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Towards a 2000-channel Microwave SQUID Multiplexed Unit for Transition-Edge Sensor Bolometer Arrays

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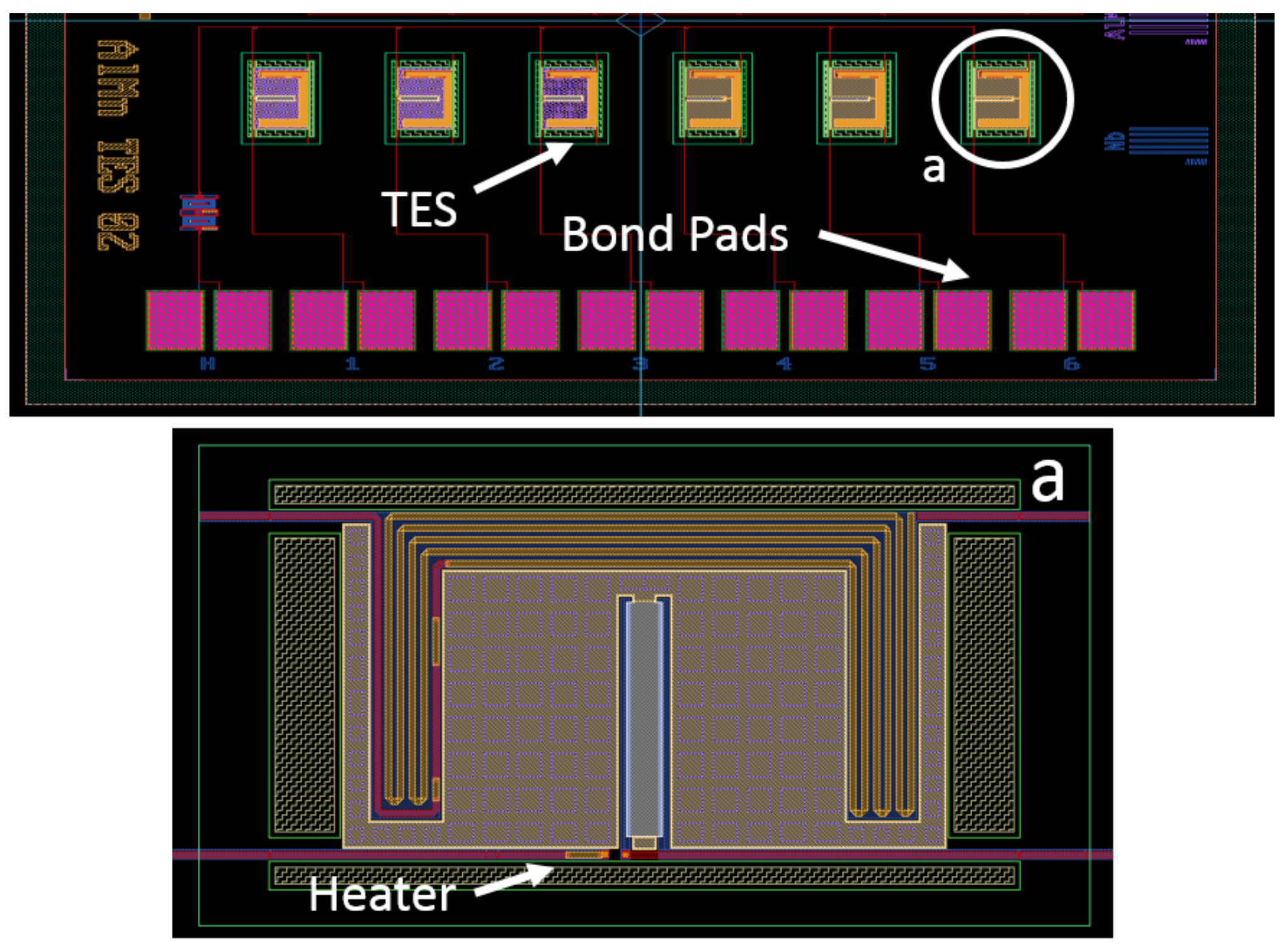
Motivation

