Recent results of a new microwave SQUID multiplexer

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We are developing a proof-of-concept microwave SQUID multiplexer containing four SQUIDs coupled to GHz frequency resonant circuits and fed with a single microwave readout line. The resonators are half-wave coplanar waveguide sections and are similar to the structures used for the microwave kinetic inductance detectors developed in our group. Optimal values for the interdigital gap capacitors were determined to maximize the sensitivity of the transmitted and reflected microwave signal with respect to changes in the dynamic resistance of the SQUID. The dc current-bias line for the SQUID has an in-line inductive high frequency filter to minimize coupling between the bias line and resonator. A high frequency modulation scheme is proposed to eliminate the need for individual flux biasing of the SQUIDs, which extends the dynamic range of the readout. In this scheme a common modulation signal is imposed on each SQUID and the received signal is demodulated at one and two times the modulation frequency to maintain sensitivity at any flux state. We present the recent results of the microwave SQUID multiplexer system operating at a readout frequency range of 10 - 11GHz.

Keywords: SQUID; Multiplexer; Bolometer.

1. Introduction

A leading candidate detector array technology for the next generation of astronomical instruments for millimeter though far-Infrared (FIR) wavelengths is the transition edge sensor (TES), which is being developed intensively at several laboratories including JPL. The readout of TES bolometers is accomplished using SQUID amplifiers, for which multiplexing techniques have been developed that serve to reduce the number of wires needed between the cryogenic detector arrays and the warm electronics. In current SQUID multiplexers, the outputs of a small (8 to 32 element) array of bolometers is encoded in either the time or frequency domain, and the combined set of signals is amplified by a relatively high-bandwidth "series-array" SQUID amplifier. The outputs of these series-arrays are read out in a non-multiplexed fashion, and hence the savings in wire count is a factor of 8 to 32, enabling arrays of thousands of detectors, but still requiring hundreds of wires. We propose to develop a new SQUID multiplexer that makes use of a technique recently demonstrated in our group for reading out a SQUID at very high frequency ($\sim 10\ GHz$). The

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"microwave SQUID" (or MSQUID) has greater bandwidth than the series-array amplifier and its output is itself multiplexable. In our new multiplexer architecture, we use a microwave SQUID in place of the series-array SQUID used in current designs. Each MSQUID can read out 100 detectors, because of its comparatively greater bandwidth, and we can multiplex the output of at least 100 MSQUIDs. In this way we can achieve a significant increase in multiplexing factor, potentially 10,000 detectors with a single set of wires.

To demonstrate the feasibility of the new concept, we are developing a prototype device. A series of microwave resonators with frequencies $\sim 10\ GHz$ are each loaded by a dc SQUID to a degree that depends on the flux state of the SQUID. By using resonators with high quality factors and slightly different resonance frequencies, many of these resonator-coupled SQUIDs may be read out with a single excitation line and cryogenic amplifier. Recent noise measurements of the device demonstrated $\sim 5\mu\Phi_0/\sqrt{Hz}$ performance at 4.2 Kelvin. We also present a new technique for modulating the SQUID array in series that alleviates the need to individually flux-bias the SQUIDs. The new MSQUID device has applications to the readout of detector arrays for astronomy and fundamental physics experiments in space.

2. Principles and Design

SQUID multiplexers have been demonstrated using both time and frequency division schemes.[1-2] Most recently, Irwin and Lehnert[3] has demonstrated a frequency-division multiplex technique using an array of SQUIDs operated at microwave frequency (600 MHz). In the microwave SQUID multiplexer, each SQUID is part of a resonant circuit with a unique resonance frequency. A comb of microwave frequencies is used to simultaneously excite all of the resonant circuits of the array. The quality factor, Q, of the resonance varies as the flux state of the DC SQUID changes. Typically SQUID readout electronics employ feedback to keep the flux in the SQUID loop at a sensitive part of the modulation function and to linearize the output. Despite the large bandwidth advantage of the new microwave technique, separate feedback lines for each SQUID of a large array would be ultimately impractical. To overcome this difficulty, we propose to operate the SQUID multiplexer system in non-flux-locked mode. Normally non-flux locked operation is hampered by the periodic nature of the SQUID response function, which limits the dynamic range and leads to the possibility that stray magnetic fields bias the SQUID at a point of degraded sensitivity. We propose to circumvent this problem by applying a high frequency modulation to all of the SQUIDs in series, which can eliminate the need of a multiplexed flux-biasing circuit. Figure 1 shows the schematic of the microwave SQUID multiplexer and the photo of a device that was recently designed and fabricated at the Microdevices Laboratory at JPL. This device contains four SQUIDs with resonant circuits fed with a single microwave readout line. The SQUIDs are ac-coupled to the meandering half-wave resonator circuits similar to the structures used to multiplex microwave kinetic inductance detectors[4]. Optimal values for the interdigital gap capacitors were determined to maximize the sensitivity of Q with respect to changes in the dynamic resistance of the SQUID. The dc current-bias line for the SQUID has an in-line inductive high frequency filter to minimize coupling between the bias line and resonator. The coplanar waveguide (CPW) design is similar to the one used by P. Day et. al.[4]

