7-2017

Series SQUID Array Amplifiers Optimized for MHz Frequency-Domain Multiplexed Detector Readout

S. T. P. Boyd
University of New Mexico, stpboyd@unm.edu

John C. Groh
University of California, Berkeley

John A. Hall
STAR Cryoelectronics, LLC

Aritoki Suzuki
Lawrence Berkeley Laboratory

Robin Cantor
STAR Cryoelectronics, LLC

STAR CRYOELECTRONICS

THE UNIVERSITY of NEW MEXICO

BERKELEY LAB

LTD-17
PB-8

Series SQUID Array Amplifiers Optimized for MHz Frequency-Domain Multiplexed Detector Readout

S. T. P. Boyd[1], John C. Groh[2], John A. Hall[3], Aritoki Suzuki[4], and Robin Cantor[3]

[1]University of New Mexico, Albuquerque, NM
[2]University of California, Berkeley, CA
[3]STAR Cryoelectronics LLC, Santa Fe, NM
[4]Lawrence Berkeley National Laboratory, Berkeley, CA

1. Introduction

The CMB-S4 next-generation ground-based cosmic microwave background experimental program aims to provide definitive measurements of the early universe using telescopes with ~500,000 detectors. In this report, we describe the initial results of a project to develop low-noise **S**eries **S**QUID **A**rray **A**mplifiers (**SSAA**s) that are suitable for **F**requency **D**omain **M**ultiplexed (**FDM**) readout for large CMB instruments. The new series SQUID array amplifier designs exhibit excellent performance characteristics – smooth output characteristics that simplify tuning and operation, high transimpedance (400 V/A), low current noise referred to the input (5.9 pA/Hz^{½}), low input inductance (11 nH), and low power dissipation (18 nW) that for the first time will enable these devices to be co-located on the focal plane of CMB experiments, thereby reducing unwanted parasitics from cabling.

2. Optimization Goals

For the initial part of the project:

reduced input inductance

- Reduced input inductance allows closer channel packing and stable detector operation in FDM. [1]

smooth *V*-Φ curves

- Huber *et al*. [2] demonstrated a relationship between irregular features in the *V*-Φ curve of SSAAs and RF resonances, which in turn can lead to irregular features in the transimpedance at frequencies above a few MHz. Smooth *V*-Φ curves thus indicate that SSAA bandwidth can be expanded to support more channels.

reduced power dissipation

- For future large-pixel-count CMB experiments, it is desirable to co-locate the SSAAs on the 100 mK stage in close proximity to the pixels and the band pass filters to reduce parasitic impedance from connecting transmission lines.

while maintaining the transimpedance (~500 V/A), input coupling (25 μA/Φ_0), and current noise (~3.7 pA/Hz^{½}) of the benchmark NIST SSAA [2].

3. Technical Approach

UNM Center for Advanced Research Computing

Design Calculations

- Lumped-Element Simulations
  - Custom code developed by SB to simulate nonlinear SQUID dynamics, run at Center for Advanced Research Computing at the University of New Mexico [3].
- Harmonic Circuit Analysis
  - Commercial software was used to study: 1) SQUID-SQUID broadcast via the input circuit, 2) the impact of transmission-line resonances of the input coils on the function of the input circuit and SQUID-SQUID broadcast, and 3) screening of the SQUID inductance by the resistively-shunted input coils.
- Finite-Element Calculations
  - Customized commercial software was used to calculate SQUID and input coil inductances, input coupling, capacitance, and transmission-line parameters.

Design Strategies

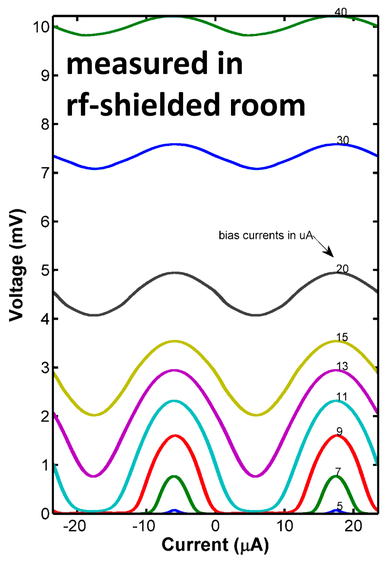
- Reduce input inductance, power dissipation, and probability of resonances
  - larger-inductance SQUID loop
  - lower critical current reduces power dissipation
  - low-turn-count input coils reduce input inductance and possible resonance modes
- Wide-ranging designs: 72 different designs across two generations combining
  1. both second-order and first-order gradiometer SQUID designs;
  2. damping resistances on the input coils, both extra-coil and intra-coil[2];
  3. skeletonized SQUID washers to reduce capacitive coupling of the SQUIDs to the input circuit
  4. "mosaic" arrays, alternating two different SQUID designs with equal input mutuals in a checkerboard pattern, so that nearest neighbors have different Josephson frequencies, but the V-Φ transfer functions add constructively.

