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Multiplexed Readout of CMB Polarimeters

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Abstract. This paper describes contributions to the workshop, "Technology Development for a CMB Probe of Inflation," held at NIST in Boulder CO, Aug. 25-28, 2008 concerning technologies to read out direct detectors (including bolometers and microwave kinetic inductance detectors) in a CMBPol satellite mission. The large number of polarimeters required for a satellite mission will likely make it necessary to multiplex the output signals into a small number of readout channels at the cold state. We describe both the cryogenic components and the present-generation warm readout electronics, consider the benefits and challenges of each option, and analyze their technology readiness level and needed additional investments.

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1. Introduction

The first technology recommendation of the report of the Task Force for Cosmic Microwave Background Research was "technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors." The recommendation also identified that "It is important to keep open a variety of approaches until a clear technological winner has emerged. Nevertheless, highest priority needs to be given to the development of bolometer-based polarization sensitive receivers." For arrays of a thousand or more bolometer-based polarization-sensitive receivers, constraints on complexity and heat load make it difficult to route separate leads from each bolometer to the warm readout electronics. It is necessary to multiplex the signal from many bolometers at the cold stage into a smaller number of output channels. One of the challenges in fielding a thousand or more bolometer-based polarization sensitive receivers is the development of appropriate readout technology.

In this paper, we present an analysis of the state of the art of three leading multiplexed readout technologies for polarization-sensitive bolometers: time-division multiplexing (TDM), MHz frequency-division multiplexing (FDM), and GHz frequency-division multiplexing with superconducting microresonators. All three techniques can be used to read out superconducting transition-edge sensor (TES) bolometers [1], and the third can be also used with microwave kinetic inductance detectors (MKIDs) [2]. In each case we present a technology overview, an analysis of benefits and challenges, and a discussion of technology readiness level (TRL) and needed investment.

2. Time-Division SQUID Multiplexers

Principal section authors: Kent D. Irwin and Mark Halpern

The superconducting transition-edge sensor is a leading bolometer technology for a CMBPol satellite mission. The low noise, low power dissipation, and low impedance of Superconducting Quantum Interference Devices (SQUIDs) make them the preamplifier of choice for TES bolometers.

In time-division multiplexing (TDM), many SQUID-coupled TES bolometers are read out through 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 many 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[3]. 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 [4] (ACT), in particular, has acquired a season of data in 2007 with 900 functioning pixels in one 32 × 32 array, and is observing in 2008 with three 32 × 32 arrays. Other instruments for CMB measurements include the SPIDER balloon-borne CMB polarimeter [5], BICEP-2 [6], the Keck Array [6], and Clover [7]. The X-ray calorimeters that are being developed by NASA for the International X-Ray Observatory (IXO) use similar TDM SQUID multiplexers. A full complement of SQUID multiplexers has also been tested for the SCUBA-2 submillimeter camera [8], 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 [9][10] (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 through 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, the Keck Array, and Clover.

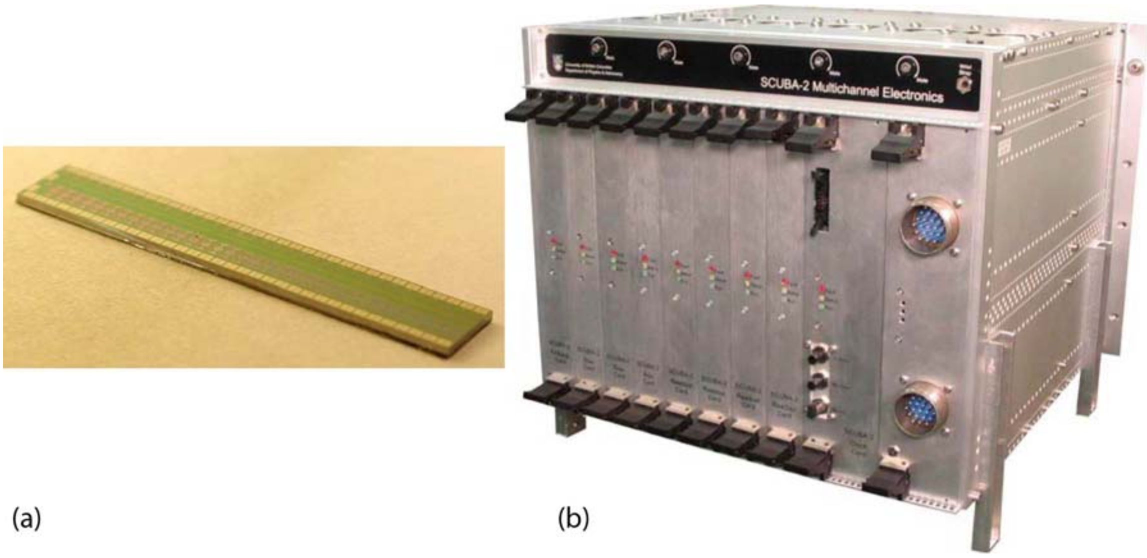

Fig. 1. (a) A 32-channel SQUID multiplexer chip. The chip dimension is 3 mm × 20 mm. The 32 SQUIDs are turned on sequentially and read out through one output channel. (b) A Multi-Channel Electronics (MCE) module fabricated by the University of British Columbia. This module can instrument up to 32 output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

