High-gain cryogenic amplifier assembly employing a commercial CMOS operational amplifier

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Abstract: We have developed a cryogenic amplifier for the measurement of small current signals (10 fA to 100 nA) from cryogenic optical detectors. Typically operated with gain near 10^7 V/A, the amplifier performs well from DC to greater than 30 kHz, and exhibits noise level near the Johnson limit. Care has been taken in the design and materials to control heat flow and temperatures throughout the entire detector-amplifier assembly. A simple one-board version of the amplifier assembly dissipates 8 mW to our detector cryostat cold stage, and a two-board version can dissipate as little as 17 μW to the detector cold stage. With current noise baseline of about 10 fA/(Hz)$^{1/2}$, the cryogenic amplifier is generally useful for cooled infrared detectors, and using blocked impurity band detectors operated at 10 K the amplifier enables noise power levels of 2.5 fW/(Hz)$^{1/2}$ for detection of optical wavelengths near 10 μm.

I. INTRODUCTION

Amplifiers which operate at cryogenic temperatures have been developed to maximize the performance of cryogenic detectors in a number of applications, particularly in cases where a small current across a large impedance must be sensed [1-4]. By replacing an external room-temperature amplifier with a cryogenic amplifier circuit fully or partially within the cryogenic enclosure, the Johnson noise associated with the resistance of the sensing electronics can be lowered. By placing the amplifier near the detector within the cryogenic enclosure, the bandwidth of the device can also be significantly extended, as a result of reduced circuit capacitance. Cryogenic amplifiers have been useful for optical detectors, particularly for photon-counting and far-infrared sensing [5-9], but in many cases the associated amplifiers are custom-designed rather than commercially available. In the optical calibration community, there has been significant work done on developing low-noise room-temperature amplifier circuits [10,11], but little work in the development of cryogenic amplifiers.

Blocked-impurity-band (BIB) detectors are cryogenic semiconductor-based optical devices with low dark currents capable of sensing into the far-infrared [12,13]. BIB detectors with an active layer of arsenic doped silicon (Si:As) exhibit excellent responsivity from 2 μm to 30 μm and are used in infrared space telescopes [14,15], military applications, and by the National Institute of Standards and Technology (NIST) as the basis for the calibration transfer of low-power infrared standards [16,17]. The Si:As BIB detector is typically operated at temperatures from 8 K to 12 K , and presents an effective impedance of 1 MΩ to 1 GΩ. BIB detectors have high responsivity, speed, linearity and spatial uniformity [18], but their sensitivity and bandwidth can be limited by room-temperature amplification of their output current.

We have developed cryogenic amplifier (cryo-amplifier) assemblies, based upon a commercial CMOS operational amplifier (op-amp), designed for use with Si:As BIB detectors. In our laboratory, BIBs are usually operated within infrared calibration chambers which have three regions of cooling: a shroud at 77 K which shields the experimental space from room-temperature radiation; an optics plate held at 15 K to 20 K by cooled gaseous helium; and a liquid helium cryostat at 2 K to 4.2 K to which detectors can be mounted or heat-strapped. The BIB detectors are used for both AC and DC measurements of currents from 10 fA to 100 nA, and typically require gain of around 10^6 to 10^8 and operation from DC to at least 10 kHz. The thermal and radiative properties of the cryo-amplifier assembly are also very important: the power dissipation from the amplifier to the helium cryostat must be less than 10 mW in order to achieve acceptable cryostat hold times, and thermal radiation from the amplifier stage must be shielded and absorbed to ensure that the infrared light emitted is not sensed by the BIB detectors.

We have developed two basic types of cryo-amplifier assemblies. The first is a one-board design where the cryo-amplifier and detector are mounted on the same board for a compact package where the distance between amplifier and detector can be minimized. Heat from this assembly is dissipated in large part to the cryostat because the detector must be maintained at temperatures near 10 K, so the one-board assembly must be isolated from areas of the chamber other than the liquid helium cryostat. The second type of cryo-amplifier assembly is a two-board design where the amplifier board is separate from a detector board, and the two are connected by a coaxial line with high thermal impedance. In this design, most of the heat from the amplifier is dissipated to the helium gas cooled optics plate and only power from the detector board is dissipated to the cryostat (as little as 17 μW), maximizing the cryostat hold time.

