Performance of Multiplexed SQUID Readout for Cryogenic Sensor Arrays [a]

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Abstract

We report on the implementation of a multiplexer that uses superconducting quantum interference devices (SQUIDs) to read out low-impedance cryogenic detectors. Using prototype chips, a circuit was built which interfaces eight input SQUID channels with a close-packed array of eight transition edge sensor (TES) infrared bolometers. Circuit elements were measured and crosstalk specifications are reported. Digital feedback is employed, for the first time, to flux lock a single element in the array of SQUIDs.

As the technology of low temperature detectors such as TESs matures, measurement systems are needed to instrument multiple pixels. Cryogenic detector arrays are planned for next-generation measurements in ground-based and satellite-based sub-millimeter and X-ray astronomy experiments. Other applications, including mass spectrometry and X-ray microcalorimetry, will also benefit from the development of large scale arrays. We have built a multiplexer (MUX) for eight superconducting quantum interference device (SQUID) read-out channels interfaced with an eight pixel transition edge sensor (TES) array [1,2]. In conjunction with our efforts to fabricate large scale arrays of these ultra-sensitive detectors, we are developing a technology to enable the readout of large numbers of pixels.

We have previously described the structure and function of a SQUID MUX to read out large format arrays of low impedance devices. The MUX was designed to read out devices without degradation of the signal-to-noise ratio of single pixel detectors and to have power dissipation requirements compatible with cryogenic refrigeration systems. As an example, we calculated that the SQUID multiplexer met these constraints for TES bolometers and that 1000 pixel arrays were feasible [1]. Here, we have interfaced a SQUID multiplexer with superconducting devices. We describe the performance of the MUX and report experimental parameters relevant to array readout.

Referring to the circuit diagram of the SQUID multiplexer (without detectors) which is shown in Fig. 1, we identify the components of the SQUID MUX and describe its mode of operation. A column of SQUIDs is created by connecting the output lines of the first stage SQUIDs in series. A separate detector modulates the current in the SQUID input coils L_1 which causes the first-stage SQUID output voltages to vary. The individual first-stage SQUIDs are biased with a voltage applied across the address resistors R_{add}. The bias is cycled through all of the pairs of address lines, labeled *Addr. 1* to *N+1*, turning each of the *N* SQUIDs on sequentially. With only one SQUID active at a time, noise and signal from the separate

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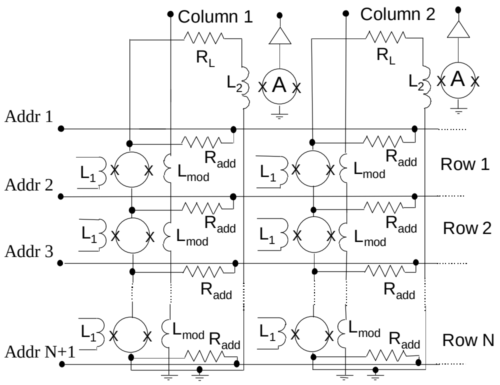

Fig. 1 SQUID multiplexer circuit diagram

Signal Coupling	
$M(L_1\text{-}L_{SQ})$	339.8 pH ± 0.2 pH
$M(L_{mod}\text{-}L_{SQ})$	18.4 pH ± 0.2 pH
Crosstalk Sources	
M(Bias Line-L_2)	15 fH ± 5 fH
$M(L_1\text{-}L_{SQ}$(column neighbor))	275 fH ± 10 fH
$M(L_1\text{-}L_{SQ}$(row neighbor))	$M(L_1 - L_{SQ})\dfrac{R_{SQ}}{2R_{add}}$

Table 1. Mutual inductances of SQUID MUX circuit elements and combinations.

channels are not added. Also, feedback to linearize the first stage SQUIDs is coupled to each SQUID in the column through the inductors L_{mod} which can also be connected in series. Each column is read with a 100 dc-SQUID series array by placing the column in a loop with a series resistor R_L and series array input inductor L_2 [3]. Each additional column requires an additional series array read-out and column feedback lines, but the address lines of the first-stage SQUIDs are connected in parallel creating rows of SQUIDs which are activated simultaneously.

We have fabricated prototype MUX chips using the above design which have a column of eight input SQUIDs coupled to an on-chip series array. The on-chip series resistor R_L is chosen to be about a factor of two greater than the dynamic resistance of the input SQUID so that the applied bias current can exceed the critical current of the SQUID without turning on other SQUID channels. Two MUX chips have been mounted on the cold plate of a adiabatic demagnetization refrigerator (ADR) with an array of bolometers and wired in a 2x4 configuration (i.e. each column has four first stage SQUIDs coupled to separate bolometers). The rows thus contain two SQUIDs in parallel with $R_{add} = 10\ \Omega$.

