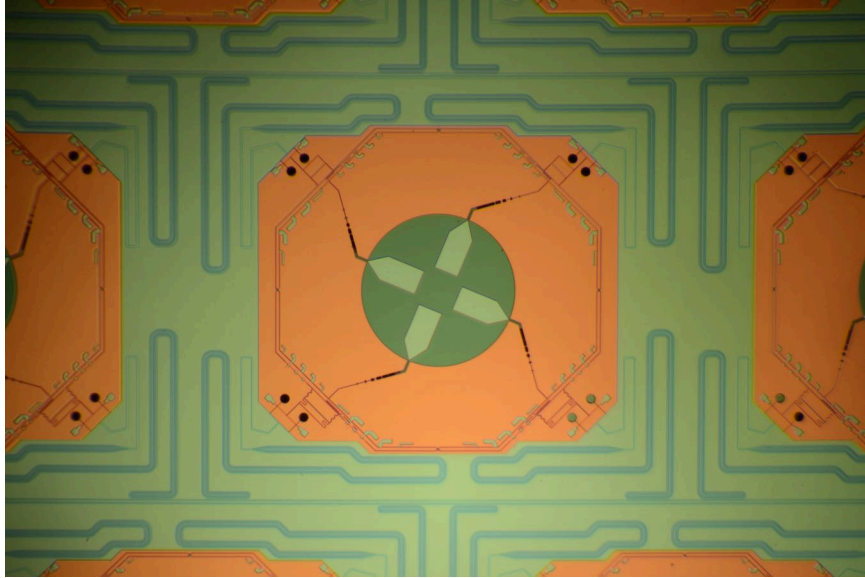
HFSS/Sonnet simulation results show the expected absorption efficiency is approximately 90% taking into account all of the elements in the circuit except the OMT probes.

Noise Sources and Expected NEP @ 150 GHz



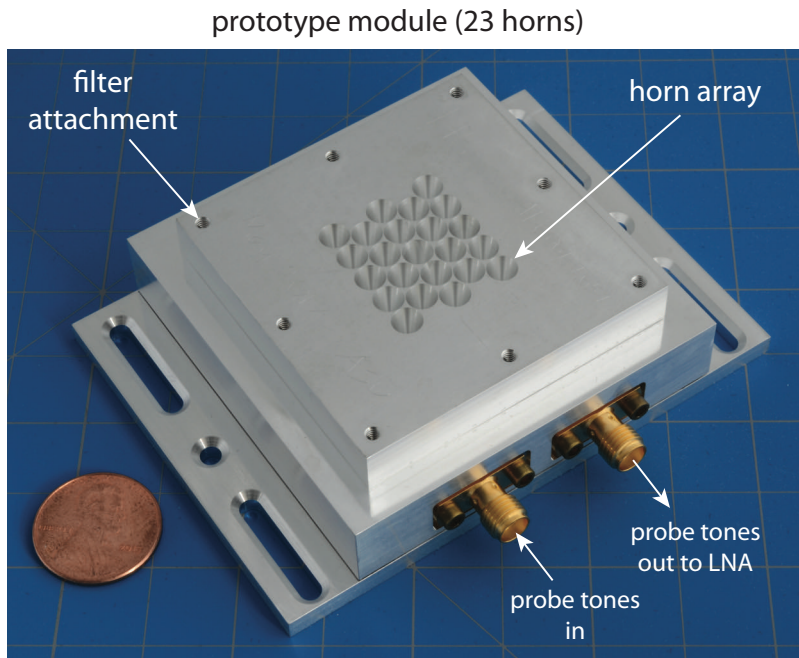
We have **plans to fabricate aluminum manganese sensors**, which will make the MKIDs photon-noise dominated at lower absorbed power levels.

Photographs of First Devices

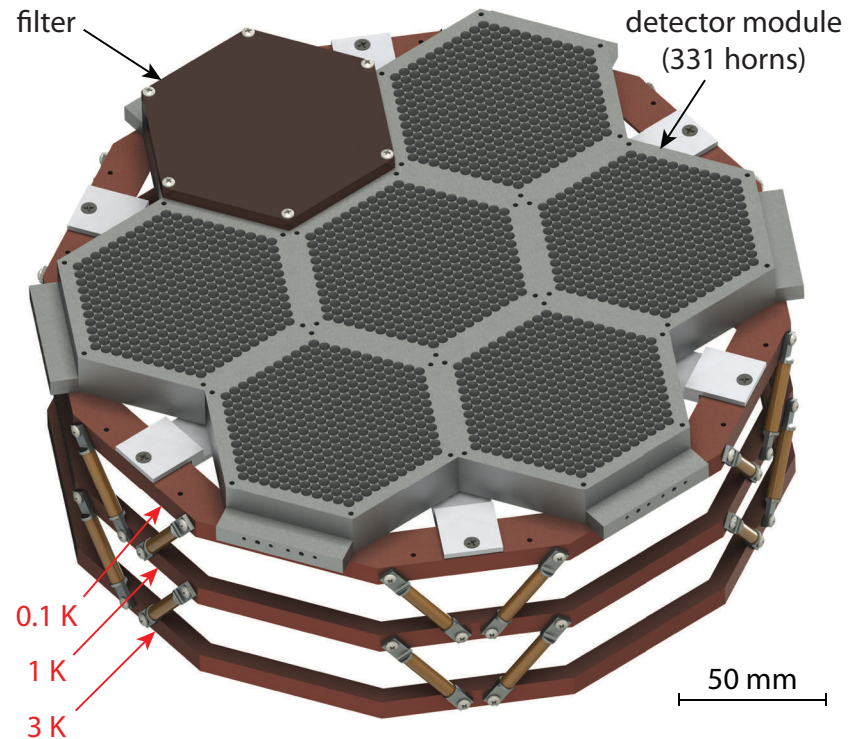


Fabricated at Stanford

Multi-Chroic MKID Array Goal

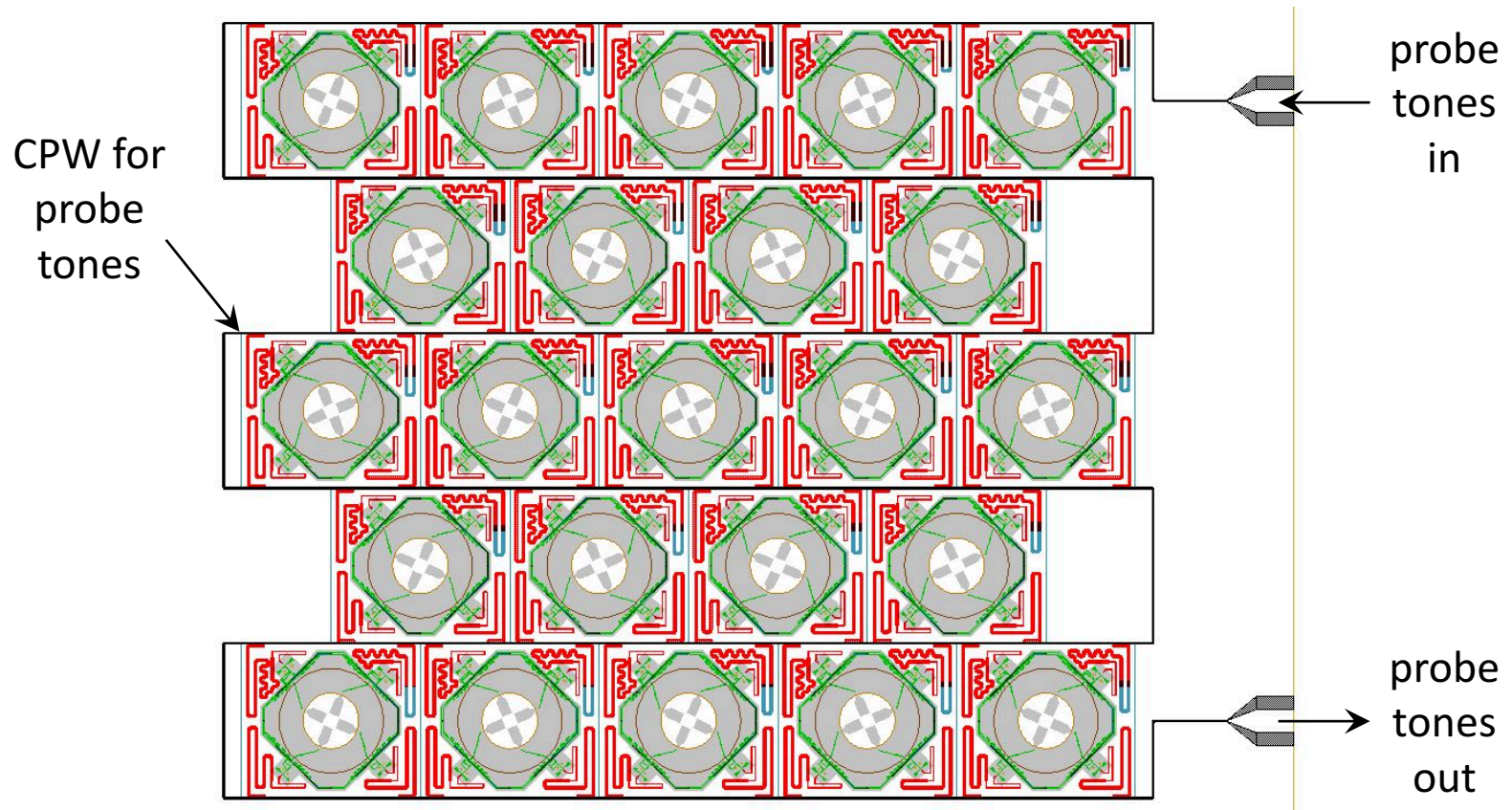


start with scalable, 23-element
prototype module ...



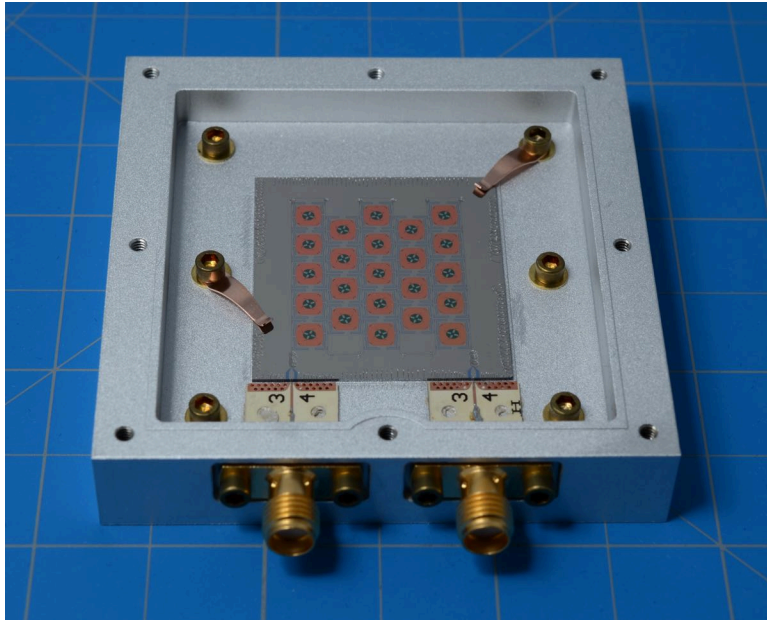
... scale up to 2317 horns or
9268 detectors

Layout of Prototype Array

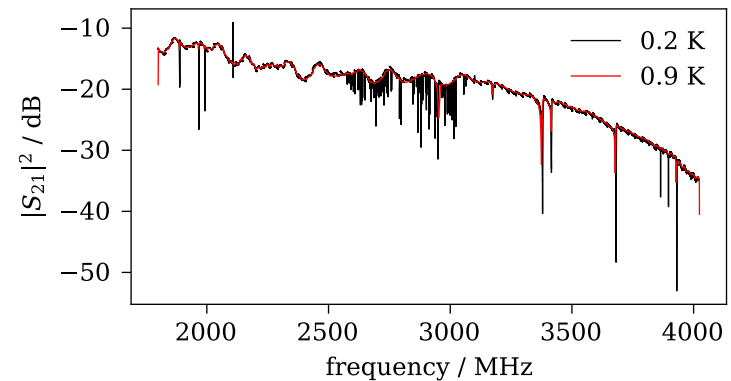
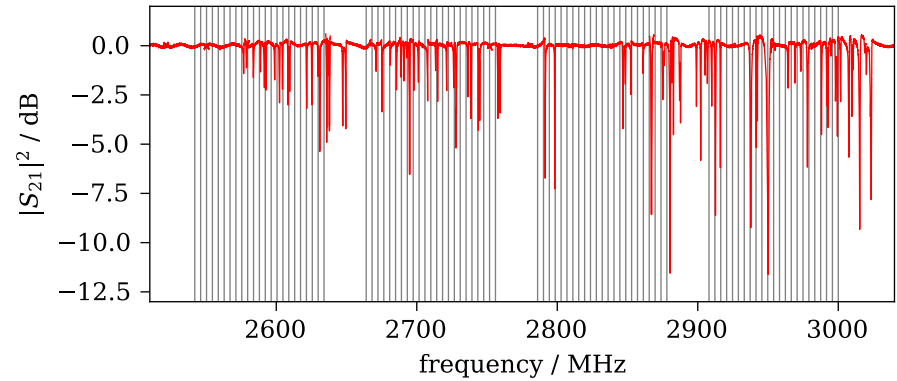


