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Thermally, Electrically Conductive Adhesive Manages to Control Heat in PCBs

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Thermal management is a critical element in the design and manufacturing of printed circuit boards (PCBs) for a wide range of applications. Quite simply, heat can be destructive. The more effectively that heat is dissipated from a PCB, the better the opportunity for a long, reliable operating lifetime for that PCB. Attaching a heat sink to the PCB can be an important step in the thermal management process, and several methods are available for attachment, including sweat soldering, fusion bonding, mechanical press fit, and the use of thermally conductive adhesive. Each approach has strengths and weaknesses, although the use of thermally conductive adhesive may be the simplest procedure. A number of studies performed with Thermally and Electrically Conductive Adhesive (TECA) materials may help to shed some light on the benefits of using such thermally conductive adhesives, and these studies will be reviewed in three segments: fabrication techniques and testing, thermal performance, and electrical performance.

Although TECA materials have been commercially available for many years, they have not been widely adopted as part of a thermal management solution mainly due to a number of material limits. But the recently released company TECA film materials detailed in this report overcome many of the limitations that previously plagued thermally conductive adhesive materials, including concerns for lead-free solder-reflow compatibility, problems with uncontrolled flow during PCB lamination, poor RF electrical performance at frequencies above a few GHz, and variations in electrical performance when operating at elevated temperatures.

This new TECA film is formulated from a special hydrocarbon adhesive system that has proven to be quite robust when enduring multiple lead-free solder reflow cycles. Proper lamination is an important step in using these TECA materials with many different types of circuits, and these new films can be laminated by means of processes readily employed by PCB fabricators. The TECA material can be processed by using a short lamination cycle and higher cure temperature or a longer lamination cycle and lower cure temperature. For example, the material can be laminated at +175°C for 45 minutes while held under pressure or at +150°C for 60 minutes while held under pressure. The pressure required during lamination ranges from 80 to 140 psi, with higher amounts of pressure applied when laminating large and/or rough surfaces.

As part of any manufacturing process, prior to lamination, it is often necessary to cut TECA material to a particular shape, and this can be done by means of steel rule die, routing, or laser cutting. In preparation for lamination, a temporary heat tack is often required, which can be achieved by means of 50 psi and +125°C for 5 minutes.

The lamination cycles recommended for this new TECA material generally yield circuits with minimal, consistent flow, since the TECA material features well-controlled flow characteristics, with 5 mils flow per 1 mil of TECA material thickness. Flow during lamination refers to the amount that the cut-out area is reduced. The new TECA material film is currently available with nominal thicknesses of 2 and 4 mils, and the 2-mil-thick material will typically flow less than the 4-mil-thick material. The flow behavior of the TECA material can vary as a function of lamination conditions, so a DOE should be implemented to establish a proper procedure when using TECA materials for any type of PCB build.

To better understand how TECA materials behave when fabricating PCBs, a study was performed to evaluate different lamination conditions for standard as well as for difficult-to-bond-to surfaces. The thinner, 2-mil-thick TECA material was used to bond PCBs to aluminum surfaces plated with electroless nickel immersion gold (ENIG). The aluminum plates were 0.125 in. thick. Lap-shear testing was performed per ASTM D1002 using a production mechanical tester with a 5000-lb. load cell. Test samples were aligned to yield a vertical bond area between the aluminum plates that would be tested. Lap-shear test results above 500 lb. are considered good. Samples were subjected to numerous conditions prior to testing. Table 1 provides a summary of the four different lamination cycles which were evaluated, with results for the four cycles shown in figure 1.

Table 1. Lamination evaluation matrix of different lamination cycles

	Held Constant				Variables	
Cycle	Ramp (°C/min.)	Dwell (min)	Material and Surface Type	Surface Roughness, Rq (µin)	Cure Temp (C°)	Pressure (psi)
1	4	60	ENIG Plated Aluminum	38	175	80
2	4	60	ENIG Plated Aluminum	38	175	130
3	4	60	ENIG Plated Aluminum	38	150	80
4	4	60	ENIG Plated Aluminum	38	150	130

