Linearized SQUID Array for High Bandwidth Frequency-Domain Readout Multiplexing

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Abstract. We have designed and demonstrated a Superconducting Quantum Interference Device (SQUID) array linearized with cold feedback. To achieve the necessary loop gain three series array SQUIDs, each consisting of 100 SQUID elements, are connected in series to form a 300 element series array. A feedback resistor completes the loop from the SQUID output to the input coil. The short feedback path of this Linearized SQUID Array (LISA) allows for a substantially larger flux-locked loop bandwidth as compared to a SQUID flux-locked loop that includes a room temperature amplifier. While the expected bandwidth of the LISA is ≈100 MHz, the measured bandwidth for our system is limited to 10 MHz by the warm amplifier that follows the LISA. The bandwidth, linearity, noise performance, and 3 Φ_0 dynamic range of the LISA are sufficient for its use in our target application: the multiplexed readout of transition-edge sensor bolometers.

1. Introduction

A new generation of fully lithographed Transition-Edge Sensor (TES) bolometers has been developed (cite) for astronomical observations in the far-IR to millimeter wavelength range. These devices allow for large scale arrays of $10^3 - 10^4$ or more bolometers(cite SCUBA2, APEX, EBEX,SPT), providing a substantial leap forward in sensitivity. A significant challenge for scaling these systems to larger arrays is readout multiplexing. We have developed the superconducting quantum-interference device (SQUID) based frequency-domain readout multiplexer (fMUX) [9–11]. The fMUX is currently deployed on two active experiments [4, 8] and will be used for a number of experiments in the near future (cite POLARBEAR, EBEX). A complementary SQUID-based readout multiplexing technique is time domain multiplexing ([1–3] and UBC).

With the fMUX system, the number of detectors that can be instrumented with a single amplifier is proportional to the readout bandwidth. Our bandwidth of $\sim$ 1 MHz, which allows multiplexing of 8-16 channels, is limited by the fact that the SQUID feedback electronics includes a stage at room temperature. In this paper we report on the design and performance of a Linearized SQUID Array (LISA) that moves the first stage of the feedback electronics to the cryogenic stage. This configuration allows for an increase in bandwidth and the number of multiplexed pixels by a factor of ten.

In this paper we describe the design and testing of the LISA. The dynamic range, linearity, and input noise of the LISA meet our design specifications and we have achieved a readout bandwidth of 10 MHz.

2. Primary Application

Our target application for the LISA is the multiplexed readout of transition edge sensor (TES) bolometer arrays (CITE) for the detection of mm-wavelength radiation. These cryogenic detectors employ a $\sim$3 mm metal absorber that is weakly coupled to a $\sim$250 mK thermal bath. Radiation incident on the absorber induces a temperature rise. This temperature change is measured with a TES thermistor that is attached to the absorber. Large arrays of these TES bolometers can be manufactured photolithographically making possible a new generation of mm-wavelength observations using thousands of sensors, such as the experiments listed in section 1.

With our fMUX readout sytem, the TES devices are biased into their superconducting transition with 0.3 MHz or higher sinusoidal bias voltages. A change in the incident radiation power induces a change in the TES resistance that amplitude modulates the sinusoidal current. We multiplex the readout of several TES bolometers, each biased at a different sinusoidal frequency, by summing their output currents at the input coil of a DC SQUID transimpedance amplifier operating in a flux-locked loop (FFL) configuration. The TES thermistor typically has an impedance of $\sim 0.5 - 2\Omega$, a noise current of 10-50 pA/$\sqrt{\text{Hz}}$, and requires a bias voltage of $\sim 5\mu\text{V}_{RMS}$.

The SQUID electronics performance requirements for this application are: (1) white noise much lower than the TES noise ($\leq$ 5pA/$\sqrt{\text{Hz}}$), (2) sufficient ($>$ 1 MHz) bandwidth to accomodate many carriers, (3) input impedance much lower than the TES impedance ($\ll 0.5\Omega$) across the entire bandwidth, (4) sufficient transimpedance ($Z_{trans} > 150\Omega$) to override the 1 nV/$\sqrt{\text{Hz}}$ noise of a warm amplifier which follows the system, (5) large (> $10\mu A_{RMS}$ dynamic range, and (6) good linearity. Low frequency noise in the SQUID electronics is not an issue as the signals of interest are modulated on carriers above 0.3 MHz.

We chose the dynamic range requirement such that the system can handle at least one full sized carrier. This allows a user to tune the system in a straight forward manner. Tuning typically involves choosing the appropriate bias voltage level for a particular sensor. After configuration for a single carrier, that carrier is nulled with an out-of-phase, unmodulated copy of the carrier signal injected at the input coil of the SQUID. Once the first carrier is nulled, a second one can be added without increasing the dynamic range requirement. Thus, the number of channels that can be multiplexed with a single set of SQUID electronics is fundamentally limited by the bandwidth of these electronics.

