

Thermally Stabilized Transmit/Receive Modules

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Abstract — RF-hybrid technologies enable smaller packaging and mass reduction in radar instruments, especially for subsystems with dense electronics, such as electronically steered arrays (ESA). Despite benefits from RF-hybrids in spaceborne radars, necessary increases in the power density of these electronics requires improved thermal management and reliability. We are designing thermally stabilized RF-hybrid T/R modules using new materials for improved thermal performance of electronics. We are combining advanced substrate and housing materials with a thermal reservoir material, and develop new packaging techniques to significantly improve thermal-cycling reliability and performance stability over temperature.

I. INTRODUCTION

We are developing new RF hybrid packaging materials and techniques to improve their thermal performance, which will significantly improve their reliability while maintaining instrument performance. The benefit of this innovation is to improve the trade-space between increasingly dense, higher power-handling RF-hybrids and their long term reliability. This is accomplished by reducing thermal cycling stress thru increased thermal transfer at each level of fabrication, from bare die to subsystem housing, while also reducing thermal variability with embedded phase change material. These technologies enable the fabrication of more compact RF hybrid electronics, which is especially important to developing lower cost compact antenna array feeds, such as that being considered for the DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) radar.

The benefits of improving RF hybrid thermal performance and reliability will extend to all future earth science instruments that employ RF hybrids. These benefits are especially important for future radar instruments, since radar electronics experience significant internal thermal cycling due to power cycling of their high power transmitters. Radar mode changes, which are typically driven by science requirements, and instrument power cycling, which is used to conserve power, can cause dramatic changes in the average heat output by the radar transmitters. The repetitive heating and cooling of the transmitter impacts all nearby electronics and will stress the attachment points of the RF die and all supporting hardware. This cycling will eventually break wire/ribbon bonds or cause die to crack and/or detach from the substrate. To mitigate the impact of thermal cycling one typically mounts components further apart and/or adds

additional mass to improve heat spreading. This direct approach to thermal management is well established for traditional fabrication in which each higher level of hardware is mounted in another box or bolted to a plate for mechanical stability and heat spreading. This approach is impractical and a limiting factor for high density, high power hybrid electronics. This is especially true for electronically steered arrays where the electronics are locally dense (each T/R module), but also distributed over large distances (the N-number of T/R modules over the entire array).

If successful, these new technologies will allow electronics to be packed tighter or run at higher power, while reducing the temperature and thermal cycling through a significant increase in thermal transfer, and heat storage.

II. CONCEPT

We are investigating improved thermal stability and thermal cycling mitigation of RF hybrid modules by integrating four key technology areas:

- PCB (printed circuit board) material with high thermal conductivity.
- Custom alloys with low CTE, and high thermal conductivity for use in housing materials.
- Advanced phase change materials integrated within the housing of each TR module.
- Investigation of an ultrahigh thermal conductivity carbon fiber array/phase change material combination for integration with the housing material for very high power modules.

The heat in RF hybrids typically originates in one or more highly localized areas, which can build up to damaging levels or spread to more sensitive electronics. An effective thermal design removes the local heat and moves it away quickly, so we are investigating heat spreading materials. This, however, can also increase thermal-mechanical stresses if the active device must handle power cycling or duty cycle changes. To handle this we are combining housing material that has a CTE (coefficient of thermal expansion) that more closely matches that of the active die. We are also investigating the addition of a PCM (phase change material) thermal capacitor,

which absorbs heat during times of high thermal output. Lastly, we are investigating more efficient devices for key electronics.

First, the localized heat generated from the RF hybrid's high power die is difficult to transport away from the very small die. In conventional power packaging, the heat generated by high power devices is addressed by increasing the mass of high thermal conductivity, high heat capacity materials in contact with the device and to maintain a safe distance as well as thermal isolation between the high heat generating components and heat sensitive devices. To maintain the small size and low mass of the RF hybrid assembly, it is critical to investigate advanced thermal control options. If the heat is not dissipated quickly, the temperature of the high power die and neighboring devices may exceed their maximum operating temperatures.

