

Advanced Packaging Materials and Techniques for High Power TR Module

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Abstract—The higher output power densities required of modern radar architectures, such as the proposed DESDynI [Deformation, Ecosystem Structure, and Dynamics of Ice] SAR [Synthetic Aperture Radar] Instrument (or DSI) require increasingly dense high power electronics. To enable these higher power densities, while maintaining or even improving hardware reliability, requires advances in integrating advanced thermal packaging technologies into radar transmit/receive (TR) modules. New materials and techniques have been studied and compared to standard technologies.

I. INTRODUCTION

New radar systems, such as DSI (the proposed DESDynI [Deformation, Ecosystem Structure, and Dynamics of Ice] Interferometric SAR [Synthetic Aperture Radar]) [1], that employ array fed reflectors, require higher RF power densities than traditional flat panel phased arrays. To enable large numbers of densely-packed, transmit/ receive (TR) modules capable of even higher output power, design of the thermal packaging is increasingly more important. This paper details the investigation of new packaging materials and techniques to improve thermal performance to significantly improve reliability, while enabling advancements in instrument performance.

High power, compact arrays enable the use of large reflector-based architectures, such as SweepSAR [2], which significantly reduce instrument mass and its associated cost. Higher power, more compact arrays, however, dramatically increase the power density, both RF and DC, due to the smaller size and higher power. Thermal dissipation in these arrays is a key challenge, and requires integrated thermal management to maintain, and possibly improve, overall reliability in the presence of increased thermal variations.

The key benefit of the advanced packaging techniques discussed in this paper is in improving the trade-space between increasingly dense, higher power-handling RF-hybrids and their long term reliability on-orbit. This is accomplished by reducing thermal cycling stress through more efficient electronics, increasing thermal transfer at each level of fabrication, reducing CTE (Coefficient of Thermal Expansion) mismatches, while also decreasing thermal

variability with embedded phase change material. These techniques enable the fabrication of more robust, compact electronics. This is a key challenge to implementing the DSI instrument with the most affordable architecture.

The first step to reduce thermally induced fatigue is to increase overall efficiency, therefore reducing the amplitude of power cycling induced thermal variability. This is accomplished through using Gallium Nitride (GaN) transistors for the power amplifiers, which is quickly becoming an industry standard [3]. The next step is moving heat from hot areas quickly to avoid reducing the mean expected lifetimes of adjacent components and devices interconnects. This is done using PCB and housing materials with high thermal conductivity, and well matched CTEs.

The final step in this integrated approach to thermal packaging design is the introduction of a “thermal capacitor”, which effectively low-pass filters heating from power cycling. The thermal capacitor discussed in this paper is PCM (Phase Change Material), which absorbs heat through a phase transition of the material. This concept is not new for ground-based electronics, see for example [4], however, established techniques rely upon gravity and are not applicable to spaceborne instruments. The PCM technology discussed is designed for use in microgravity.

II. HIGH EFFICIENCY ELECTRONICS

A. Gallium Nitride Power Amplifiers

GaN (Gallium Nitride) technology shows great promise for RF power amplifiers [5], high power RF and DC switches [6], as well as robust LNAs (Low Noise Amplifiers) [7]. With significantly higher temperature survivability, higher breakdown voltage and lower input impedance than silicon bipolar, along with excellent predicted resistance to total dose radiation [8], GaN is currently the most promising new technology for advancing high-power spaceborne RF electronics.

This work supported by NASA’s Advanced Component Technology Program ACT-08-0062.

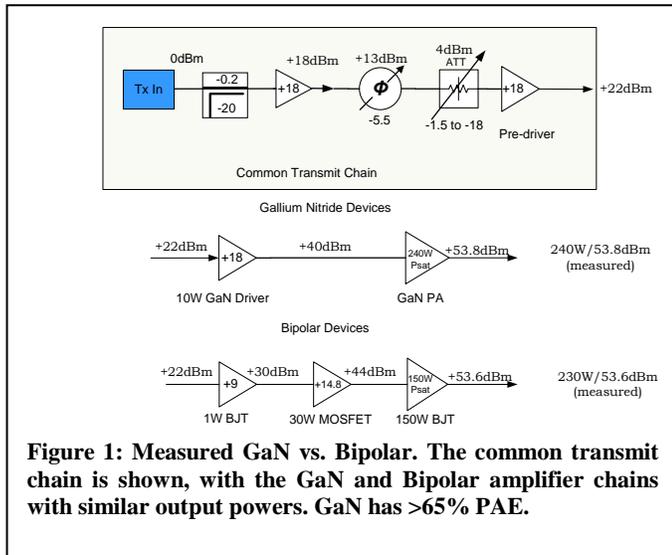


Figure 1: Measured GaN vs. Bipolar. The common transmit chain is shown, with the GaN and Bipolar amplifier chains with similar output powers. GaN has >65% PAE.