3. Linearized SQUID Array

The response of of a SQUID has traditionally been linearized with a feedback loop that includes a transistor amplifier operating at 300K. The bandwidth of this flux-locked loop circuit is limited by propagation delays along the wires connecting this amplifier to the SQUID which operates at the cold stage temperature ($\sim$ 4K). The current fMUX bandwidth of 1 MHz is achieved by constraining the wire length between 300K and 4K to be < 0.1m. Further reductions in wire length are not cryogenically feasible.

A significant increase in bandwidth can be achieved by either moving the transistor amplifier to the cold stage or eliminating it entirely from the feedback loop. The latter is preferable, since a transistor amplifier would present a significant heat load to the cold stage. With the amplifier removed from the circuit, a configuration of SQUID devices can be used to produce the necessary loop gain while maintaining the circuit's transimpedance.

One such configuration, referred to as the 'SQUID op-amp', has been demonstrated [7]. That device uses a parallel cascade of SQUIDs to increase the loop gain of the circuit. While each of the SQUIDs in the parallel cascade contributes to the loop gain and linearizes the circuit, the dynamic range of the circuit is limited by the final stage SQUIDs. For the multiplexed readout of TES bolometers, we require a device that extends both the linearity and dynamic range of the composite SQUID devices.

To meet our requirements, we have developed and tested the Linearized SQUID Array (LISA) concept (Figure 1). The LISA eliminates the warm transistor amplifier from the flux locked loop by using a series configuration of SQUIDs to simultaneously linearize the circuit and extend the dynamic range. The LISA prototype we discuss in this paper consists of three series array SQUIDs, each consisting of 100 SQUID elements, themselves connected in series to form a 300 element series array. The output voltage of the LISA is coupled back to the input coil with a feedback resistor to complete the feedback loop.

In designing and testing any SQUID FLL, we focus on three figures of merit: the closed loop gain, A_{loop}, the forward gain, or transimpedance, Z_{LISA}, and the input noise current, i_n. The closed loop gain quantifies the ability of the feedback electronics to extend the dynamic range and linearity of the SQUIDs that form the LISA. The transimpedance measures the output voltage produced for a unit current flowing through the input coil of the LISA.

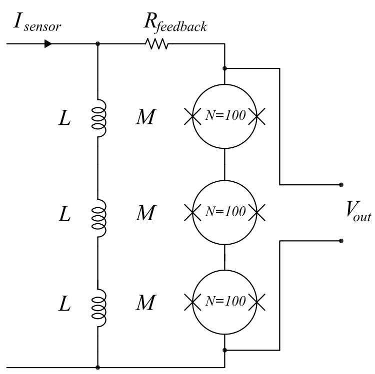

Figure 1. Schematic of Linearized SQUID Array (LISA). Three one hundred element series array SQUIDs are connected in series. A feedback resistor connects the SQUID output to the input coil, completing the feedback loop.

The input noise current determines the sensitivity with which currents can be read out with the LISA.

If the system consists of only an input-coil coupled SQUID-like component and a feedback resistor R_{FB}, the loop gain will be:

$$A_{loop} = \frac{Z_{SQ}}{R_{FB} + R_{SQ}} \quad (1)$$

where Z_{SQ} and R_{SQ} are the SQUID transimpedance and output impedance, respectively. The transimpedance is the product of the mutual inductance between the input coil and the washer of the SQUID and the slope of the voltage response to applied flux:

$$Z_{sq} = \frac{\partial V}{\partial \phi} \mid_{max} M_{sq}. \quad (2)$$

A current supplied to the input coil of the LISA produces an output voltage $v_{LISA} = -i_{coil} Z_{LISA}$. The LISA transimpedance is thus

$$Z_{LISA} = ((R_{FB} + R_{SQ}) || Z_{SQ}) \left(1 - \frac{R_{SQ}}{R_{FB} + R_{SQ}}\right). \quad (3)$$

Finally, the expected current noise is a quadrature sum of the intrinsic noise from the component SQUID arrays, i_{SQ}, and the Johnson noise of the feedback resistor, i_{FB}:

$$i_n = \sqrt{i_{SQ}^2 + i_{\mathrm{FB}}} \quad (4)$$

Equations 1 and 3 show a fundamental limitation on performance that depends on the properties of the individual SQUIDs that form the LISA. The feedback current is determined by the series combination of R_{FB} and R_{SQ} and the output voltage of the LISA divides between a voltage drop across R_{FB}, which couples to subsequent readout electronics, and across R_{SQ} which is contained on the SQUIDs themselves. Thus, for large output resistances $R_{SQ} \gg R_{FB}$ the loop gain approaches the limit Z_{SQUID}/R_{SQUID} and the transimpedance approaches zero. In choosing or designing SQUIDs for the LISA, the ratio R_{SQ}/Z_{SQUID} should be minimized.

