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The Microwave SQUID Multiplexer for Cosmology and Cryogenic Particle Detection

Thematic Areas:

■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF6) Calorimetry

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Abstract: Cryogenic sensors have found a large range of applications for astroparticle detection. Due to integration complexity and thermal loading from cryogenic wiring, the ability to read out multiple detectors on a single wire with cryogenic multiplexing technologies with minimal readout noise penalty is of utmost importance as experiments are scaled to ever larger detector counts. The microwave SQUID multiplexer (μmux) couples an incoming detector signal to a unique GHz-frequency resonance, thus combining the multiplexability of MKIDs with the clean separation of detection and readout interfaces. This enables multiplexing factors up to two orders of magnitude larger than conventional cryogenic multiplexing schemes. The wide frequency operation span enables large detector counts for low-bandwidth bolometric applications such as CMB cosmology while maintaining clean interfaces between the detection and readout schemes. Additionally, the large frequency bandwidth and fast resonator response allow for cryogenic particle detection, such as low-mass threshold dark matter searches, beta decay end point measurements to determine the lightest neutrino mass, and coherent elastic neutrino-nucleon scattering. Recent developments in warm electronics have enabled rapid progress in μmux development and maturity across several application areas.

Introduction Superconducting and/or cryogenic sensors have become widespread in astroparticle detection thanks to developments in repeatable fabrication, availability of commercial refrigeration tools, and technological superiority for several applications. Particularly popular examples are transition-edge sensors [1 2] and magnetic micro-calorimeters [3], which have been deployed in experiments measuring WIMP-like dark matter [4], millimeter and sub-mm wavelength photons [5], x-ray and gamma-ray spectra [6 7], and neutrinos [8], among others.

The multiplexer works by means of inductively coupling the incoming sensor signal to an rf SQUID, which is in turn inductively coupled to a unique microwave frequency resonator. Changes in flux threading the SQUID loop shift the frequency of the microwave resonance. A common flux ramp line is coupled to all of the SQUIDs and ramped much faster than the individual sensor signal, thus linearizing the SQUID response and eliminating the need for individual feedback lines. This flux ramp has the additional benefit of transforming the incoming detector signal into a phase modulation of the SQUID response. Thus, a single microwave transmission line on a pair of coaxial cables may read out thousands of individual sensors across a typical 4-8GHz bandwidth [9 10].

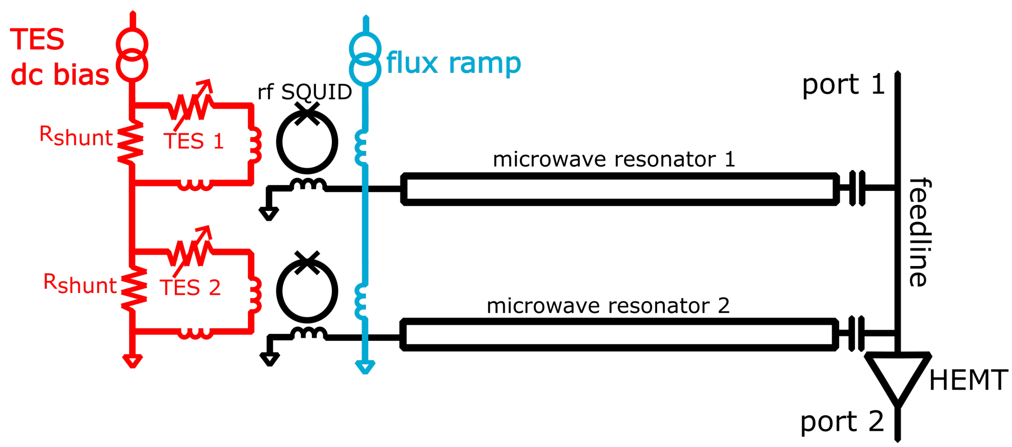

Figure 1: A circuit diagram for μmux used with transition-edge sensors (TESs). The working principle is similar for magnetic microcalorimeters (MMCs), except the dc-biased TESs are replaced with individual MMCs.

For mm and sub-mm photon detection applications, typical Q factors achieved and generous spacing between resonators to avoid frequency collisions allow for O(4000) channels to be multiplexed on a single readout line. This represents almost two orders of magnitude improvement over typical time-domain or MHz-frequency domain multiplexing schemes presently in use. [11 12] For cryogenic particle detection applications, the large operating bandwidth allows for large electrical bandwidth and fast response.

Recent Development Recent developments in warm rf electronics have enabled rapid progress in the maturity of μmux. In particular, the advent of tone-tracking electronics which "follow" the resonance dip as it is modulated, ensuring that the input microwave excitation tone is always attenuated by the 10-20dB resonance dip. This development, combined with advances in the linearity performance of cryogenic amplifiers, has opened a pathway for μmux to reach its full multiplexing potential [13 14].

