MULTIPLEXED READOUT OF SUPERCONDUCTING BOLOMETERS

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Abstract

Studies of emission in the far-infrared and submillimeter from astrophysical sources require large arrays of detectors containing hundreds to thousands of elements. A multiplexed readout is necessary for practical implementation of such arrays, and can be developed using SQUIDs, such that, e.g., a 32×32 array of bolometers can be read out using ∼100 wires rather than the >2000 needed with a brute force expansion of existing arrays. These bolometer arrays are made by micromachining techniques, using superconducting transition edge sensors as the thermistors. We describe the development of this multiplexed superconducting bolometer array architecture as a step toward bringing about the first astronomically useful arrays of this design. This technology will be used in the SAFIRE instrument on SOFIA, and is a candidate for a wide variety of other spectroscopic and photometric instruments.

keywords: Bolometers, SQUIDs, multiplexing, transition edge sensors, far infrared, submillimeter

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Introduction

Advances in bolometer fabrication have made possible the construction of submillimeter-wavelength bolometer arrays with up to 100 detectors (e.g., CSO – SHARC[1], JCMT – SCUBA[2], IRAM 30m – MAMBO[3]). Currently, the sensitivity of these instruments is background-limited, so deep- and wide-field surveys are limited by the number of detectors and the amount of observing time available. In order to achieve a leap to ∼10,000 detectors (of order the largest size usable on current and foreseen telescopes), a scalable detector architecture must be demonstrated. In this paper, we present a demonstration of an architecture which can be scaled to kilopixel arrays using superconducting sensors and a multiplexed amplifier technique[4] to reduce the wiring overhead. In our implementation, we choose to use the close-packed geometry, which yields an improvement in mapping speed per focal plane area[5]. However, the superconducting detectors can be used regardless of array geometry, and are equally feasible for arbitrary array implementations. Detector arrays of this type are currently being developed for use in the SAFIRE instrument for SOFIA[6] and for upgraded ground-based spectrometers FIBRE[7] and SPIFI[8].

Superconducting Bolometers

The transition between the superconducting and the normal state can be used as an extremely sensitive thermometer (a Transition Edge Sensor, or TES). A thin film, held at its transition temperature, requires only a tiny additional heat input to warm it above its transition, increasing the resistance by a large fraction. In fact, the superconducting transition can be very sharp, yielding a dimensionless sensitivity $\alpha \equiv d\log R/d\log T \approx 1000$. Recently, we have fabricated thin film superconducting bilayers of molybdenum and gold[9] and molybdenum and copper[10]. One such transition is shown in Figure 1; it features a bilayer with 400Å of molybdenum and 750Å of gold, yielding a normal resistance of 330mΩ. Near its transition temperature of 440mK, the sensitivity reaches $\alpha \sim 1100$.

Because the transition region is narrow (≈1mK) compared to the temperature above the heat sink (150mK above a ^{3}He refrigerator at 300mK), the TES is nearly isothermal across the transition. In use as a detector, the power applied to raise the TES into its transition region is nearly constant. This has the effect that the response becomes linear to better than 1%, substantially better than the typical linearity achieved with semiconducting bolometer thermistors. Typically, additional devices can be fabricated with transition temperatures reproducible to

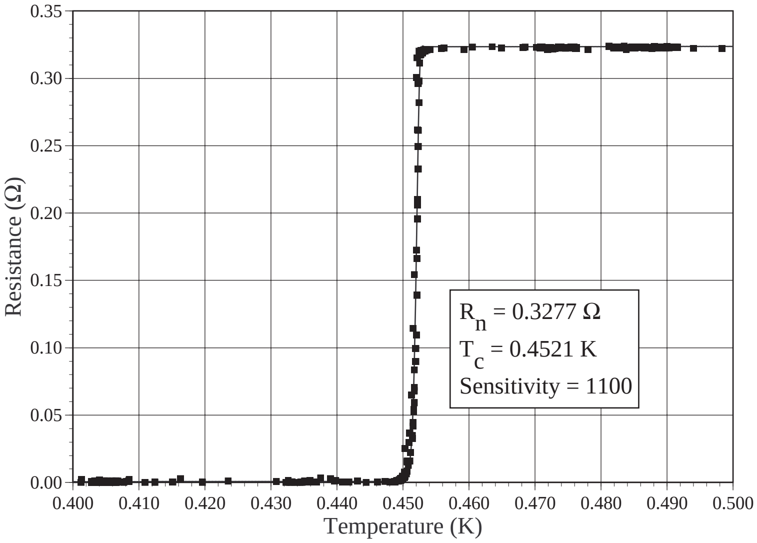

Fig. 1.— Superconducting transition of a MoAu bilayer.

