ALMA MEMO NO. 437

Miniature, Modular Heat Sinks for ALMA Cryostats

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Abstract

Proposed receiver cartridges for ALMA may utilize up to 96 wires for SIS mixer bias, IF amplifier bias, thermometry and other functions [1]. To reduce heating of the mixer block and minimize the load on the 4 K refrigerator stage, heat sinks will be required on the 80 K, 12 K and 4 K stages. The present concept for the receiver cartridges requires disassembly of each thermal stage to effect repairs. Heat sinks utilizing connectors simplify disassembly, thus improving the mean time to repair. The large number of wires and connections will require a simple, reliable heat sink capable of being mass-produced for the expected 64 receiver cartridges.

The main body of this report describes two different heat sink designs utilizing Nanonics “Dualobe” connectors configured in a modular arrangement for simple installation in receiver cryostats. In Appendix B, a simpler but less effective heat sink is described. The measured thermal performance of all the heat sinks is presented.

Design and Construction

The basic design of the heat sink is shown in Figure 1. The assembly consists of an FR-4 printed circuit board 0.060″ (1.5 mm) thick, containing 25 parallel copper conductors, 0.016″ (0.41 mm) in width, 0.009″ (0.23 mm) spacing x 0.0003″ (0.008 mm) thick. The board is epoxied to an OFHC copper “shunt plate” which is in turn bolted to the dewar's cold surface. Stycast 2850FT epoxy is used because it has a high thermal conductivity and its total thermal contraction is well matched to that of copper down to cryogenic temperatures [2,3]. Catalyst 24LV is mixed with the epoxy to ensure a short cure time and low viscosity while curing [4]. The epoxy thickness is 0.005″ (0.127 mm), fixed by steps in the bottom of the shunt plate that run along the edge of the PCB. The copper shunt plate and printed circuit board were gold-plated before assembly [5].

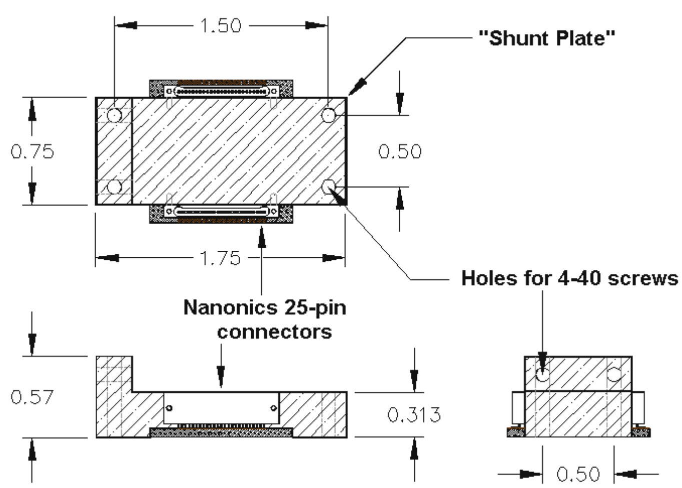

Figure 1. Design of a modular heat sink with Nanonics connectors. Dimensions are in inches.

A Nanonics, 25-pin female, in-line, surface-mount connector [6] is soldered on to each end of the circuit board. The connectors are also rigidly bolted to the body of the shunt plate so they cannot move, thus preventing the circuit traces from being pulled off the printed circuit board when a mating connector is removed. It should be noted that the individual pins of the Nanonics connectors are rigidly captivated in the potting so they will not pull up as the connectors are separated. A photograph of a completed heat sink is shown in Figure 2.

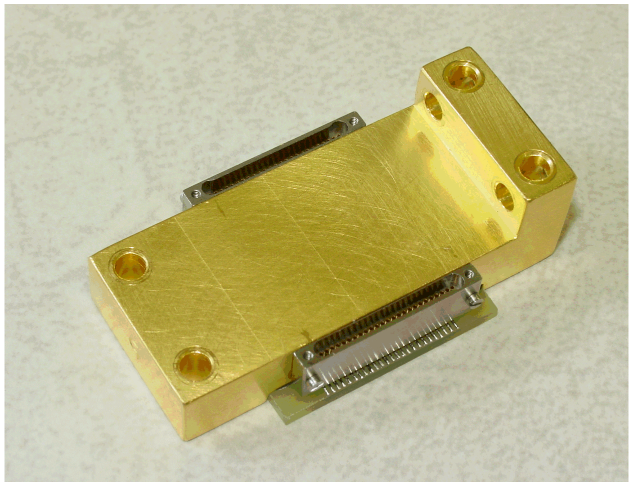

Figure 2. Photograph of the completed heat sink.

The heat sink can be mounted either flat on the cold plate, in which case it takes up about 1″x1.8″ of area (2.5x4.6 sq. cm), or vertically, at the expense of performance due to the slightly smaller contact area.

Space in the ALMA receiver cartridges is limited. For this reason, a much smaller version of the heat sink was designed as shown in Figure 3. With a footprint of approximately 0.7 square inches (4.5 sq. cm), this "mini heat sink" occupies less than 1/6 the area of the larger unit in either orientation. However, due to the much smaller contact area between the PC board and thermal shunt, performance of the mini heat sink is not as good as that of the larger one. Additional details of both heat sinks are described in Appendix A.

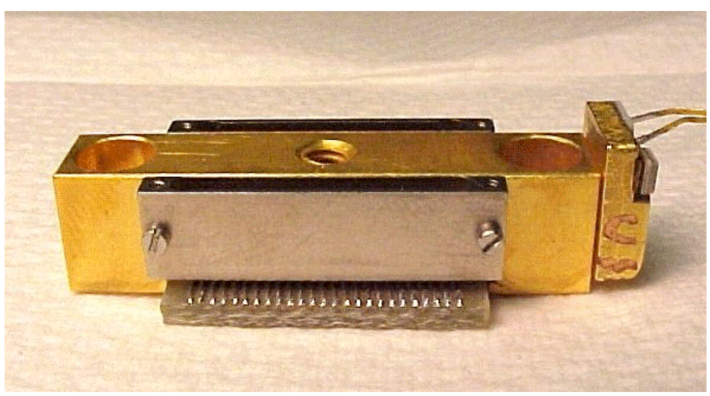

Figure 3. A miniature version of the larger heat sink.

Testing

For the thermal conductivity tests, a pair of special connector blocks was made (shown in Figure 4). The test blocks consist of a mating 25-pin male, in-line, surface-mount connector with its leads soldered to a block of OFHC copper 0.25″x0.25″x1.0″ wide (6.4 x 6.4 x 25.4 mm). The copper block shorts all the pins of the male connector. A 100-ohm, 1/4W metal film resistor is fixed with GE 7031 varnish [7] into a hole in the block to serve as a heater. A silicon diode temperature sensor is mounted on top of each block to determine the temperature. One of the sensors is designated "T1," the other "T2." A third diode, "T3," monitors the temperature of the shunt plate. In the discussions below, “T1” and “T2” also refer to the test blocks themselves.

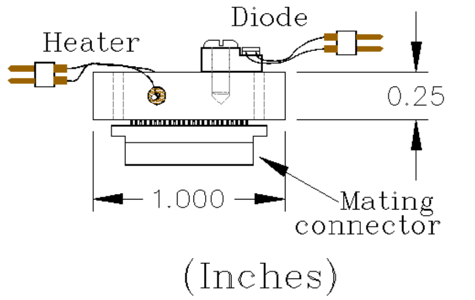

Figure 4. A test block to evaluate the thermal performance of the heat sinks.