23 elements in the array

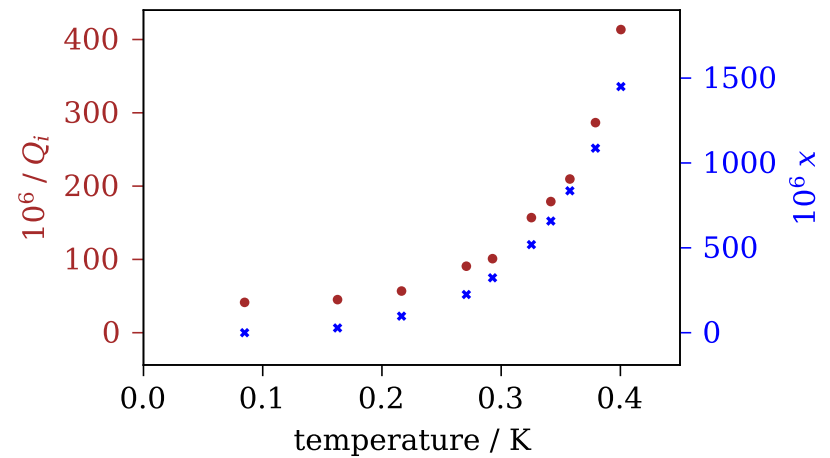
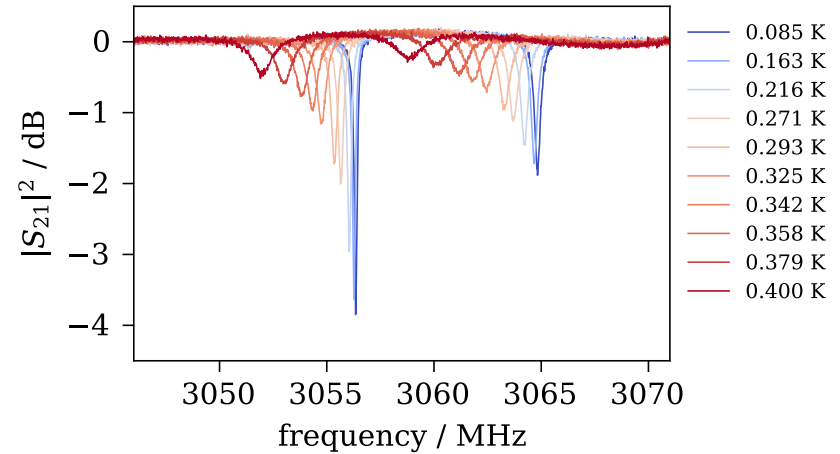
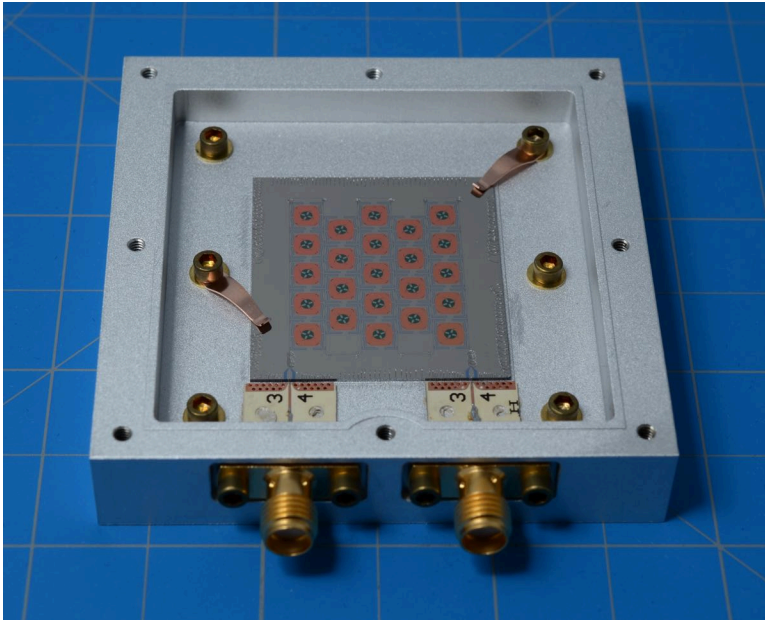
Development of Multi-Chroic MKIDs