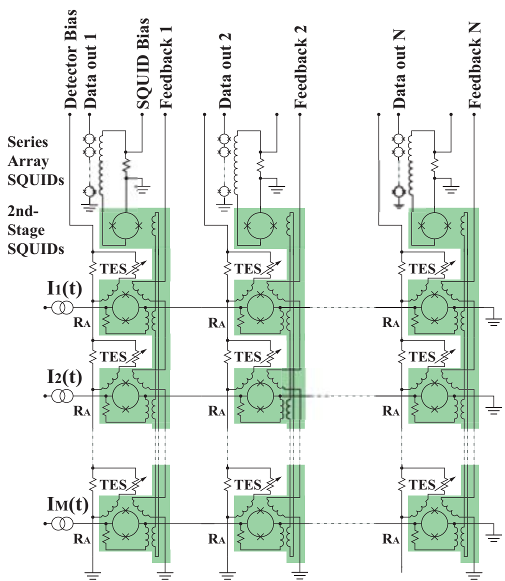

Fig. 2. Circuit diagram for time-division SQUID multiplexer with M × N pixels. The first-stage SQUIDs in each column are coupled through a common transformer to the second stage. A single common feedback line is used to linearize all of the first-stage SQUIDs in each column.

Journal of Physics: Conference Series **155** (2009) 012004 doi:10.1088/1742-6596/155/1/012004

2.1. SQUID TDM: 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'), which is 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 consume 15 times less power.

2.2. SQUID TDM: 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 IXO satellite program, there is already an effort to explore a system that can be flight qualified. However, unlike CMBPol, IXO 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, when properly optimized, 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.

Journal of Physics: Conference Series **155** (2009) 012004 doi:10.1088/1742-6596/155/1/012004

2.3. SQUID TDM: Technology Readiness and Needed Investment

TDM SQUID multiplexers and the MCE electronics are now at Technology Readiness Level (TRL) in the high 4s, having been demonstrated in a relevant environment at the kilopixel scale (e.g. ACT / SCUBA-2). It remains to demonstrate TDM SQUID multiplexers in a relevant environment simulating a satellite to achieve TRL 5. 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 been 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 tests 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.

3. MHz Frequency Domain SQUID Multiplexers

Principal section authors: Matt Dobbs and Adrian Lee

A key technology for deploying large format Transition Edge Sensor (TES) bolometer arrays on satellite platforms is SQUID-based multiplexed readout systems. The Frequency domain multiplexed readout (fMUX) was developed for mm-wavelength observations using large arrays of TES bolometers by LBNL, U.C. Berkeley, and McGill. The system, with its original “analog” backend electronics [11][12][13], targeted ground based telescopes and is deployed on the APEX-SZ instrument [14] and the South Pole Telescope (SPT) [15]. These instruments have achieved unprecedented on-sky noise performance. The analog backend draws too much power for balloon or

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satellite applications. In the course of the analog system's development, fast ADCs and FPGAs with substantially increased gate-count and reduced power consumption became available. This allowed for the development of a new digital backend [16] for the fMUX system that dissipates an order of magnitude less power, making it amenable for stratospheric balloon payloads. This Digital fMUX (DfMUX) system is being deployed for the EBEX balloon-borne CMB polarimeter [17] and the ground-based POLARBEAR [18] instrument. The DfMUX also provides a path to further substantial power reductions by grouping many more bolometers together in a multiplexer module. With the digital fMUX system, the power consumption is roughly proportional to the number of multiplexer modules and not to the number of bolometer pixels.

The frequency-domain multiplexer reads out many TES bolometers on a single set of wires without appreciably contributing to the system noise. The detectors are low impedance (≈½ Ω) devices cooled to sub-Kelvin temperature. The sky signals are modulated in the bandwidth 0.05-100 Hz by the motion of the telescope or optics. The low-frequency noise specification places strict requirements on all aspects of the system and distinguishes the firmware and digital algorithms employed in this system from other modulation/demodulation applications such as software-defined radio. The electronics system also tunes the detectors to the optimum bias point by adjusting their voltage bias and tunes the SQUID pre-amplifiers using bias currents to obtain the best noise performance and dynamic range.

Advantages of the DfMUX system include: (1) bolometer signals are modulated above microphonic and low frequency noise, (2) there is no fundamental limit on the number of detectors that can be multiplexed in a module, other than available bandwidth, (3) no heat dissipation on the sub-Kelvin stage, (4) the system is highly modular, and (5) individual bolometer biases and the detector readout bandwidth can be software configured.

The fMUX system is complementary to the time domain multiplexed system [19], [20] developed at NIST and UBC. Recently the NIST group began work on a system that frequency-multiplexes SQUIDs (rather than bolometers) at microwave frequencies [21][22]. The DfMUX electronics described here is a lower frequency version of what is needed for the backend of this future RF-SQUID multiplexing system.