Measurements were made at 12 K, 20 K, 35 K, 50 K, 77 K and at 100 K with the heat sink mounted on a temperature-controlled stage in a Gifford-McMahon closed-cycle system. Temperatures were stabilized to ±0.01 K by a Lakeshore 330 temperature controller. A radiation shield made of thin folded copper foil completely surrounded the heat sink in the cryostat.

At each temperature, current was applied to T1 in discrete steps up to 50 mA, which corresponds to a power of 250 mW dissipated in the heater resistor. At each current step, the three sensors were allowed to reach equilibrium and the temperatures recorded. The temperature of T2 and the shunt plate, T3, both rise slightly with increasing input power. The increase in T2 reflects the heat leakage along the heat sink, while the increase in T3 depends on the thermal resistance between the heat sink body (shunt plate) and the cold plate.

After allowing T1 to cool back to the base-plate temperature, the procedure was repeated by heating T2 and monitoring all three temperatures. A third run was made while heating T1 and T2 simultaneously, which allows the effective shunt conductances to be extracted directly, as described below. In practice for the third run, the two heaters were wired in series and the same current was applied to both. No attempt was made to equalize T1 and T2, though the temperature increases tended to remain within ±10% of each other.

Analysis

To calculate the thermal performance of the heat sink properly, it is necessary to construct a thermal equivalent circuit. A thermal “Pi” model was used to evaluate the data. By analogy to electrical circuits, voltage becomes temperature and current becomes heat flow (power). Referring to Figure 5, by symmetry, if T1 and T2 are heated simultaneously, there should be no heat flow through G3. G1 and G2 can be determined directly by the temperature rise in T1 and T2 as a function of input power. G1 and G2 should be identical by symmetry, though they are not, most likely due to variations in the epoxy thickness across the heat sink. An average was taken of the two measured values, G1'= G2' = (G1 + G2) /2.

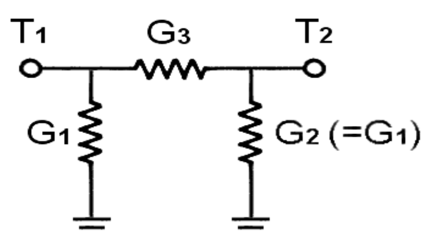

Figure 5. A two-port thermal model for the heat sink.

G3 is determined by heating T1 and monitoring the temperature at the other end. The output temperature, T2, is divided by G2 and G3 as in the case of a voltage divider, and the expression is rearranged to give

$$G3 = G2 \cdot T2 / (T1 - T2)$$

Conversely, G3 can also be determined by heating T2 and monitoring T1, and the expression is

$$G3 = G1 \cdot T1 / (T2 - T1)$$

Again, the two values should be the same, though they are not, and so an average of the two runs was used.

Figures 6 and 7 show G1 and G3, respectively, plotted as a function of input power at each of the measured temperatures for the big heat sink mounted horizontally. As expected from material properties, *both* conductivities decrease with temperature [8].

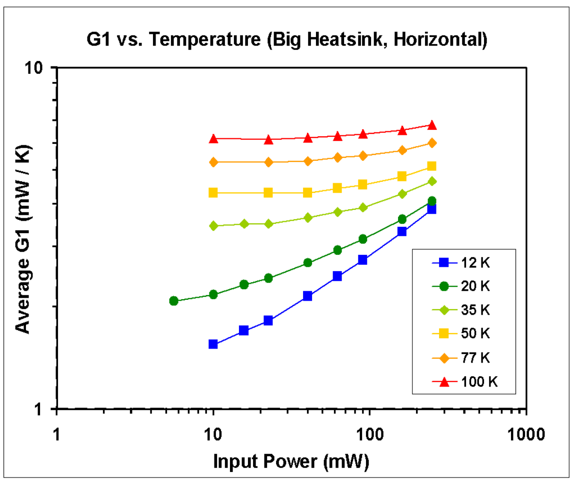

Figure 6. G1 for the big heat sink mounted horizontally.

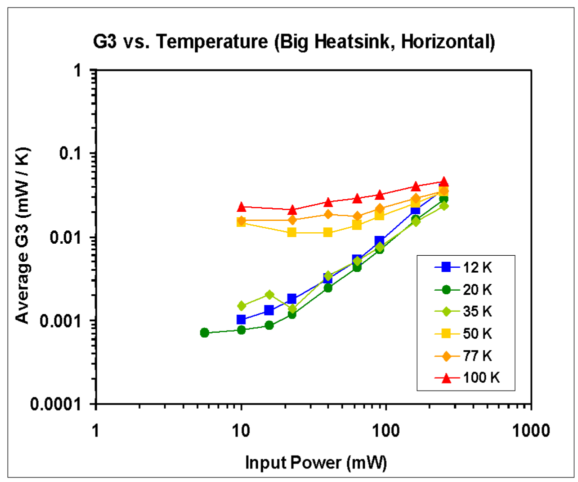

Figure 7. G3 for the big heat sink mounted horizontally.

Ideally, the heat sink should take all of the heat brought in by the leads and shunt it to the cold plate. There should be no rise in the temperature of devices connected to the output. Referring to the Pi circuit model, the output temperature is given in the unloaded (open–circuit) case by

$$T2 / T1 = G1 / (G1 + G3)$$

A good "figure of merit" for the heat sink is thus the ratio (G1 + G3) / G3, which is plotted in Figure 8. The value is on the order of 1,000 for the big heat sink and can be thought of as the “temperature attenuation” of the device.

In a practical application, the “open circuit” case just described corresponds to a worst-case scenario, where a device connected to the output of the heat sink cannot be adequately thermally anchored, and the heat sink is relied upon to remove all of the heat from the wiring. Figure 9 shows the calculated temperature rise with no load at the output (ΔT_2) as a function of the power applied to the input of the heat sink. For example, with 20 mW input, the maximum temperature rise at the output remains less than 0.01 K at all operating temperatures. This plot, though an average of two data runs, most closely represents the actual measured data when heating one side of the heat sink.

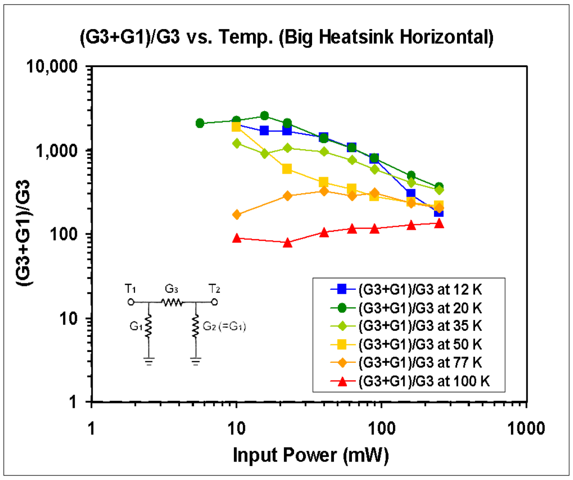

Figure 8. "Figure of merit" for the big heat sink mounted horizontally.

