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A High-Capacity Microwave SQUID Multiplexer Chip Screening System

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Abstract

The microwave SQUID multiplexer (μMUX) is a high channel-count multiplexer that, when coupled to low-temperature detectors such as Transition Edge Sensor (TES) Bolometers, has applications across astronomy and physics. Our primary application is for the Simons Observatory, an array of CMB polarimeters utilizing over 70,000 μMUX readout channels, located in the Atacama Desert. To facilitate the delivery of high-quality multiplexers to the project, we have developed a high-throughput microwave SQUID screening measurement system, capable of measuring microwave devices operating over the frequency range of 4–8 GHz. Here, we present the hardware design comprised of a cryogen-free 100 mK 2-stage Adiabatic Demagnetization Refrigerator (ADR) cryostat, microwave packages which hold μ MUX chips, and the microwave readout chain necessary to do these measurements. In addition, we describe the screening protocols and show example results.

Keywords SQUID multiplexer · Microwave SQUID · Cryostat · Cryostat design · Microwave detectors · RF

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1 Introduction

The Simons Observatory (SO) is an array of Cosmic Microwave Background (CMB) imagers in the Atacama Desert which will put tighter constraints on many cosmological parameters and produce a catalog of galaxies and extragalactic sources [1]. The experiment will use over 70,000 readout channels coupled to Transition Edge Sensor (TES) bolometers spread across four different telescopes.

The number of cryogenic sensors to be deployed is an order of magnitude larger than the previous generation of CMB imagers. A new multiplexer—the microwave SQUID multiplexer (μMUX)—has been developed to handle this large number of detectors. The μMUX is a frequency division multiplexer in which the signal from a cryogenic sensor is transduced into the frequency shift of a microwave resonator by means of an RF-SQUID. The multiplexer operation and performance is well described in the literature [2–4].

In this paper, we describe a high-throughput, cryogenic measurement system for efficient characterization of μMUX chips. The goal of the system is to rapidly screen for yielded devices so that deployment-quality multiplexers are selected for integration into the focal plane modules described in McCarrick et al. [5].

2 Multiplexer Chip Topology

The design of the measurement screening system is driven by the multiplexer chip and how chips are combined to form a larger array, and as such we describe the topology briefly here. The fundamental unit of screening is a 4×20 mm^2 chip, many of which are produced on a single silicon wafer, each with a fraction of the final assembly's total readout channels. This modularity of chips is important such that one can replace a single chip if electrical or mechanical issues arise, rather than fabricating an entirely new wafer. Multiplexer chips fabricated at NIST span 4–8 GHz, and as such we have developed the testbed to operate over this frequency range. The standard multiplexer chip has been described previously [2], and an optical micrograph of one chip is shown in Fig. 1. Each 4×20 mm^2 chip contains 65

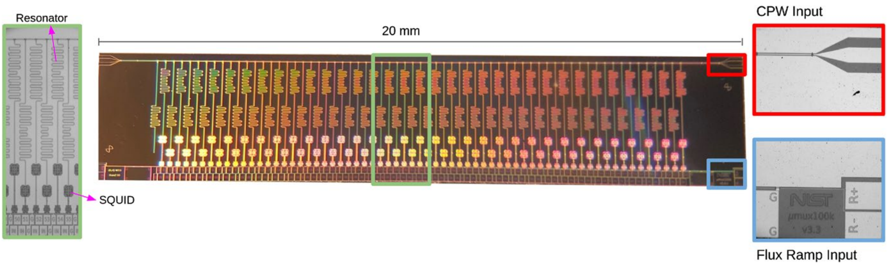

Fig. 1 Optical micrographs showing the layout of a single μMUX chip, including CPW line (red), flux ramp input (blue), and the SQUID coupled resonators (green). (Color figure online.)

