New Developments in PCB Laminates

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With the ever accelerating demands in printed circuit board (PCB) design, the choices of advanced laminate materials have become fewer and fewer. The trends continue towards higher frequency requirements, exotic via structures, shrinking hole to hole pitch, multiple lamination cycles, increased operating temperature, and more stringent environmental regulations for halogen-free and lead-free solder assembly! These constantly evolving new challenges for the PCB industry have made many of the tried and true materials obsolete. Demands for high speed digital (HSD), high density interconnect (HDI), halogen free, lead-free processable materials are becoming more prevalent and the laminate technology supporting these demands is still in the early stages and in some cases does not yet exist.

Until recently, halogen free laminates struggled with thermal stability as well as poor electrical performance. This paper will outline recent developments for a halogen free laminate system that is unique in regards to these issues. Due to the uniqueness of this material, comparisons of the thermal and electrical properties will be done using halogenated flame retardant PCB materials, which have been extensively used in the PCB industry.

To be clear, there are several laminates, which have been on the market for decades that are halogen free, however, are not flame retardant. The most common flame retardant technologies used in laminate manufacturing are well understood chemistries containing bromine, a halogenated substance, thought to be an environmental concern. Laminate suppliers have made excellent progress with new halogen free flame retardant technologies; however, their use has been focused on lower performance laminate systems.

The difficulty is developing a material technology to make a laminate flame retardant and halogen free and still have the reliability and performance properties the PCB industry demands. Depending on the halogen free technology employed, there are various tradeoffs of the different properties. The halogen free technology used here, while meeting the standard demands for PCB laminates, also addresses the need for improved thermal stability and electrical performance. The property combinations that are achieved by use of this proprietary material technology appears to be unique in the PCB industry at this time. Rogers Corporation's Theta® circuit materials use this technology; an abbreviation of "TH" will be used in this paper for this product when comparing to other products. A basic description of the other products used for comparison in this study is given in table 1.

Material ID	Material description
TH	Halogen free flame retardant, mid loss, thermally stable
Comp1	Standard flame retardant, mid loss, used extensively
High Tg FR-4	Standard flame retardant, high loss, used extensively
Comp2	Standard flame retardant, mid loss, thermally stable
Comp3	Standard flame retardant, mid loss, thermally stable

Table 1. Basic material descriptions of comparison materials for this paper. These materials were chosen due to their extensive use in the PCB industry and their combination of properties, which give good resolution for comparisons.

Thermal stability can mean many different things and to clarify, this paper will be discussing relatively short term thermal stability as opposed to long term thermal aging.

The short term issues are mostly related to material testing, circuit fabrication and assembly. The thermal topics discussed will be Tg, CTE, lead-free soldering, 288°C solder float and eyebrow crack testing.

The TMA (Thermal Mechanical Analysis) testing can be used to determine several material properties. The TMA is used to determine the Tg (glass transition temperature) and CTE (coefficient of thermal expansion). In general a laminate with a higher Tg is considered more thermally robust in the PCB fabrication process. When, in fact, the Tg, Td and CTEz (CTE for the z axis or thickness) should all be considered to determine the thermal robustness. A PCB material with a CTEz of 70 ppm/°C or less is typically considered good for the circuit fabrication process and pth (plated through hole) reliability. An ideal X-Y CTE would be matched to copper which is about 17 ppm/°C, however, in practice that is seldom encountered.

A drawing showing the basic characteristics of a TMA curve is shown in figure 1.