II. DESIGN OF THE CRYOGENIC AMPLIFIER

The amplifier circuit, shown in Figure 1, is an op-amp implementation of a transimpedance amplifier, using a basic circuit found in standard electronics textbooks [19]. The circuit components have been carefully chosen and tested to optimize performance for our application.

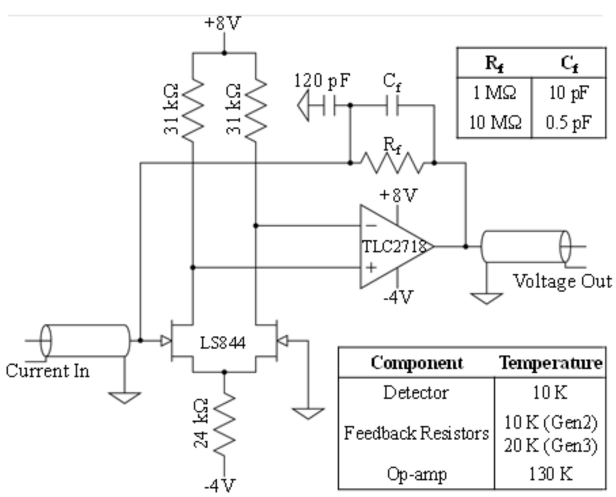

FIG. 1: Schematic of the cryogenic amplifier circuit. The entire circuit can be mounted to the cold plate of a liquid helium cryostat, but the amplifier itself must be thermally isolated to allow it to reach higher temperatures.

The first generation of the cryo-amplifier (Gen1) used an Analog Devices OP27 op-amp [20]. The OP27 offered low noise and high bandwidth. However, its BJT (bipolar junction transistor) input stage was unsuitable for the very low currents to be measured. The LS844 dual N-channel JFET (junction gate field-effect transistor) preamplifier was used to remedy this situation, as well as to keep the inputs of the OP27 within its common mode range. This circuit was powered from a split DC supply of ±12 V and operated at a temperature of approximately 80 K. The OP27 was found to start reliably at this temperature, and operated at a higher temperature due to self-heating. Power dissipation in the op-amp was approximately 100 mW.

The second generation of the cryo-amplifier (Gen2) used a Texas Instruments TLC271B op-amp [20], reducing the power consumption of the circuit dramatically. In medium bias mode, the TLC271B dissipates a fraction of a milliwatt. The TLC271B has a dual MOSFET (metal-oxide-semiconductor field-effect transistor) input stage which is suitable for operation in this circuit without the LS844 preamp. However, the preamp improves the bandwidth of the circuit, so it was retained in the design. The TLC271B is designed to operate from a single DC power supply of up to 16 V. The unusual supply arrangement of -4 V and +8 V was chosen to allow the measurement of small AC signals (e.g., photodetector viewing a chopped radiation source) while still allowing for the measurement of significant DC signals. This generation of the cryo-amplifier was designed to operate down to 4.2 K. To achieve this, the op-amp and the preamp are thermally isolated from the rest of the circuit along with a 20 kΩ resistor. The resistor, connected across the supply lines, serves as a heater for the semiconductors, which must be heated to around 130 K for proper operation. The total power dissipation of the circuit is less than 8 mW (mostly due to the heater resistor). There were two reasons for designing this amplifier to operate down to 4.2 K. First, this allowed the BIB detector to be mounted directly to the amplifier printed circuit board (PCB), minimizing the distance between the detector and amplifier, which minimized stray capacitance and noise pickup. Second, it provided a reduction in Johnson noise by cooling the feedback resistors to a lower temperature. The Gen2 design allowed for the use of multi-pixel BIB detectors with pixel selection carried out by a multiplexor (MUX) system comprised of several small latching relays on the amplifier PCB. The MUX selected between seven pixels and a calibration line (a coaxial cable which allowed a known current to be injected into the cryo-amplifier).

