Superconducting multiplexer for arrays of transition edge sensors

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We report the design and testing of an analog superconducting time-division multiplexer to instrument large format arrays of low-temperature bolometers and microcalorimeters. The circuit is designed to multiplex an array of superconducting quantum interference devices, thereby simplifying wiring and room temperature electronics. We have fabricated a prototype 8×1 multiplexer chip and show a switching rate of 1 MHz. We calculate that a 32×32 array or larger is feasible. © *1999 American Institute of Physics.* [S0003-6951(99)00826-8]

We describe an analog superconducting circuit to multiplex (MUX) the superconducting quantum interference device (SQUID) readout of large format arrays of transition-edge sensors and present the multiplexed readout of eight SQUID channels with a first-generation multiplexer chip. Arrays of cryogenic x-ray microcalorimeters[1] and infrared bolometers[2,3] are now being used for astronomical measurements. The success of these instruments has created a need for larger arrays with multiplexed readout. In addition, cryogenic calorimeters and bolometers based on transition edge sensors (TES) coupled to SQUIDs show promise of faster and more sensitive single-pixel performance.[4,5]

A transition edge sensor (TES) consists of a superconducting thin film which is voltage-biased into the narrow temperature region of the transition between the superconducting and normal states. Photons incident on the TES increase the temperature and, therefore, the electrical resistance of the film. With the voltage across the film held fixed, the absorption of photons decreases the electrical current, which is then measured using a SQUID.

A SQUID current amplifier consists of a SQUID and an input coil which converts an applied current to a magnetic flux, which in turn causes the SQUID voltage output to vary. The nonlinear response of the SQUID is usually linearized by applying a feedback flux. Each SQUID current amplifier has eight terminals: two for the input coil used to apply the signal flux, two for the SQUID bias current, two for the output voltage, and two for the coil used to apply the feedback flux [Fig. 1(a)]. When multiple channels are instrumented, the number of wires that connect to room temperature can become prohibitive.

The number of wires to room temperature can be significantly reduced by connecting the outputs of many SQUIDs in series, and turning on the SQUIDs one at a time to time-division multiplex the input signals. For an $N\times 1$ column of SQUIDs, the number of output voltage wires thus can be reduced to two per column [Fig. 1(b)]. Since only one SQUID is on at a time, the feedback leads for the column of SQUIDs can also be connected in series, reducing them to two per column. The $N\times 1$ MUX is designed with $N+1$ bias current wires so that the SQUIDs can be turned on separately, a slight reduction from the $2N$ wires needed to bias independently instrumented SQUIDs.

The number of bias current wires can be further reduced by placing M single-column multiplexers in parallel and turning each row of SQUIDs on with common bias lines (Fig. 2). In this circuit, the bias voltage is applied in parallel to the SQUIDs in each row. This bias voltage is converted to a bias current by a resistor placed at each SQUID. In this way an array of $N\times M$ SQUIDs can be wired with $2M$ output leads, $2M$ feedback leads, and $N+1$ bias, or ''address,'' lines. If the circuit is grounded cold, only M output leads, M feedback leads, and $N+1$ address lines must be connected to room temperature.

In this multiplexing scheme, all the TESs remain on continuously. Since the current through each TES is sampled, it must be averaged (low-pass filtered) before the SQUID amplifier to prevent loss of information (degradation of the signal-to-noise ratio) in the signal bandwidth. This averaging is accomplished by a one-pole low-pass filter formed by the loop inductance L and the dynamic resistance R_{TES} of the TES. The loop inductance consists of the input inductance of the SQUID, the inductance of an optional additional ''Nyquist filter'' coil L_{NYQ}, and the stray inductance. The Nyquist frequency of the sampling is chosen to be far enough above the desired signal bandwidth and low-pass filter that negligible information is lost.

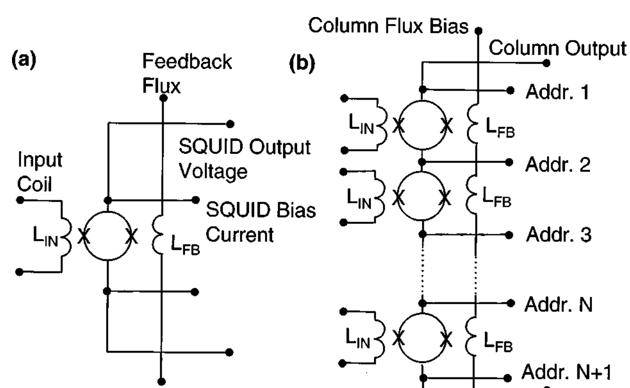

FIG. 1. (a) Wiring diagram for a single SQUID. Six connections to room temperature are required for bias, readout, and feedback. (b) Diagram for N SQUIDs connected in series with each SQUID turned on by a pair of address lines. Wire count to room temperature is $N+5$.