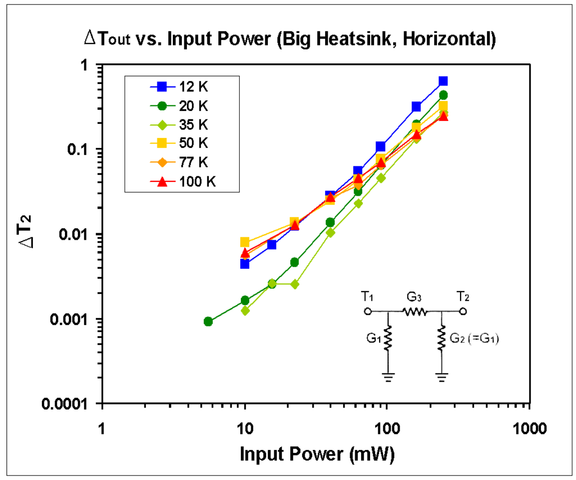

Figure 9. Output temperature rise vs. input power for the big heat sink, horizontal.

When mounted vertically, the heat sink contact area to the cold plate is reduced and the heat is removed through only one end of the plate. As a result, it is expected that the performance of the heat sink will be degraded. Results are plotted in Figures 10-13, showing the attenuation of the heat sink is reduced by approximately a factor of 10 at low temperatures for low input powers. A similar effect was seen in the earlier designs (see Appendix B).

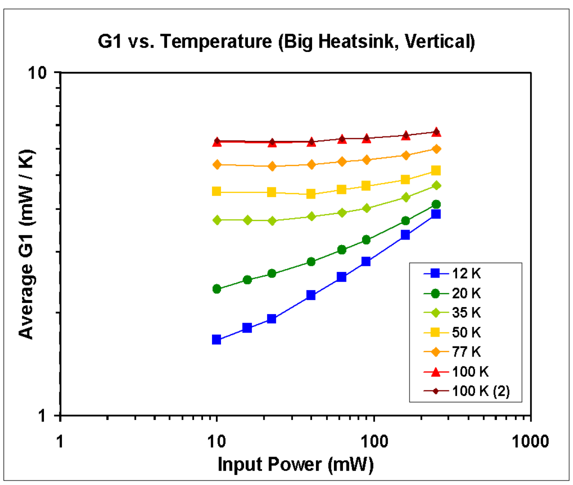

Figure 10. G1 for the big heat sink mounted vertically.

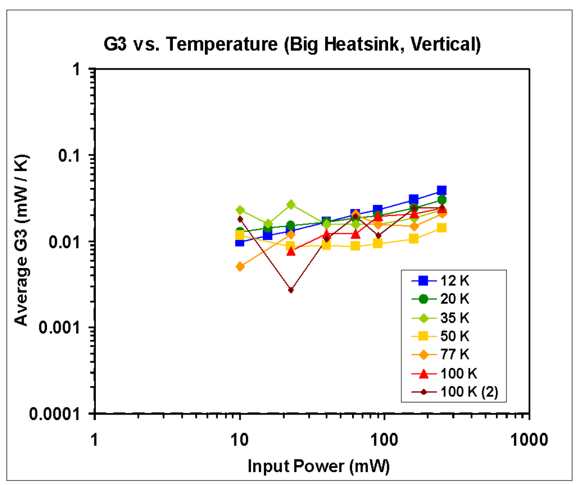

Figure 11. G3 for the big heat sink mounted vertically.

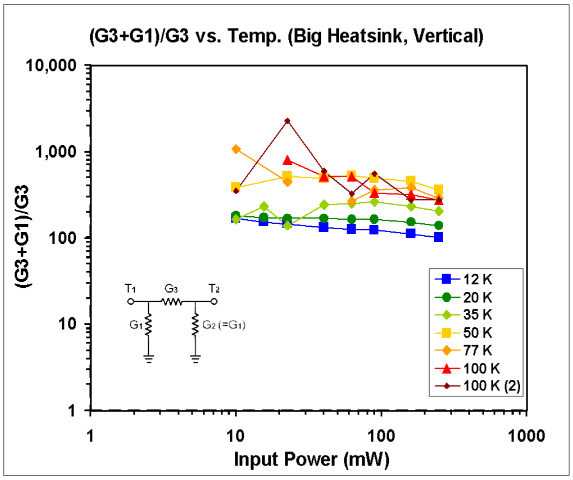

Figure 12. "Figure of merit" for the big heat sink mounted vertically.

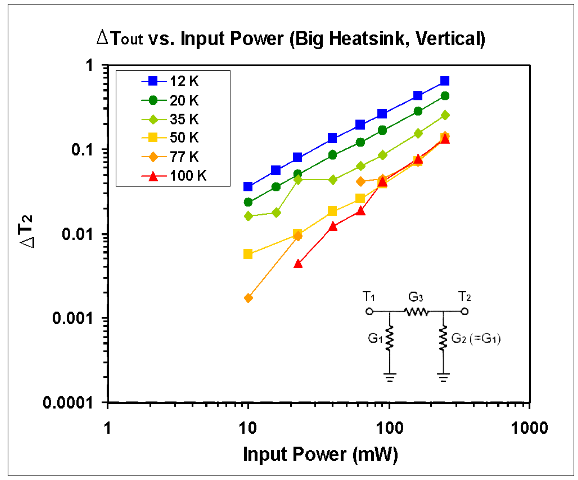

Figure 13. Output temperature rise vs. input power for the big heat sink, vertical.

Data for the "miniature" heat sink are shown in Figures 14-21. This device has a much smaller contact area between the PCB traces and the shunt plate, and poorer overall performance is the price paid for the reduction in size. As can be seen from the figures, the attenuation is reduced by an order of magnitude relative to the "big" heat sink in both orientations. There is little difference between the heat sink mounted vertically versus horizontally, indicating that the PCB contact area, and not the heat sink mounting, is the performance-limiting factor.

In contrast to the "big" heat sink, however, the "mini" heat sink becomes significantly *less* effective as it is cooled. The thermal conductivity of many insulators, including epoxy, falls monotonically with decreasing temperature. The conductivity of copper, on the other hand, can rise an order of magnitude between 100 K and 20 K [8,9]. As seen in the plots, G1 drops with decreasing temperature as expected from materials properties, but G3 remains relatively constant suggesting again that the short printed circuit traces are the performance-limiting factor.

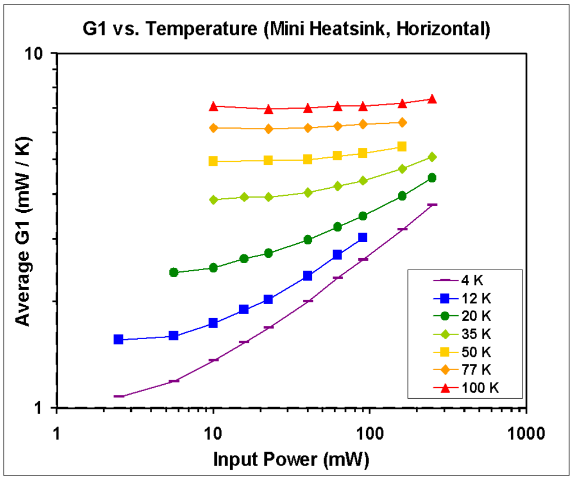

Figure 14. G1 for the mini heat sink mounted horizontally.

