# A Single SQUID Multiplexer for Arrays of Low Temperature Sensors

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We present the design and experimental evaluation of a superconducting quantum interference device (SQUID) multiplexer for an array of low-temperature sensors. Each sensor is inductively coupled to a superconducting summing loop which, in turn, is inductively coupled to the readout SQUID. The flux-locked loop of the SQUID is used to null the current in the summing loop and thus cancel crosstalk. The sensors are biased with an alternating current, each with a separate frequency, and the individual sensor signals are separated by lock-in detection at the SQUID output. We have fabricated a prototype 8 channel multiplexer and discuss the application to a larger array.

There is a growing need to instrument large arrays of low-temperature sensors with SQUID ammeter readouts. Applications include biomagetic imaging[1] and astronomical observations. In particular, sensors using a voltage-biased superconducting transition are being developed for astronomical observations in the x-ray[2], UV-optical[3], and far-IR to mm-wave[4] wavelength ranges.

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 electronics. With a multiplexer, the number of wires for a n-element array can vary as $\sqrt{n}$, rather than n. Chervenak *et al*.[5] have developed a SQUID multiplexer which allows a row of sensors in an array to be read out with a single SQUID ammeter. In their design, there are as many first-stage SQUIDs as sensors being multiplexed, but only one SQUID is “turned on” at a time by selectively applying its bias current though a control line. A single second-stage SQUID ammeter reads the output of a row of first-stage SQUIDs, which are connected in series.

In this Letter, we present the design and test results of a multiplexer that requires only a single SQUID to instrument a row of array elements. In our scheme, each sensor is biased with an alternating current at a distinct frequency significantly above the roll-off frequency of the sensor and all the signals are inductively coupled to a superconducting “summing loop” as shown in Fig. 1(a). The SQUID measures the current in the summing loop via a conventional coupling coil. Feedback from the SQUID output is used to null the total current in the summing loop. The absence of any net current flowing in the summing loop eliminates direct crosstalk between channels.

In our analysis, we assume that all sensor transformers have the same sensor-side inductance $L_s$, summing-loop-side inductance $L'_s$, mutual inductance $M_s=\alpha_s\sqrt{L_sL'_s}$, and coupling coefficient $\alpha_s$. The subscript f is used for the analogous properties of the feedback transformer. The SQUID inductance is L, the coupling coil inductance is $L'_i$, and the coupling coefficient is $\alpha$. The current $I_j(\omega_j)$ from the j-th sensor induces a flux in the summing loop $\Phi_j=M_sI_j(\omega_j)$. The total flux, $\Phi_1+\Phi_2+\cdots$, which is induced in the summing loop, must be cancelled by feedback flux $\Phi_f=M_fI_f$, where $I_f$ is the feedback current. Thus,

$$I_f=\sum_{j=1}^{n}M_sI_j(\omega_j)/M_f\ . \qquad (1)$$

Since $I_j(\omega_j)$ is at a distinct frequency $\omega_j$, the output signal from the SQUID will contain distinct frequencies that can be separated by lock-in detection.

In order to understand the noise performance of the multiplexer and to optimize the choice of transformer inductances, we compute the noise current at each multiplexer input which produces a noise at the SQUID equal to its flux noise $\Phi_N$[6]. The noise current $i_s$ produces a flux noise $M_si_s$ in the summing loop and hence a noise current

$$i'=\frac{M_si_s}{nL'_s+L'_f+L'_i}, \qquad (2)$$

in the loop. Equating $i'$ to the current noise in the loop that is equivalent to the flux noise $\Phi_N$ of the SQUID gives

$$i_s=\frac{\Phi_N}{M_i}\frac{nL'_s+L'_f+L'_i}{M_s}=\frac{\Phi_N}{\alpha\sqrt{LL'_i}}\frac{nL'_s+L'_f+L'_i}{\alpha_s\sqrt{L_sL'_s}}. \qquad (3)$$