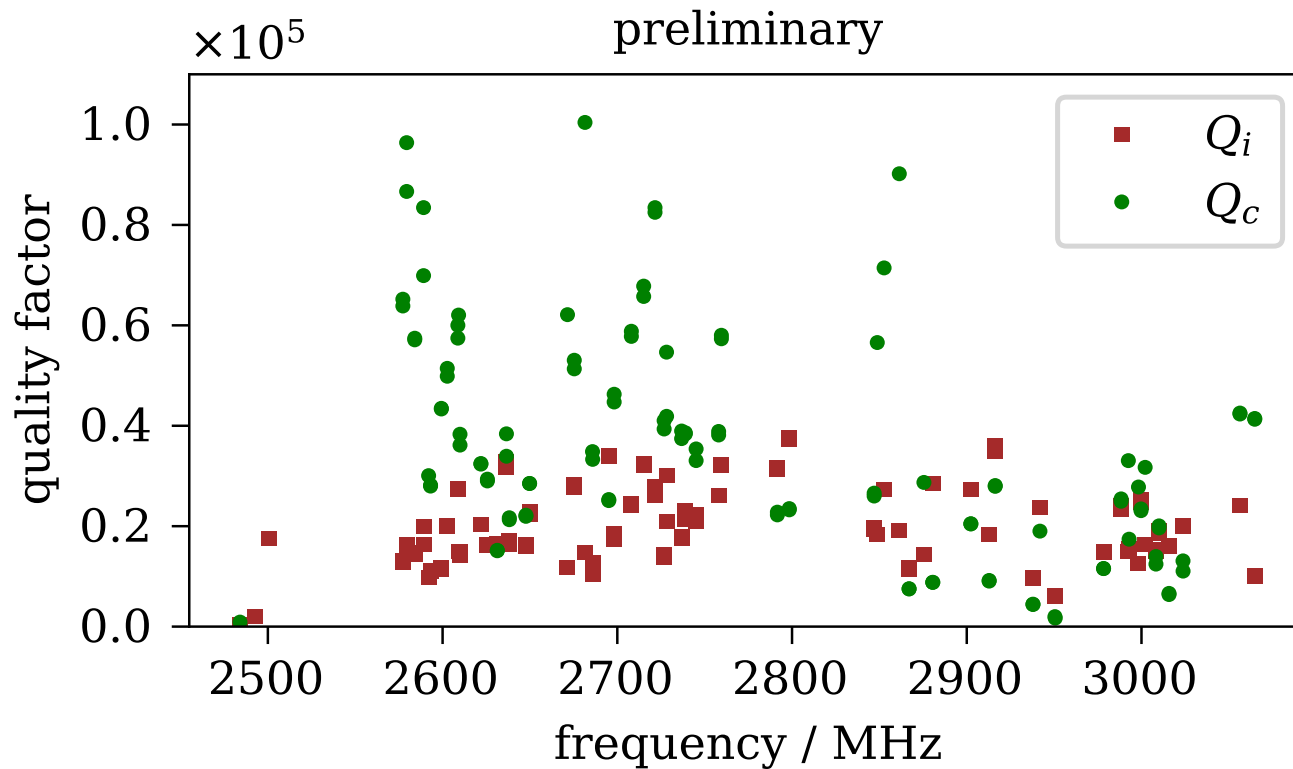
92 of 92 resonators found



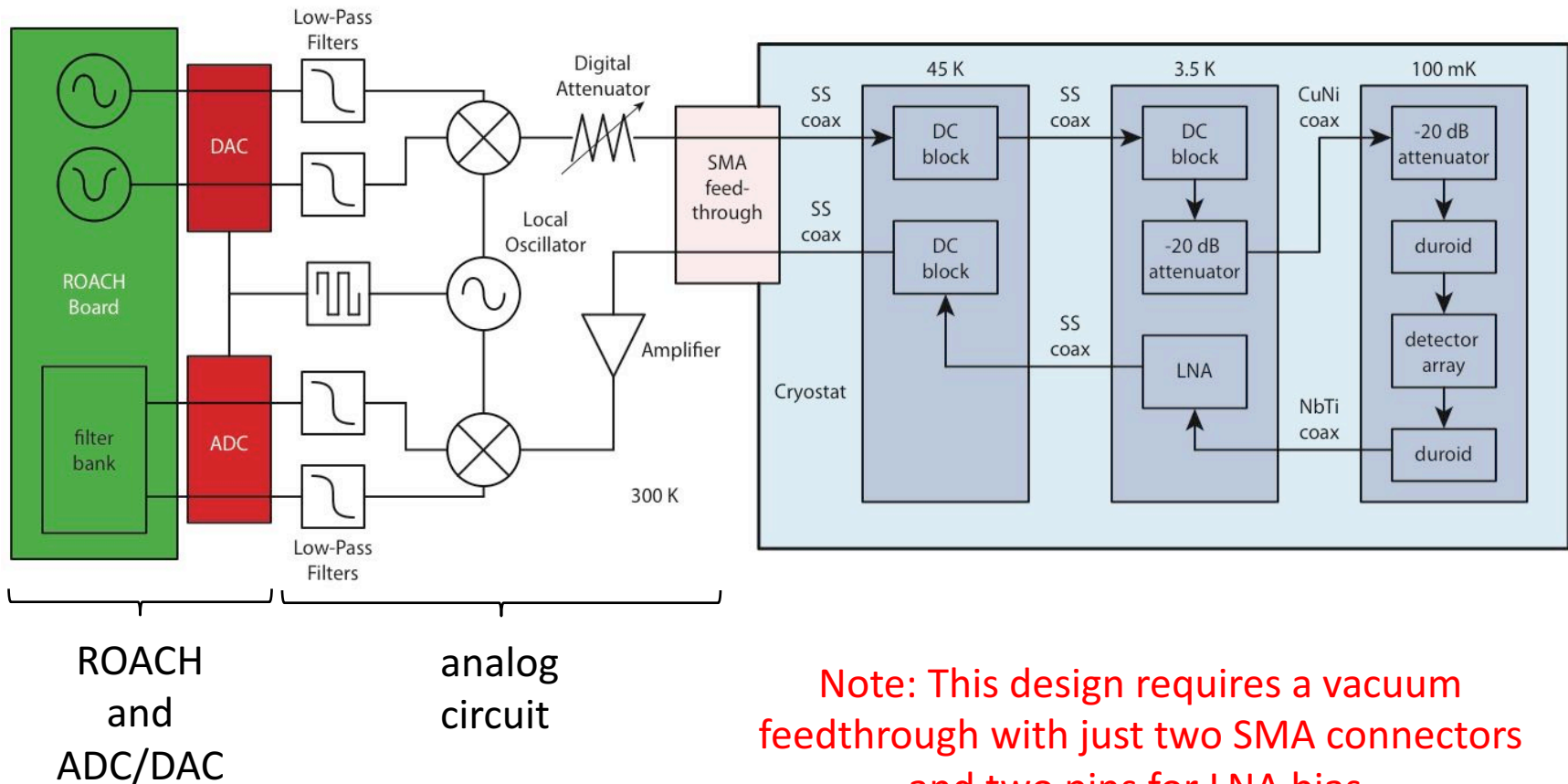
Development of Multi-Chroic MKIDs



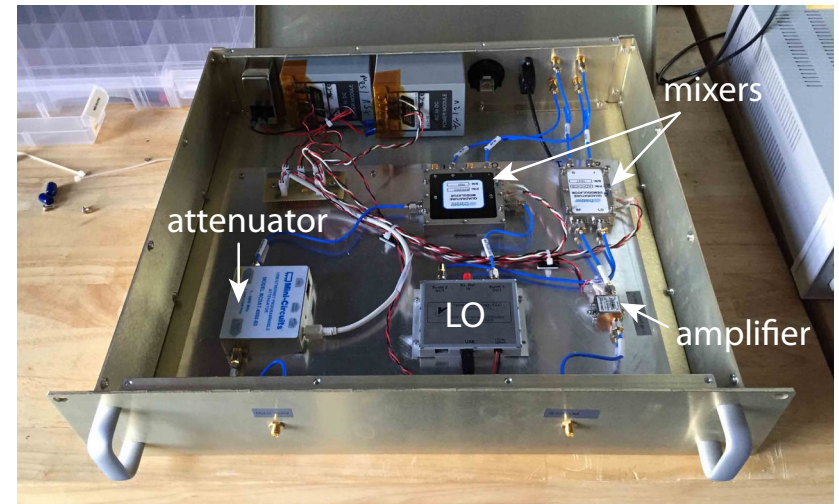
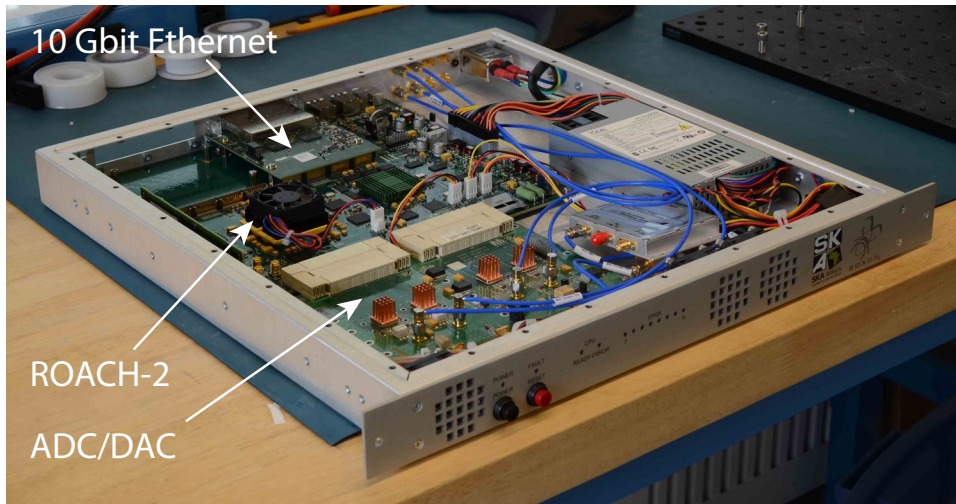
Development of Multi-Chroic MKIDs



Schematic of Readout System



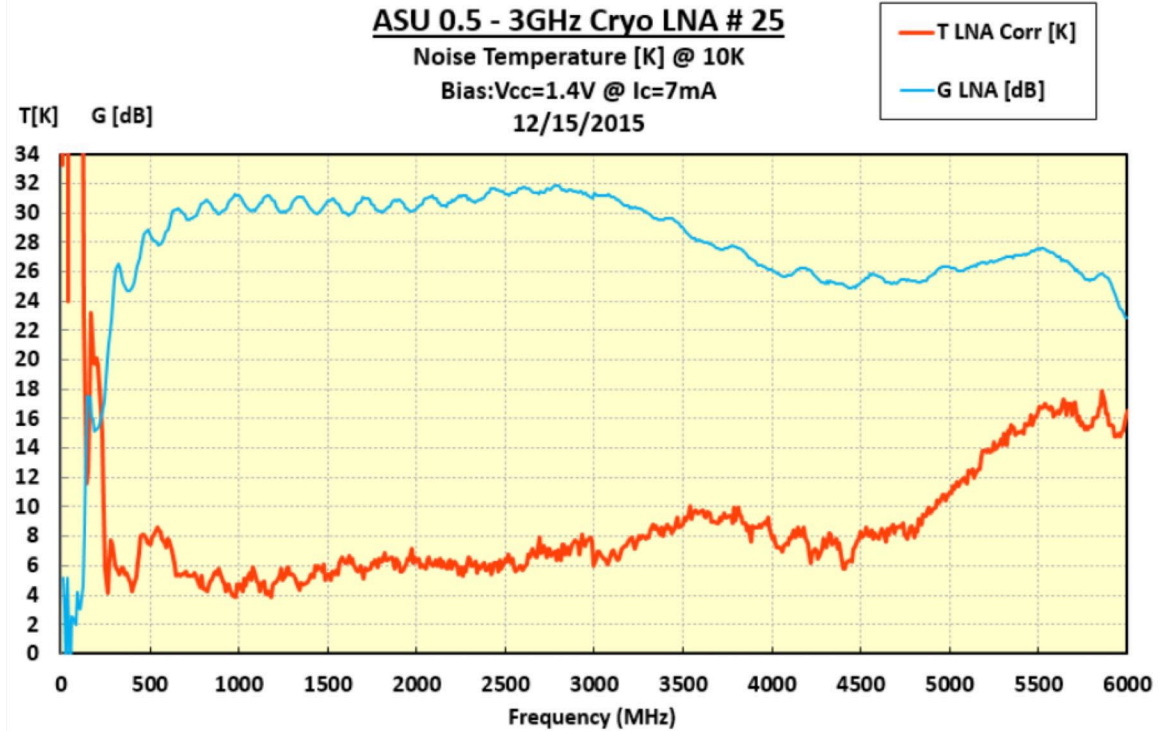
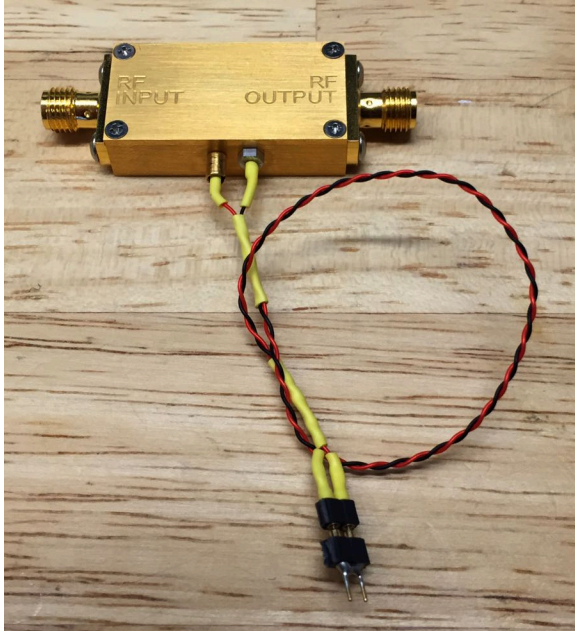
ROACH-2, ADC/DAC, and Analog Circuit



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.