2%, repeatable normal state resistances, and stray resistances of less than 3mΩ. The bilayer process allows the transition temperature to be tuned by varying the relative thicknesses of the normal metal (gold or copper) and superconducting metal (molybdenum) layers. In this manner, detectors optimized for performance in a variety of different optical loads and operating temperatures (e.g. broadband imaging, narrowband spectroscopy) can be produced.

In order to bias the TES, a voltage source is provided by passing a current through a parallel arrangement of a small shunt resistor and the TES (Figure 2). Because the sensitivity of a TES is large ($\alpha \sim 1100$ for the film in Figure 1 vs. $\alpha \sim 5$ for a semiconducting thermistor), a voltage-biased TES is stabilized by strong electrothermal feedback[11]. In this mechanism, an increase in temperature yields a sharp increase in resistance, which reduces the current flowing through the TES, lowering the bias power and decreasing the temperature. This enables the devices to respond very quickly (time constants of $\lesssim$1ms) compared to its physical time constant.

Multiplexed SQUID Amplifier

A low-impedance detector such as a superconducting TES is well-matched by a superconducting quantum interference device (SQUID) amplifier. From a fundamental standpoint, a SQUID amplifier functions as a magnetic flux to voltage converter, with extremely low output voltage noise. A voltage-biased TES in series with a "pickup" inductor placed near a SQUID will induce a changing magnetic flux through the SQUID when the TES resistance changes. As in Welty & Martinis[12], we use a first stage SQUID to drive a series array of SQUIDs. This "series array" SQUID can produce a full-scale output voltage swing of order 4 mV, readily amplified by room-temperature electronics.

A SQUID can be switched rapidly between its superconducting state and an operational state by biasing the SQUID with roughly 100μA of current. If we stack n SQUIDs in series with $n+1$ electrical "address" leads as shown in Figure 2, driving current between an adjacent pair of leads will result in only one SQUID being operational at a time. With the other SQUIDs in the superconducting state, the output voltage across the entire array is exactly the voltage across the one active SQUID. In this manner, only one amplifier is necessary for n detectors, although at a data rate n times faster. Adding in connections for a common TES bias and feedback signal, a total of $n+7$ wires are needed.

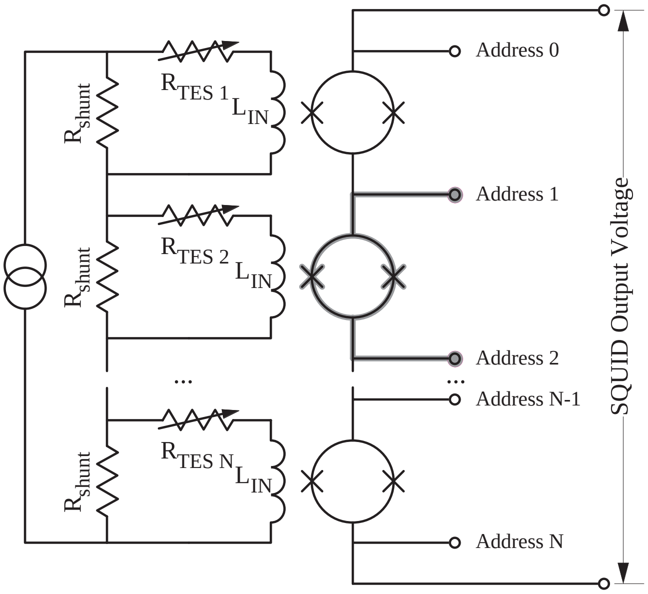

Fig. 2.— Simplified schematic of a SQUID multiplexer.

The SQUID response function is a voltage output which is a periodic function of the input magnetic flux. In order to simplify operation, we have built a digital feedback loop to linearize the output. For each multiplexed device, the instantaneous value of the flux is stored in memory; the next time this device is read out, the opposite of the flux is applied to the SQUID loop through a feedback coil (not shown in Figure 2). In this manner, the total flux through the SQUID loop is nulled, and the feedback signal is proportional to the input signal.

