Time-Division SQUID Multiplexers

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Abstract. We describe the present state of the art of time-domain SQUID multiplexers to read out large arrays of superconducting transition-edge sensor (TES) bolometers. Time-division SQUID multiplexers are used in a large range of millimeter- and submillimeter-wavelength astronomical instruments, including ACT, SPIDER, BICEP-2, SPUD, Clover, and SCUBA-2. They are also being developed for use in the Constellation-X X-ray observatory. We describe the advantages and disadvantages of time-division multiplexers, and consider the technological readiness level for a CMB polarimetry satellite mission. We describe both the cryogenic components and the present-generation warm readout electronics.

1. Introduction

The superconducting transition-edge sensor (TES) is a leading bolometer technology for a CMB Polarimeter satellite mission (CMBPol). The low noise, low power dissipation, and low impedance of Superconducting Quantum Interference Devices (SQUIDs) make them the preamplifier of choice for TES bolometers. More than a thousand bolometer elements are likely to be required for CMBPol. For arrays this size, constraints on complexity and heat load make it difficult to route separate leads from the bolometer to the warm readout electronics. It is thus necessary to multiplex the signal from many bolometers at the cold stage into a smaller number of output channels.

In time-division multiplexing (TDM), many SQUID-coupled TES bolometers are read out in a single set of wires by turning the SQUIDs on sequentially (Fig. 1a). With proper design, the multiplexed SQUID amplifiers do not appreciably contribute to the system noise. SQUID TDM is a mature technology that is being deployed in a large number of astronomical instruments with multiplexing factors up to 40:1. It is being used in arrays with sizes greater than that required for CMBPol.

Time-division multiplexed (TDM) SQUID amplifiers systems have been developed for TES bolometers by NIST, NASA/Goddard Space Flight Center, and the University of British Columbia (UBC). The first multiplexed TES bolometer instrument tested on a telescope was the TDM FIBRE instrument in 2001[1]. There are now a number of TDM instruments for Cosmic Microwave Background (CMB) measurements deployed in the field and in various stages of development. The Atacama Cosmology Telescope[2] (ACT), in particular, has acquired a season of data in 2007 with 900 functioning pixels in one 32×32 array, and has recently begun the 2008 observing season with three 32×32 arrays. Other instruments for CMB measurements include the SPIDER balloon-borne CMB polarimeter[3], BICEP-2[4], SPUD[4], and Clover[5]. The Constellation-X X-ray Microcalorimeter Spectrometer (XMS) uses similar TDM SQUID multiplexers. A full complement of SQUID multiplexers has also been tested for the SCUBA-2 submillimeter camera[6], which has 10,240 pixels.

The warm readout electronics for TDM has gone through multiple generations of development at NASA/GSFC, NIST, and the University of British Columbia. The present generation of control electronics is the Multi-Channel Electronics[7,8] (MCE) developed at the UBC (Fig. 1b). Each MCE module controls up to 1,280 TES pixels (the 10,240 pixels in SCUBA-2 are controlled by 8 MCE modules). The MCE sets the detector biases, controls the SQUID multiplexer stages, and reads out the signal from one array of up to 41 × 32 pixels in 32 output channels. The MCE provides automatic optimization of operating points for the bolometers and SQUID amplifiers, and implements a digital Proportional Integral Differential (PID) servo loop to apply feedback to the switched first-stage SQUIDs to keep them in a linear regime at optimal gain. The MCE, originally developed for SCUBA-2, is also in use in ACT, SPIDER, BICEP-2, SPUD, and Clover.

