A Compact, Modular Package for Superconducting Bolometer Arrays

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***Abstract*— As bolometer arrays grow to ever-larger formats, packaging becomes a more critical engineering issue. We have designed a detector package to house a superconducting bolometer array, SQUID multiplexers, bias and filtering circuitry, and electrical connectors. The package includes an optical filter, magnetic shielding, and has well-defined thermal and mechanical interfaces. An early version of this package has been used successfully in the GISMO 2mm camera, a 128-pixel camera operating at a base temperature of 270mK. A more advanced package permits operation at lower temperatures by providing direct heat sinking to the SQUIDs and bias resistors, which generate the bulk of the dissipation in the package. Standard electrical connectors provide reliable contact while enabling quick installation and removal of the package. The design compensates for differing thermal expansions, allows heat sinking of the bolometer array, and features magnetic shielding in critical areas. It will be scaled to 1280-pixel arrays in the near future.**

I. Introduction

The state of the art for far-infrared and submillimeter instruments being developed for ground-based, airborne, and space-based observations now consists of arrays of broadband detectors containing at least a thousand elements. The largest operational cryogenic detector array from NASA's Goddard Space Flight Center to date is the 384-pixel bolometer array manufactured for the Caltech Submillimeter Observatory (CSO) SHARC-II instrument [i]. This array uses a design for close-packing detectors to achieve a near unity filling factor. However, the bolometers use semiconducting thermistors read out by individual FETs for every pixel. Future instruments require bolometer arrays with many more pixels, and may require sensitivity of 100 times better. A design using superconducting transition edge sensor (TES) bolometers and multiplexed SQUID readouts can achieve this, in part due to the scalability of a suitable multiplexed readout. A TES bolometer has a faster response time than an identically designed, same sensitivity semiconducting bolometer (or a more sensitive bolometer for the same response time) due to the strong negative electrothermal feedback intrinsic to a voltage-biased TES [ii]. TES bolometers are inherently low impedance devices, so they are well matched to being read out by DC SQUID amplifiers [iii]. These amplifiers have a large noise margin over the TES Johnson noise and bolometer phonon noise. This permits the bolometer to be read out in a multiplexed fashion by a suitable SQUID multiplexer [iv], thereby reducing the amplifier size and the wire count. Because SQUID multiplexed amplifiers operate at the base temperature of the bolometer, they can be coupled very closely, removing the complex interfaces necessary with semiconducting bolometers. Past work by our group has resulted in the demonstration of such detector systems operating using SQUID multiplexers [v], optical detection of light while multiplexing [v], Johnson-noise-limited readout by SQUID multiplexers [vi], near-phonon-noise-limited bolometers [vii]. Recently, we have fielded the largest superconducting bolometer array to be used at a telescope [viii]. This paper details our design of a package to house an array of multiplexed TES bolometers that is compact, modular, and scalable to at least 1,280 detector elements.

II. The GISMO Camera

We began work in late 2005 on a new bolometer camera that became GISMO, the Goddard-IRAM Superconducting 2 Millimeter Observer [ix]. Optimized to operate in the 2mm atmospheric window at the IRAM 30m radio telescope on Pico Veleta, Spain, this camera was conceived as a means of field-testing superconducting bolometer arrays fabricated using the recently-developed backshort-under-grid architecture [x, xi, xii]. GISMO can also produce cutting-edge scientific results, being optimized for large-area surveys of the very high redshift ($z \geq 5$) universe [xiii]. The bolometer array was designed with 128 pixels arranged in an 8×16 format, with wiring brought out along the beams between pixels to connect to a 4×32 array of SQUID multiplexers. In order to simplify the assembly and test of the instrument, we wished to develop an integrated, compact cryogenic detector package that contained the detector array, SQUID readouts, all necessary thermal and mechanical structures, magnetic shielding, an optical bandpass filter to limit the wavelength range of light entering the package, and a set of electrical connectors to communicate into the package. We also sought to use several aspects of this package as the point of departure in designing a detector package able to accommodate 32×40 bolometer arrays based on the SCUBA-2 multiplexer developed by NIST/Boulder [xiv].

III. Schematic Diagram

The design of the 4×32 readout is based on heritage to earlier instrument developments using the NIST/Boulder 1×32 time-domain SQUID multiplexers [xv , xvi]. This includes both readout electronics development [xvii, xviii] and instruments that have been successfully used on ground-based telescopes [xix, xx]. One important property of these SQUID readouts is that they operate naturally at the very low temperatures required by sensitive bolometers (in this case, at 300 mK). They dissipate little power (4 nW per 1×32 multiplexer, only a few times more than the dissipation in the bolometers themselves), and can therefore be closely coupled to the bolometer array wafer. In addition to the multiplexer, a superconducting Nyquist filter inductor and a bias shunt resistor must be included for each pixel.

The schematic diagram of the electrical wiring in the 4×32 package is shown in Figure 1. The diagram for a 32×40 package is very similar, with the addition of a dark SQUID channel that acts like row 41, but has no TES, bias, or filter on the input. Designed as a three-stage amplifier, the high gain third stage requires of order 1 μW of power and hence is located in a physically separated package, which is thermally connected to the ^{4}He bath. The first stage SQUID multiplexer inputs are shown (in green in color versions of this paper), along with the input coil, feedback coil, and transformer coil. Feedback provided by the room temperature electronics exactly nulls the signal from the input coil, so that the input SQUID is operating at a nearly constant locus on its flux-voltage characteristic. This provides, to first order, linear response from the SQUID, and results in the error term being the flux transformed out into the summing loop that couples to the second stage SQUID. It should be noted that the transformer coil does not couple directly to the SQUID, but instead is used to sense the changing voltage across the SQUID with flux by the changing current through the parallel address resistor.