The third generation of the cryogenic amplifier (Gen3), is a repackaging of the second generation circuit, with the amplifier section separated from the detector section on separate

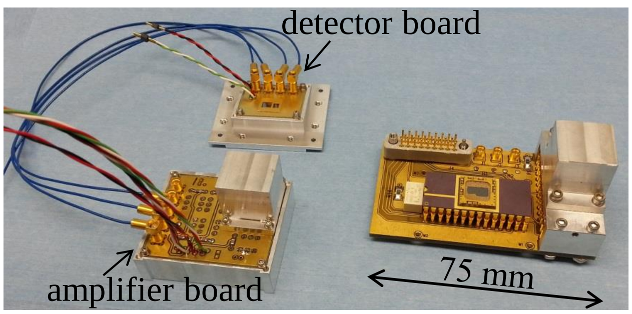

FIG. 2: Photograph of the Gen2 (right) and Gen3 (left) cryo-amplifier assemblies. Separation of the Gen3 version into detector and amplifier boards reduces dissipation at the detector stage from 8 mW to less than 20 μW.

boards. With the already low power dissipation of the second generation circuit, significant reduction in power dissipation is not feasible without significant reduction in performance. Separation of the amplifier and detector (what we call the "two-board solution") allows the amplifier power to be dissipated remotely, away from the detector cryostat. In the case of our cryogenic vacuum chamber, the amplifier power is dissipated at the inner cryoshield, which is cooled by a continuous flow of cold helium gas to a temperature of approximately 20 K. Removing this 8 mW heat load from the detector cryostat (a liquid helium reservoir) significantly increases the hold time, and therefore, the time between cryostat fills. Heat dissipation to the cryostat from the bias, heater and thermometer loads to the detector board is estimated to be 17 μW. Figure 2 shows the one board (Gen2) and two board (Gen3) realizations of the cryogenic amplifier assembly.

The Gen3 cryo-amplifier incorporates a modified MUX, smaller and less complicated than in the Gen2 design. The MUX in this amplifier selects between three pixels and the calibration line. It also incorporates the additional feature that it can connect whichever pixel is selected directly to the calibration line, bypassing the cryo-amplifier altogether, and allows the option of using an external amplifier during testing. The PCB for the amplifier section of the Gen3 design is a four-layer board. The top and bottom layers are mostly ground plane along with the control lines for the MUX relays. The amplifier signal lines are routed on the two internal layers, with shielding provided by the surrounding ground planes. The bottom of the amplifier PCB, with feedback resistors and latching relays, is shown in Figure 3.

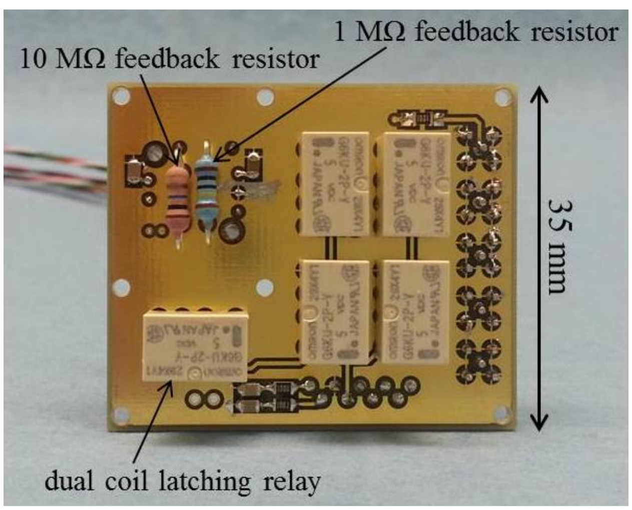

FIG. 3: Photograph of the bottom of the Gen3 amplifier board, showing the feedback resistors and latching relays.

As in the Gen2 amplifier, the op-amp and preamp are thermally isolated from the main PCB. In the Gen2 design, the isolation was accomplished using two 1.6 mm diameter by 16 mm long fiberglass rods as standoffs. Electrical connections were made using very small gauge stainless steel capillary tubing. The fiberglass rods were attached to the PCBs using epoxy. For the electrical connections, the capillary tubing had to be cut to precise length and then pre-soldered using acid flux and low temperature silver solder. The acid flux had to be thoroughly removed before assembly into the amplifier, and there was always the possibility that the acid flux could be drawn inside the capillary tubing and be sealed in by the solder. The parts had to be examined under a microscope to make sure that the ends of the capillary tubing were not sealed over with solder and then the insides had to be flushed with solvent before assembly. In the Gen2 design the cryo-amplifer board was thermally isolated from the cryostat by polyimide tubing standoffs, and anchored by a heat strap.

