Thermal Design Techniques improve Solid State Power Amplifier Performance

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ABSTRACT

This paper describes the basic thermal design of a new class of Microwave Power Amplifier used in Satellite Communication Systems. By combining a new heatsink technology along with a thorough thermal design, it is shown that Solid State Power Amplifiers can be manufactured to be size, weight, and cost compatible with their vacuum tube counterparts.

Two thermal simulators are introduced and correlation is shown with the measured test results. R-Tools is an online web application that can be used by thermal designers to quickly evaluate heatsink performance. Sauna is a thermal simulator by Thermal Solutions Inc. that can prove quite effective in finned plate heat transfer design.

INTRODUCTION

For many years Solid State Power Amplifers (SSPA) and Traveling Wave Tube Amplifiers (TWTA) have competed in communication services. This is particularly so in satellite communication systems in the 6 GHz and 14 GHz satellite uplink frequency bands. Traveling Wave Tube Amplifiers have always had the advantage of being able to produce a large amount of microwave energy in a single electron tube. A TWTA is capable of producing power levels in excess of 1 kilowatt from a single tube. The tube can operate at power densities of approximately 500W/cm^2. Additionally, the tube is capable of operating at anode temperatures of 800 ^{o}C. Contrast this to the typical gallium arsenide (GaAs) microwave transistor, which has power densities up to 35W/cm^2 and must not exceed a channel temperature of 175 ^{o}C.

At the present time, the highest RF output power achievable from microwave transistors is 60W at 6 GHz and 20W at 14 GHz. Therefore to produce communication amplifiers capable of output power levels greater than 100W, many transistors must be combined. Microwave device DC to RF efficiencies range from 30 to 40%. With this low efficiency and a large number of devices, it is evident that a excessive amount of power is lost to heat. Not only is the DC to RF efficiency a concern but the RF combining efficiency is also critical to the success of a solid state power amplifier. Much research has been done to develop novel, high efficiency microwave power combiners. One general result of all high efficiency combiners however is the requirement that the microwave transistors be mounted in very close proximity to one another. This results in a very complex, two-fold, heat-spreading problem. The first problem in spreading the heat from the microwave transistor involves transferring the heat from the microwave transistor chip to its mounting flange. The gallium arsenide chip must be mounted to a thermally stable metal such as kovar. The kovar carrier is then attached to a copper spreader, which is usually the mounting flange of the transistor. With the extremely small size of the microwave transistor die, this results in a relatively inefficient heat spreader. This problem is the domain of the transistor manufacturer and there is little that the amplifier designer can do about this. The heat spreading resistance or thermal impedance from the channel to the flange of the microwave device is fairly large. Channel to flange thermal resistance is typically 0.6 ^{o}C/W for a 60W, 6 GHz device and 1.2 ^{o}C/W for a 20W, 14 GHz device. This high thermal impedance of the transistor along with the high heat density created by the large number of devices creates a very difficult thermal management problem. The successful realization of high power solid state power amplifiers requires the unique combination of effective microwave combining techniques along with clever thermal design.

Size Disadvantage

Historically, solid-state power amplifier designers have used brute force techniques to handle the thermal management problem. This involves very large heat sink extrusions and heavy heat spreading plates. The pressure drop and fin length of these heatsinks typically require large fans to produce the required volumetric airflow. This results in solid-state amplifiers that are usually 3 to 4 times larger and 4 to 5 times heavier than the TWTA equivalent. Even though it has been accepted that solid-state amplifiers are much more reliable than TWTAs, the size and weight differential is a difficult hurdle for the SSPA. TWTA reliability has been improving in recent years, making it more difficult to sell SSPAs based on the reliability advantage alone. Additionally the reliability advantage of the SSPA can only be realized by careful observation of the maximum device operating temperatures. If the transistor is operated above its maximum channel temperature of 175 ^{o}C then the reliability decreases. This places the SSPA designer in a very difficult position when trying to reduce the size of high power amplifiers. In the past, the increased size and weight of the SSPA have completely eliminated their use in mobile and aeronautical applications. It is somewhat less critical in base station applications but along with the additional size and weight usually come higher initial cost. This higher cost has been yet another dilemma that has been associated with the SSPA.

