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Characterization of a prototype SCUBA-2 1280 pixel submillimetre superconducting bolometer array

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ABSTRACT

We present the results of characterization measurements on a 1280 pixel superconducting bolometer array designed for operation at wavelengths around 450 µm. The array is a prototype for the sub-arrays which will form the focal plane for the SCUBA-2 sub-mm camera, being built for the James Clerk Maxwell Telescope (JCMT) in Hawaii. With over 10 000 pixels in total, it will provide a huge improvement in both sensitivity and mapping speed over existing instruments. The array consists of molybdenum-copper bi-layer TES (transition edge sensor) pixels, bonded to a multiplexer. The detectors operate at a temperature of approximately 175 mK, and require a heat sink at a temperature of approximately 60 mK. In contrast to previous TES arrays, the multiplexing elements are located beneath each pixel (an "in-focal plane" configuration). We present the results of electrical and optical measurements, and show that the optical NEP (noise equivalent power) is less than 1.4×10^{-16} W Hz$^{-0.5}$, and thus within the requirement of 2.9×10^{-16} W Hz$^{-0.5}$.

Keywords: TES, superconducting detectors, submillimetre astronomy, large format, imaging, array, SCUBA-2, detectors, characterization, JCMT

1. INTRODUCTION

Detectors for sub-millimetre wave astronomy are still in their infancy. Over the last ten years, available instruments have improved from single pixel detectors to arrays containing hundreds of pixels. Further gains in pixel count are necessary in order to fully exploit existing telescopes; however, the increase in pixel number must not be at the expense of sensitivity.

Sub-millimetre astronomy was revolutionised by the 131-pixel SCUBA instrument on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii.[1] A new instrument, SCUBA-2,[2] with over 10 000 pixels, and a large improvement in sensitivity and mapping speed, is expected to provide a further revolution. One important feature of the SCUBA instrument was simultaneous two-color operation, with one detector array operating at wavelengths of 450 µm and another at 850 µm; SCUBA-2 will operate in a similar manner.

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Bolometers are the most sensitive detectors for broadband measurements at sub-mm wavelengths.[3] Most existing instruments for sub-mm astronomy use semiconductor bolometers. The SCUBA instrument contained an array of discrete bolometers, each one constructed separately by hand. With this approach it is impractical to construct arrays of more than a few hundred pixels. Larger pixel counts are made practical by fabricating many pixels on a single silicon wafer.[4] However, manual operations are still required for the construction of each pixel. Furthermore, it is not possible to provide a multiplexed read-out without a prohibitive increase in noise; each channel therefore requires a separate read-out system. The resulting number of wires and size of read-out electronics puts a severe limit on the number of pixels that can be operated. Furthermore, semiconductor bolometers have reached the sensitivity limit that is believed possible for this technology.

A different detector technology has therefore been chosen for SCUBA-2, which uses superconducting rather than semiconducting detectors. A bolometer operates by measuring a change in temperature due to variations in incoming radiation; both semiconductor and superconducting bolometers achieve this by measuring a corresponding change in resistance. A superconducting detector makes use of the resistance change across the superconducting phase transition. As the temperature of a superconductor is increased, it will undergo a phase transition into the non superconducting ("normal") state. The electrical resistance changes rapidly with temperature in the phase transition, which can be made to have a width of a few millikelvin. This provides the basis for a very sensitive detector, known as a transition edge sensor, or TES.

It is, of course, necessary for the detector to be operated over this narrow temperature range. This is achieved by operating the detectors with a constant voltage bias, rather than the constant current usually employed with semiconductor bolometers. This provides negative feedback to temperature changes caused by changes in incident power. If the temperature is increased, the resistance increases and the Joule heating will decrease, causing the TES to cool, and thus opposing the temperature increase. Therefore there is no need for active temperature control to keep the detectors in the superconducting phase transition. The feedback also has the advantage of suppressing Johnson noise.