The method for isolating the amplifier from the main PCB was improved in the Gen3 design. The thermal isolation in the Gen3 design used two pieces of polyimide tubing, as can be

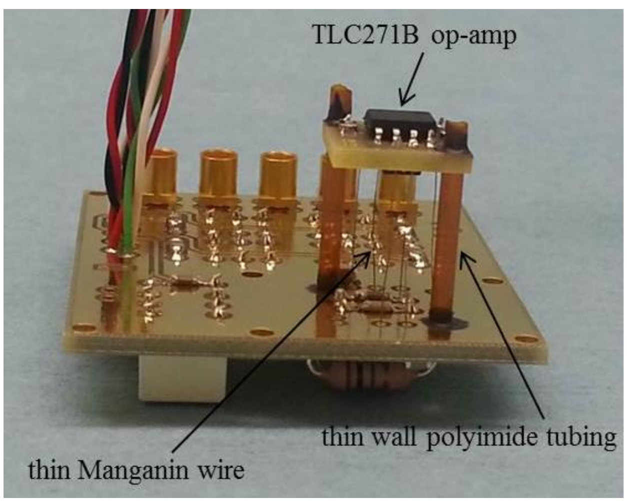

FIG. 4: Photograph of the Gen3 amplifier board assembly from the side, showing the polyimide standoffs and thin Manganin wires used to achieve thermal isolation of the amplifier from the amplifier board.

seen in Figure 4. The tubing was 1.45 mm inside diameter with a wall thickness of 0.09 mm. A fixture was made utilizing two 1.4 mm diameter stainless steel rods that slip inside of the polyimide tubing. All of the amplifier components can be positioned on the rods and then the epoxy is applied. Electrical connections were made using 0.1 mm diameter Manganin wire to help maintain thermal isolation of the op-amp. The Manganin wire can be soldered directly into the PCBs with non-corrosive flux and can be cut to length after soldering. In the Gen3 design the amplifier board was thermally isolated from the cold optics plate using G10 (fiberglass epoxy laminate) standoffs, and the detector board was thermally isolated from the cryostat using polyimide tubing standoffs and a heat strap. For both the Gen2 and Gen3, there is a metal enclosure around the isolated amplifier "tower" as can be seen in Figure 2. This enclosure serves as electrical shielding for the amplifier and it also helps contain thermal radiation from the amplifier which could be directly sensed by the BIB detectors.

Selection of the feedback resistors for thermal stability is critical for both the Gen2 and Gen3 designs, as these resistors must operate reliably down to 4.2 K. Through thermal testing, we have found various precision metal film resistors with excellent thermal stability. For example, the 1 MΩ resistors that we use typically change less than 5% from 300 K to 4.2 K. The 10 MΩ resistors change less than 12% over this temperature range. Some types of thin film resistors that we tested changed more than 300% with most of that change occurring below 20 K. This extremely high resistance versus temperature slope at the operating temperature resulted in the gain of the amplifier being strongly temperature dependent, a problem not seen when using the thermally stable resistors.

III. AMPLIFIER TESTS AND PERFORMANCE RESULTS

Gain and noise measurements were made on the cryo-amplifier assemblies, both DC and AC. The AC measurements were made both at room temperature and with the cryo-amplifier assembly near 10 K to determine how bandwidth and noise change with cooling. Gain was determined by injecting a known current into the input or calibration line of the amplifier, and measuring the voltage output. Noise measurements were made both with the amplifier input open, and with various BIB detectors attached by a coaxial cable. The one-board amplifier assembly was designed and fabricated first, and the two-board version was made after, instituting various improvements identified from testing with the one-board assembly. The noise, gain and bandwidth results from the two types of assemblies were similar, but as a consequence of changes made between designs, the bandwidth and noise performance of the two-board version were somewhat better.

