Improvements in Microwave Laminates for Power Amplifier Reliability and Efficiency

George Qinghua Kang, Michael T. Smith, John C. Frankosky

Arlon, Inc., Materials for Electronics Division

1100 Governor Lea Road, Bear, DE 19701, U.S.A.

Abstract

Demands for higher data rates and capacity have continued to drive RF and Microwave electronics continue toward higher frequency and higher power requirements. These power and frequency demands have increased the heat burden on power amplifiers and related electronics while competing requirements have pushed to reduce device size and weight while exposing electronics to greater environmental conditions. The resulting combination has been a decrease in overall efficiency resulting in higher operating temperatures and a resulting decline in reliability. Most RF system engineers highlight the "Arrhenius Equation," in which a 10°C increase in operating temperature doubles the failure rate for a typically component. In other words, the ability to get heat away from components, reduce or eliminate hot-spots, reduce overall device operating temperature will increase product life. Innovations focused on increasing thermal conductivity and temperature stability of the dielectric while maintaining low loss are being introduced in the industry. A benefit to these advances can result in greater phase stability, which is critical to impedance network transformers utilized for matching networks of power amplifiers. For power amplifiers, the shift in dielectric properties with temperature increases reflections and directly reduces efficiency. For antenna designs, a significant shift in resonance frequency and bandwidth roll off at specific frequencies, results in lower gain performance. The resulting combination of new materials with better heat transfer and better thermal stability of the dielectric results in devices that operate more efficiently and more reliably over time. Applications and test data have shown the benefit of increased board thermal conductivity on reducing the maximum case temperature of the RF power amplifier FET transistors, as demonstrated by the hot spot thermal images of experimental boards with different thermal conductivity properties. TDR (time-domain reflectometer) tests have also shown that the temperature stability of dielectric constant in RF/Microwave laminates provides greater stability of electrical phase or electrical length in high frequency circuit elements that phase shifts greatly affect the performance, such as the impedance matching networks in power amplifiers.

Index Terms — High frequency laminates, Power amplifiers, Impedance matching networks, Thermal conductivity, Phase stability, Dielectric thermal stability, Efficiency and reliability

Introduction

Trends in the electronic industry continue to drive materials to satisfy higher power and higher thermal stability requirements [1-4]. Customers have highlighted the "Arrhenius Equation" in which a 10°C increase in temperature typically doubles component failure rate (see Figure 1). In other words, get the heat away from components, reduce or eliminate hot-spots, reduce overall device operating temperature and increase product life.

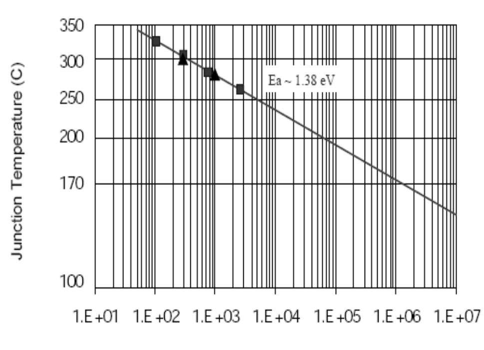

Figure 1 Arrhenius Chart Junction Temperature Failure Rate

Many techniques have been developed to improve heat rejection in electronics, including engineered heat sinks, thermal interface materials and whole subsystems (cooling fans and heat pipes). This pursuit has extended to RF and microwave circuit board substrate materials. Innovations focused on increasing thermal conductivity (TC) while maintaining low loss are being introduced in the industry.

Increasing the thermal conductivity of the laminate allows heat to flow away from temperature sensitive devices and solder joints, minimizing maximum temperatures seen at junctions. This increases component and solder joint reliability. It reduces work hardening and minimizes thermal excursion caused by the thermal coefficient of expansion.

Selection of the proper engineered ceramics can benefit the microwave laminate by providing greater phase stability across temperature excursions. Phase stable ceramics can dampen the temperature sensitivity of the low loss PTFE (i.e. Polytetrafluoroethylene or Teflon) resin used in microwave laminates. This allows designers to minimize dead bandwidth which is lost to dielectric constant drift as operating temperature changes. For antenna designs, a significant shift in resonance frequency and bandwidth roll off at specific frequencies, results in lower gain performance Thermal stability feature is critical to phase sensitive devices such as impedance network transformers utilized for matching networks of power amplifiers.

Microwave Substrate Materials

A. PTFE-type laminates

In RF and Microwave applications, which includes antennas, components, power amplifiers and high power RF transmitter networks, low loss and low variance in dielectric constant are at a premium. Materials which offer these properties were traditionally low dielectric constant composites comprising PTFE, or more recently, other low loss thermoset polymers.

Traditional low loss composites are commercially available and include both woven and non-woven fiberglass reinforced PTFE. Non-woven fiberglass reinforced PTFE are available in a limited range of dielectric constant (DK), from approximately 2.2 to 2.33. Woven fiberglass reinforced PTFE is available in a much wider range of relative contents and so are available in a wider range of dielectric constant values. These start at about 2.2 and range to greater than 3.0. There are tradeoffs between properties, and as PTFE content is reduced, laminate cost decreases and mechanical strength increases. A negative association is that loss tangent also increases as shown in Figure 2 for the results at 10 GHz.