High Performance Heatsink

In an effort to reduce the size and weight of high power amplifiers, designers have looked toward using higher density finned heatsinks. There are some heat sink vendors offering high-density folded fin heatsink designs. While these designs achieve high fin density they are typically fabricated by epoxy glue attachment to a heat spreader plate. This results in a heatsink that is unable to cope with the high heat density that is encountered in the SSPA. R-Theta, Inc of Mississauga Ontario has recognized this problem and developed a high density heatsink that uses a fin swaging process to dramatically increase the efficiency of high density finned heatsinks.

The heatsinks used in this SSPA application were bonded using a metal displacement process referred to as “Swaging”. The Swaging process, depicted in Figure 1, can be described as a cold forming process, which is used in the fabrication of high fin density heatsinks. Currently, this process involves the placement of fins with a tapered base into a slotted base plate and then the application of a rolling pressure on the opposite sides of each fin. This results in vertical and lateral pressure of the base unit material, which tends to push the fin toward the bottom of the groove in the base. This secure connection provides very good thermal contact between the fins and base and also prevents air and moisture from entering the grooves, thereby preventing corrosion and allowing the heatsink to be anodized

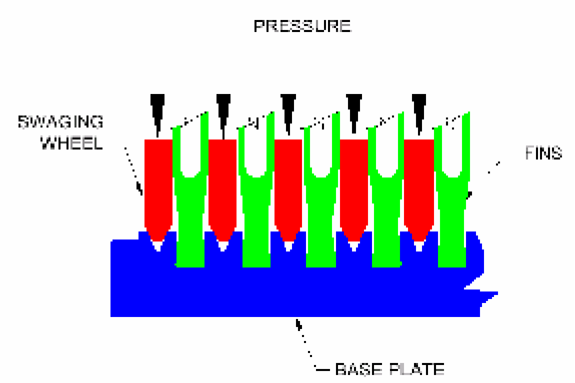

Figure 1: Swaging process of tapered fins into the grooves of a baseplate with the application of rolling pressure on opposite sides of each fin.

Generally, the heatsink base plate area, fin height and fin-center-to center distance were illustrated in Figures 2. The Aluminum Hollow Fin heat sink was swaged with an average fin center-to center distance of 3.43mm. The individual Hollow fin is extruded with a wall thickness of 1 mm and an overall average thickness of 3.8mm. The hollow fin is extruded with a tapered thick foot (see Figure 1). The thicker fin base helps to secure the connection between the fins and the baseplate and results in good thermal contact through the swaging process. The extrusion process used to produce the Aluminum Hollow fins is flexible enough to allow for different fin body and fin base geometries as shown in Figure 2.

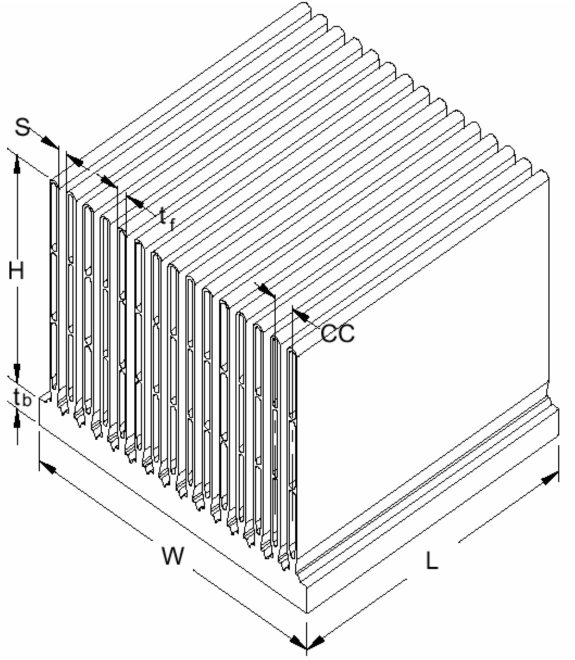

Figure 2: Heatsink geometry and dimensions

Design of a 400W 6 GHz Amplifier Heatsink

A 400W, 6 GHz Solid State Power Amplifier is a popular and useful output power level for Satellite Earth Station transmitters. Because of the superior distortion characteristics of the solid-state power amplifier, a 400W SSPA is approximately equivalent to a 1 kW TWTA. In order to achieve low distortion from a TWTA it must be operated well below its maximum output power capability. The SSPA can be operated much closer to its maximum rated output power, resulting in a more efficient amplification system. Even with this efficiency improvement the SSPA still requires 1630 Watts of DC input power to produce 400 Watts of microwave power at 6 GHz. The amplifier designer cannot assume that the amplifier will always be operating at maximum output power as this is under control of the Earth Station engineer. Therefore the heatsink must be designed to handle the entire 1630Watt dissipation. The size of the heatsink for the amplifier is 355mm wide (W) by 381 mm (L) long. The heatsink must accept two 200 W amplifier modules. The output power from the modules is combined using a wave-guide combiner to achieve the 400W power level. Figure 3 shows the modules on the hollow fin heatsink.