The greatest impact of GaN technology on TR module performance is increased efficiency and reduction of thermal stresses, which is the focus of this paper. Several devices from multiple manufacturers have been evaluated for performance and reliability. Measured results indicate PAE (power added efficiency) in the range of 60% to 70% for individual power amplifier stages, yielding an expected overall TR module efficiency of approximately 45%, when operated in CW mode, or 50W average power consumption for 180W RF output power at 10% duty cycle, which is the anticipated duty cycle of DSI, see Figure 1.

GaN devices for the transmit chain of the TR module decreases DC power, and its associated thermal dissipation, while slightly increasing transmit power, see Figure 2. This decreases the power consumption of the proposed DESDynI radar array by almost 250W.

	Common				16
	Pout	DC	Peak DC	Avg DC	Modules
	[W]	[W]	[W]	[W]	[W]
GaN	240	9	405	47	747
Bipolar	230	9	563	62	992
GaN Improvement	10	0	28%	25%	25%

Figure 2: Measured DC power consumption and RF output power for GaN and Silicon Bipolar transmit chains. The DSI baseline is for 16 modules—showing DC power savings of 25%, with an additional 160W transmitted power (total).

The ESS (Energy Storage System) for this transmit chain is crucial to the proper operation of the TR module and radar instrument. A custom ESS has been developed and tested. At ambient temperature and pressure, this ESS is 88% efficient. The design and results of the ESS will be discussed in a separate paper [9].

B. Rad-Hard, High-Efficiency Voltage Regulators

Space qualified voltage regulators typically have drop-out voltages in the range of 1-1.5 volts, which significantly decreases the overall module’s efficiency. A new, rad-hard by design POL (Point Of Load) regulator has been tested for RF applications. Typically, POL regulators are too noisy for use with RF amplifiers. Using quieter, rad-hard technology may enable RF applications to employ POL regulators for space. Preliminary tests show that the switching noise, while still present on the output of the regulator itself, does not affect the LNA under test, with efficiencies of approximately 95%.

III. ADVANCED MATERIALS

Once the most efficient design has been developed, the long-term reliability of the TR module can be improved if the effects of thermal cycling can be mitigated. In the absence of system level active temperature control, which is impractical for distributed electronics such as a phased arrays, closely matching the CTE between materials and quickly moving heat away from hot spots can decrease mechanical stresses on the many interconnects inside of a TR. Controlled Expansion (CE) alloys provide a solution for high thermal conductivity with low CTE, taking the best properties from aluminum and Kovar, respectively, and are discussed below.

A. CTE Matched Silicon Aluminum Alloy

Typical housings for space qualified TR modules are made from either Kovar or 6061 Al. Although Kovar has a coefficient of thermal expansion (CTE) close to those of GaAs and Si, it also possesses a 10x reduction in thermal conductivity and a 3x increase in density compared to 6061 Al. 6061 Al provides improved heat dissipation properties, but has a CTE that is nearly 4x that of Kovar.

A series of controlled expansion (CE) bulk spray deposited Si-Al alloys developed by Sandvik Osprey for electronic packaging applications, are being evaluated for TR housings. These CE housing materials combine a CTE approaching that of Kovar, with a thermal conductivity approaching that of 6061 Al, and a density that is less than that of both materials. The mechanical behavior of select Si-Al alloys was evaluated for space flight applications and direct attachment of active devices, over thermal cycling from -55 to +125°C [10]. The alloy compositions are shown in Table 1, and in Table 2 their CTEs are compared to other materials typically found in TR modules.

Table 1. CE Alloy Compositions

Alloy	Composition (wt.%)
CE7	70Si-30Al
CE9	60Si-40Al
CE11	50Si-50Al
CE13	42Si-58Al

A typical GaAs die, see Figure 3, was attached to each of four gold-plated CE alloys, using 80Au-20Sn solder at 300°C. The assemblies were exposed to 790 MIL-STD 883G-B thermal cycles (-55 to 125°C) without failure. For detailed results see [10].

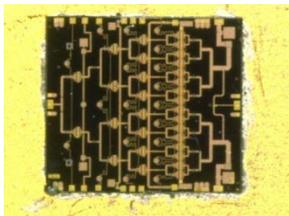


Figure 3: Photo of GaAs RF power amplifier attached to CE alloy (gold plated). Samples with CE7, 9, 11 and 13 were exposed to 790 thermal cycles (-55 to 125°C) with zero failures.