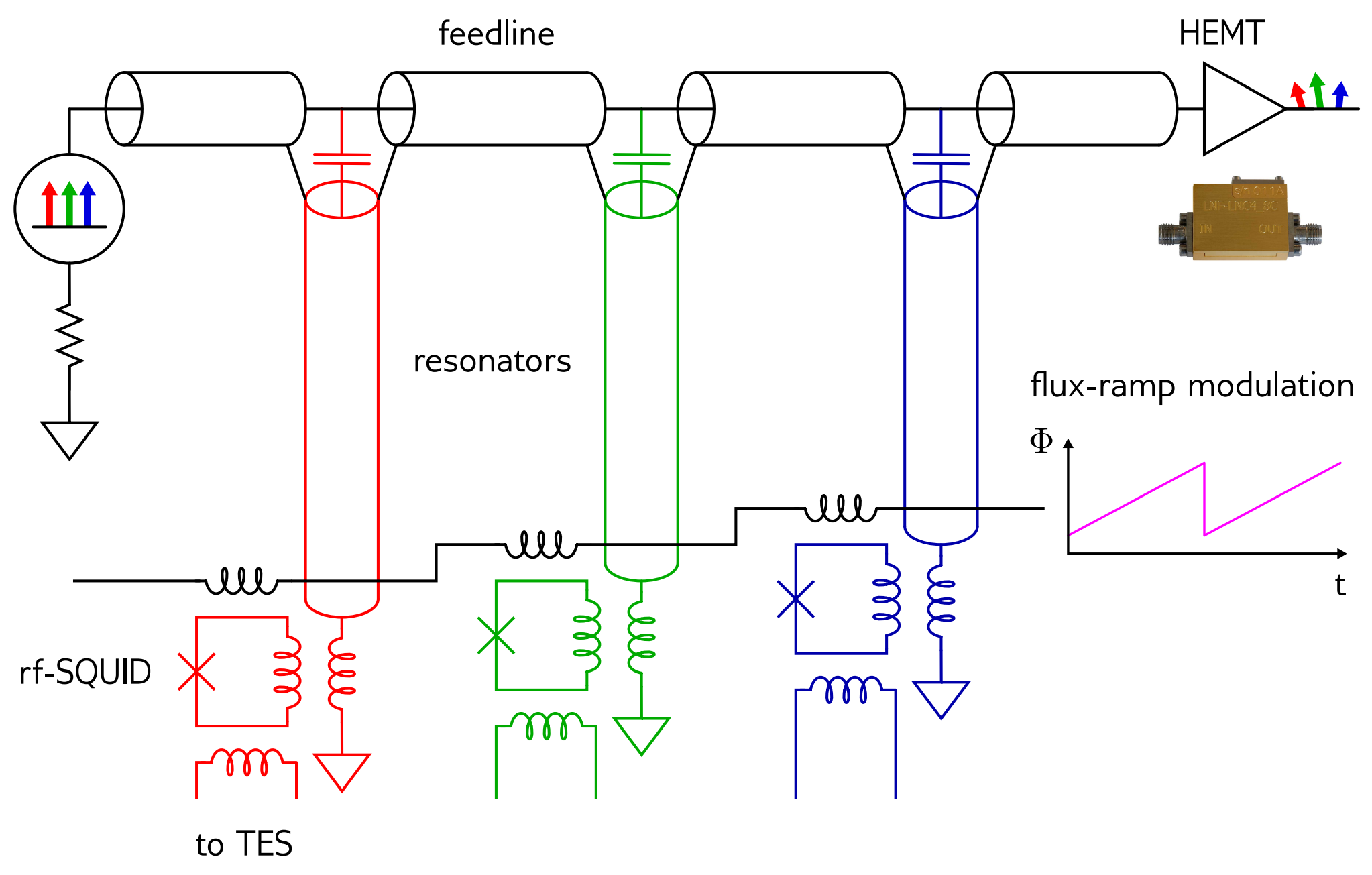
With next-generation cosmic microwave background (CMB) instruments, such as the Simons Observatory that is developing focal planes with over 50,000 pixels and CMB-S4 requiring an order of magnitude more, there is an ever-growing need for readout systems with both higher multiplexing factors and more streamlined detector packaging. Current systems, such as time-domain (TDM) and frequency domain multiplexing (FDM), have currently fielded systems with $\sim$ 70 multiplexed channels. Both these systems use SQUIDS as their first-stage low noise amplifier.

The microwave SQUID multiplexer (μMUX)[1,2] is a recently-developed technology that has the potential to read out thousands of detectors on a single pair of coaxial cables. In contrast to TDM and FDM which use DC-SQUIDs, μMUX uses rf-SQUIDs. The majority of publish work on μMUX has been for spectroscopic applications. Here we discuss the use of μMUX for bolometric applications. We present proof-of-principle results and discuss our plans to enable a 2000 channel multiplexing factor.