Multiplexer-compatible chips consisting of 32 L≈1 μH superconducting inductors and 32 low-value bias resistors (R≈2 mΩ) are fabricated by NIST/Boulder and NASA/GSFC, respectively. The inductors, shown in purple in Figure 1, have a pass-through aspect not emphasized in the figure, and with a coil on the side connected to the shunt resistor and a coil on the side connected to the TES. This balancing provides symmetry while achieving the function of bringing the integrated signal to the multiplexer. The bias shunt resistors, shown in blue, have a pass-through provided by bridging wirebonds over the bias loop (the vertical portion of the wiring in the blue area). These accommodations allow the compact arrangement of the readout circuit, which is the subject of Section V.

IV. The 8x16 Bolometer Array

The detector array design and performance has been detailed elsewhere [xxi], and so only a brief summary will be made here. For orienting the reader, a photo of two arrays is shown in Figure 2. The pixel pitch is 2 mm to avoid complicated optical coupling at pitches <λ while keeping a small overall size. The detector chip is 32 mm × 48 mm and has a pair of 3 mm diameter holes spaced by 41 mm to enable mounting. Gold heat sink pads next to the holes are used to enable gold wirebonds to make thermal attachment to the array. In Figure 3 we show an enlarged view of a single pixel. Each corner of a pixel connects to the beams that make up the structural grid of the suspended bolometer at two places, so there are a total of eight legs providing a saturation power of ~32 pW between 300 mK and T_C~450 mK. The TES is the small gold rectangle near the upper edge, located so as to minimally interfere with the optical absorption. A back-side coating of bismuth provides high efficiency absorption at many wavelengths, and a reflective λ/4 backshort tunes this absorption to peak efficiency at the desired 2 mm wavelength.

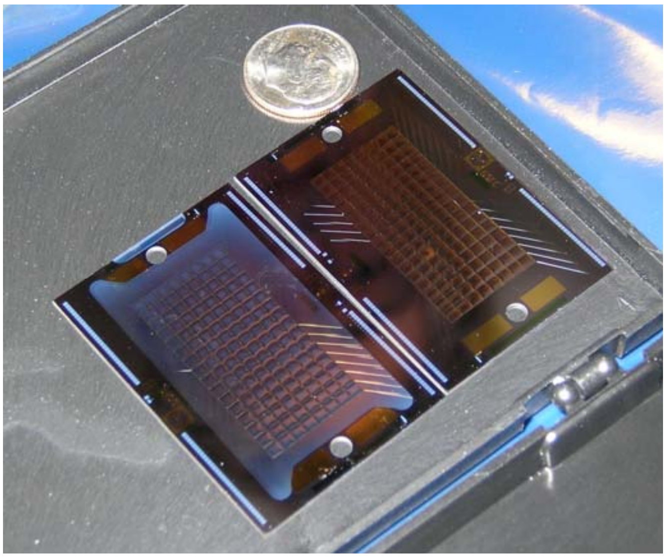

Figure 2. A photo of two transition edge sensor bolometer arrays for GISMO shows the scale of the active area as well as the areas for signal connections and heat sinking or mechanical attachment.

Figure 3. This micrograph of a single pixel shows the style of thermal attachment to the beams making up the bolometer array grid. The TES is the small gold rectangle at the top edge