As well as increased sensitivity compared to semiconductor based bolometers, superconducting bolometers have several advantages. It is possible to fabricate an entire array using silicon micromachining techniques; all operations are carried out on the whole array, rather than on individual pixels. It is also practical to use a multiplexed readout, reducing wire count and size of electronics to a reasonable level.

TES detector arrays have previously been constructed in which the multiplexer is located on a separate silicon wafer, positioned away from the detectors. The SCUBA-2 focal planes are constructed from sub-arrays of 1280 pixels. With such a high pixel count, such an arrangement would be impractical, due to the large number of wires that would be required between the detectors and the multiplexer. The alternative is to use an "in-focal-plane" architecture, in which the detector and multiplexer wafers are bonded together, with the multiplexing element corresponding to each pixel being located beneath that pixel. The wafers are bonded together with indium bump bonds; these also carry electrical signals between the two wafers and provide a path for thermal conduction. While this is a new design for TES arrays, a similar scheme has been used for silicon semiconductor detectors connected to a CMOS multiplexer.[5]

SCUBA-2 requires two types of sub-array; one optimised for operation at wavelengths of 850 µm and the other at 450 µm. To date, we have successfully tested a prototype of one of each type of sub-array. Tests on the 850 µm subarray were carried out first, and are described elsewhere.[6] This paper describes tests carried out on a 450 µm sub-array. These were carried out both in a testbed dedicated to SCUBA-2 array tests, as well as in the SCUBA-2 instrument itself.

2. DESCRIPTION OF THE ARRAY

Each of the two arrays in SCUBA-2 is made up from four sub-arrays of 1280 pixels each. A sub-array is contained in a sub-array unit which provides electrical and mechanical interfaces between the sub-array and the instrument, as well as a circuit board maintained at a temperature of approximately 1 K. A brief description is given here; more detail can be found elsewhere.[7,8]

The layout of a sub-array unit is shown in Figure 1. The sub-array itself is formed from a detector wafer[9,10] (shown in Fig. 2) and a multiplexer wafer[11–13] (shown in Fig. 3); these two silicon wafers are bonded together with indium bump bonds. The detector wafer contains 1280 pixels, in a 32x40 format. The sensing element of each pixel is a molybdenum-copper TES; weak thermal linking to the heat sink is provided by a silicon nitride membrane. Each pixel also contains a resistive heater, which will be used to compensate for changes in optical power as the sky background changes. This enables the pixels to be operated at a chosen bias point for a wide range of sky powers. In order to operate with the required