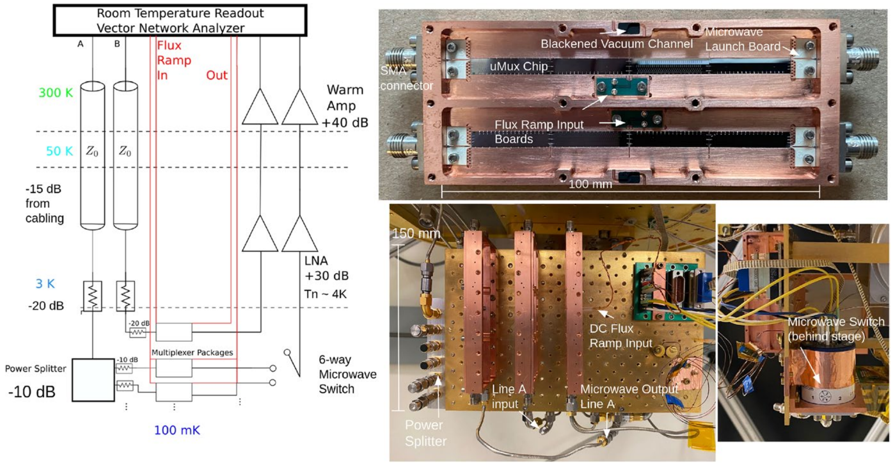

Fig. 2 *Left*: Diagram of the cryostat cabling. Note that attenuation at the input of the package totals −55 dB. *Top Right*: Photograph of a microwave package, which contains eight μMUX chips. *Bottom Middle*: Three microwave packages mounted to the mK stage. (Some coaxial cabling removed for visual clarity). *Bottom Right:* Zoom in view of 6-way microwave switch (Sect. 3.4) (Color figure online.)

readout channels and one bare resonator, which exhibits no flux response and is used for calibration and mitigation of systematic pickup. Each resonator has a designed bandwidth of 100 kHz, and the minimum designed nearest neighbor spacing is 1.8 MHz. Wirebonded connections, both between adjacent chips and between chips and mating circuits, consist of a co-planar waveguide (CPW) microwave feedline and a dc line used for flux ramp modulation, described in Mates et al. [6]. Additionally, grounding bonds are made around the perimeter of every chip.

3 Measurement System

3.1 Cryostat

The cryostat is a dry 2-stage 100 mK ADR providing temperature stages of 50, 2.7, 1 K and 100 mK. To attenuate magnetic fields at the device location, the bottom half of the 300K vacuum jacket contains an internal cylindrical shell of high magnetic permeability. The ADR unit is surrounded by vanadium permendur, supplied by the vendor. No shielding surrounds the microwave device boxes. We have installed two independent RF lines. A schematic of the cabling is shown in Fig. 2. Most of the coaxial cabling inside the cryostat is 2.42 mm cupronickel (CuNi-CuNi) coaxial cable, the exception being from the output connection of the 100 mK stage to the interface of the 2.7 K stage, which is 1.72 mm niobium-titanium (NbTi-NbTi). One RF chain contains a 6-way microwave switch mounted to the 100 mK stage (see Sect. 3.4). Thus, the screening system is capable of measuring 7 independent microwave circuits in a single cooldown.

Our 100 mK stage has a 203×127×4 mm^3 gold plated copper mounting plate which can accept five microwave packages. The temperature of the devices is monitored by use of two ruthenium oxide (RuOx) thermometers, one mounted to the front side of the millikelvin plate and another attached to the 100 mK cold finger. With five microwave packages and the microwave switch installed on the 100 mK stage, the ADR achieves a minimum temperature of 60 mK and a 12 hour hold time at the device screening temperature of 120 mK.

3.2 Microwave Package Design

As with all microwave devices, performance of the μMUX depends on the environment in which the chips are embedded. One concern is the excitation of box modes in the necessarily large device box. As shown in Fig. 2, we designed an 8-chip copper microwave package which, by use of a lid and splitting the RF path into two 4-chip runs divided by a copper septum, avoids microwave box modes for frequencies < 8 GHz. The mass of each package is 200 g. Between the lid and box, we include a blackened vacuum pump-out channel, which consists of a castable epoxy made of a mixture of Stycast 2850FT/Catalyst 23LV and powdered carbon lampblack that has been directly milled to produce a meandered channel.

Each half of the packaging has non-magnetic SMA connectors that can either be attached to individual RF lines or chained together. The SMAs are connected to 50 Ω impedance microwave launch boards, located inside of the package, that in turn connect to the CPW of a μMUX chip. Near the inside wall of the package, circuit boards connect the flux ramp inputs to header connectors on the opposite side of the box.

3.3 Assembly and Packaging of μMUX Chips

Careful and well-practiced assembly of μMUX chips is important to ensure sufficient thermal contact, good electrical connections, and that chips can be reused after screening. We place chips into channels machined into the base of the package to make the bonding surfaces co-planar. The chips are mounted with thinned rubber cement (1:1 ratio of rubber cement to thinner by weight), which we find provides sufficient heat-sinking at sub-Kelvin temperatures and allows chip removal after screening.

