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SQUID Noise in a 176-Pixel FDM Demonstrator for the SAFARI Far-Infrared Spectrometer

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Abstract

We are developing the frequency-domain multiplexing (FDM) readout for the SAFARI far-infrared spectrometer on board the SPICA space observatory. Each readout channel comprises a set of ~160 TESs and LC filters and is read out with a SQUID preamplifier. Baseband feedback is applied to overcome the dynamic range limitations of the SQUID. We have carried out extensive characterization of a test readout system coupled to a 176-pixel TES bolometer array in order to understand and optimize the system. We present our latest measurements of this 176-pixel FDM demonstrator, focusing on the noise contribution from the SQUID.

Keywords TES bolometer array · FDM readout · SAFARI · SQUID noise

1 Introduction

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) [1], a candidate mission for the European Space Agency's M5 program, will use a large (2.5 m diameter) primary mirror cooled to ≤ 8 K to enable high-spectral-resolution, sky-background-limited observations of the cold dusty Universe in the mid- and far-infrared. SPICA's prime instrument is the SAFARI (SPICA Far-infrared Instrument) spectrometer. SAFARI will cover the spectral range $\lambda = 34\text{--}230$ μm simultaneously with four grating modules, each containing a diffraction grating and linear detector

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array to sample the dispersed spectrum [2]. The dispersed spectra are measured with linear arrays of transition-edge sensor [3] (TES) bolometers. The four detector arrays will contain a total of ~ 3500 TES detectors. We have demonstrated the required NEP ($\leq 2 \times 10^{-19}$ W/ $\sqrt{\text{Hz}}$) [4] and optical efficiency ($\geq 50\%$) [5] for single detectors fabricated at SRON [6].

SAFARI's TES bolometers are biased with an AC voltage and read out with SQUID preamplifiers. To reduce the wire count and the heat load on the system, SAFARI uses frequency-domain multiplexing with baseband feedback [7, 8]. There are 24 readout channels, each reading out 160 detectors using a two-stage SQUID preamplifier and a higher-temperature low-noise amplifier (LNA). The current noise contribution (referred to the input coil of the SQUID preamplifier) from the flight readout is required to be less than ~ 10 pA/ $\sqrt{\text{Hz}}$ [7].

This paper describes measurements of the noise in a 176-pixel demonstrator for the SAFARI FDM readout. Because we are using a single-stage SQUID, we do not expect to meet SAFARI's readout noise requirement in this setup. The noise requirements for this setup are looser than the flight case; we require the readout noise of our experimental setup to be low enough for us to measure the intrinsic noise in the TESs, i.e., less than ~ 30 pA/ $\sqrt{\text{Hz}}$.

2 The SAFARI FDM Readout with Baseband Feedback

The FDM readout scheme is shown in Fig. 1. The TESs are connected in series with narrow band-pass cryogenic lithographic LC filters designed and fabricated at SRON [9]. The room-temperature SRON Demux electronics generate a comb of tones with frequencies ranging from ~ 1 to ~ 4 MHz. Each of these tones is tuned to match the resonant frequency of one of the LC filters and provides an AC voltage bias to the corresponding TES. The LC filters also reject wideband Johnson noise in the circuit. All the TES bias signals can be adjusted independently so that all detectors are biased optimally, mitigating the effects of detector non-uniformity across

Fig. 1 FDM readout scheme (Color figure online)

an array. The TES currents are summed at the input coil of a SQUID preamplifier (point A in Fig. 1). In the FDM demonstrator setup described in this paper, the TES currents are read out with a single-stage SQUID at the base temperature (50 mK). In the final instrument, a second SQUID amplifier stage on the 1.8 K temperature level of the grating module provides additional amplification. The signal that appears at the output of the SQUID is essentially an amplitude-modulated version of the AC bias signal, with a phase shift due to the electronics. After further amplification by an LNA at a higher temperature, the signal (point B in Fig. 1) is demodulated and a comb of frequencies is generated with the appropriate phases and amplitudes to cancel out the SQUID output when applied to the feedback coil of the front-end SQUID. This feedback signal (point C in Fig. 1) is linearly proportional to the power absorbed by each TES bolometer. The feedback is carried out on the amplitude of the generated tones. Since this amplitude varies no faster than the bandwidth of the TES, this scheme is known as baseband feedback.