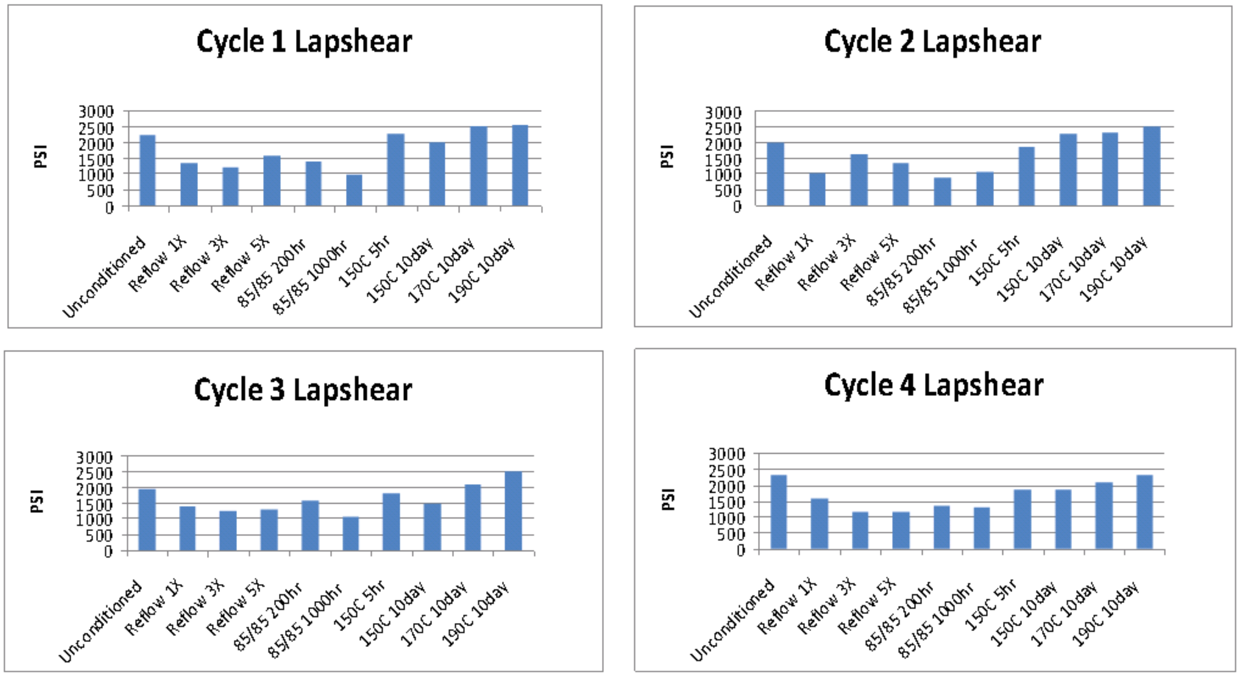


Figure 1. These are the lap-shear results from the different lamination cycles of table 1, with samples subjected to a variety of conditions prior to testing.

The results for the four lamination cycles shown in figure 1 reveal that the new TECA material is quite robust and capable of handling multiple and demanding thermal environments. The labels in figure 1 for Reflow 1X, 3X, and 5X refer to data collected from samples following exposure to 1, 3, and 5 cycles of lead-free solder reflow, respectively. Additional results in figure 1 provide data for aggressive thermal testing, such as samples subjected to 85% relative humidity (RH) at +85°C for 200 and 1000 hours. The data in figure 1 include a variety of different thermal tests, including one quite extreme test, at +190°C for 10 days. Although some small differences can be found in the different laboratory shear results regarding the four different lamination cycles, the results indicate that this new TECA material is very thermally robust.

Electrical resistance testing was also performed on the samples, using a production test fixture with gold-plated electrodes, with a nanovolt micro-ohmmeter and four-wire test setup to measure resistance. The results of these resistance tests are shown in figure 2 for the four lamination cycles.