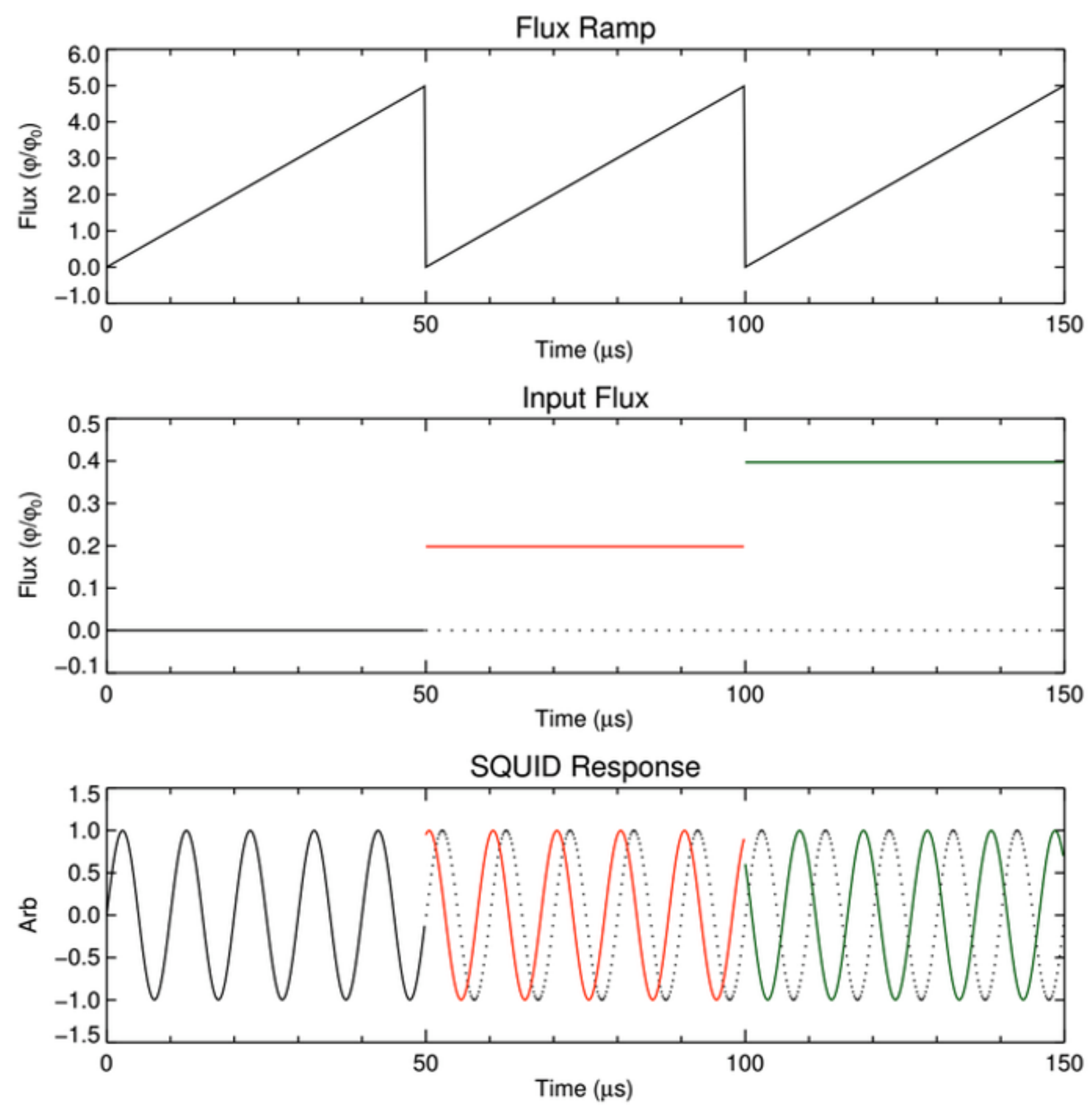
CMB TES text pixels used in the small-scale bolometer demo

Operation Principle



- Each channel consists of a dissipation-less rf-SQUID couped to a quarter-wave resonator with its own unique resonant frequency
- rf-SQUID acts as variable inductance
- All resonators are capacitively coupled to a coplanar waveguide feedline
- Microwave resonant tones are sent down the feedline to interrogate the resonances before being amplified by a 4 K HEMT
- A common flux ramp linearizes the SQUID response
- Density is limited by both the bandwidth of the warm readout electronics and the resonator spacing

Flux-Ramp Modulation



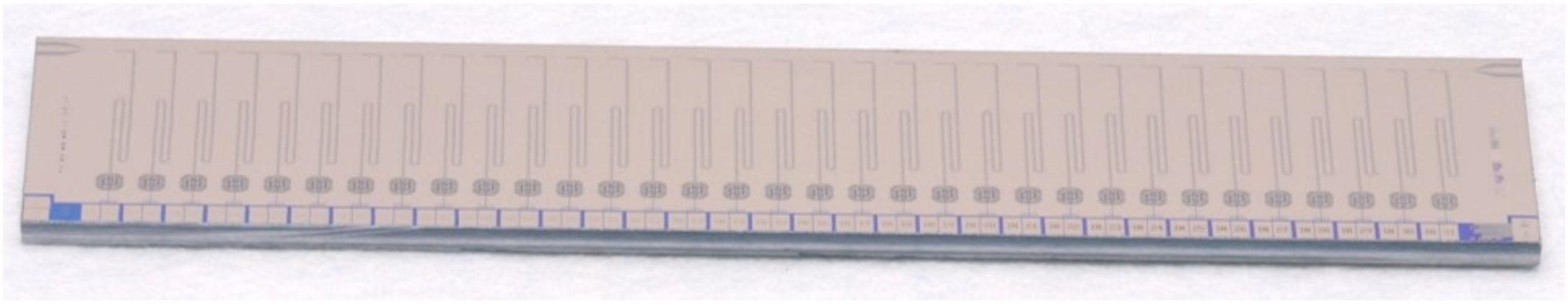
- Needed to linearize the SQUID response[3]
- An additional source of flux is coupled to all SQUIDs
- A sawtooth function is applied that ramps through $\sim 2\Phi_0$
- TES signal appears as a phase shift
- Demodulation of the data produces a readout rate at the sawtooth ramp rate
- Also modulates the detector signal above the resonator's 1/f knee