3.1. MHz FDM: Technology Overview

A. System Description

The frequency domain multiplexer (DfMUX) is shown schematically in Fig. 3. For the EBEX system, the bolometer sensors R_{bolo} are biased with sinusoidal voltages in the frequency range from 300 kHz to 1 MHz. Each bolometer is biased at a different frequency. Intensity variations from the sky-signal change the bolometer resistance and amplitude modulate the bolometer current such that the sky-signal from each bolometer is transferred to a sideband adjacent to its carrier. Thus, the signals from different bolometers within a module are uniquely positioned in frequency space, so they can be summed and connected through a single wire to a SQUID preamplifier operating at 4K. Each bolometer is connected through a series resonant LC circuit[*] that defines the bias frequency. This allows the bias frequencies for all bolometers in a module to be applied through a single wire, as the tuned circuit selects the appropriate frequency for each bolometer. Only two wires are needed to connect the bolometers of a readout module on the sub-Kelvin stage to the 4K stage on which the SQUIDs are mounted. The tuned circuits also limit the bandwidth of the bolometer Johnson noise, which would otherwise contribute to the noise in all other channels of the module. Refer to [13] for a detailed description of the readout system's cold circuits.

[*] The first generation superconducting inductors for this system were fabricated at TRW which has closed its superconducting fab facility. The present generation is being fabricated at NIST. The capacitors are off-the-shelf ceramic chip devices.

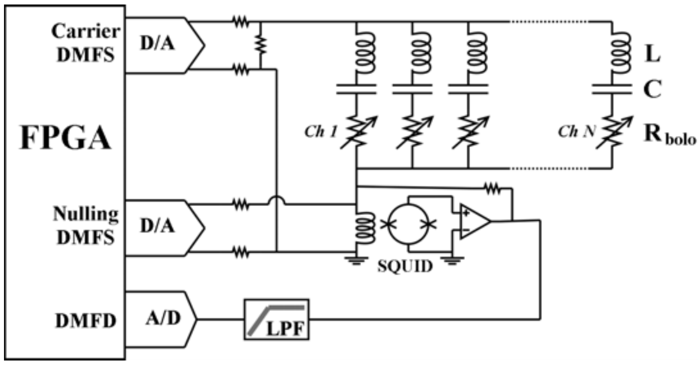

Fig. 3: The digital frequency domain multiplexer system is shown schematically.

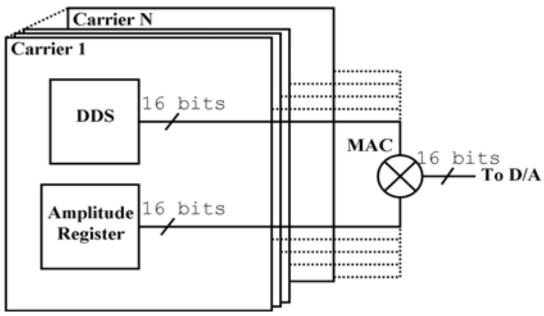

Fig. 4: The Digital Multi-Frequency Synthesizer algorithm is shown schematically.

The comb of bias carriers is synthesized with a *Digital Multi-Frequency Synthesizer* (DMFS). It produces a comb of sine waves using an algorithm implemented in firmware. It converts the signal to analog using a 16-bit D/A operating at 25 MHz. The DMFS firmware is shown schematically in Fig. 4. Each sinusoidal carrier is synthesized using a Direct Digital Synthesizer algorithm [23]. A ‘comb’ of carriers is created by multiply-and-accumulating the DDS outputs with an amplitude control register for each sine wave. The comb is sent to the cryostat as a differential signal on a shielded twisted pair cable.

The sky-modulated signals from the bolometers are pre-amplified with a SQUID as it has the necessary noise temperature and has low input impedance. To maintain constant voltage bias across the TES, the input resistance of the SQUID must be small compared with the TES resistance. This is achieved by operating the SQUID with shunt feedback from the output of the room-temperature amplifier that follows. The feedback amplifier has a high gain × bandwidth product, so connections between the SQUID and the room temperature electronics must be short. Negative feedback also linearizes the SQUID response, reducing intermodulation between the bias carriers.

Since the carrier amplitudes are orders of magnitude larger than the sky signals, we cancel the carriers at the SQUID input with a second comb (synthesized with a second DMFS), referred to as the nulling signal. The nulling comb is an inverted version of the original carrier comb, and serves to remove the large carrier signals. It does not affect the carrier sidebands, which contain the information of the sky-signals. The use of the nulling signal dramatically reduces the dynamic range requirements of the system. Nulling factors of 10^3 are routinely achieved.

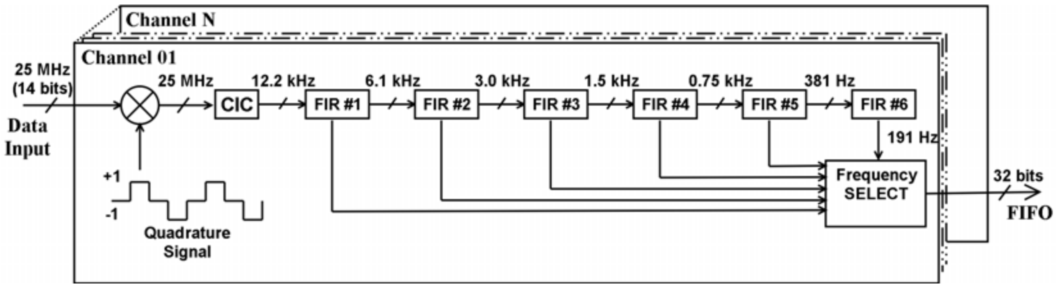

Fig. 5: The Digital Multi-Frequency Demodulator algorithm is shown schematically.