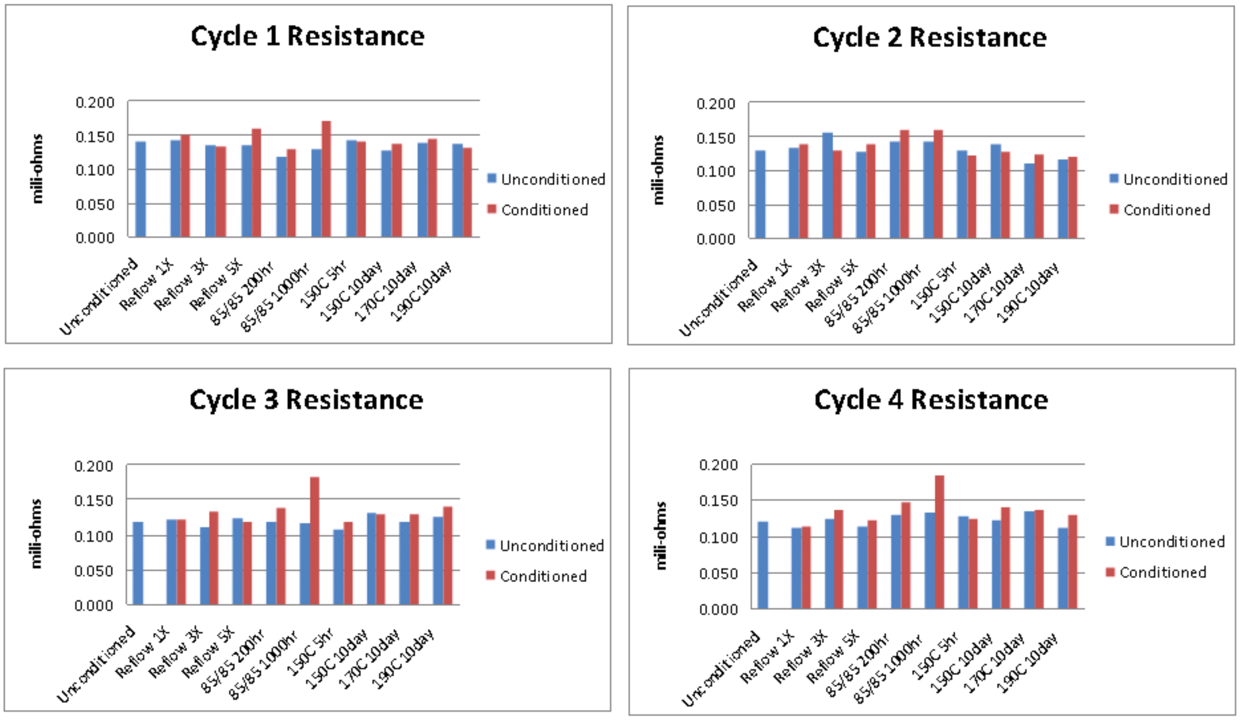


Figure 2. These plots compare the results of electrical resistance testing performed on samples from table 1 subjected to a variety of thermal conditions.

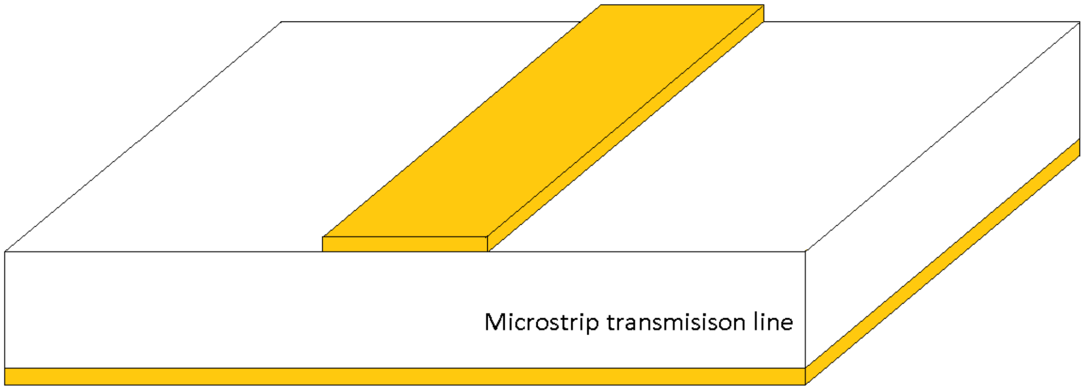
As the values in figure 2 indicate, the new TECA material maintains consistent performance even when subjected to a variety of different thermal conditions. The TECA material exhibits an electrical volume resistivity of 0.00038 Ω·cm, which is considered quite good. The four-wire test results show less than 0.5-mΩ change in resistance for a variety of thermal conditions, which is also quite good.

Still, thermal, electrical adhesive materials can provide promising results at DC but fall short at higher frequencies, during RF testing, so it was necessary to also evaluate the RF performance of the new company TECA material to better understand its expected behavior in higher-frequency applications. For these RF tests, two different types of microstrip transmission lines were used as the test circuits, a straight microstrip transmission-line circuit and a grounded coplanar-launched microstrip transmission-line circuit. Both circuits were 8 in. long and main bodies of the two circuits were identical. They differed at the ends where the end-launch connectors were attached. The coplanar-launched circuit included ground planes around the signal conductor at the edges of the circuit where the connectors were attached. These ground areas featured plated-through-hole (PTH) viaholes for the shortest possible ground return path to the connector.

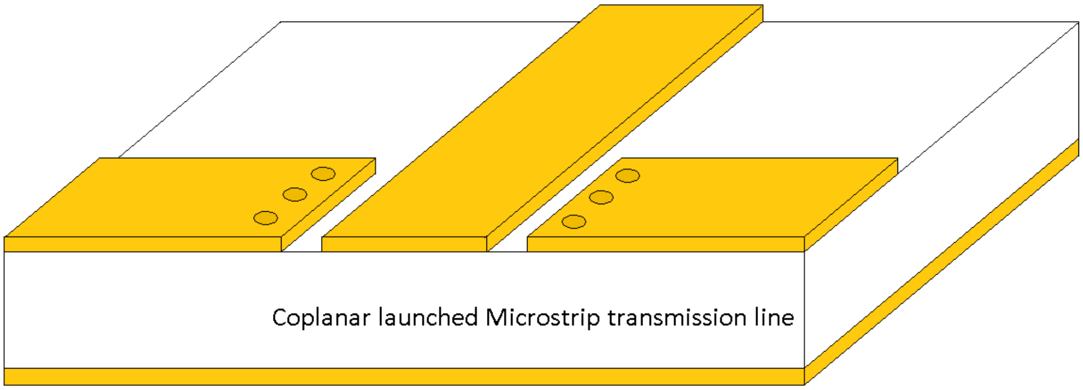
Minimizing the negative impact of the ground return path on the microstrip transmission-line propagation helps optimize the performance of a microstrip circuit. Basically, a microstrip circuit board consists of a signal conductor or transmission line on a top copper circuit layer, a middle dielectric layer, and a ground plane on a bottom copper layer. Signal energy propagates along the signal conductor or transmission line with a ground energy that returns under the signal conductor (on the ground plane) to the source of the energy. The performance of the circuit is affected by numerous material factors, including the loss and thermal characteristics of the conductive metal (typically copper) and the dielectric material.

