Advanced Packaging Materials and Techniques for High Power TR Modules

B1P6

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Advanced Thermal Packaging Technologies for RF Hybrids

PI: James Hoffman, JPL

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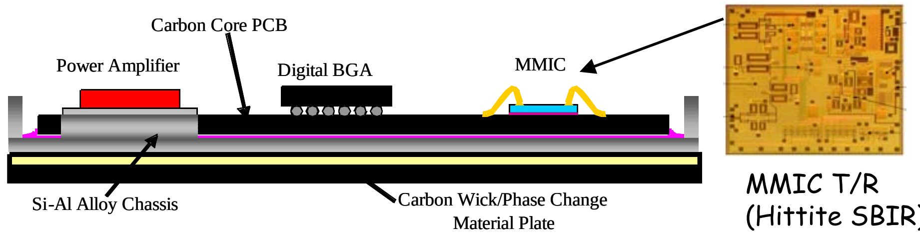
Objective

- Develop improved RF hybrid fabrication techniques using new materials—and proven materials in new ways—to increase hybrid's RF power-density capacity while improving reliability over thermal cycling by improving thermal conductivity at all levels of hybrid fabrication.
- Combine the thermally advanced RF hybrid with a chassis designed with Phase Change Material (PCM) used as a thermal capacitor, reducing internal temperature swings to improve reliability over thermal cycling.
- Demonstrate that these improved RF hybrids enable more compact and cost-effective electronically steered feeds for spaceborne radars such as those in DESDynI Mission.



RF hybrid with the new thermal materials, to be built using the existing MMIC T/R (photograph shown) from a recently completed SBIR, and commercially available Power Amplifier and digital control in a ball grid array (BGA) package.

Approach

Build prototype RF hybrid Transmit/Receive (T/R) module and the demonstration model of the antenna feed tile to show improved power handling and reliability by:

- using new materials and techniques to improve thermal transfer at all levels of module fabrication,
- building prototype (~150W) hybrid T/R modules with new technique and materials, using an existing low-power Monolithic Microwave Integrated Circuit (MMIC) based T/R — using a PCM as thermal capacitor,
- incorporating T/Rs into antenna array feed demonstration model to show reliability and power handling of the new RF hybrid module.

Key Milestones

Complete thermal models of RF Boards	12/09
Complete testing of individual materials	12/10
Complete Standard TR design	7/11
Complete Advanced TR design	2/11
Complete Standard TR build/test	09/11
Complete Advanced TR build/test	11/11
Complete "" Analysis by Model	12/11

	TRL_{IN}	$TRL_{Current/Final}$
TR Thermal Capacitor	3	4**(4)**
Stablcor/RF	3	4(5)
CE Alloy TR Chassis	3	5(6)
GaN Power Amplifier	3	4(5)
Advanced TR	2	4(6)

Co-Is/Partners:

Linda DelCastillo, Gaj Birur, Paul Rosen, JPL

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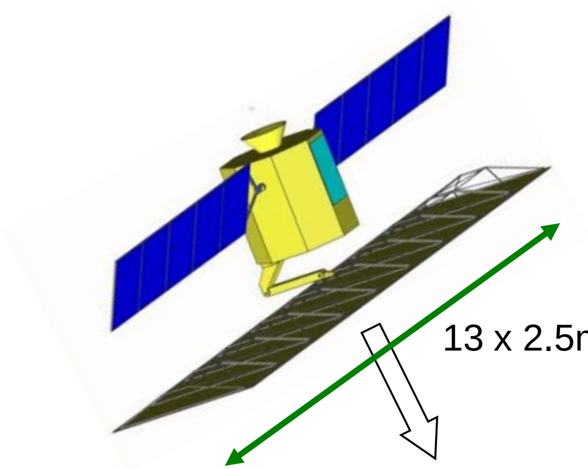
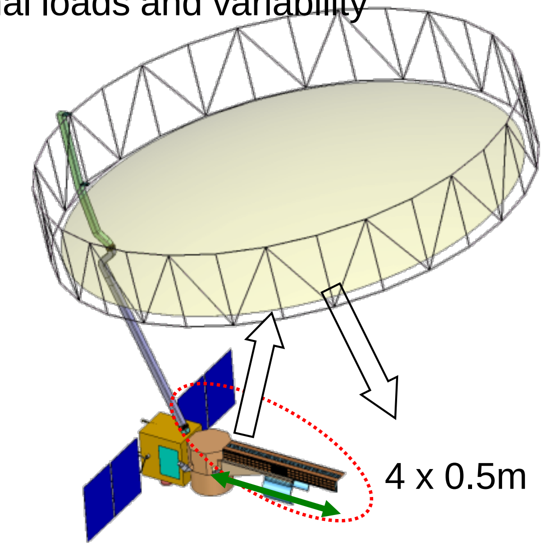
High Power Density Phased Arrays:
Enabling SweepSAR Architectures

- SweepSAR Architectures reduce mission resources, while maintaining or improving science quality, over traditional phased array architectures.
- SweepSAR increases imaging area, reducing the repeat-pass interval from weeks to days
- SweepSAR also increases the RF power density and thermal dissipation density dramatically, see below
- The technologies being developed in this work aim to enable this new instrument architecture, while:
  - Maintaining or improving reliability with the higher thermal loads and variability
  - Increase allowable RF power density
  - Improve instrument stability over temperature and time



Standard Phased Array

Assuming
3kW RF Peak
Transmit



SweepSAR:
Phased Array Feed

- Lower RF Power Density (92 W/m^2)
- Larger Radiator Area (32.5 m^2)
- Higher Thermal Inertia

- Higher RF Power Density (1500 W/m^2)
- Smaller Radiator Area (2 m^2)
- Lower Thermal Inertia

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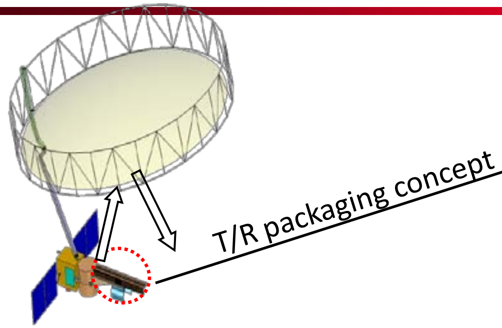
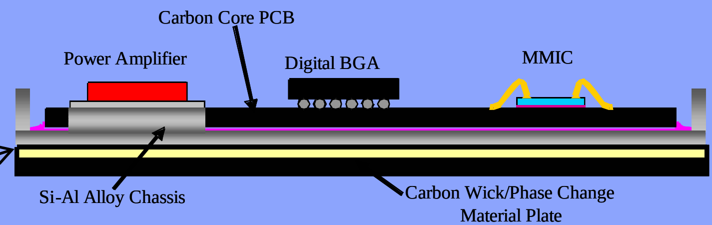
Overall Concept

