Transformer-coupled TES Frequency Domain Readout

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Motivation

Frequency domain multiplexing (fMUX[1], Figure 1) is a mature readout scheme for TES detectors in the millimetre and sub-millimitre bands. It is implemented at MHz carrier frequencies for the South Pole Telescope, POLARBEAR, and Simons Array, and will be deployed on the LiteBIRD space polarimeter.

The low detector noise and impedance cause existing implementations to use SQUID transimpedance amplifiers.

Here an alternative first-stage amplification technology is introduced that:
- is simpler, while preserving performance
- is inherently more linear that SQUIDs
- requires no tuning

Hardware

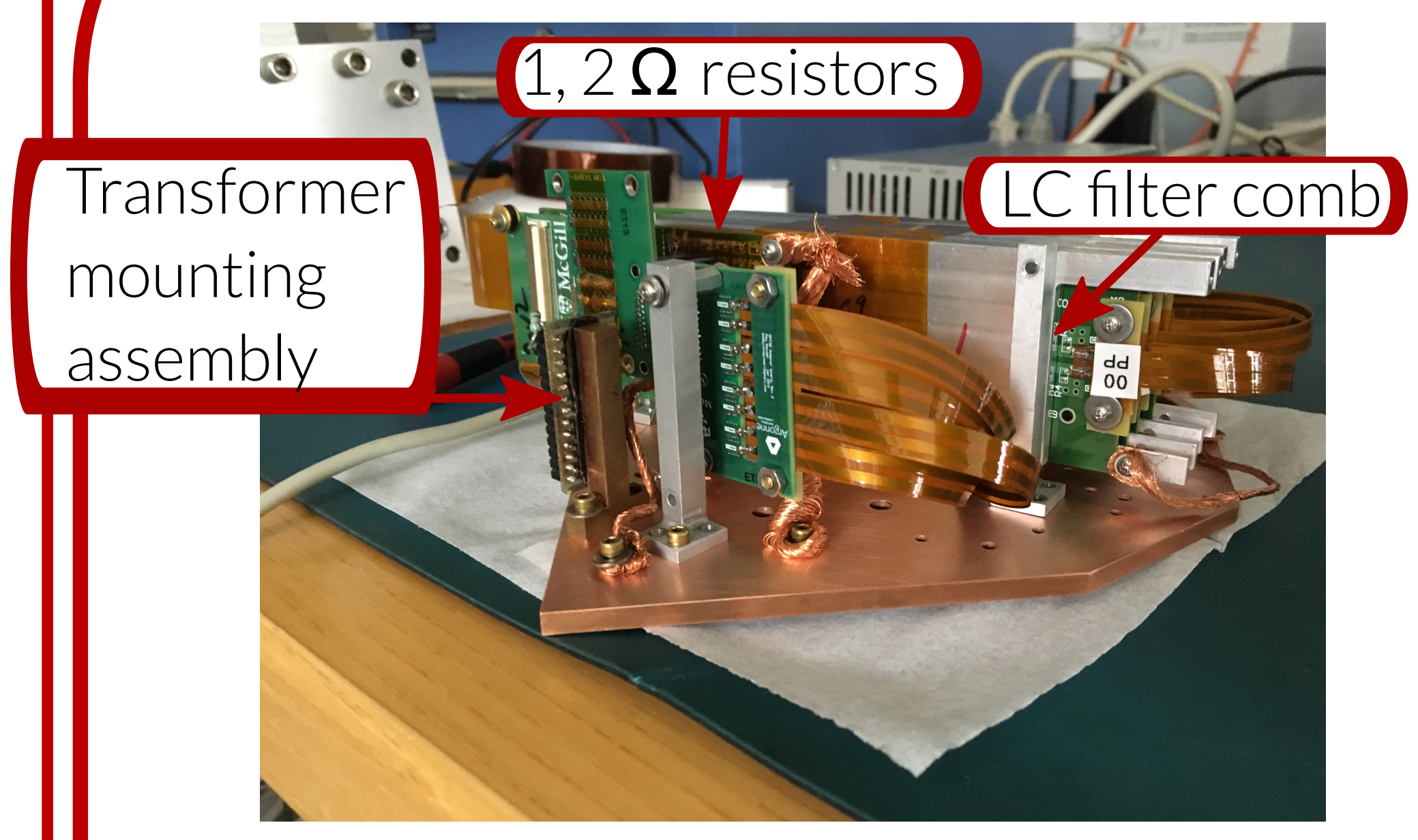


Figure 2

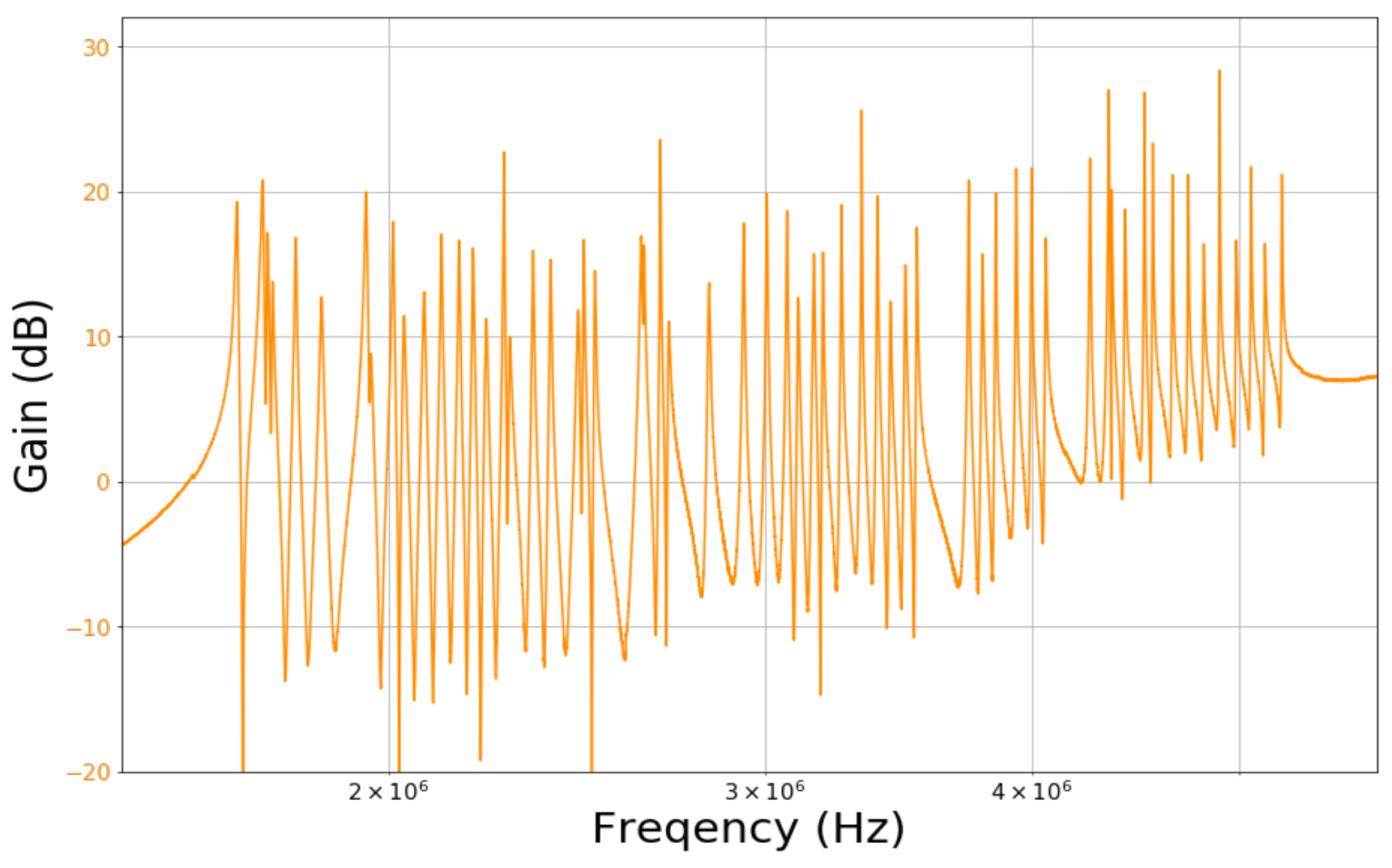
Above: a standard South Pole Telescope (SPT-3G) LC filter comb[3], manufactured at Lawrence Berkeley National Lab, isolates each channel in frequency space.