Depending on a circuit design, TECA may or may not be part of a microstrip circuit's ground return path. In many cases, because TECA is part of the ground return path, it can have a negative impact on microstrip circuit performance. In the past, while TECA materials may have been necessary for a particular circuit structure, those materials were also known to negatively impact microstrip performance above 5 GHz. Fortunately, the new TECA materials under evaluation show the potential for use at frequencies considerably above 5 GHz. This earlier limit at around 5 GHz has been assumed to be due to TECA-related material properties, such as lower conductivity as well as change in conductivity as the operating temperature of the TECA material increases. Such concerns must be addressed in any evaluation of the new TECA materials, especially if they are being considered for applications above 5 GHz.

Figure 3 provides three-dimensional (3D) views of the two microstrip transmission-line circuits used in the study of the new TECA material, depicted without TECA and heat sink. The first is a standard, straight microstrip transmission line while the second employs a coplanar launch with PTH viaholes at the signal launch area, which is at the interface of the connector conductor and the microstrip transmission line. Figure 4 shows side views of the two microstrip transmission-line circuits, with TECA and heat sinks.



3D View



3D View

Figure 3. These 3D views show the two types of microstrip circuits being evaluated for microwave performance with TECA (TECA and heat sinks are not shown in this figure).

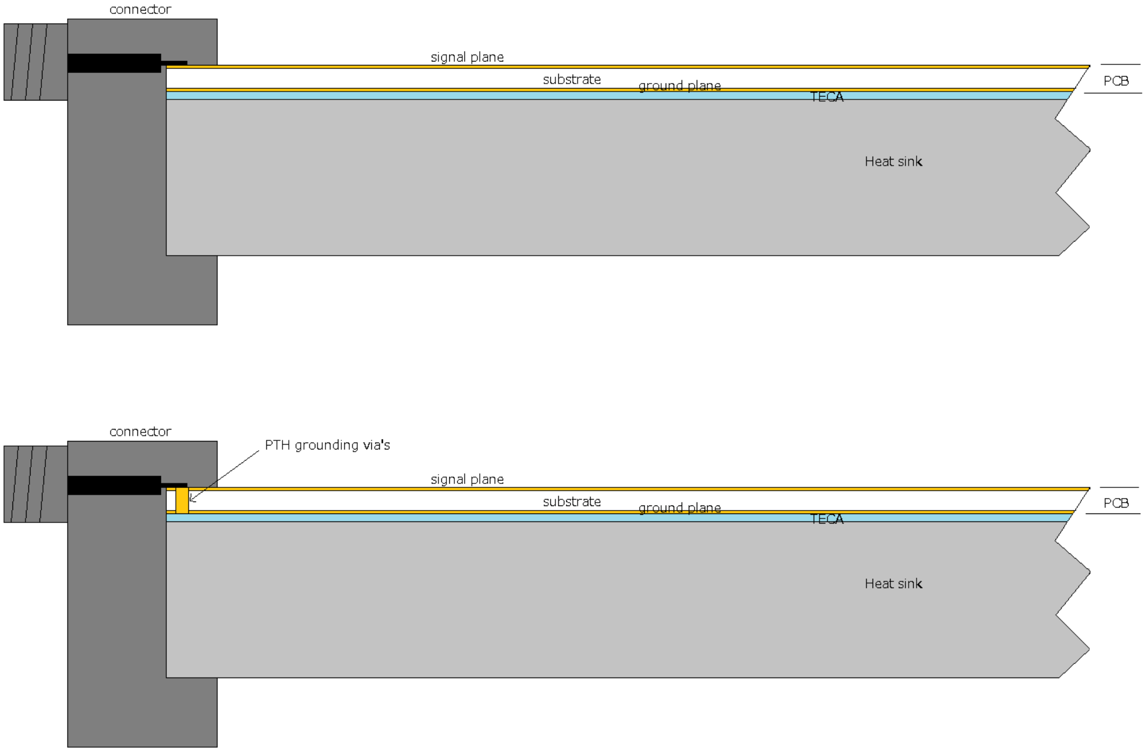


Figure 4. These are side views of the two microstrip circuits of figure 3, including the TECA material and heat sinks.