NASA

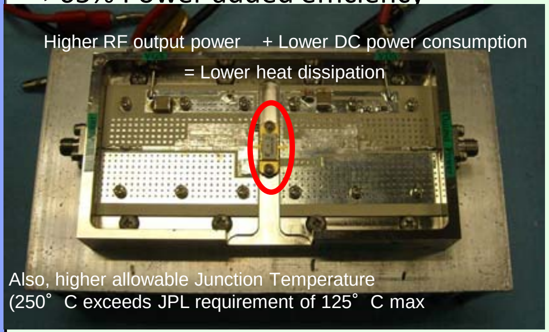


Target Application:
High power phased array feed
T/R modules



- High efficiency electronics
  - Gallium Nitride Power Amp
  - RadHard point of load regulators for RF circuits
- Ultra-efficient high-voltage power supply
- Carbon-composite PCB for enhanced thermal conductivity
- CTE (coefficient of thermal expansion) matched chassis materials to enable direct die attach for RF hybrid circuits
- Phase Change Material (PCM) thermal capacitor to absorb heat during high-duty cycle operations

Gallium Nitride Power Amplifiers:
- 200W RF output
- >65% Power added efficiency

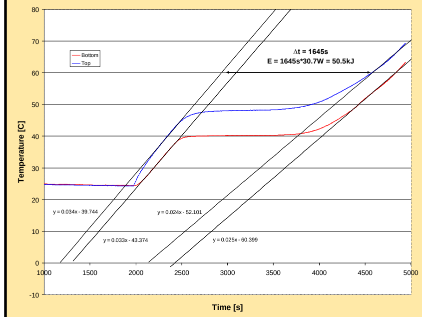


M. Jenabi, J. Hoffman

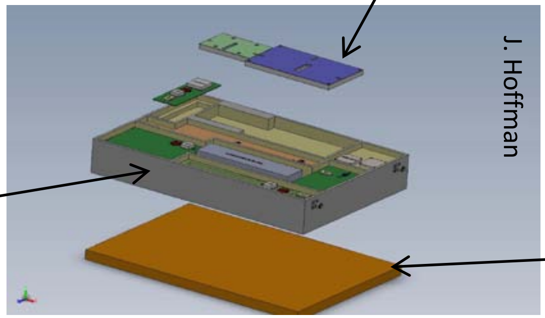
V. Vorperian, G. Sadowy

- 88% efficient pulsed power conditioner
  - Powers 200W GaN power amplifier
  - Powers all 5V RF amplifiers

Phase change material:
- ~1000x heat capacity of aluminum
- maintains temp over peak loads



J. Miller, G. Birur, J. Hoffman



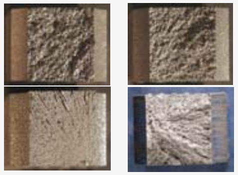
J. Hoffman

Integrating all technologies to increase maximum transmit power and reliability

Silicon-Aluminum chassis material:

- Much better coefficient of thermal expansion (CTE) match to electronics (~5ppm/K) than aluminum (7.2 ppm/K versus 23.6 for aluminum), reducing stress
- 7x better thermal conductivity than Kovar and less than 1/3rd the mass

L. DelCastillo, J. Hoffman



Four different silicon-aluminum alloys

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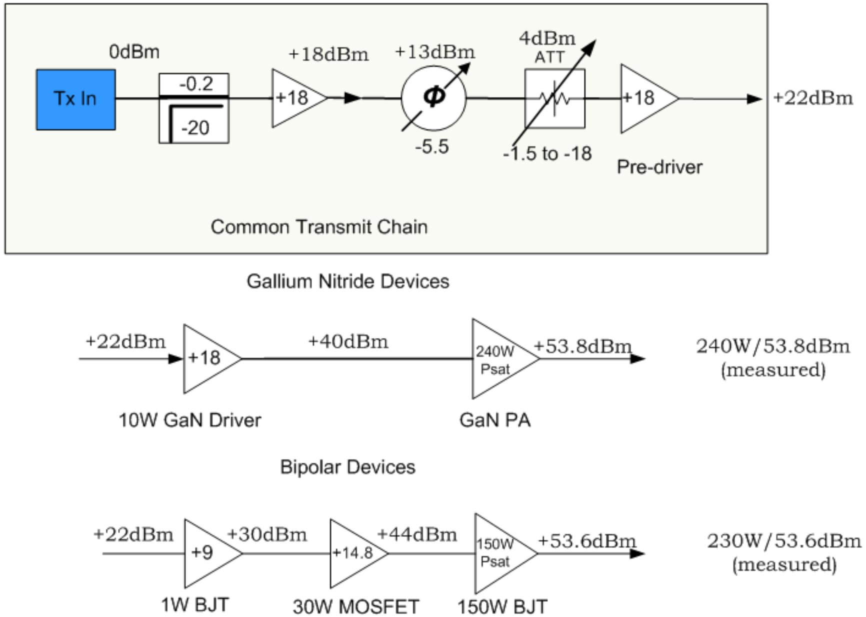
High Efficiency Electronics: "Make less heat"



	Pout	Common DC	Peak DC	Avg DC	48 Modules
	[W]	*[W]*	*[W]*	*[W]*	*[W]*
GaN	240	8.55	405	46.7	2241.6
Bipolar	230	8.55	563	62	2976
GaN Improvement	10	0	-158	-15.3	-734.4

GaN HPA

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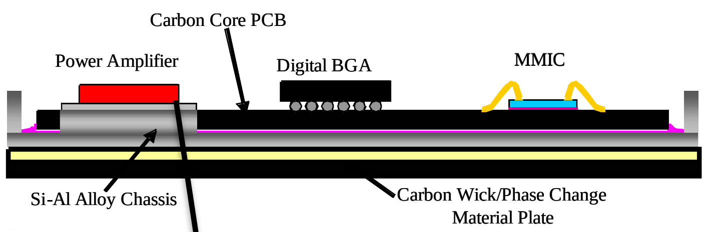
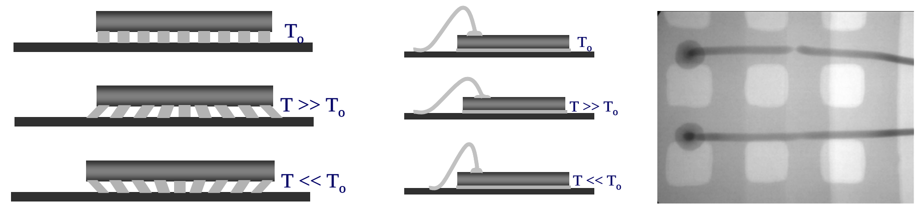
High Thermal Conductivity PC Board Materials

“Get the heat away from localized components”

