A Time-Domain SQUID Multiplexer System for Read-Out of Superconducting Transition-Edge-Sensor Arrays*

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***Abstract*— The development of time-domain SQUID multiplexers enables the integration of superconducting transition-edge sensors (TES) into arrays with thousands of elements while maintaining a manageable number of readout channels. The applications for detector arrays range from high-count-rate x-ray microanalysis systems to focal-plane arrays for imaging at wavelengths from the submillimeter to gamma ray. We present results from recent measurements of a two-dimensional TES array. The measurements focus on the heat-pulse response of a TES measured with multiplexed read-out and show no degradation of energy resolution with eight detectors multiplexed. We describe the system architecture, including the cryogenic SQUID amplifier chain, the analog interface electronics, and the digital feedback electronics.**

I. Introduction

The development of detectors based on superconducting transition-edge sensors has led to a variety of innovative approaches for the detection of photons in the wavelength range of millimeter-wave through γ-ray. The low noise, low power, and low impedance of superconducting quantum-interference devices (SQUIDs) make them ideal amplifiers for first-stage signal conditioning. Independent SQUID-coupled TES elements are adequate for the readout of small numbers of detectors. However, the readout of large-scale, two-dimensional arrays of cryogenic detectors presents several challenges. Both wire count and power dissipation scale with pixel count in a non-multiplexed, conventional layout. Multiplexing can be used to reduce these and other problems associated with scaling.

Applications for this technology range from materials analysis[1] to astronomical imaging [2], [3]. The FIBRE instrument, a Fabry-Pérot interferometer operating in wavelength bands centered at 350 μm and 450 μm and using an array of eight SQUID-multiplexed TESs, has been demonstrated in an astronomical application [4].

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II. System Description

A system block diagram has been included as Fig. 1. A detailed description of the system architecture and design can be found in reference [5]. An array of superconducting transition-edge sensors is coupled directly to an integrated SQUID multiplexer circuit (SMUX) developed at NIST [6], [7]. These components are mounted on a platform cooled to ≤100 mK. Low-inductance wiring connects the SQUID multiplexers to SQUID series array (SA) amplifiers [8] at 4 K. The millivolt-level SA signals are carried to room temperature on Cu-Ni flexible transmission lines of low thermal conductivity. The lines pass through the cryostat wall into a shielded enclosure, where they terminate on a variety of analog interface electronic cards. These cards provide SA signal amplification, biases for configuring the amplifier chain operating point, and signal pass-through for multiplexed address and feedback signals. The analog interface electronics connect to the digital feedback electronics via coaxial cables.

The digital electronics are composed of three varieties of circuit boards that are rack mounted in a 3U crate. A clock (CLK) card provides the master clock and line clock for system synchronization. These clocks are distributed electrically on the backplane of the crate for the other resident system cards. The clocks are also sent optically over fibers to the system controller (host PC). The master clock frequency is 50 MHz. The line clock is programmable and has a maximum frequency of 1.56 MHz.

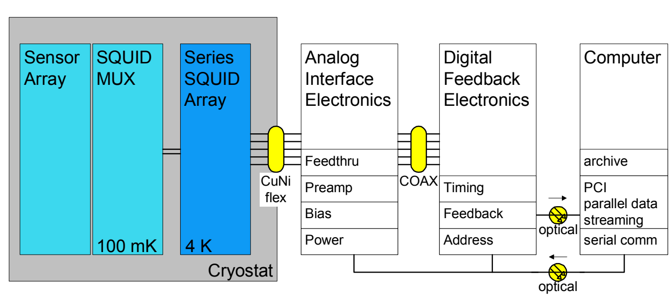

Fig. 1 - System block diagram.

The heart of the system is the digital feedback (DFB) card. This card has a 12-bit analog-to-digital converter (ADC) for sampling the SA voltage signal, a field-programmable gate array (FPGA) for determining the error signal and computing the feedback signal in a multiplexed mode, and a 14-bit digital-to-analog converter (DAC) for driving the feedback to the first stage SQUIDs of the SMUX.