As depicted in figures 3 and 4, the ground return path for the coplanar-launched microstrip transmission line has a channel very near the connector, for efficient propagation with minimal loss. The straight microstrip transmission-line circuit, on the other hand, relies solely on the performance of the TECA material for its ground return path. Figure 5 shows that, especially with increasing frequencies above around 25 GHz, the two approaches can yield significant differences in insertion-loss performance. Still, for the straight microstrip circuit that relies so heavily on the TECA material for its ground return path, it is providing quite acceptable performance through 25 GHz, which is noteworthy compared to earlier TECA materials that have been limited to about 5 GHz.

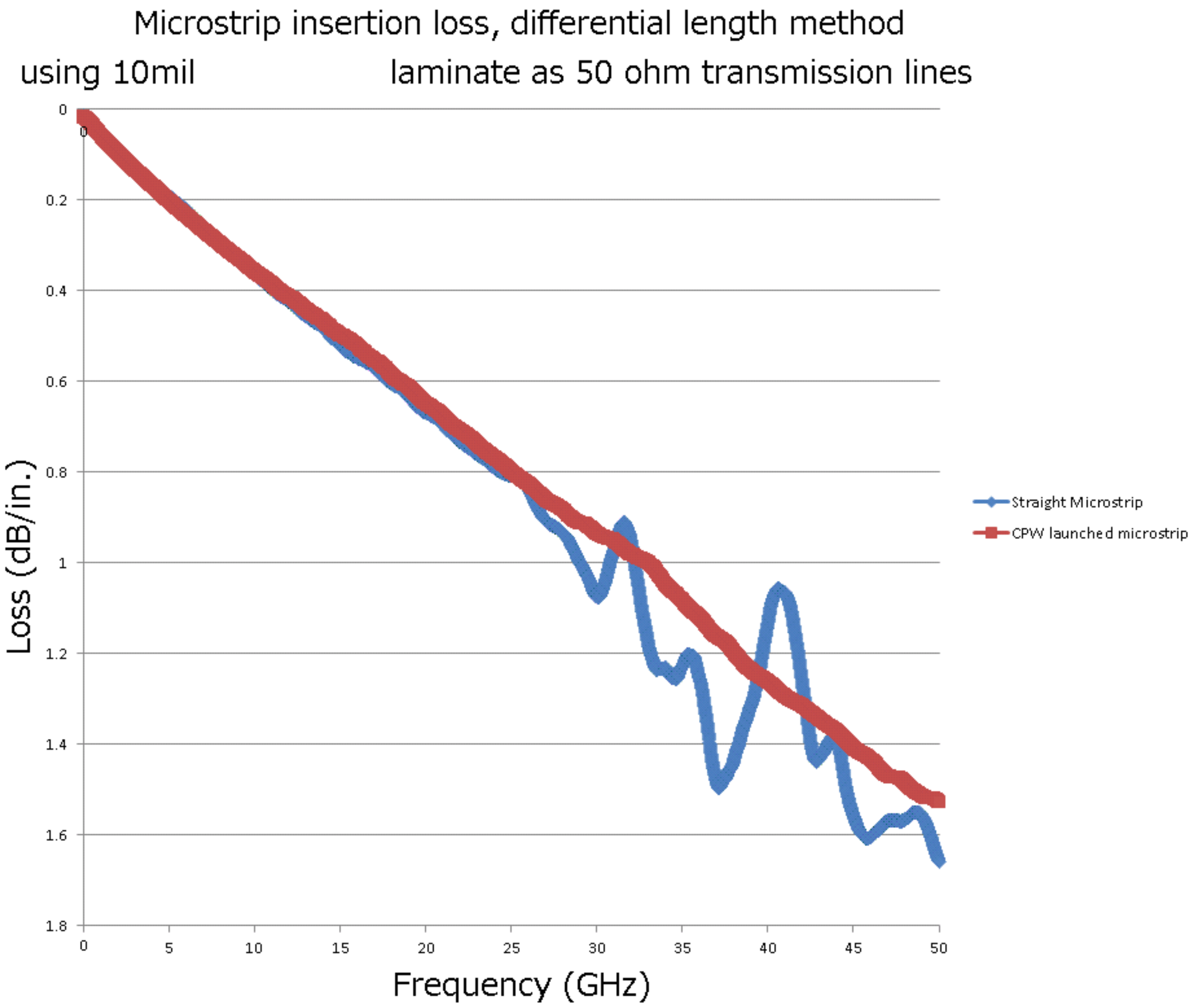


Figure 5. Comparing the insertion losses of the two microstrip circuit designs using the same circuit materials, TECA, and heat sink.