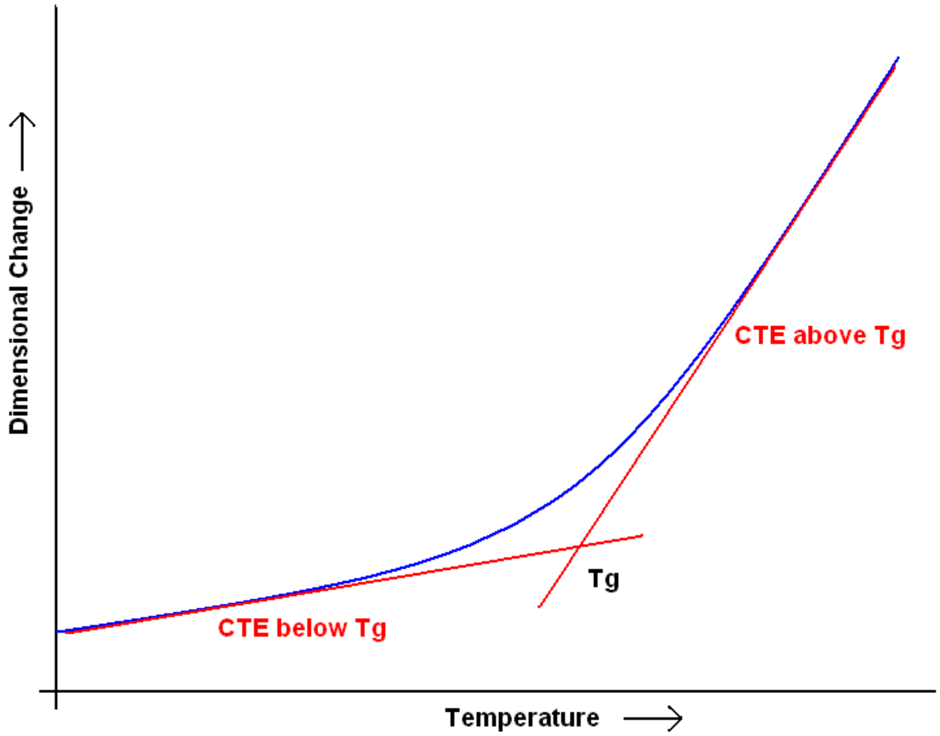


Figure 1. Simplified drawing for showing the aspects of a TMA curve.

Material datasheets report the CTE differently and typically report the value, which is below the Tg. A more meaningful description of the CTE would be reporting it as a value below the Tg and above the Tg. This is typically called alpha1 (below Tg), alpha2 (above Tg) and it is very common for a PCB material to have a very significant different alpha1 and alpha2 values.

In some cases, a CTE is reported as a percentage of overall expansion across a very wide range of temperatures. Some Tg, Td and CTE values from datasheets are shown in table 2 and the CTE's are assumed to be alpha1 values.

Material	Tg(°C)	Td(°C)	CTE
TH	180	390	50 ppm/°C
Comp1	210	350	70 ppm/°C
High Tg FR-4	170	300	3.9%
Comp2	200	360	55 ppm/°C
Comp3	176	360	35 ppm/°C

Table 2. Typical Tg, Td and CTE values of various PCB materials.

Evaluating the TMA curve for a material is suggested when trying to understand exactly what the material thermal characteristics are at specific temperatures. The TMA curve for the TH material is shown in figure 2.