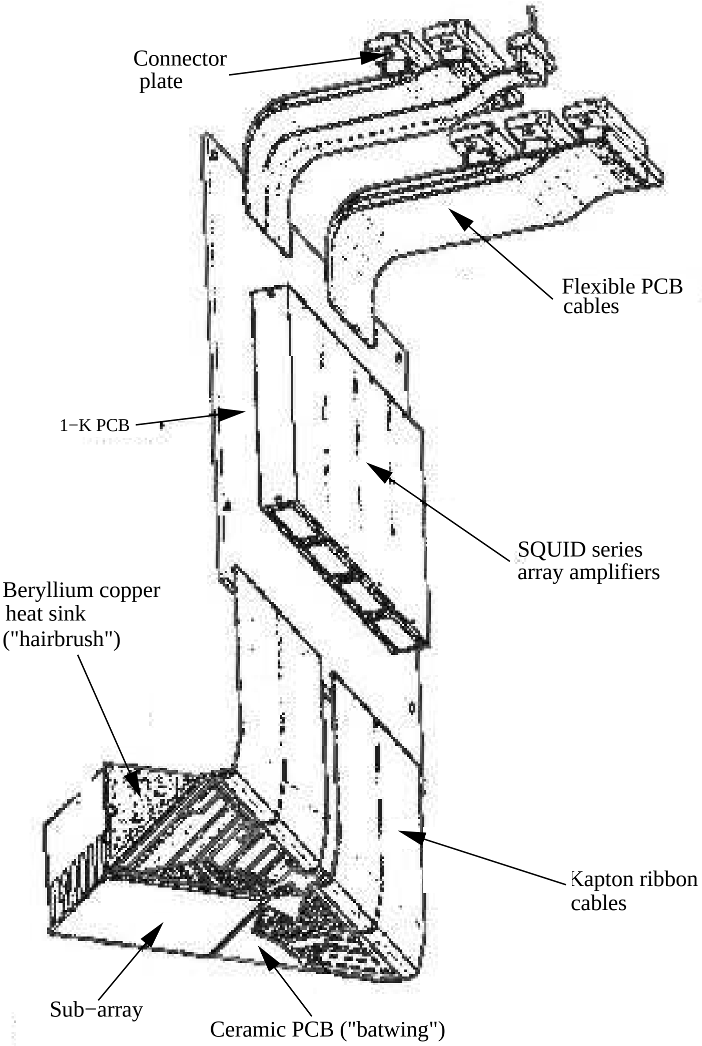

Figure 1. The layout of a sub-array unit, consisting of the detector sub-array, the detector heat sink, the 1-K PCB and the cabling to the connector plate.

sensitivity, the detector wafer must be cooled to a temperature below 60 millikelvin (the sensors themselves are heated by the bias current, the pixel heaters and absorbed radiation to a temperature of approximately 175 mK). This is achieved by mounting the sub-array on a beryllium copper heat sink, which is linked by copper straps to the mixing chamber of a dilution refrigerator.

The heat sink (known as the "hairbrush") consists of a grid of separate tines, one for each pixel. Each tine is bonded to the sub-array with epoxy. It is important that the tines are not bridged by the epoxy. To ensure this, a drop of epoxy is deposited on each time using a commercial liquid deposition system. This scheme prevents stress from differential thermal contraction between the beryllium copper and the silicon from damaging the wafers when they are cooled to cryogenic temperatures.

The signals from the pixels are read through the multiplexer wafer, using a time division multiplexing scheme. Each pixel has a corresponding SQUID which is biased to read out the pixel. The output from all the SQUIDs in a single column is read out by a further SQUID. Signals are then amplified by SQUID series arrays; these are units of 100 SQUIDs connected in series. Due to the high power dissipated in these units, they cannot be mounted at millikelvin temperatures,

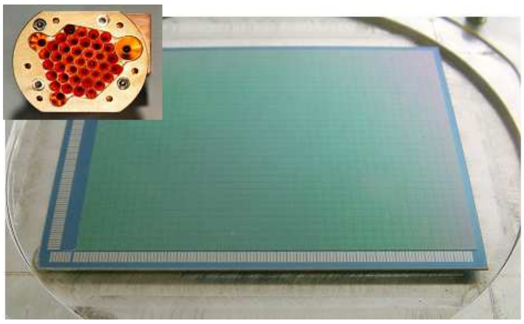

Figure 2. A SCUBA-2 detector wafer (the inset shows a SCUBA focal plane for comparison).

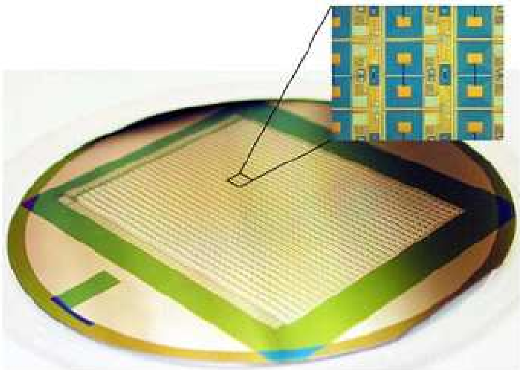

Figure 3. A SCUBA-2 multiplexer wafer.

and are instead located on a circuit board (the 1-K PCB) which is maintained at a temperature of approximately 1 K.