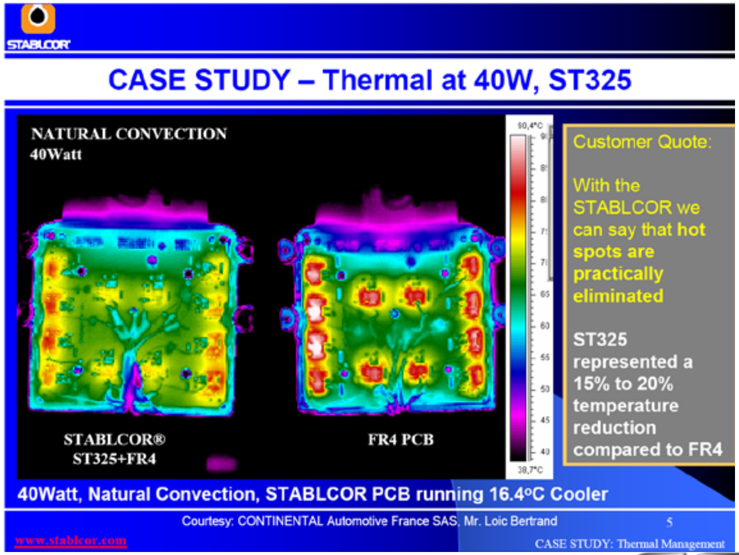


“Hot” components are typically designed to handle their own thermal loads, as shown in the high power transistor below:



On compact designs, nearby components are overstressed by continued power cycling of hot components, leading to early failures, especially in non-convective environments such as space

- Carbon impregnated PCBs significantly increase thermal conductivity
- Case study (right) shows significant decrease in nearby heating
- We investigated the use of carbon impregnated PCB for high power RF applications
  - R6002, R4003, R4003 w/ Stablcor
  - R6002 showed better thermal performance than R4003, as expected from datasheets and modeling
  - No difference in RF performance was seen for our test structures
  - R4003 w/ Stablcor is in assembly



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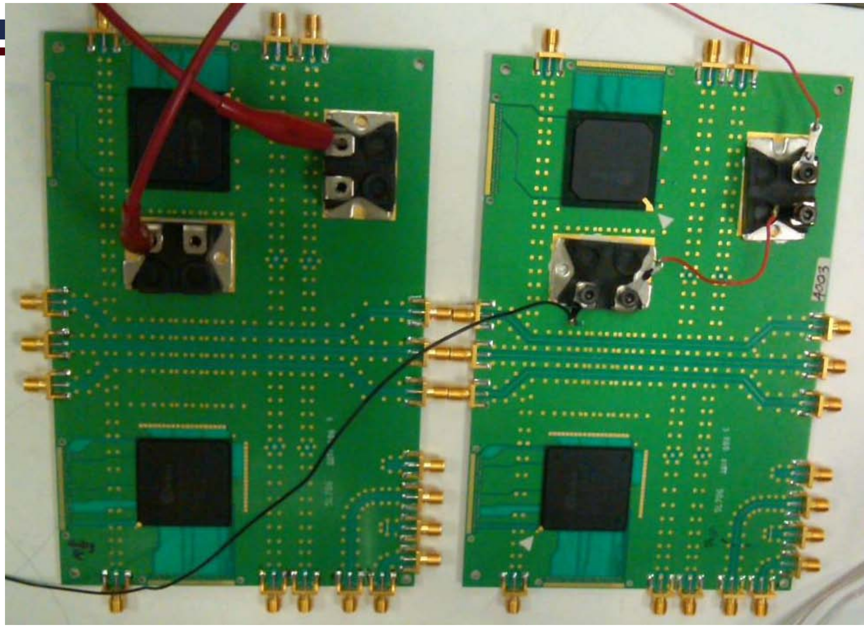
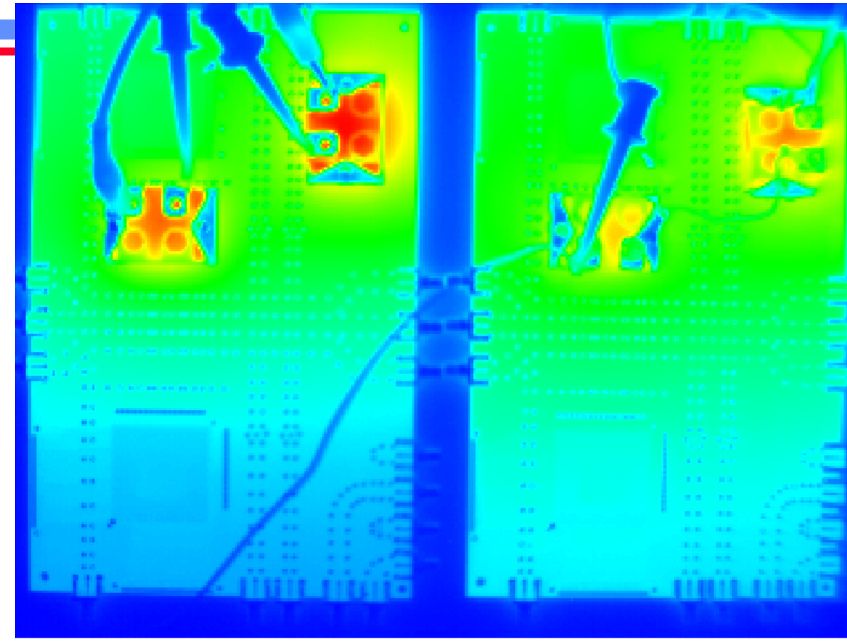
PCB Thermal Comparison





Rogers 4003 w/Stablcor
Weight=313g

Rogers 4003 w/thick Cu
Weight=357g

•Resistive heaters on both boards were powered at 20V and 1A. IR images were taken after 1.5 minutes. Peak temperatures reached 100° C, with the carbon core laminate board being about 10° C higher than the thick Cu board.

•Both assemblies are currently being thermal cycled to determine whether there is any difference in the reliability of the daisy chain BGA portion of the assemblies.

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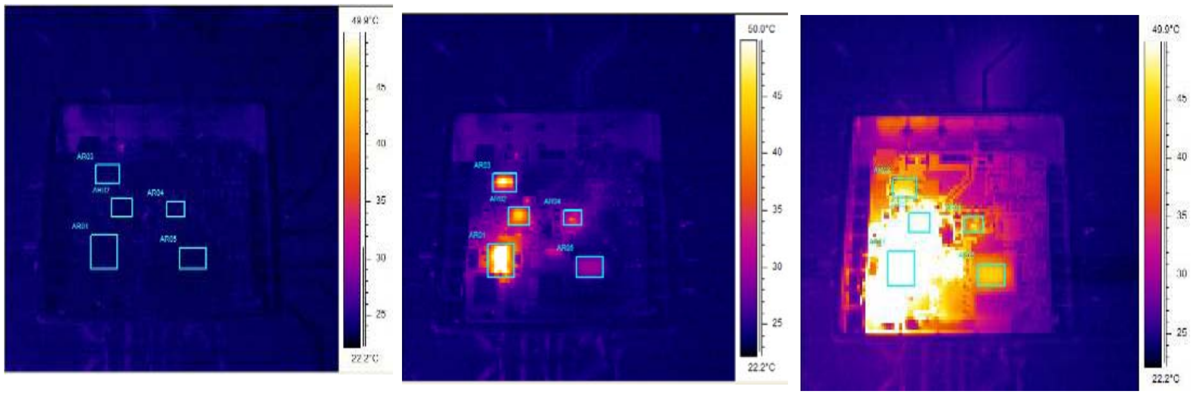
Custom Alloys
“constrain deformation over temperature”



- The three thermal images above are taken from a 2 W 1.5inx1.5in L-band T/R following 0 sec, 5 sec, and 10 sec of power. The power amplifier, heat source, was connected directly to the PCB. Although the RF part was able to function at the higher temperature, all of the support electronics in the vicinity of the component ceased operation due to excessive heating.
- To minimize this issue, the high power components could be directly attached to the metal chassis. If there is a large coefficient of thermal expansion mismatch between the device and the metal chassis, such an attachment could lead to device cracking or degradation of the attachment material and ultimately failure of the circuit.