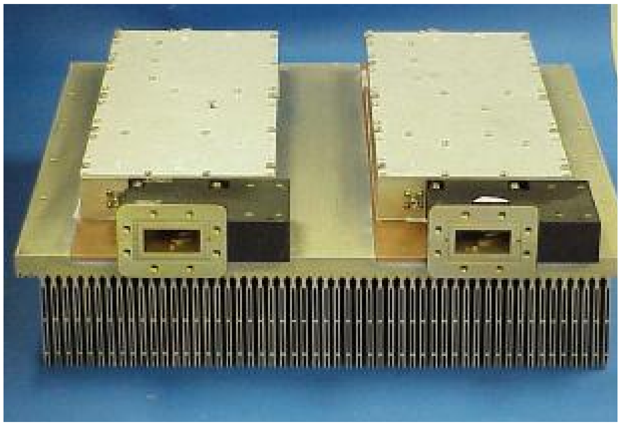

Figure 3. Amplifier modules mounted to hollow fin heatsink.

A parallel set of fans is used in a push-pull arrangement to develop the system airflow. Using the Papst W2G115 for all four fans resulted in a measured fin velocity of 5 m/s (1000 LFM). The design goal is to achieve less than 75 ^{o}C flange temperature on the RF output transistors.

Heatsink evaluation using R-Tools

Power electronic designers require quick and accurate heat sink solutions. With the advent of the Internet, and realizing the potential of providing interactive design capability on the Web, R-Theta has introduced R-Tools®; a completely interactive on-line thermal design tool for heat sinks. The R-Tools mathematical engine is located on a web server at R-Theta Inc. R-Tools simulation can be run on an Internet browser, which is capable of utilizing Java Applets. R-Tools® thermal modeling is based on a set of analytical models for conduction heat transfer in the solid elements coupled with natural and forced convection heat transfer models in the cooling airflow. The conduction heat transfer model in the baseplate of the heat sink is based on the steady state solution of the Laplace equation for general rectangular geometry. The solution is based on a general three-dimensional Fourier series solution, which satisfies the conduction equation in the base plate. For the forced convection air-cooled fins, an analytical model is used to predict the average heat transfer rate. The model used is a composite solution based on the limiting cases of fully developed and developing flow between parallel plates. Because the R-Tools® is analytically based, the solution is achieved within a few seconds, a very short time compared to the several hours required for a full CFD simulation. R-Tools® provides a method for quickly and accurately testing various heat sink configurations. The use of analytically based design tools allows the user to perform the thermal design of the heat sink concurrent with the optimization of the electrical and manufacturing elements prior to any prototype or testing. This approach results in reduction in design time and better reliability in the finished product.

Figure 4 shows the temperature map on the baseplate of the heat sink. The temperature shown in the Figure 4 is the maximum temperature on the heat sink baseplate under each individual power device. R-Tools provides hydraulic parameters for the heat sink performance such as the pressure drop and Reynolds number. The pressure drop can be used to determine the appropriate fan, which can deliver this volumetric flow rate for the system. Temperature of the devise channel (junction) can be calculated using R-Tools. This can be achieved by providing interface thermal resistance R_{sc} and Channel to Case devise thermal resistance R_{cc} (junction to case thermal resistance R_{jc}). Those temperatures are based on the average temperature under the devise. The average temperature under the hottest four devises is shown in Table 1.

Table 1: R-Tools temperature Results for heat sink, case and junction.

