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 improvements in integrating advanced thermal packaging technologies into radar transmit/receive (TR) modules. New materials and techniques have been studied and are now being implemented side-by-side with more standard technology typically used in flight hardware.

High power, compact arrays would enable the use of large reflector-based architectures, such as SweepSAR [2], which would 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 would require integrated thermal management to maintain, and possibly improve, overall reliability in the presence of increased thermal variations.

The proposed DSI mission is currently developing a high power (>100W) TR module using the best accepted practices available to space-flight development, including some results of prior work developed by this task [3] and others [4]. As we have investigated and developed advances in thermal packaging, the DSI team has incorporated these developments that fit within the accepted flight norms, such as best thermal interfaces, best PCB materials, best practices for housing mechanical design. One key technology adopted by the baseline design for DSI, is the use of a Gallium Nitride (GaN) transmitter chain, which would significantly reduce the thermal dissipation of the unit—by approximately 25% [3]. Some differences in the Advanced portion of this thermal packaging study that remain are narrowed down to the novel CE (Constrained Expansion) alloys and the PCM (Phase Change Material) thermal capacitor, which are not currently planned in the proposed instrument’s baseline design.

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 proposed DSI instrument with the most affordable architecture.

A key technology, not yet accepted into the baseline design since it is a new technology and not required to meet current flight requirements, is the “thermal capacitor”, which is enabled by PCM (Phase Change Material). The PCM effectively low-pass filters dynamic heating due to power cycling. For instrument with very dynamic operational modes, such as radars that employ burst mode for regional spotlight SAR, the thermal capacitor would allow instrument designers to keep the thermal radiators modestly sized to the long term average power dissipation, rather than the peak dissipation. This concept is not new for ground-based electronics, see for example [5], however, established techniques rely upon gravity to pull the phase change material to the heat spreader and are not applicable to spaceborne instruments. The PCM technology investigated as part of this work is designed for use in microgravity.

2. TRANSMITTER PACKAGING

The final two stages of the transmitter chain for DSI, namely the Driver Amplifier and High-Power Amplifier (HPA) would employ GaN (Gallium Nitride) technology. GaN shows great promise for RF power amplifiers [6], high power RF and DC switches [7], as well as robust LNAs (Low Noise Amplifiers) [8]. With significantly higher temperature survivability, higher breakdown voltage and lower input impedance than silicon bipolar, along with excellent predicted resistance to total dose radiation [9], GaN decreases the thermal load of the overall TR module by approximately 25% [10].

The greatest impacts of GaN technology on high power TR module reliability and performance are increased efficiency and reduction of thermal stresses. While measured results indicate PAE (power added efficiency) in the range of 60% to 70% for individual power amplifier stages, a large amount of heat must still be removed without the benefit of convection.

Components with high thermal output, such as the HPA (High Power Amplifier) and the Driver amplifier, must have excellent thermal and electrical contacts to the chassis in order to dissipate heat and maintain an effective ground plane for performance. These components are mounted directly to the carrier, as shown in Figure 1. These carriers are then attached to the overall chassis. This allows for easier rework, which is a critical feature to maintain high reliability while keeping costs reasonable.

Table 1. Comparison of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE(x/y) (ppm/°C)</th>
<th>Thermal Cond. (W/m-K)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.5</td>
<td>124</td>
<td>2.3</td>
</tr>
<tr>
<td>GaAs</td>
<td>5.4</td>
<td>50</td>
<td>5.3</td>
</tr>
<tr>
<td>Cu</td>
<td>16.4</td>
<td>398</td>
<td>8.93</td>
</tr>
<tr>
<td>Kovar</td>
<td>5.9</td>
<td>17.3</td>
<td>8.36</td>
</tr>
<tr>
<td>6061 Al-T6</td>
<td>23.6</td>
<td>167</td>
<td>2.7</td>
</tr>
<tr>
<td>CE7 (70Si/30Al)</td>
<td>7.2</td>
<td>120</td>
<td>2.42</td>
</tr>
<tr>
<td>CE9 (60Si/40Al)</td>
<td>9.1</td>
<td>129</td>
<td>2.46</td>
</tr>
<tr>
<td>CE11 (50Si/50Al)</td>
<td>11.4</td>
<td>149</td>
<td>2.51</td>
</tr>
<tr>
<td>CE13 (42Si/58Al)</td>
<td>12.8</td>
<td>160</td>
<td>2.6</td>
</tr>
</tbody>
</table>
This increases the estimated thermal resistance of the combined carrier/chassis due to the extra interface, but the overall impact has been shown to be minimal, as shown below. Typical carriers for space qualified TR modules are made from either Kovar or 6061 Al. Although Kovar has a coefficient of thermal expansion (CTE), see Table 1, 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 Aluminum. 6061 Al provides improved heat dissipation properties, but has a CTE that is nearly 4x that of Kovar. The CE13 alloy in the Advanced package has a CTE of 12.8 ppm/°C, roughly half of 6061 Al and a thermal conductivity of 160 W/mK, as compared to 6061 Al, which is 167 W/mK.