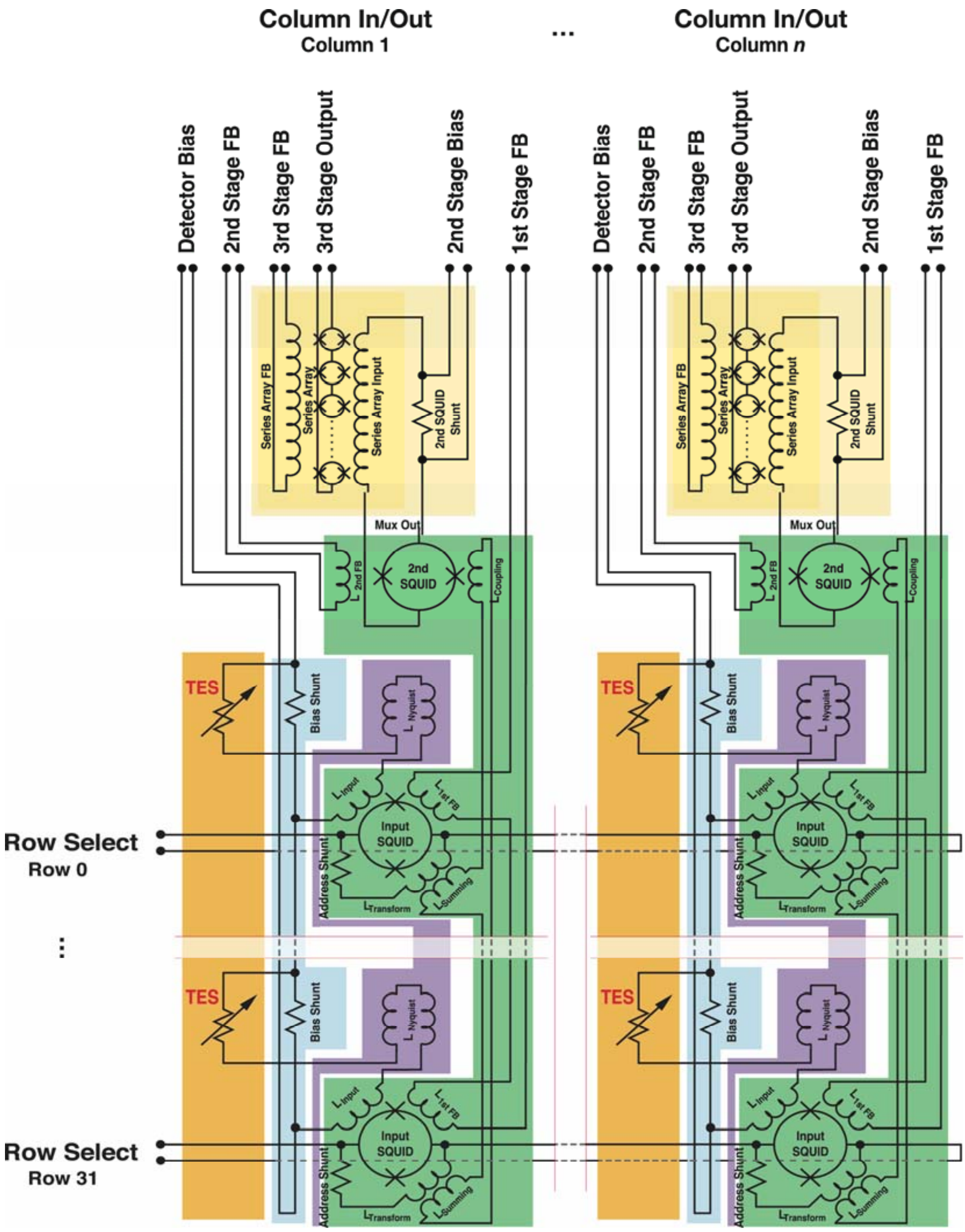

Figure 1. The schematic diagram of the multiplexed system shows that each column requires six pairs of wires for bias and readout, while the total number of address pairs is 32 when wired directly or 8 when wired using a demultiplexing address driver [xviii]. The readout unit consists of a single set of the SQUID/Nyquist/Shunt (green/purple/blue) chips as detailed in Section V. The series array amplifier (yellow) chips at the top are located in a different housing at a higher temperature.

V. Readout Unit

We have designed the readout circuit above to enhance its modularity and robustness. The overall goal is to produce a small-volume modular readout unit to provide multichannel cryogenic readout within the GISMO detector package and also within other future detector packages. At the same time, we sought to provide well-engineered electrical, mechanical, magnetic, and thermal interfaces.

To ease the electrical interfaces, we have designed a ceramic circuit board that brings wire bonds out to large, reusable pads for more bond cycles and improved chip heat sinking. The circuit board traces also bring pads to only two edges as opposed to the three necessary before. The circuit boards, shown in Figure 4, consist of 99.6% alumina ceramic 0.5mm thick with silkscreened gold traces, custom manufactured by Emtron Hybrids [xxii]. Mounting holes at the corner permit attachment to a thermal/mechanical

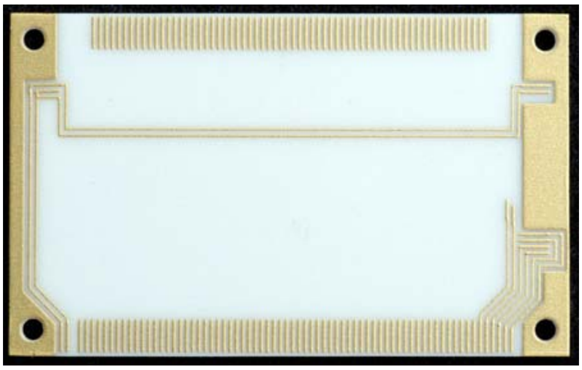

Figure 4. An alumina ceramic readout circuit board with gold traces prior to adding superconducting shorts to reduce stray resistance. The board measures 15 mm by 25 mm.

structure, discussed below. The design requires superconducting traces to prevent loss and heating; this effect is particularly important for the second stage output and detector bias lines, respectively, where the impact is most notable. It proved challenging to achieve very low total loop resistances in these boards, as the requirement of ≤10 mΩ necessitates high purity normal metals for the bond pads and superconducting traces for the wiring runs. We used pure gold wiring and shorted many of the traces with superconducting aluminium bond wires to ensure the lowest possible parasitic stray resistance. Aluminum wirebonds within the readout chips and to traces on the circuit board carry all signals. A photo of an assembled readout board is shown in Figure 5, along with an enlargement showing some of the trace-shorting wirebonds in Figure 6.

In the earlier GISMO detector packages, the ceramic carrier was glued directly to a metalized fiberglass board. While the coefficient of thermal expansion (CTE) mismatch is not exceptional, being on the order of 3 mm/m total, some failures were seen on repeated thermal cycling. It is possible that the combined CTE mismatch including the Nb foil was too great, producing large shears across a very small volume. We therefore designed a flexible metal bracket to hold the

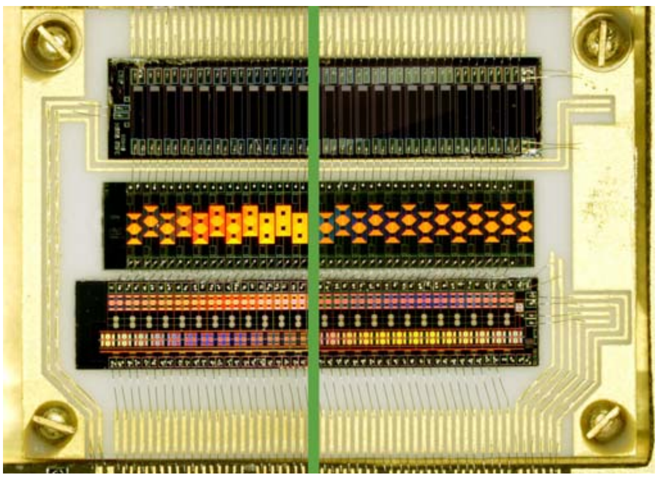

Figure 5. A composite photograph of a completed readout unit; several of the 32 channels have been cropped out of the middle. The chips are, from top to bottom, the shunt, Nyquist inductor, and SQUID multiplexer.