DC gain measurements at 10 K have shown that the feedback resistors are near nominal at cryogenic temperatures, with the gain at the 10^6 V/A setting equal to approximately 1.05×10^6 V/A and the gain at the 10^7 V/A setting equal to approximately 1.11×10^7 V/A. The

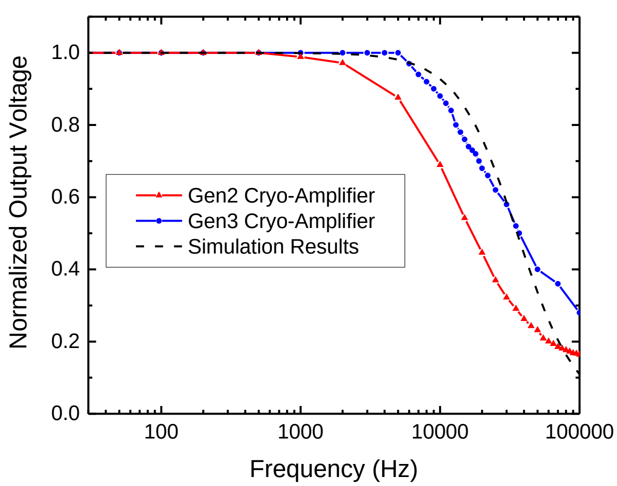

FIG. 5: Normalized AC gain for the cryo-amplifier at 10 K. The -3 dB rolloff frequency at 10 K is approximately 37 kHz for the Gen3 cryo-amplifier.

normalized AC gain results are shown in Figure 5 for a constant amplitude current injected at a series of frequencies using a waveform generator. It can be seen that the -3 dB rolloff frequency at 10 K for the Gen3 cryo-amplifier is approximately 37 kHz.

DC noise measurements with the amplifier assembly at 8.3 K exhibit significant 1/f noise (and possibly background signal from the cryostat), and the results for the 10^6 V/A and 10^7 V/A gain settings for the Gen3 cryo-amplifier are shown in Table I. Measurements were made with a commercial digital multimeter using a total integration time of 60 seconds. Data with the detector attached to the cryo-amplifier input with a coaxial line were taken with the detector biased with -2 V, just as they are in normal operation. The smallest detectors show little increase in noise from the open amplifier data, but the largest detectors can exhibit excess noise on the

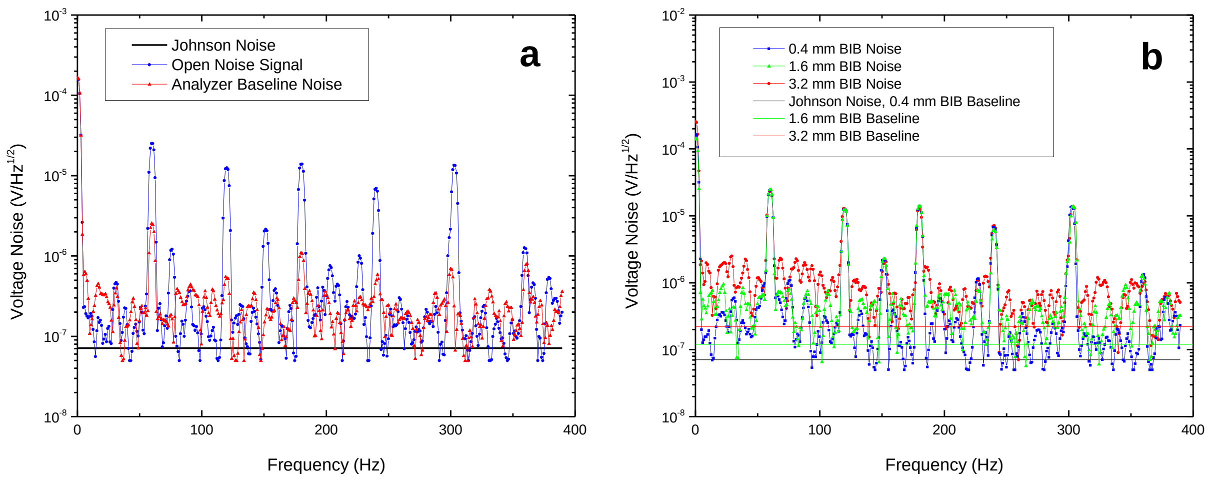

FIG. 6: Frequency-dependent noise out to 400 Hz for the cryo-amplifier on the 10^7 V/A gain setting at 8.3 K. In plot (a) the open amplifier noise and analyzer noise exhibit baselines close to the calculated Johnson noise for the feedback resistor at 8 K. In plot (b) the noise for the amplifier attached to the BIB detectors of different sizes are compared. Attached to the smallest detector, the amplifier noise baseline is close to the Johnson noise, and the baseline for the largest detector is about three times greater.