For any TECA material included as part of a high-frequency circuit, a real concern must be to evaluate how much the TECA material contributes to the insertion loss of the circuit, and whether its insertion-loss behavior changes after undergoing lead-free solder reflow. To evaluate insertion-loss performance with TECA, the worst-case circuit design, the circuit with straight microstrip transmission lines, was considered as the test case. Insertion-loss testing was performed prior to lamination of the TECA, then insertion-loss testing was performed with the TECA material and heat sink as part of the circuit's ground return path. Insertion-loss testing was also conducted after each of two lead-free-solder reflow cycles for comparison.

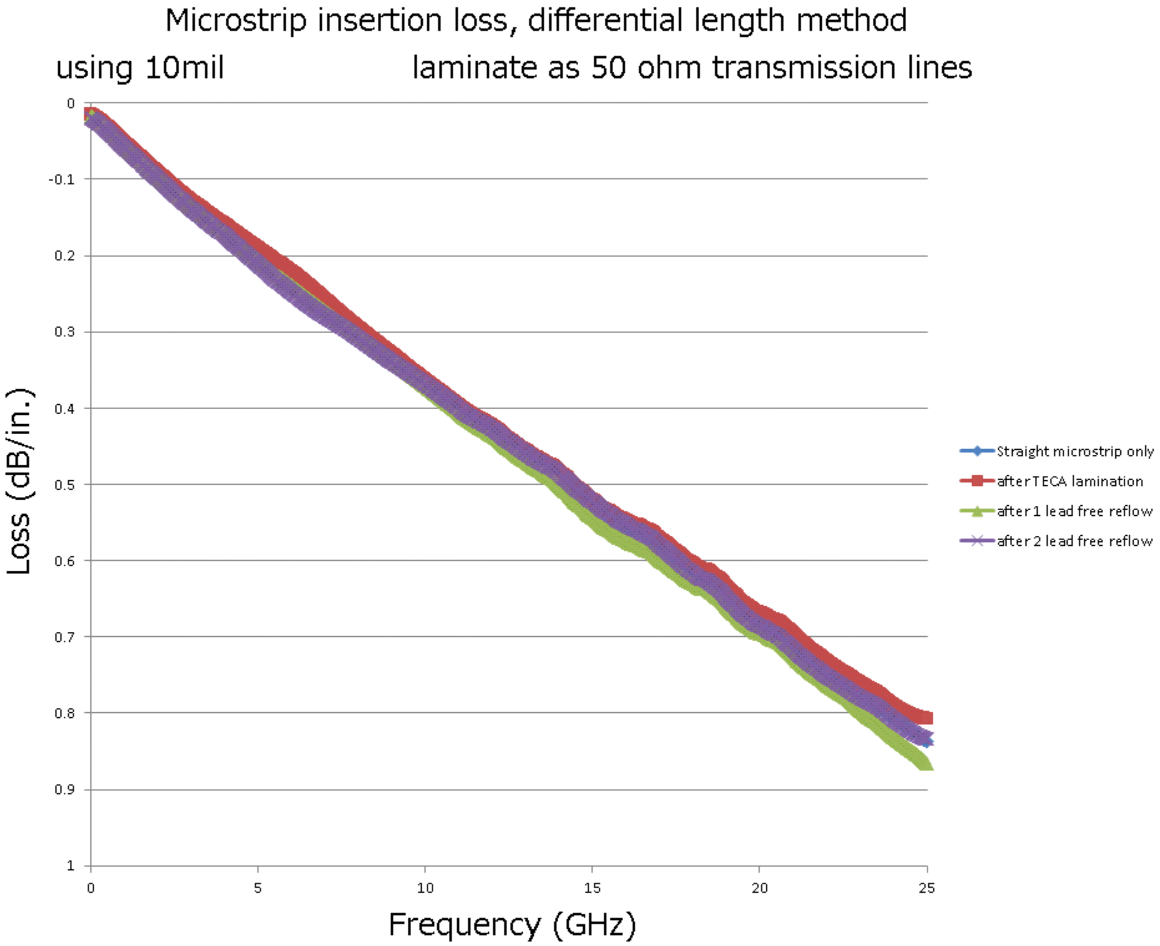


Figure 6. These curves of insertion loss with frequency compare the performance of the bare straight microstrip circuit, after TECA-heat-sink lamination, and after two lead-free solder reflow cycles.

Figure 6 compares measured insertion loss versus frequency for the bare straight microstrip transmission-line circuit, the circuit following the TECA heat-sink lamination, and following two lead-free-solder reflow cycles, with very little apparent difference in insertion loss except at the highest frequencies.

Thermal management is an important part of any circuit that must operate at higher power levels and/or maintain consistent performance across a wide operating temperature range, and the new TECA material supports consistent thermal flow from a circuit to a heat sink or other thermal reservoir by means of a thermal conductivity of 6 W/m/K. Figure 7 provides a comparison of the dramatic difference a well thermally connected heat sink can make for a circuit (right) compared to the same circuit without the heat sink (left).