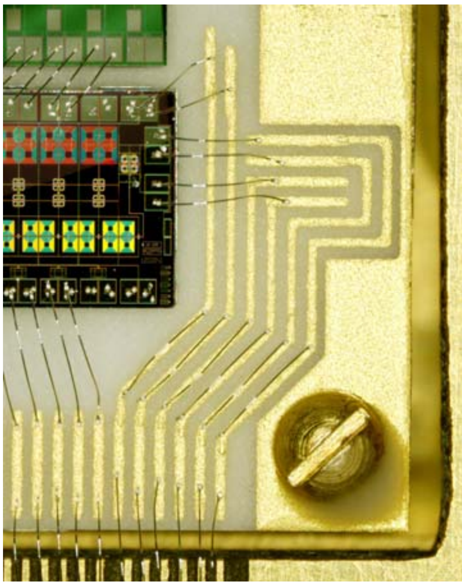

Figure 6. This in-progress photo of the wirebonding shows the first leg of superconducting bonds to short out critical gold traces.

ceramic circuit board (Figure 4) and the Nb foil separately. This grappler bracket, shown in Figure 7, uses flexures to accommodate the CTE mismatch between the ceramic and the copper of the bracket. The circuit board is attached to the grappler bracket by means of four 000-120 brass screws, nuts, and washers. A three-point 0-80 screw mount to the bottom side permits a quasi-kinematic mounting of the readout assembly. The Nb foil is glued to the back side of the ceramic board, alleviating the CTE problems across the foil. The assembly process is shown in Figure 8.

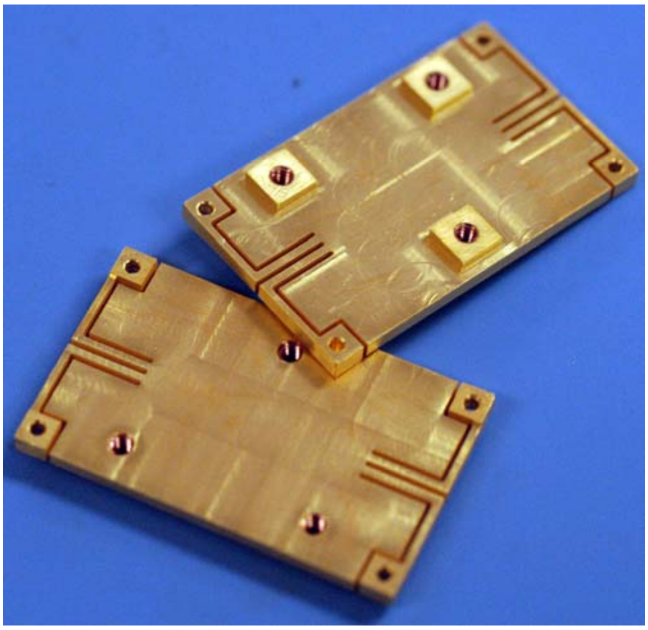

Figure 7. The grappler brackets are made from OFHC copper with wire EDM flexures, gold plated to provide good thermal contact to both the ceramic circuit board and the copper detector package box. Parts made by Zen Machine and Scientific Instrument [xxvi].