order of millivolts. The AC noise results at 8.3 K for the 10^7 V/A gain setting for the Gen3 cryo-amplifier are presented in Figure 6, and include data for the open amplifier and the amplifier with detectors attached. The Johnson noise limit for the measurement is approximately $7.13 \times 10^{-8}\ \mathrm{V}/\sqrt{\mathrm{Hz}}$, and the baseline of the spectrum analyzer used in the data collection was around the same value. The noise baseline from the open amplifier and for the amplifier attached to the smallest detector were also near the Johnson limit. The larger detectors showed somewhat higher noise baselines: the amplifier attached to the medium size detector had a

TABLE I: DC noise for the cryo-amplifier at 8.3 K. The $k = 1$ statistical uncertainty in the last two digits of each noise signal mean is given in parentheses.

Amplifier Input	Noise Signal Mean (V)	
	10^6 gain	10^7 gain
Open	$3.68338(22)\times10^{-3}$	$3.01840(12)\times10^{-3}$
0.4 mm square BIB	$3.64187(25)\times10^{-3}$	$3.10191(39)\times10^{-3}$
1.6 mm square BIB	$4.4700(26)\times10^{-3}$	$1.1664(17)\times10^{-2}$
3.2 mm square BIB	$4.456(16)\times10^{-3}$	$1.1157(77)\times10^{-2}$

baseline near $1.2 \times 10^{-7}\ \mathrm{V}/\sqrt{\mathrm{Hz}}$, and the noise baseline with the largest detector was approximately $2.2 \times 10^{-7}\ \mathrm{V}/\sqrt{\mathrm{Hz}}$. Spectral noise spikes seen in the amplifier characteristic are at frequencies which also display noise spikes in the spectrum analyzer data without the cryo-amplifier output attached. The noise baseline is fairly flat over the bandwidth of the device for frequencies greater than 10 Hz. Amplifier data taken at room temperature and 10 K exhibit an approximately five-fold improvement in noise baseline at low temperature as a result of the reduced Johnson noise associated with the feedback resistor.

IV. DISCUSSION AND CONCLUSIONS

The DC gain results in Figure 5 show the bandwidth of the Gen3 cryo-amplifier is near 40 kHz, more than sufficient for use of our optical detectors in Fourier Transform Spectrometer (FTS) measurements. The bandwidth exhibited by the amplifier agrees well with simulation results of the amplifier circuit, also shown in Figure 5. The AC noise baseline for the cryo-amplifier agrees well with the Johnson noise calculated for the feedback resistor at the cold stage operating temperature, as seen in Figure 6. Measurement of the amplifier noise at room temperature and cryogenic temperatures showed that there is approximately a five-fold decrease in the level of the noise baseline between 300 K and 10 K. Excess noise extrinsic to the cryo-amplifier was measured when any but the smallest BIB detectors were attached to the amplifier.

Given the approximately $10\ \text{fA}/\sqrt{\text{Hz}}$ current noise level of the cryo-amplifier assembly and the responsivity of the BIB detectors, a noise level for optical powers as low as $2.5\ \text{fW}/\sqrt{\text{Hz}}$ is attainable for a 3 mm square detector at optical wavelengths near 10 μm.

We have developed cryogenic amplifier assemblies employing a commercial CMOS op-amp, for use with low temperature optical infrared detectors. These cryogenic assemblies are well-suited for low-noise measurement from DC to 30 kHz and dissipate less than 8 mW total power and as little as 17 μW to the detector cooling stage. Future testing will investigate the relative tradeoffs between power dissipation and noise for the one- and two-board designs. Separating the detector and cryo-amplifier with thermally resistive coaxial line limits the power dissipation to the detector stage but can increase pickup noise and microphonics. Depending on experimental conditions, further measurements will help optimize the length and materials used for the electrical link between the cryo-amplifier and detector.

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20. Reference is made to commercial products to adequately specify the experimental procedures involved. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these products are the best for the purpose specified.

Figure and Table Captions

Figure 1: Schematic of the cryogenic amplifier circuit. The entire circuit can be mounted to the cold plate of a liquid helium cryostat, but the amplifier itself must be thermally isolated to allow it to reach higher temperatures.

Figure 2: Photograph of the Gen2 (right) and Gen3 (left) cryo-amplifier assemblies. Separation of the Gen3 version into detector and amplifier boards reduces dissipation at the detector stage from 8 mW to less than 20 μW.

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