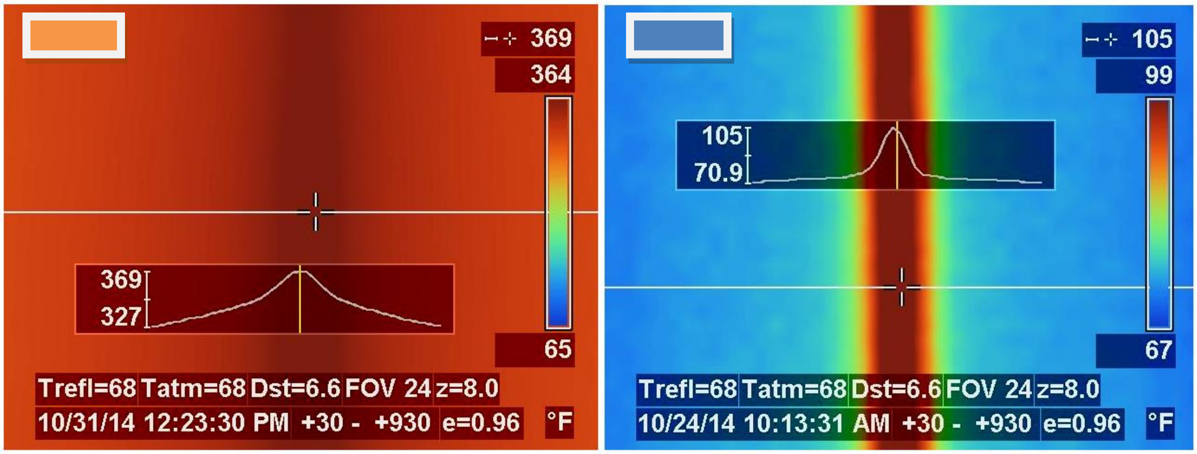


Figure 7. Comparison of the same circuit without a heat sink attached on left and with a heat sink attached on the right picture. Both pictures are the top view and zoomed in for magnification of the conductor width which is about 21mils wide.

The thermal images of figure 7 are top views of the microstrip circuit and material noted in figure 6, with (right) and without (left) TECA and heatsink. Each circuit has 85 W of applied RF power at 3.32 GHz. As the image on the left-hand side of figure 7 reveals, the temperature of the circuit without the TECA and heatsink is much higher and spread across the width of the circuit. The maximum temperature of this circuit is located at the center of the signal conductor, approximately +325°F. As the right-hand image, with the TECA and heatsink, shows, minimal heat spreading occurs, with a maximum temperature of +105°F and most of the heat flow occurring through the circuit substrate and into the heatsink below.

To understand the heat flow within a PCB, it may helpful to adopt a model based on simple physics as shown in figure 8, with heat flow taking place from a hot reservoir with a high temperature, T_H, to a cold reservoir with a cold temperature, T_C.

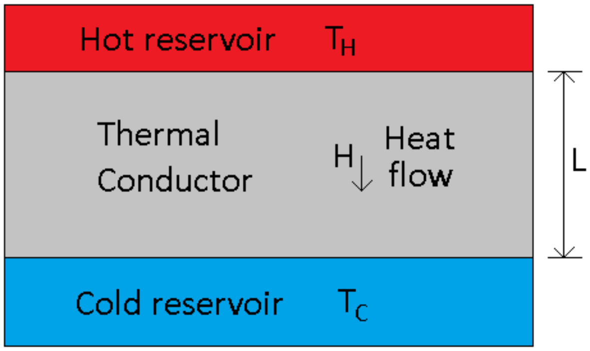


Figure 8. This basic thermal model can apply to a microstrip circuit, where the signal plane is assumed to be the hot reservoir and a ground plane with heat sink is assumed to be the cold reservoir.

Based on the simple model represented in figure 8, a heat flow (H) formula follows:

$$H = -k \cdot A \cdot \left(\frac{T_H - T_C}{L} \right)$$

where

k is thermal conductivity (in W/m/K), A is the area (in m^2), T_H is the temperature (in K) of the hot reservoir, T_C is the temperature (in K) of the cold reservoir, and L is the distance (in m) between the hot and cold reservoirs. This heat flow equation is appropriate as a simple representation of a thermal model for a microstrip circuit. The microstrip circuit consists of a top conductor layer, a ground plane as the bottom conductor, and a dielectric substrate between the conductor layers. The thermal model of figure 8 assumes that heat is generated on the signal plane, which serves as the hot reservoir. In an actual microstrip circuit, the heat generation is much more complex. In the thermal model of figure 8, the dielectric substrate acts as a thermal conductor to transfer heat from the signal plane to the ground plane, assuming that the ground plane has a heatsink attached and acts as a cold reservoir. Unfortunately, the circuit substrate is a poor thermal conductor and does not effectively promote heat flow from a hot to a cooler area. For example, the thermal conductivity of copper, a good thermal conductor, is about 400 W/m/K. In comparison, the thermal conductivity of most commercial PCB substrate materials is only about 0.2 to 0.3 W/m/K, providing only a small fraction of the thermal conductivity of a good thermal conductor, such as copper.

