The Simons Observatory 220 and 280 GHz Focal-Plane Module: Design and Initial Characterization

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Abstract

The Simons Observatory (SO) will detect and map the temperature and polarization of the millimeter-wavelength sky from Cerro Toco, Chile, across a range of angular scales, providing rich data sets for cosmological and astrophysical analysis. The SO focal planes will be tiled with compact hexagonal packages, called universal focal-plane modules (UFMs), in which the transition-edge sensor (TES) detectors are coupled to 100 mK microwave-multiplexing electronics. Three different types of dichroic TES detector arrays with bands centered at 30/40, 90/150, and 220/280 GHz will be implemented across the 49 planned UFMs. The 90/150 GHz and 220/280 GHz arrays each contain 1764 TESes, which are read out with two 910x multiplexer circuits. The modules contain a series of routed silicon chips, which are packaged together in a controlled electromagnetic environment and operated at 100 mK. Following an overview of the module design, we report on early results from the first 220/280 GHz UFM, including detector yield, as well as readout and detector noise levels.

Keywords Cosmic microwave background · Microwave SQUID multiplexing · Transition-edge sensor detectors

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1 Introduction

The millimeter-wavelength sky contains rich information about the origins and evolution of our universe. The temperature and polarization patterns in the cosmic microwave background (CMB) give us a precise snapshot of this cosmological epoch, about 380,000 years after the big bang. Simons Observatory (SO)\(^1\) will build four telescopes, one large-aperture telescope (LAT) [1] and three small-aperture telescopes (SATs) [2], to observe the millimeter sky from the Atacama Desert in Chile at an elevation of 5200 m. The telescopes will observe at six frequency bands between 30 and 280 GHz with over 60,000 transition-edge sensor (TES) detectors. This paper focuses on the highest frequency detector modules, which have dichroic pixels with frequency bands centered at 220 and 280 GHz.

The small-aperture survey aims to constrain the tensor-to-scalar ratio \(r\), which parameterizes the primordial gravity-wave polarization signal [3]. Measuring in the 220/280 GHz band enables the removal of foreground sources, such as galactic dust, in CMB polarization maps. The large-aperture survey will make small-angular-scale measurements of the CMB temperature anisotropies and polarization [3]. One target of this survey is to use the Sunyaev–Zeldovich effects to study structure in the late universe (\(0 < z \lesssim 10\)). The thermal-SZ effect, in which CMB photons interact with high-temperature electrons, has a frequency dependence such that 220 and 280 GHz measurements will measure the null and peak of this spectrum.

The SO focal-plane modules are called universal focal-plane modules (UFMs) for their universality between the two types of telescope receivers (LAT and SAT). The UFMs are hexagonal packages that couple the transition-edge sensor (TES) detectors to the telescope optics and the 100 mK microwave-multiplexing readout components. There will be three types of UFMs corresponding to the SO frequency bands: a low-frequency (LF) array with pixels centered at 30/40 GHz, a mid-frequency (MF) array at 90/150 GHz, and a ultra-high-frequency (UHF)\(^2\) array at 220/280 GHz. The common multiplexer design and overall architecture has been published in McCarrick, et al. [4]. The MF modules are reported on in [5]. Thirteen UHF focal-plane modules will be built for use in both a SAT (7x UFMs) and the LAT (6x UFMs). This paper describes the design and characterization of a prototype UHF UFM for SO.

2 Methods

Here we describe the components and design of the first UHF prototype detector module. The device consists of the detectors and optical coupling, where the photons are absorbed and converted to an electrical signal, and the readout, where that signal gets amplified via a microwave-multiplexing scheme.

\(^{1}\) https://simonsobservatory.org/.

\(^{2}\) For historical reasons, SO calls the highest detector frequency band the “ultra-high” frequency to distinguish it from Atacama Cosmology Telescope (ACT) high-frequency (HF) arrays.
2.1 Detectors and Optical Coupling

The UHF detector array wafer, which is fabricated at NIST on a 150 mm-diameter silicon wafer, consists of 432 pixels. At the center of each pixel (see Fig. 1) is the polarization sensor: the orthomode transducer (OMT), which couples orthogonal linear polarizations of incident photons to superconducting wiring lithographed on the detector wafer. Inline microstrip filters define frequency bands, such that each pixel measures two orthogonal polarizations in two frequency bands centered at 220 and 280 GHz, with a total of 1728 optical TESes per array. There are an additional 36 “dark” TESes, which are not coupled to OMTs and are used in detector calibration.

A monolithic gold-plated aluminum feed-horn array with spline-profiled horns efficiently couples incident power to the OMTs while preserving beam symmetry [6]. The horn array also has the flange that interfaces to the focal plane in the optics tube, therefore setting the focus of the beam. There are four additional wafers that are part of the optical coupling stack that complete the waveguide from the feed horn to the OMT and provide a quarter-wavelength reflection to improve coupling efficiency.

2.2 Readout Components

The SO readout technology, microwave multiplexing, works by coupling each detector to a microwave resonator with a unique frequency between 4 and 6 GHz via a superconducting quantum interference device (SQUID). These resonators are capacitively coupled to a common transmission line, and the signals are amplified and demodulated with SLAC microresonator radio frequency (SMuRF) electronics [7].
With this architecture, up to 910 detector channels can be read out with a single pair of coaxial cables. Because the UHF detector wafers house 1764 detectors, two 910x multiplexing circuits are used to read out a single UFM. (Some readout channels are left uncoupled to detectors.)