The second thermal issue associated with RF hybrids results from repeated heating and cooling cycles associated with environmental thermal cycling or power cycling of the module. Due to the coefficient of thermal expansion (CTE) mismatch between the die and the substrate or housing, any increase in temperature will result in considerable stresses being generated between the die and the substrate, within the wirebond, and within the die. **Figure 1** illustrates the influence of temperature on deformation of electrical interconnects and attachment materials. The x-ray image to the right of the figure shows a wirebond that has failed due to thermal cycle related fatigue. If left unmitigated, thermal cycle related fatigue can drastically reduce MTBF (Mean Time Before Failure).

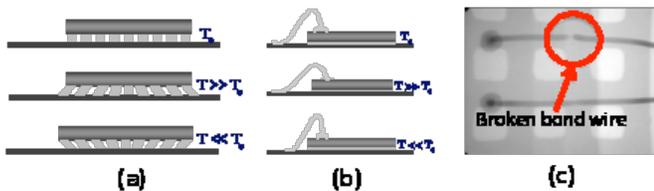


Figure 1. (a) Schematic illustrating the influence of temperature on assemblies composed of materials with differing CTEs. (b) X-ray image of hybrid assembly that failed due to thermal cycle related fatigue.

III. CHASSIS: SILICON ALUMINUM ALLOY

One technique to remove heat quickly from high power devices is to attach the die directly to the housing material (chassis). The default housing material for space flight hardware is 6061 Al, since it is inexpensive, easy to machine, and has good thermal conductivity. Unfortunately, CTEs for Al (23.6 ppm/°C for 6061 Al-T6) and Si (2.3-4.7 ppm/°C) or GaAs (5.4-5.72 ppm/°C) are very different, resulting in

significant stresses being concentrated either at the die attach material or within the die during the large thermal excursions caused by the intense local heating of high power electronics. An Al chassis may still be used, but an intermediary material, such as Cu-Mo-Cu (5.8 ppm/°C) die-attach preforms (aka, moly tab), must be inserted between the die and the Al housing to mitigate the CTE mismatch. The drawbacks to this technique include the need to design, procure, and bond an additional component (the moly tab), which is most often custom-made for each device, the addition of at least two potential failure sites (moly tab itself and the attachment), and the inability to inspect the attachment of the moly tab to the chassis. Poorly attached moly tabs will result in very poor RF and thermal performance, but may not manifest problems until late stage thermal testing. The CTE mismatch could potentially be alleviated through the use of a Kovar (5.9 ppm/°C) chassis material (the second standard material used for high frequency chassis). Kovar, which is a steel alloy, has a much better matched CTE to that of the die and hot parts may be attached directly to the Kovar chassis. Kovar, however, has two significant drawbacks for T/R arrays. Firstly, Kovar is significantly more dense (8.36 g/cm³) than is Al (2.7 g/cm³), and has very poor thermal conductivity (17.3 W/mK for Kovar compared with 167 W/mK for 6061Al-T6). An array with Kovar T/R modules will require more mass, and it will be very difficult to remove the heat from the T/R modules.

To mitigate the issues associated with CTE mismatch issues without the use of copper moly tabs We are investigating the implementation of spray deposited Si-Al housing materials, which allow for direct die attach, as a means. We are evaluating four different controlled expansion (CE) Si-Al alloys, as summarized in Table 1. We evaluated the mechanical behavior of each of the CE alloys. In addition, we evaluated the direct attachment of GaAs die to Ni-Au plated CE7, CE9, CE11 and CE13 substrates using 80Au20Sn solder and Ag conductive epoxy as the die attach materials. Following attachment, the assemblies were thermal cycled according to MilStd 883.

Table 1. Summary of Housing Material Properties

Material	CTE (ppm/°C)	Therm. Cond. (W/m-K)	Density (g/cm ³)
Kovar	5.9	17.3	8.36
6061 Al-T6	23.6	167	2.7
CE7 (70Si30Al)	7.2	120	2.42
CE9 (60Si40Al)	9.1	129	2.46
CE11 (50Si50Al)	11.4	149	2.51
CE13 (42Si58Al)	12.2	160	2.55

IV. PHASE CHANGE MATERIAL

To increase the thermal capacity of the module, we plan to embed a PCM thermal capacitor within the bottom layer of the housing. This method of thermal control is effective during power cycling of the TR modules during flight, due to mode changes or power cycling. As this material liquefies, it absorbs heat until the phase change is complete, stabilizing temperature changes.