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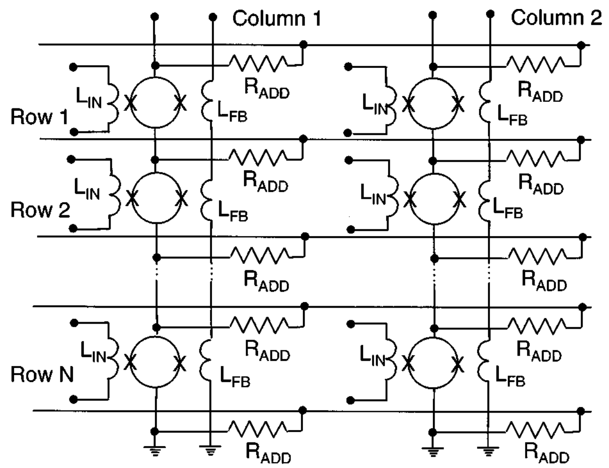

FIG. 2. Wiring diagram for additional columns of the multiplexer (two columns shown). With common SQUID bias lines to each column, only $2M+N+1$ leads to room temperature are required for $M\times N$ SQUIDs.

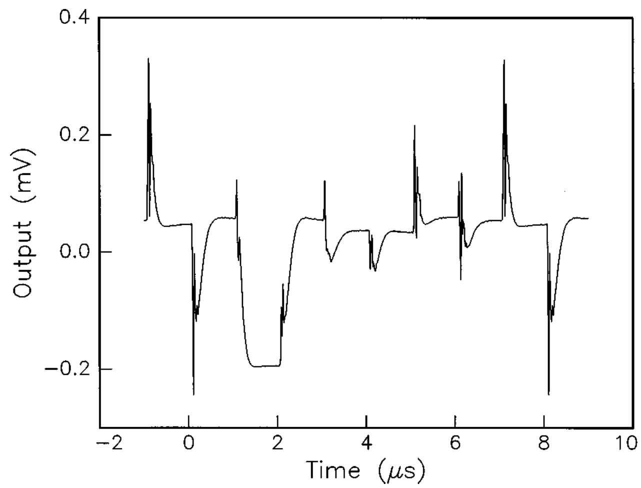

FIG. 4. Output waveform of a 1×8 SQUID MUX column operated at 1 MHz. After a ~0.5 μs switching transient, the SQUID signal is stable for ~0.5 μs and measured.

Broad bandwidth coupling of the SQUID output to room temperature amplifiers can be achieved by connecting each multiplexed first-stage SQUID column to a series combination of a load resistor R_{LOAD} and the input coil of a second-stage 100-SQUID series array (Fig. 3).[6] The load resistor is made larger than the dynamic resistance of the SQUID so that the loop current through a series-array input coil and the ''off'' SQUIDs remain well below the SQUID critical current for any applied flux.

A prototype chip was fabricated to test the multiplexing circuit in Fig. 3. It consists of an 8×1 array of input SQUIDs with outputs connected in series and coupled to the input of an on-chip series array. Different values for R_{LOAD} and L_{SA} are selected using on-chip wirebonds. The flux noise of the first-stage SQUID referenced to its input coil is measured to be 1.2 $\mu\phi_0/\mathrm{Hz}^{1/2}$ at 0.3 K and 2.5 $\mu\phi_0/\mathrm{Hz}^{1/2}$ at 4 K where ϕ_0 equals *h/2e*. The SQUIDs have a normalized capacitance $\beta_c=0.3$, normalized inductance $\beta_L=1$, critical current 100 μA, SQUID loop inductance $L_{\mathrm{SQUID}}=20$ *p*H, and 0.5 Ω junction shunt resistors. Other circuit parameters used for the 8×1 chip were the mutual inductance of the input coil to the first stage $M_{\mathrm{IN}}=425$ pH ($L_{\mathrm{IN}}\sim 150$ nH), a mutual inductance of 19 *p*H between the feedback coil and the first stage SQUID. Selectable parameters $R_{\mathrm{LOAD}}=1.55$ or 10 Ω, and series-array SQUID input coil inductance $L_{\mathrm{SA}}=6$ or 600 *n*H.

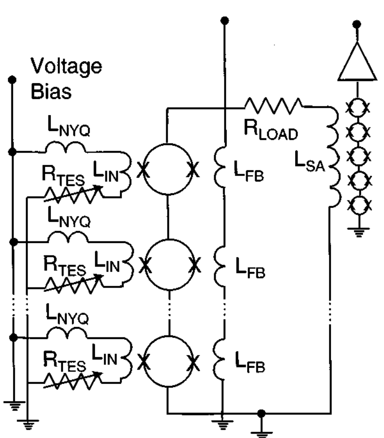

FIG. 3. Circuit diagram for a SQUID column connected to TES devices and read out by a 100 SQUID series array. A low pass filter at the SQUID input is formed by $L_{\mathrm{NYQ}}+L_{\mathrm{IN}}$ and the resistance of the TES sensor.