R-Tools	T_1	T_2	T_{case3}	T_{case4}
$T_{heatsink}$	66	70	67	65
T_{case}	70	74	71	68
$T_{channel}$	145	149	146	143

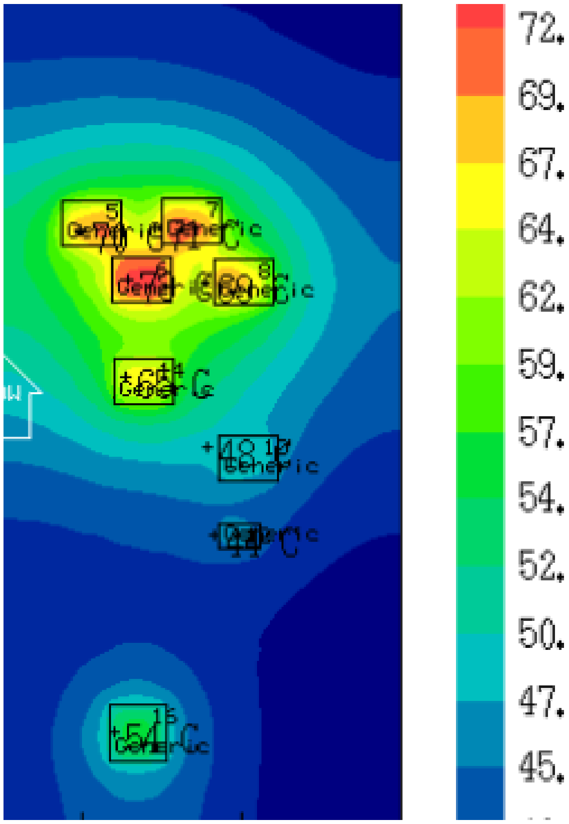

Figure 4: R-Tools simulation results for the Amplifier heat sink for velocity 5m/s (1000LFM) and ambient temperature of 25°C.

R-Tools results showed that the hollow fin heat sink would be capable of dissipation the heat out of the transistors. The case temperature under the hottest devices on the module is less than 75°C and the channel temperature is well below the maximum specified temperature of 175 °C.

Table 2 shows a very remarkable agreement between R-Tools results and measured case temperature.

Table 2: R-Tools, Sauna results compared with measured case temperature.

	T_{case1}	T_{case2}	T_{case3}	T_{case4}
R-Tools	70	74	71	68
Measured	72	73	73	71
Sauna	69	72	70	69

Detailed Heatsink Design using Sauna

Once the basic heatsink configuration has been determined using R-Tools, the detailed heatsink design can proceed. The detailed heatsink design is implemented with Sauna. Sauna is a Windows based thermal design software by Thermal Solutions Inc. It is quite effective in heatsink designs that include a stack of interface materials or plates. The plate stack-up is a typical problem encountered in most RF amplifier designs. It is usually impractical to have the microwave transistors mounted directly to the heatsink. In each 200W amplifier module, the transistors are mounted to an aluminum (T6061) housing. The amplifier housing is then mounted to the heatsink (T6063). In each case there is a thermal interface material, which must be taken into account. A cross section of the thermal interfaces is shown in Figure 5.

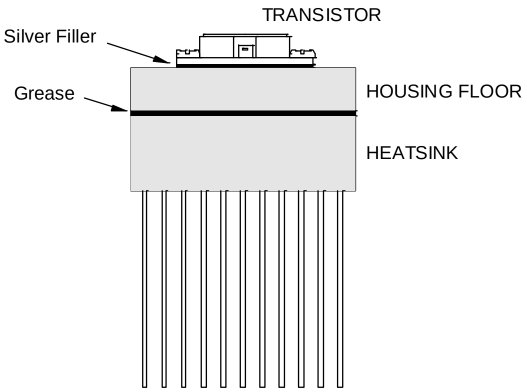

Figure 5. Cross Section of Thermal Interfaces.

The completed Sauna thermal model is shown in Figure 6. The figure shows 16 transistors modeled as heat sources on the T6061 amplifier housing floors. Sauna creates an electrically equivalent network of nodes and resistors throughout the plates. It uses the classic thermal network method of calculating the heat transfer throughout the plates and across the interfaces between plates. The program automatically calculates the resistor and node values based on the plate dimensions and material properties chosen.

