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Single-SQUID Frequency-Domain Multiplexer for Large Bolometer Arrays

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Abstract—We describe the development of a frequency-domain superconducting quantum interference device (SQUID) multiplexer which monitors a row of low-temperature sensors simultaneously with a single SQUID. Each sensor is ac biased with a unique frequency and all the sensor currents are added in a superconducting summing loop. A single SQUID measures the current in the summing loop, and the individual signals are lock-in detected after the room temperature SQUID electronics. The current in the summing loop is nulled by feedback to eliminate direct crosstalk. We have built an eight-channel prototype and demonstrated channel separation and signal recovery.

I. INTRODUCTION

Observations in the far-IR to mm wavelength region are opening a new window on the universe. For example, recent measurements of the cosmic microwave background anisotropy by BOOMERanG [1] and MAXIMA [2] lend strong support to inflationary cosmological models with a geometry close to flat. A new population of dusty luminous objects that may account for a significant fraction of all star formation is being explored by ground-based telescopes such as SCUBA/JCMT. Both of these types of observation have been possible only because of large steps in the sensitivity of bolometric receivers. In the future, further large steps in sensitivity will be possible by increasing the size of bolometer arrays. Large-format arrays of Voltage-biased Superconducting Bolometers (VSB) with SQUID readouts are being developed for this purpose [3].

If an individual readout circuit is used for each array element, a major limitation on the array size is the difficulty in implementing the large number of wires from the sensors to the cryogenic electronics and on to the room temperature. With a multiplexer, the number of wires can be greatly reduced. The large noise margin of the SQUID readout makes multiplexed readouts for large arrays possible. The NIST group is producing a time-domain multiplexer which has a

SQUID switch for each sensor [4]. We are exploring multiplexing in the frequency-domain with a single SQUID per row of sensors. We have built an eight-channel prototype and demonstrated the channel separation and signal recovery.

II. MULTIPLEXER

The design of our multiplexer is schematically shown in Fig. 1. Each sensor is ac biased at a distinct frequency significantly above the rolloff frequency of the sensor and all the signals are inductively coupled to a superconducting summing loop. The SQUID measures the current in the summing loop via

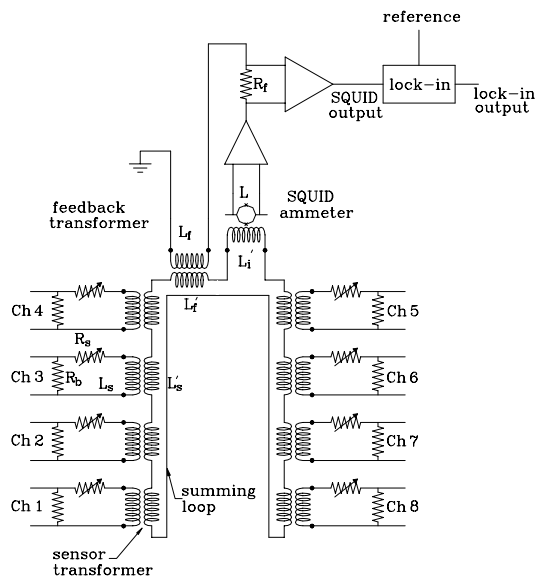


Figure 1. Schematic of the eight-channel SQUID multiplexer. For test purposes, resistors $R_s=0.47\Omega$ are used to simulate the sensors being multiplexed, which is voltage biased by the bias resistors, $R_b=0.02\Omega$.

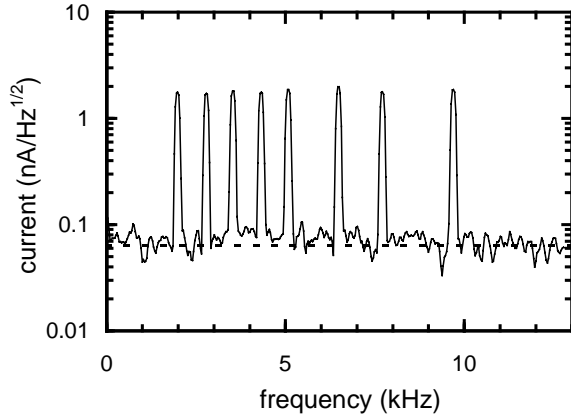


Figure 2. Spectral density of the current fed back from the SQUID output into the summing loop, illustrating channel separation. The bias frequencies are 1.97, 2.78, 3.52, 4.31, 5.06, 6.45, 7.86, and 9.66kHz for channels 1-8, respectively.

a conventional coupling coil. Feedback from the SQUID output is used to null the total current in the summing loop, eliminating direct crosstalk between channels.