The SQUID amplifiers are 100-element series-array devices [24] manufactured by NIST in Colorado. Each SQUID device is operated in shunt-feedback with a low-noise bipolar transistor op-amp located on a custom room temperature SQUID controller circuit board. These boards also include digital control electronics and DACs to provide the bias currents and tuning functionality.

After amplification, the comb of sky-signal-modulated carriers output by the SQUID controller is transmitted to the Digital Multi-Frequency Demodulator (DMFD) on a twisted pair cable. The comb is digitized with a 14-bit A/D converter operating at 25 MHz. The over-sampling improves the resolution beyond 14 bits. Since the sky-signals occupy only a small fraction of the waveform's total bandwidth, it is not feasible to store the entire waveform on disk. The signals are processed in real time.

Inside the FPGA, the DMFD input data is sent down a set of parallel algorithm pipelines, each of which consists of a quadrature mixer, Cascade-Integrator-Comb (CIC) [25] low-pass filter, and a chain of band-defining FIR filters. There is one pipeline for each detector channel in the comb. A basic schematic of the configuration is shown in Fig. 5.

The low-pass filtering of the waveform is challenging. Low-frequency (typically 0.05-100~Hz) signals need to be maintained while filtering and sub-sampling the waveforms by a factor of roughly 10^5 to reduce the 25 MHz sampling rate to the ~200 Hz data rate that will be recorded on disk. The user can easily change the output data rate and hence the bandwidth of the system by bypassing some of the FIR filters with software commands. This is a powerful tool for debugging during the integration phase of the instrument's commissioning, where typically a larger bandwidth is desired to measure detector properties such as electrical and thermal time constants.

Four DfMUX modules are contained on a single 6U VME board, shown in Fig. 6. Each motherboard can handle 4 multiplexer modules. The digital circuits, including a powerful Xilinx Virtex4 LX160 FPGA, reside on this FPGA motherboard, while the low-noise analog converters, amplifiers, and filters ride 'piggy-back' on two mezzanine boards. The total number of detectors that can be demodulated by a single FPGA is determined by its gate count, but this gate count has been increasing faster than Moore's law over the last decade. A SQUID controller board, which is capable of handling 8 SQUID modules, forms an intermediary between the cold SQUIDs and the analog signals coming from the DfMUX backend.

The electronics attaches timestamps to the bolometer data from either an IRIG-B-encoded GPS signal or Manchester-encoded system clock. High-level commands ("set up squids", "set up bolometers") are encoded as TCP/IP packets and sent to the boards over standard Ethernet. Bolometer data is streamed off the board as UDP Ethernet packets. Each board has an embedded processor running μCLinux allowing it to run autonomously. It has its own watchdog circuit and temperature monitors. A monitoring system is being developed that will recognize configuration bit-flips due to single event upsets and correct for them.

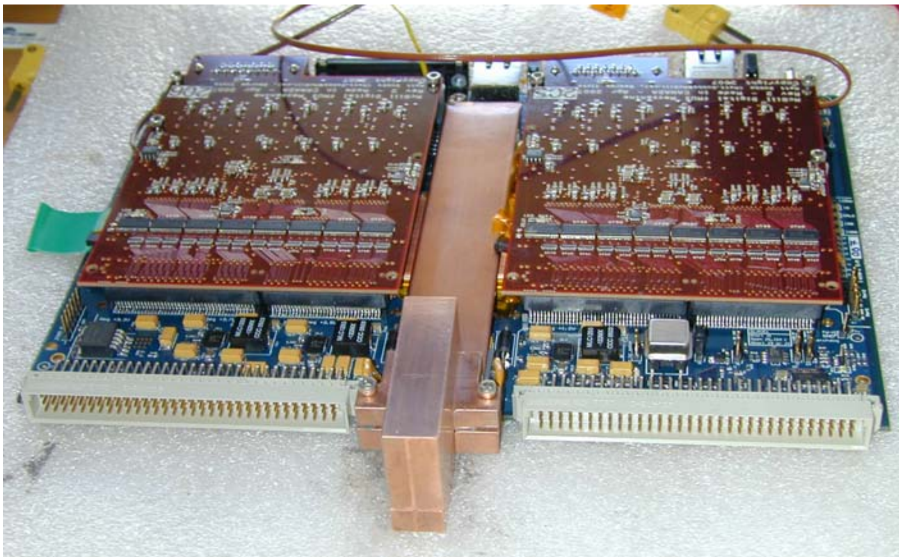

Fig. 6: The digital fMUX backend electronics. An FPGA motherboard is shown (large lower blue board) with two of its analog converter mezzanine boards attached (smaller upper red boards) and the copper convective heat pipe and conductive heat sink.

The SQUID controller and cold components of the system were developed at LBNL/UC Berkeley and are described in [14], [15]. The room temperature digital backend electronics developed at McGill are described in [16]. The heat dissipation scheme being employed for EBEX was developed at U. Minnesota. Performance validation of the digital system in the laboratory can be found in [16] and [26].

B. Channel spacing

The number of detectors that can be grouped together in a multiplexer comb is defined by the SQUID pre-amplifier system bandwidth divided by the carrier spacing.

Our present SQUID system has a bandwidth of just above 1 MHz, limited by phase shifts along the wires that connect the 4K SQUID to the room temperature amplifier that forms part of the flux-locked loop. There are several suggestions for SQUID systems that could greatly improve this bandwidth while maintaining the necessary system loop gain and linearity. One example is the Linearized SQUID Array (LISA) that is outlined in [13] and has recently been further developed. Bandwidths of 5-10 MHz have been achieved with LISA.

