# Single SQUID Multiplexer for Arrays of Voltage-biased Superconducting Bolometers

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**Abstract.** We describe 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. In order to avoid the accumulation of Johnson noise in the summing loop, a tuned bandpass filter is inserted in series with each sensor. For a 32-channel multiplexer for Voltage-baised Superconducting Bolometer (VSB) with a time constant ~1msec, we estimate that bias frequencies in the range from ~500kHz to ~600kHz are practical. The major limitation of our multiplexing scheme is in the slew rate of a readout SQUID. We discuss a "carrier nulling" technique which could be used to increase the number of sensors in a row or to multiplex faster bolometers by reducing the required slew rate for a readout SQUID.

## 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) using transition-edge sensors and 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 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 developing a multiplexing scheme in the frequency domain with a single SQUID per row of sensors [5]. In this paper, we explore the limitations of the frequency domain multiplexer.

## 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. A bandpass filter in each channel, which is tuned for the bias frequency, is used to avoid the accumulation of the Johnson noise in the summing loop. By breaking up the inductor into a tuning inductor ($L_k$ for the k-th channel) and a coupling inductor ($L_s$), if we keep $L_k \gg L_s$, we can independently adjust the resonance frequency, $\omega_k = 1/\sqrt{L_k C_k}$, and the mutual inductance, $M_s = \alpha_s \sqrt{L_s L_s'}$, of the channel to the summing loop. All the sensor transformers have the same sensor-side inductance $L_s$, and summing-loop-side inductance $L_s'$, and we assume the coupling coefficient $\alpha_s = 1$. The frequency-selectivity of the filter in a channel allows us to combine all the bias lines into one, where we apply a comb of bias frequencies. The SQUID measures the current in the summing loop, and the individual signals are lock-in detected after the room temperature SQUID electronics. Feedback from the SQUID output is used to null the total current in the summing loop.

In our multiplexing scheme, the inductances $L_s$ and $L_s'$ are the two important parameters that can be adjusted to increase the number of sensors to be multiplexed by considering the SQUID noise current and the required slew rate. In our earlier report [5], we have shown that the equation

$$nL_s' = L_f' + L_i' \qquad (1)$$

minimizes the noise current at each multiplexer input $I_N$ which produces a noise at the

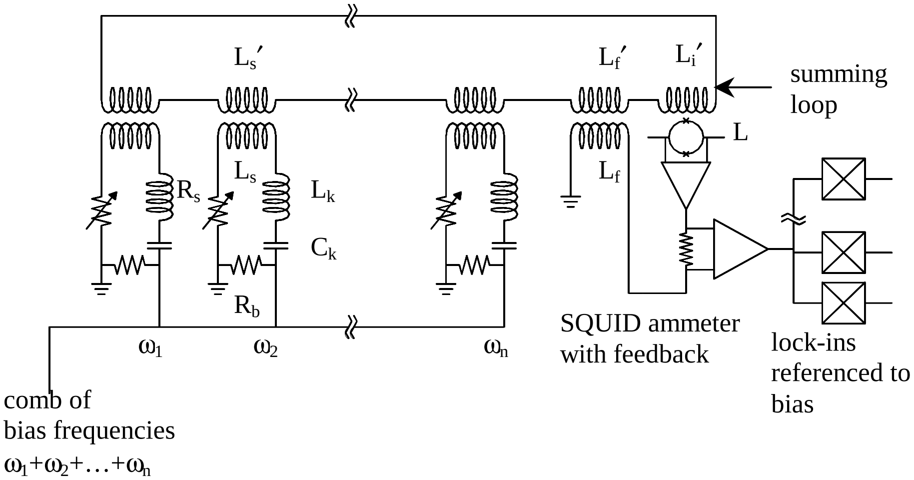

**FIGURE 1.** Schematic of the single SQUID frequency domain multiplexer.

SQUID equal to its flux noise $\Phi_N$ [5]. In eq. (1), n is the number of sensors, $L_f'$ is the summing-loop-side inductance of the feedback transformer, and $L_i'$ is the SQUID input coil inductance. The noise current $I_N$ can be calculated as, using eq. (1),

$$I_N = \frac{\Phi_N}{M_i}\frac{nL_s' + L_f' + L_i'}{\sqrt{L_s L_s'}} = \frac{2n\Phi_N}{M_i}\sqrt{\frac{L_s'}{L_s}} , \tag{2}$$