In the austral summer of 2018/19, a single receiver of the Keck Array, part of the BICEP/Keck series of CMB polarimeters, was retrofitted with a μmux 150GHz focal plane and deployed to the South Pole for the 2019 observing season [15]. The μmux electronics were integrated with existing time-domain multiplexing (TDM) electronics operating on other receivers, timing, and telescope control/DAQ systems to produce an end-to-end demonstration of μmux for CMB. The on-sky performance in optimized readout channels was found to be comparable to the performance of the same TES detectors operating with time-domain multiplexing in a previous deployment, allowing for a direct comparison of readout technologies.

The compatibility of the dc-biasing for TESs between TDM and μmux allow for minimal changes to the focal plane package architecture, while the microwave plumbing allows for overall simplification and massive reduction of the readout wiring, making μmux an attractive upgrade for existing TDM systems seeking to expand their multiplexing capability without a total experimental redesign. This additionally allows for the separate optimization, fabrication, and characterization of the detector and readout elements, allowing for large scale production for big experiments.

Future CMB experiments that intend to use μmux include the BICEP Array high frequency receiver, the Ali-CPT telescope, and the Simons Observatory, each of which intend to deploy over 20,000 TESs at mK temperatures in a single cryostat. A significant amount of development has gone into the large-scale packaging, wiring, and integration of μmux for each of these experiments.[16 17] Further development is underway to explore repeatable packaging of μmux devices while maintaining good rf transmission.

The large bandwidth and fast response of μmux makes it an attractive option for calorimetry applications in addition to the aforementioned developments in bolometry. μmux systems are being developed for a number of terrestrial and space-based x-ray calorimetry experiments, including beamline spectrometers and the Lynx x-ray satellite mission[7 18 19]. In addition to TES-based calorimeters, μmux has additionally been developed for magnetic microcalorimeters[20], particularly for direct neutrino mass measurements with the end point energy of ^{163}Ho as in HOLMES or ECHo[21 22]. The need for multiplexing arises not only from the need for larger statistics but also the desire to avoid pileup at any given detector. Here, the key advantage of μmux lies in the ability to better resolve the pulse shape of an incoming photon since it is not limited by the switching time of the SQUID as in time- or code- division multiplexing systems or the complications of putting the inductor in the bias circuit as in MHz-frequency domain multiplexing systems.

Future Applications The recent rapid progress of μmux demonstrates its promise for cosmology and particle physics applications. The large readout bandwidth and fast response make it particularly attractive for cryogenic particle detection experiments, while the high multiplexing factor and minimal noise penalty allow for a wide variety of cosmological applications. Renewed interest in microwave resonator-based experimental techniques thanks to recent developments in quantum computing architectures additionally have contributed to the availability of rf parts and expertise.

Upcoming CMB experiments will set tight constraints on primordial gravitational waves, light relics, the sum of the neutrino masses and the neutrino mass hierarchy, the universe's expansion history and dark energy, and several dark matter scenarios, among other cosmological parameters of interest. As these experiments seek to deploy tens or even hundreds of thousands of cryogenic detectors in order to maximize sensitivity, the multiplexing advantage of μmux becomes ever more apparent. Spectroscopic measurements of cosmic dawn and other mm- and sub-mm wave experiments similarly benefit from low-noise cryogenic multiplexing at large scales. To truly harness the multiplexing benefit and make large arrays possible at scalable cost and timeline, the parallel development of fabrication and characterization of large numbers of TESs and microwave SQUIDs, as well as installation and calibration resources will be necessary.

TES and MMC-based cryogenic sensors for ultra-sensitive particle detection are enabled by μmux, which offers large readout bandwidth and relatively high multiplexing factors with fast response. These include end point measurements for direction measurement of the lightest neutrino mass, coherent elastic neutrino-nucleon scattering measurements, and light dark matter direct detection. The cryogenic particle detection community stands to benefit massively from the relative maturity of photon detector-based focal plane multiplexing technologies, presenting a viable path to distributed massive non-focal plane experiments with thousands or even tens of thousands of detectors.

References

[1] K.D. Irwin, “An application of electrothermal feedback for high resolution cryogenic particle detection” *Appl. Phys. Lett.* **66**, 1998 (1995). DOI: 10.1063/1.113674

[2] F.S. Porter, G.V. Brown, J. Cottam, Cryogenic Particle Detection, *Topics in Applied Physics* (Springer, Berlin, 2005), p. 359. DOI:10.1007/10933596-8

[3] M. Wegner, N. Karcher, O. Krömer, D. Richter, F. Ahrens, O. Sander, S. Kempf, M. Weber, and C. Enss, “Microwave squid multiplexing of metallic magnetic calorimeters: status of multiplexer performance and room-temperature readout electronics development”, Journ. of Low Temp. Phys. 193, p. 462, (2004). DOI:10.1007/s10909-018-1878-3

