Transformer-coupled TES Frequency Domain Readout

System Overview

Motivation

Frequency domain multiplexing (fMUX) is a mature readout scheme for TES detectors in the millimetre and sub-millimetre 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 is proposed:

- It is inherently more linear than SQUIDs
- Requires no tuning
- Sustained performance at sub-Kelvin temperatures
- Between 50 to 200 turns ratio
- High input impedance (<<1 \( \Omega \))
- The challenge is its noise match, 18k \( \Omega \)

System Requirements & Benefits

1. Low noise: commercial GaAs FET amplifiers offer input noise temperature better than or equal to that of SQUIDs in use for fMUX.
2. Low input impedance (<<1 \( \Omega \)): 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 \( \mu \) 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.

Hardware

Figure 2

Above: a standard South Pole Telescope (SPT-3G) LC filter comb \(^1\), 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.

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/\( \sqrt{Hz} \) 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 (\( v_n = 1nV/\sqrt{Hz} \)):

<table>
<thead>
<tr>
<th>System Optimisation</th>
<th>( N = 130 )</th>
<th>( R_2 = 50k\Omega )</th>
<th>( f_m = 4pA/\sqrt{Hz} )</th>
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<td>Parameters</td>
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<td>( Z_m = 0.11\Omega )</td>
<td>( Z_{trans} = 400\Omega )</td>
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References