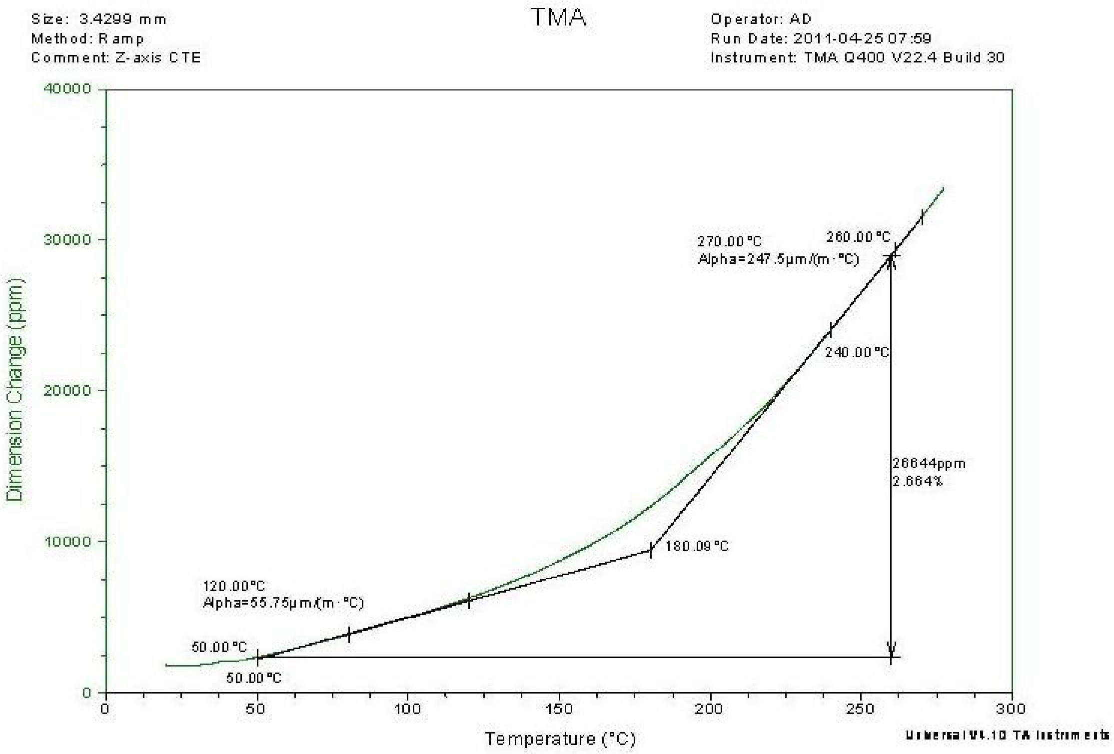
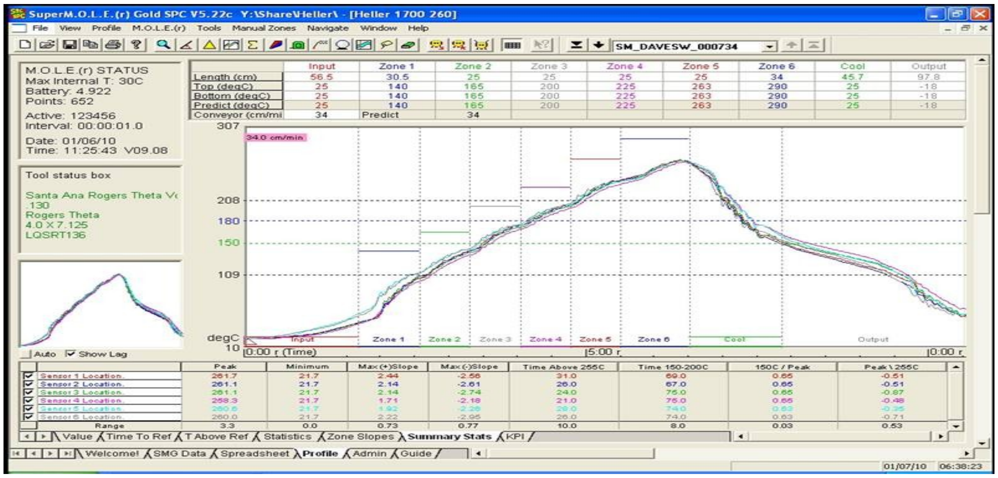


Figure 2. Typical TMA curve of TH material.

The above information is in regards to the laminate only and when a circuit build is evaluated, the TMA curve is a composite of the different materials used. The laminate and prepreg thermal characteristics will be considered, as well as, the plated copper used in the circuit build.

Another test that will evaluate a circuit build and the raw materials is the lead-free solder reflow test. This test will subject the circuit to typical lead-free solder reflow conditions for multiple cycles. The repeated cycle testing is meant to simulate a worst case scenario for assembly and multiple rework procedures. The cycle will have a time for ramp up to temperature, a hold temperature and cool-down as shown in figure 3. The TH materials have passed this test consistently when tested for 10 cycles at 260°C.