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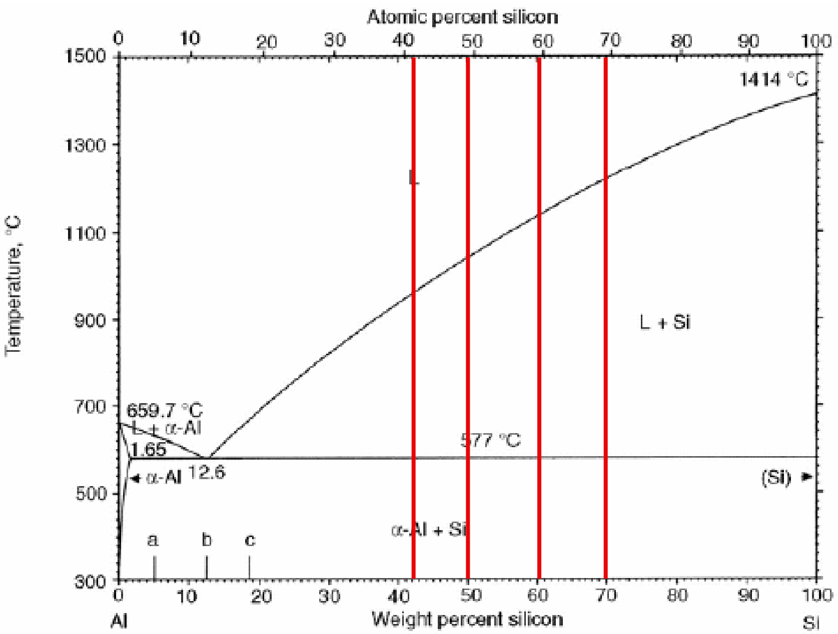
Controlled Expansion (CE) Alloy

- Current housings for RF modules in space-based applications are generally made from either Kovar or 6061 Al.
- The controlled expansion (CE) spray deposited Si-Al housing materials discussed herein 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.

Material	CTE (x-y) (ppm/°C)	Thermal Cond. (W/m-K)	Density (g/cm³)
Si	2.5	124	2.3
GaAs	5.4	50	5.3
Cu	16.4	398	8.93
Kovar	5.9	17.3	8.36
6061 Al-T6	23.6	167	2.7
CE7 (70Si/30Al)	7.2	120	2.42
CE9 (60Si/40Al)	9.1	129	2.46
CE11 (50Si/50Al)	11.4	149	2.51
CE13 (42Si/58Al)	12.8	160	2.6



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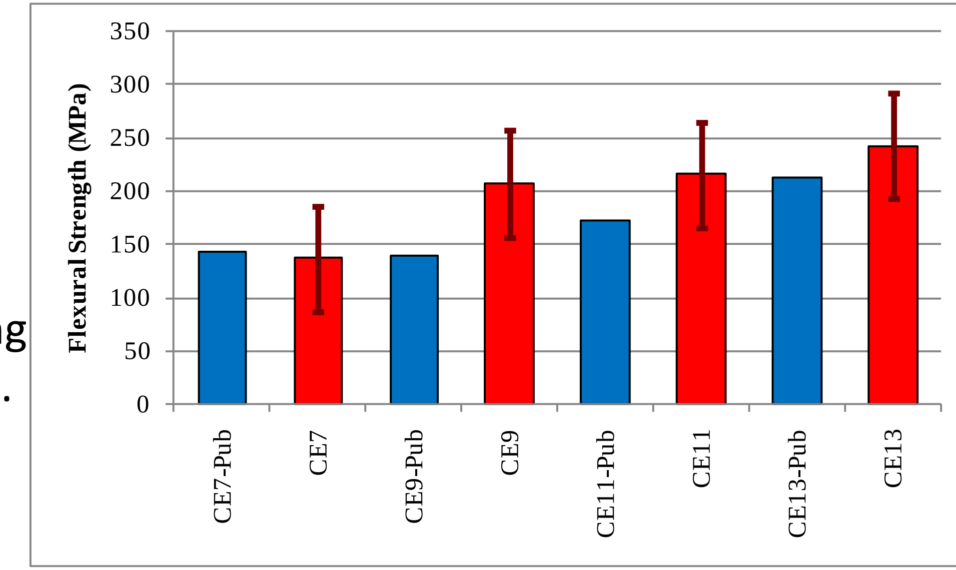
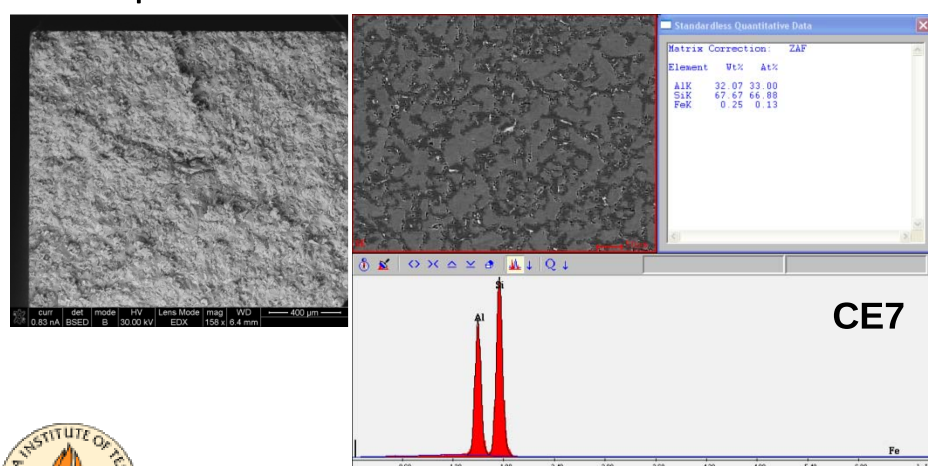
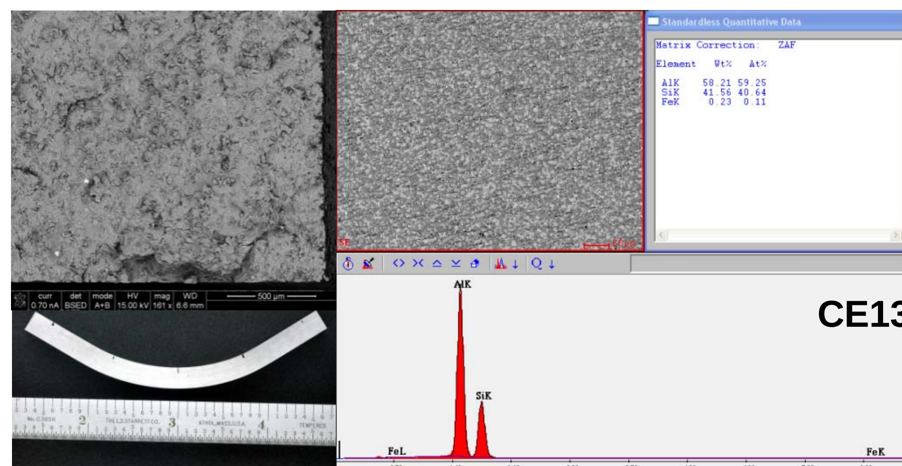
Mechanical Behavior-Bending