where $M_i=\alpha_i\sqrt{LL_i'}$ is the mutual inductance between the SQUID input coil and the SQUID, $\alpha_i$ is the coupling coefficient, and L is the SQUID inductance. The noise current $I_N$ should be less than the thermal fluctuation noise current $I_{th}$, which is the dominant sensor noise of a VSB. The noise current $I_{th}$ is calculated as

$$I_{th} = \frac{\sqrt{4k_B T^2 G}}{V_b} \approx \frac{\sqrt{4k_B T P_b}}{V_b} = \sqrt{\frac{4k_B T}{P_b}} I_b , \tag{3}$$

where T is sensor temperature, G is the thermal conductance of the sensor to the thermal bath, $P_b$ is the bias power, and $V_b=P_b/I_b$ is the bias voltage. Thus, the condition $I_N<I_{th}$ can be written as, using eq. (2) and (3),

$$\frac{2n\Phi_N}{M_i}\sqrt{\frac{L_s'}{L_s}} < \sqrt{\frac{4k_B T}{P_b}} I_b . \tag{4}$$

For a large n, a large ratio $L_s/L_s'$ should be used in order to satisfy the inequality (4). The slew rate $\Gamma$ needed to multiplex n sensors can be estimated as, with eq. (1),

$$\Gamma = 2\pi f_{max}\Phi_t = 2\pi f_{max}\frac{nI_b M_s M_i}{nL_s' + L_f' + L_i'} = \pi f_{max} I_b M_i \sqrt{\frac{L_s}{L_s'}} . \tag{5}$$

Here $f_{max}$ is the highest bias frequency, $\Phi_t$ is the total flux induced at the SQUID, and $I_b=R_s/V_b$ where $R_s$ is the sensor resistance. Eqs. (4) and (5) give the expression fo the required slew rate for n sensors,

$$\Gamma > 2\pi n f_{max}\Phi_N \sqrt{\frac{P_b}{4k_B T}} . \tag{6}$$

The maximum bias frequency $f_{max} \sim n\Delta f + f_{min}$ where $\Delta f$ is the bias frequency difference between two neighboring channels and $f_{min}$ is the lowest bias frequency. The bias frequency spacing $\Delta f$ should be determined by two factors: bolometer bandwidth and Q of the filter. If we choose $\Delta f$ to be about 10 times larger than the bandwidth of a VSB with time constant of ~1msec, the bias frequency separation should be $\Delta f \sim 3$kHz. In order for a filter to be effective in filtering Johnson noise, the Q of the filter should be

$$Q \equiv 2\pi f_k L_k / R_s \sim f_k / \Delta f , \tag{7}$$

where $f_k$ is the k-th channel bias frequency and $L_k$ is the inductance of the k-th channel tuning inductor.

Values of $L_k$ and $C_k$ should be chosen so that the condition (7) is satisfied for all the bias frequencies. An inductor with an inductance ~10μH can be fabricated in an area of ~1mm×1mm by a planar spiral coil on a square superconducting washer. A tri-layer capacitor, where an oxidized metal surface layer is used as a dielectric material of the capacitor, can have a capacitance ~10nF in an area of ~1mm×1mm. These fabrication methods are suitable for single-substrate integration with a large-format array of VSB, and also minimize an unintended variation in inductance and capacitance values across a wafer.

If we assume $R_s$~0.1Ω, for $L_k$~10μH and $C_k \lesssim 10$ nF the condition (7) can be satisfied for frequencies $\gtrsim$500kHz. Thus, for a 32-channel multiplexer for VSB's with a time constant ~1msec, the highest bias frequency is estimated to be $f_{max}$ ~ 600kHz. Typically flux noise of a SQUID is $\Phi_N \sim 3\mu\Phi_o/\sqrt{Hz}$, and the bias power $P_b$~1pW and T~0.45K for a typical VSB. For these parameter values, a readout SQUID of a 32-channel multiplexer should have a slew rate $\Gamma > 6.8\times10^7\ \Phi_o$/sec.

The required slew rate for a readout SQUID can be reduced significantly by implementing a "carrier nulling" technique. The carrier frequency carries the dc resistance of the bolometer, but the time-dependent signal is contained in sidebands. Therefore, the carrier frequency can be nulled without loosing the essential signals. For example, we can insert an additional transformer in the summing loop (not shown in Fig. 1) to which we apply a comb of bias frequencies that are properly phase shifted. Because this carrier nulling circuit can be completely separated from the SQUID feedback circuit, by nulling a large fraction of the current in the summing loop at each carrier frequency, we can effectively reduce the required slew rate for a readout SQUID. This carrier nulling technique could be useful to increase the number of sensors in a row or to multiplex faster bolometers.

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