The detector time constants define the minimum LCR filter width and ultimately the channel spacing. While detectors employed with this system typically have optical time constants >1 ms, the TES sensor itself can respond to much faster thermal signals and the filter needs to be wide enough to allow stability across the full TES bandwidth. A careful reduction of the TES time constant to just wider than the optical time constant would allow closer channel spacing. The system presently uses 16μH inductors with ½ Ω bolometers, resulting in an L/R bandwidth of 5 kHz.

Once the L/R bandwidth is defined, the frequency spacing of adjacent carriers in the bias comb is specified by the requirement that Johnson noise from neighboring channels be attenuated to a negligible level. For EBEX, the carriers occupy the bandwidth from 0.3-1 MHz with a spacing of ~50 KHz, resulting in 12 detectors per multiplexer module.

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It should be emphasized that there is nothing fundamental limiting the module channel count—by optimizing the detector time constants and implementing new SQUID technology, a factor of many should be achievable without the development of any new technology. A commensurate reduction in power consumption and sub-Kelvin heat load would be achieved. If the SQUID to room temperature feedback loop can be eliminated, the 4K-300K wire length could be greatly increased, greatly reducing the heat load there as well.

C. System configuration for EBEX
For the EBEX science flight, 12 detectors will be multiplexed per module. The 1536 bolometer system has 32 DfMUX backend boards, 16 SQUID controller boards, and 128 SQUIDs. The SQUID controllers are mounted in a Faraday cage directly on the receiver cryostat. The DfMUX boards are housed in two 6U VME racks.

D. Power and thermal considerations
The power consumption is about 4W per multiplexed module. For EBEX (12 detectors per multiplexer module) the power dissipation is ~500W for 1536 channels. By increasing the number of multiplexed detectors per module as described in the channel spacing section, this power consumption could be substantially decreased.[†]

Heat dissipated on the boards is removed through a two-stage system designed by the Hanany group at U. Minnesota. Heat is conducted from the board and ICs through thermal grease to a pair of crossed rectangular heat pipes made of copper and a convective fluid (Tradename: "Nano Spreader", developed for laptop computers by Celsia Technologies). The heat pipes, visible in Fig. 6, are terminated in a copper plug that brings the heat through the backplane to the gondola frame. The system has been thermally modeled and the results verified with a thermal-vacuum chamber at NASA's Palestine balloon facility. The heat is radiated away from the instrument using panels mounted on the bottom of the gondola.

3.2. MHz FDM: Benefits and Challenges

A. Benefits
<u>Sky signals modulated above microphonics and low frequency electronic noise</u>
With frequency multiplexing, all detectors are continuously read out without interruption or switching transients. Sky-signals are modulated at ~MHz frequencies, greatly reducing susceptibility to microphonic pickup and amplifier/SQUID low-frequency noise.

<u>No power dissipation on sub-Kelvin stage</u>
In the fMUX system, there is one 4K SQUID per multiplexed module (rather than one SQUID per detector) and there is no power dissipation from the readout system on the sub-Kelvin stage.

<u>No fundamental limit in the multiplexing factor</u>
While existing fMUX systems use multiplexing factors of just 8 or 12 channels, there is nothing fundamental limiting this number. This number reflects the relatively small investment that has been made in this technology to date. A path to substantially larger channel counts using existing technology exists.

[†] As the detector count goes up, FPGAs with larger gate-counts are needed to handle the demodulation. Fortunately the density of this technology is increasing very rapidly. We believe that much more efficient demodulation algorithms are possible as well.

Modularity

For the DfMux system, the bias and demodulation functions for a multiplexer module of detectors are provided by the same electronics board (e.g. there are no rows of bias and columns of demodulation). This provides modularity, such that if an electronics board or cryogenic wire fails, it brings down only those combs. Each board is autonomous in its execution of setup scripts, and needs only high level commands from a control computer.

Configurable bandwidth

The configurable firmware demodulator allows the bandwidth of bolometer data recorded to disk to be changed by factors of 2 with a simple software command. For EBEX, we plan to record sky data with a bandwidth of 180 Hz (381 Hz sampling), but can command the system to record data with a bandwidth up to 6 kHz anytime without changing the system tuning. This is useful for mapping out the bolometer response functions or debugging the system.

Other advantages of the fMUX system include:

- bias voltage can be configured for each bolometer separately,
- the bolometer to SQUID wiring can be interrupted with small resistances ($R \ll R_{bolo}$) allowing the use of connectors with copper contacts,
- low power dissipation on the 4K stage (one SQUID per multiplexer module).
- FPGA Vendors such as Xilinx are actively pursing satellite applications and large-gate-count devices, similar to the ones used for this system, are already space qualified.
- DSP power in FPGAs is increasing quickly—faster than Moore's law by some estimates—this will result in even lower power consumption and make processing of drastically higher channel counts possible.