From the minimization condition $\partial i_s/\partial L'_s=0$, we find $nL'_s=L'_f+L'_i$. For an array with n=8, the noise current $i_s$ is minimum at $L'_s=210\text{nH}$[7]. It is desirable to have $L_s$ large as long as the condition $\omega L_s<<R_s$ is satisfied. For n=8, $L_s=L'_s=210\text{nH}$, $M_i=10\text{nH}$, and $\Phi_N=10^{-6}\Phi_o\ \text{Hz}^{-1/2}$, the current noise $i_s$ equivalent to the flux noise $\Phi_N$ is about $3.6\times10^{-12}$ $\text{A/Hz}^{1/2}$. This value is less than the 4.2K Johnson noise current, $\sqrt{4k_BT/R_s}$, for any sensor resistance $R_s<18\Omega$. We fabricated one multiplexer with $L_s=L'_s=100\text{nH}$ and one with $L_s=L'_s=300\text{nH}$ to bracket our calculated optimum value. We tested both multiplexers and their results are nearly identical. The data presented in this Letter are obtained from the device with $L_s=L'_s=300\text{nH}$.

The transformers are made by intertwining two planar Nb spiral coils, each of which consists of 36 turns of 2.5μm wide line on a 12.5μm pitch. To achieve efficient magnetic coupling, the spirals are deposited on a square superconducting Nb washer that is slit through on one side and partially on the other[8]. Photographs of a device are shown in Fig. 1(b)

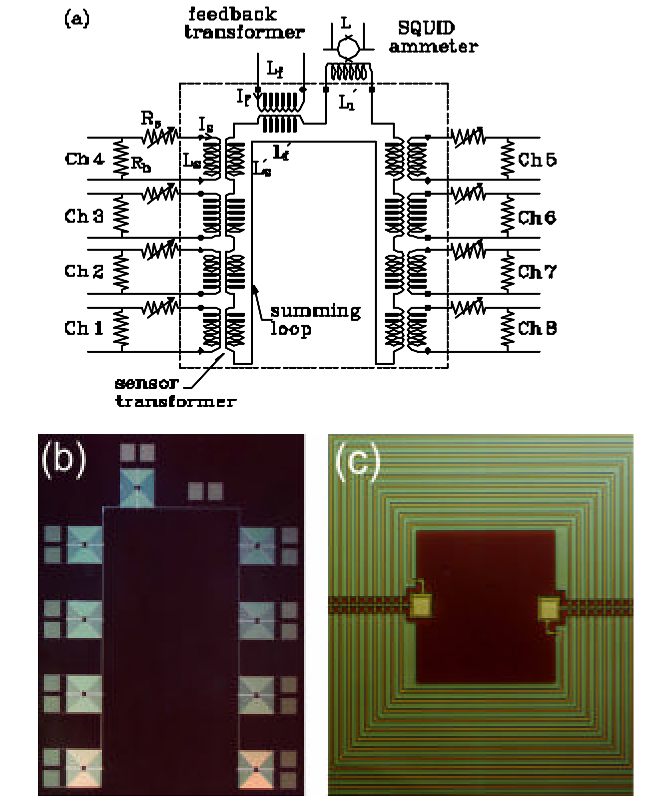


Fig. 1. (a) Schematic of the 8 channel SQUID multiplexer. For test purposes, resistors $R_s$=0.47Ω are used to simulate the sensors being multiplexed, which are voltage biased by the bias resistors, $R_b$=0.02Ω. The portion of the circuit enclosed by a dotted line is made by photolithography on a Si die. (b) A photograph of a prototype 8-channel SQUID multiplexer with $L_s = L_s'$ =100nH. Spiral coils of 25 turns are made on Nb washers with inner dimension of 100μm×100μm. (c) A micrograph showing details of a transformer near the inner hole.