The heat flow equation explains why a thinner circuit or thinner thermal conductor (with smaller L) offers improved heat flow and can achieve cooler operation under higher power levels compared to a thicker circuit. A substrate with improved thermal conductivity (k) will exhibit increased heat flow compared to a circuit material with poor k, providing the potential to achieve cooler operation under higher power levels.

To better understand various tradeoffs regarding thermal issues for PCB materials, a study was conducted based on 50-Ω microstrip transmission-line circuits such as illustrated in figures 3 and 4. Circuits were fabricated on the same types of PCB materials but with differences in thickness and copper conductor surface roughness. Increased copper surface roughness translates to increased insertion loss, and higher insertion loss can lead to increased RF heating effects on PCBs operating at higher RF power levels. As part of the study, a circuit was also fabricated and evaluated on a higher-loss PCB material. In addition, a tightly coupled grounded-coplanar-waveguide (GCPW) transmission-line circuit was fabricated and evaluated using the same low-loss circuit material as for the microstrip circuits. All circuits used the 2-mil-thick TECA material mentioned previously, laminated to a mounting plate which was mechanically screwed down to a water-cooled heatsink.

An infrared (IR) camera was used to record the heat patterns of each circuit with applied power. To ensure accurate measurements, consistent color was maintained on all circuits and surfaces in the view of the IR camera. Black paint with known emissivity was used for the color, for which the IR camera can make adjustments to achieve accurate thermal imaging. Unfortunately, the black paint increases the insertion loss of the transmission lines, so the recorded heat rises are considered worst-case results. The insertion loss (and heat rise) of the GCPW circuit was impacted to a greater degree than the microstrip circuits, since the black paint filled the gaps in the circuit's coplanar ground-signal-ground (GSG) area, which is an area of high current density.

Table 2. Different circuits and circuit materials exhibit different heat rises under similar operating conditions.

Circuit ID	Circuit material	Transmission line type	Dk	Df	Thermal Conductivity (W/m/K)	Copper surface roughness (RMS)	Insertion loss without black paint @ 3.4 GHz (dB/in.)	Insertion loss with black paint @ 3.4 GHz (dB/in.)	Heat rise (°C) 85W @ 3.4 GHz
1	[redacted]	microstrip	3.66	0.0037	0.64	2.8	0.17	0.27	22
2	[redacted]	GCPW	3.66	0.0037	0.64	2.8	0.20	0.43	27
3	20mil [redacted]	microstrip	3.66	0.0037	0.64	2.8	0.12	0.19	29
4	20.7mil [redacted]	microstrip	3.55	0.0037	0.64	0.6	0.10	0.14	22
5	20mil High Perf FR-4	microstrip	4.25	0.0200	0.25	1.4	0.36	0.37	74

Table 2 shows the circuits, circuit materials and properties, and other details of this multiple circuit/material study. It offers a great deal of information for comparing different circuit materials, and helps emphasize the complexity of comparing different thermal-management approaches with different circuits and materials. For example, Table 2 compares circuits based on the same circuit substrate but with two different types of copper, one with rough copper surface (circuit ID 3) and one with smooth copper surface (circuit ID 4). The circuit with smoother copper exhibits lower insertion loss than the circuit with rougher copper surface, with less heat rise as a result of the applied RF power.

Comparing circuit ID 1 with circuit ID 3 reveals the differences in heat rise with a change in PCB material thickness. These two circuits use the same material and copper type, differing only in thickness. Circuit ID 1 is the thinner of the two, with higher insertion loss than the thicker circuit ID 3. Higher insertion loss usually means more heat generated for a given amount of applied RF power. But as Table 2 details, thinner circuit ID 1 was actually cooler than thicker circuit ID 3 for the same applied power, due to its shorter heat flow path (L in the heat flow equation).

Table 2 provides information that can be used to compare similar circuits fabricated with different materials as well as for comparing different circuit configurations for the same circuit material. Differences in material parameters such as thermal conductivity and dissipation factor translate into different heat rises for various choices of circuits and materials. In the case of the GCPW circuit, it exhibits much higher insertion loss than the microstrip circuits, as a result of the black paint, but it does not suffer a significantly higher heat rise than the microstrip circuits. The GCPW circuit benefits from repetitive grounding viaholes that run along the edge of the signal conductor. These viaholes act as a “thermal fence,” helping to channel heat more efficiently to the heat sink.

In short, the study illustrates the complexity of achieving optimum thermal and electrical performance with any circuit, especially at higher frequencies. Tradeoffs typically involve a careful choice of PCB materials for applications at higher frequencies that must also handle higher power levels. Fortunately, emerging TECA materials are providing reliable thermal performance while also enabling electrical operation at higher frequencies, through 25 GHz.