TES Detector Noise Limited Readout Using SQUID Multiplexers

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Abstract. The availability of superconducting Transition Edge Sensors (TES) with large numbers of individual detector pixels requires multiplexers for efficient readout. The use of multiplexers reduces the number of wires needed between the cryogenic electronics and the room temperature electronics and cuts the number of required cryogenic amplifiers. We are using an 8 channel SQUID multiplexer to read out one-dimensional TES arrays which are used for submillimeter astronomical observations. We present results from test measurements which show that the low noise level of the SQUID multiplexers allows accurate measurements of the TES Johnson noise, and that in operation, the readout noise is dominated by the detector noise. Multiplexers for large number of channels require a large bandwidth for the multiplexed readout signal. We discuss the resulting implications for the noise performance of these multiplexers which will be used for the readout of two dimensional TES arrays in next generation instruments.

Scientific Motivation

Large arrays of fast, low temperature detectors are needed for a variety of disciplines, one of which is astronomy. The best suited wavelength range to study the early evolution of the universe and the assembly of the first prototype galaxies is the FIR/sub-mm regime. About half of the observable radiation energy in the universe is emitted in this wavelength range. The low photon energies combined with the requirement for large bandwidths and large arrays is still a challenge for detector development, since only bolometers meet these requirements. Semiconductor bolometers, which are the most commonly used devices at these wavelengths, cannot easily be multiplexed and are not well suited for high speed readout.

The Superconducting Transition Edge Sensor (TES) bolometer has been developed for use at wavelengths ranging from the sub-mm to X-rays. With its low impedance it is well matched for readout with SQUIDs. This scheme has a number of advantages, since SQUIDs can be operated at the detector temperature and are easily multiplexable. These properties, as well as the small time constants of TES devices, make it possible to develop large arrays of multiplexed TES detectors.
MULTIPLEXED READOUT OF DETECTOR ARRAYS

Large detector arrays require multiplexed readout

For practical reasons, such as limitation of (cryogenic) wiring and amplifiers, large detector arrays require multiplexed readout. The fundamental properties of a multiplexing system are in principle identical, independent of the scheme of choice, be it frequency- or time domain multiplexing: the required bandwidth for the readout increases linearly with the number of pixels. The noise bandwidth of the multiplexed signal is larger than that of the signals from each individual pixel and the noise requirements for the readout system are correspondingly higher, unless the de-multiplexed signal is appropriately filtered. For large arrays such filtering will be necessary and the methods to do so will differ, depending on the multiplexing scheme used.

**Multiplexer design**

Figure 1 shows a schematic which illustrates the functionality of our NIST-designed SQUID multiplexers [1]. Each individual detector couples inductively into its own dedicated first stage SQUID. \( n \) first stage SQUIDs for readout of the same number of detector pixels are stacked in series with \( n+1 \) electrical “address leads”. By driving a bias current between one adjacent pair of address lines, only one SQUID will be operational while all other SQUIDs remain superconducting. Thus the output voltage over the entire series of first stage SQUIDs will be equal the voltage across the active SQUID. The TES is biased at all times and is low-pass filtered to a response time which is longer than the readout cycle of the entire first stage.
Noise performance measurements

The phonon dominated white current noise density of TES is approximately given by
\[ i_n = \sqrt{8k_B T / R_{TES}} \]. The Johnson current noise density of a general resistor R is given by:
\[ i_J = \sqrt{4k_B T / R} \]. In order to verify the detector noise dominated performance of the
multiplexer it is sufficient to perform Johnson noise measurements of resistors with
comparable values of resistance. We tested 8 channel multiplexers which were cut
from wavers that are one revision earlier than the SQUID chips we used for the first
astronomical observations with multiplexed Transition Edge Sensor bolometers [2].
For the comprehensive noise performance tests we replaced the TES pixels with
calibrated resistors. Figure 2 shows a multiplexed measurement of the Johnson noise
of resistors at a temperature of 480 mK and the corresponding theoretical predictions
for the noise, including aliasing effects. The resistors were read out at a pixel frame
rate of 10 kHz, yielding a bandwidth of 5 kHz which is sufficient for the required
detector speed. The multiplexed signal was bandpass limited to 100 kHz.
Correspondingly all signals up to 100 kHz are aliased into the 5 kHz band (an
approximation of the actual filter roll-off above 100 kHz was incorporated in the
calculations presented in this paper). The individual detector circuits contain low-pass
filters. This allows the integration of the detector signal during one readout cycle. The
individual low-pass filter device parameters and the model predictions for the noise
are summarized in Table 1. All but one channel we measured are well modeled by a
SQUID noise contribution of 4 pA/\sqrt{Hz}. This value is consistent with the predicted
SQUID multiplexer properties (the mutual inductance in our SQUID multiplexers is ~
500 pH). Only one channel (channel 5) has elevated SQUID noise, which is caused by
a design error in the version of the multiplexers we used for the measurements.
Figure 2 demonstrates the good agreement between theoretical predictions and
measurements. If appropriately low-pass filtered, the Johnson noise of detectors
operated at values higher than 100 m\Omega becomes comparable or even less (depending
on filter rolloffs) than the aliased SQUID noise of our current eight channel
multiplexer. In current ground based operations however we do not operate our
detectors above ~100 m\Omega.

Conclusion

We have demonstrated the capability of our SQUID multiplexers to perform TES
noise dominated readout. The mutual coupling between the SQUIDs and the detector
circuits will be increased in the next generation of multiplexer chip designs leading to
further improvements in the noise performance. Future large arrays with significant
numbers of multiplexed pixels will nevertheless reach the limit at which the SQUID
noise contribution is not negligible. In this case, however, fast sampling will make
digital bandpass filtering possible. This will allow detector noise limited readout for a
larger number of pixels, limited only by the sampling rate of the readout electronics.
Figure 2. Multiplexed Johnson noise measurement with superimposed model predictions. The peak at 17 Hz corresponds to an acoustic resonance frequency of the wires in the dewar.

**TABLE 1. Johnson noise density versus SQUID multiplexer noise density**

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<tr>
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<tr>
<td>Chan. 2</td>
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<td>1.78</td>
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<tr>
<td>Chan. 7</td>
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<tr>
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<tr>
<td>Chan. 5</td>
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<td>inf</td>
<td>0.00</td>
<td>0.00</td>
<td>8.0</td>
<td>37.5</td>
</tr>
</tbody>
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Note: Column 4 “aliased Johnson noise” shows the mean, low-pass filtered and aliased Johnson current noise density in the 5 kHz band of the multiplexed channel readout. This value is less than the non-low-pass filtered Johnson noise of a resistor with the same resistance as channel 2. The low-pass filter device parameters are shown in column 2. The theoretical values for channel 0 are displayed in the table even though it did not operate properly during the measurement and is not displayed in Fig. 1.

**REFERENCES**

2. Staguhn, J.G. et al. “First Astronomical Use of Multiplexed Transition Edge Bolometers”, these proceedings