M.O.L.E.(r) STATUS
Max Internal T: 30C
Battery: 4.922
Points: 652
Active: 123456
Interval: 00:00:01.0
Date: 01/06/10
Time: 11:25:43 V09.08

Tool status box
Santa Ana Rogers Theta V(
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LQSRT136

	Input	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Cool	Output
Length (cm)	56.5	30.5	25	25	25	25	34	45.7	97.8
Top (degC)	25	140	165	200	225	263	290	25	-18
Bottom (degC)	25	140	165	200	225	263	290	25	-18
Predict (degC)	25	140	165	200	225	263	290	25	-18
Conveyor (cm/mi	34	Predict	34						

	Peak	Minimum	Max (+)Slope	Max (-)Slope	Time Above 255C	Time 150-200C	150C / Peak	Peak \ 255C
☑ Sensor 1 Location.	261.7	21.7	2.44	-2.56	31.0	69.0	0.65	-0.51
☑ Sensor 2 Location.	261.1	21.7	2.14	-2.61	26.0	67.0	0.65	-0.51
☑ Sensor 3 Location.	261.1	21.7	2.14	-2.74	24.0	75.0	0.65	-0.87
☑ Sensor 4 Location.	258.3	21.7	1.71	-2.18	21.0	75.0	0.65	-0.48
☑ Sensor 5 Location.	260.6	21.7	1.92	-2.26	28.0	74.0	0.63	-0.35
☑ Sensor 6 Location.	260.0	21.7	2.22	-2.95	26.0	74.0	0.63	-0.71
Range	3.3	0.0	0.73	0.77	10.0	8.0	0.03	0.53

Figure 3. Typical lead-free soldering reflow cycle.

Yet another thermal test, which is relatively simple, fast, and a good indicator of thermal robustness is the solder float test. This can be used to test raw materials and/or fabricated circuits. The solder float test is typically regarded as a worst case scenario due to the fact that the material / circuit is being thermally shocked; where the sample goes from room temperature up to the testing temperature nearly instantaneously. The sample is put on molten solder and timed for 10 seconds. The test is often repeated until the sample delaminates. A solder float test at 288°C for a fabricated circuit is considered difficult to pass for even one cycle. Table 3 shows the results for several different PCB materials when tested as a three layer plated through hole (PTH) stripline circuit.

Material	Halogen Free	Cycle without delamination @ 288°C
TH	Yes	>10
Comp1	No	2
High Tg FR-4	No	5
Comp3	No	4
Comp2	No	8

Table 3. Solder float delamination results at 288°C for three layer PTH circuits using different PCB materials.

A relatively difficult PCB evaluation board is a 28 layer build with 2oz copper plane layers and is 3.68mm (0.145”) thick. This circuit is a carrier class router line card test vehicle and circuits were fabricated with the TH material, evaluated and the following thermal results are shown in table 4.

TMA Thermal Analysis	Results
Tg	185.4°C
CTE, alpha1	55.02°C
CTE, alpha2	260.4°C
CTE, 50-260°C	2.63%
T260	> 30 minutes

Table 4. Thermal results of a 28 layer evaluation PCB made with the TH materials.

As a reminder from previous discussions regarding TMA of a multilayer circuit, the attributes and results listed in table 4 are a composite of the laminate, prepreg and the plated copper properties.

A fairly recent thermal evaluation that has become common for complex via structures is the eyebrow-crack test. This is for circuits with buried and/or stacked micro-vias. After lead free type thermal exposures, there can be delamination/damage to the resin at the via-prepreg interface, which is a crack that resembles an eyebrow.

This interface is often the weak link during thermal cycling for these types of circuit constructions and this can be the most difficult interconnect reliability issue to overcome.