Small-scale TES Bolometer Demo

For the measurement results shown below which verify the performance of the μMUX readout, we mounted 4 detector chips, each containing 6 TES bolometers, into a sample box. The TESs are biased on a common line via two 32-channel 374 $\mu\Omega$ shunt resistor chips in series. We omitted Nyquist inductors that would have limited the TES bandwidth. The TESs and shunts are then wired to a pair of 32-channel μMUX chips, which have resonant frequencies, f_r, in 250 MHz segments between 5-6 GHz. The bandwidth of each individual resonator is 300 kHz, and their resonant frequencies are spaced apart by 6 MHz (20 times the resonator bandwidth).

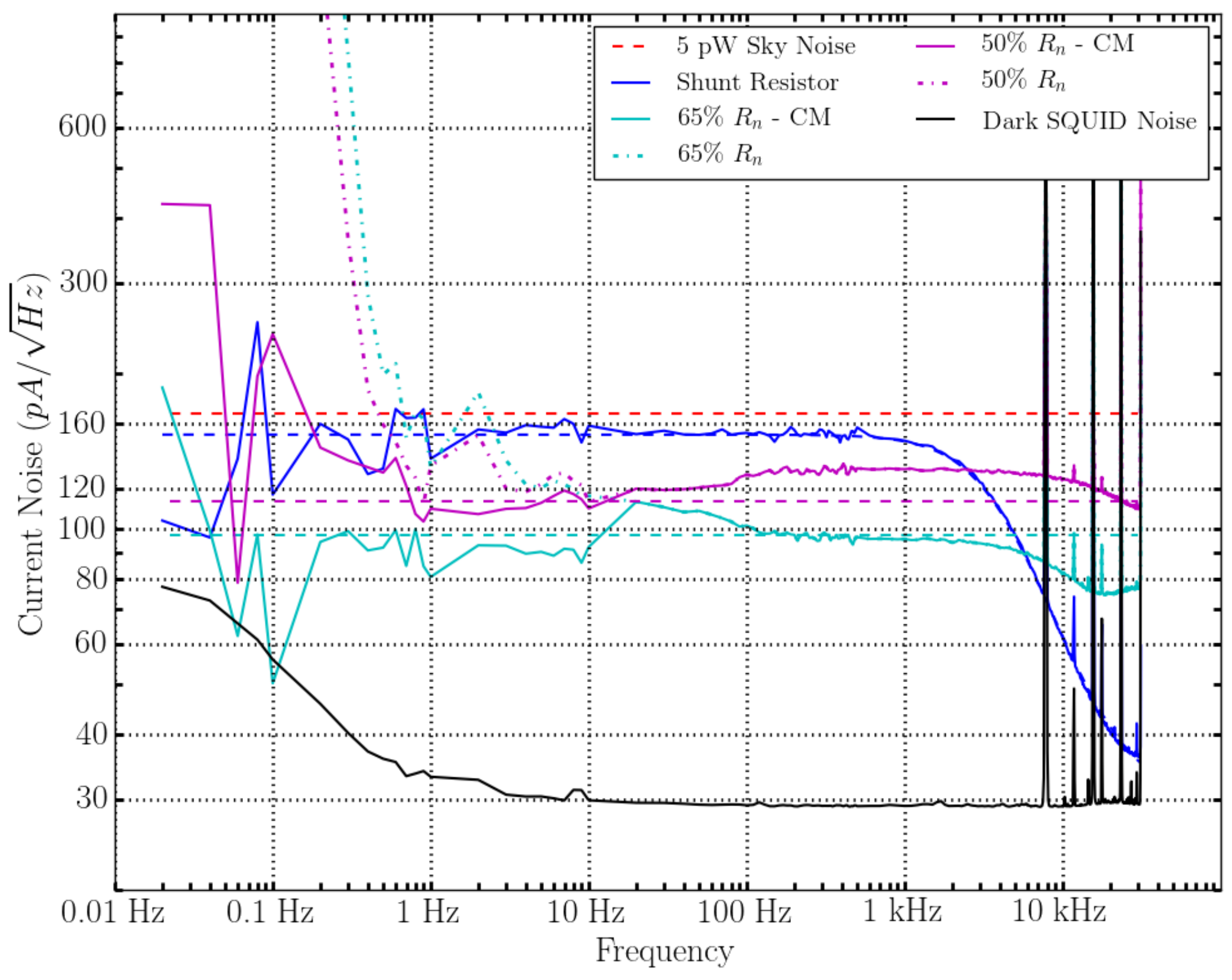
The 40 readout channels that were not wired to TESs were used to measure the readout noise floor. Finally, a common heater line was wired up to the first of the four TES chips to perform the crosstalk measurements shown below.