In order to test the functionality of the prototype chip, we cooled it in a 4 K dip probe with all wires (input, bias, and feedback) carried to room temperature. Signal generators were used to apply input signals and the circuit was operated in open-loop mode without feedback. Figure 4 shows the output waveform of the 1×8 multiplexer operated at a 1 MHz switching rate. As the address voltage is switched from one first-stage SQUID to the next, a transient signal occurs. The transient in the circuit decays in about 0.5 μs to a level at which measurements can be taken. The time constant $L_{\mathrm{SA}}/R_{\mathrm{LOAD}}$ fundamentally limits the time constant of the input SQUID signal to be read out by the series array. For the data shown in Fig. 4, we have chosen $L_{\mathrm{SA}}=6$ *n*H and $R_{\mathrm{LOAD}}=10$ Ω so that $L_{\mathrm{SA}}/R_{\mathrm{LOAD}}\sim 1$ ns, which is much faster than the observed settling time. The transient time appears to be similar for the different channels and to be dominated by parasitic elements in the circuit, probably associated with the row address lines.

Figure 5 shows eight independent input channels multiplexed at 500 kHz. The eight input signals are 1 and 2 kHz sine waves with different amplitudes and direct-current (dc) offsets, each coupled into a different SQUID channel. Here, we selected $L_{\mathrm{SA}}=600$ *n*H and $R_{\mathrm{LOAD}}=1.55$ Ω. Figure 5(a) plots the data obtained by averaging the output of the series-array SQUID during the interval after the active SQUID channel had settled. Figure 5(b) is the same data after they have been demultiplexed in software.

In the future, the SQUID multiplexer will be operated with a computer-controlled flux-locking scheme for the first-stage SQUIDs. Each time a first-stage SQUID is switched on, its output voltage is digitized, neglecting the transient signal. At the next cycle through that SQUID, the feedback error signal is corrected by the integrated error signal from the previous measurement cycle to provide flux locking.

To instrument an array of TES devices, the SQUID MUX must operate without degrading the detector sensitivity. First, in order to avoid the degradation of detector sensitivity due to amplifier noise, the current noise of the first-stage SQUID referred to the input coil must be much smaller than the current noise of a single TES. The detector is aver-

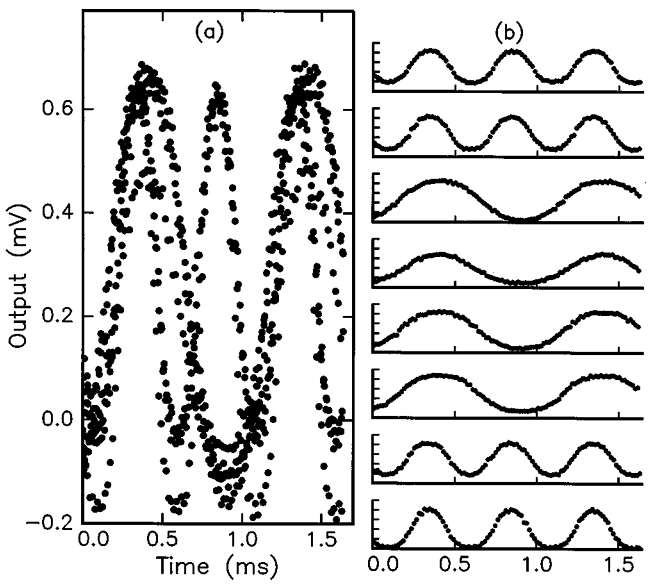

FIG. 5. (a) Data collected from a 1×8 SQUID MUX for 1.6 ms, operated in open loop mode at 500 kHz switching rate. Each dwell interval is represented by a single data point obtained by dropping the transient and averaging the remaining data. (b) Same data and axes as (a) demultiplexed into eight channels showing the successful readout of independent 1 and 2 kHz signals in the eight input SQUIDs.