Figure 3

Above: the KC05d, a low-noise cryogenic GaAs FET, commercially-available and manufactured by Stahl Electronics[2].

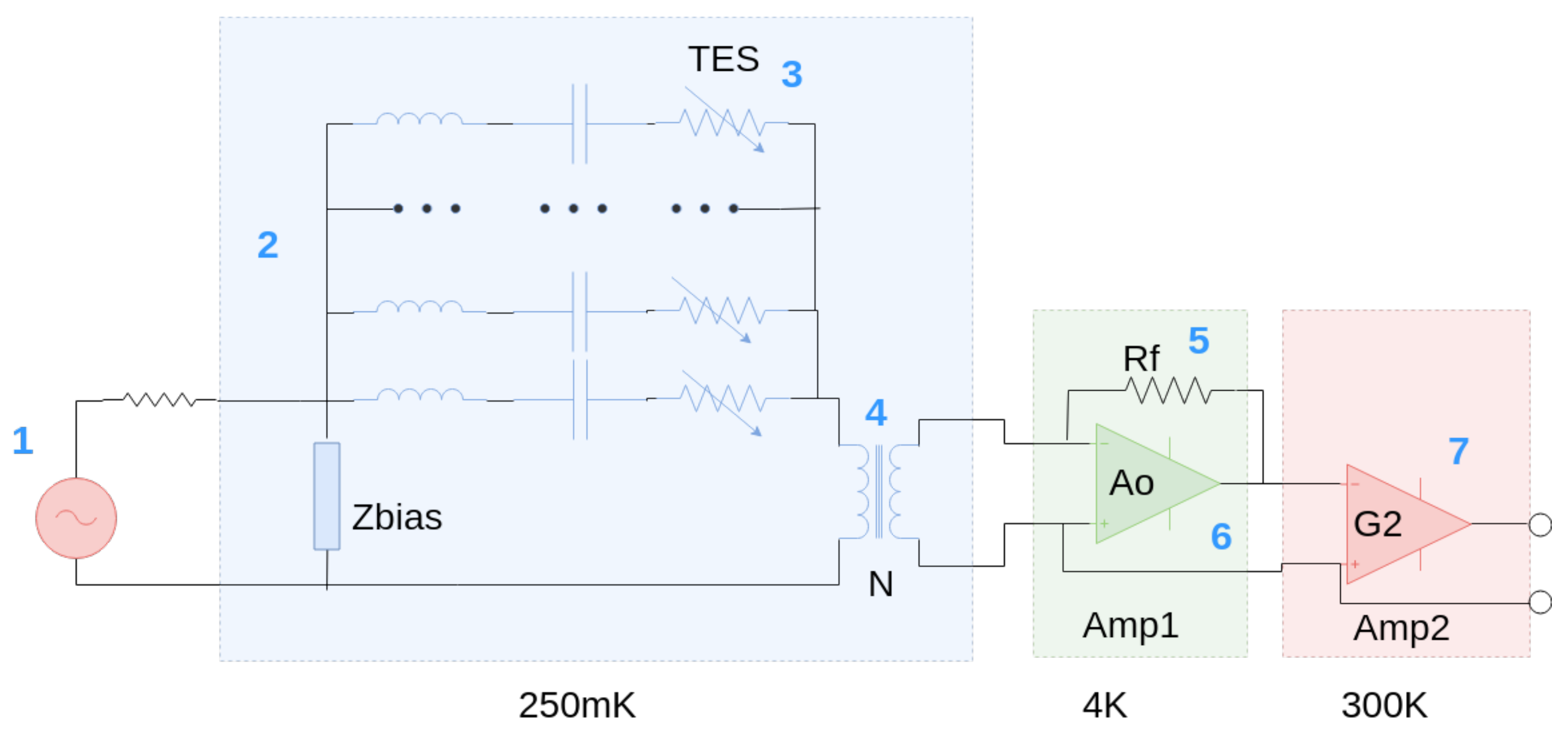
Below: a network analysis of the filtered system, showing 63 multiplexed channels distributed logarithmically from 1.5 to 6 MHz.