A ceramic PCB is also mounted on the hairbrush; the detector wafer is connected to this PCB via wire bonds, and this is connected to the 1-K PCB via ribbon cables. These consist of niobium tracks evaporated onto 50 µm thick Kapton tape; this design minimizes the thermal conduction down the cables. Flexible layers in the 1-K PCB extend to a connector plate. This provides a connection to a harness running to the room temperature electronics. The harness consists of Monel clad niobium-titanium wires woven into a ribbon cable.

3. TEST ENVIRONMENTS

The 450 µm prototype has been measured in two systems; the SCUBA-2 testbed, and the SCUBA-2 instrument itself. The SCUBA-2 testbed, located at Cardiff University, enables a full sub-array unit to be characterised under varying conditions. The system has been used to evaluate the two prototype sub-arrays, and will be used to characterize the science grade sub-arrays before integration in the instrument. The testbed replicates the mechanical and electrical interfaces of the instrument, so that a sub-array unit can be mounted in the testbed without modification. The testbed harness is identical to the harnesses used in the instrument apart from its length. Cooling is provided by a dilution refrigerator constructed by the same company as the fridge used in the instrument.[14] A more detailed description of the testbed is given elsewhere.[6] Figure 4 shows a sub-array unit mounted in the testbed system.

The testbed and the instrument offer different possibilities for tests. The testbed contains sub-mm illuminators[15] which can be modulated at a speed of approximately 2 Hz to simulate astronomical signals. The radiation output from these illuminators has been calibrated using measurements in a separate system. The instrument does not have internal illuminators, but can view either the outside environment or a cold shutter. In both cases, the optical path passes through band-defining filters. While the testbed environment is designed to be similar to that of the instrument, it cannot replicate the conditions

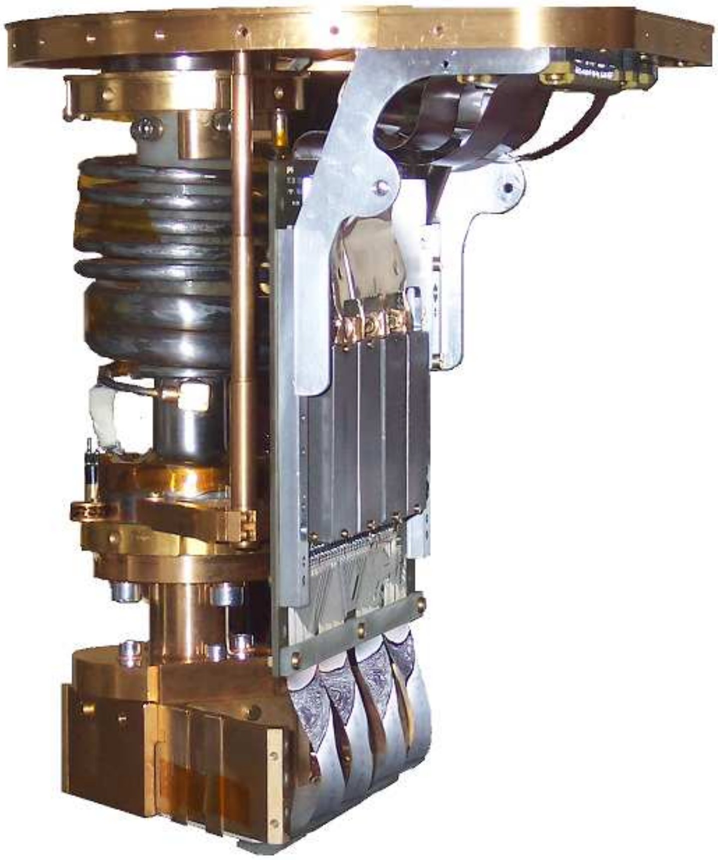

Figure 4. A sub-array unit mounted in the Cardiff SCUBA-2 testbed. The sub-array is mounted in a similar orientation to the diagram in Fig. 1. The dilution unit of the dilution refrigerator can be seen to the left of the sub-array unit.

perfectly. In particular, cooling to a temperature of 4 K in the testbed is provided by a conventional helium bath, rather than pulse tube coolers as in the instrument. Tests carried out in the instrument are therefore very important, particularly to demonstrate that the array performance is acceptable in the presence of any vibration from the coolers. Figure 5 shows an image of the sub-array mounted in the focal plane unit[16] which is part of the instrument. Figure 6 shows the focal plane unit in place in the instrument. The instrument level tests described here were performed with the instrument at the Astronomy Technology Centre, Edinburgh.