The SO multiplexing architecture uses microwave-multiplexer (μmux or mux) chips that are fabricated at NIST, operated at 100 mK, and include the microwave resonators, SQUIDs, and coupling inductors [4]. The multiplexer chips, each of which have 65 channels, are fabricated in sets of 14 chips with complementary resonators spanning the 4 to 6 GHz readout bandwidth. These chips are packaged in the universal microwave-multiplexing module (UMM), which sits behind the detector stack in the UFM. A silicon routing wafer distributes the electrical signals between the mux chips, the detector wafer, and circuit boards that connect to optics tube wiring. The mux chips and routing wafer are packaged in a copper box that reduces box-mode coupling and provides grounding.

2.3 UHF and MF UFMs

The UHF UFM design closely mirrors the MF UFM design, as they both use the same readout and optical coupling technologies. On the readout side, the UMMS are completely interchangeable between the MF and UHF UFMs. The optical coupling, however, depends on the wavelength such that the UHF has a smaller antenna (OMT) size, different horn profile, and different flange height to align the detectors to the telescope focus. A comparison of the MF and UHF detectors and horn arrays can be found in Fig. 1.

2.4 The First UHF Module

The first prototype module, labeled UFM-Uv8, was assembled from a tested UMM and the first SO UHF detector wafer fabricated at NIST. The UMM was assembled
according to standardized protocols [8], which were developed to minimize variation between the modules. Integrating the UHF detector optical stack involved additional assembly, including precision alignment of the detectors to the feed-horn array with dowel pins, adding gold wire bonds between the detector wafer and horn array for heat sinking, and electrically coupling the UMM with aluminum wire bonds around the perimeter. Photographs from the UFM-Uv8 assembly can be seen in Fig. 2.

3 Results

The prototype UHF module, UFM-Uv8, was tested in a dilution refrigerator equipped with a microwave SQUID multiplexing readout chain similar to the SO design [9]. The UFM has two readout chains, which are labeled “North” and “South,” each of which is coupled to half of the 1764 TES channels. The UFM was first measured with a vector network analyzer (VNA) to determine the S-parameters as a function of frequency, which can be seen in Fig. 3. These plots validate the RF environment of the multiplexer, as we see a relatively flat transmission and deep resonances (median dip depth -8 dB) at frequencies that correspond to a resonator

Fig. 3 Left: transmission (S21) plots for the North and South multiplexers of the prototype UHF UFM. Each dip in the transmission corresponds to a resonator, i.e., a readout channel. Note that the difference is power levels between North and South is due to differences in the amplification chain. Upper right: Histogram of resonator internal quality factor ($Q_i$). Lower right: Histogram of channel noise when the detectors are superconducting (blue) and normal (orange). The noise data were measured with SMuRF over 5–50 Hz. The datasets analyzed during the study are available from the corresponding author on reasonable request (Color figure online)
channel. Histograms of the per-channel internal quality factor ($Q_i$) can also be found in Fig. 3. The median value and spread in the $Q_i$ data are consistent with the seven-chip package reported in Dober, et al. [10], confirming that the detector module packaging did not degrade the microwave environment. Table 1 reports the resonator yield statistics, which exceeds the SO performance requirements at $> 90\%$.

Following the VNA measurement, the UFM was tested with SMuRF electronics. These warm electronics provide the bias power for the detectors, flux ramp modulation for the SQUIDs, and GHz probe tones for the resonators. We used SMuRF to make noise measurements when the detectors were superconducting and normal. A histogram of the superconducting and normal noise, both of which achieve the SO performance requirements for mapping speed, can be found in Fig. 3. Note that the noise is higher when the TESes are superconducting, due to the Johnson noise in the shunt resistors (for a full accounting for the UFM noise, see [4]). We then took I-V curves on the detectors, i.e., measured the current through the TES while voltage-ramping through the superconducting transition, to confirm their operability. We found that the transition temperature for the detectors was between 160–170 mK, within the SO specification range. See Fig. 4 for plots of the detector response. Table 1 shows the detector–readout coupling and detector response yield.

4 Discussion

With this first screening of UFM-Uv8, we have confirmed some of the fundamental features of the design: the multiplexer coupling to detectors was validated, detectors were able to be operated, and the overall noise and yield numbers meet the SO specifications. We plan to further characterize the optical performance of this array, including measuring detector response to a cold blackbody source to determine saturation powers and optical efficiency. The prototype array will also be used to validate the optics of the SO UHF receivers.
Table 1  *Upper table:* Resonator yield statistics for the prototype UHF module. Nominally, each half of the UFM will have 910 resonators when all 28 multiplexer chips are present. Note that one of the chips in UFM-Uv8 was damaged, which accounts for the 4% loss in the final assembly. The final column reports the number of resonator readout channels that were identified with SMuRF. *Lower table:* Detector yield statistics for prototype UHF module. The number of wired channels corresponds to how many detectors were nominally coupled to resonators. To determine which detectors were in fact coupled to the readout, a sine wave was input on the bias line and the corresponding resonator channel read out with SMuRF. The number of I–V curves indicates the number of detectors that responded to voltage-ramping through their transition. Note that due to an understood issue with a prototype SMuRF component, one bias group with 160 detectors was not operable, which accounts for most of the 10% yield drop between the sine-wave and I–V curve response.

| Module half | Nominal number | Number in final assembly | Number measured with SMuRF |
|-------------|----------------|--------------------------|-----------------------------|
| North       | 910            | 846                      | 791                         |
| South       | 910            | 910                      | 841                         |
| Total       | 1820           | 1756                     | 1632                        |
| Percentage  |                | 96%                      | 90%                         |

| Detector frequency | Number of wired channels | Number of sine-wave responses | Number of I–V curves |
|--------------------|--------------------------|-------------------------------|----------------------|
| 220 GHz            | 900                      | 793                           | 774                  |
| 280 GHz            | 800                      | 681                           | 534                  |
| Total              | 1700                     | 1474                          | 1308                 |
| Percentage         | 96%                      | 84%                           | 74%                  |

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