Figure 4



System Overview

Figure 1



1. 1.5 to 6 MHz carriers bias the detectors, with multiplexing factors of ~100 (see Fig. 3).

2. A NbTi LC comb (Fig. 2, 4) isolates bolometer channels in frequency space.

3. To show proof of concept in the prototype system, 1 and 2 **Ω** resistors are used instead of true TES bolometers; their sub-Kelvin Johnson noise is the test signal (similar scale as bolometer signals).

4. Molypermalloy powder (MPP) core transformer, with turns ratio N=50. Tested to maintain magnetic permeability at cryogenic temperatures and MHz frequencies.

5. Feedback resistor Rf sets both the system input impedance as $Z_{in} = \frac{R_f}{N^2 A_o} \sim 0.2\Omega$ and the cold stage transimpedance as $Z_{in} = \frac{R_f}{N}$ $\sim 200\Omega$

6. Low noise, cryogenic GaAs FET amplifier (Fig. 3) (open loop gain A_o=28, v_n=0.3 nV/√Hz, in=17fA/√Hz). Large dynamic range eliminates need for input signal nulling. Dissipates 10mW on the 4K stage.

7. Second-stage warm amplification sets signal level before connecting to digital readout.

System Requirements & Benefits

1. Low noise: commercial GaAs FET amplifiers offer input noise temperatures better than or equal to that of SQUIDs in use for fMUX.
- KC05d from Stahl Electronics[2] has 0.37nV/√Hz x 17fA/√Hz at 1MHz.
- The challenge is its noise match, 18k**Ω**.

2. Low input impedance (<<1**Ω**): high-turns-ratio MHz transformer is used to step down the impedance of the FET, operated in transimpedance follower mode. Cryogenic MHz-frequency transformers are not commercially available. Transformer requirements:
- High **μ** at MHz frequencies
- Between 50 to 200 turns ratio
- Sustained performance at sub-Kelvin temperatures

3. Minimal thermal load: no dissipative components on the sub-Kelvin stage; possible to use very long wires between stages.

4. "Set and forget" tuning: unlike SQUIDs, which are tuned after reaching 4K but before detector bias turn on, the system can be powered up and biases applied at any stage. Detector biases can therefore be optimized once and left on, even when cycling cryo stages.