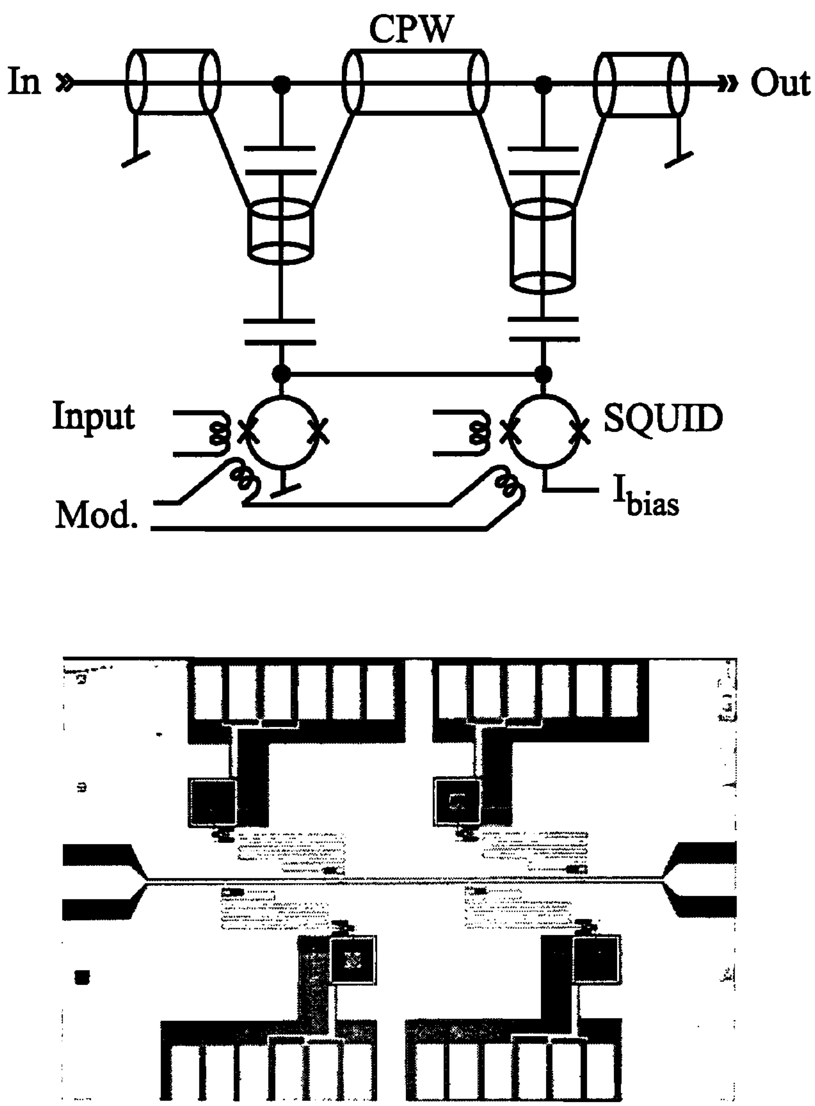

Fig. 1. Schematic of the microwave SQUID multiplexer and a photo of the prototype device. The device can be easily scalable for a large size array. Individual SQUID chips share common current bias and modulation. The SQUID multiplexer is operating in the open-loop mode such that the feedback line for individual SQUIDs are not necessary. The size of the chip is 3 mm x 5 mm.

The main components of our multiplexer consists of (1) a set of tank circuits used for the AC bias of the bolometers[2](2) the MSQUID, and (3) a multiplexable microwave-frequency backend electronics based on commercially available high-speed-digital frequency generation/ demodulation cards[5]. The later is a critical component of the system because it is important that the back-end electronics not rely on individual components for each pixel of the detector array. In the digital back-end, the frequency comb used for the bolometer excitation is generated digitally. The signals from the MSQUID array, after down-conversion from the several-GHz carrier frequencies, are directly digitized with fast ($100MHz - 1GHz$) A/D converters, then demodulated using a fast FPGA.