- Four point bend tests were performed on CE7, CE9, CE11, and CE13 according to ASTM C1161-02c (08).
- The bend strengths observed were higher than those provided in the published data.
- As expected, specimens exhibited increasing flexural strength with increasing Al content.
- Failure was observed to be significantly influenced by surface finish and imperfections.







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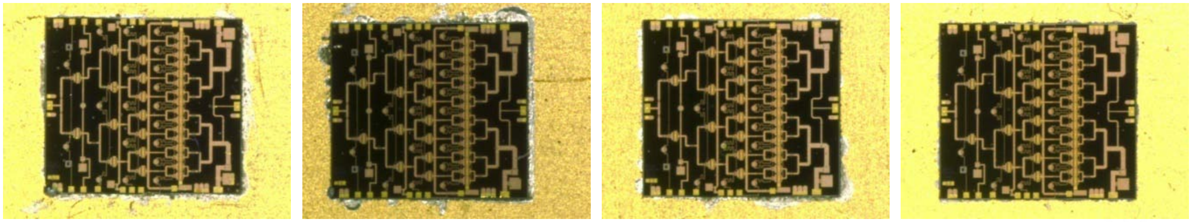
Thermal Cycling Results

- Due to the high Si content, the alloys exhibit low and stable CTEs, approaching those of Si, GaAs and InP active devices.
- A previous study on the reliability of GaAs solder attach to various substrates indicated that devices placed under compressive stress, as is the case with the high temperature solder attachment to substrates having a higher CTE than GaAs, did not degrade through life testing until the substrates exceeded a CTE of 16.5 ppm/° C. [*J. Pavio and D. Hyde, "Effects of Coefficient of Thermal Expansion Mismatch on Solder Attached GaAs MMICs," IEEE MTT-S Digest, 1075-1078, 1991*]
- To verify the results of this study, GaAs mechanical die were attached to Ni/Au plated substrates of CE7, CE9, CE11, and CE13, using eutectic AuSn solder . The assemblies were exposed to 995 MIL-STD-883G Method 1010.8, condition B thermal cycles (-55 to 125° C) without failure.

CE7, CE9, CE11, and CE13 assemblies following 995 thermal cycles



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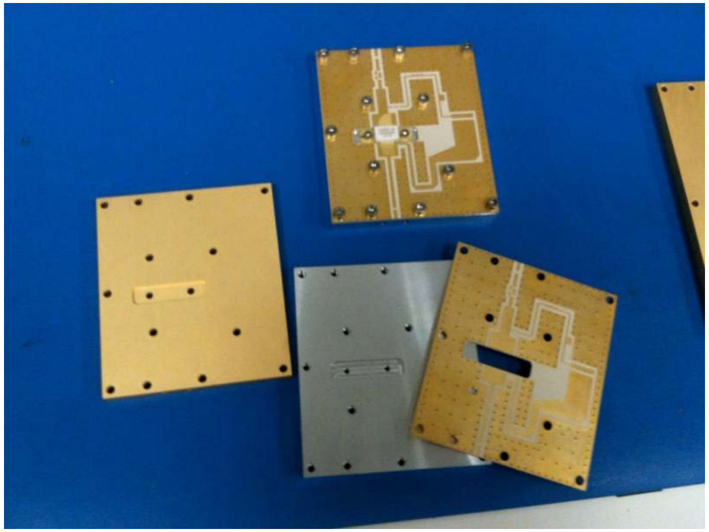
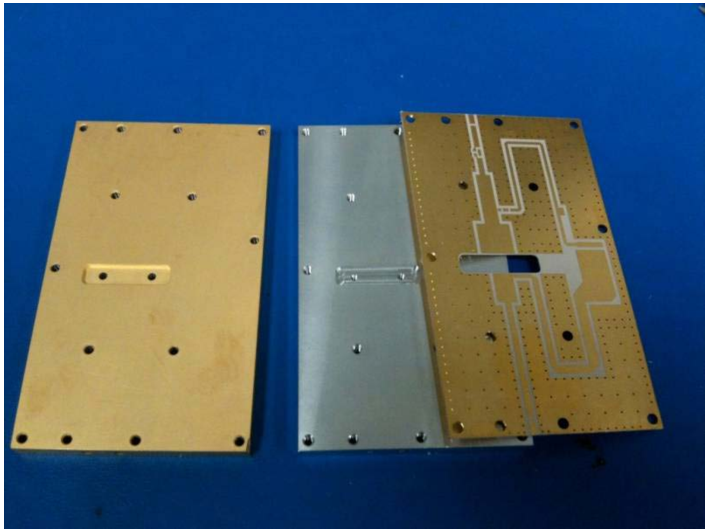
Substrate and Housing Applications

- For the current evaluation, baseplates for a GaAs power amplifier circuit were machined from CE7 and CE11.
- Photographs of the two baseplates are provided below, along with the associated power amplifier circuit.





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PCM Unit

"reduce thermal variations"

- The Phase Change Material (PCM) package was built by Energy Science Laboratory Inc. (ESLI) for the thermally stabilized T/R RF Module project.
- Eicosane paraffin wax is used as the PCM because of its high latent heat capacity & melting point temperature (36 C) for the T/R RF module operation.

- Because of the low thermal conductivity of the wax, carbon fibers are impregnated into the wax to provide added conductivity, and should enable the unit to function regardless of gravity
- The paraffin wax is stored in the cells of a honeycomb structure that forms the core of the PCM unit. Carbon fibers are distributed in the cells to provide high thermal conductivity along the thickness of the unit. The lateral in-plane thermal conduction is two orders of magnitude lower for the current PCM package design.

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PCM Testing: Uniform Heat Distribution

- A larger heater spreads the heat and prevents hot spots in the PCM.
- Utilizing some form of a heat spreader will create a uniform temperature distribution and ensure an even melting profile in the paraffin. Uneven melting within the PCM will cause the PCM to be underutilized and temperature to rise more quickly than predicted.