We have measured the coupling between inductive elements of the SQUID multiplexer circuit, with results summarized in Table 1. The measurements were obtained using a MUX chip with a thin piece of niobium foil placed under the chip. The superconducting foil is observed to provide additional shielding from the coupling of both off-chip flux generated in the circuit and stray flux trapped in the magnetic shielding without degrading the performance of the chip. The current in the TES devices is calibrated by measuring the mutual inductance *M* of both the feedback coil and the input coil to the first stage SQUID. The effective turns ratio of the phase-locked loop is then calculated; $M(L_1\text{-}L_{SQ})/M(L_{mod}\text{-}L_{SQ}) = 18.5 \pm 0.2$ is measured for the MUX chip where $L_{SQ} = 20$ pH, the self inductance of the SQUID. However, the effective current measured by the amplifier chain is influenced by several other couplings on the chip. For example, the TESs are continuously biased, with current always flowing through the inductors L_1 which are coupled to the active SQUID on the chip. We have measured this coupling for the "column neighbor" SQUID, the SQUID in the closest proximity to the coil with active TES bias. There is also concern that the larger currents flowing near the MUX chip can couple directly to the series array. Since the TESs are voltage biased, the TES bias lines carry the highest currents to shunt resistors near the detectors. As shown in Table 1, these sources of crosstalk are below the 1% level of the coupling of the signal current. With the wiring diagram shown in Fig. 1, the principle source of crosstalk is between "row neighbors", the SQUIDs that share address lines and are active during the same cycle in different columns. Voltage changes due to signals in one SQUID modulate the bias of its row neighbors. For a DC row bias, the amplitude of this modulation is determined by the ratio of the dynamic resistance of the biased SQUID, $R_{SQ} = 1.2\ \Omega$, and the sum of the address resistors as shown in Table 1. This crosstalk dependence can be suppressed below the expression in Table 1 by voltage biasing the address lines, accomplished by placing a shunt resistor in parallel with the address resistors of each row such that $R_{sh} << R_{add}/N$ where N is the number of columns.

Other potential sources of crosstalk stem from the parasitic coupling of various currents to the inductors L_1 . For example, there is the direct coupling of the coil L_{mod} to the input coil L_1. Moreover, the switching transient as the first stage SQUID is activated is coupled into the input coil L_1.

In previous work [1], we discussed the Nyquist filtering constraints on the readout of a continuously biased TES sensor while switching its readout SQUID. The constraint

$$L_1 \geq \frac{R_{TES}\, g}{pF_{pixel}} N$$

was derived to satisfy stability conditions for the detector and provide sufficient Nyquist filtering before the readout SQUID [1]. Here, $g = 3$ sets the Nyquist filtering to an acceptable level, F_{pixel} is the rate at which the SQUIDs are multiplexed, N is the number of SQUID channels in a column, and R_{TES} is the bias resistance of the detector. This constraint can be satisfied by moving part of the series inductance to an "external" inductor L_{NYQ} which is not coupled to the first stage SQUID. We have designed a "Nyquist filter chip" $L_{NYQ} > L_1$ which allows the constraint (Eq. 1) to be met without over-coupling to the first stage. Further, the switching transient crosstalk coupled into L_1 is effectively filtered before the devices.

To implement SQUID multiplexing, each first stage SQUID requires independent feedback signal. A computer must track which SQUID is "on" in each column and apply feedback current to L_{mod} proportionate to its output during its previous "on" cycle. This is accomplished by digitizing the output of each frame (the time to cycle the first-stage bias through the N rows of SQUID channels) and creating pulses for each SQUID channel to be applied to the feedback coils L_{mod} during the next frame. Below, we show that a first stage SQUID can be locked up with digital feedback when a pulse of heat is put into the TES. In Fig. 3, we show the feedback output on a fine time scale showing the discrete steps used to feedback the integrated SQUID output. The inset shows that the feedback output tracks the entire duration of the pulse in the TES. In Fig. 2, we also show the digital flux locking of one SQUID channel in the array while the SQUID is switching at F_{pixel} = 65 kHz. The TES bias of that SQUID channel is modulated with a sine wave.

In summary, we have evaluated the performance of a circuit to multiplex SQUIDs for cryogenic array readout. Sources of crosstalk in the circuit are identified and measurements indicate that the crosstalk can be designed to be at or below the 1% level. Digital feedback for multiplexed channels is demonstrated for the first time and preliminary results are encouraging.

Acknowledgments

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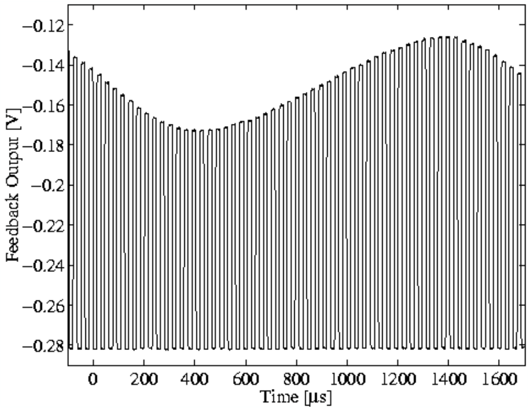

Fig. 2 Digital feedback is used to flux lock a first stage SQUID channel switching at 65 kHz.

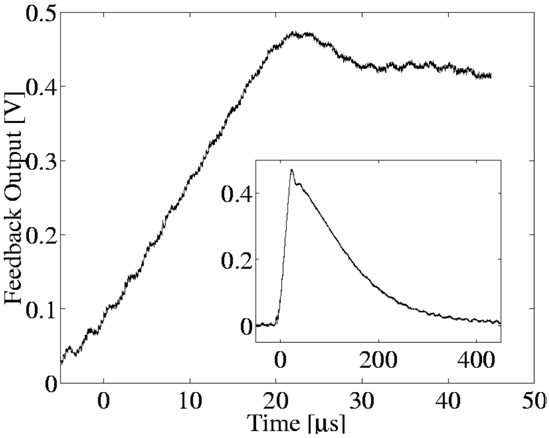

Fig. 3 Digital feedback is used to lock-up a single input SQUID. A heat pulse in the TES is measured

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