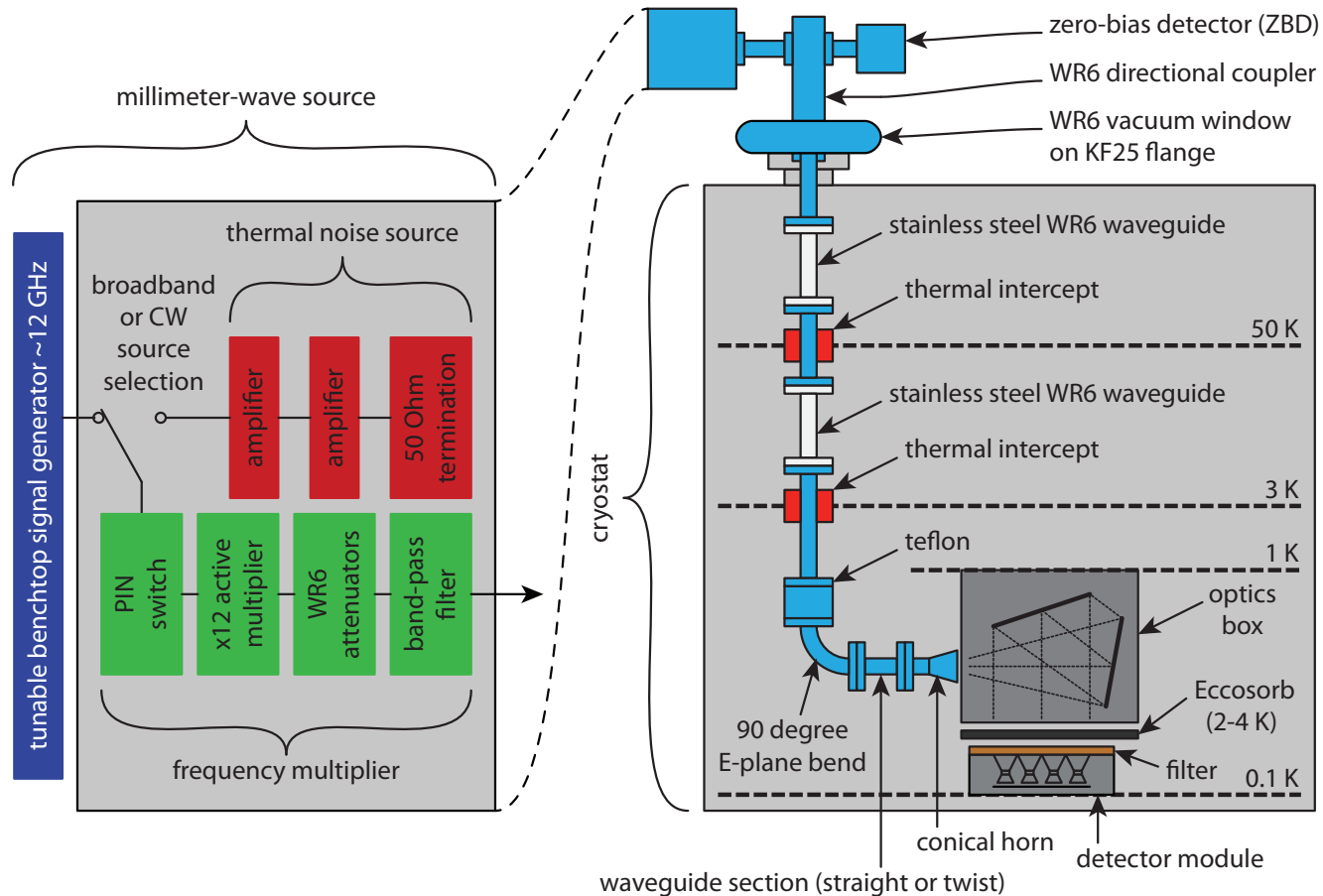
SiGe LNA from ASU

SiGe LNA from ASU



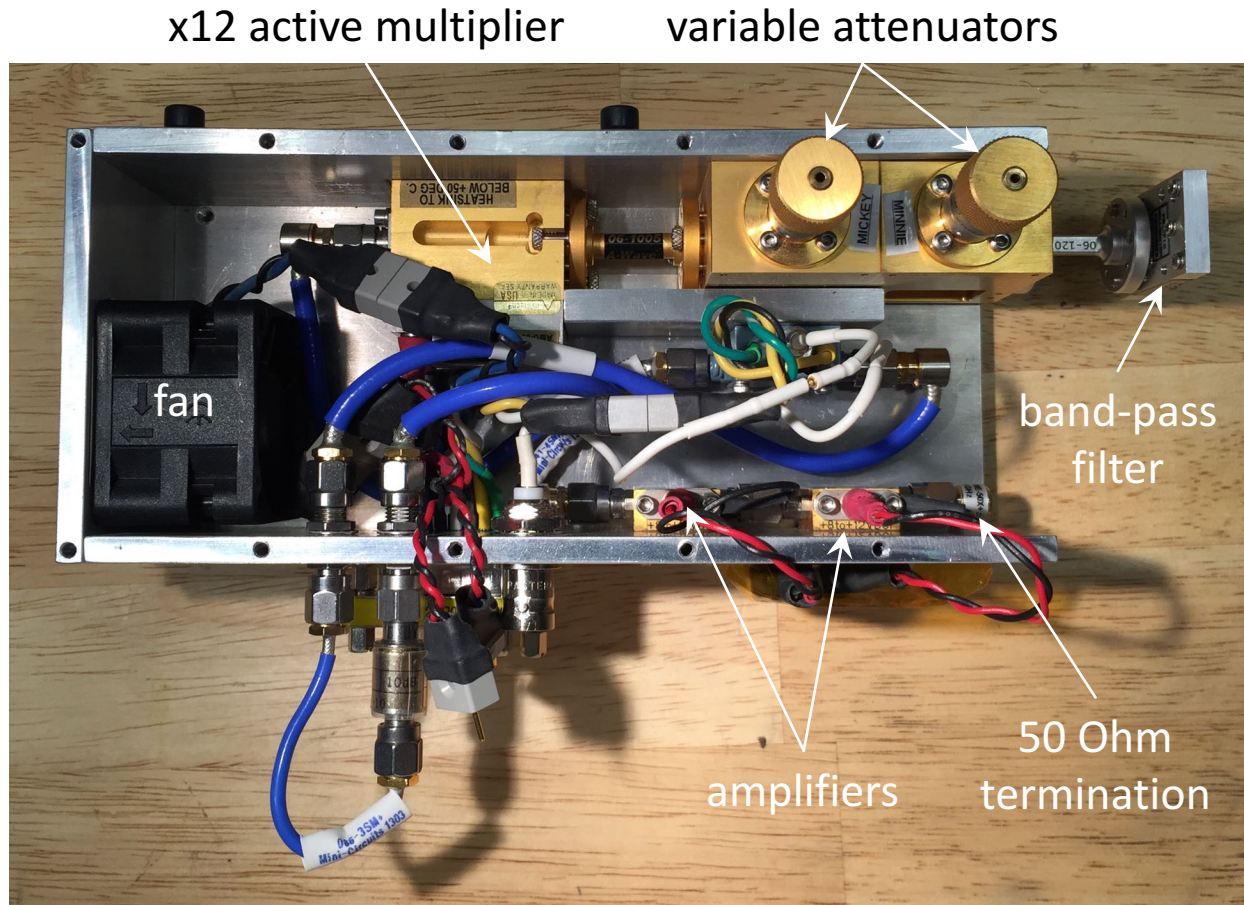
resonant frequencies around 3 GHz

Schematic of Experimental Setup



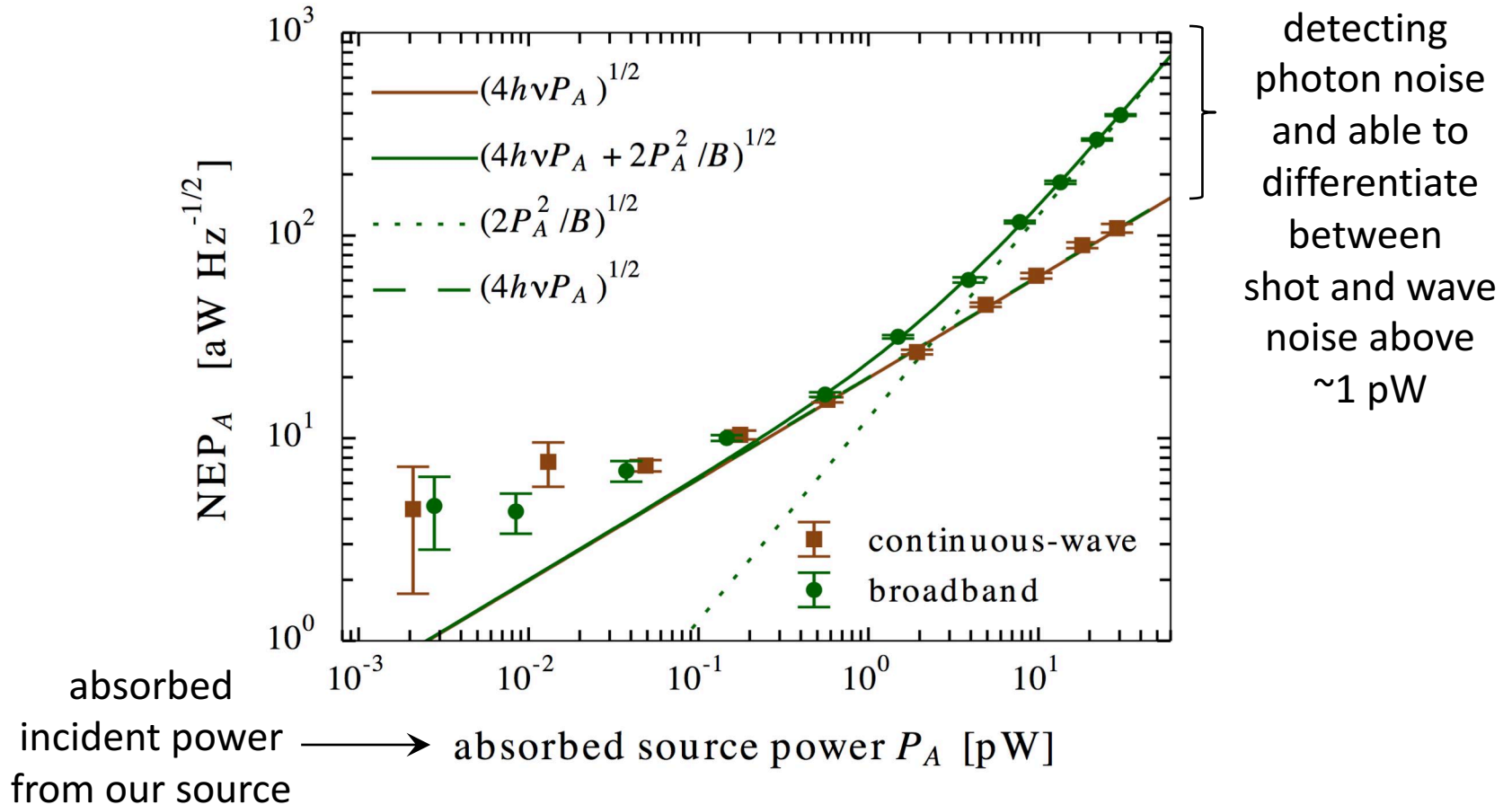
See Flanigan et al. (2016) *APL*, 108, 083504.

External Millimeter-Wave Source



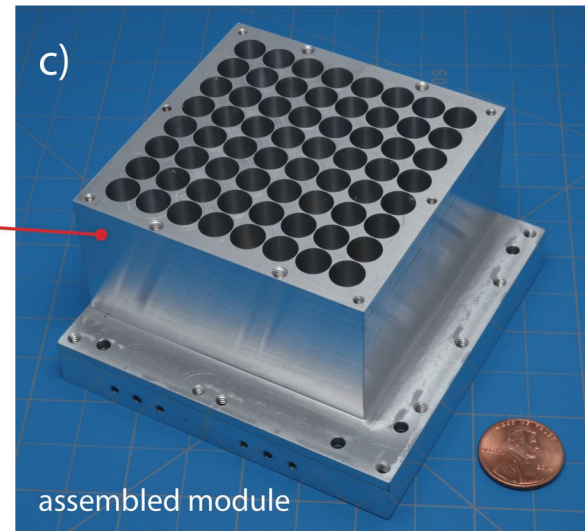
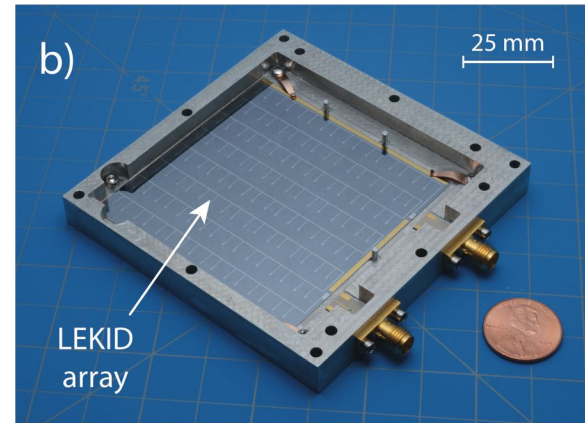
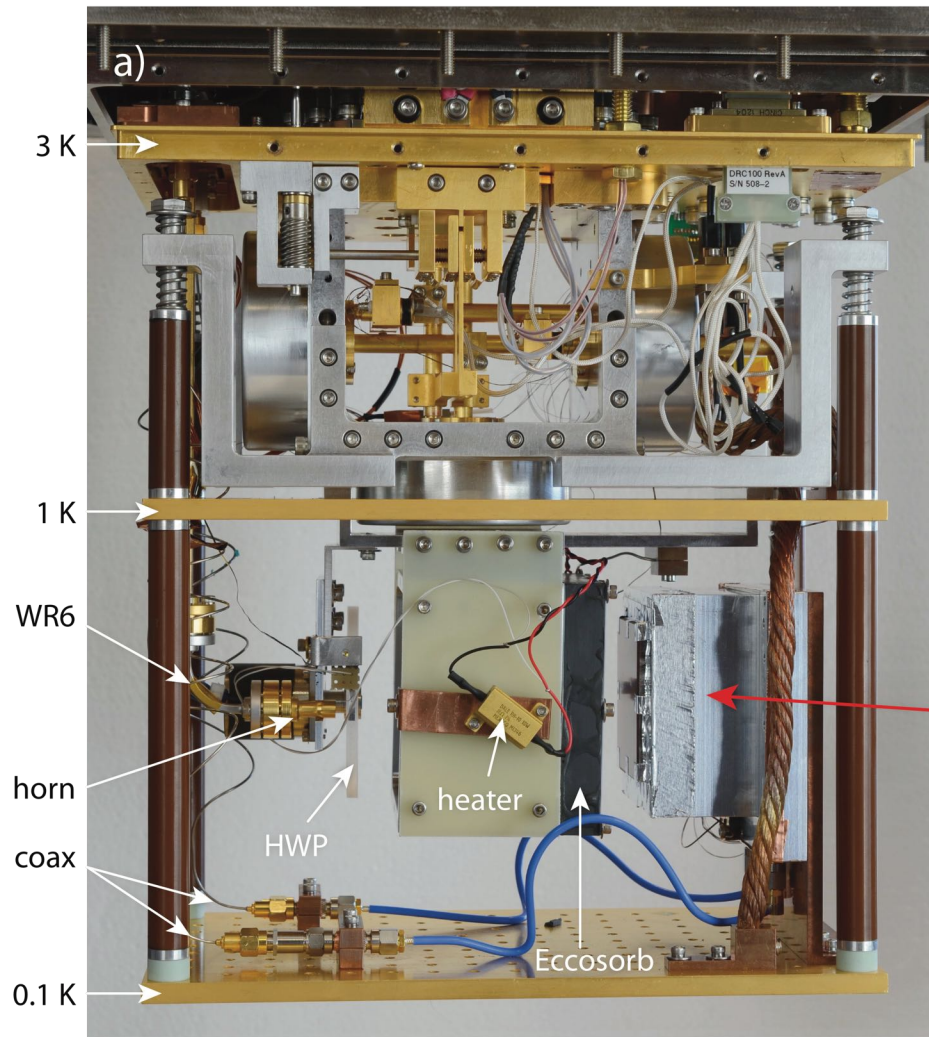
See Flanigan et al. (2016) *APL*, 108, 083504.

LEKID Example: Measured Photon Noise

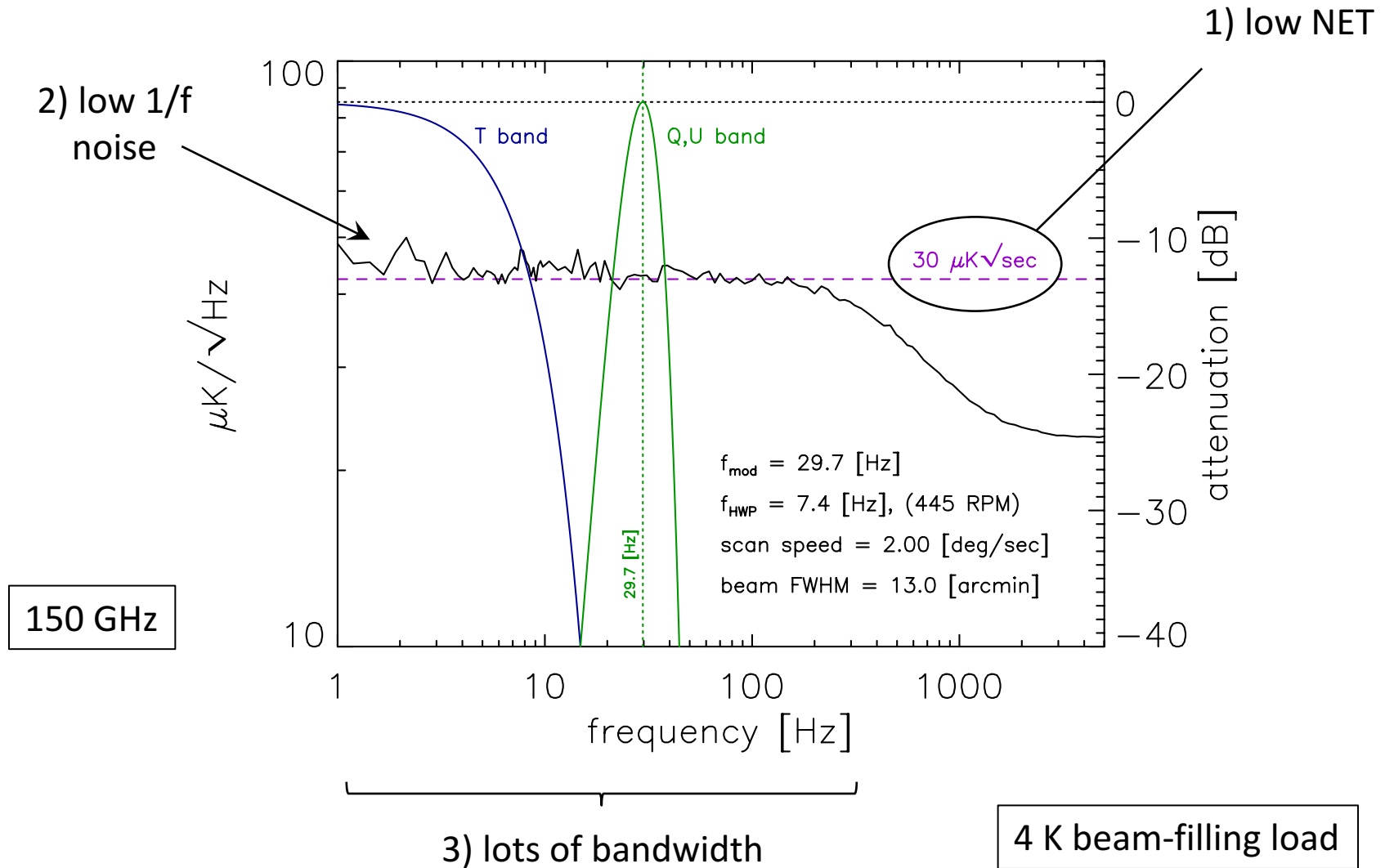


See Flanigan et al. (2016) *APL*, 108, 083504.