Image 5: Top View of the PCM with Large Heater

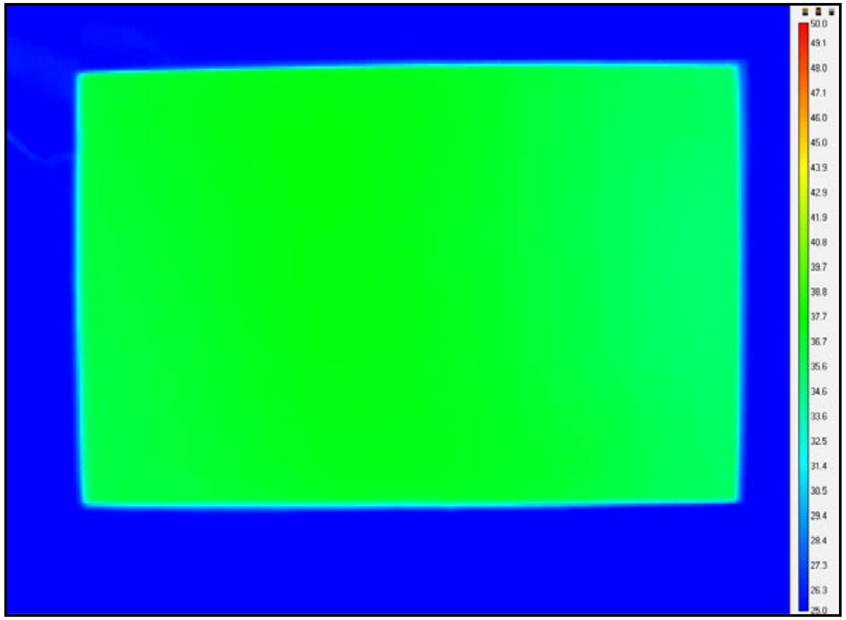

Image 6: Bottom View of the PCM with Uniform Temperature Distribution

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PCM Testing

- Because the heat spreader works so well, the previous slides were quite boring, so…
- As shown below, a concentrated heat source conducts only in the vertical direction with little horizontal conductivity creating a hot spot. A heat spreader between the heat source and the PCM would be required to distribute the heat and ensure that the PCM melts uniformly.