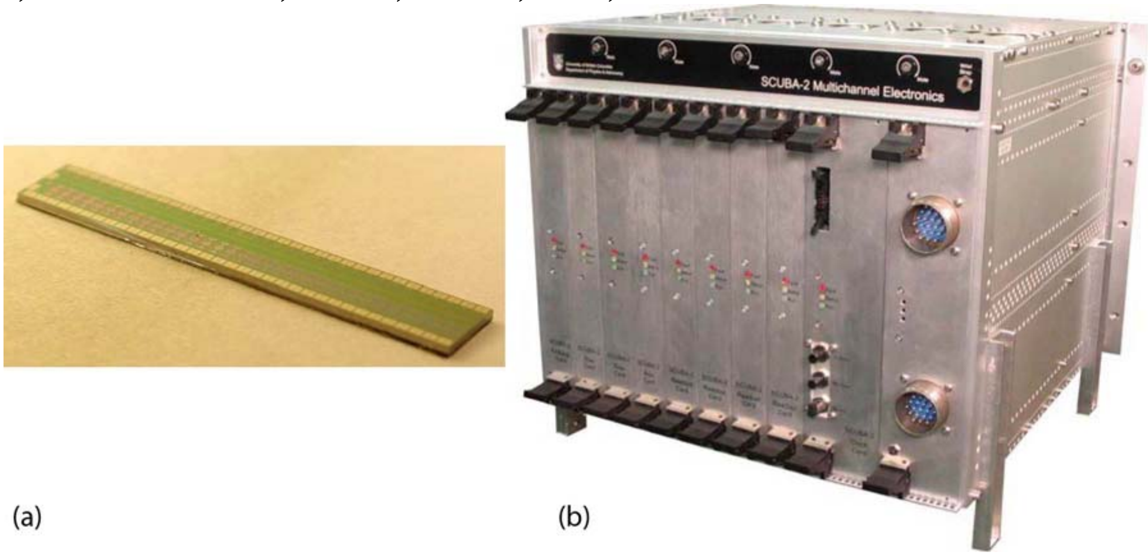

Fig. 1. (a) A 32-channel SQUID multiplexer chip. The chip dimension is 3 mm × 20 mm. The 32 SQUIDs are turned on sequentially and read out in one output channel. (b) A Multi-Channel Electronics (MCE) module fabricated by the University of British Columbia. This module can instrument up to 32 output channels, and read out up to 1,280 TES bolometer channels.

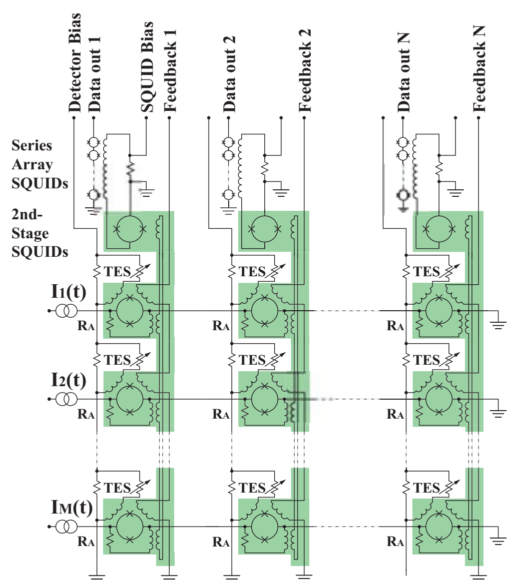

Fig. 2. Circuit diagram for time-division SQUID multiplexer with M × N pixels. The first-stage SQUIDs in each column are coupled through a common transformer to the second stage. A single common feedback line is used to linearize all of the first-stage SQUIDs in each column.

2. Technology Overview

When a superconducting transition-edge sensor is biased at a constant voltage, the current through the device drops when optical power is absorbed. In TDM, each TES is instrumented by a separate first-stage SQUID that measures this current drop. The bandwidth of the TES is limited by a one-pole low-pass L/R filter formed by the inductance of the SQUID's input coil (and possibly an extra inductor) and the resistance of the TES. A two-dimensional (M rows × N columns) array of pixels is read out by sequentially turning on the first-stage SQUIDs in every column, one row at a time (Fig. 2). The row of SQUIDs is turned on by a set of M row-select currents ($I_1 \ldots I_M$) from 0-1V, 14-bit video DACs in the address-card (AC) in the MCE. The AC firmware controls up to 41 DACs with user-specifiable order, rate, and voltage settings. The typical 'on' time in each row is about 1 μs. Thus, in an array with a 41:1 multiplexing factor, every pixel in the array is revisited with a frequency of about 20 kHz (the 'frame rate'), well above the signal frequency in the bolometers.

A ~1 ohm address resistor, R_A, shunts each first-stage SQUID. The current through the address resistor is inductively coupled to a second-stage SQUID shared by all the first-stage SQUIDs in a column. The coupling to the second stage occurs through a transformer coil that is common to all of the first-stage SQUIDs. A feedback flux is provided to the switched first-stage SQUIDs to linearize them. Since only one SQUID in each column is on at a time, one feedback coil can be common to all first-stage SQUIDs in the column (Fig. 2). The feedback current is provided by a PID feedback servo loop implemented in firmware in the MCE. The feedback signal in the SQUIDs, which compensates for changes in current through the TES bolometers, constitutes a measurement of the optical input power to each TES.

The output from each column of SQUIDs is amplified by a series array of SQUIDs (Fig. 2) that can be located at either the base temperature or at 4 K, and then by a preamplifier followed by a 14-bit, 50 MHz video ADC in a readout card (RC) of the MCE. The PID loop is also implemented in the RC. Each RC couples to eight columns and handles independent feedback loops for up to 8 × 41 TES pixels; each MCE can accommodate 4 RCs. The PID output is based on the reading from the previous visit to a given row. It is applied to the first-stage SQUID feedback lines using a 14-bit video DAC with 0-1 V range. Since the frame rate of 20 kHz far exceeds the detector bandwidth, a 4-pole Butterworth IIR low pass filter with a cutoff consistent with the detector thermal time constant is implemented in RC firmware after the signals have been demultiplexed. To aid in diagnosing new arrays, the MCE can output unfiltered data at the frame rate of approximately 20 kHz or for short bursts at the ADC rate of 50 MHz.