The TH material has been evaluated with this test and found to do better than any materials tested to date, where solder floats at 288°C for 6 cycles were passed without issue. Another material which has been used extensively in the PCB industry (Comp1) typically fails this test at 3 cycles. A picture of the TH material after 6 cycles is shown to the left in figure 4 and the picture on the right is the circuit made on Comp1 materials and failing at 3 cycles.

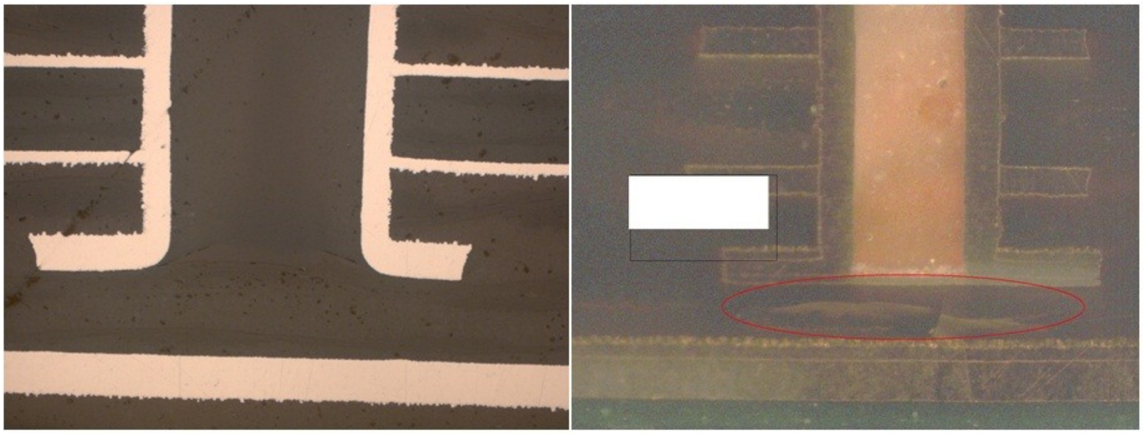

Figure 4. Eyebrow crack testing on a high layer count PCB with micro-vias. Left picture is a PCB built with TH material and passing this test after 6X. Right picture is a failure after 3X with a PCB built using the common Comp1 materials.

Electrical performance can be an issue regarding standard PCB materials as well as halogen free materials. All halogen free circuit materials at this point in time are considered high loss materials in regards to high frequency electrical performance, with the exception of the TH material which is considered mid loss.

There are several aspects to consider for electrical performance, regarding high frequency applications. The most dominant issue would be insertion loss; however dielectric constant (Dk) can be an issue as well.

Dispersion is the change in phase velocity with increasing frequency. Structures that propagate TEM modes, such as plane waves, coaxial cable, and balanced stripline circuits with lossless dielectrics are “non-dispersive,” and exhibit no change in phase velocity with frequency. Non-TEM mode structures such as waveguides are highly dispersive even when propagating in a lossless medium. “Quasi-TEM” mode structures such as microstrip and unbalanced or non-homogeneous stripline circuits are slightly dispersive.

When propagating in lossy media, however, even TEM modes can exhibit dispersion, due to the change in “dielectric constant” of the dielectric material with increasing frequency. In general, the dielectric constant of a lossy medium decreases with increasing frequency. The degree of dispersion is generally proportional to the dielectric loss.

These features are demonstrated by plotting the Dk versus frequency, calculated from the measured differential phase length of 50 ohm transmission lines in stripline (figure 5).