We have built a 1×8 SQUID multiplexer which we tested using the circuit described in Chervenak at al.[4]. One sine wave and one triangle wave input each were fed into a cold electronics setup so as to mimic the modulation of a signal from infrared light. The multiplexed amplifier was switched between these inputs, amplified, digitized, and demultiplexed to recover the original input waveforms (Figure 3). The performance features low distortion with $\ll$1% typical crosstalk, highlighting the excellent fidelity of the amplifier. It should be pointed out that the TES is biased at all times, and is low-pass filtered using an inductor with time constant $L/R \sim 20\mu$s to a response time slower than the multiplex switching time. Effectively, the inductor and TES integrate the signal, so that the multiplexer samples an integrated signal; no loss of signal-to-noise is introduced even though the signal from each TES is read out for a shorter time. This is true provided that the noise contribution of the SQUID and room temperature electronics is substantially less (by a factor of more than $\sqrt{n}$) than that of the TES. Furthermore, in order to remain stable, the devices must be sampled faster than $f_{L/R} = (3+2\sqrt{2})f_{TES} \approx 100\,\mathrm{kHz}$[13].

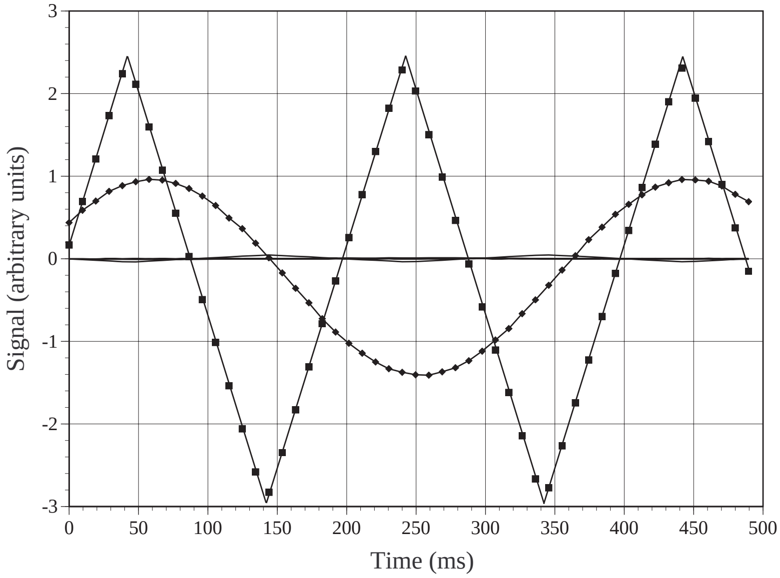

Fig. 3.— Time series of data from eight demultiplexed SQUID multiplexer channels. One SQUID channel has a sinusoidal input flux (diamonds), one has a triangle-wave input flux (squares), and the rest have no applied flux (no points). Only the two channels with applied signal show substantial response, except for a $\sim 2\%$ crosstalk to the subsequent channels.

Optical Performance

Optical performance was measured in a test setup designed to calibrate low-background detectors for SPIRE[14]. This setup used a helium-cooled blackbody consisting of a textured, black, carbon-loaded epoxy (Epotek 920) wall in a gold-coated cavity. Selectable apertures allow the throughput to the blackbody to be chosen. The blackbody can be heated to cover temperatures between 2K and 40K. A metal-mesh bandpass filter at 350μm wavelength (850 GHz) with a fractional bandpass of $\sim$1/10 reduced the total transmitted power to be within the range of our bolometers, which were designed to saturate (i.e., be driven normal) at 5 pW. The result of the blackbody calibration is shown in Figure 4, where the measured power has been corrected for a narrowband bolometer absorptivity of 90%. The measured response follows the theoretical power very well up to a saturation power of $\sim$2 pW.