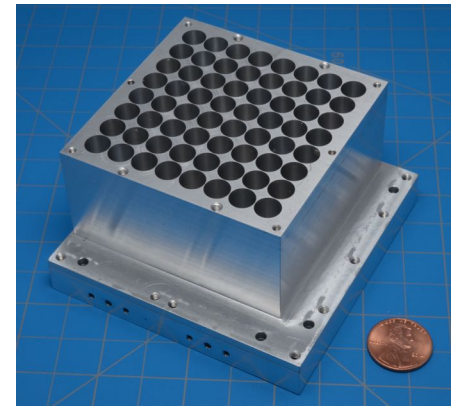
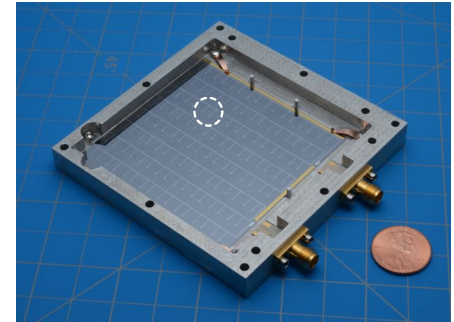
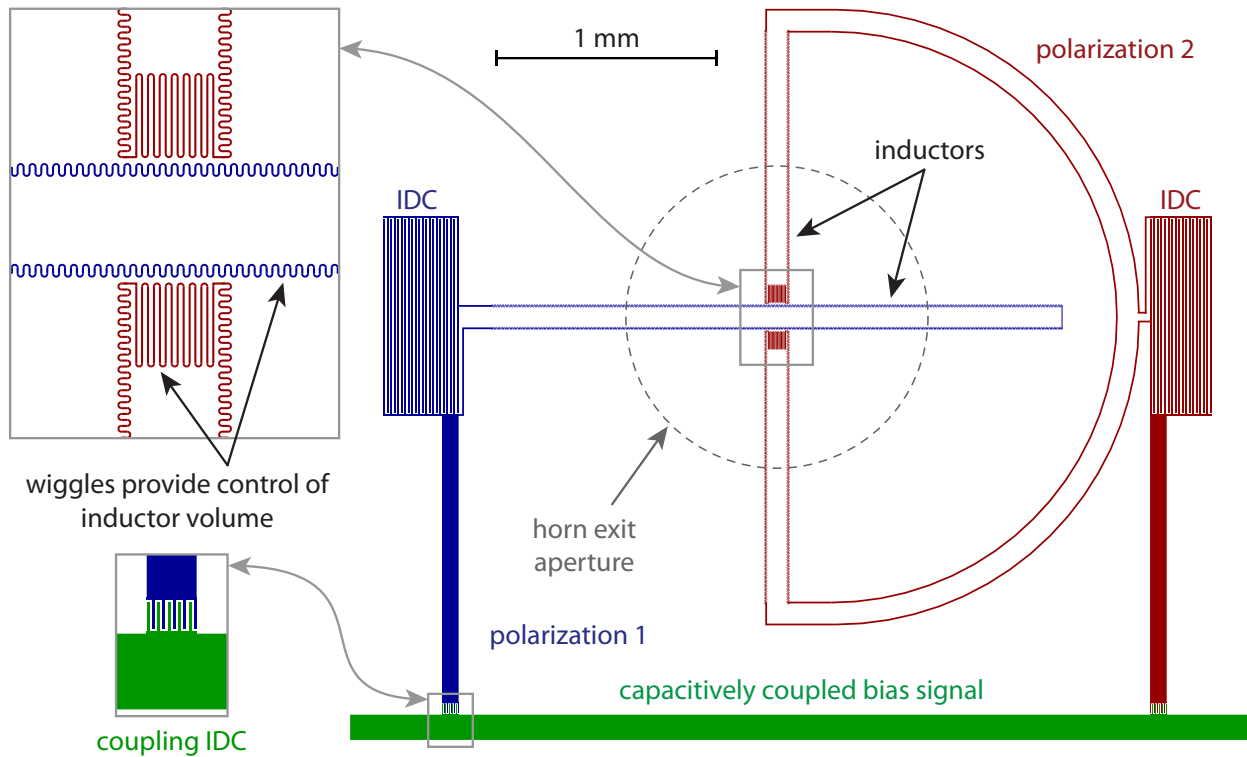
Optical Test Setup



LEKID Example: Measured Noise Spectra



Dual-Polarization LEKIDs



McCarrick et al. (2017) *in preparation*.

see LTD17 poster PA-5

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. Tucker²

¹⁾ *Department of Physics, Columbia University, New York, NY 10027, USA*

²⁾ *School of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, UK*

³⁾ *School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA*

⁴⁾ *SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*

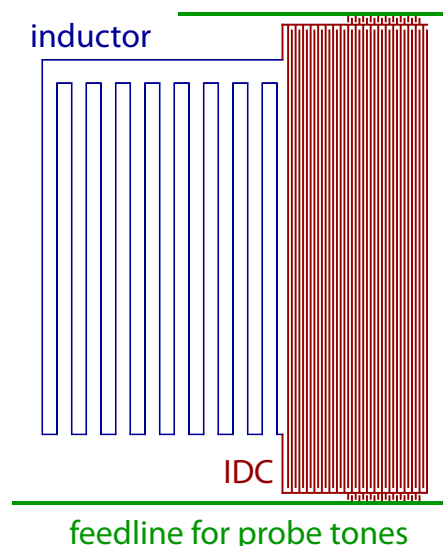
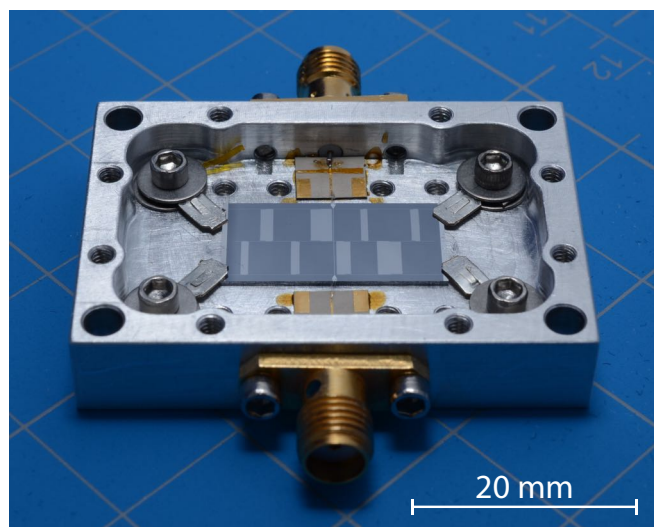
⁵⁾ *NASA, Jet Propulsion Laboratory, Pasadena, CA 91109, USA*

⁶⁾ *Department of Physics, Stanford University, Stanford, CA, 94305-4085, USA*

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

(Dated: 31 January 2017)

see LTD17
poster
PA-12



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

Summary

- We are developing scalable modular arrays of **horn-coupled, polarization-sensitive MKIDs for CMB studies** that are each sensitive to **two spectral bands: 150 and 235 GHz**.
- Array layout is almost complete. Module **fabrication will finishing this summer**.
- We anticipate **photon noise limited performance** above ~ 1 pW of loading.
- **ROACH-2 readout** system has been developed.
- We have plans to fabricate **aluminum manganese sensors**, which will make the MKIDs photon-noise dominated at lower absorbed power levels (see LTD17 poster PA-12).
- We are **also developing dual-polarization LEKIDs** (see LTD17 poster PA-5).

Backup Slides

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}

¹*Department of Physics, Columbia University, New York, New York 10025, USA*

²*School of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, United Kingdom*

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*

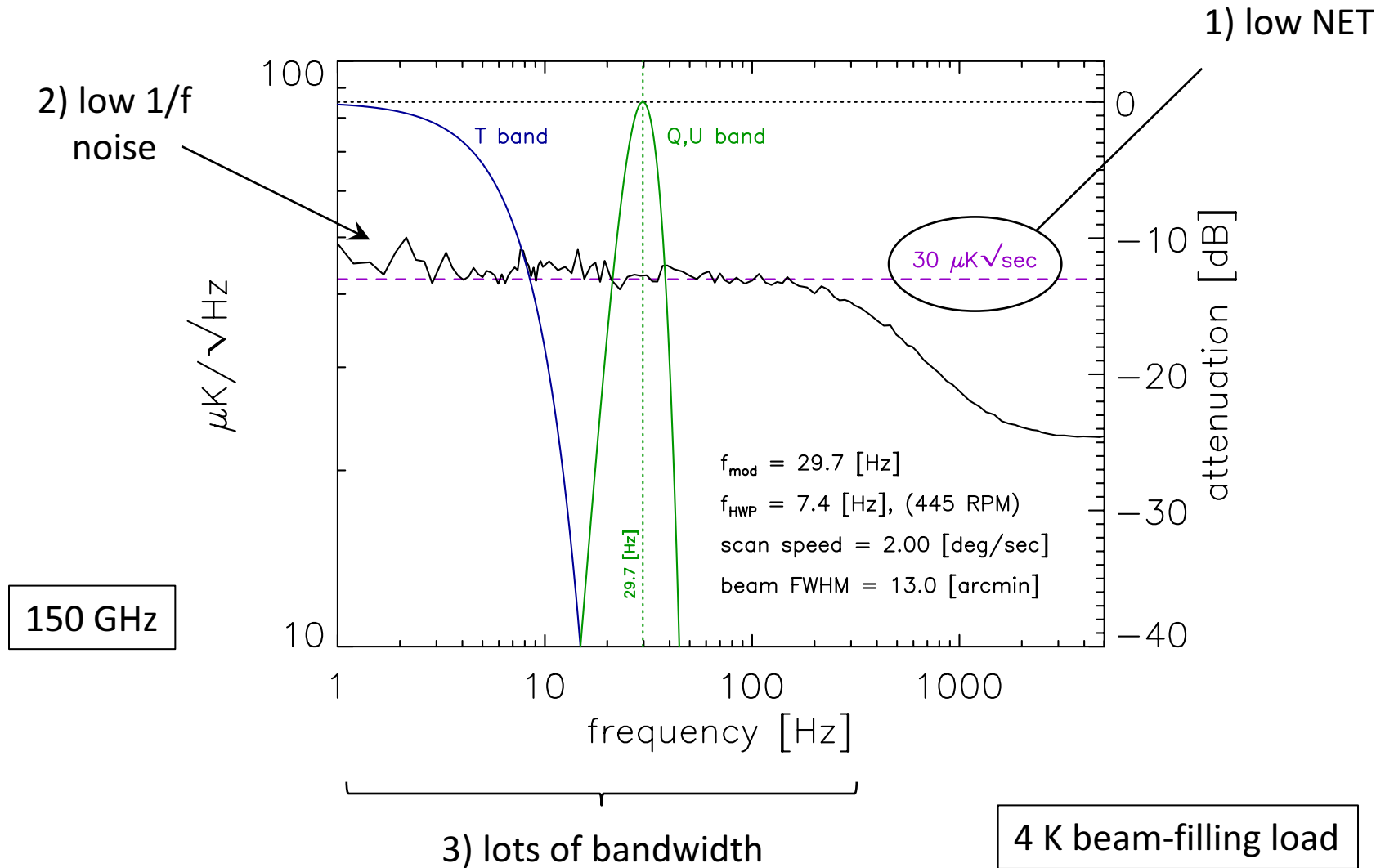
⁶*Department of Physics and School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, USA*

⁷*Naval Research Laboratory, Washington DC 20375, USA*

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.