Performance

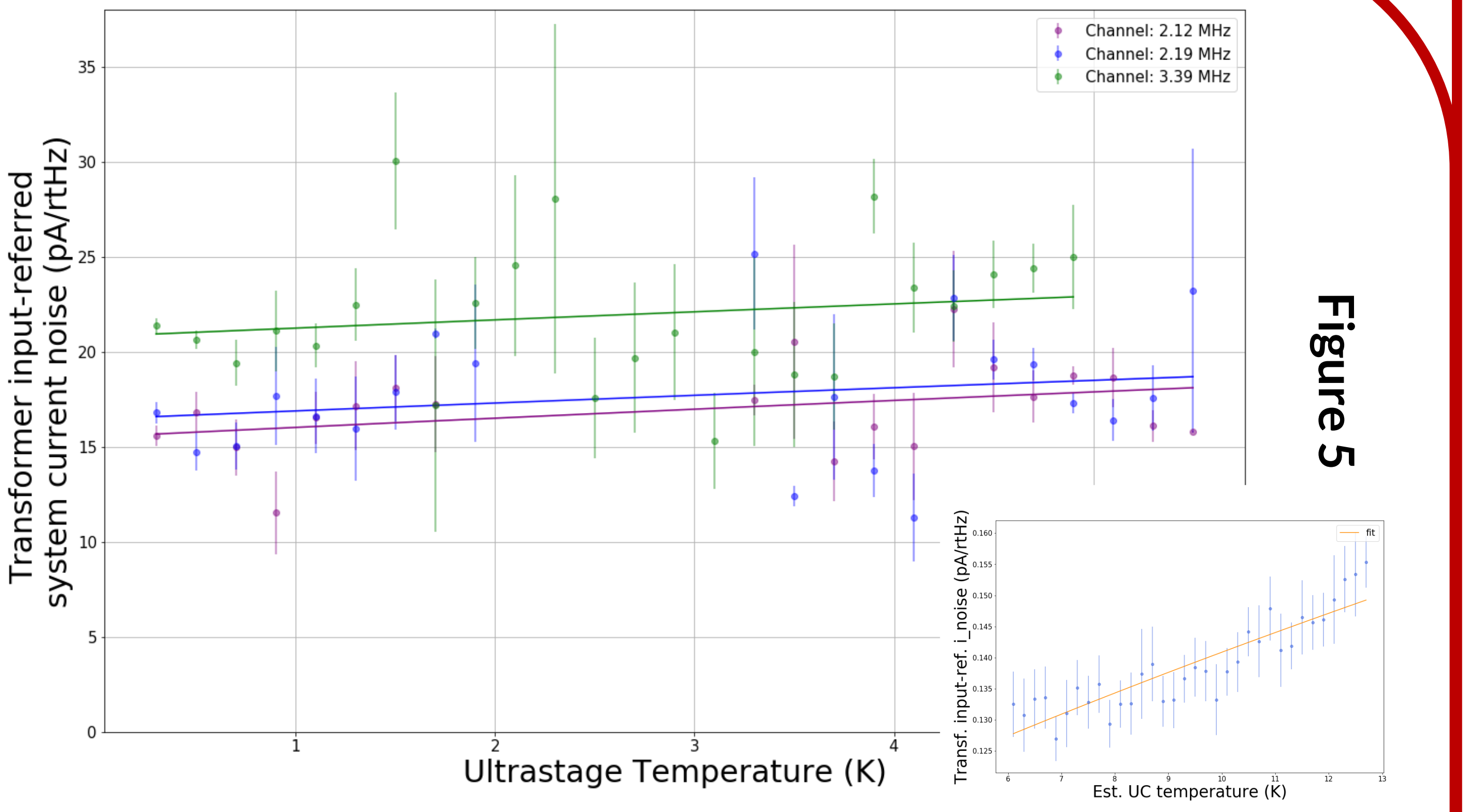


Figure 5

Above: current noise in the low-input impedance transformer primary loop as a function of sub-Kelvin stage temperature, for three channels. Temperature-dependence (fit to resistor Johnson noise) is evident in the high-T regime (inset; showing one channel only).