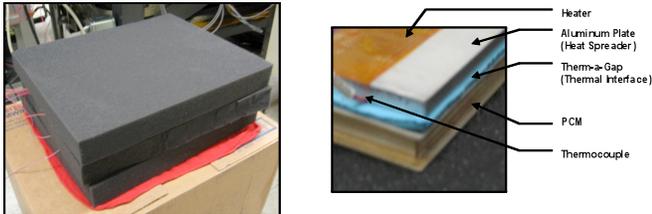


Figure 2. PCM Testing and characterization. On the left, the PCM is shown enclosed in insulating material. The exposed PCM, heat spreader, interface, thermocouple and heater are shown on the right.

The thermal capacity of the PCM unit is experimentally determined by melting the PCM in the unit and monitoring the unit temperature over the time. The PCM package and a heater plate are enclosed in an insulated box for this test, as shown in Figure 2. The insulated box significantly reduces the convective and radiative parasitic heat losses. The heater plate, shown on the right side of the image is a 1/4" thick aluminum plate (about the same foot print as the PCM unit) with a film heater attached on one side. A thermally conductive interface material is used between the plate and the PCM unit to improve the heat transfer.

Temperature data is taken at the top and bottom sides of the encapsulated PCM to find its energy storage capability (Figure 3). The heat is absorbed as the sensible heat by the wax until it reaches its melting point, see. The subsequent heat melts the wax while the temperature remains at its melting point until all the wax is melted. The product of the time duration the wax remains at its melting point and the heater level is the latent heat thermal capacity of the PCM unit. The results indicate the latent heat energy storage capability to be 50.5 kJ (compared with the data sheet approximating 48.7kJ).

The offset between the top and bottom temperatures can be attributed to the resistance of the thermal interface material. The initial and final temperature slopes are approximately even for both surfaces, the steeper profile found at the end due to a higher specific heat in the liquid phase.

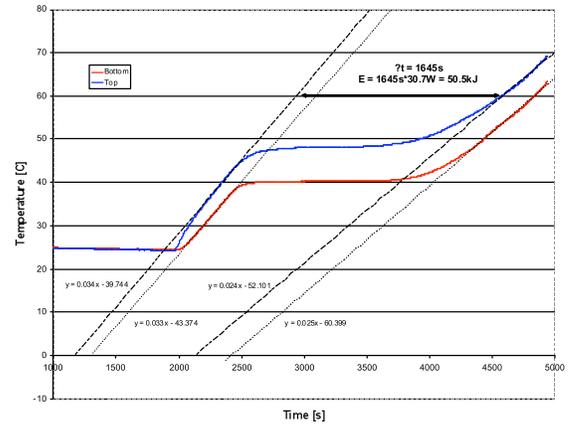


Figure 3. Measurements determined the latent heat of the PCM plate to be 50.5kJ, which compares well with the estimated 48.75kJ. Blue line is temperature measured at the bottom of the heat spreader, and the red, the top of the PCM.

The optical and IR image for the PCM under test is shown in Figure 4. With an appropriately sized heat spreader the PCM absorbs all of the heat until the phase change ceases (material is melted). The heat spreader is crucial to building an effective thermal capacitor with the PCM.

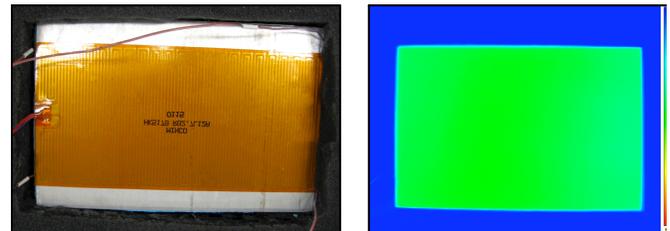


Figure 4. Optical (left) and infrared (right) images of the top and bottom of the PCM plate, respectively. With adequate heat spreading the entire reservoir of PCM absorbs the heat, shown by the uniform IR image.

As shown in Figure 5, if an undersized heat source is attached directly to the PCM plate the PCM material directly under the hot component melts, but the remaining reservoir does not contribute to the heat absorption. An example of a small hot component is a power amplifier, but is simulated here with a small heater. To use the PCM plate effectively, we must provide a good thermal interface and adequate heat spreading.