The output of each SQUID is lock-in detected both at f and $2f$, giving outputs I and Q, where

$$I(\Phi) = \langle \sin\omega t \cdot S(\Phi + A\sin\omega t)\rangle, \tag{1}$$

$$Q(\Phi) = \langle \cos 2\omega t \cdot S(\Phi + A\sin\omega t)\rangle, \tag{2}$$

and $\langle\rangle$ indicates time average. A is the amplitude of the flux modulation, ω is the angular frequency and S is the SQUID modulation function. Φ represents the external magnetic flux. A phase angle can be defined by

$$\theta(\Phi) = \arctan\left(\frac{Q(\Phi)/Q_m}{I(\Phi)/I_m}\right), \tag{3}$$

where I_m and Q_m are the maximum values of I and Q. The demodulation and calculation of θ can be accomplished using a digital signal processor. For a non-sinusoidal SQUID modulation function, the function deviates slightly from linearity. The non-linearity can be measured by sweeping the flux state of the SQUID with the input held at zero, then corrected for in the DSP software. A numerical simulation showed the non-linearity could be less than one percent. Signals greater than a single flux quanta can be measured by keeping track of the phase wrapping.[6]

3. Test Results

To demonstrate the concept, we have designed and fabricated a multiplexer chip that contains four SQUIDs with resonant circuits fed with a single microwave readout line. Initial tests showed the four distinct resonance lines near 10 GHz.[6] The Q of the individual circuits was approximately 500. To demonstrate the flux sensitivity, we have measured the RF response of the CPW line at four different input bias levels. The single SQUID input flux sensitivity results are shown in Fig. 2. For this measurement, we have used a commercial network analyzer. Figure 3 shows the noise measurements. Noise measurement at 4.2K demonstrated $\sim 5\mu\Phi_0/\sqrt{Hz}$. The signal at 33 kHz is a test signal.

4. Summary

There are many applications of the new SQUID multiplexer readout scheme. Transition Edge Sensor (TES) and Magnetic Micro Calorimeter (MMC) detector have been advanced over many years. These detectors have been proposed for many missions including SAFIR, CMB-Pol, Constellation-X, and have been used in dark matter searching experiments. The SQUID readout has been a leading technology for amplifying signals at low temperature close to the detectors without dissipating heat. As one requires more detectors at low temperature, it becomes very critical to minimize the number of leads to the first amplification stage at low tempera-

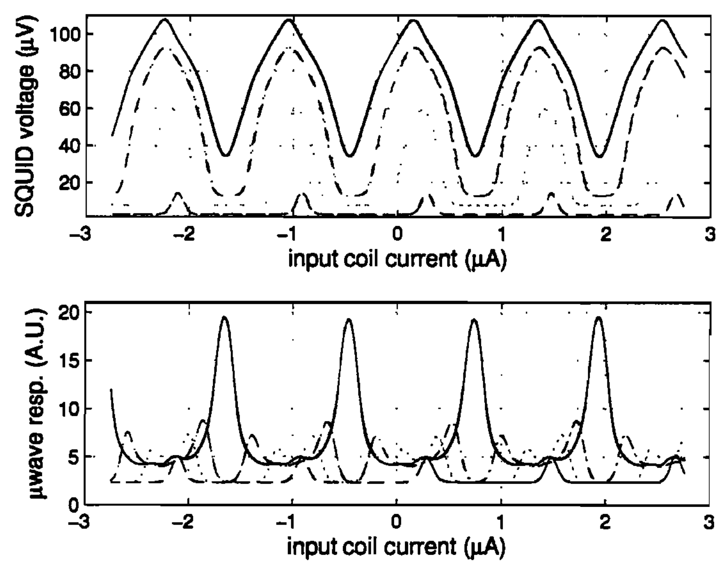

Fig. 2. Preliminary data on input coil sensitivity of the first channel SQUID. The measurement showed DC (top) and RF (bottom) responses of the SQUID as a function of the input current at 4 different bias levels. The measurements were performed at 4.2K

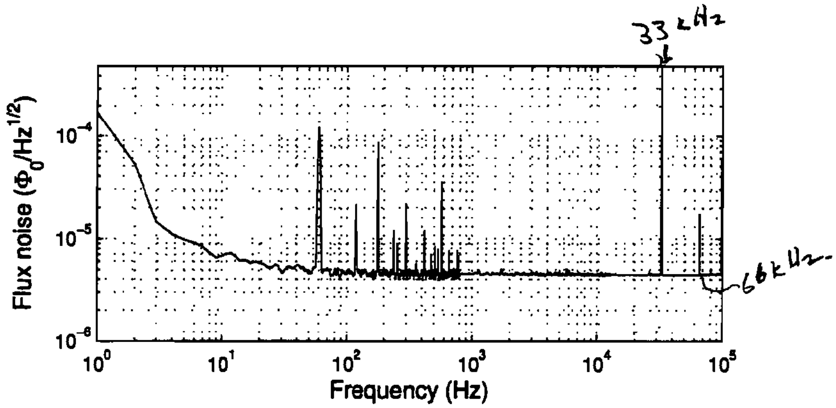

Fig. 3. Noise data of the first channel SQUID.

ture. In this paper, we described a new SQUID multiplexing technique and a chip design utilizing X-band microwave frequencies. A new modulation scheme is also introduced to linearize the SQUID transfer function enabling further minimization of required lead wires. By supplying AC-bias signals for the entire array of detectors on a single set of wires, and similarly supplying the dc bias and modulation signals in series, we can potentially read out a 1,000-10,000 detectors with only 3 pairs of wires and a single microwave coaxial cable.

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