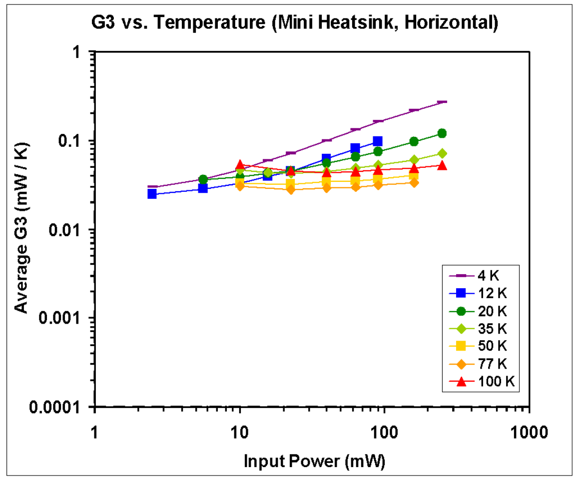

Figure 15. G3 for the mini heat sink mounted horizontally.

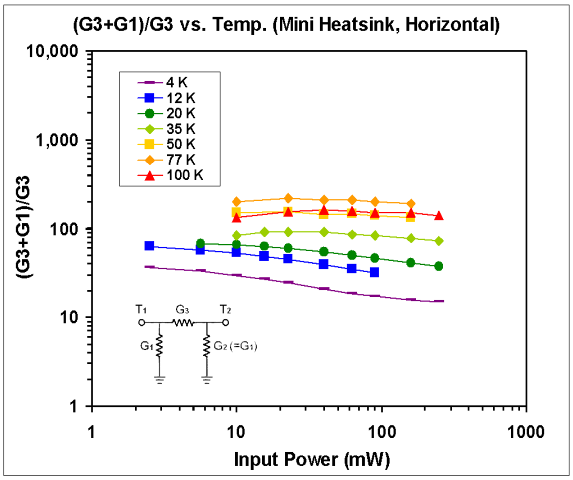

Figure 16. "Figure of merit" for the mini heat sink mounted horizontally.

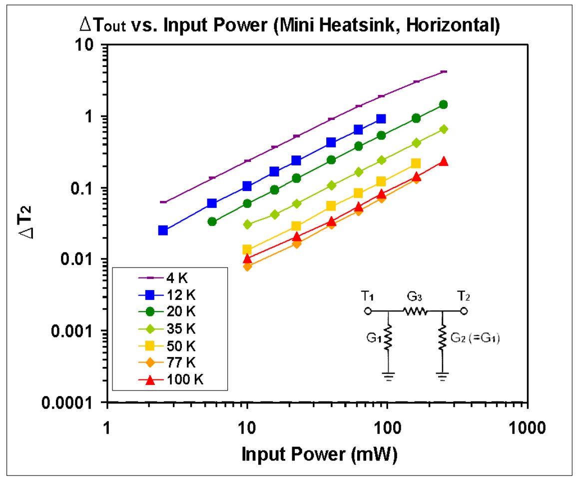

Figure 17. Output temperature rise vs. input power for the mini heat sink, horizontal.

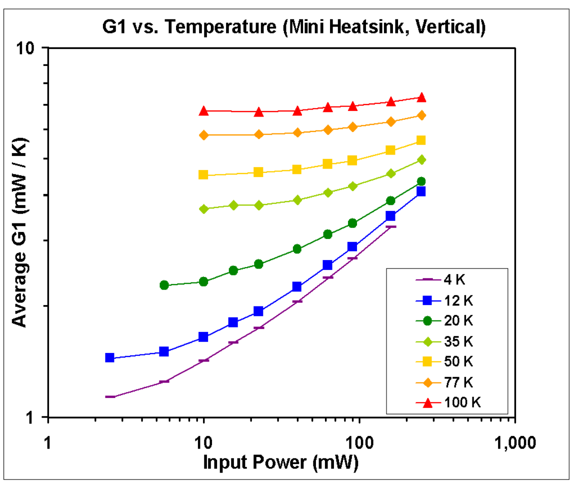

Figure 18. G1 for the mini heat sink mounted vertically.

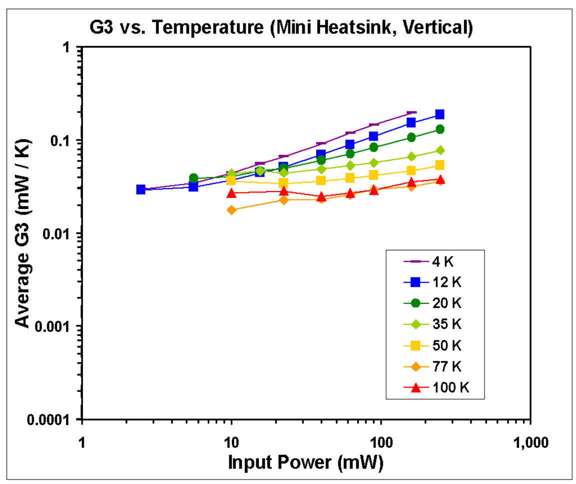

Figure 19. G3 for the mini heat sink mounted vertically.

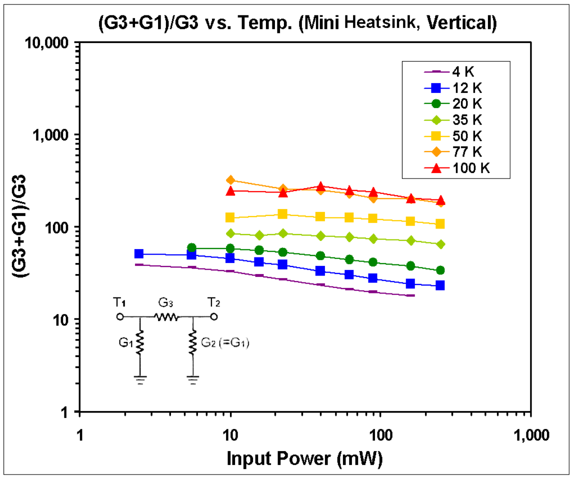

Figure 20. “Figure of merit” for the mini heat sink mounted vertically.

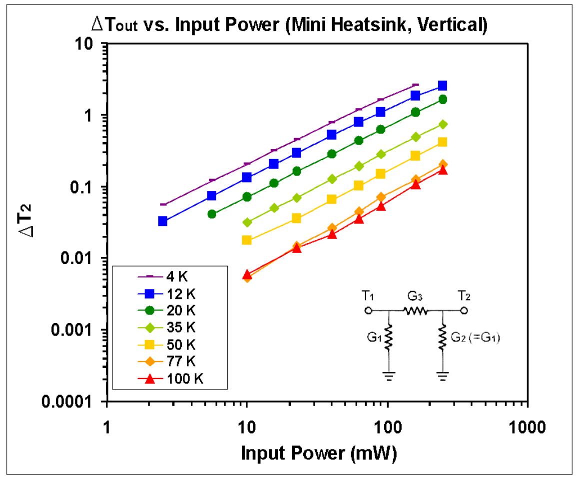

Figure 21. Output temperature rise vs. input power for the mini heat sink, vertical.

Discussion

From the measurements presented here, it is difficult to draw any general conclusions about other heat sink geometries. Performance will be significantly affected by changes in the epoxy thickness, dimensions of the circuit traces, mounting geometry, etc. Nevertheless, some extrapolations can be made from the current designs to provide guidance in building other types of heat sinks.

It is not practical to make the epoxy significantly thinner. As the epoxy thickness is reduced to less than about 0.0015″ (0.038 mm), machining burrs can become an invisible problem. An early batch of heat sinks built for evaluation in one of the CDL test dewars developed shorts to ground after being cooled. Lapping the shunt plates and applying new circuit boards fixed the problems, but the more robust solution was to increase the epoxy thickness. Excessively thin epoxy layers can also compromise the bond strength. The heat sinks thus have a practical minimum epoxy thickness of a few mils (≈100 microns).