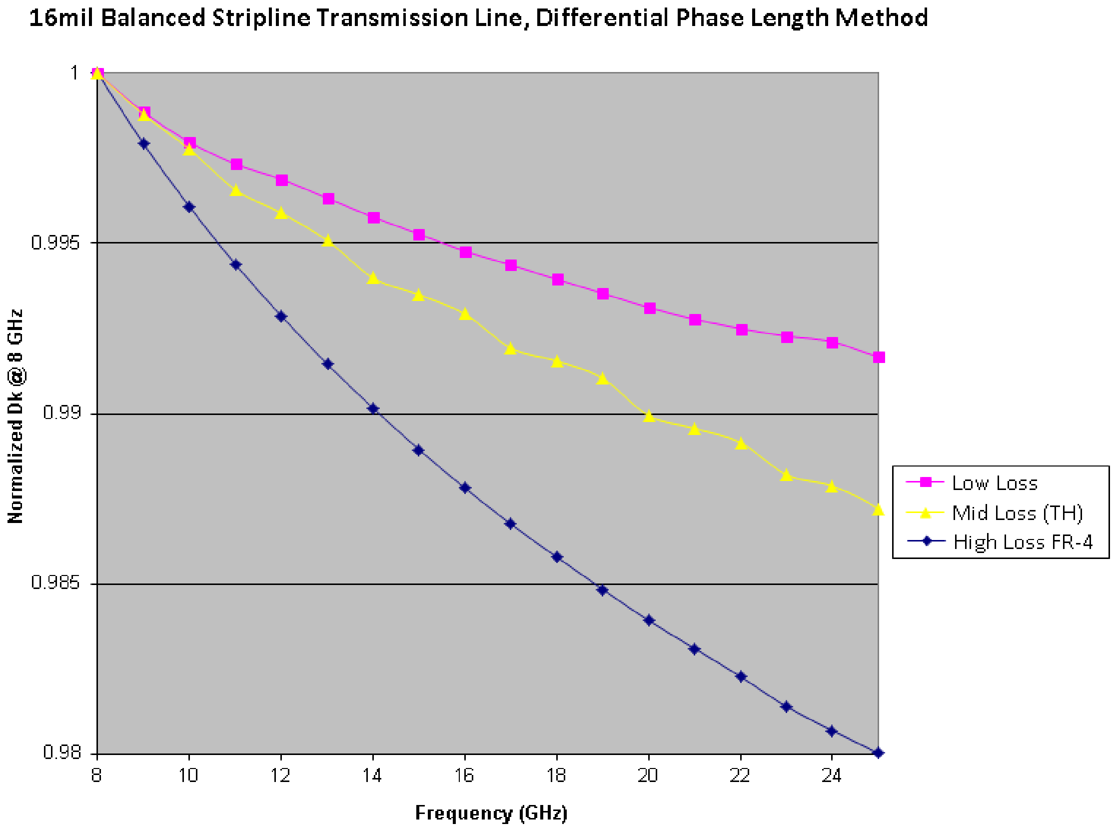

Figure 5. Normalized Dk over a range of frequencies for stripline circuits made on three different materials and showing the effects of material dispersions.

The higher loss FR-4 material exhibits a 2% decrease in the calculated substrate Dk from 8 to 25 GHz, while the lower loss materials exhibit substantially lower dispersion. Low dispersion is desirable in high-speed digital applications since the dispersion effect can contribute to pulse broadening and the narrowing of eye diagrams.

The topic of electrical loss is another subject of concern for high frequency PCB's. This is a relatively complicated subject with many PCB issues to be considered. There are loss issues related to materials, circuit fabrication, plated finishes, assembly and circuit design. Within any one of these areas of concern, there are many subsets. To discuss the material related issues of loss, it is only fair that the circuits used for comparison will have the same design, type of copper, thickness of substrate and finish.

As an extension of the previous work done using simple PTH stripline circuits, loss characterization was considered as well. Again, the stripline circuits were the same design and thickness, where the main difference was the materials used. A comparison of circuit loss is shown below in figure 6.