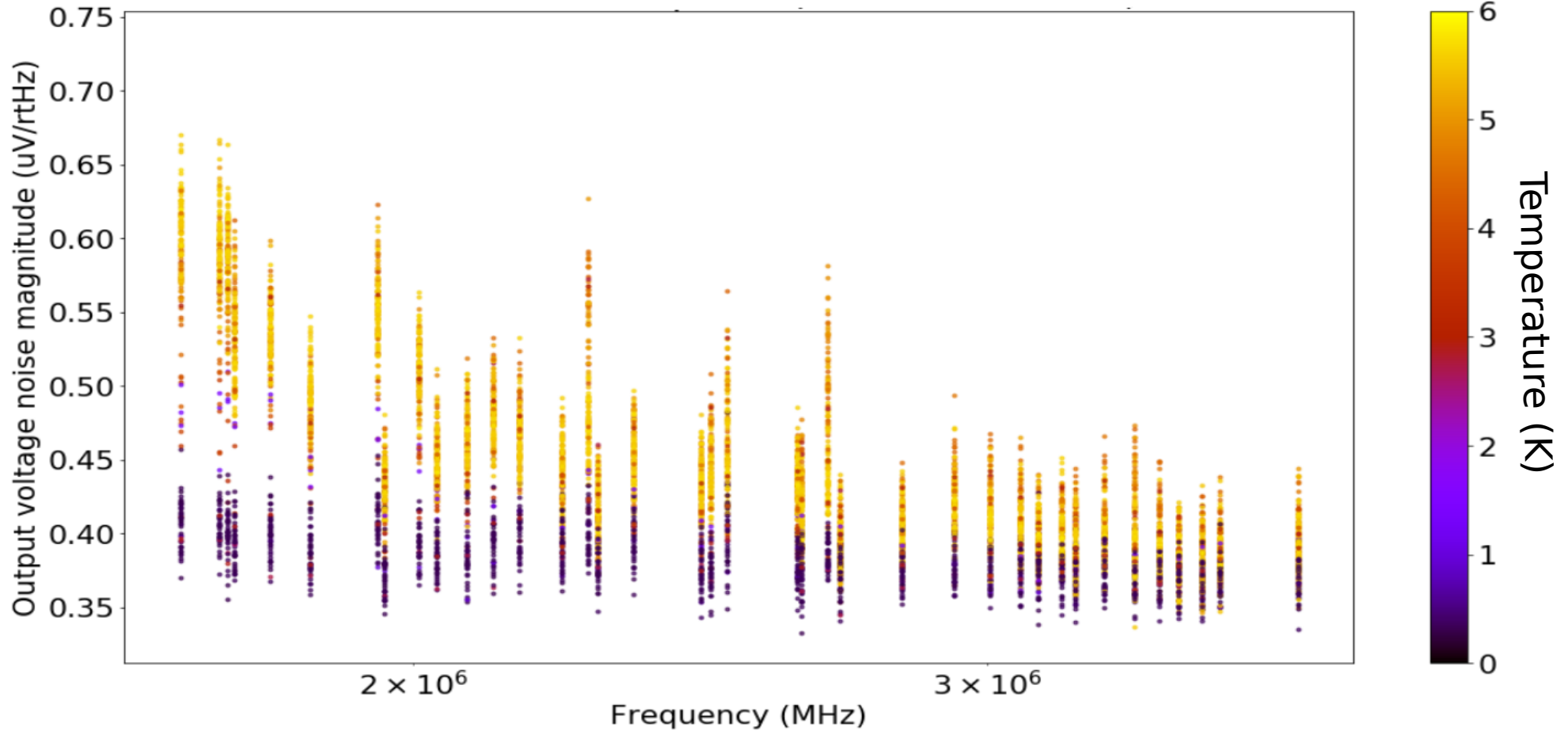
Noise contributions from both amplification stages are the dominant contributors to the readout noise: in the prototype configuration, for which we have not designed custom amp circuits, 15pA/√Hz through the primary loop.