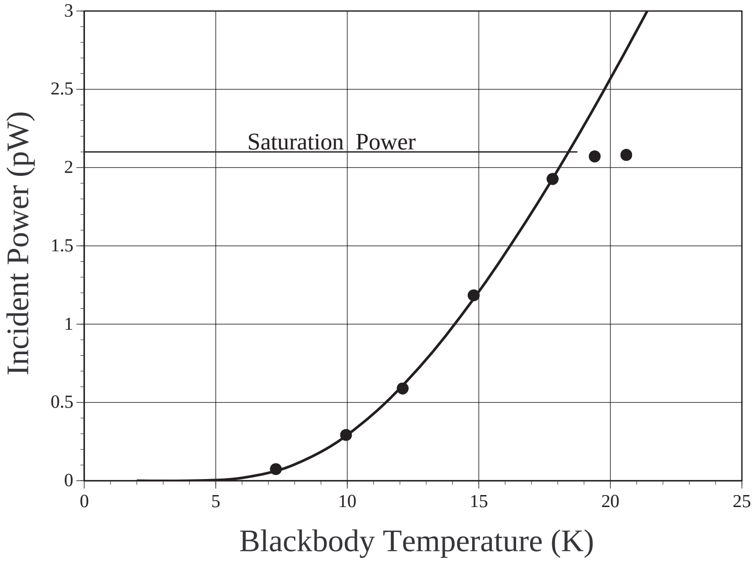

Fig. 4.— Photometry of a single TES bolometer exposed to blackbody radiation at 350μm, corrected for 90% absorption efficiency.

In addition to calibration with the blackbody, the test setup permits an external source to be used. In order to reduce the optical load to an acceptable level, a 1% transmissive neutral density filter is placed in the beam. The time constant was measured by using a rapidly chopping blade with a hot/warm load. An upper limit of $\tau \leq$2ms was found, limited by the speed of the chopper. A Fourier transform spectrometer was used to measure the frequency response, which was limited by the bandpass filter.

No bandwidth degradation due to inefficiencies in the absorbing coating were seen. Also, a beam map was made, and excellent rejection of out-of-beam power was found.

During the chopping measurements, a set of 8 bolometers were read out with a frame rate of 10kHz, providing a demonstration of multiplexed readout of an infrared signal. The detection of the chopped signal in multiplexed bolometers is shown in Figure 5. A 300K/77K source was modulated at $\sim$ 2Hz in the beam from all detectors simultaneously. The optical signal for each detector was fed back using the digital feedback loop to maintain each SQUID at a constant total flux. After demultiplexing, it is apparent that the signal levels are maintained with high fidelity.

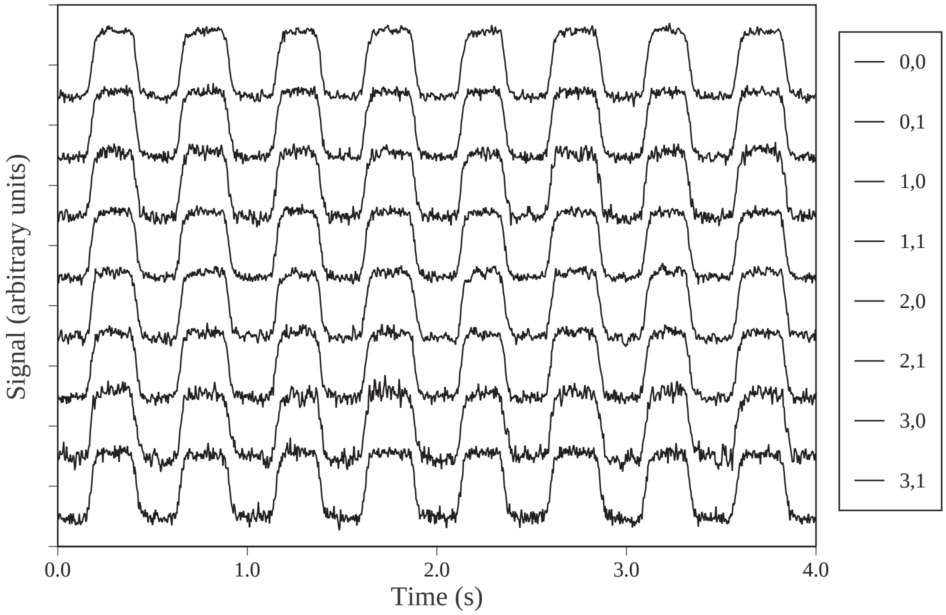

Fig. 5.— Demultiplexed signal from a chopped hot/cold load seen by 8 detectors simultaneously. The relative amplitudes are uncertain at a $\sim$30% level.

Conclusions

We have demonstrated superconducting transitions in molybdenum/gold and molybdenum/copper bilayers, which look promising for use as TES films on sensitive bolometers. Excellent linearity and fast response are seen, and optical efficiency of 90% has been achieved. A multiplexed SQUID amplifier has been fabricated and is shown to provide low-noise, high-fidelity readout of several TES detectors with a single signal output. This architecture can be extended to two-dimensional arrays with modest increase in the total number of wires. We believe that a large-format (thousands of detectors) bolometer array can be made with this technology, having application in future far-infrared instruments.

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