B. Challenges

Stray inductance

To maintain good voltage bias across the TES, the loop that includes the LC filter, SQUID input, and bolometer should be dominated by the bolometer impedance. Stray inductance between the sub-Kelvin and 4K stages spoils this voltage bias. For the analog system, low-inductance lead-coated copper strip-lines are used for the majority of the distance from the SQUIDs to detectors, with a heat-gap created by several inches of Nb twisted pairs. The inductance is dominated by the twisted pair. While this inductance is low enough for sub-MHz operation, it would not work at substantially higher frequency. The short length of twisted pair adds extra heat loading to the sub-Kelvin stage. The Hanany group at U. Minnesota are developing Nb superconducting strip-lines for EBEX by rolling thin Nb wire flat and suspending the traces between Kapton films. This is expected to provide a simple and cost effective solution that is both low inductance and low thermal conductivity.

4K–room temperature wire lengths

The SQUID flux locked loop, as it is presently implemented, includes a room temperature amplifier in the feedback loop. To maintain stability at high loop gain, the wire length between these devices must be kept short (<20cm), loading the 4 K stage. We note that a system with cold feedback, like the LISA pre-amplifier described above, would remove this constraint.

Readout white noise

white noise sources that do not modulate the carrier (such as SQUID and readout electronics noise) are enhance by a factor $\sqrt{2}$ post-demodulation. This is true of any AC-biased bolometer system. For a system with carefully optimized bolometer parameters, this is usually not an issue, as this noise is, even after the enhancement, small compared to other noise sources.

Low frequency D/A noise

The stability of the DMFS waveforms is extremely important to maintain good low frequency performance for temperature anisotropy measurements. The DMFS carrier, DMFS nuller, and DMFD are all clocked with the same crystal oscillator such that clock jitter cancels out to first order. The largest contributor is the low frequency noise from the transistors in the D/A converter output ladder. This low frequency transistor noise is modulated up to the carrier tone frequency by the D/A switching and appears as sidebands on the tones. While the older analog fMUX system suffered from low frequency noise with a low frequency knee typically at 1 Hz, this has been greatly improved for the digital system, where the knee sits at ~0.1 Hz. The location of the knee is determined by the amplitude of the bolometer bias, and so will be lower yet for low thermal conductivity bolometers such as those that will be used on satellite platforms.

Inter-modulation distortion

Any SQUID system is inherently non-linear. Since the SQUIDs in the fMUX system must handle many large carriers, inter-modulation distortion products are produced. Accurate nulling greatly reduces this effect. If the carriers were located at arbitrary frequencies, this distortion would create a forest of inter-modulation distortion products from these tones. Fortunately, there is some flexibility in the specification of the carrier frequency for each LCR resonance. By specifying that every carrier frequency is a multiple of (i.e.) 117 Hz, these distortion products are forced to live post-demodulation at either DC or a 117 Hz. It is easy to notch out this frequency off line.

3.3. MHz FDM: Technology Readiness and Needed Investment

Overall, MHz FDM is presently at a Technology Readiness Level (TRL) in the high 4s, having been demonstrated at close to the kilopixel scale in the South Pole Telescope. The DfMUX system is presently at TRL 4. Components have been prototyped and strung together end-to-end in the laboratory with TES bolometers to demonstrate performance, including noise [16,26]. Two areas need more attention and investment: space qualification for FPGAs, and pre-amplifier bandwidth.

Space qualification for FPGAs

The system makes heavy use of DSP implemented with Xilinx Virtex-4 FPGAs. The vendor has identified satellite and aerospace applications as an important market, and has an active program of space qualification. Recently Xilinx announced a new space grade version of the Virtex-4 line called Virtex-4QV [27]. This line includes a model that has 25% more processing power than the device presently used in the digital backend.

The McGill team has modest funding from the Canadian Space Agency and NSERC to work with an industrial partner (COM DEV) to explore technology that corrects configuration bits in FPGAs that have been flipped by single event upsets (SEUs). The strategy is to allow and expect SEUs, but recognize and correct them quickly. COM DEV has experience in this regime from systems it flew on the MAESTRO payload.

Pre-amplifier Bandwidth

Presently, the number of multiplexed detectors and hence the power consumption and heat load on the sub-Kelvin stage is limited by the bandwidth of the SQUID pre-amplifier system. Very little research, time, or funding has been invested to improve this bandwidth. A relatively small investment here will likely provide substantial returns. The goal is to produce a high-bandwidth (>~10 MHz) SQUID pre-amplifier system that does not use warm components inside the feedback loop.

3.4. Summary and future prospects

Recent developments in the processing power of FPGAs have allowed for the development of digital backend electronics for a SQUID-based frequency domain multiplexer system that operates with large arrays of sub-Kelvin Transition Edge Sensor bolometers. This new technology has sufficiently low power consumption to allow for the readout of large focal plane arrays on stratospheric balloon platforms. The system will be deployed on the EBEX instrument in 2008/9.

A number of important advantages, discussed above, make this system attractive—while its primary disadvantages are addressable with existing technology.

Substantial reductions in power consumption could be achieved by improving the bandwidth of the SQUID pre-amplifier flux-locked loop. An increase in bandwidth of a few MHz would result in power reduction by a factor of many. Space qualification of the large gate-count Virtex-4 FPGAs employed in the system has already been undertaken the vendor, Xilinx.

To bring the system up to the maturity level necessary for satellite platforms, an investment similar to that made for the UBC TDM electronics is probably necessary. Fortunately, there are no fundamental limits or boundaries that stand in the way of this development—the number of detectors grouped together in a multiplexed module is limited only by the bandwidth of the analog electronics so large advances are in principle possible.