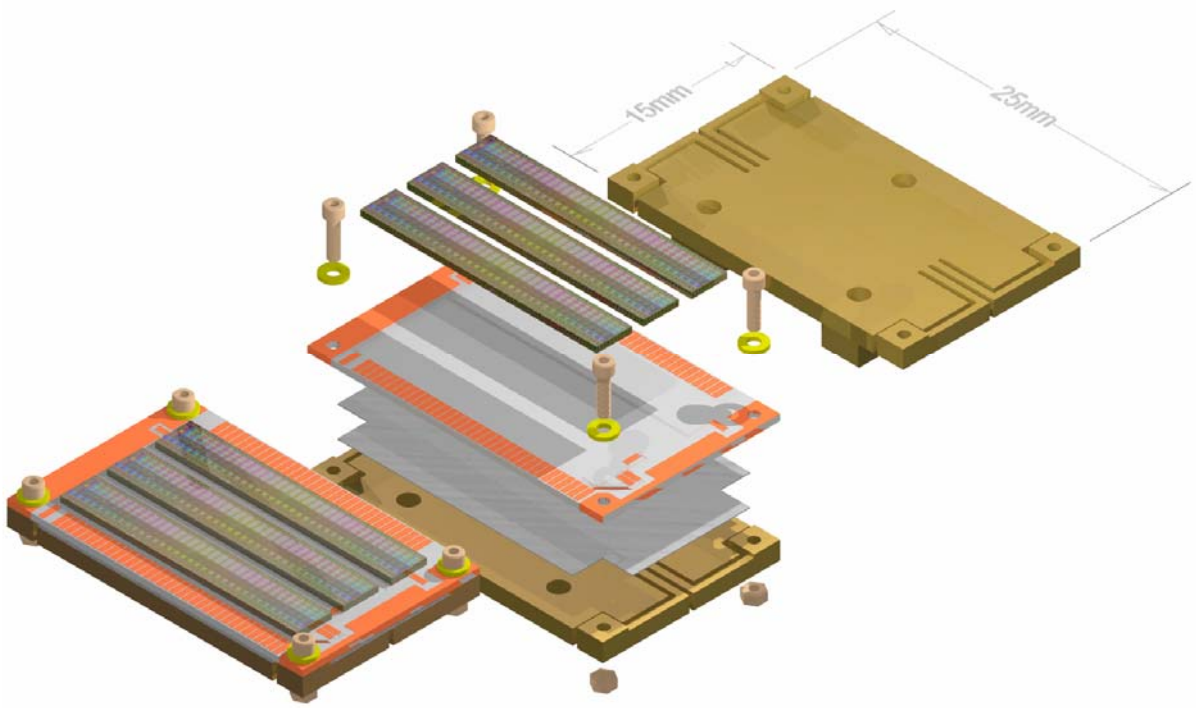

Figure 8. The assembly drawing of the readout circuit shows the parts described in the text.

VI. Detector Package Design

Our design for the GISMO 4×32 detector package incorporates several key elements that contribute to its proper function. It was designed for small overall volume (11.9 cm × 8.8 cm × 1.9 cm) and mass. Simple electrical connections were required for an easily mateable/demateable interface to the detectors and readouts. Robust thermal interfaces were necessary to enable heat sinking of the critical parts. We also needed to provide magnetic shielding at several levels and to maintain a light-tight package except for a window with a bandpass filter [xxiii], so that the environment inside the package would be free of both stray magnetic fields and stray light.

A. First Generation Package

The first generation GISMO detector package was used for an engineering observing run in November 2007 [viii]. For this package, we used small but readily available connectors for the electrical interface: microminiature D connectors with a dense footprint, with three connectors providing cable attachments to three 4K electronics boards. The detector package volume is to a certain extent determined by the connectors; they limit both the length and height of the overall package.

Magnetic shielding was accommodated by means of a niobium foil (see section 2.1), but augmented by an overall shield made of lead tape that was wrapped around the detector package after assembly. The entire cryostat is magnetically shielded with high permeability material [xxiv], and hence the superconducting shields should operate in a small magnetic field environment. Unfortunately, residual magnetic susceptibility was seen during the observing run; some pickup of the Earth's magnetic field was seen on all SQUID channels. The GISMO cryostat has a very large (~20cm) window with the detector package roughly one window diameter inside. It is most likely that magnetic flux penetrates far down into this region. In this case, flux trapping would occur when the insufficiently shielded Nb foil goes through its superconducting transition, leading to degraded performance from the SQUID amplifiers.

The three microminiature D connectors are a large fraction of the total heat capacity of the detector package, and additionally require large penetrations through the magnetic shielding. The second-generation package uses two Nanonics [xxv] connectors for the same wiring, reducing the volume of connectors by around an order of magnitude and shrinking the penetration area by a factor of several.

The detector array is mounted on a copper-plated alumina ceramic board that is epoxied to four flexure mounts built into the base of the copper detector package. The array is surrounded by a fiberglass circuit board with eight copper wiring layers, plated on both sides with bondable gold. The readout assemblies are glued to this board and are wirebonded to both it and the detector array. The array is heat sunk by means of many gold wire bonds to the upper layer of the fiberglass board, which is attached to a copper braid that penetrates the package and is used to provide direct cooling from the 300 mK ^{3}He cooling system to the detector package interior. An overall view of the completed detector package is shown in Figure 9 (with no lid) and Figure 10 (with lid, optical filter, and magnetic shielding applied).