These materials have application in high power TR modules for directly attaching bare die parts to the chassis. This eliminates additional manufacturing steps, as well as minimizes the thermal resistance between parts and the module, by reducing interfaces and materials. These alloys may be employed as the overall TR module housing or as a subcircuit carrier in a larger module.

Table 2. CTEs of Various Relevant Electronic Packaging Materials

Material	CTE (ppm/°C) 25°C
Al	23.6
Al2O3	6.7
CE7	7.2
CE9	9.1
CE11	11.4
CE13	12.2
Cu	16.6
GaAs	5.4-5.72
Kovar	5.87
Si	2.3-4.7

B. Carbon Impregnated PCB

For devices that must mount to a PCB, as opposed to the direct die attach, discussed above, efficient heat removal can still be critical.

Large FPGAs, such as the Xilinx V5, can develop significant localized heat that must be removed. Similarly, packaged high power RF amplifiers, or transistors can generate significant thermal cycling stresses on surrounding components (the RF power devices themselves are typically designed to survive and are more robust than the supporting electronics.) To move the heat of PCB mounted components, and to reduce the risk of overstressing vias, carbon impregnated PCB material from Stablcor™ was investigated alongside the best more standard materials.

A test structure, which includes FPGA packages, microstrip, stripline, buried and blind vias, was designed and

fabricated using selected PCB materials. The temperature rise, due to active components, was monitored in several locations (noted 1,2,3). The results and materials modeled are shown in Figure 4. Those highlighted in green border have been fabricated and are being tested for stability of RF performance of stripline and microstrip, over power cycling, and reliability of vias and FPGA attachment.

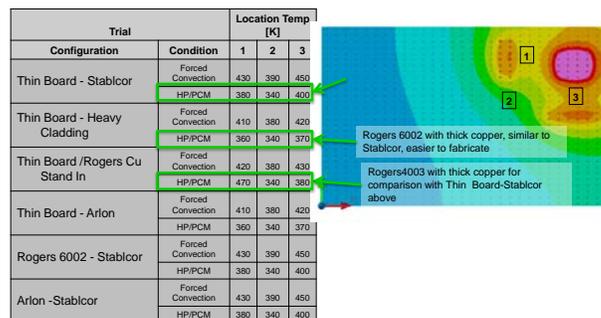


Figure 4: Modeled thermal performance of several PCB layers, or stacks. Rogers 6002, Arlon TC350, Rogers4003, with and without Stablcor™.

IV. PCM: THERMAL CAPACITOR

PCM, or phase change material, absorbs significant amounts of heat through the phase transition of its constituent material. This concept is not new and has been used to cool CPUs [4], however these heat sinks require gravity. ESLI (Energy Science Laboratories, Inc) attempts to overcome this limitation through incorporating a carbon fiber matrix to distribute the heat throughout the PCM without requiring gravity.

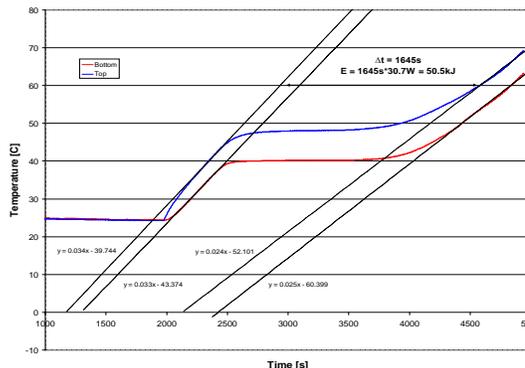


Figure 5: Measurement of PCM latent heat. The state transition region shows a stable temperature for ~1645 s.

The PCM thermal capacitor allows densely packed, high power TR modules to operate at nearly a constant temperature over defined periods of operation. Our nominal design is for a 5 minute period, with a 50% duty cycle, and a maximum temperature of 50C. Eicosane paraffin wax is used as the material because of its high latent heat capacity and melting point temperature of 36C, allowing margin for thermal resistance of the TR module. The latent heat storage of the

PCM was experimentally determined to be 50.5kJ, as compared to its design requirement of 48.7kJ, see Figure 5.

V. INTEGRATED TR MODULE

Each of these technologies is being integrated into a flight-like TR module, targeted at the DESDynI radar, capable of more than 100W transmit power using the high efficiency GaN PA, high thermal conductivity using the advanced materials, high peak thermal capacity using the PCM, with increased reliability through lower thermal variability and controlled expansion materials.

Final design and thermal analyses of the integrated TR module are currently underway. The TR module, see Figure 6, includes a >65% efficient transmitter, 90% efficient power supply, embedded PCM, and a chassis machined from controlled expansion alloys.