A complication with any dense frequency division multiplexed readout is correctly mapping measured resonators in frequency space to physical resonators on the chips that host them. Frequency collisions between chips is avoided by placing alternating, non-sequential frequency band chips in any one package. As seen in the frequency survey of Fig. 3, the large separation between resonator groups ensures the measured characteristics of one readout channel is correctly assigned to a unique chip.

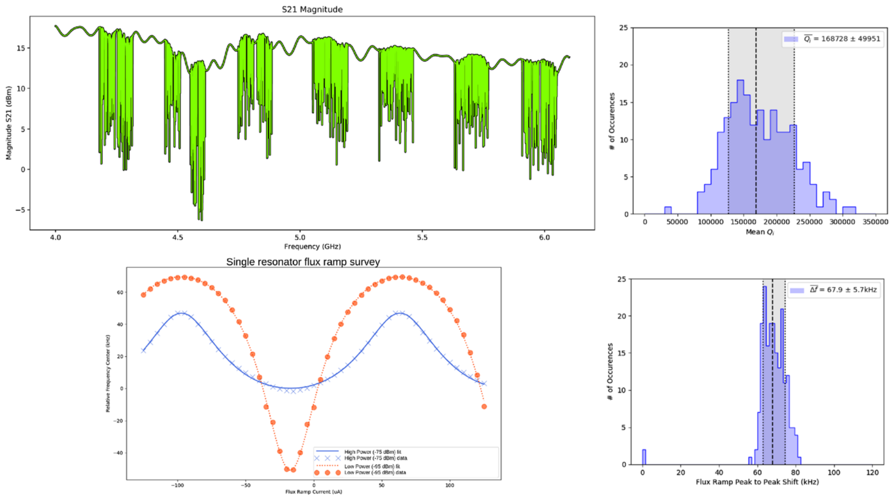

Fig. 3 Example data products from a standard flux ramp survey. *Upper left:* Frequency survey at optimal microwave power of 7 individual μMUXchips, each containing 65 resonators for a total of 455 resonators. Individual resonators are difficult to see because we are taking a full 4–6 sweep. *Lower left:* Single channel frequency shift versus applied flux at both high (−75 dBm, blue) and low (−95 dBm, orange) microwave power determined from a flux ramp survey. Notice the large SQUID gain compression at higher power. *Upper and Lower Right:* Example histograms of resonator fit parameters. Notice a few resonators exhibit no flux response, which are the bare resonators discussed in section 2 (Color figure online.)

To conserve bonding area for the final assembly, we use single 25 μm diameter Al wire bonds for both the microwave and flux ramp lines, and use 1 bond/mm to tie the chip Nb ground plane to the device package on both the north and south side of the chips. Although the use of a single wire on the CPW center conductor results in a $\sim 30\ \Omega$ impedance mismatch at 6 GHz for each chip-to-chip microwave connection, we find that the resulting ~ 2 dB peak-to-peak ripple does not compromise the screening results. We note however that these impedance mismatches are the dominant source of coupling quality factor (Q_c) variation. A study of wirebond density shows that 1 bond every 2 mm allows for the internal quality factor (Q_i) to reach over 100,000 and thus our chosen ground bond density is sufficient enough to mitigate accidentally poor wirebond connection between the chip's ground plane and the ground plane of the package.

We make use of an automated wirebonder for screener box preparation. Wirebonding one package of 8 chips takes 15 min and contains 400 total wire bonds. Prior to installation in the cryostat, the DC connectivity of both the microwave and flux ramp lines are probed, as well as assessing if there are shorts to ground on either line.

3.4 Microwave Switch

The 6-way, 18 GHz latching relay microwave switch[1] mounted to the 100 mK stage more than triples the number of devices that can be measured in a single cooldown. The heat dissipated (from Joule heating and mechanical motion of the switch) is tolerable during an ADR cycle, but reduces the magnet's hold time, and therefore standard practice is to exercise the switch between ADR cycles when the 100 mK stage is thermally connected to the 2.7 K stage.

An additional complication concerns the heat capacity of the switch, which is expected since the unit contains ferromagnetic material. The cooling of the device is limited by the poor thermal conductance of components inside the switch, and we find this extends the initial cooldown time by 3 hrs in order to let the switch thermalize properly. For our intended purpose, the increased device throughput outweighs these operational inconveniences. Furthermore, we observe no adverse affects from the ferromagnetic materials in the switch. The minimum distance from the switch to any device is 130 mm. We have measured devices from the same wafer with and without the microwave switch and with packages installed in perpendicular SQUID orientations and extract the same device parameters to within measurement error and chip-to-chip variation.