3 176-Pixel FDM Demonstrator

3.1 Experimental Setup

The resonance frequencies are distributed alternately between two LC filter chips on either side of the TES array to improve the isolation of frequency neighbors. This reduces cross talk due to the mutual inductance of the coplanar wiring. The carrier separation is 16 kHz. The 176-pixel array contains 163 usable TES bolometers plus eight resistors for calibration. The TES bolometers are Au/Ti bilayers on silicon nitride membranes with Ta absorbers. The TESs have a transition temperature $T_c \approx 107$ mK and a design saturation power of 20 fW for a bath temperature of 65 mK and an NEP of 7×10^{-19} W/ $\sqrt{\text{Hz}}$. The 176-pixel experiment is mounted in a cryogen-free adiabatic demagnetization refrigerator in a lighttight box with magnetic shielding. The array is read out with a single-stage SQUID [10] fabricated at Physikalisch-Technische Bundesanstalt (PTB) in Berlin, and the SQUID is read out using SRON room-temperature electronics. We have previously demonstrated multiplexed readout of 132 pixels using this setup [11].

4 Readout Noise Measurements

Recently, we have been investigating the noise contributions in the readout of the 176-pixel FDM demonstrator. We started by characterizing the noise in the room-temperature LNA of the SRON front-end electronics (FEE) [12]. Given the intrinsic flux noise ($\sim 0.2 \mu\Phi_0/\sqrt{\text{Hz}}$) of the SQUID and the measured LNA noise, we would expect the readout noise in this 176-pixel demonstrator to be LNA-dominated. To investigate this, and to obtain a global picture of the SQUID noise, we carried out systematic measurements of the output voltage noise of the system for a range of SQUID bias and feedback current values.

In order to compare our measurements with the expected flux noise of the SQUID, we used the SRON room-temperature electronics to apply a MHz-range AC signal to the SQUID feedback. The peak-to-peak amplitude of this calibration tone was chosen so that it caused a flux excursion in the SQUID of about 1% of a magnetic flux quantum (Φ_0). This enabled us to calculate the flux noise from the output voltage noise (integrated over a small line-free region of the spectrum near the calibration tone). The calibration tone was chosen to be large enough to be visible in the output spectrum, but small enough that the SQUID response would be nearly linear, minimizing power loss into harmonics. We set the calibration tone amplitude as follows. First, we applied a small-amplitude tone to the SQUID feedback coil and observed the output of the LNA (point B in Fig. 1) in the time domain. For small tone amplitudes, the SQUID response was approximately linear so the output was sinusoidal. As the amplitude was increased, the output became distorted and we began to see dips at the peaks and troughs of the output sinusoid where the tone was sweeping past a maximum or minimum of the sinusoidal V – Φ curve of the SQUID. In this way, it was possible to adjust the amplitude of the tone so that it swept out a complete flux quantum. The amplitude was then reduced by a factor of 100 to give a tone with a flux amplitude of $0.01\Phi_0$. Since we wanted to measure the broadband noise level, we chose the frequency of the calibration tone (typically ~ 1.55 MHz) to lie in a line-free region of the noise spectrum, avoiding the LC resonances and other features. The noise level was taken as the mean over a small line-free region (1.6–1.7 MHz) near the calibration tone. This enabled us to measure the flux noise, which could be converted into current noise referred to the SQUID input coil using the known mutual inductance of the SQUID input coil. The noise measurements were taken in open-loop mode, i.e., without the baseband feedback applied.

These noise measurements were taken for three different configurations: nothing connected to the input coil of the SQUID (“Bare SQUID”); one half of the LC filters and TESs connected (“Half Array”); and the Half-Array configuration with a low-pass filter across the SQUID input coil (“Half Array with Snubber”).