[4] B. Cabrera, R. Clarke, A. Miller, S.W. Nam, R. Romani, T. Saab, B. Young, “Cryogenic detectors based on superconducting transition-edge sensors for time-energy-resolved single-photon counters and for dark matter searches”, *Physica B: Condensed Matter*, Vol. 280 1-4 p. 509-514 (2000). DOI:10.1016/S0921-4526(99)01849-9

[5] The CMB-S4 Collaboration, *CMB-S4 Technology Book* (2017). arXiv:1706.02464

[6] S.R. Bandler, “Development of magnetic microcalorimeters for x-ray astronomy”, Proc. SPIE 5501, High-Energy Detectors in Astronomy, (2004). DOI:10.1117/12.552231

[7] J.A.B. Mates et al., “Simultaneous readout of 128 X-ray and gamma-ray transition-edge microcalorimeters using microwave SQUID multiplexing”, *Appl. Phys. Lett.*, **111**, 062601 (2017). DOI:10.1063/1.4986222

[8] S. Kempf, M. Wegner, A. Fleischmann, L. Gastaldo, F. Herrmann, M. Papst, D. Richter, C. Enss, “Demonstration of a scalable frequency-domain readout of metallic magnetic calorimeters by means of a microwave SQUID multiplexer.” *AIP Advances* **7**, 015007 (2017). DOI: 10.1007/s10909-014-1153-1

[9] K.D. Irwin, K.W. Lehnert, *Appl. Phys. Lett.* **85**, 2107 (2004). DOI:10.1063/1.1791733

[10] J.A.B. Mates, G.C. Hilton, K.D. Irwin, L.R. Vale, K.W. Lehnert, “Demonstration of a multiplexer of dissipationless superconducting quantum interference devices.” *Appl. Phys. Lett.* **92**, 023514 (2008). DOI: 10.1007/s10909-012-0518-6

[11] S.W. Henderson et al., “Readout of two-kilopixel transition-edge sensor arrays for Advanced ACTPol”, *Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII* (2016). DOI: 10.1117/12.2233895

[12] A. Bender et al., “On-Sky performance of the SPT-3G frequency-domain multiplexed readout”, *J. Low Temp. Phys.* Vol. 199 1-2, p. 182-191 (2020), DOI:10.1007/s10909-019-02280-w

[13] S.A. Kernasovskiy, S.E. Kuenstner, E. Karpel, et al. “SLAC Microresonator Radio Frequency (SMuRF) Electronics for Read Out of Frequency-Division-Multiplexed Cryogenic Sensors.” *J Low Temp Phys* **193**, 570 (2018), DOI:10.1007/s10909-018-1981-5

[14] S.W. Henderson, Z. Ahmed, J. Austermann, et al. “Highly-multiplexed microwave SQUID readout using the SLAC Microresonator Radio Frequency (SMuRF) electronics for future CMB and submillimeter surveys”, *Proc. SPIE 10708*, **1070819** (2018), DOI:10.1117/12.2314435

[15] A. Cukierman et al., "Microwave multiplexing on the Keck Array", *J. Low Temp. Phys.*, Vol. 199 p. 858-866 (2020). DOI: 10.1007/s10909-019-02296-2

[16] M.S. Rao et al., "Simons Observatory Microwave SQUID Multiplexing Readout: Cryogenic RF Amplifier and Coaxial Chain Design", *J. Low Temp. Phys.*, Vol. 199 3-4 (2020). DOI: 10.1007/s10909-020-02429-y

[17] H. McCarrick, "Universal microwave multiplexing modules: the Simons Observatory cryogenic readout system with a 1764 multiplexing factor", Presentation at Low Temperature Detectors 18 (2019). https://agenda.infn.it/event/15448/contributions/95840/

[18] D.A. Bennett et al., "Microwave SQUID multiplexing for the Lynx x-ray microcalorimeter", *J. of Astronomical Telescopes, Instruments, and Systems*, **5(2)**, 021007 (2019). DOI:10.1117/1.JATIS.5.2.021007

[19] The Lynx Team, "The Lynx Mission Concept Study Interim Report," (2018). arXiv:1809.09642

[20] A. Puiu, et al., "Updates on the transition-edge sensors and multiplexed readout for HOLMES", *J. Low Temp. Phys.* 193, 1167 (2018). DOI:10.1007/s10909-018-1950-z

[21] D.T. Becker, et al., "Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment microcalorimeters", *Journal of Instrumentation*, Vol 14 (2019). DOI: 10.1088/1748-0221/14/10/P10035

[22] O. Sander, et al., "Software-defined Radio Readout System for the ECHo Experiment", *IEEE Transactions on Nuclear Science*, Vol 66, 7 (2019). DOI: 10.1109/TNS.2019.2914665