A combination of software and firmware commands has been developed for the MCE that autonomously characterizes a 1280 pixel array and chooses optimized biases and feedback currents for the full array (about 2100 free parameters) in a few minutes.

A clock card (CC) in each 1,280-pixel MCE module communicates with the computer through a dual fiber-optic link. It also dispatches incoming control commands through the backplane to the appropriate cards and generates the master clock for the modules. The data-acquisition computer sends commands to the MCE through its fiber-optic link and receives data packages. An external controller with a 25 MHz clock synchronizes the data acquisition of multiple MCEs. It also provides numeric tags that are written to each data frame for data synchronization during analysis.

The power dissipation of an MCE module used to control a 1,280-pixel array is presently about 175 W. Approximately 40% of this power budget is used to run the video analogue-to-digital converter (ADC) in each column. New boards are in production in which these have been replaced with 50 Mhz serial video ADCs that consume15 times less power.

3. Benefits and Challenges

A. Benefits

Warm electronics: maturity, power dissipation, and path towards flight qualification

The warm electronics for SQUID TDM are relatively simple and mature. The MCE uses commercial components (DACs, ADCs, and FPGAs) that have been readily available for some time. While a large investment was required at UBC to develop the MCE, this was due to the complexity of the firmware, not because of challenges in the performance of individual components. The power dissipation of the MCE (about 175 W for 1,280 pixels) is also quite low and work is under way to reduce it further.

The MCE operates at 20 kHz frame rates that are extremely fast compared to the bolometer thermal response times. In a fully optimized system for CMBPol, it would be possible to operate the warm electronics an order of magnitude slower. This would reduce the power dissipation, and also make it possible to use legacy electronic components that have already been flight qualified. As part of the Constellation-X satellite program, there is already an effort to explore a system that can be flight qualified. However, unlike CMBPol, Constellation-X requires high frame rates, so it does not have the potential of using legacy components.

The MCE have been tested for cosmic ray induced upsets by exposing them to a neutron flux corresponding to a 30-day stratospheric balloon flight. The electronics showed no loss of function during the test.

Wiring length

SQUID TDM has a significant engineering budget for wiring length. This is because the delay time of the propagating feedback signal can be longer than the row switching time, since the PID algorithm is implemented based on information from the previous frame. Thus, the wiring between the cold stage and the warm electronics can be several meters long.

Demonstrated Multiplexing Factor

TES instruments multiplexed with SQUID TDM have been demonstrated to operate with a 40:1 multiplexing factor, with no appreciable degradation to the bolometer performance from aliased detector noise, amplifier noise, or switching transients. The theoretical limit on the number of channels that can be multiplexed in each column is set by bandwidth per pixel, available bandwidth, and by aliasing of SQUID noise. Present implementations are very far from these theoretical limits. However, unlike superconducting microresonators, practical constraints on geometry are likely to limit the multiplexing factor to somewhere near 100:1, so TDM technology will not in the long term be as scalable as GHz microresonators.

Low-frequency noise

SQUID TDM systems tend to be robust against low-frequency noise from SQUIDs and amplifiers. Because SQUID noise (but not bolometer noise) is degraded by aliasing during sampling, the TES bolometers are significantly overcoupled to the SQUIDs to prevent loss in bolometer performance. Thus, even though the amplifier / SQUID low-frequency knee is typically above 10 Hz, the bolometer noise is typically above the amplifier / SQUID noise down to very low frequencies (tens of millihertz).

Compact filter elements

The filter elements in analog cryogenic multiplexers can be the physically largest part of the cryogenic multiplexer circuits. However, SQUID TDM has very compact filter elements. In SQUID TDM, the bandwidth is limited by a one-pole filter formed by the SQUID inductor and the resistance of the TES. Since a TES bolometer used for TDM can be biased at a very low resistance (e.g. 2 mΩ), a bandwidth of 5 kHz can be achieved by a lithographically fabricated 60 nH inductor, which can fit in an area of less than 0.1 mm^2.

In MHz FDM, the bandwidth is limited by an LC resonant filter, which requires physically larger filter components. If the bandwidth is limited to 5 kHz, a simultaneous optimization of the L and C elements drives the TES bias resistance to about 0.5 Ω. Then, a 16 μH inductor and 1.6 nF capacitor are required for a 1 MHz resonance with 5 kHz bandwidth. The inductor is typically lithographically fabricated with an area of about 2 mm^2. The capacitor is often a component soldered onto a circuit board.