aged by the *L/R* low-pass filter at all times, but the first-stage SQUID is operated with a duty cycle of only $1/N$. Thus, the effective bandwidth of the SQUID noise is N times larger than that of the detector noise, so that the noise power of the SQUID must be at least $\sqrt{N}$ times smaller. To avoid degradation of the signal, we require that $S_{I(\mathrm{TES})}=\beta N S_{I(\mathrm{SQUID})}$, where $S_{I(\mathrm{TES})}$ is the power spectral density (PSD) of the current noise of the TES, $S_{I(\mathrm{SQUID})}$ is the PSD of the current noise of the SQUID referred to the input of the input coil, and β limits detector sensitivity degradation by the SQUID readout to an acceptable level. We typically choose $\beta \geqslant 3$. For a TES operated in the extreme negative electrothermal feedback limit, the theoretical current noise spectral density $S_I(\mathrm{TES})$ in the signal bandwidth is $S_{I(\mathrm{TES})}=8k_BT/R_{\mathrm{TES}}$,[7] where k_B is Boltzmann's constant, and T is the operating temperature of device. Further, $S_{I(\mathrm{SQUID})}=S_\Phi/(\alpha^2 L_{\mathrm{IN}} L_{\mathrm{SQUID}})$, where α is the coupling constant between the input coil of the SQUID and the SQUID loop and S_Φ is the PSD of the flux noise of the SQUID. Thus, the maximum number of pixels which can be multiplexed is

$$N_{\mathrm{MAX}}=\frac{8k_BT\alpha^2 L_{\mathrm{SQUID}}}{\beta S_\Phi}\left(\frac{L_{\mathrm{IN}}}{R_{\mathrm{TES}}}\right). \quad (1)$$

For the second constraint, setting the frequency of the *L/R* filter too close to the thermal response frequency of the TES detector causes instabilities and oscillations. When the TES detectors are biased in the extreme negative electrothermal feedback limit, the condition for critical damping of these oscillations is $f_{L/R}=(3+2\sqrt{2})f_{\mathrm{TES}}$,[8] where $f_{L/R}=R_{\mathrm{TES}}/(2\pi L)$ is the knee frequency of the *L/R* filter and f_{TES} is the thermal response frequency of the TES. The inductance L is the sum of L_{IN}, the optional Nyquist filter inductance L_{NYQ}, and the stray inductance. In order to set an upper limit on the number of pixels which can be multiplexed, we assume that L is dominated by the input inductance of the SQUID. Then, $R_{\mathrm{TES}}/(2\pi L_{\mathrm{IN}})=(3+2\sqrt{2})f_{\mathrm{TES}}$, and, substituting into Eq. (1) we arrive at a condition that combines the noise requirements of the SQUID and the stability requirements of the detector:

$$N_{\mathrm{MAX}}=\left(\frac{4}{3+2\sqrt{2}}\right)\frac{k_BT\alpha^2 L_{\mathrm{SQUID}}}{\pi\beta S_\Phi f_{\mathrm{TES}}}. \quad (2)$$

The final constraint on array design is that the frame rate f_{frame} must be fast enough to avoid aliasing high-frequency noise into the signal bandwidth. To avoid degradation of the signal, we require that $\gamma f_{L/R}=f_{\mathrm{NYQ}}$, where $f_{\mathrm{NYQ}}=2f_{\mathrm{frame}}$ is the Nyquist frequency of the sampling and γ is determined by the maximum acceptable detector sensitivity degradation due to aliased noise. We typically choose $\gamma>3$ in bolometers so that the *L/R* filter rolls off the detector noise by at least 10 dB at the Nyquist frequency. For single-photon calorimeters, the randomness of photon arrival times introduces a significant statistical component into the high frequency signal spectrum, which must also be filtered above the Nyquist frequency, possibly requiring γ to be significantly larger. The Nyquist frequency is $f_{\mathrm{NYQ}}=F_{\mathrm{sample}}/2N$, where F_{sample} is the rate at which the multiplexer circuit switches between adjacent pixels. Then, since $f_{L/R}=(3+2\sqrt{2})f_{\mathrm{TES}}$, the required sampling rate is

$$F_{\mathrm{sample}}=2\gamma(3+2\sqrt{2})f_{\mathrm{TES}}N. \quad (3)$$

Our initial design goal is a 32×32 array with 32 readout channels. We have demonstrated single TES bolometer pixels operating at $T=0.45$ K, with a bandwidth $f_{\mathrm{TES}}=20$ Hz and noise equivalent power $\mathrm{NEP}=1.5\times10^{-17}$ W/Hz$^{1/2}$. Our prototype SQUID MUX chip has $L_{\mathrm{SQUID}}=20$ *p*H, $\alpha=0.3$, $S_\Phi=(2.5\mu\phi_0/\sqrt{\mathrm{Hz}})^2$ (operated at 4 K), and we choose $\beta=3$. From Eq. (2), the SQUID sensitivity and detector stability conditions allow up to 325 pixels to be multiplexed in each column, an order of magnitude larger than our design goal. For instrumenting a 32×32 array, we have the flexibility to place most of the filter inductance in an external Nyquist filter L_{NYQ} rather than on the SQUID. This decoupling of the TES and the SQUID offers the advantage of reducing the effects of transients on the TES devices. Taking $N=32$, the required sampling rate is at least 75 kHz [from Eq. (3)]. Since our prototype chip can be switched faster, in principle, larger arrays can be instrumented.

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