Fabrication

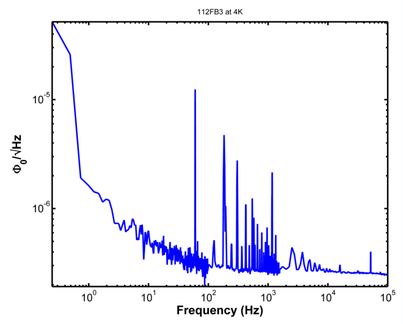
- Two generations of SSAAs fabricated using STARCryo commercial SQUID process
  - 36 different designs per generation
  - Yields on devices tested to date are 100%.

4. Characteristics at 4K

- First generation performance ranking
  1. first-order gradiometric SQUIDs with solid (non-skeletonized) washers
  2. second-order gradiometric SQUIDs with solid washers
  3. 1st-order gradiometric SQUIDs with skeletonized washers
- Second generation
  - specialized to first-order gradiometric SQUIDs with solid washers
  - 36 designs varying SQUID damping, details of SQUID wiring, and input coil damping

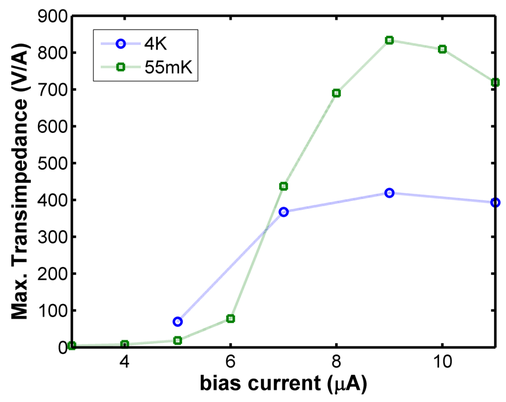


112F Array Parameters	Typical Values	
Chip Size	4.5 x 3	mm
Temperature	4.2	K
Number of SQUIDs	112	-
Array input coil inductance L_m	11	nH
input & feedback coupling $1/M_m$	23.6	μA/Φ_0
Flux expulsion heater resistance	250	Ω
SQUID resistance R/2	2.6	Ω
SQUID critical current $2I_c$	11.5	μA
$\beta = 2LI_c/\Phi_0$	0.56	-
$\beta_c = 2\pi I_c R^2 C/\Phi_0$	0.28	-
Array voltage swing ΔV	2.4	mV
Array transfer coefficient $\partial V/\partial\Phi$	9.4	mV/Φ_0
Array gain (transimpedance)	400	V/A
Output dynamic resistance R_d	290	Ω
Array flux noise $S_F^{½}$, f > 100 Hz	250	nΦ_0/Hz^{½}
Array power dissipation	18	nW

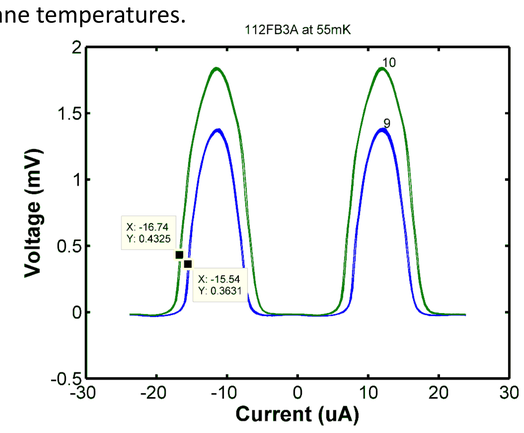


Results from the second generation SSAA designs at 4K. This design had 112 SQUIDs. Left: voltage-current curves remain smooth over the full bias-current range of the PFL-102 readout electronics. Transimpedance of 398 V/A is reached at 11uA of bias current. Bottom: Noise spectrum of the same device, demonstrating white noise level of 250 nΦ_0/Hz^{½} (5.9 pA/Hz^{½} at the 23.6 μA/Φ_0 input coupling) at 4 K. This performance was typical for several design variants using 112 SQUIDs of Type F. SQUIDs of Type F displayed the largest transfer function amplitudes while remaining robustly smooth.