Result: *Measured* LEKID Noise



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}

¹*Department of Physics, Columbia University, New York, New York 10027, USA*

²*School of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, United Kingdom*

³*School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, USA*

⁴*STAR Cryoelectronics, Santa Fe, New Mexico 87508, USA*

⁵*Department of Physics, Arizona State University, Tempe, Arizona 85287, USA*

⁶*Jet Propulsion Laboratory, Pasadena, California 91109, USA*

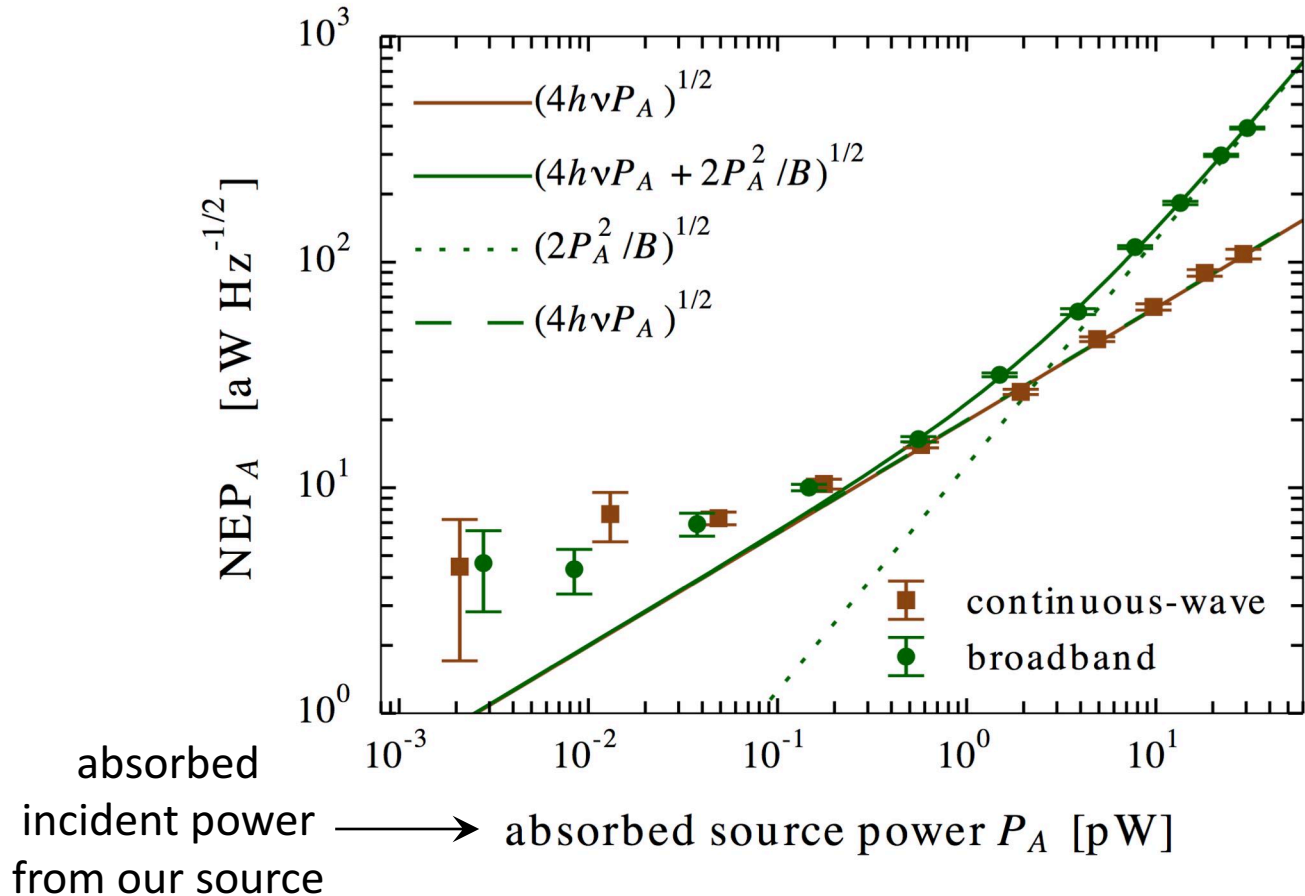
⁷*Naval Research Laboratory, Washington, DC 20375, USA*

⁸*Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, California 91125, USA*

(Received 20 October 2015; accepted 14 February 2016; published online 25 February 2016)

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

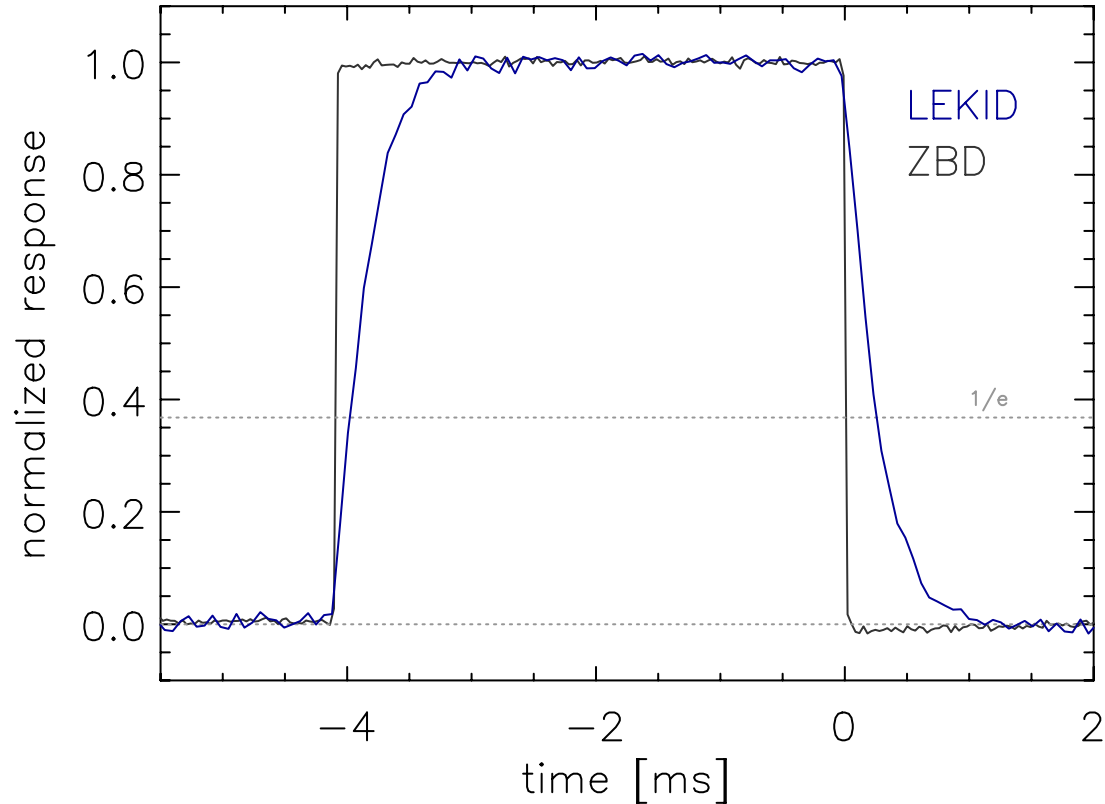
Measured Photon Noise



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

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

Other LEKID Measurements



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.**

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}

^aDepartment of Physics, Columbia University, New York, NY 10025, USA

^bSchool of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA

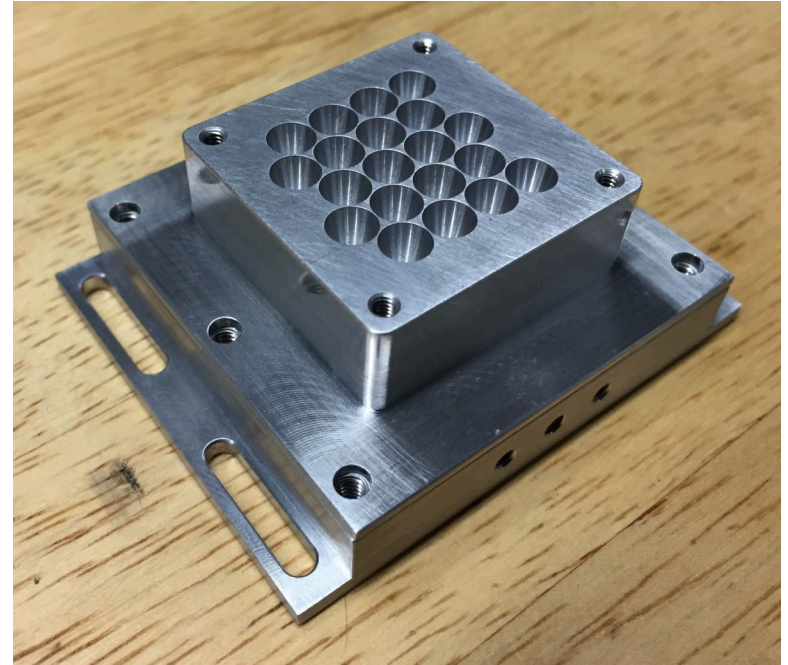
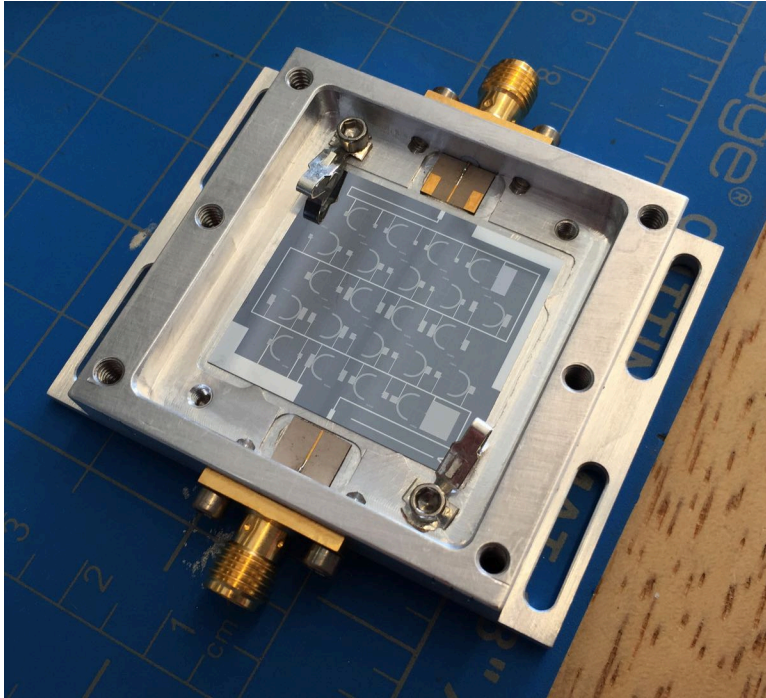
^cJet Propulsion Laboratory, Pasadena, CA 91109, USA

^dCaltech, Pasadena, CA 91109, USA

^eSchool of Physics and Astronomy, Cardiff University, Cardiff, Wales CF24 3AA, UK