4. Frequency-Division Multiplexing for Superconducting Microresonators

Principal section authors: Benjamin A. Mazin, J.A.B. Mates, and Kent D. Irwin

A large community has converged on the idea of using high quality factor superconducting microresonators to achieve dense frequency domain multiplexing at microwave frequencies. This technique uses wide bandwidth high electron mobility transistors (HEMTs) to provide several GHz of bandwidth with noise temperatures below 5 Kelvin, potentially allowing thousands of detectors to be read out through a single transmission line. This technique, developed originally for microwave kinetic inductance detectors [28], is also applicable to transition edge sensors coupled to resonators through rf SQUIDs [22], and Normal-Insulator-Superconductor detectors [29].

4.1. GHz FDM: Technology Overview

In a MKID [2], shown to the right in Figure 7, a high Q (10^4-10^6) superconducting resonator with a resonant frequency between 1-20 GHz is fabricated lithographically. Incident photons (panel b) change the surface impedance of the superconductor, causing a change in the amplitude (panel c) and phase (panel d) of a microwave probe signal send past the resonator at the resonant frequency. Since the transmission far away from the resonance is unity, we can multiplex many MKIDs off a single transmission line by setting each MKID's resonant frequencies to be slightly different with lithography. This is analogous to the different tones produced by different length pipes in a pipe organ. Using this approach, groups have recently demonstrated resonator-to-resonator frequency scatter below 1 MHz (Figure 2).

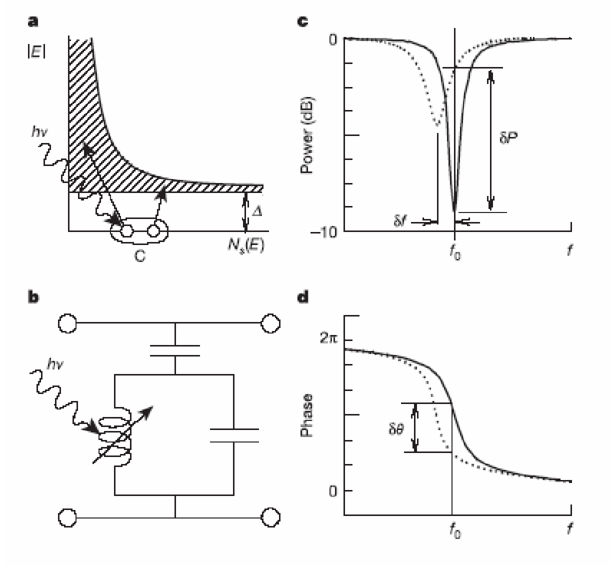

Figure 7. The mechanics of a MKID.

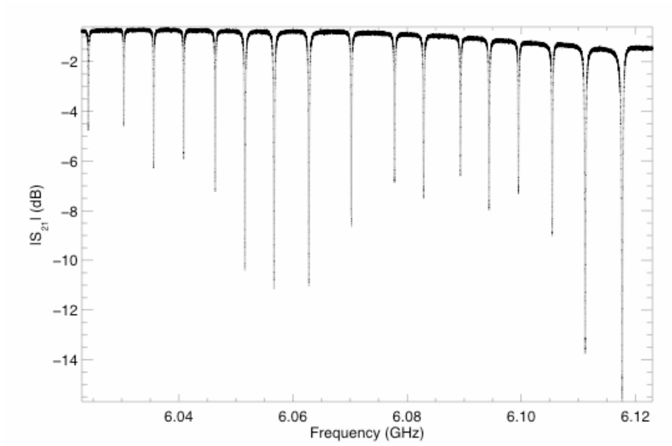

Figure 8. Transmission past a microwave MKID array.

Superconducting transition-edge sensors can also be read out in superconducting microresonators by coupling them through an array of microwave SQUIDs. In a microwave SQUID array, each high-Q resonator is loaded with a dissipationless rf-SQUID. The flux-variable inductance tunes the resonance frequency without affecting Q. Any detector that a SQUID can read out can be multiplexed this way, in particular the TES. To linearize the response one can apply flux feedback if the number of detectors is small. If the number of detectors is large one can utilize the SQUID flux periodicity to modulate the signal, for example by applying a common flux ramp to all SQUIDs in the array. This is a form of phase modulation and it both linearizes the SQUID response and up-converts the detector signal to higher frequencies in the bandwidth of the resonance. It requires more bandwidth per detector and additional room-temperature computation, but makes it possible to modulate above the 1/f noise of the resonators and the HEMT. The lithography for defining closely spaced resonances is essentially the same as for MKIDs, and the SQUIDs can be fabricated on the same wafer as the TESs.

In order to read out an MKID or microwave SQUID array, a comb of frequencies is generated with a sine wave at the resonant frequency of each individual resonator. This comb is then sent through the device, where each sensor imprints a record of its illumination on its corresponding sine wave. The comb is then amplified with a cryogenic HEMT and brought outside the cryostat. The comb is then digitized, and the phase and amplitude modulation of each individual sine wave is recovered in room temperature electronics. Aside from a HEMT amplifier, there are no cryoelectronics. Compared to existing low-frequency TES SQUID multiplexers, much of the complexity is moved from the base temperature to room temperature, where the full power of modern microwave electronics is available. In the case of the microwave SQUID array, the signal will be entirely in the phase direction, and higher readout data rates will be required to sample the external magnetic modulation signal required to linearize the SQUID response.