5. Characteristics below 100 mK

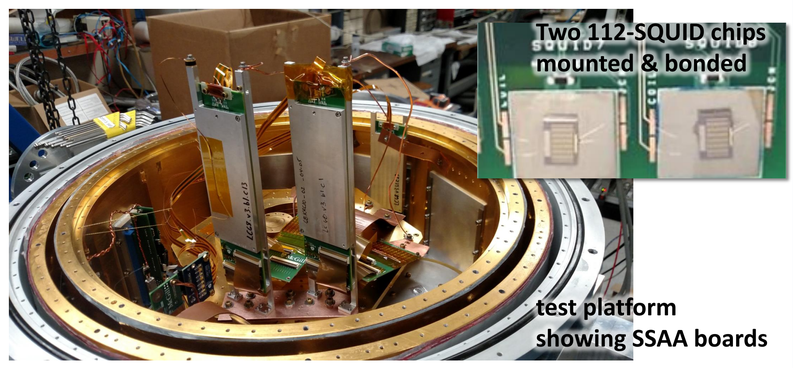


Maximum transimpedance of the 112-SQUID SSAA **doubles** when we operate at lower temperature (here 55mK) comparable to future CMB focal plane temperatures.



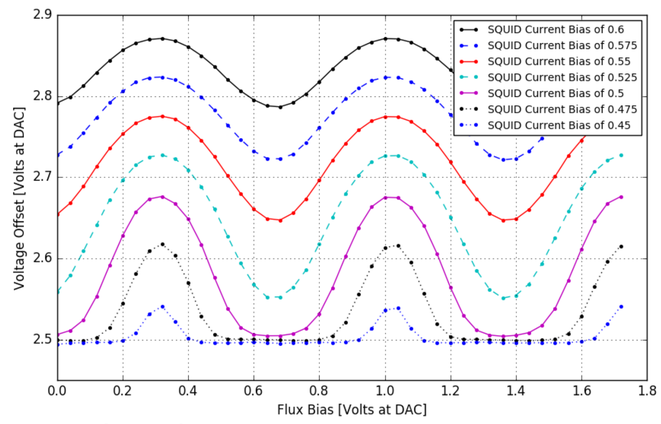
Voltage-current characteristics at 9uA and 10uA bias currents yielding maximum transimpedance at 55mK. Characteristics remain **smooth**. Operating points for transimpedance ~**800 V/A** are indicated. Dissipated power at these bias points is **<5nW**.

6. 4K Results with FDM Readout



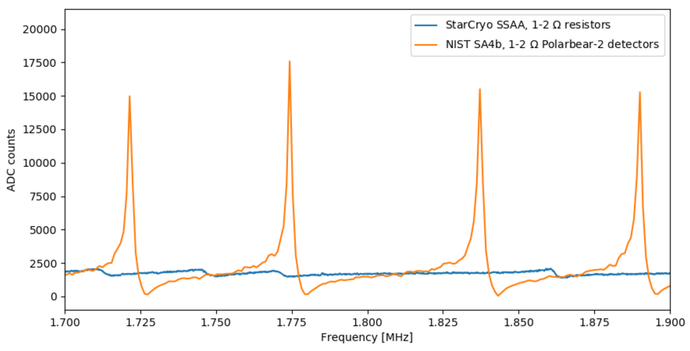
- PTC cryostat with frequency multiplexing readout electronics used by POLARBEAR-2, SPT-3G, and Simons Array. [4-6]
  - Cooldown #1: nothing attached to input coils
  - Cooldown #2: connected to mock detectors in full readout chain (nominal telescope configuration)

Tuning and Transimpedance



- Smooth V-phi curves persist in FDM environment
- 300-400 Ohm of usable transimpedance, depending on choice of current bias (nonlinearity and dynamic range concerns)

Nuller Network Analysis



- Initial evidence of reduced SSAA input impedance Z_{SSAA}. In the limit that (Z_{SSAA} + Z_{wiring}) / ($Z_{bolometer}$) -> 0, this line should be flat.

Acknowledgments

S.B. and R.C. thank Martin Huber for helpful discussions. S.B. thanks the staff at the UNM Center for Advanced Research Computing for their support. This work supported by U. S. DOE under Contract No. DE-SC0015805.

References

1. M. A. Dobbs *et al*., "Frequency multiplexed superconducting quantum interference device readout of large bolometer arrays for cosmic microwave background measurements," Rev. Sci. Instrum. vol. 83, 073113, 2012.
2. Martin E. Huber *et al*., "DC SQUID series array amplifiers with 120MHz bandwidth," IEEE Trans. Appl. Super. vol. 11, pp. 1251-1258, March 2001.
3. UNM Center for Advanced Research Computing, http://www.carc.unm.edu/
4. Tijmen de Haan *et al*., "Improved Performance of TES Bolometers using Digital Feedback," Proc. SPIE 8452, 84520E (2012), DOI 10.1117/12.925658.
5. Amy N. Bender *et al*., "Digital frequency domain multiplexing readout electronics for the next generation of millimeter telescopes," https://arxiv.org/abs/1407.3161

25-A Bisbee Court, Santa Fe, NM 87508, USA • Phone: 505.424.6454 • Fax: 505.424.8225 • www.starcryo.com • Email: info@starcryo.com