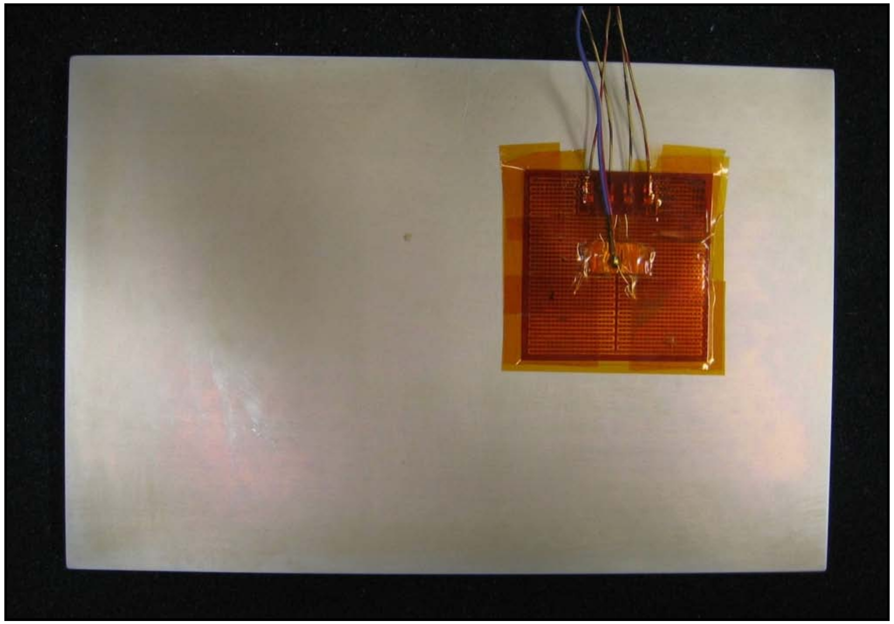

Image 3: Top View of the PCM with Heater

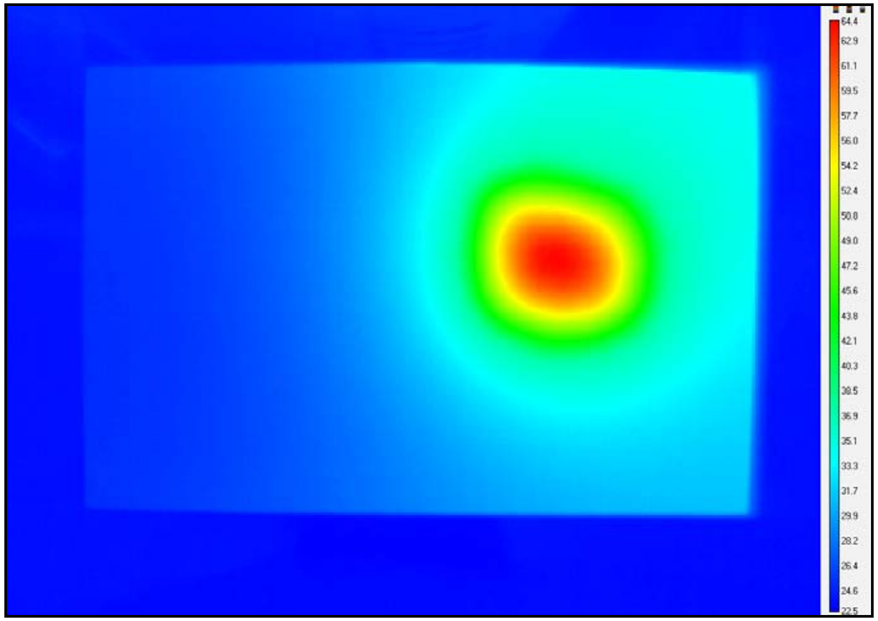

Image 4: Bottom View of the PCM with Hot Spot

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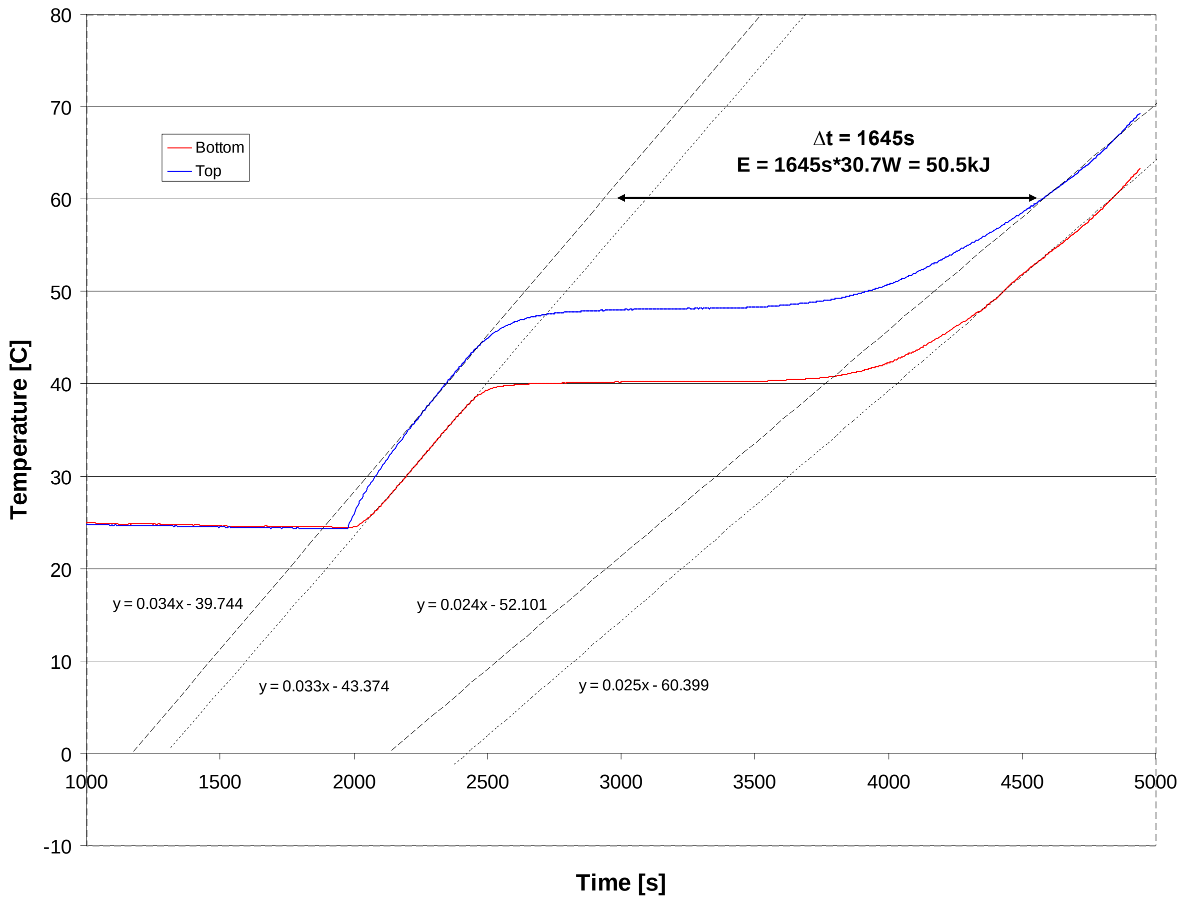
Thermal Capacity of the PCM Unit

- Nearly 30 minutes (27) for TR module with 120W peak (30W dissipation)—original DSI design
- Greater than 15 minutes for 180W peak (50W dissipation)—current DI design



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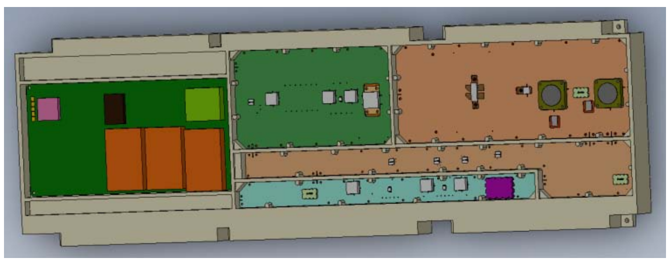
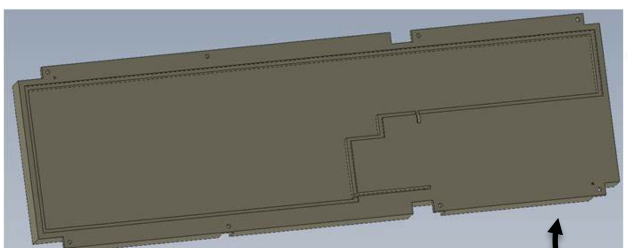
Application of Integrated Technologies: DESDynI SAR (SweepSAR)

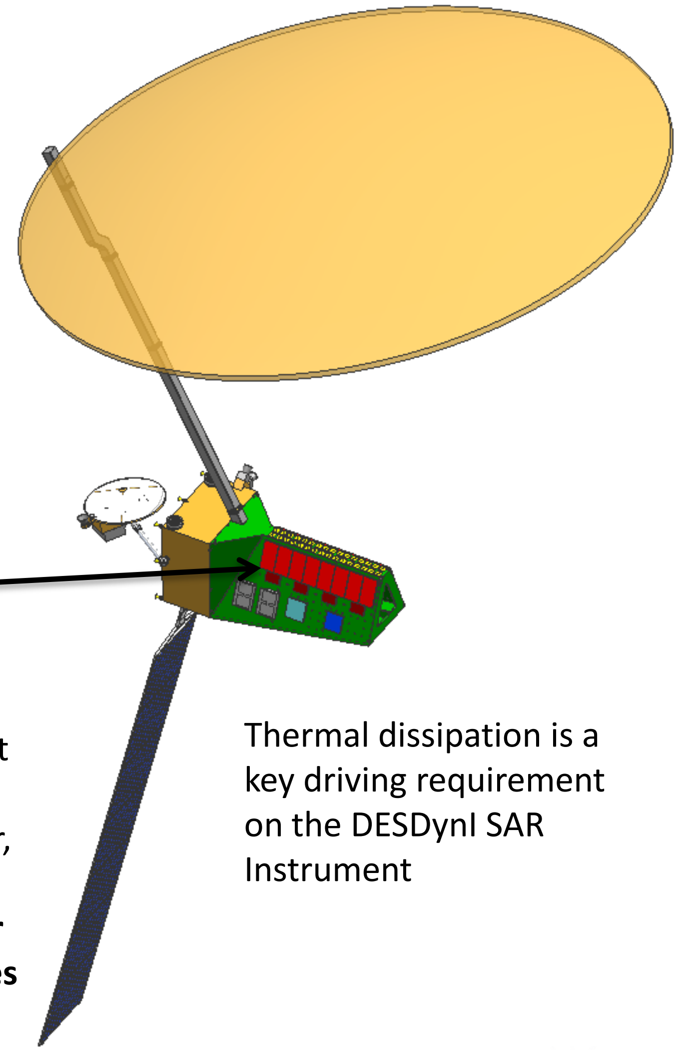
The introduction of these new technologies reduce thermal variability, improving reliability, and enable higher power densities for high power TR modules, like those for the proposed DESDynI Synthetic Aperture Radar





thermal radiator is "bottom" of the module, which faces out towards cold space

Phase change material (PCM) sits between hot electronics and thermal radiator, **stabilizing temperature for up to 40 minutes of operation**