Performance of the big heat sink mounted horizontally was difficult to assess because, for low input powers, the temperature changes at the output test block were comparable to the resolution of the temperature sensor diodes. Most of the temperature rise was dominated by the temperature rise in the shunt plate (“T3”) itself. It is not likely that a larger printed circuit surface area will improve the heat sink’s operation. On the other hand, it is clear the “mini” heat sink is approaching a lower limit of acceptable performance for many applications. Thus, for future designs with similar epoxy thickness, a surface area of 0.004 – 0.016 square inches (0.1 – 0.41 sq. mm) per conductor will serve as a good starting point.

The effects of conductor and epoxy thickness were not explored systematically. One-half ounce copper circuit boards, standard for many printed circuit board fabricators, were used. For reference, the cross-sectional area of the traces is comparable to that of 40 AWG wire.

Finally, the connectors themselves contribute very little to the performance of the heat sink as little heat is shunted through the connector body. As a result, performance of the heat sinks is expected to be independent of the type of connector used. The heat sinks can even be used without connectors by soldering wires to the circuit traces directly, and the thermal conductivity data presented in this memo should remain applicable.

References

[1] Kerr, A. R., “Mixer-Preamp to Receiver Interface Considerations for ALMA Band 6,” ALMA Memo #344, January 18, 2001. Available on-line at http://www.alma.nrao.edu/memos/.

[2] Swenson, C. A., “Linear Thermal Expansivity (1.5-300 K) and Heat Capacity (1.2-90 K) of Stycast 2850FT,” *Rev. Sci. Instrum*. 68 (2), February 1997, p. 1312.

[3] Richardson, Robert C., Smith, Eric N., *Experimental Techniques in Condensed Matter Physics at Low Temperatures*, Addison-Wesley Publishing Company, Inc., C. 1988.

[4] Emerson & Cuming, 46 Manning Rd., Billerica, MA 01821. www.emersoncuming.com.

[5] 200 micro-inches of gold was applied to the blocks by the NRAO “bright gold” process, which uses an arsenic-brightened sulfite gold bath, BDT-200, made by Oxy Metal Industries. The circuit board was plated using an electroless gold bath.

[6] Nanonics manufactures a series of space-qualified miniature connectors with 0.025″ pin spacing rated for cryogenic use. The connectors meet MIL-SPEC 8513 and reliability was discussed by J. E. Effland, “Reliability of Nanonics Dualobe Connectors,” ALMA Memo #356, March 2001. Available on-line at http://www.alma.nrao.edu/memos/.
Note: Nanonics has recently been purchased by Tyco Electronics, Harrisburg, PA 17105. www.tycoelectronics.com. (800) 533-6752. The receptacles (on the PC board) are part number SSM025L44HN. The mating plugs on the test blocks are part number SSM025B44N.

[7] Lakeshore Cryotronics, Inc., 575 McCorkle Blvd., Westerville, OH 43082.

[8] *e.g*., see White, Guy K., *Experimental Techniques in Low-Temperature Physics*, third ed., Clarendon Press, Oxford, 1979.

[9] It is likely that the behavior of the mini heat sink is dominated by the shunt conductance of the epoxy rather than the series conductance of the copper traces. The heat flow through the glass-filled epoxy cuts off before the leakage through the relatively short traces does as the heat sink cools. Refer to the plots of G3 in the Pi model analysis.

Appendix A - Construction Details of the Heat Sink

Figure A1 shows the printed circuit board layout for the larger heat sink. The smaller design uses a shorter section cut from the same board. A shop drawing of the big heat sink is shown in Figure A2. Some specific features of the design are listed below.

For the big heat sink:

- The standard Nanonics connectors have holes in the side of the receptacle threaded for 1.0mm x 0.25 threads/mm pitch. The screws used to secure the connectors to the shunt plate need to have the thread relieved to avoid cross-threading the shunt plate or breaking a screw. It is preferable to drill out the threads of the connector rather than machining the very small screws.
- Currently both connectors are mounted facing each other on the shunt plate. The result is that pin 1 of the input connector connects to pin 25 of the output connector, pin 2 to pin 24, etc. The solution is either to use an even number of heat sinks or to use connectors that have the pins bent in the opposite direction on one side of the heat sink. The connectors can be ordered from Nanonics with the pins bent in opposite directions.
- The connectors are mounted so the pins of the connectors stick out to the sides, and can be soldered *after* the PC board is epoxied to the shunt plate.
- The design includes a 5-mil high shoulder milled into the channel that supports the PC board. This insures a consistent minimum epoxy thickness.
- During assembly, use only enough epoxy to cover the shunt plate as it tends to squeeze out from under the sides of the PC board.

For the mini heat sink:

- Countersinking the screw head on the long axis of the heat sink is essential. This allows 1¼″ screws to be used, which is the largest practical size available in brass for a 4-40 screw, fillister head. Countersinking the holes on the short axis (as shown in the main text in Figure 3) is not recommended, as the countersinks intersect the through-hole.

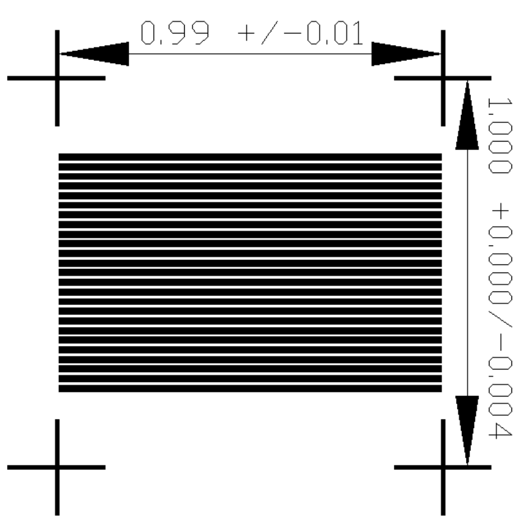

Figure A1. Printed circuit board layout for the large heat sink. Dimensions are in inches.