Two systems were used to read out the detectors. One system, developed at the National Institute for Standards and Technology (NIST), was used for many of the measurements in the testbed. This system was capable of addressing a quarter of a sub-array simultaneously. Some measurements in the testbed, and all the tests in the instrument, were performed using a prototype model of the electronics to be used at the telescope (the multi-channel electronics, or MCE, developed at UBC). This system can address a full sub-array simultaneously; each subarray will have its own set of electronics at the telescope.

4. RESULTS

Both readout systems were capable of reading out large numbers of pixels simultaneously. However, the readout chain for each pixel is quite complex, with several parameters requiring accurate tuning. In normal operation, these parameters will be set up automatically. However, the software to carry out this task was unavailable at the time of these tests, and the set-up had to be carried out by hand. Most measurements were therefore carried out on a small number of pixels at a time. As our experience in “tuning” these parameters improved, we were able to move to tests with larger numbers of pixels. Figure 7 shows a simultaneous measurement of 72 pixels responding to a modulation in the detector bias. The

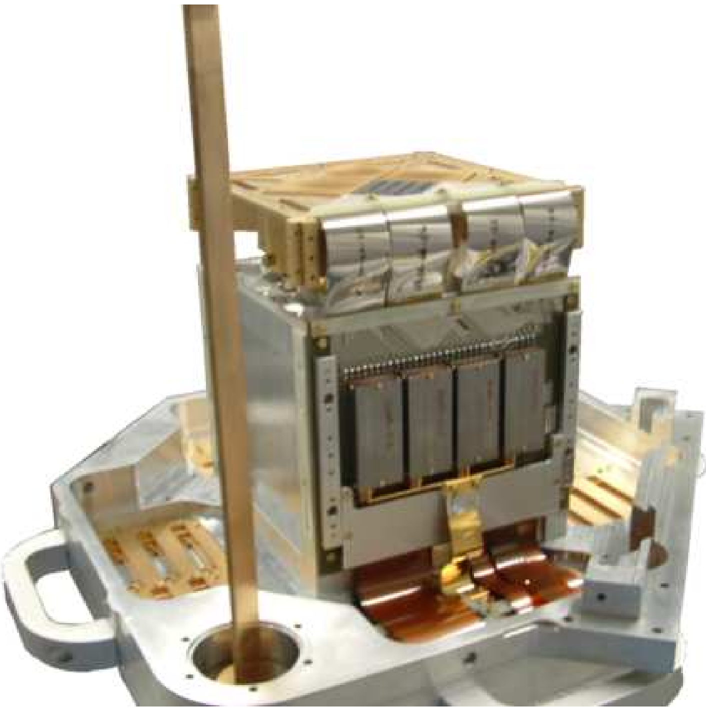

Figure 5. A sub-array mounted in the focal plane unit which is part of the instrument. In operation, this structure will contain four sub-arrays, making up a full focal plane. Note that the sub-array unit is upside-down compared to Fig. 4.

Figure 6. The focal plane unit shown in Fig. 5 mounted in the SCUBA-2 instrument. The sub-array unit is mostly hidden by the 1-K radiation shielding; only the connector plate is visible.