For an experimental evaluation of our multiplexing scheme, we have fabricated a prototype eight-channel multiplexer. The transformers are made by thin-film deposition and photolithography, which are suitable fabrication techniques for single-substrate integration with a large-format arrays of sensors. The inductances of the transformers are chosen to minimize the SQUID noise current at the multiplexer input. Details of the multiplexer fabrication and the SQUID noise current optimization procedures are reported elsewhere [5]. We used resistors $R_s=0.47\Omega$ as mock sensors that are voltage-biased by the bias resistors, $R_b=0.02\Omega$, and a commercial set of SQUID and readout electronics.

Fig. 2 shows the SQUID output measured with a spectrum analyzer with each resistor R_s voltage-biased at frequencies ranging from ~ 2 kHz to ~ 10 kHz. The currents through the resistor R_s are 20nA rms. All the bias frequencies are well resolved, and the mixing between bias frequencies is $\lesssim 0.05\%$. This demonstrates that the sensor currents can be monitored simultaneously with a single SQUID ammeter. The background noise is in good agreement with that predicted from Johnson noise, which is the quadrature sum of the contributions from all eight R_s and shown by the dotted line.

In order to verify the signal recovery and to test for crosstalk between channels, we simultaneously amplitude modulate the bias voltage for channels 1 to 7 by 2% at frequencies ranging from 1.6Hz to 19Hz, and measure the SQUID output with a lock-in amplifier. Trace (a) in Fig. 3 is an example of the sensor signal recovery for channel 5, where the 5.06kHz bias voltage is amplitude modulated at 8.6Hz. As expected, a peak centered at 8.6Hz is observed. However, when the lock-in reference is obtained from the 9.66kHz bias of channel 8, which is not amplitude modulated, only the background noise appears as shown by trace (b). When the modulation is increased, a crosstalk $\lesssim 1\%$ is observed which may come from the drive electronics.

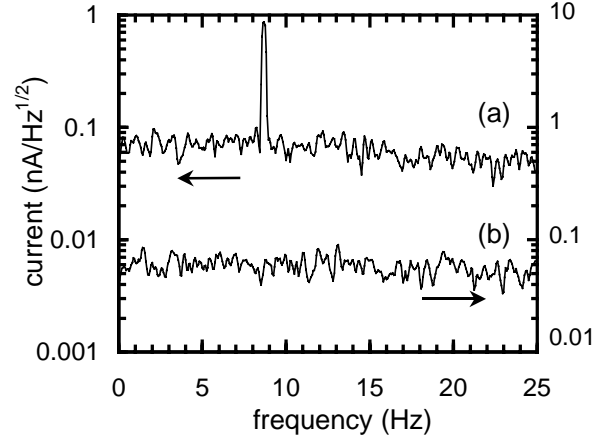


Figure 3. Spectral density of the output of a lock-in amplifier connected to the SQUID output. The bias for channels 1-7 are simultaneously amplitude modulated by 2% at 1.6, 2.9, 3.7, 5.7, 8.6, 13.0, and 19.0 Hz, respectively. The bias for channel 8 is not amplitude modulated. Trace (a) is obtained when the lock-in is referenced to the bias frequency for channel 5, and demonstrates signal recovery from that channel. Trace (b) is obtained when the lock-in is referenced to the bias frequency for channel 8, and shows the absence of crosstalk.

Two factors will limit the total number of sensors that can be multiplexed: one is the ratio of the sensor bandwidth to the SQUID bandwidth, and the other is the addition of noise from each sensor in the summing loop. The bandwidth of a flux-locked SQUID is mainly set by slew rate. The sensor noise current is the quadrature sum of photon noise, thermal fluctuation noise, and Johnson noise. Photon and thermal fluctuation noise act like signal and create sidebands on the bias frequencies. Since the widths of these sidebands are limited by the bolometer time constant, they do not overlap if the bias frequencies are properly separated. However, the Johnson noise contributions from the sensors are broadband and add incoherently in the summing loop. This accumulation of Johnson noise from a large array could be avoided by inserting an appropriate bandpass filter in each channel.

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