For multiplexing, row-address drivers must operate in sync with the DFB cards to turn on the appropriate first-stage SMUX SQUIDs. A DFB card that has been programmed to function as an address driver (designated ADDR card), using the DAC to drive a row of first stage SQUIDs, handles this task.

For two-dimensional multiplexing, the system is configured such that each column of detectors is read out by a single series array. A dedicated DFB card monitors each series array. Each row of the array is bias-driven by a single ADDR card. So, for example, an 8x8 array can be fully instrumented with a single crate of electronics comprised of a CLK card, eight DFB cards, and eight ADDR cards.

Each DFB card has a fiber-optic link to the host PC for data transfer. These fibers terminate at optical receivers on a 16-channel PCI card developed specifically for this system. Data streaming is regulated by the master clock (50 Mbit/s). A 14-bit feedback signal, 16-bit error signal, and 2 housekeeping bits are streamed for each line-sampling event for each column of the array.

III. Experimental Results & Discussion

For the experimental results presented in Fig. 2, a 2 x 4 subsection of an 8 x 8 detector array was connected in a one-dimensional array configuration to a 1 x 32 SMUX circuit. All eight TES's were biased in their transition. Eight address-line drivers were used to sequentially bias the eight first-stage SQUIDS of the SMUX wired to the pixels (the remaining 24 first stage SQUIDs were not connected for this experiment).

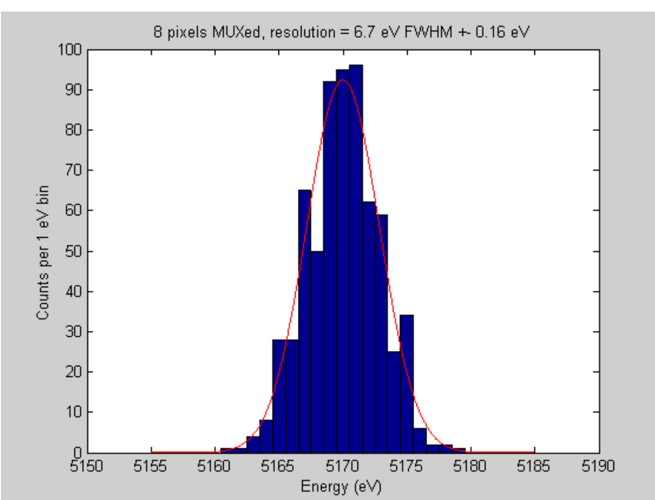

Fig. 2 – A histogram of single-pixel heat-pulse energy. The data were acquired with eight pixels multiplexed. A FWHM energy resolution of 6.70 +/- 0.16 eV results from a Gaussian fit to the data.

Multiplexed digital feedback was used to keep all eight channels locked and the feedback and error signals were streamed to disk.

Under these conditions, calibrated 5.17 keV pulses of Joule heat were injected into one of the pixels. The data stream from the digital feedback for this pixel was then analyzed for the pulse response.

Fig. 2 is a histogram of the measured energy of the pulses. The figure shows a full-width half-maximum (FWHM) energy resolution of 6.70 ±0.16 eV while multiplexing eight pixels. The results for multiplexing two and four pixels are nearly identical: FWHM 6.40 ±0.16 eV, and 6.70 ±0.16 eV, respectively. No appreciable degradation in energy resolution is observed as a result of the multiplexing. This is despite no correction for arrival time in the pulse analysis algorithm and no efforts to synchronize the heat-pulse train with the digital sampling.

IV. Conclusion

We have demonstrated a complete system for the readout of superconducting transition-edge sensor arrays. Results of the measurement of the energy of heat pulses applied directly to a single detector pixel show no degradation of energy resolution for a multiplexing factor of up to eight.

Refinements to the system currently underway include the implementation of a multi-channel address-line driver and a rack power-conditioning card. Our goal upon completion of these electronic development tasks is to be able to accommodate arrays of up to 8 columns by 40 rows with a single crate of read-out electronics.

Experiments on multiplexed 2-D detector arrays illuminated with a Fe55 x-ray source are in progress.

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