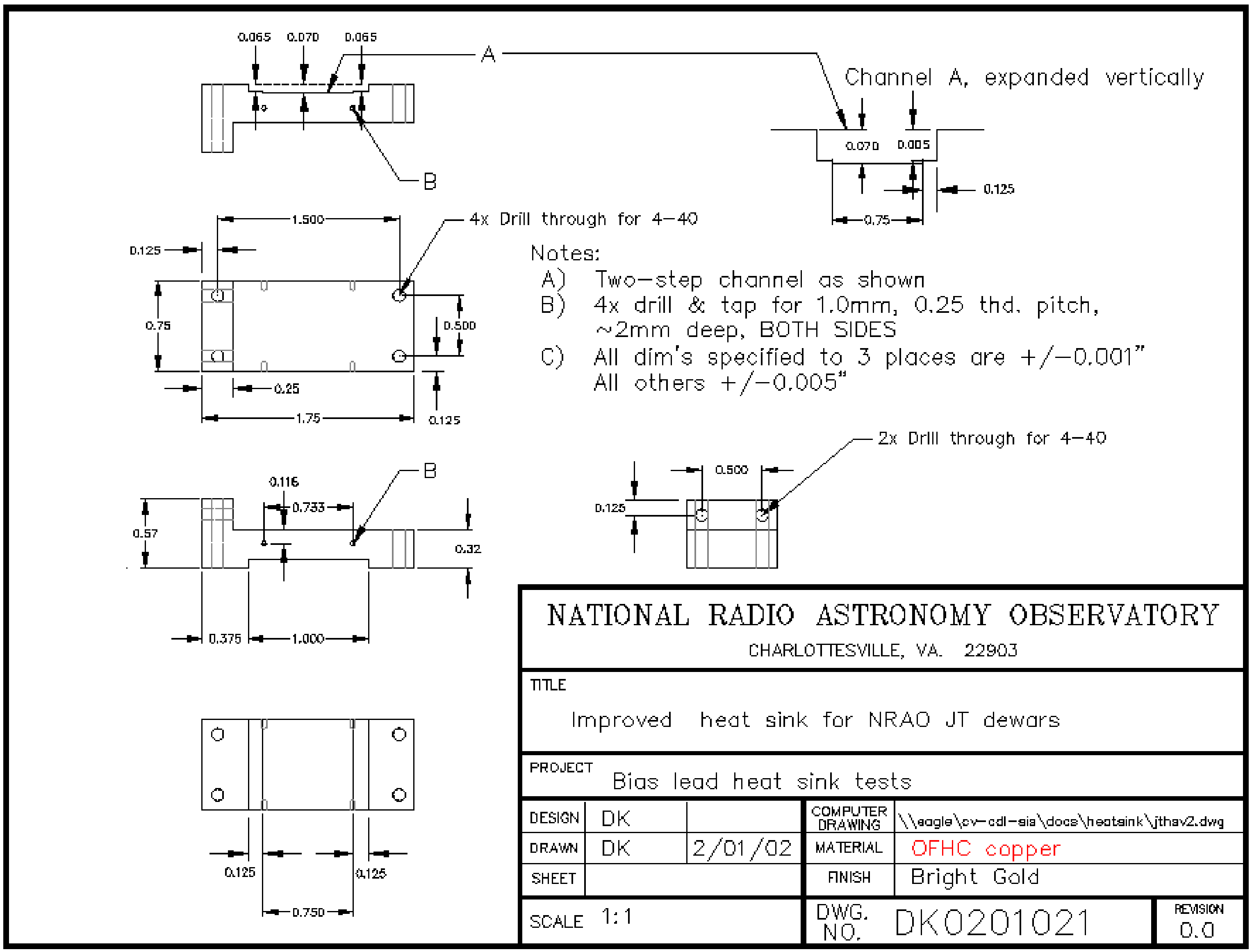

Figure A2. Design of the heat sink "shunt plate." Dimensions are in inches.

Appendix B – Older Heat Sink Measurements

In the process of developing the larger heat sink, some prototype designs were built and tested. The layout of the first heat sink, designated "Hs1," is essentially the same as the design described above; however, the circuit traces were 0.001″ thick (0.0254 mm), corresponding to "2-ounce" copper circuit board. The board was separated from the shunt plate with Mylar squares while glueing so the Stycast 2850 epoxy was 0.0025″ (0.064 mm) thick. The trace length in contact with the shunt plate was 0.75″ (19 mm). Otherwise, the measurement and data analyses were the same. Results for this device are presented on the following page in Figures B1-B8.

A second heat sink of this type, #11, was removed from service and tested, but only in the vertical orientation. Because the circuit board was not recessed into the shunt plate, it stuck out slightly below the plate and made it impossible to mount this device horizontally. The dimensions are the same as Hs1; however, the PCB trace thickness was 0.0012″ (0.030 mm) and the epoxy was 0.0018″ (0.046 mm) thick. Data are presented in Figures B9-B12. Heat sink #11 was measured at 12 K, 20 K and 77 K only.

Finally, another approach was tried, as illustrated by the heat sink plate in Figure B13 below. A meandering path was milled in an OFHC copper block 0.25″ thick by 1″ wide by 1.75″ long (6.4 x 25.4 x 44.5 mm). Twelve pairs of Lakeshore 38-gauge, enamel-insulated, phosphor-bronze wire were fixed in the grooves by Apiezon type "N" high-thermal conductivity vacuum grease[1] and the assembly was bolted down in the test cryostat. A pair of test blocks similar to those shown in Figure 4 were soldered directly on to the ends of the phosphor-bronze wire which stuck out from the heat sink block approximately ½″ (1 cm). Thermal tests were carried out in the same manner as for the printed circuit heat sinks. Only 12 K and 77 K measurements were carried out because of the very long thermal time constant of this heat sink. The high thermal resistance of the phosphor bronze prevented the heater blocks, T1 and T2, from reaching equilibrium quickly, and single measurements took several hours each. The results, presented in Figures B14-B17, are not very encouraging as the "figure of merit" for this device is only ~100, a factor of 10 below that of the printed circuit designs.

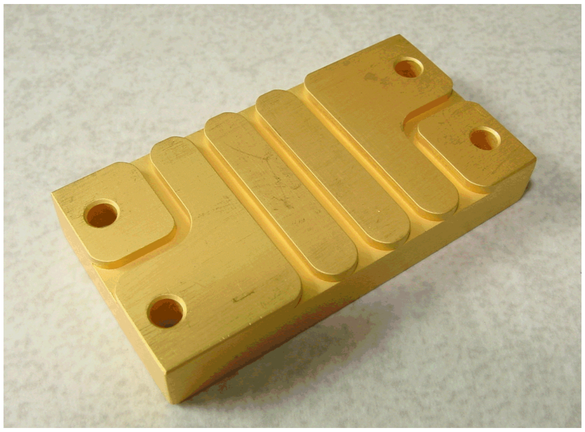

Figure B13. A heat sink block used to clamp down 12 pairs of phosphor bronze wire with Apiezon N high-conductivity vacuum grease[1].

[1] Apiezon Products, M&I Materials, Ltd., P.O. Box 136, Manchester M60 1AN, UK. www.apiezon.com. Also available from Lakeshore Cryotronics, Inc., 575 McCorkle Blvd., Westerville, OH 43082.

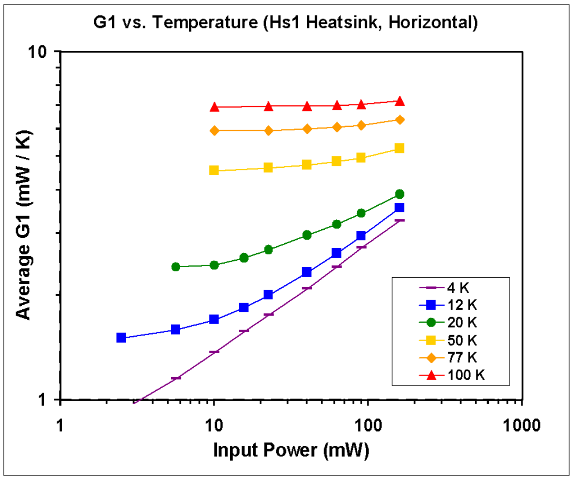

Figure B1. G1 for the original heat sink, horizontal.