To evaluate the effectiveness of the PCM in the Advanced TR packaging, three HPAs with carriers were tested with and without the PCM. The HPA carriers themselves were manufactured from CE 11, Al 6061, and CE7. The carriers were then mechanically clamped to a thermal plate with a layer of standard thermal grease to improve thermal conductivity to the plate, without the potential for damaging the PCM, of which we have only one, see Figure 2. The devices were biased at 28V and 1A, per manufacturer recommendations, and left on to reach thermal equilibrium—or in the case of the PCM, it is more correctly defined as quasi-equilibrium since the PCM should drastically reduce the temperature of the boards through its characteristic phase change properties, but only until all of the material has changed state. For this PCM, which was measured to have 50.5kJ of thermal capacity and the estimated thermal load of the three amplifiers, the PCM will remain effective for approximately 10 minutes, which is significantly less than our testing duration.

The devices under test were monitored with a thermal imaging camera. Thermal images were taken of the dynamic heating of the HPA boards, both with and without PCM between the HPA carriers and the heat sink, see Figure 3 and Figure 4, which are the planned configurations for the packaging of the proposed DESDynI instrument and the Advanced TR module, respectively. The thermal models, which were performed assuming thermal equilibrium, indicated that components could rise above their safe limit (~150°C at our power dissipation). When the components rose past 125°C, the test was terminated. The resulting thermal image shown in Figure 3, shows the three components mounted with just the standard aluminum heat sink, and showed a rapid rise (under 1 minute) to temperatures approaching the fail-safe limit.

In Figure 4, the thermal image of the quasi-equilibrium state of the components with the PCM thermal capacitor is shown. At first glance, the image appears slightly better, but not markedly so, with the central component still turning red, however, the images are not on the same scale. If imaged at the same scale, the tests with the PCM do not show much contrast since the temperature range is approximately half. Left for several minutes, the PCM version settled at a peak temperature of 69°C. After about 10 minutes, we would expect the temperature to begin rising rapidly, since the PCM would have completely changed state, but we did not run it to this extreme out of caution for the PCM, as overheating can damage the unit.

The PCM is most useful in cases where there are short duration modes in which the instrument would undergo very large, dynamic thermal input, such as a burst mode or high-resolution mode. PCM is able to temporarily absorb large amounts of heat, and radiate it out more slowly, so that one may design thermal radiators for average load, rather than peak load. This can drastically reduce the sizing of a thermal system.

The CE alloys in this test were used to determine if their lower thermal conductivity would impact the overall performance. As seen in Figure 3 and Figure 4, the performance of the CE alloy carriers was as good as the Al 6061 version. In fact the Al 6061 version had the hottest component during the PCM test, but this was likely due to its position in the middle and not to its conductivity. We plan to repeat these tests with the same components, but in different locations to confirm this theory. The best use of the CE alloys is for direct attachment of bare die components. The constrained expansion allows one to directly attach die to the chassis floor, similar to Kovar, but the thermal conductivity is far better. To confirm this, an RF GaAs MMIC 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].
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.