4 Screening Procedure

The fundamental screening data set required is a flux ramp survey. A flux ramp survey is a set of S_{21} frequency sweeps over which the DC flux applied to the RF-SQUIDs is stepped in discrete intervals spanning at least one magnetic flux quantum. However, because device performance is dependent on temperature and microwave power, and also to minimize total screening time, screening proceeds in several measurement steps rather than full 4-8 GHz sweeps.

We start by stabilizing the temperature of ADR stage to 120 mK, the base temperature for all measurements, by use of a PID controller. We perform a frequency survey over the full frequency range of the devices under test to determine the rough frequency placement of the resonators. Selecting 5 resonators from each chip, we then perform a 2.5 dB stepped power sweep to determine the appropriate microwave power (P_{probe}) for use in subsequent screening steps. P_{probe} is defined as the unweighted average of the microwave powers which maximize the resonator Q_i's in this subset. P_{probe} is typically −75 dBm at the location of the on-chip microwave launch reference plane. We then perform another full frequency survey at P_{probe} (see Fig. 3 upper left). A peak-finding algorithm windows the data into 1 MHz sections, which each contain a single resonance, and subsequently fits the data to a resonator response model [7] to extract each resonance frequency f, Q_i, and Q_c.

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[1] Radiall R573.453.625, Certain commercial instruments are identified to specify the experimental study adequately. This does not imply endorsement by NIST or that the instruments are the best available for the purpose.

To determine the magnetic flux to frequency shift response, we then perform a flux ramp survey at a microwave power 20 dB lower than P_{probe}. This power setting avoids SQUID gain compression. We use 50 flux steps spanning slightly more than one flux quantum. To decrease measurement time, a dynamic frequency window around each resonator, typically about 1 MHz, is measured rather than sweeping the full 4-8 GHz range. We then fit the center frequency for each flux step using the same resonance response model, and plot the magnetic flux versus resonator center frequency. An example is shown in the lower left of Fig. 3, which includes a high microwave power response curve to illustrate SQUID gain compression.

We use all of these data products (f,Q_i,Q_c, and peak-to-peak frequency shift df_{pp}) to determine the yield of each chip, flag defect channels, and produce wafer-scale statistics (see Fig. 3 upper and lower right for examples). The data acquisition time for an 8-chip package containing 528 resonators is 6.6 hrs. As such, a full wafer containing 32 μ MUX chips can be packaged and screened within one work week.

5 Conclusion

We have described a high-throughput μMUX screening system and packaging procedure, which is routinely used for the delivery of multiplexer chips for the Simons Observatory. The approach packages multiple chips, each with resonators spanning different frequency ranges, into custom-designed microwave packages. Up to five 8-chip packages may be installed in a cryogen-free 100 mK cryostat, and thus, in principle, 2640 channels may be screened in a single cooldown. A maximum of 1848 channels has currently been demonstrated. In spite of the added thermal mass and heat dissipation, the use of a 100 mK microwave switch has more than doubled measurement throughput. The screening procedure has been described and example measurements shown.

While the system currently satisfies our needs, substantial gains in throughput may be possible. Most impactful would be wafer-scale-screening (before chip dicing), for example by using a cryogenic electrical probe card. Exploring the feasibility of this approach is the subject of future research.

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References

1. The Simons Observatory. Collaboration et al., JCAP **2**, 056 (2019). https://doi.org/10.1088/1475-7516/2019/02/056
2. B. Dober et al., Appl. Phys. Lett. **118**, 062601 (2021). https://doi.org/10.1063/ApplPhysLett.5.0033416
3. B. Dober et al., Appl. Phys. Lett. **111**, 243510 (2017). https://doi.org/10.1063/1.5008527
4. J. A. B. Mates,"The microwave SQUID multiplexer," Ph.D. thesis, University of Colorado, Boulder, (2011)
5. H. McCarrick, E. Healy, Z. Ahmed, K. Arnold, et al., *ApJ*(2021) arXiv:2106.14797
6. J.A.B. Mates et al., J. Low Temp. Phys. **167**(56), 707–712 (2012). https://doi.org/10.1007/s10909-012-0518-6

7. J. Gao (2008) The Physics of Superconducting Microwave Resonators. Dissertation (Ph.D.), California Institute of Technology. https://doi.org/10.7907/RAT0-VM75.