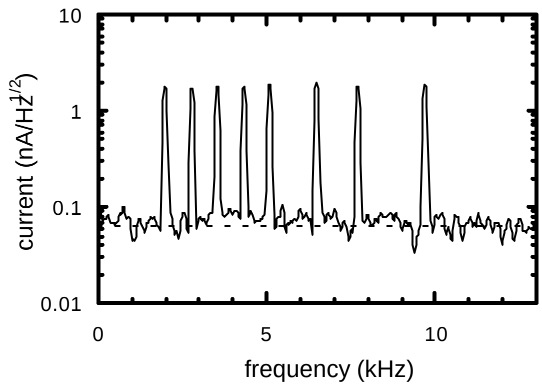


Fig. 2. Spectral density of the current fedback from the SQUID output into the summing loop, illustrating channel separation. The current through the resistors $R_s$ are 20nA rms at 1.97, 2.78, 3.52, 4.31, 5.06, 6.45, 7.68, and 9.66kHz for channels 1 to 8, respectively. The dotted line indicates the predicted total Johnson noise. The height of the peaks here and in Fig. 3 is suppressed by our choice of a spectral density display averaged over a bin width of 33Hz.

and 1(c). In the first fabrication step, the square Nb washers and Nb traces in the slits that connect to the inner end of each spiral are defined by photolithography on a Si wafer coated with a 150nm thick sputtered Nb film. After depositing a 100nm thick $SiO_2$ insulating layer, we etch vias through it at both ends of the traces. We then sputter a 100nm thick Nb layer and pattern it into two intertwined spiral coils. The coils on one side of the 9 transformers have contact pads to which the sensors (for $L_s$) or leads from the SQUID electronics (for $L_f$) are attached. The coils on the other side are patterned to be in series to form the summing loop. The spirals on adjacent transformers are wound in opposite senses to minimize pickup of ambient magnetic field noise. The transformers are spaced by a gap equal to their widths to reduce magnetic coupling between channels.

The inner and outer dimensions of the square washers are 150μm×150μm and 1mm×1mm, respectively. Both the self and mutual inductances are measured to be about 310nH, which is in good agreement with the estimated value of 300nH[9]. The loop gain using the feedback transformer shown in Fig. 1(a) is measured to be 0.47 of that for the original commercial SQUID system[7]. The comparable loop gain ensures proper functioning of the commercial SQUID electronics. The 10mm×10mm Si die containing the transformers is mounted on a circuit board along with the bias resistors, $R_b$=0.02Ω, and the simulated sensor resistors, $R_s$=0.47Ω. The summing loop is connected to the SQUID with superconducting Nb wire, which is bonded directly to the Nb pads on the die. The resistors $R_s$ are bonded to the die with Al wire. The loaded circuit board is mounted into a probe which is dipped into a liquid helium storage dewar. The probe is shielded by two outer layers of Cryoperm[10] and an inner layer of Nb. The SQUID and its input coil in their own Nb shield are located inside these shields.

Figure 2 shows the SQUID output measured with a spectrum analyzer with each resistor $R_s$ voltage-biased at frequencies ranging from ~2kHz to ~10kHz[11]. The currents through the resistors $R_s$ is 20nA rms, and the frequencies are unequally spaced to avoid overlap of harmonics. All the bias frequencies are well resolved, and the mixing between bias frequencies is 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. The total Johnson noise current, which is the quadrature sum of the contributions from all 8 $R_s$, is shown by the dotted line.

In order to verify the sensor 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 1.97kHz 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 cross talk 1% is

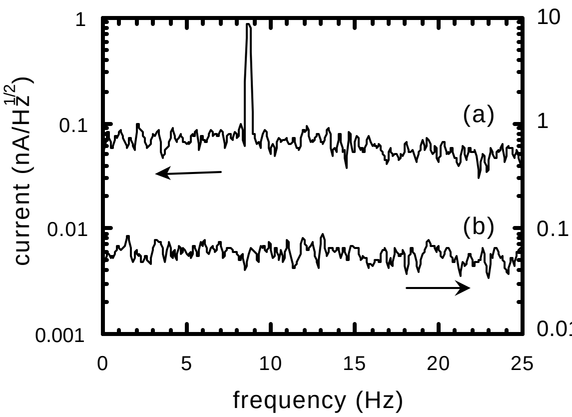


Fig. 3. Spectral density of the output of a lock-in amplifier connected to the SQUID output. The biases for channels 1 to 7 are simultaneously amplitude modulated by 2% at 1.6, 2.9, 3.7, 5.7, 8.6, 13.0, and 19.0Hz, respectively. The bias for channel 8 is not amplitude modulated. Trace (a) is obtained 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.

observed which may come from the drive electronics.