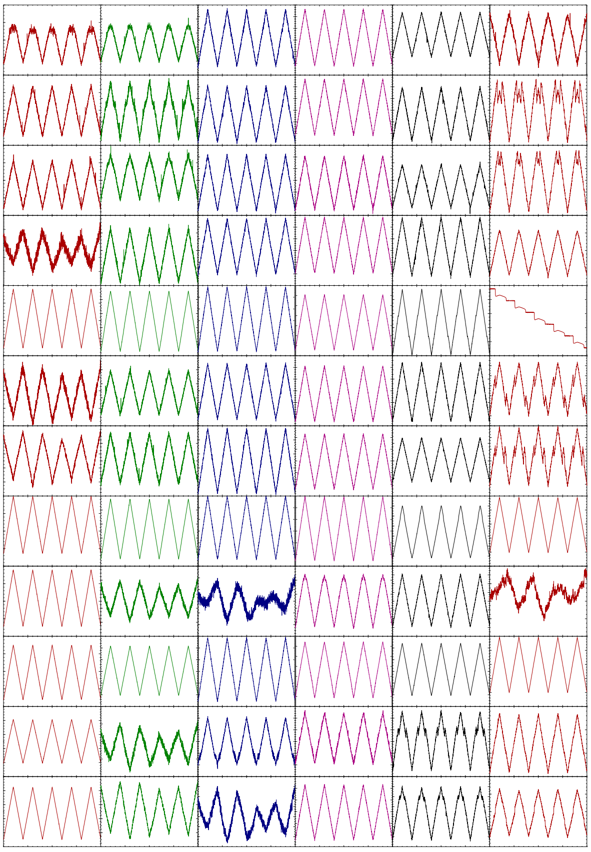

Figure 7. The response to a bias modulation measured simultaneously by pixels in 12 rows in 6 columns. For each graph, the x-axis shows time, and the y-axis shows detector current.

multiplexer and read-out system was very stable; once it had been configured, the settings (such as the bias to the various SQUID stages) remained valid from day to day.

A common method of characterising detectors is to measure the detector current as a function of applied bias; this is sometimes called a load curve. Figure 8 shows sets of load curves taken on three pixels with the detectors in the instrument. Measurements were made for a set of different power settings for the pixel heaters. The load curves show the characteristic shape for a TES. Fig. 8 also shows the same measurements plotted as electrical power in the TES as a function of bias voltage.

A property of TES detectors is that in the superconducting transition, the total power (optical + electrical (from the detector bias and pixel heaters)) is constant to a very good approximation. Therefore the measured power in the transition for a given load curve (with the heater power held constant) should not vary with detector bias. Moreover, if a measurement is made with a different heater power, the electrical power in the detector should change accordingly. These effects can both be seen in Fig. 8.

Above the superconducting transition, the detector acts as a simple resistor; the power is proportional to the square of the detector voltage and does not depend on the heater setting.

The (electrical) responsivity of the detectors can be obtained by calculating the difference in detector current at a given bias voltage for pairs of load curves taken with different heater powers. As is expected for a TES detector, the responsivity, S, was in good agreement with the relation $S = 1/V$, where V is the voltage across the detector. The resulting values for the responsivity varied from approximately 5×10^5 to 8×10^6 A/W, depending on bias. These values are in agreement with measurements made by applying a modulation to the detector bias, as well as those obtained on single pixel devices.