This proof-of-concept circuit demonstrates that both low input impedance and low noise can be achieved in a SQUID-less readout system across several MHz. Its performance will be optimized in our next prototype. For example, designing the system to be used with a standard low-noise room temperature amplifier (v_n=1nV/√Hz):

System Optimization	
Parameters	**Performance**
$N = 130$	$Z_{in} = 0.1\Omega$
$A_o = 30$	$Z_{trans} = 400\Omega$
$R_f = 50k\Omega$	$i_{n,sys} = 4pA/\sqrt{Hz}$

High-Z test

Figure 6



Above: to demonstrate amplifier noise performance (in high impedance configuration, Fig 7, below), the system output voltage noise is shown as a function of resistor temperature for each channel. Amplifier noise is small compared to the resistors' Johnson noise.

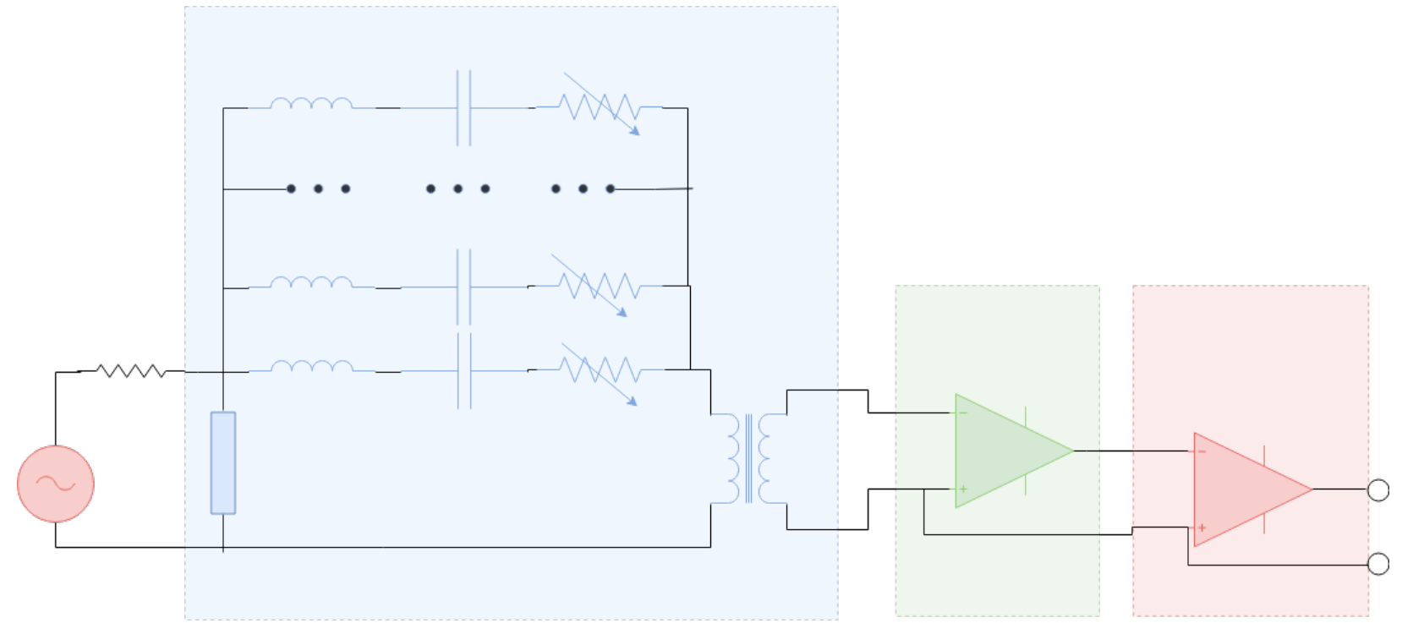


Figure 7

References

1. M. A. Dobbs et al. (2012) arXiv:1112.4215 [astro-ph.IM]
2. Stahl Electronics, NextGen3 KC05d V.2014 Dual Channel Cryogenic Super Low Noise Amplifier. https://www.stahl-electronics.com/
3. A.N. Bender et al: SPIE Proceedings, Vol 9914, 2016.