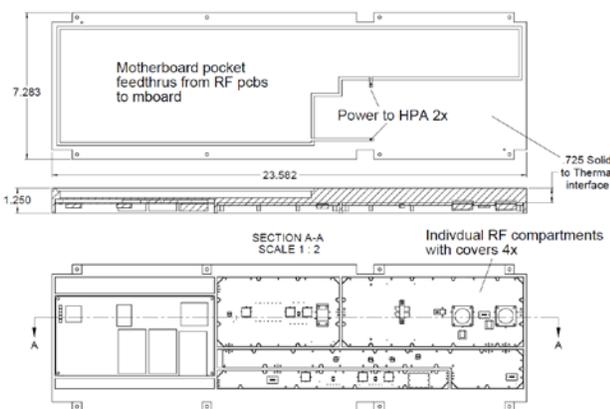


Figure 6: Integrated TR Module Fabrication Drawing. Note that a solid surface is placed under the high power amplifier. The PCM will be placed in this pocket for the advanced TR, increasing the time this TR can operate at full power without an increase in temperature.

VI. SUMMARY

Advanced materials and fabrication techniques are being investigated to improve performance and reliability of high power TR modules. Several promising technologies exist to reduce waste heat, increase thermal conductivity, reduce mechanical stresses through CTE matching, and reducing thermal cycling extremes through thermal capacitors (PCM). These technologies have been tested separately, and are in the process of being integrated into a test unit.

Successful integration of these technologies allows for packaging of higher power density electronics, while maintaining reliability. This work helps to enable more cost effective radar architectures for earth remote sensing, such as SweepSAR, which is being considered for the proposed DESDynI radar.

ACKNOWLEDGMENT

This work is supported by NASA's Earth Science Technology Office, Advanced Component Technology Program and the DESDynI Project, and was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

REFERENCES

- [1] "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", National Research Council of the National Academies, The National Academies Press, 2007.
- [2] Freeman, A., Krieger, G., Rosen, P., Younis, M., Johnson, W., Huber, S., Jordan, R., Moreira, A., "SweepSAR: Beam-forming on receive using a reflector-phased array feed combination for spaceborne SAR," *Radar Conference, 2009 IEEE*, vol., no., pp.1-9, 4-8 May 2009, doi: 10.1109/RADAR.2009.4977140
- [3] J. Shealy; *et al.*, "Gallium nitride (GaN) HEMT's: progress and potential for commercial applications," *Gallium Arsenide Integrated Circuit (GaAs IC) Symposium, 2002. 24th Annual Technical Digest*, vol., no., pp. 243- 246, 2002
- [4] Webb, R.L.; Yamauchi, S.; Denko, S.; Tochigi, K.K.; "Remote heat sink concept for high power heat rejection," *Components and Packaging Technologies, IEEE Tran. on*, vol.25, no.4, pp. 608- 614, Dec 2002
- [5] K. Joshin; Kikkawa, T.; "Recent progress of high power GaN-HEMT for wireless application," *Microwave Conference, 2006. APMC 2006. Asia-Pacific*, vol., no., pp.1027-1032, 12-15 Dec. 2006
- [6] B. Wang; Tipirneni, N.; Riva, M.; Monti, A.; Simin, G.; Santi, E.; "An Efficient High-Frequency Drive Circuit for GaN Power HFETs," *Industry Applications, IEEE Transactions on*, vol.45, no.2, pp.843-853, March-april 2009
- [7] M. Rudolph; Behtash, R.; Hirche, K.; Wurfl, J.; Heinrich, W.; Trankle, G.; "A Highly Survivable 3-7 GHz GaN Low-Noise Amplifier," *Microwave Symposium Digest, 2006. IEEE MTT-S International*, vol., no., pp.1899-1902, 11-16 June 2006
- [8] T. Hussain; Micovic, M.; Tsen, T.; Delaney, M.; Chow, D.; Schmitz, A.; Hashimoto, P.; Wong, D.; Moon, J.S.; Ming Hu; Duvall, J.; McLaughlin, D.; "GaN HFET digital circuit technology for harsh environments," *Electronics Letters*, vol.39, no.24, pp. 1708- 1709, 27 Nov. 2003
- [9] G. Sadowy, V. Vorperian, "Multi-Mission, High Performance, High Reliability Electronic Power Conditioners for Pulsed Solid-State Power Amplifiers.," JPL 2010 Research Poster Conference, November 2010
- [10] L. Del Castillo, J. Hoffman, G. Birur, "Advanced Housing Materials for Extreme Space Applications," IEEE Aerospace Conference 2011.