Thermal dissipation is a key driving requirement on the DESDynI SAR Instrument

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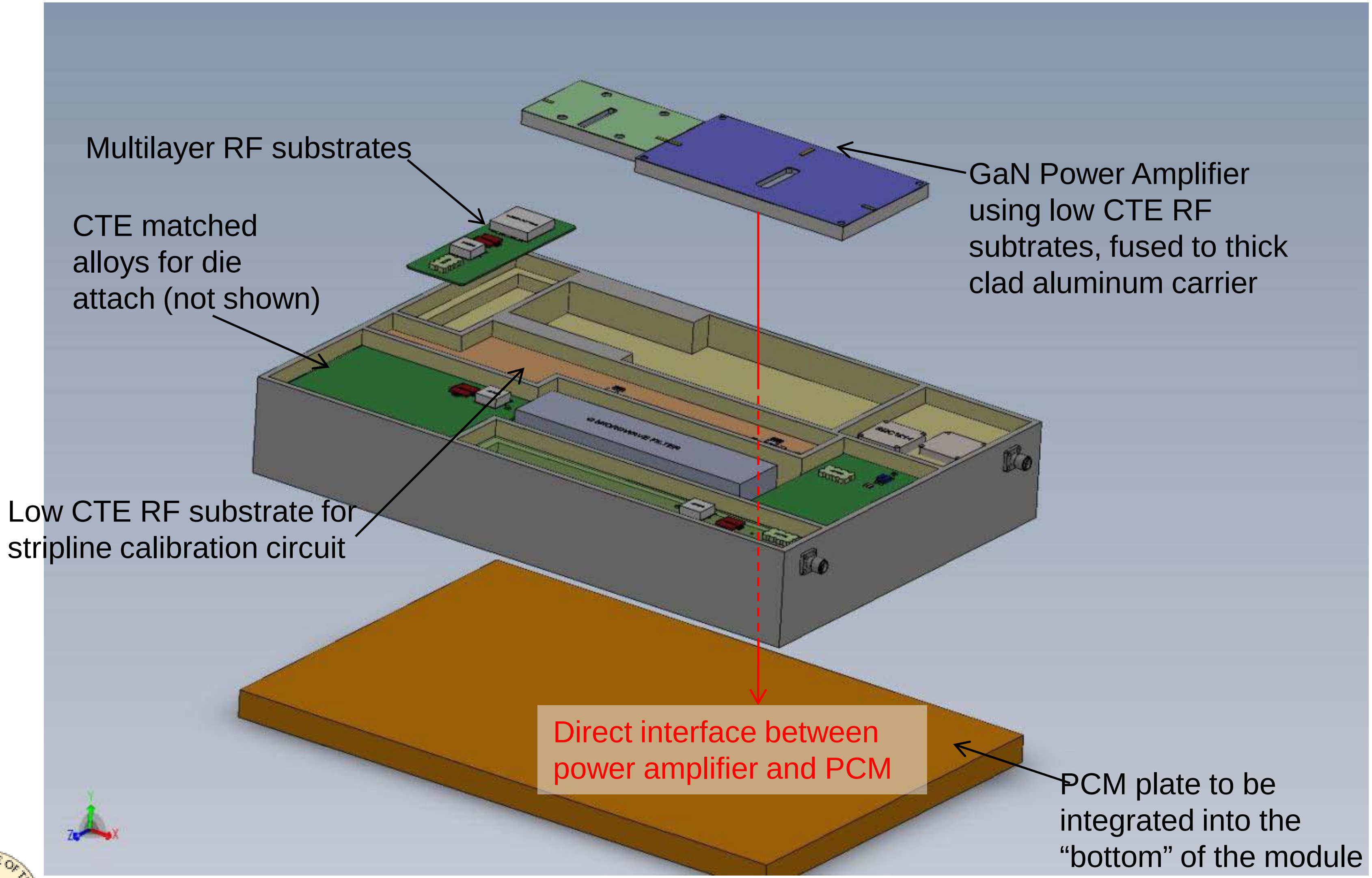
TR Module Integration



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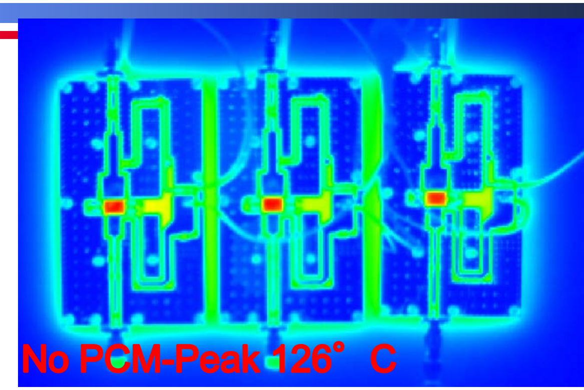
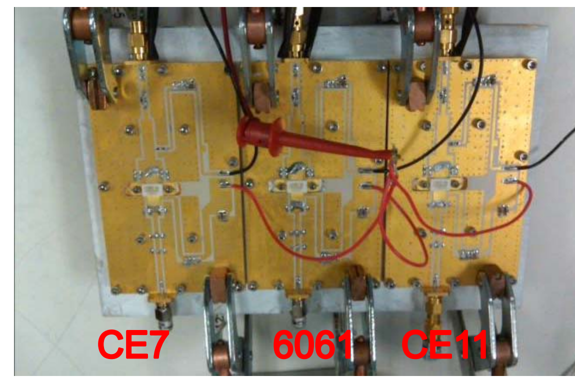
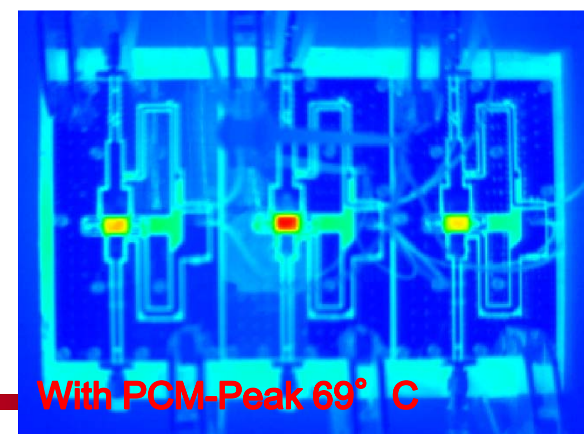
Integration GaN/Si-Al/PCM

- Two substrates were designed for the active evaluation of packaged devices and printed circuit boards directly attached to the plated SiAl alloys CE7 and CE11, along with a set of baseline 6061Al substrates.
- Devices were bolted onto the carriers and the PCBs were attached using Ag filled epoxy.
- The thermal behavior of the three assemblies was evaluated prior to thermal cycling. The amplifiers were biased at 28V and 1A, without RF, to obtain the worst case thermal condition.
- Without the PCM plate, the temperature continued to rise and the test was terminated when the devices reached 126° C.
- With the PCM plate, the device temperature reached 69° C and stopped.
- The assemblies are now being thermal cycled







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Summary

- Individual technologies have been investigated to improve key areas of reliability (thermal variability, CTE mismatch)
- These technologies are being combined to create a high-power, high-power density TR module, which enables SweepSAR
- Initial measurement/analysis of these technologies indicate significant improvement in reliability
- Modeled performance indicates integrated technologies will reduce thermal variability by at least 50% which:
  - improves reliability
  - allows higher power density electronics
  - enables SweepSAR architectures

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