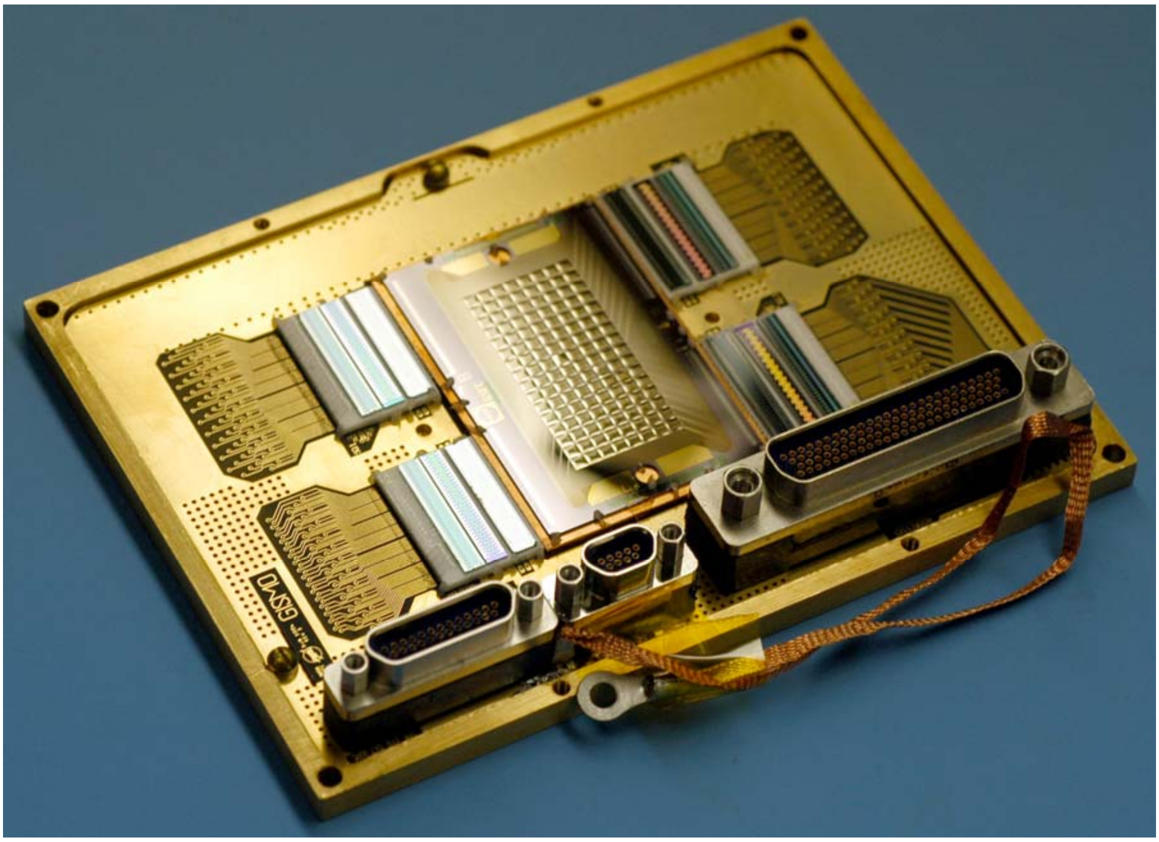

Figure 9. View of the first-generation detector package with the lid, filter, and magnetic shielding removed. The copper braid thermal connections are near the bottom; three connectors sit at the edge of the package; a gold-plated fiberglass circuit board handles the interconnections and holds the readouts.

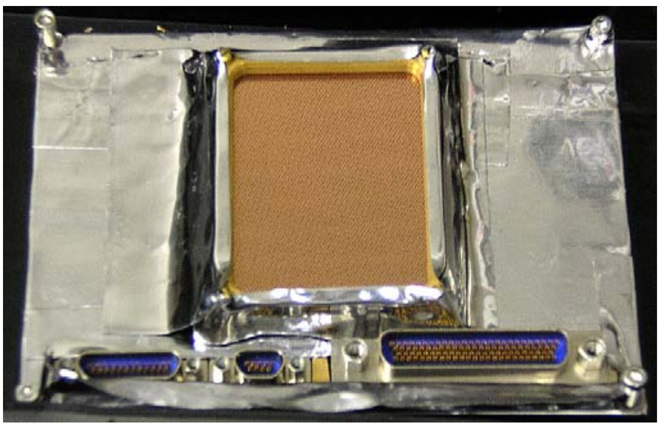

Figure 10. Completed first-generation detector package, showing the connectors, bandpass filter, and overall lead tape shielding.

B. Second Generation Package Design

Our second-generation detector package is designed to maintain most aspects of the interface while improving several aspects of its performance. The robust mechanical connection and heat sinking of the readout chips was discussed in Section V. This design reduces the overall surface area of the fiberglass board, which permits larger arrays to be mounted in the center. There is enough space to situate our prototype 32×40 detector arrays, which have a footprint of around 41×51 mm, easily within its 53×65 mm central space, with the extra area to be used by a suitably designed heat sinking ceramic board. As mentioned above, the connectors were changed to Nanonics type, which are much smaller. In the near future we plan on implementing superior stray light rejection by blackening the inside of the detector package lid, and superior magnetic field rejection by placing symmetric layers of Nb foil and Metglas [xxiv] on the top (where possible) and bottom surfaces. We have also made the detector array's ceramic board screw-mounted onto flexures to permit more accurate and reliable attachment to the detector package base.

This package was fabricated by Zen Machine & Scientific Instrument [xxvi] and has been tested with a 128-pixel array in August 2008, for an expected observing run in the October 2008. A 1,280-pixel version will be produced following this. Pictures of the package design and assembly and several key components are shown below in Figure 11-15.

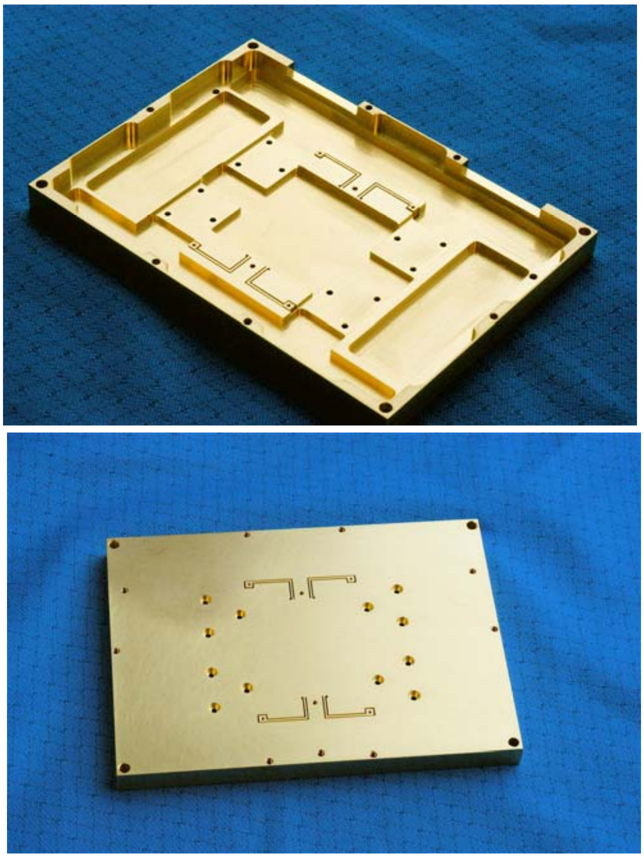

Figure 11. Second-generation detector package box base, as seen from the inside (top) and outside (bottom). Many internal features are lightweighting.