4.1 Bare SQUID Versus Half Array

In order to isolate the causes of readout noise in the demonstrator, we first disconnected the SQUID from the LC filters and then reconnected one of the LC filter chips (88 resonators). As shown in Fig. 2, reconnecting the Half Array increases the voltage noise and reduces the AC transfer. The effect is much larger at mK temperatures, especially at the peaks and troughs of the V – Φ curve. The cause of this temperature dependence is unclear. We see the same noise below and just above the transition temperature of the TESs, so it does not appear to be due to the quality factor of the LC resonators changing. A possible cause is that there is less damping at mK temperatures because the Al wirebonds are superconducting. This led us to suspect that out-of-band resonances in the SQUID input circuit might be involved. The performance of SQUID amplifiers is known to be affected by parasitic capacitance in the input circuit as well as loading of the input circuit [13]. The parasitic

Fig. 2 SQUID noise versus feedback current for Bare-SQUID and Half-Array configurations at two different temperatures. Left: 3.6 K. Right: 70 mK. From top: SQUID flux noise; output voltage noise; DC dynamic resistance; AC transresistance; and DC V - Φ curve (Color figure online)

capacitance leads to resonances in the SQUID loop and hysteresis in the I - V curves accompanied by excess noise [14].

4.2 Half Array with Snubber

We added an RC snubber, i.e., a low-pass RC filter ($2\ \Omega$, $10\ \text{nF}$), across the summing point at the SQUID input coil in order to block the out-of-band resonances. This approach has previously been found to result in smoother V - Φ curves and lower noise [14]. As shown in Fig. 3, the snubber reduces the readout noise so that we recover the performance of the Bare-SQUID configuration at the high-transfer bias points. At 3.6 K, the voltage noise is higher than for the Bare SQUID (except at the V - Φ -curve minimum), but the higher AC transresistance compensates for this. The behavior is different at mK temperatures: The snubber suppresses the excess voltage noise almost completely near the maximum of the V - Φ curve, but we still see significantly increased voltage noise near the minimum of the V - Φ curve.

5 Discussion and Conclusions

Connecting the LC filters and TESs to the SQUID input coil results in an increase in output voltage noise, which is worse at mK temperatures where the quality factor is higher. Since the snubber mitigates this, we conclude that this excess noise

Fig. 3 SQUID noise versus feedback current for the Bare-SQUID and Half Array with Snubber configurations measured at two different temperatures. Left: 3.6 K. Right: 65 mK (Color figure online)

is likely due to out-of-band resonances. With the snubber installed, we recover the Bare-SQUID performance at the high-transfer set points. Figure 4 shows usable bias points with input-referred current noise of 15–20 $\text{pA}/\sqrt{\text{Hz}}$, meeting our requirement of 30 $\text{pW}/\sqrt{\text{Hz}}$ and allowing us to measure the intrinsic TES noise comfortably. We

Fig. 4 Noise for Half Array with Snubber. Left: input-referred current noise. Upper right: measured and expected [12] voltage noise. Lower right: dynamic resistance measured and needed to account for measured voltage noise (Color figure online)

plan to replace the single-stage SQUID with a two-stage SQUID to improve this further. LNA noise can account for the output voltage noise at the high-transfer set points if the MHz dynamic resistance is slightly higher than the DC value. We know from measurements of this LNA that the current noise is significant in addition to the voltage noise [12]. We intend to investigate this further by modeling the circuit and by reconfiguring the readout so that we can measure the AC dynamic resistance. However, there is still excess noise at the minimum of the V – Φ curve that cannot be accounted for by a high AC dynamic resistance (Fig. 4). In practice, this does not affect the operation of the SQUID amplifier, as it occurs where the AC transfer is low. Nevertheless, it is unclear why we recover the Bare-SQUID noise performance at the peaks of the V – Φ curve, but not at the troughs. The interaction between input-circuit resonances and the SQUID is complicated [15], and a detailed analysis is outside the scope of this work. However, we note that the circulating currents in the SQUID at the peak and trough will be different and speculate that this may be involved.

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