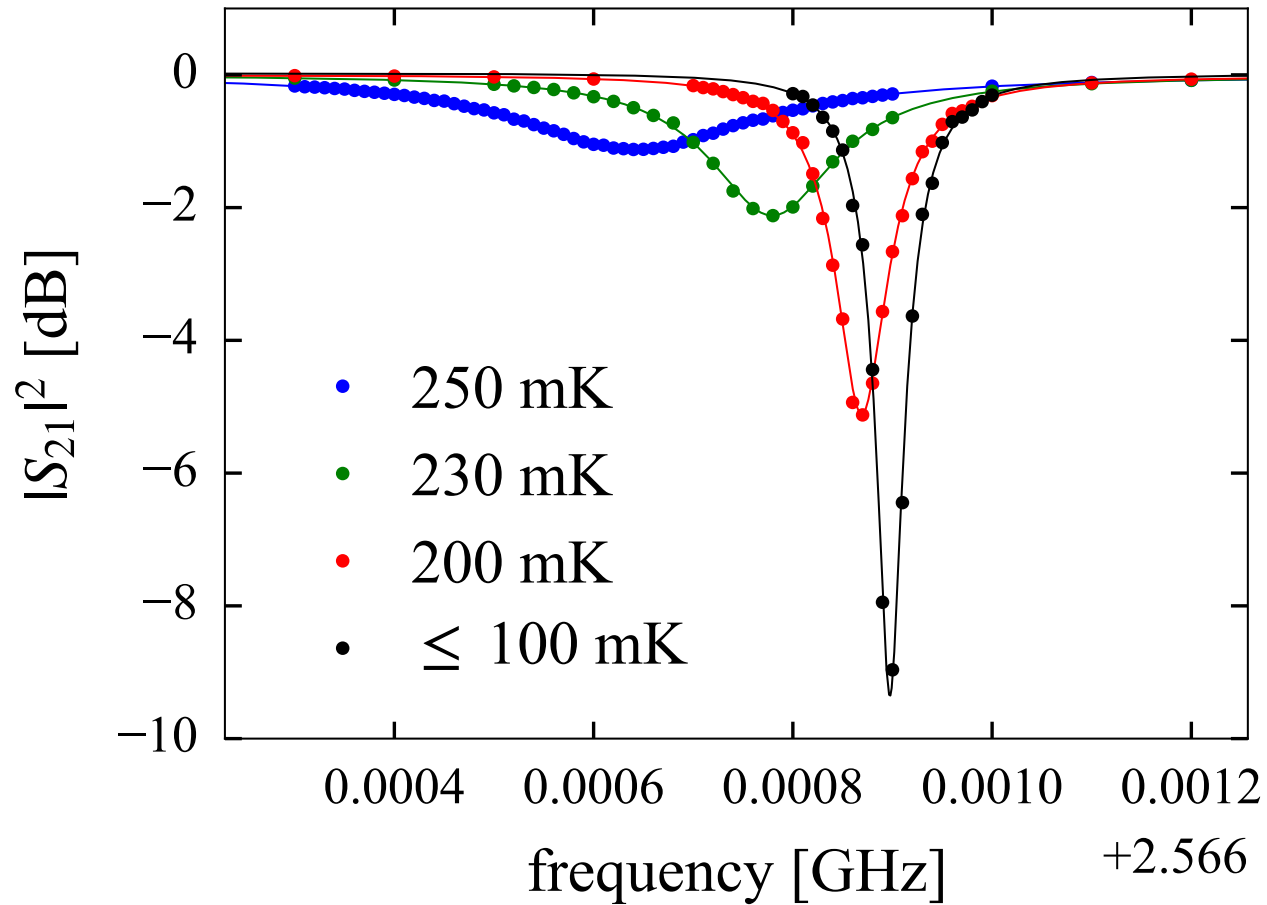
Project supported in part by a grant from the ***Research Initiatives for Science and Engineering*** program at Columbia.