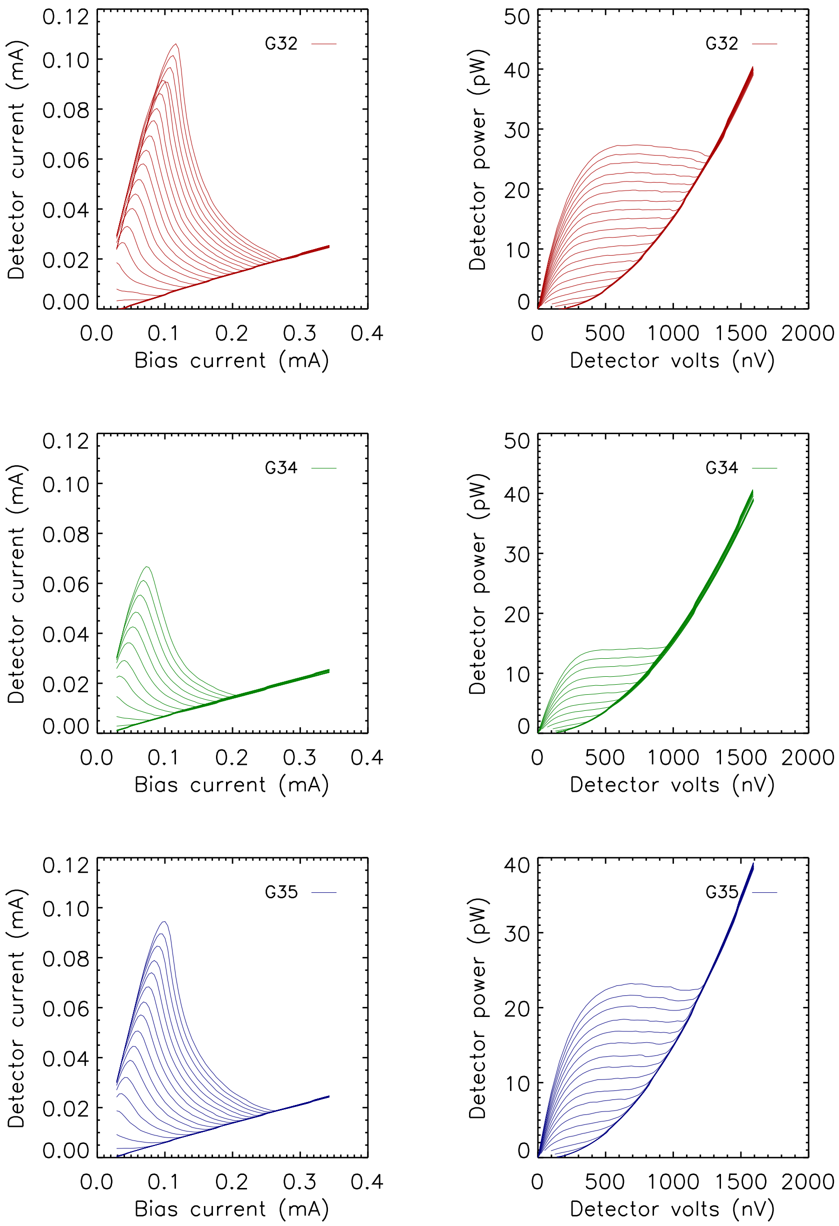

Figure 8. Left hand side: load curves (detector current as a function of bias current) measured on three pixels. Right hand side: Detector power as a function of detector voltage for the same pixels. Each graph shows a family of load curves taken with different values for the heater power. The heater power increases with decreasing detector power.

The response to optical radiation was measured in the instrument by taking sets of load curves viewing different optical loads. The instrument contains an internal shutter maintained at a temperature of approximately 1.5 K. With the shutter open, the detectors view the cryostat window. Fig. 9 shows the results of such measurements; with the shutter open, the detectors view a mirror placed over the cryostat window. The total power (from the detector bias and the pixel heaters) can be seen to remain constant for a set of measurements, as is expected for a TES device. This agreement is achieved by assuming that for each pixel approximately 54 % of the power from the heater is absorbed by the detector; this is in