μMUX17a



One of the two 32 channel μMUX chips used in the measurements shown below

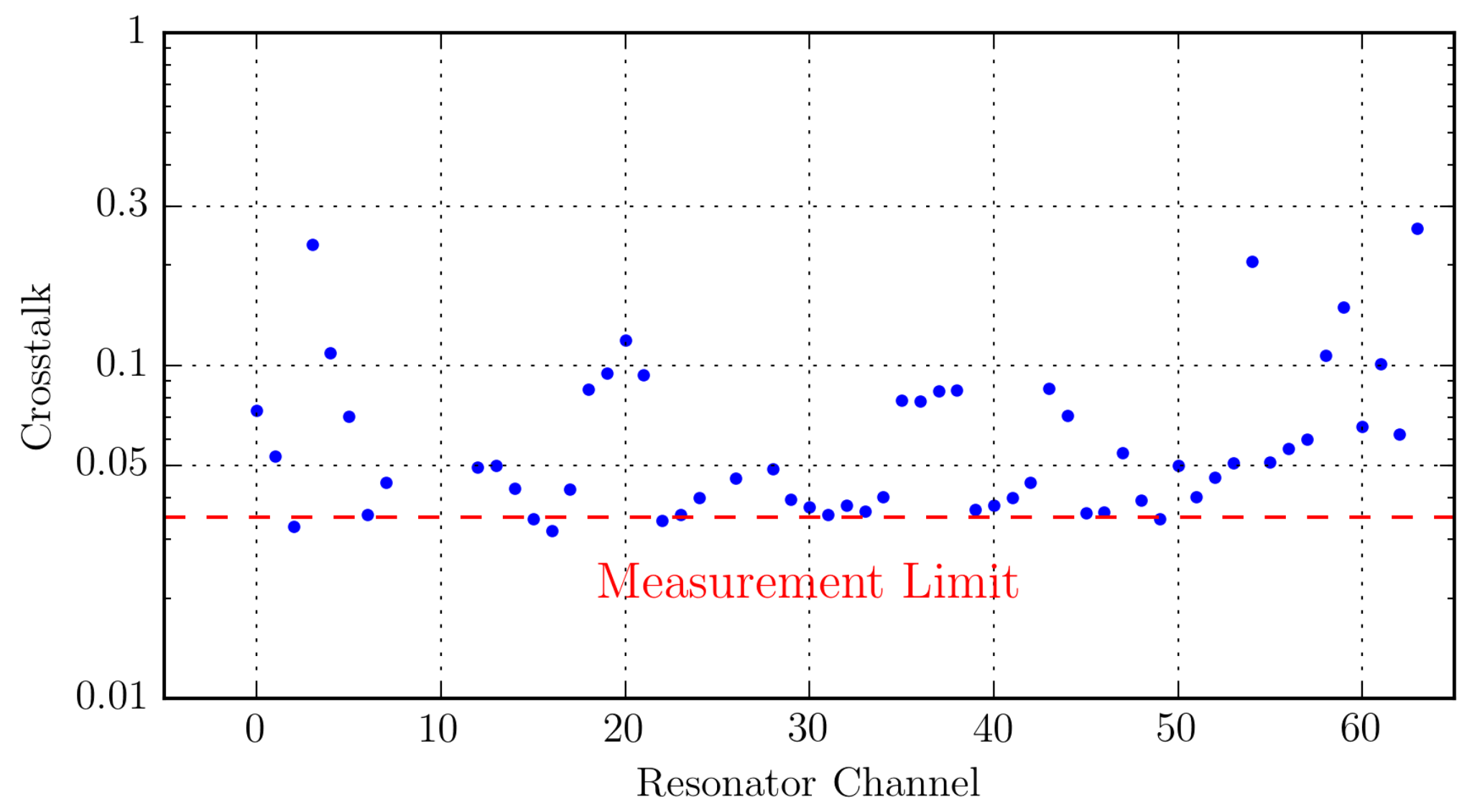
Measured Noise Performance



- Measurements were taken at a bath temperature of 150 mK to simulate a typical radiative load for ground-based CMB observations
- The dashed lines are predicted noise levels
- The solid blue line is the measured shunt resistor noise while the TES is in the superconducting state
- The solid magenta and cyan lines are the measured detector noise at 50% and 65% R_n after applying a 3-mode singular value decomposition while the dotted lines show the unsubtracted noise
- The solid black line is the average of all dark readout channels and exhibits a noise level of 29 pA/$\sqrt{Hz}$
- This noise level can be further reduced by increasing the readout tone power

Measured Crosstalk Performance

Minimizing detector crosstalk is a critical requirement for CMB observations. Near-term CMB receivers target <0.3% crosstalk which enable measurements of the tensor-to-scalar ratio to $r \simeq 3.2 \times 10^{-34}$. The level of sensitivity required for this measurement should be achievable in next-generation CMB experiments.