Dual-Polarization LEKIDs Under Development

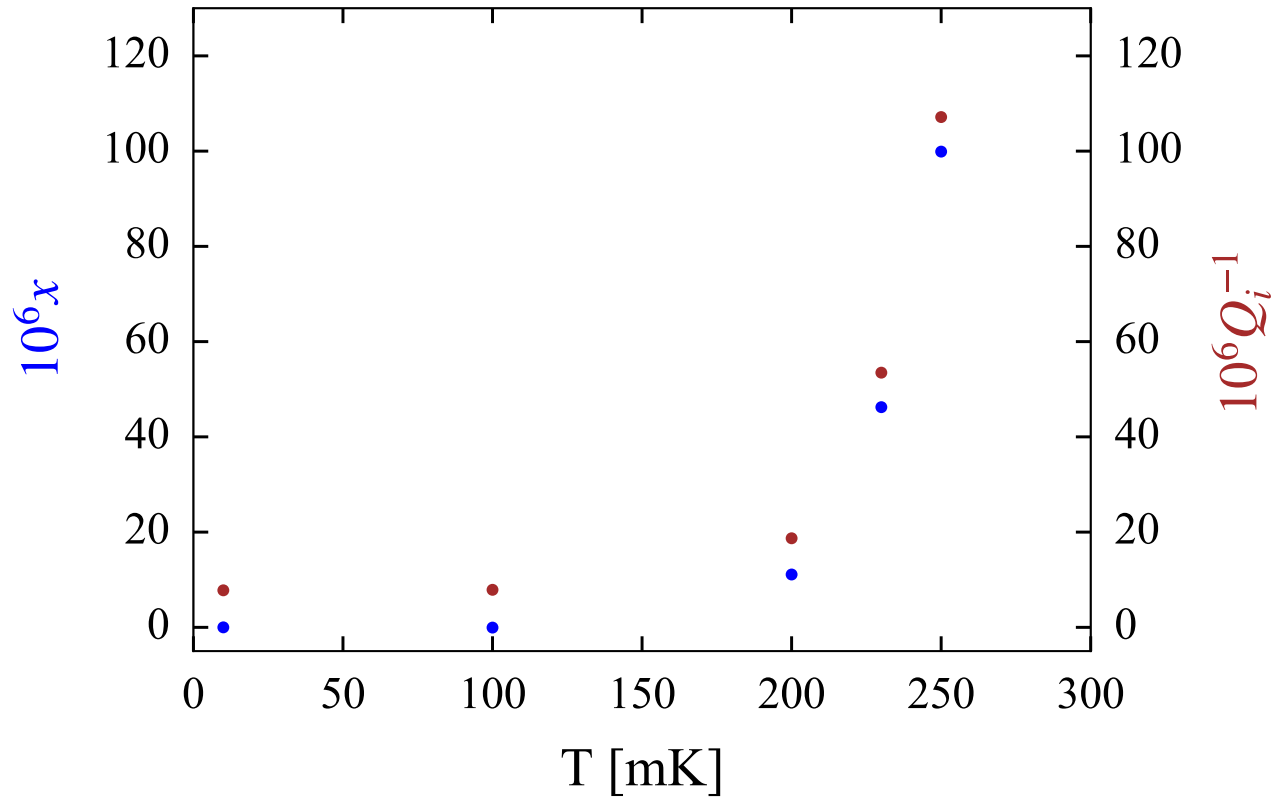


device arrays fabricated at NASA/JPL

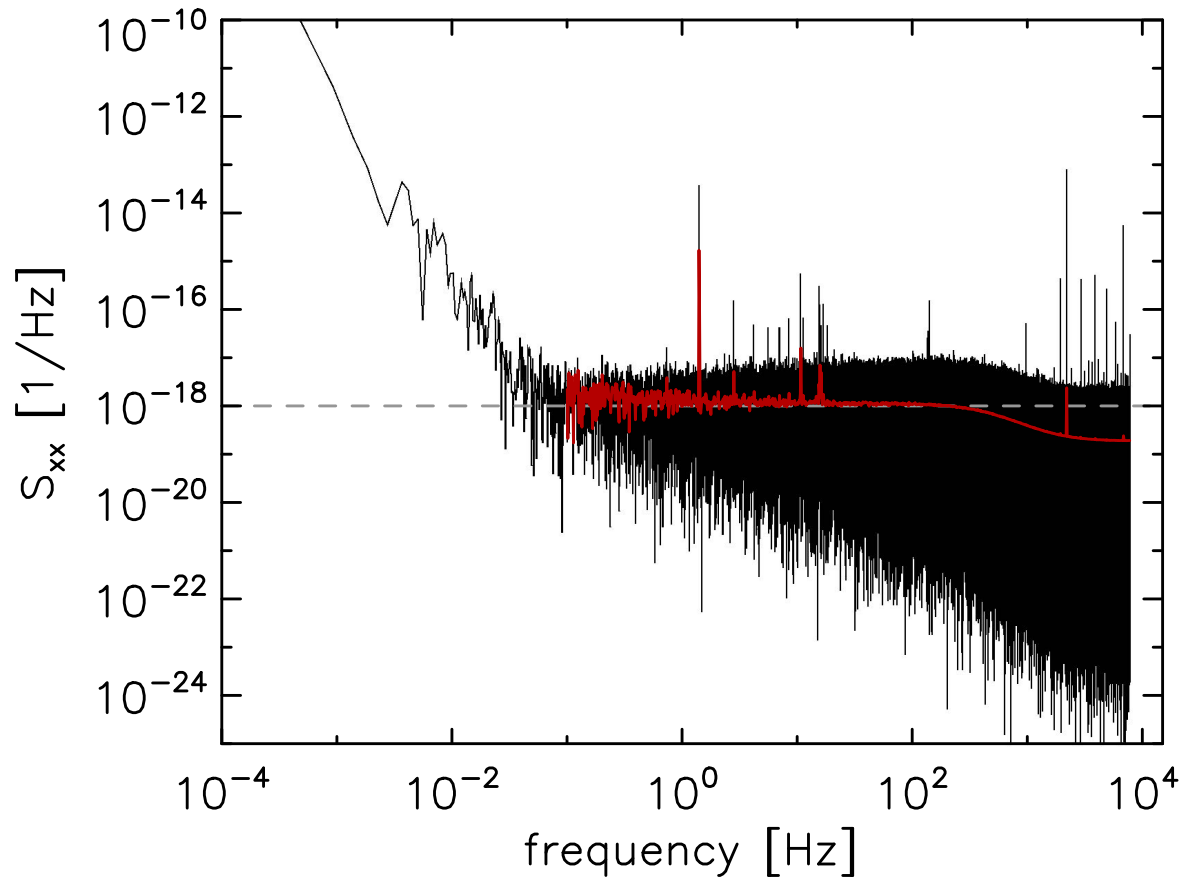
Simulated Performance of Resonators



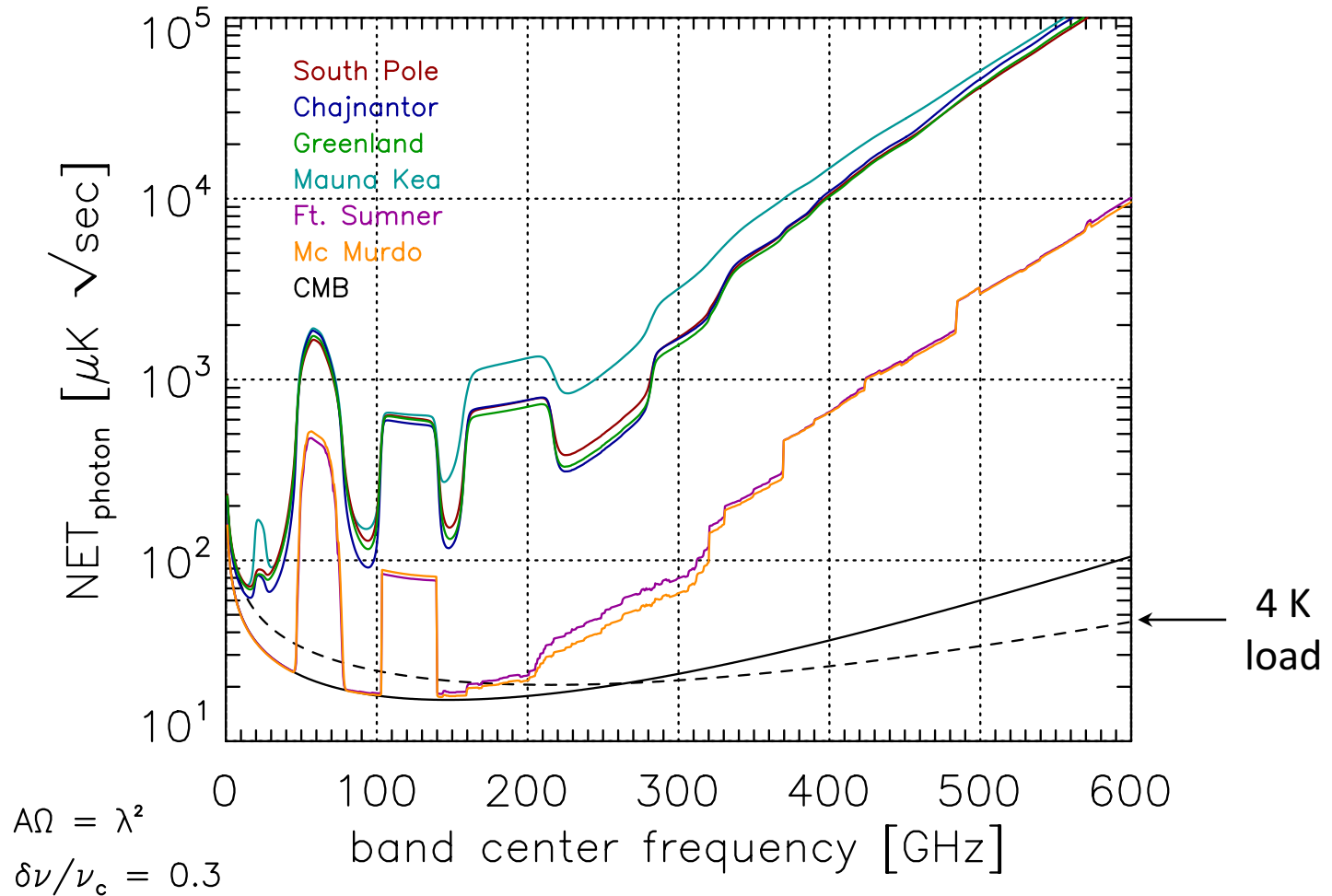
Simulated Performance of Resonators



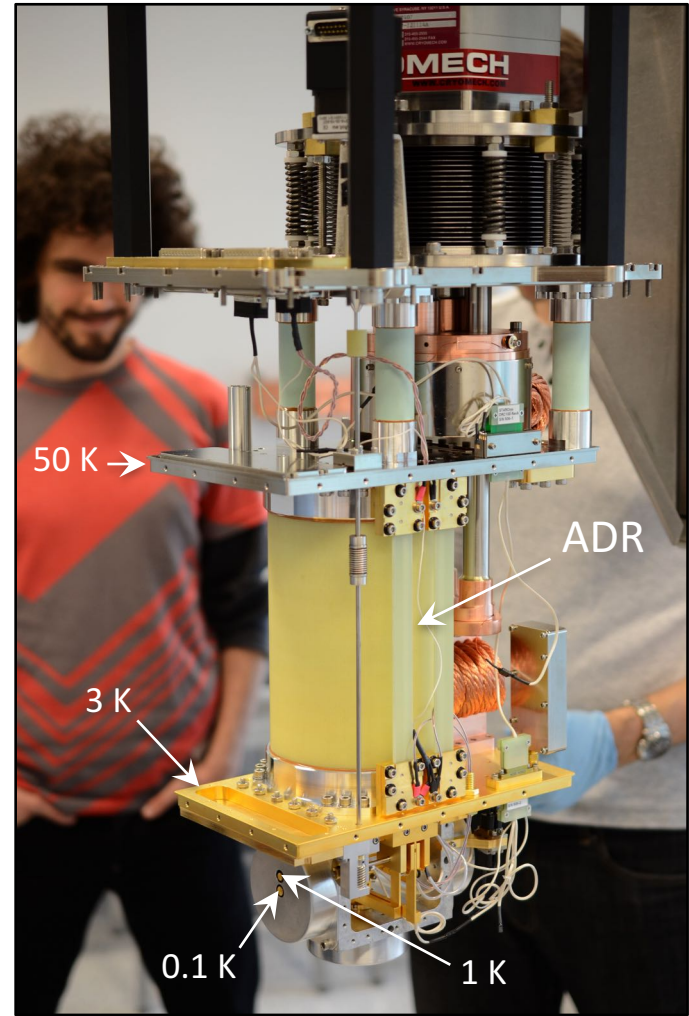
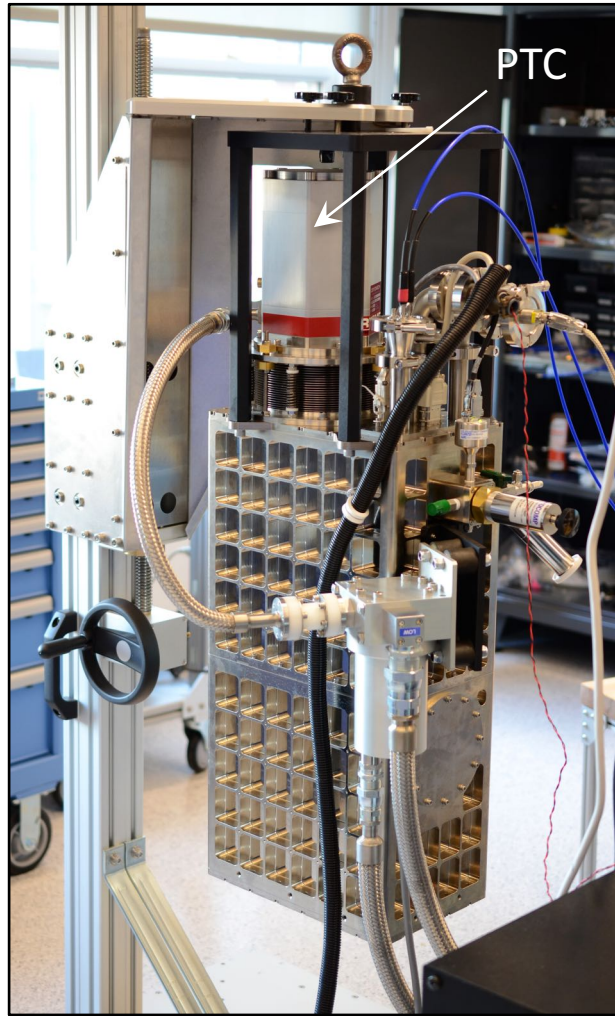
Low-Frequency Noise Properties



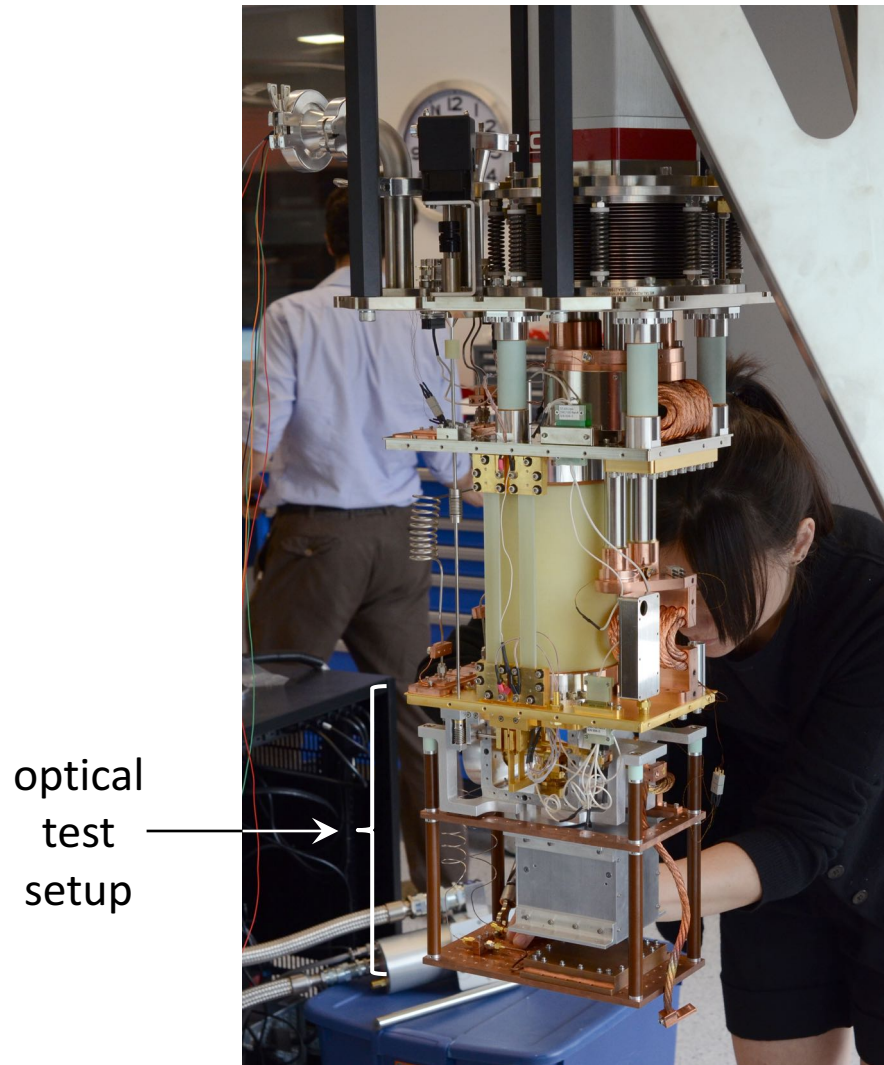
Interpreting the NET Result



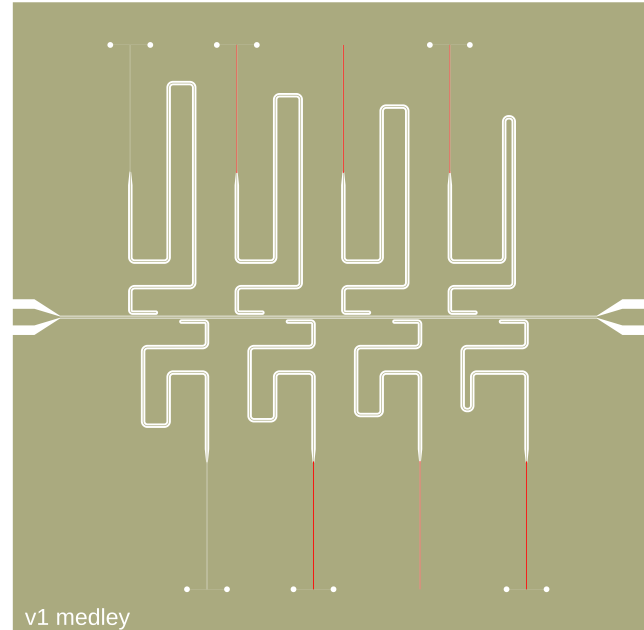
STAR Cryoelectronics DRC-102 ADR Cryostat



STAR Cryoelectronics DRC-102 ADR Cryostat



Prototype MKID Devices



We are currently dark-testing mini arrays of resonators to optimize the MKID design.

Our Design Based on ACT/SPT Devices

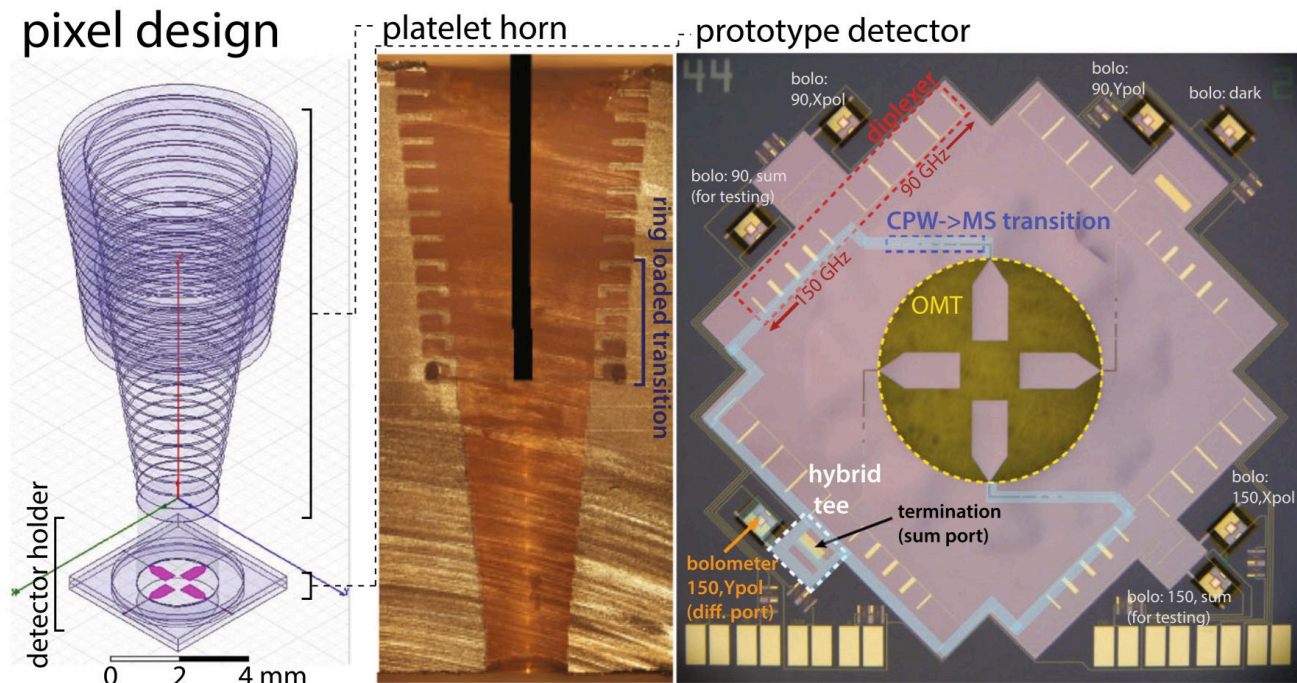


Fig. 1 *Left* design of a single horn coupled multichroic polarimeter with labels on the major components. *Center* a photograph of a cross-section of a broad-band ring-loaded corrugated feed horn fabricated by gold plating a stack of etched silicon platelets. *Right* a photograph of a prototype 90/150 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