The total number of sensors that can be multiplexed will be limited by two factors: 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. We illustrate these limitations by the example of multiplexing Voltage-biased Superconducting Bolometers (VSB). For a VSB with a time constant $\tau$=10μs, the bolometer bandwidth is $1/2\pi\tau \approx$16kHz. The bandwidth of a flux-locked SQUID can be as high as several MHz for the current at typical bias voltage of a VSB[12], which is more than adequate to multiplex 100 sensors.

The second factor sets a more stringent limit. The noise current of a VSB is the quadrature sum of noise currents from photon noise, thermal fluctuation noise, and Johnson noise. Photon noise and thermal fluctuation noise act like signals 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. The rms Johnson noise is effectively multiplied by $\sqrt{n}$ . This accumulation of Johnson noise from a large array could be avoided by inserting an appropriate bandpass filter in each channel.[13] For a well optimized VSB, the thermal noise is a factor ~2 larger than the Johnson noise.[14] Without filters, the combination of thermal and Johnson noise increases by a factor 1.5 for n=8. When the sensor noise is dominated by photon noise, which increases with photon frequency, the number of VSB's that can be multiplexed without filters will increase significantly. Our multiplexer is especially useful for sensors where Johnson noise is not dominant, or where there is no Johnson noise as in the kinetic inductance bolometer.[15]

When multiplexing n sensors, the number of wires required to connect the sensor stage to room temperature is 2n+6 (2n for sensor bias, 2 for SQUID feedback, and 4 for SQUID bias and output), which is the same as in the design of Chervenak *et al*. However, our design requires only a single SQUID per row of sensors. Since switching is not required, our approach may be advantageous for sensors with short response times, such as microcalorimeters for UV/optical and X-ray detection.

The authors are indebted to X. Meng for technical support in the device fabrication. This work was supported by the National Science Foundation Grant FD97-31200, NASA Grant FDNAG2-1275, and by the Director, Office of Science, Office of Basic Energy Sciences of the U. S. Department of Energy under Contract No. DE-AC0376SF00098. The transformer dies were fabricated at the Berkeley Microfabrication Laboratory.

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[6] We neglect the current noise in the SQUID loop. This is a good approximation for the parameters of interest in this Letter, but not necessarily appropriate under all circumstances, particularly at higher frequencies.
[7] $L'_f$ is not defined by the minimization process, but plays little role if it is much less than $L'_i$. For convenience, we choose $L_f = L'_f = L'_s$. We used a Quantum Design series 50 DC SQUID with $L'_i$=1.9μH and $M_i$=10nH, and Model 5000 DC SQUID controller.
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[9] $L_s=N^2(1.25\mu_o d)$ where N is the number of turns and d is the dimension of the inner hole. We assume $\alpha_s$=1.
[10] Purchased from Amuneal Manufacturing Corp., 4737 Darrah St. Philadelphia, PA 19124.
[11] The noise of the oscillator used for the bias is smaller by a factor ~10 than the noise of a VSB, $\sqrt{SD_V(b)}/V_b : \sqrt{SD_I(s)}/I_s \approx 1:10$, for G=$10^{-10}$ W/K[14]. Here, $SD_V(b)$ and $SD_I(s)$ are the spectral densities characterizing the voltage noise of the oscillator and current noise of a VSB. $\sqrt{SD_I(s)}/I_s = 6\sqrt{k_B/G} \approx 2.2\times10^6$ Hz$^{-1/2}$ for G=$10^{-10}$ W/K, $V_b$ is the rms voltage amplitude from the oscillator, and $I_s$ is the current through the VSB, respectively.
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[13] A simple filter can be made by connecting a capacitor ($C_s$) in series with the inductor $L_s$. The reactances of $L_s$ and $C_s$ cancel at the bias frequency. Then, the value of $L_s$ is not limited by the voltage-bias condition for a VSB, and the electrical stability condition[16] for a VSB in the extreme negative electrothermal feedback limit does not apply. Choosing a large $L_s$, and thus a large $M_s$, we can keep the SQUID noise smaller than the noise current $i'$ in the summing loop in Eq. (2) even for a 100 channel array.
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