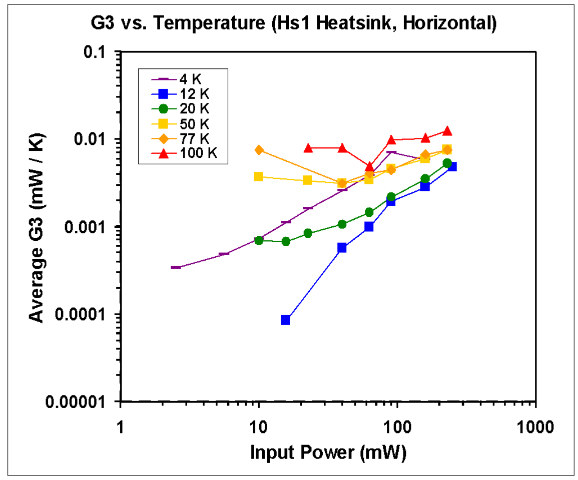

Figure B2. G3 for the original heat sink, horizontal.

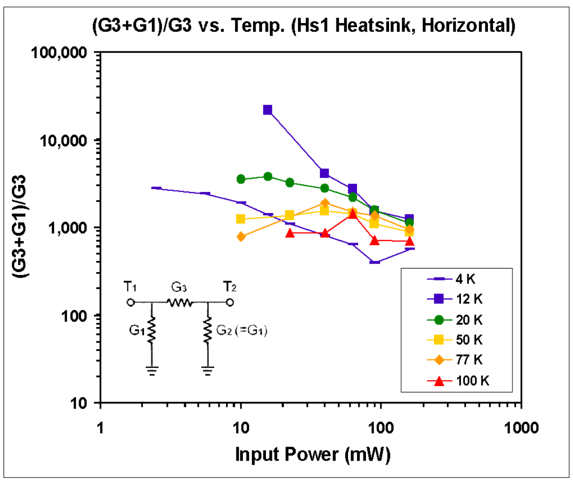

Figure B3. "Figure of merit" for the original heat sink mounted horizontally.

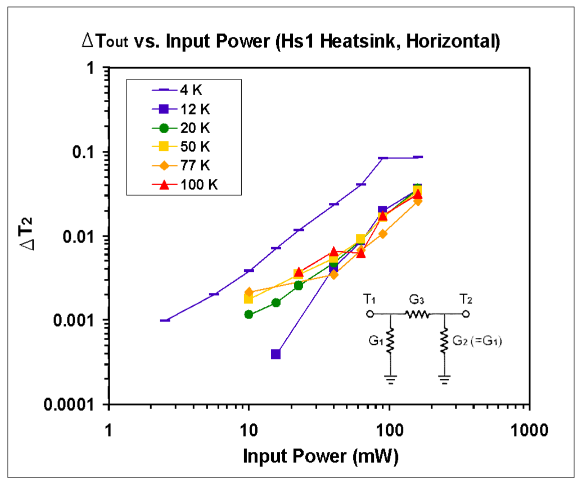

Figure B4. Output temperature rise vs. input power for the original heat sink, horizontal.

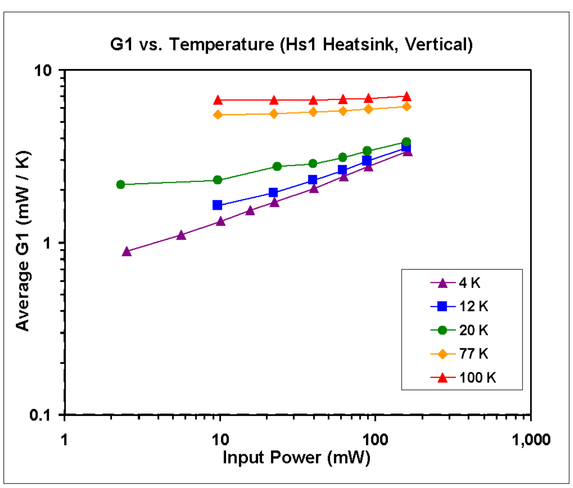

Figure B5. "Figure of merit" for the original heat sink mounted vertically.

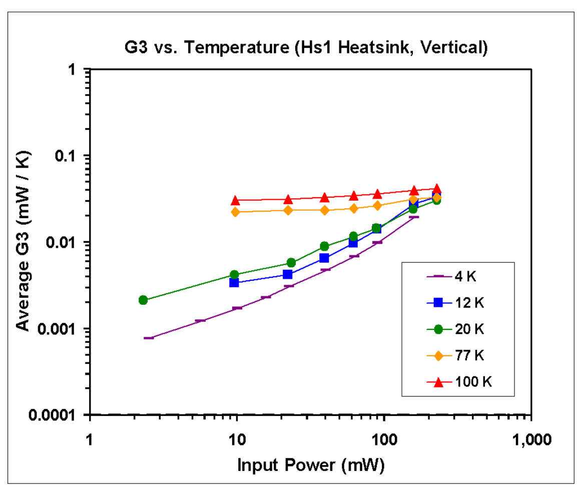

Figure B6. G1 for the original heat sink, vertical.

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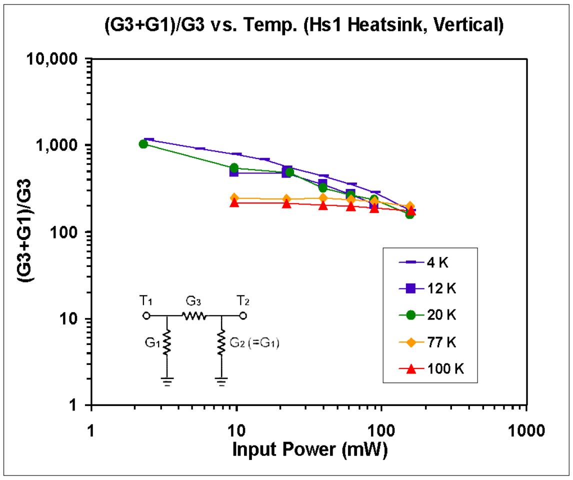

Figure B7. G3 for the original heat sink, vertical.

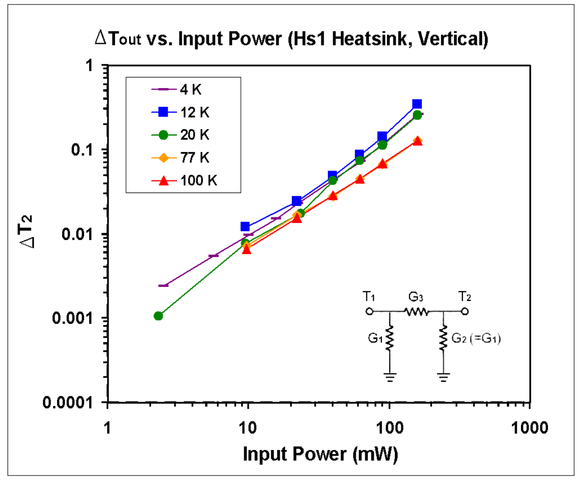

Figure B8. Output temperature rise vs. input power for the original heat sink, vertical.

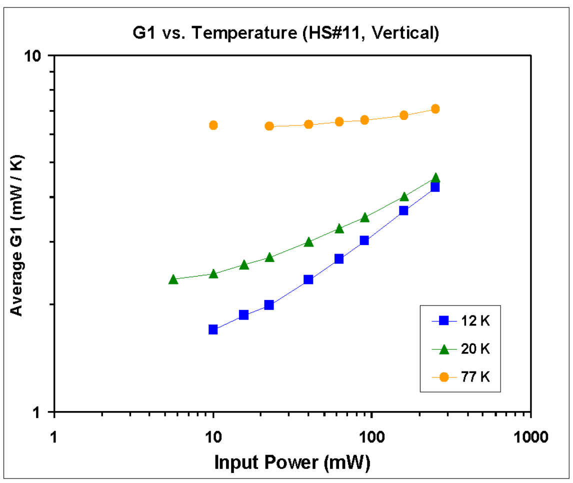

Figure B9. G1 for heat sink #11, vertical.