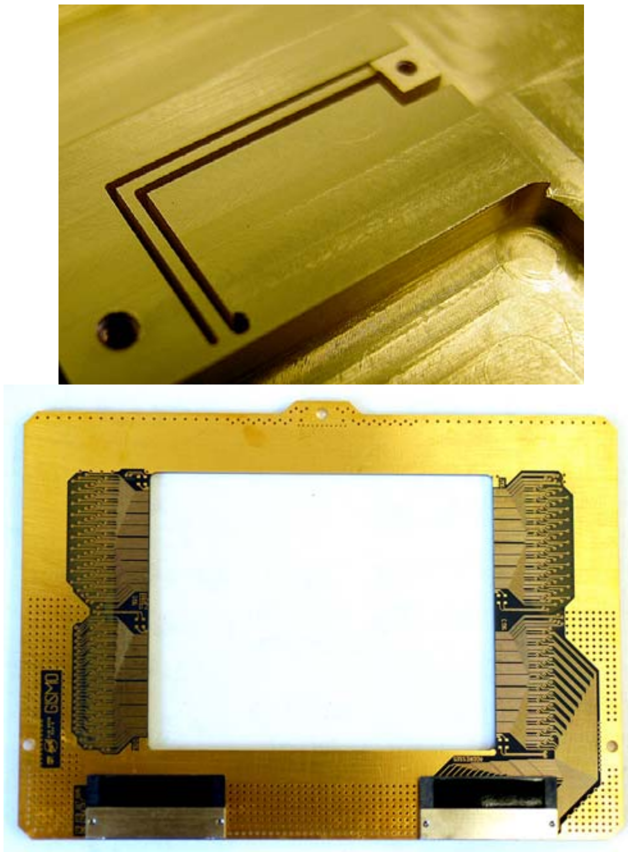

Figure 12. (Top) Close-up of a detector array flexure mount (1 of 4); (Bottom) Fiberglass circuit board with Nanonics connectors.

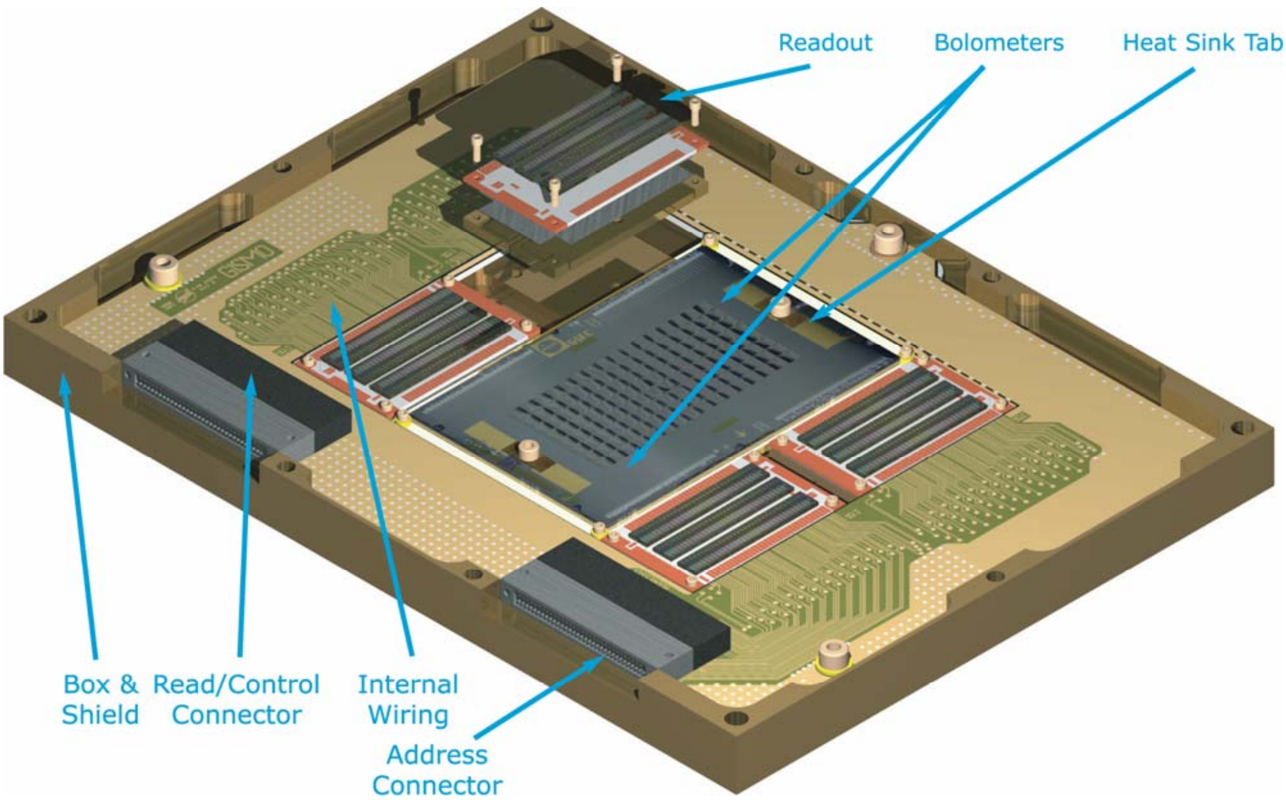

Figure 13. This rendered drawing shows the layout of each element in the detector package.