Experimental Description:

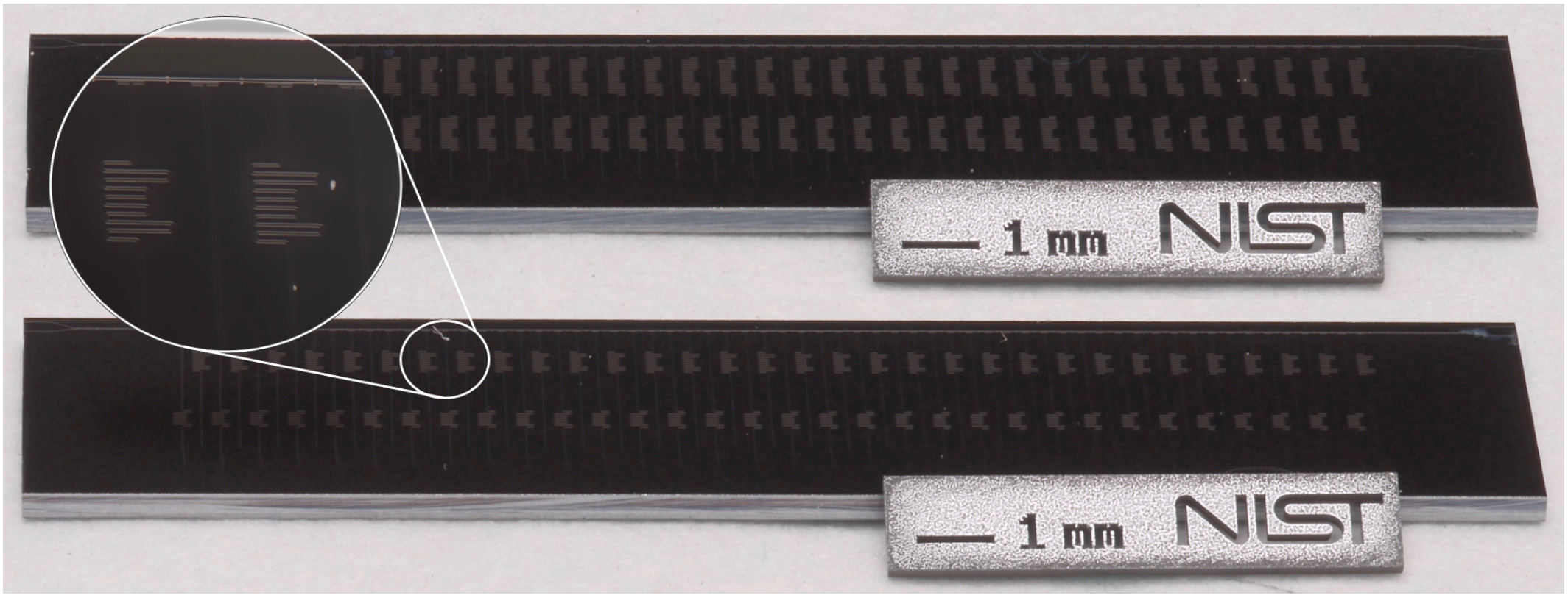
- Injecting a 1.11 pW rms 50 Hz power signal via the heaters located on 6 biased TESs on frequency channels 8, 9, 10, 11, 25 and 27
- Measuring the ratio of the amount 50 Hz of pickup in other channels to the signal in most responsive injection channel

Results:

- Most channels, including those neighboring injection channels, show crosstalk $\sim$0.035%
- This 0.035% level is the minimum crosstalk signal we are able to measure with this method and should serve as an upper limit
- All channels with elevated crosstalk are attached to biased TESs
- This suggests that another crosstalk mechanism, such as coupling through the bias lines, is at work
- Despite this, the highest crosstalk level measured was 0.258%, which is still below the required 0.3%