The technique described above, where a comb of frequencies is created, modified, then digitized and analyzed, is very common in modern wireless communications, where it is usually referred to as software-defined radio (SDR). An implementation suitable for reading out detectors is shown in Fig. 9. In this implementation, dual 400 MHz, 16-bit digital to analog converters play back a pre-computed waveform to generate the comb. Since two D/As are used, we can use an IQ modulator, which allows us to produce signals within a 400 MHz wide band centered on our LO frequency (usually 2-6 GHz). After the comb passes through the detector, it is mixed back down to baseband with another IQ modulator, low pass filtered, then digitized with dual 400 MHz, 14-bit analog to digital converters. After digitization, the signals are passed to a fast field programmable gate array (FPGA). There are many algorithms that can be run in the FPGA to demodulate the signals. The simplest is a direct digital downconverter (DDC) that simply digitally multiplies the complex input signal by sine wave at the desired frequency. This shifts the frequency of interest to 0 Hz. A digital filter followed by decimation gives the desired output data stream.

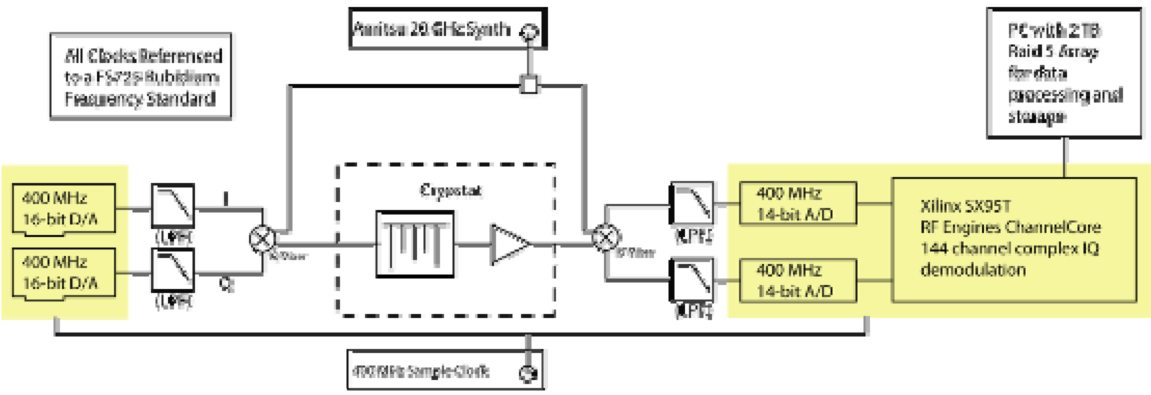

Figure 9. A block diagram of a SDR readout.

4.2. GHz FDM: benefits and challenges

A SDR readout allows a drastic simplification of the focal plane. This simplification cascades through the system, lowering costs at every stage. For instance, a MKID based focal plane will only need several wires going between 4K and the array, while a TDM TES multplexer will require hundreds. This drastically simplifies the construction of the focal plane, and also significantly lowers the cooling requirements.

The advantage of moving the readout complexity from 4 Kelvin to room temperature cannot be overstated. The entire hardware set developed to allow SCUBA-2 is extremely powerful, but large and very expensive due to the requirement of having one SQUID per pixel. Also, since these multiplexers are completely custom they do not gain much from external developments. In the two years since experimentation on these readouts first started, there has been a factor of 4 improvement in the speed of 14-bit A/D converters. The ability of SDR readout power to scale with Moore's law ensures that they will grow significantly more powerful with time.

The drawback of these systems for space applications is that they require flying fast, precise A/Ds, D/As, and FPGAs. Flight ready versions of these components tend to lag their ground-based counterparts, so the bandwidth of space-based SDR readouts will be lower than ground-based systems. The complex signal processing may also consume a significant amount of power at room temperature, in the worst case as high at 0.1 Watts/pixel.

4.3. GHz FDM: Technology Readiness and Needed Investment

The first SDR readout for LTDs was demonstrated in the lab in 2006 [28]. In April 2007, Caltech and the University of Colorado brought a SDR readout to the Caltech Submillimeter Observatory (CSO). This MKID demonstration camera proved the technology viable for ground-based operations [30]. This work has brought the readout to a TRL of the low 4s, and has enabled Caltech and Colorado to successfully propose to the NSF for a much larger camera for the CSO. The MKID camera on the CSO will read out approximately 2400 pixels in 8 GHz of bandwidth, making it by far the largest microwave FDM readout. This camera will push the readout to a TRL in the high 4s, having demonstrated a kilopixel-scale implementation, and lacking a demonstration in a relevant environment simulating a satellite to achieve TRL 5.

5. Conclusions

All three multiplexing techniques described in this paper are at a TRL of 4 or higher, and are progressing rapidly. Each of them are being deployed in suborbital cameras of the kilopixel scale, and both TDM and MHz FDM are being deployed in balloon-borne CMB polarimeter experiments (SPIDER using TDM, and EBEX using MHz FDM). If appropriate additional investment is made, we do not anticipate that the readout techniques and electronics will be a source of high technological risk for a CMBPol space mission. SQUID TDM and FDM are rapidly approaching a level of TRL 5. While each has its benefits and challenges, it is likely that either would work well for a CMBPol satellite. GHz FDM based on superconducting microresonators are also evolving rapidly, and they promise focal-plane simplification and scalability to even larger array sizes.

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