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. 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 and allow increased transmit power. 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 proposed DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) radar, and robust high-frequency electronics, such as is required for the proposed SWOT (Surface Water Ocean Topography) mission.

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 (Coefficient of Thermal Expansion), 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.

III. Chassis: Silicon Aluminum Alloy

To remove heat quickly from high power devices we want 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 intermediary material, such as Cu-Mo-Cu (5.8 ppm/°C) die-attach preforms (aka, moly tab), may be inserted between the die and the Al housing to mitigate the CTE mismatch. However, one needs to design, procure, and bond an additional component (moly tab), which is most often custom-made for each device, and this adds at least two potential failure sites, which cannot be inspected. Poorly attached moly tabs will result in 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. Kovar's CTE is better matched to the die and hot parts may be attached directly to the Kovar chassis. This has two significant drawbacks for T/R arrays. Firstly, Kovar is significantly more dense (8.36 g/cm^3) than is Al (2.7 g/cm^3), 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.

We are investigating the use of spray deposited Si-Al housing materials, which allows for direct die attach, has excellent thermal conductivity and CTE match. 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

This material appears to be ideal for the high-power, densely packed electronics in the proposed array for DESDynI, as it will allow for excellent CTE matching and allow heat to flow freely to the thermal radiators. It is also very well suited for fabricating robust high-frequency electronics required for the radar proposed for SWOT, which is planned to operate at 36GHz. The GaAs die evaluated in the die-attach studies reported in this paper is a 2W Ka-band power amplifier, suitable for space applications.

IV. PHASE CHANGE MATERIAL(PCM)

To increase the thermal capacity of the module, we are embedding 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 instrument mode changes.. As this material liquefies, it absorbs heat until the phase change is complete, stabilizing temperature changes.

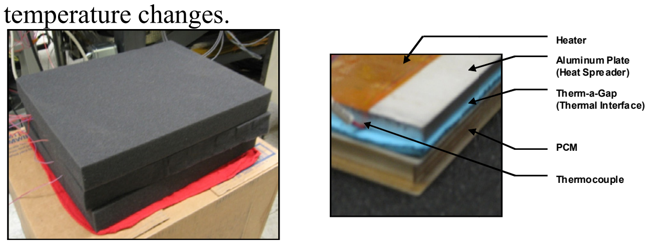

Figure 1. PCM testing and characterization. On the left, the PCM is shown enclosed in insulating material. The exposed PCM, heat spreader, interface, thermocouple and heater are shown on the right.

The thermal capacity of the PCM unit is experimentally determined by melting the PCM in the unit and monitoring the unit temperature. The PCM and heater plate are enclosed in an insulated box for this test, as shown in Figure 1.

Temperature is taken at both sides of the encapsulated PCM to determine its energy storage (**Figure 3**). The results indicate the latent heat energy storage capability to be 50.5 kJ.

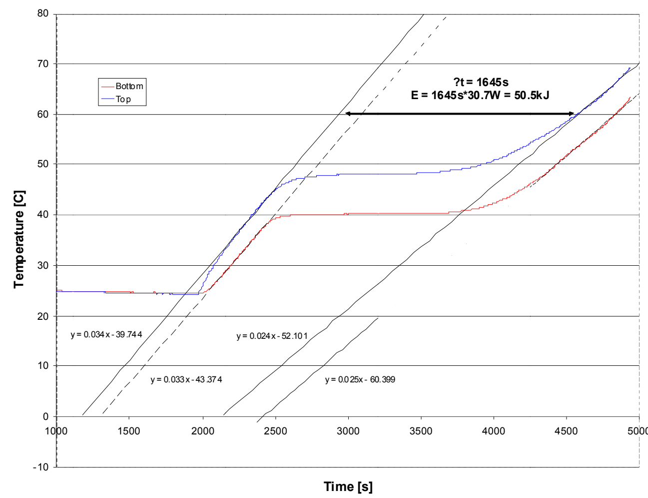

Figure 3. Measurements determined the latent heat of the PCM plate to be 50.5kJ, which compares well with the estimated 48.75kJ. Blue line is temperature measured at the bottom of the heat spreader, and the red, the top of the PCM.

V. PCB MATERIAL

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

The PCB test structure is shown in **Figure 4**. 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.

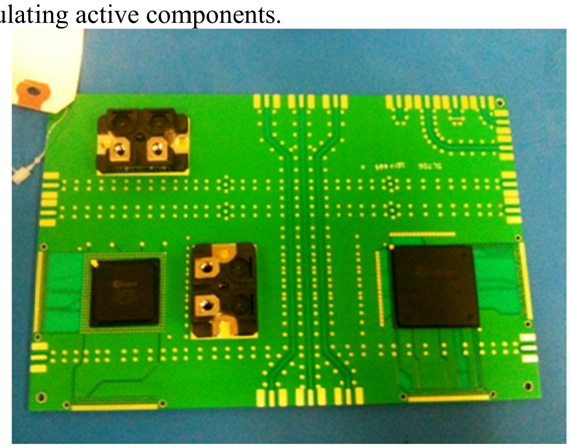

Figure 4. PCB test structure in fabrication. All versions of the PCB materials have the same layout, for comparison. This image shows the daisy-chain FPGA packages for BGA testing.

VI. Efficient Electronics

In cooperation with the DESDynI project we are evaluating GaN (Gallium Nitride) devices for high power, L-band.power amplifiers (~200W, 1.2 GHz). These devices have higher gain than standard bipolar devices and higher efficiency, so transmitters require fewer gain stages and have overall lower thermal dissipation. These characteristics are beneficial to building robust, thermally stabilized TR modules since less waste heat is generated, and the overall thermal cycling is reduced.

The receiver chain and other standard power devices are being designed to use new RF-quiet point-of-load regulators. Typically, one would use linear regulators to minimize power supply noise, but the efficiency is very poor due to the high drop-out voltage, especially for space qualified linear regulators. By using rad-hard, RF quiet POL regulators, we are improving regulator efficiency to over 90%. The utility of these devices for flight applications are under review, both for performance and reliability.

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 proposed DESDynI TR module so that we can incorporate the appropriate advances from this work, and to leverage the baseline DESDynI module as a comparison. Once both designs are complete and fabricated, we will evaluate the performance, thermal variability, and robustness of the standard and advanced packaging designs.

Acknowledgment

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