New High-Density μMUX Design

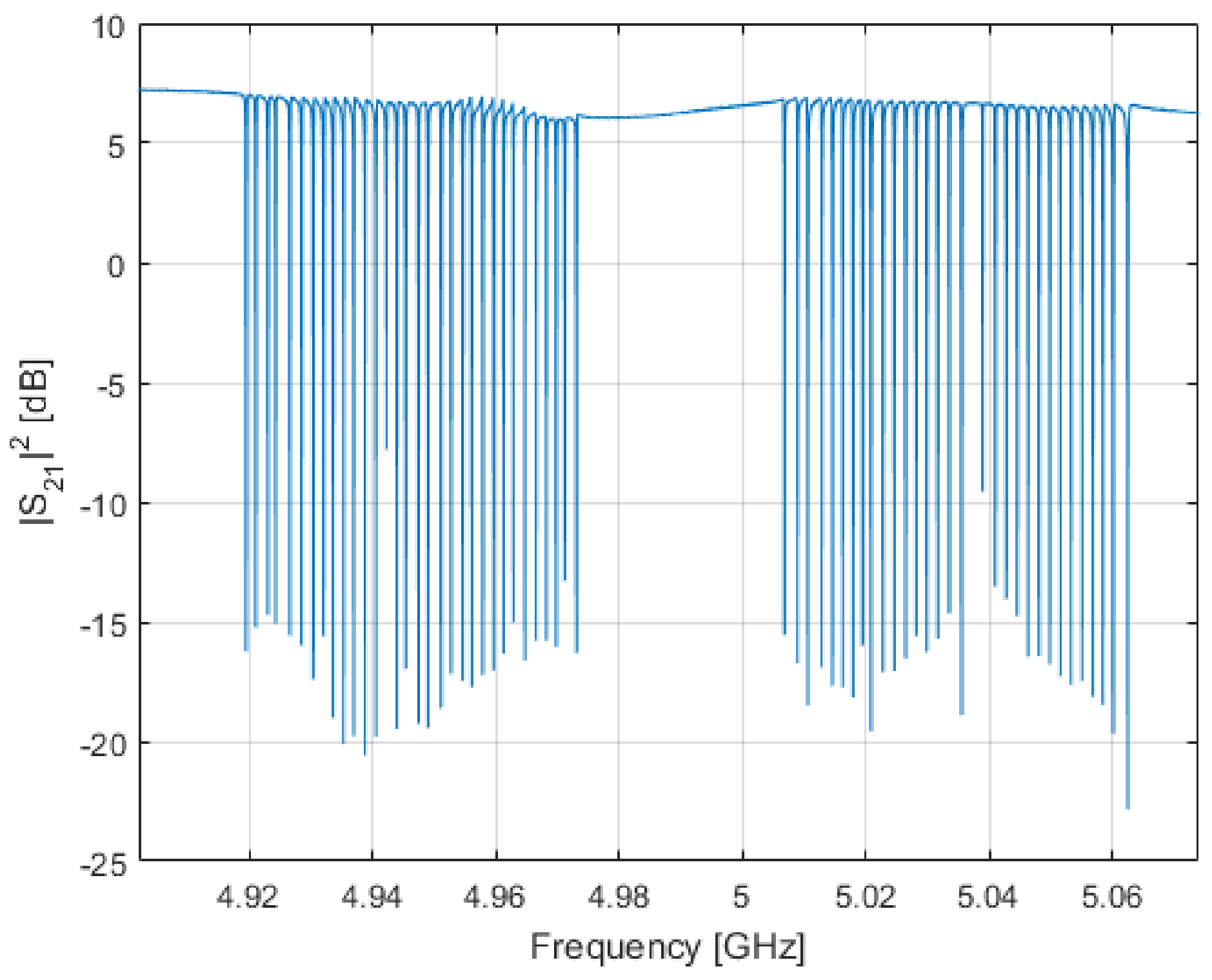
μMUX17b



Above are two new types of μMUX test chips
(top: 5 GHz, bottom: 7 GHz) that have a variety of new features:

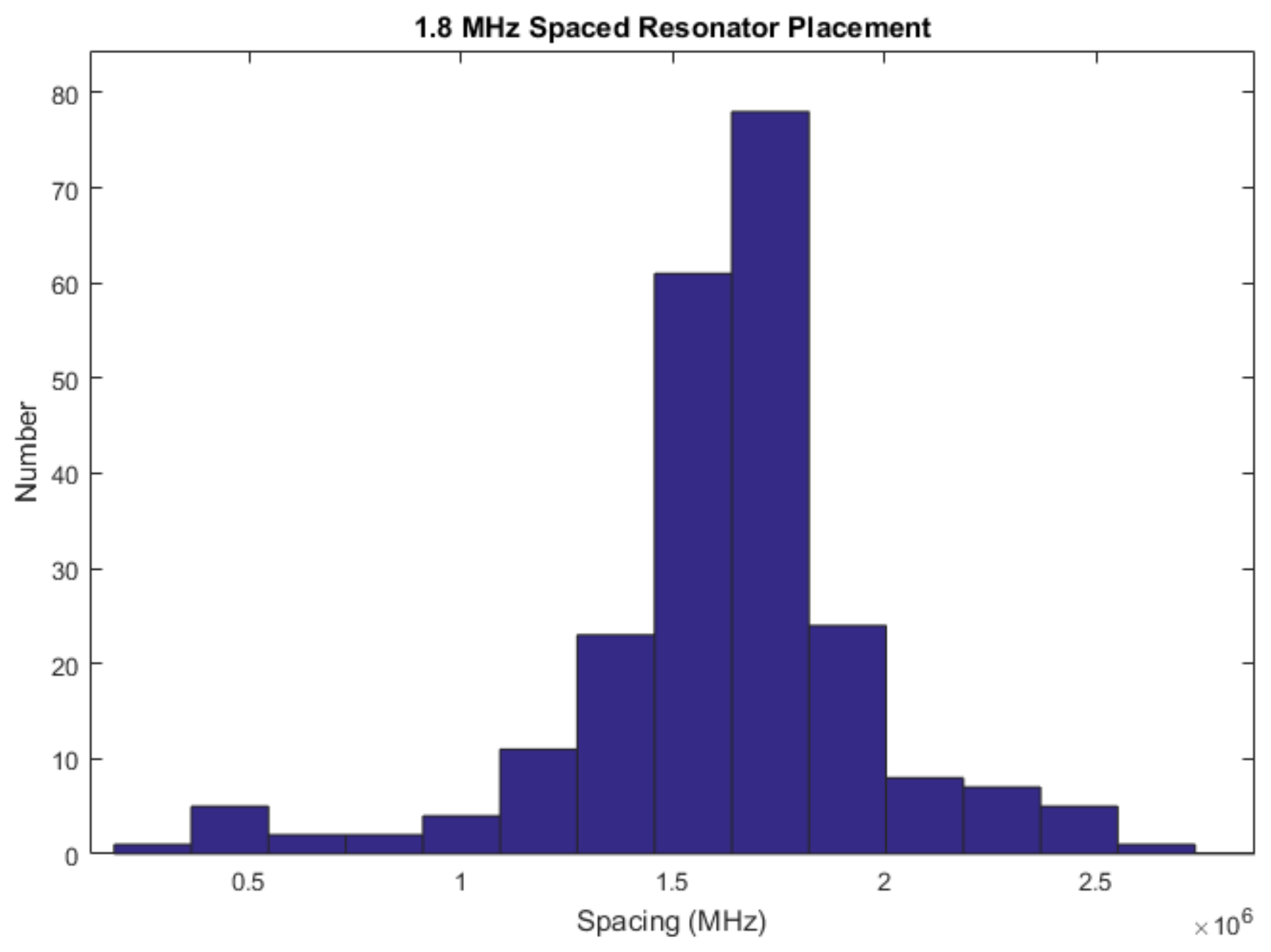
- Resonators utilize new 'wiggle' design that doubles the linear density while maintaining the same physical separation
- The new design maintains the same physical footprint (20x4 mm) as previous designs.
- Resonant frequency spacing has been reduced from 6 MHz to 1.8 MHz to allow up to 2000 channels in a 4-8 GHz readout system
- Resonator bandwidth has been reduced from 300 kHz to 100 kHz to maintain the same linewidth separation
- In lieu of IDCs, T-bar capacitive couplers (see inset) have been utilized which maintain the ground plane near the feedline

S21 Measurement of the 5 GHz Band



Transmission measurements, shown above, were taken with a VNA and used to fit for the resonator's f_r, Q, and bandwidth for several sets of 5 and 7 GHz resonator band test chips.

Resonant Frequency Placement



The above histogram shows the measured spacing between nominally 256 resonators from two sets of 5 and 7 GHz resonator band test chips. The results show:

- Only 1 set of the 256 resonators are below the 5 linewidth crosstalk cutoff (<5 MHz)
- The standard deviation of the resonator spacing is 352 kHz, which is one-third of the previous attainable spread
- This will enable the required resonator yields of >99% on the full 2000 channel μMUX design

Future Work

- Fabricate new μMUX resonator design with SQUID and Flux ramp line
- Verify the frequency placement is not degraded from SQUID introduction
- Measure readout noise and crosstalk performance
- Integrate into medium-scale ($\sim$500 pixel) TES bolometer demo
- Design full-scale detector array and readout packaging

Citations

1) Mates, John Arthur Benson. The microwave SQUID multiplexer. PhD thesis, University of Colorado, 2011.
2) Mates, J. A. B., et al. "Demonstration of a multiplexer of dissipationless superconducting quantum interference devices." Applied Physics Letters 92.2 (2008): 023514.
3) Mates, J. AB, et al. "Flux-ramp modulation for squid multiplexing." Journal of Low Temperature Physics 167.5 (2012): 707-712.
4) Ade, P. A. R., et al. "Bicep2. III. INSTRUMENTAL SYSTEMATICS." The Astrophysical Journal 814.2 (2015): 110.

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