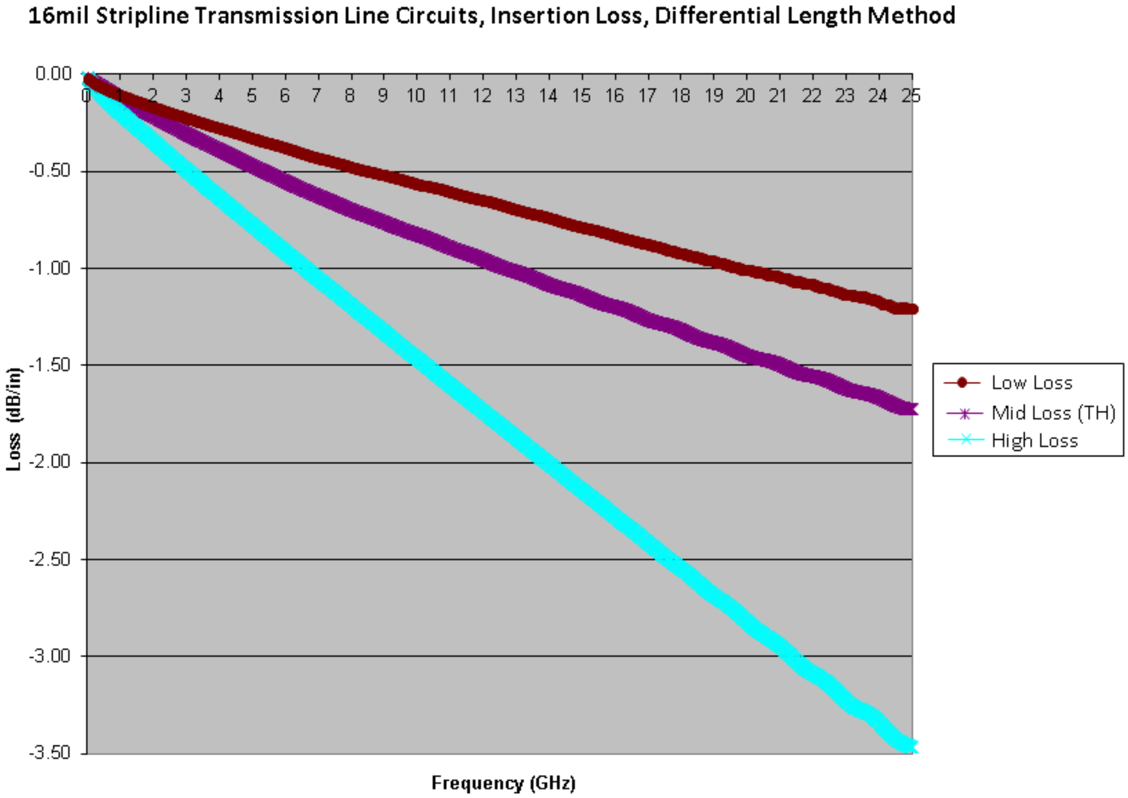

Figure 6. Insertion loss of stripline circuits made with different materials.

Lastly, a quick comment on how dielectric constant can influence losses. If a controlled impedance circuit is changed to a material of a lower Dk, then the conductor width will need to be increased in order to maintain the same impedance. The conductor width increase will lower the conductor losses and ultimately the overall losses.

In summary, there are few halogen free flame retardant laminates available and for those on the market currently, they are not considered mid loss and thermally stable. Theta circuit materials appear to be unique where they meet both these criteria along with other necessary requirements for good PCB fabrication and reliability. The difficulty is comparing materials to this unique material fairly. The appropriate comparisons were done here with materials that have a long proven record in the PCB industry and as a group these comparison materials have the attributes to verify thermal stability and mid loss performance. Through multiple lead-free solder reflows, 288°C solder floats, eyebrow crack testing and other demanding high reliability tests not addressed in this paper, such as HATS, CAF, IST, liquid-to-liquid and moisture conditioning, it was found that this newly developed halogen free material is very thermally stable. The electrical properties were found to be very good as well. The claim of a mid-loss material was verified from insertion loss testing compared to well-known low loss and high loss materials. Also, material dispersion of the dielectric constant was found to be very good and consistent over frequency which can enable a much more stable eye diagram for high speed digital applications.