4. Performance

Our prototype LISA is designed with three SQUID array chips wired in series. Each SQUID array is a single chip containing a 100-element series array SQUID [6]. This array has an input inductance of 160nH, an input current noise of $\sim$!2pA/$\sqrt{\text{Hz}}$, a mutual inductance $M_{sq} =$ 80 pH, a maximum transimpedance Z_{sq}, of 450Ω, and an output impedance, R_{sq},

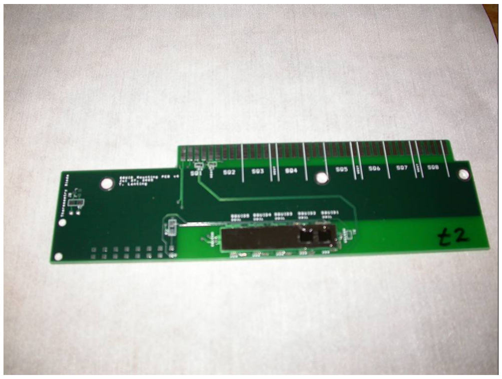

Figure 2. Photo showing the PC mounting board housing the 2-SQUID LISA prototype

of 80 Ω. We chose a feedback resistance of $R_{FB} = 230$ Ω.

4.1. Tuning

Tuning a SQUID device and its associated electronics typically involves first choosing a SQUID Josephson junction current bias that maximizes the amplitude of the voltage-flux relation, then choosing an appropriate flux bias to maximize the SQUID transimpedance. Finally, a switch is closed, enabling the flux-locked loop.

The LISA has a permanent connection between its output and input so we find the appropriate junction current bias and flux bias simultaneously. First we measure a series of voltage-flux relations for different values of the junction current bias. We then choose the junction bias that maximizes the dynamic range and the flux bias that moves the device, in the absence of input signa,) to the middle of this dynamic range.

4.2. Dynamic Range

Once an optimal point is chosen for the LISA, we measure its dynamic range (maximum peak-to-peak applied signal) by applying a direct current to the input coil and measuring the output voltage (voltage-current or voltage-flux relation). Figure 3 shows this measured relation for three SQUID devices in series without feedback, and the same relation for the LISA. The intrinsic sinusoidal response has been linearized over a dynamic range of $37 \pm 1\ \mu A_{pp}$.

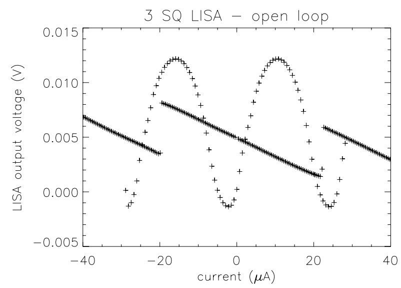

Figure 3. LISA response to applied input current with and without application of cold feedback.

We expect that the maximum current allowed at the input coil to increase from the open loop value of 26 μA to

$$i_{pp} = 26\ \mu A\left(\frac{1}{2} + \frac{2A_{loop}}{2\pi}\right) \quad (5)$$

where A_{loop} is the closed loop output impedance of the cold FLL as defined in section 3 but corrected for having three 100-element array SQUID devices in series:

$$A_{loop} = \frac{nZ_{SQ}}{R_{fb} + nR_{SQ}} \quad (6)$$

Using the properties of the individual LISA components, we expect $A_{loop} = 3.2$. This loop gain predicts, using equation 5, a dynamic range of 39 μA_{pp} in good agreement with measurement.

4.3. Bandwidth

We measured the bandwidth of the LISA with a network analyser [5]. We apply a sinusoidal current at the LISA input and measure the output voltage across two decades of frequency (1 MHz to 100 MHz). The sinusoidal current is applied differentially and the output single-ended voltage is measured directly with the network analyser. We measure a bandwidth of 10 ± 1 MHz. This measured bandwidth is currently limited by a room temperature second stage amplifier. However, the output impedance of the LISA and the capacitance of the cabling connecting the cryogenic output to the room temperature electronics limit the ultimate bandwidth we can achieve with the prototype architecture to $\sim 12 - 15$ MHz.

4.4. Noise

We coupled the output voltage of the LISA to a spectrum analyser and measured the noise from 1 to 100 MHz with the junction bias current on and off. The noise measured with the bias current off, 1.3 nV/, measures the baseline noise of the room temperature readout electronics. With the bias current on, the noise increases by 25% to 1.65 nV/. This increase is the combination of the Nyquist current noise from the feedback resistor and the intrinsic current noise from the individual SQUID devices.

4.5. To Include or Not?

Also discuss the limitations that stray capacitances produce. How much detail to include in terms of LISA perfomance equations? (i.e. eqn for loop gain, eqn for dynamic range, eqn for forward gain with and without the effect of stray capacitance and inductance.) Some discussion of running with external loop?

5. Conclusions

The performance of the prototype LISA shows that it has the requirements for reading out multiplexed TES bolometers. The bandwidth is increased by an order of magnitude from the current SQUID electronics, allowing the multiplexed channel count to increase by this same factor.

- Future prospects with digital mux?
- Comparison to best TDM performance?
- Discussion of hybrid room temp feedback and cold feedback?

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