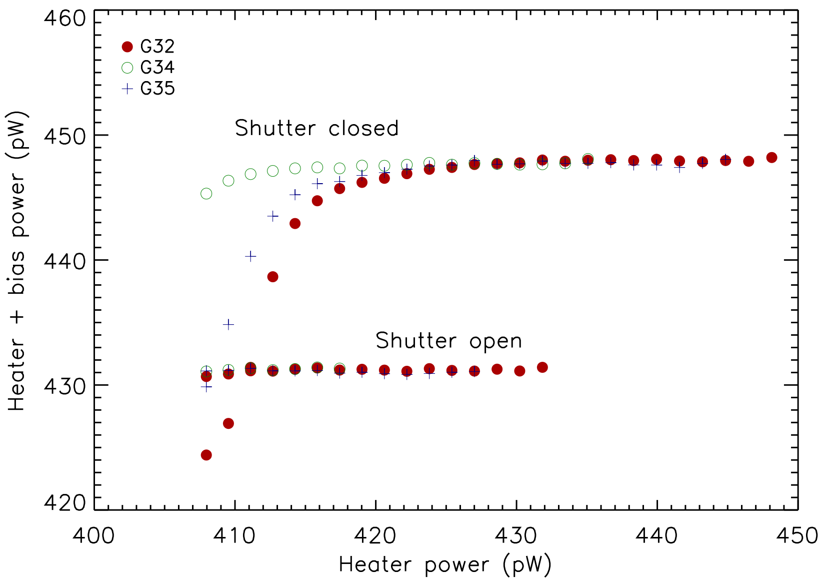

Figure 9. Total electrical power (from the detector bias and the pixel heaters) in the superconducting transition for measurements on three pixels with the array viewing either an internal cold load ("shutter closed") or a mirror outside the cryostat ("shutter open"). The measurements with the shutter closed correspond to the load curves shown in Fig. 8. The pairs of measurements for a given pixel have been offset slightly along the y-axis to bring them into agreement and thus to show the excellent agreement for the change in power with the shutter open and closed between the three pixels.

reasonable agreement with the findings from tests on single pixel devices. When the shutter is opened, the electrical power drops to compensate for the increased optical power. The change in electrical power (and thus in optical power) for the three pixels is in excellent agreement.

Optical measurements were also carried out in the *testbed*; here, the power was obtained from the internal sub-mm illuminator. The total power at the detectors could be calculated from the known properties of the intermediate filters, along with a calibration for the illuminator carried out in a separate cryostat. The measured power was in good agreement with the expected values.

The good agreement between bias, heater and illuminator power suggests that we have a good calibration both for the detectors and for the testbed itself. This is important in order to obtain reliable values for the detector noise equivalent power (NEP).[17]

Measurements in the instrument gave an electrical NEP of 2.5×10^{-16} W Hz$^{-0.5}$. This value was obtained from the power spectral density calculated from measurements of the detector signal (in the superconducting transition) over a period of 250 seconds, along with the responsivity measured from load curves. This value is just outside the requirement of 2.1×10^{-16} W Hz$^{-0.5}$. However, this value is an upper limit because the prototype readout electronics were limited to a pixel frame rate of 1 kHz, which significantly undersamples the pixels and thus increases the observed noise. A firmware upgrade will allow higher frame rates as planned in normal use. This is expected to reduce the white noise by approximately a factor of 4.

A value for the optical NEP was obtained from tests carried out in the testbed. Here, the illuminator was modulated at a frequency of 2 Hz while sampling the detector current at a frequency of 48.8 kHz. The NEP was then obtained by Fourier transforming the resulting data and comparing the magnitude of the response at the illuminator modulation frequency with the noise floor. Values of below 1.4×10^{-16} W Hz$^{-0.5}$ were obtained. This exceeds the requirement of 2.9×10^{-16} W Hz$^{-0.5}$. However, these values are also an upper limit. For these measurements, the room temperature electronics were modified to allow more dynamic range when taking load curves. A consequence of this was to reduce current resolution, and the measured current noise was at the level of bit noise expected from the digital to analogue conversion. We therefore expect that the true optical NEP is somewhat lower than this figure.

Finally, it should be noted that most of the measurements presented here, including the electrical NEP, were carried out in the instrument, and thus with cooling provided by pulse tube coolers. It is clear that any vibration from the coolers does not prevent successful operation of the detectors.

5. CONCLUSIONS

We have shown that the pixels in the prototype sub-array operate in a stable fashion, with results from characterization measurements that are both self-consistent and consistent with the expected values. The read-out system is also stable, with optimal parameters for the SQUID stages remaining constant from day to day. An upper limit for the electrical NEP measured in the instrument is close to the requirements for the array, even in the presence of pulse tube coolers. The optical NEP, measured in a testbed, was within the requirements. These results have enabled the start of production of the science-grade arrays that will make up the focal plane of the SCUBA-2 instrument.

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