3. INTEGRATED PACKAGING

The overall integrated package is being designed to improve reliability over thermal cycling and to be modular, so that it is easily reworkable in a flight development environment. What this implies is that key parts that may need to be attached or removed and re-attached must be on a subcarrier that can withstand the mechanical and thermal environments of the re-work process. For example, if a component fails on the Transmit Driver board, the process to replace the damaged part must not over-stress the surrounding components and interfaces, otherwise a cascade of failures may occur, causing many cycles of rework. These kinds of stresses can lead to latent damage, the impact of which may not be noticed until very late in the instrument development, including on-orbit.

To improve reworkability, the modules are designed to have easily removable subcircuits, which are mounted to carriers for easy testing and integration. Each carrier may be removed, without any damage to the surrounding carriers or components, and reworked independently. These may be re-tested, and then re-integrated into the overall module. The current baseline module packaging is shown in Figure 5.

Typically, the best RF performance, including isolation, proper match, and best insertion loss, is achieved with a standard RF feedthru, such as is shown in Figure 6. For external connections, this is easily achieved by machining a hole in the chassis and soldering (or similar) the RF feedthru into the chassis. If there are feedthrus on more than a single side of a PCB, it becomes difficult, if not impossible, to remove the PCB for rework without also removing a feedthru. Also, interior holes for feedthru connections have the added challenge that direct machining of interior walls is not possible. These holes are created using EDM (Electron Discharge Machining), which is more complex and
expensive than direct drilling. The interior feedthrus also must be removed in order to remove a PCB for rework.

Figure 6: Standard RF feedthru. The impedance matched insert is typically soldered into a hole in the chassis wall. This is not difficult for exterior walls, but requires EDM (Electron Discharge Machining) for interior walls, and must be removed to remove the PCB.

To allow for easy rework, the TR module would be constructed using removable thru-hole walls, see Figure 7. These provide the isolation required for high power, high gain TR modules, and allow one to use standard RF feedthrus, while enabling easy removal of PCBs and carriers.

Figure 7: Removable RF feedthrus enable high RF performance and easy removal of PCBs and carriers for rework.

module has an integrated thermal radiator in the “floor” of the module. All of the “hot” components are directly attached to the floor of the module, which would become the external radiator of the module on the spacecraft, see Figure 8 (a). The prototype TR module is assembled, in the traditional sense, with the RF components and PCBs sitting on a solid ground plane (the floor) (Figure 8(b)). The module is then flipped upside down, so that the “floor” Figure 8 (c) would face out to cold space as shown in Figure 8 (a).

Figure 8: The TR modules (red boxes in (a)) for the proposed DSI would be directly attached to the antenna feed structure (the green portion in (a)), with the thermal radiator incorporated into the “floor” of the TR module (b). The TR module, after assembly, would be flipped upside down (c), so that the standard floor of the module, which provides the chassis ground and typical path for thermal dissipation, would be facing cold space.

The baseline TR module packaging for the proposed DESDynl radar has Al 6061 carriers with a solid chassis of the same material, shown in Figure 9 (a), whereas the Advanced module, currently being fabricated as a technology development, utilizes CE alloy for the carriers, reducing the CTE mismatches, and incorporates a copper heat spreader (brown) and PCM thermal capacitor (green) shown in Figure 9 (b), rather than a solid aluminum thermal radiator.
4. SUMMARY

Several promising technologies and techniques for high power TR module packaging have been incorporated into the baseline design of the TR modules for the proposed DESDynl SAR Instrument. A few advanced technologies, which have not been incorporated into the baseline design, including the PCM thermal capacitor and the CE alloys, are being integrated into an Advanced module, to compare the thermal performance of the baseline flight to the Advanced designs technologies.

Successful integration of these technologies being investigated as part of the NASA Advanced Component Technology task, 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 an architecture being considered for the proposed DESDynl radar instrument.

REFERENCES


**BIOGRAPHIES**

James Hoffman is a Senior Engineer in the Radar Technology Development Group at JPL. He received his BSEE from the University of Buffalo, followed by MSEE and PhD from Georgia Tech in planetary remote sensing. He has worked in the design of instruments for remote sensing applications for more than 10 years. In previous technology development tasks, he successfully developed a new low power digital chirp generator, which has been integrated into several radar flight instruments. He has experience designing radar systems for both technology development and space flight hardware development, and is currently the RF lead for the proposed DESDynI radar instrument.

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