The high operational frequency of GHz superconducting microresonators makes it possible for them to use compact resonant filter elements. The frequency band is defined by quarter-wave coplanar waveguide stubs that are typically 5-10 mm long, and meandered into a fairly compact configuration.

<u>In-focal-plane multiplexing</u>

Because the cryogenic filter elements for SQUID TDM are very compact, and the SQUIDs have very low power dissipation, it is possible to integrate them into the focal plane (as is done in SCUBA-2). This is even more straightforward in superconducting microresonators, since they operate at GHz frequencies with relatively small filter elements. In contrast, it would be difficult to integrate the large filter elements into the focal plane for SQUID FDM: leads are usually routed out of the focal plane from every pixel to the filter elements.

B. Challenges

<u>SQUID fabrication</u>

In a TDM SQUID multiplexer circuit, a SQUID must be fabricated and tested for each TES pixel. (In contrast, MHz FDM SQUID multiplexers use only one SQUID series array per multiplexed set of pixels). However, many TDM SQUID channels are integrated onto each chip, and the fabrication challenge for TDM SQUID multiplexers for CMBPol is manageable. There is now a mature process at NIST that can fabricate and test sufficient TDM SQUID multiplexer chips for CMBPol.

<u>Power dissipation on the sub-K stage</u>

In TDM SQUID multiplexers, the SQUID amplifiers dissipate power at the base temperature. In contrast, the SQUIDs in MHz FDM SQUID multiplexers are located at a higher temperature stage. GHz Superconducting microresonator multiplexers (both MKIDs and microwave SQUID multiplexers) dissipate negligible power at the base temperature.

In the present generation of TDM SQUID multiplexers, a power budget of about 10 nW is allocated for each multiplexed column of up to 40 SQUIDs. In the case that this power dissipation is too high, SQUIDs with much lower power dissipation have already been demonstrated in TDM SQUID multiplexer chips, which would drop the power budget to about 1 nW per multiplexed column, or about 30 nW per kilopixel.

<u>Achievable Multiplexing Factor</u>

While a large multiplexing factor is used with TDM SQUID multiplexers (40:1), and while the fundamental limit on TDM SQUID multiplexers can be higher than 1000:1, practical constraints are likely to limit the multiplexing factor to about 100:1. A 12:1 multiplexing factor has been demonstrated with MHz FDM, but this is expected to increase significantly in the future. Because of the multi-GHz available bandwidth and resonator quality factor, GHz superconducting microresonator multiplexers can potentially be scaled to much higher multiplexing factors than either MHz multiplexing technology.

4. Technical Readiness and Needed Investment

TDM SQUID multiplexers and the MCE electronics are now at Technology Readiness Level 5, having been demonstrated in a relevant environment at the kilopixel scale (e.g. ACT / SCUBA-2). TDM SQUID multiplexers have attractive advantages, and their performance in most ways is already at the level that would be required for a CMBPol satellite mission. However, investment is still needed in several areas:

Power dissipation

Power dissipation at the cold stage (including engineering margin) is presently 10 nW per multiplexed column. This power budget can readily be reduced by a factor of 10, if required. Single channels with lower power designs have been demonstrated on TDM chips. If a design study indicates the lower power is required, a full demonstration should be prioritized.

Yield

Multiplexer pixel yields of greater than 90% can be routinely achieved. The Atacama Cosmology Telescope was populated with 96 TDM 32-channel chips, most of which had a 100% yield. Furthermore, over 10,000 TDM pixels have screened for SCUBA-2. A flight instrument would be required to start with 100% yield on all of the multiplexer chips. Some investment in improving the yield of the process would improve the rate at which perfect chips could be produced.

SQUID flight qualification

SQUIDs have already been flight qualified for the Gravity-Probe B experiment. Radiation hardness test should also be conducted on TDM SQUID chips.

Systematic error requirements and magnetic shielding

The systematic error specifications for a CMBPol mission are extremely stringent. A full systematic error budget needs to be developed. The characteristics of the multiplexers are an important part of this study. One key issue that must be considered is the sensitivity of the SQUID multiplexers to scan-synchronous magnetic fields from the instrument. The present generation of TDM SQUIDs are gradiometric, and thus insensitive to first order to uniform fields and field gradients. However, magnetic shielding is still required. Systematic error concerns are likely to place the strongest constraint on the characteristics of the required magnetic shielding, including its weight.

Warm electronics development

The present warm electronics are based on FPGAs. Although the particular FPGAs used in the MCE have been demonstrated to be sufficiently robust for ground-based and balloon operations, they are not space qualified. Non-FPGA designs can be made for three of the MCE cards, but radiation-robust solutions based either on older, previously space qualified FPGAs or newly qualified parts must be found for the RC and CC functions.

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