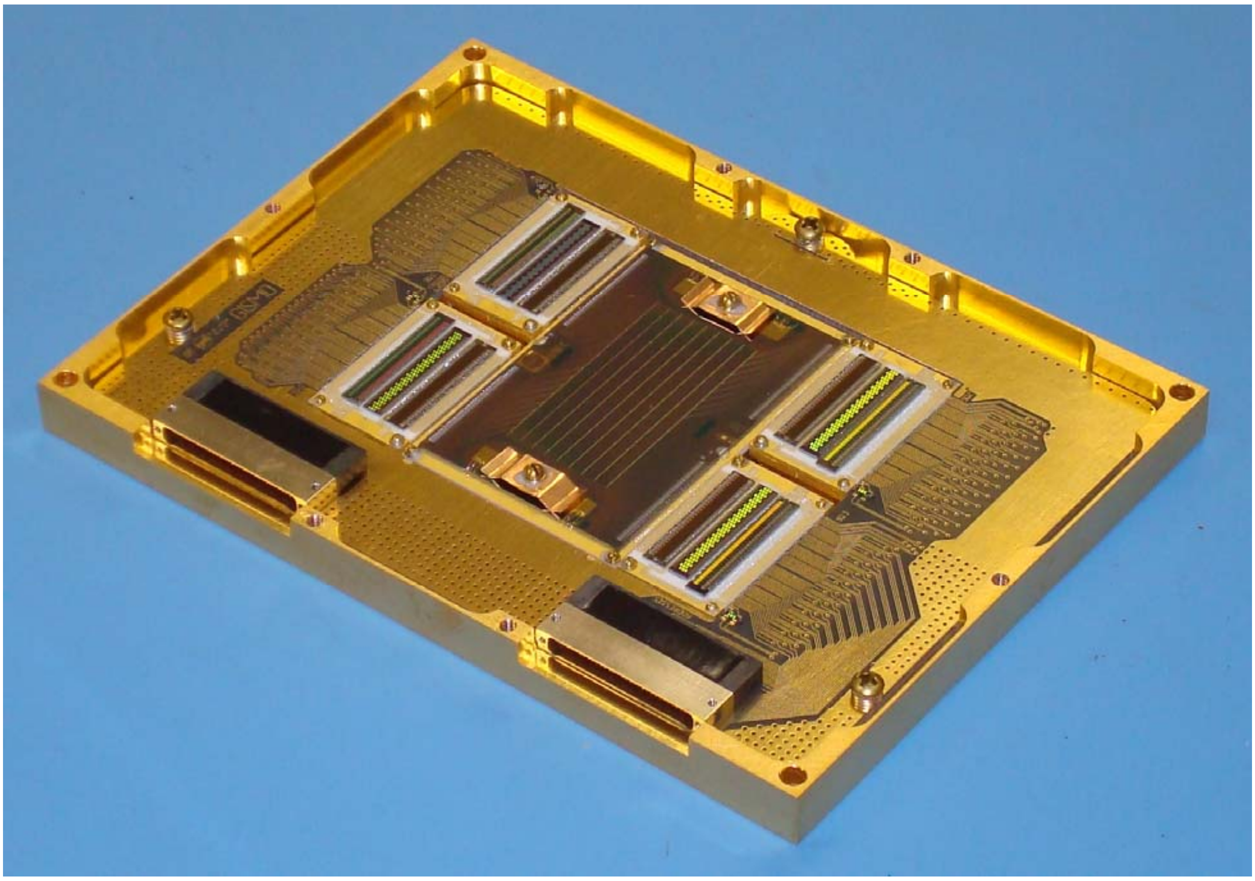

Figure 14. When completed, the detector package bears a strong resemblance to the design.

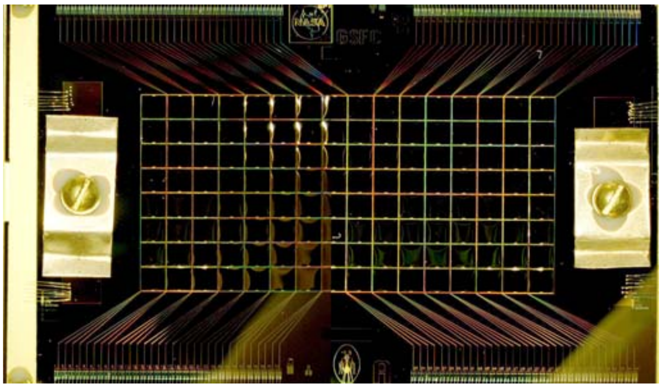

Figure 15. A close-up photo of the mounted detector array shows the two spring clips that hold the array in place, the aluminium TES connection bonds along the top and bottom edges, and the gold heat sink wirebonds at the left and right edges. A vertical seam is visible at the center where two photos were joined.

CONCLUSIONS

We have designed and constructed a package for low temperature superconducting bolometer arrays that performs several optical, thermal, mechanical, electronic, and magnetic roles. It has been successfully used in the GISMO 128-pixel camera for an observing run that yielded novel astronomical data. A second-generation package has been developed and is under construction to improve upon the design in ways meant to improve performance and enhance reliability. A third generation package is currently being worked out that will provide similar capability for arrays in formats up to 1,280 pixels.

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[25] Nanonics connectors of type STM065; Tyco Electronics; 1050 Westlakes Drive, Berwyn, PA 19312 USA; Tel: 610-893-9800; http://www.tycoelectronics.com/components/

[26] Zen Machine & Scientific Instrument, 1568 Steamboat Valley Rd., Lyons CO 80540-1658 USA; +1 303.823.5842