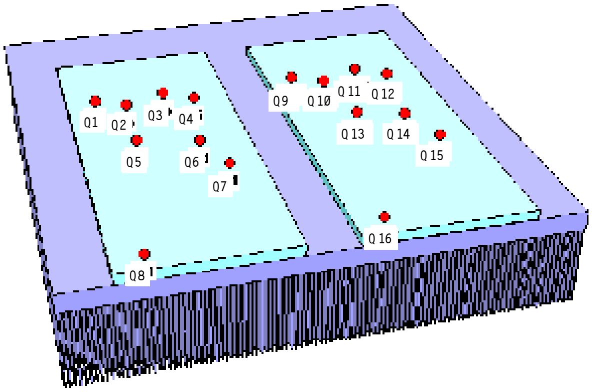

Figure 6. Sauna Model of Heatsink and Amplifier Modules

The fin linear air velocity is then entered into the program along with the ambient temperature. The program quickly calculates the steady state temperatures throughout the heatsink assembly along with the channel temperature of the transistors. Sauna lends itself well to performing what-if analysis. Plate dimensions, heat source positions, and fin dimensions can be readily changed to determine the optimum heat transfer. Figure 7 shows the computed heat transfer results for one of the amplifier modules. The temperatures directly above the heat source node are the transistor's simulated case temperature and channel temperature respectively. The heatsink is colorized to show the thermal contours across the plate assembly. The actual measured transistor flange temperatures for the hottest four devices are shown in the inset. The difference between the measured flange temperatures and the simulated flange temperatures is no greater than 3 degrees Celsius. The program is able to achieve very good correlation with the measured results. This is particularly impressive considering the interface stack up and the high heat density created by the close proximity of the RF output transistors. In this case, the design goal of 75 **°C** maximum device flange temperature has been achieved (see Table 2).

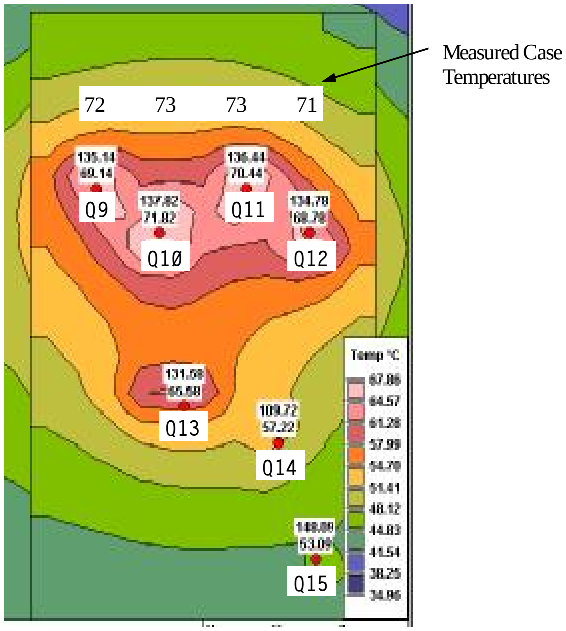

Figure 7. Simulated and measured device temperatures.

Figure 8. Comparison of new and old 400W, 6 GHz Solid State Power Amplifiers.

Conclusions

It has been demonstrated that excellent thermal engineering can be achieved through the use of low cost and free software tools. Reliable thermal design tools can prove invaluable to the design engineer. Costly and time-consuming trial and error techniques can now be replaced with thorough design.

Good thermal design, along with an innovative new heatsink technology has combined to produce an exciting new series of Solid State Power Amplifier. Solid State Power Amplifiers can now be manufactured with tremendous size and weight reduction. This allows SSPAs to be used in installations that were previously the domain of Traveling Wave Tube Amplifiers. The 400W 6 GHz amplifiers described in this paper is now equal to, or smaller than its competing TWT amplifiers. To fully appreciate the size and weight reduction, consider the comparison shown in Figure 8.
The amplifier on the left is the new SSPA using the Hollow Fin heatsink technology. The amplifier on the right is its predecessor, which used combinations of extruded heatsinks. Both amplifiers are in standard EIA racks. The old style amplifier is 425 mm high and weighs 79 kg. The new amplifier is 178 mm high and weighs 38 kg. This represents a 60% reduction in rack height and a 50% reduction in weight. Along with this size and weight reduction comes a comparable decrease in manufacturing cost. For the first time, Solid State Power Amplifier technology is truly comparable in size, weight, and cost to the Traveling Wave Tube. Now considering the inherent reliability and distortion advantage of solid-state devices, the Solid State Power Amplifier is poised to be the preferred amplifier in Satellite Communication Earth Stations.