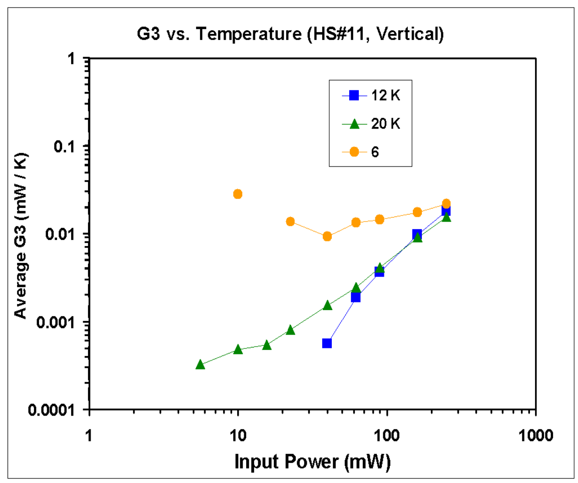

Figure B10. G3 for heat sink #11, vertical.

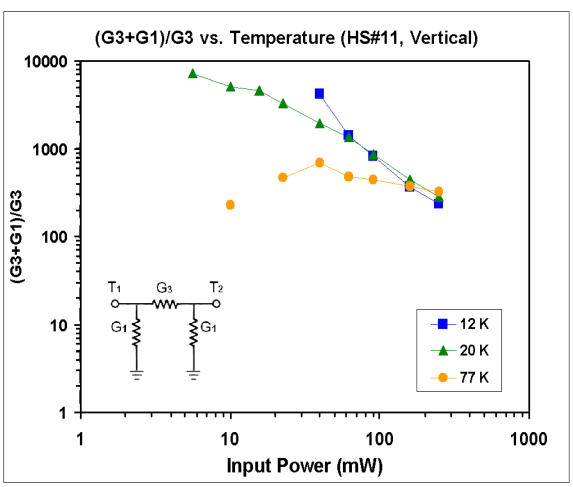

Figure B11. "Figure of merit" for heat sink #11 mounted vertically.

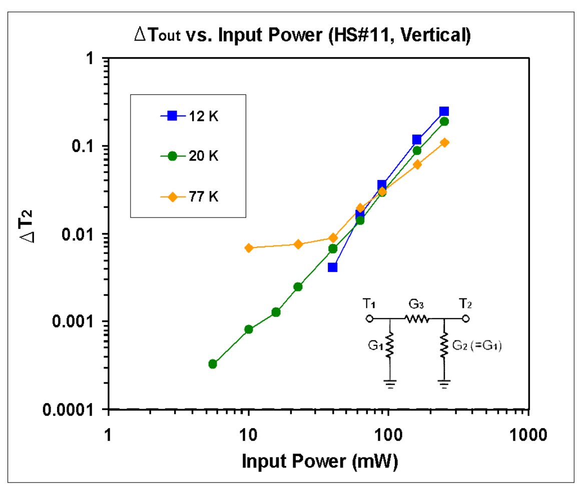

Figure B12. Output temperature rise vs. input power for heat sink #11 mounted vertically.

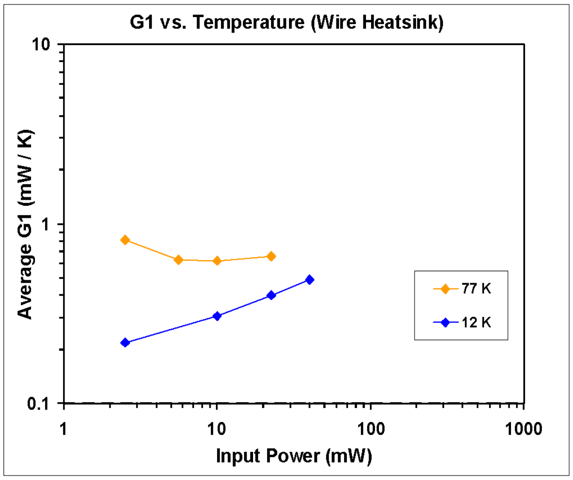

Figure B14. G1 for the wire heat sink.

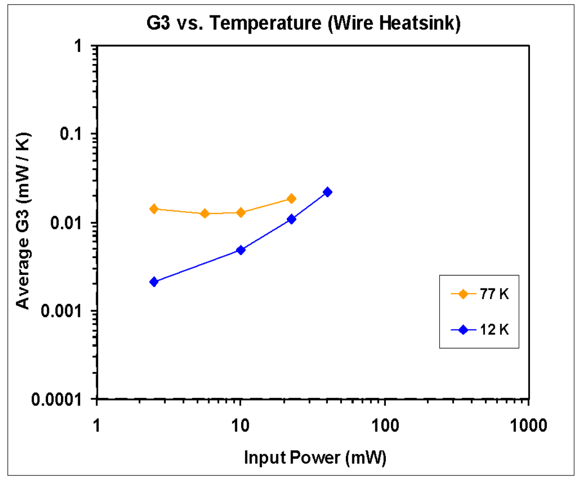

Figure B15. G3 for the wire heat sink.

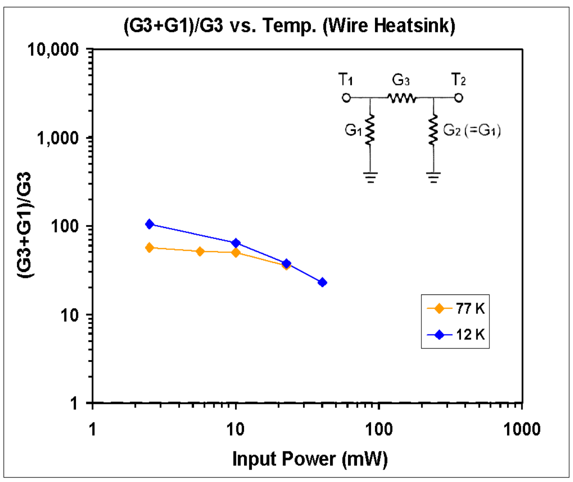

Figure B16. "Figure of merit" for the wire heat sink.

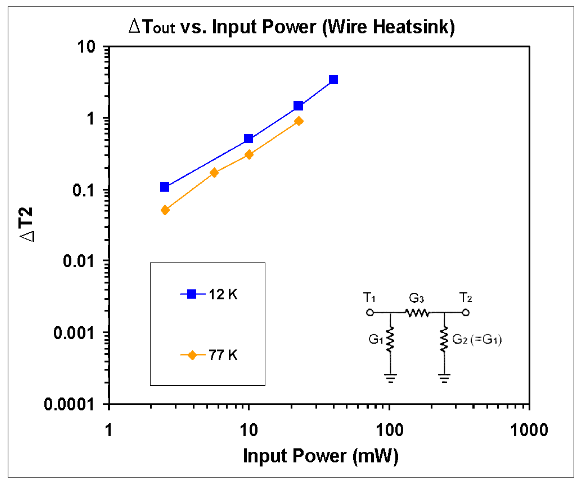

Figure B17. Output temperature rise vs. input power for the wire heat sink.