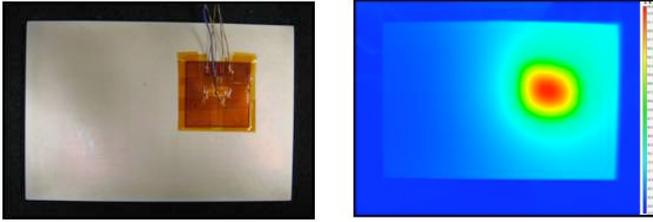


Figure 5. Optical (left) and infrared (right) images of the PCM with an undersized heater. The undersized heater simulates the heat from a discrete component and highlights the need for an effective heat spreader.

V. PCB MATERIAL

To efficiently conduct heat away from high power components and protect more sensitive components, we have been evaluating highly thermally conductive PCB material that incorporates a carbon core laminate (CCL) layer. These thermally and electrically conductive CCL composites exhibit very good in-plane thermal conductivity, low CTE, and can readily be implemented within a traditional printed wiring board design.

We have designed and fabricated a PCB test structure to evaluate the efficacy of the different materials and combinations. We fabricated an FR4 version as a control. The other versions include a Duriod™ Rogers 6002 only PCB stackup, which we consider to be representative of the state of the art in traditional low CTE, high frequency options. We then fabricated a Rogers 4003C version, both with and without the CCL layer. Our initial plan was to include a version of the Rogers 6002 with a CCL layer, but the manufacturing requirements of the two materials were too incompatible.

The PCB test structure is shown in **Figure 6**. The test structure includes an RF calibration section, microstrip and stripline for RF performance/stability testing, two BGA (ball grid array) FPGA packages, and power resistors for simulating active components. The FPGAs are daisy-chain packages that are used to test the reliability of the BGA attachment over temperature. All PCB stackup versions have the same layout for comparison.

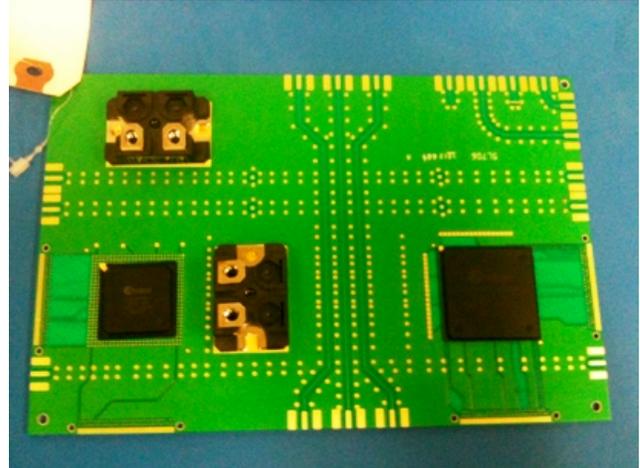


Figure 6. PCB test structure in fabrication. All versions of the PCB materials have the same layout, for comparison. This image shows the daisy-chain FPGA packages for BGA testing, as well as the power resistors to simulate active components.

VI. GALLIUM NITRIDE

The DESDynI project has been supporting development of GaN (Gallium Nitride) power amplifiers. These devices have higher gain than standard bipolar devices and higher efficiency, so transmitters require fewer gain stages and have overall lower thermal dissipation. We have been supporting the packaging concept of the power amplifier block and plan to use the power amplifiers in our final TR module demonstration.

To improve manufacturability and improve thermal stability we modeled the power amplifier design on lower CTE materials, which are also multilayer compatible. This design turned out to have other design advantages and is now the baseline design. We will be comparing the results of the different designs (on different substrates) and monitoring them with an infrared camera. With this test we will monitor the overall thermal output, estimate junction temperature, and estimate stresses from the CTE mismatches. The results of this study will help to identify the best, most stable and reliable material and attachment methods for using GaN in flight.

VIII. INTEGRATED TR MODULE

Once all of the testing of the individual technologies is complete, we will be incorporating them into a complete TR module design. This design is intentionally following the development of the DESDynI TR module so that we can incorporate the appropriate advances from this work into the DESDynI module, and to leverage the baseline DESDynI module as a comparison.

VIII. CONCLUSION

We have prototypes several of the technologies required to reduce thermal cycling and thermal stress. These included a PCM thermal capacitor, carbon composite PCB layers, advanced PCB manufacture, silicon aluminum alloy, and more efficient amplifiers. We successfully tested the PCM thermal capacitor, and completed bend testing and die attachment testing of the alloy. The next step is to integrate these technologies into TR module and perform dynamic testing.

ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.