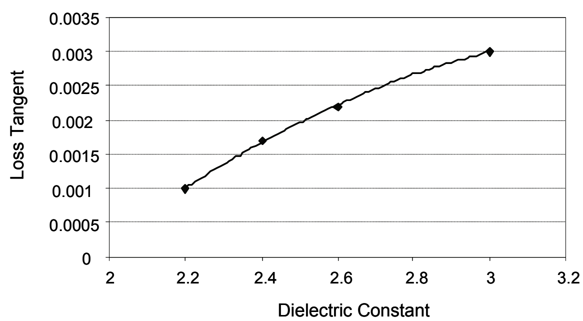

Figure 2. Loss Tangent vs. Dielectric Constant for PTFE/Glass Laminates at 10 GHz

From a design perspective, the primary sources of loss in laminate performance are the dielectric loss (i.e. loss tangent or dissipation factor) and the conductor loss. Thus, choice of cladding is another important consideration for selection of board materials in RF designs. Differences in copper grain structure matter, especially for higher frequency applications. Conductor loss increases with conductor surface roughness. Smoother copper foils and often heavier cladding is chosen to help reduce heat generated from this loss and manage heat dissipation.

B. Ceramic filled materials

A variety of ceramic fillers were introduced to manipulate dielectric constant in PTFE-based microwave materials. This expanded the range of RF laminate dielectric constant to 10.2 and higher. With innovatively engineering the ceramic fillers, ceramic-filled PTFE-based substrates can also achieve low loss tangent which changes the trend shown in Figure 2, and thus lower signal distortion and loss to heat for these microwave laminates, such as a dissipation factor of 0.0020 at 10 GHz for the DK3.5 and DK6.15 laminates discussed in this paper. Several other benefits are noted in this discussion; they relate to a substrate's thermal conductivity and its ability to improve heat rejection, as well as thermal stability of substrate's dielectric constant (i.e. TCEr, thermal coefficient of dielectric constant) and thermal expansion (i.e. CTE) which will be discussed as follows.

Increased Thermal Conductivity

A. Sources of heat

While this paper discusses RF and microwave materials for use as printed circuit board substrates, it is useful to consider the prevalent heat sources common to these applications. Some heat sources are extrinsic; mounted active components (see Figure 3) are supplied with power and generate heat regardless material on which they are mounted. As well known, an important, figure-of-merit measure for RF power amplifier's efficiency is called power-added efficiency (PAE or η_{PAE}), which is defined as the efficiency of the RF power amplifier (PA) to convert the input DC power (or DC driving power) to the wanted contribution in the RF output power as shown in equation (1).

$$\eta_{PAE} = \frac{P_{RF\_Out} - P_{RF\_In}}{P_{DC}} \times 100\% \qquad (1)$$

where,

P_{DC} = the DC input power (or driving power);

P_{RF_In} = the RF input power to PA;

P_{RF_Out} = the RF output power from PA.

So it readily obtains how much of the heat (P_{Diss}), which is the amount of DC power not converted to the useful RF power, needs to be dissipated from the RF power amplifier (see equation (2).

$$P_{Diss} = P_{DC} - \left(P_{RF\_Out} - P_{RF\_In}\right) = P_{DC}\left(1 - \eta_{PAE}\right) \qquad (2)$$

With typical RF and microwave high power amplifiers, their PAE's are in the range of 15-55%. There is a tremendous amount of heat generated from RF signal amplification and need to be removed from the PA transistors for continuous operation of the amplifiers and associated systems.

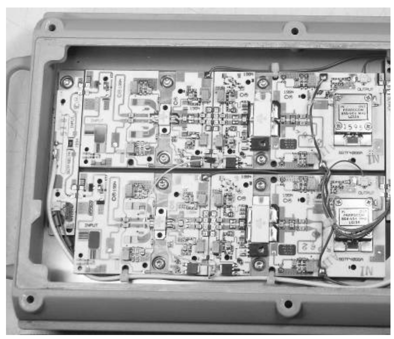

Figure 3. A Microwave Power Amplifier Board

Intrinsic sources of heat include dielectric and conductor losses. Especially as higher frequency applications are considered, board materials which offer lower electrical loss reduce heat generation in passive components like couplers, filters and feed networks, as well as in power amplifiers. Meanwhile, the low-loss board materials if also possessing higher thermal conductivity would help dissipate the heat more efficiently from the "hot" spots on the boards or from the systems and thus, improve system performance, efficiency and reliability. A study using thermal monitoring on the AlGaN/GaN high power HFET transistors for the relationship of the peak surface temperature to the PAE at different heat dissipation power levels (P_{Diss}) has revealed that there is a strong link between the magnitude of the thermal effects and the device efficiency [5]. It shows that when the PAE decreases, the peak surface temperature increases dramatically and vice versa.

B. Increased substrate thermal conductivity

Conventional RF substrate materials having a thermal conductivity (TC) of 0.2 to 0.25 W/m-K, and ceramic-filled products range from 0.4 to 0.6 W/m-K do not provide enough heat removal and heat spreading capacity to high frequency, high power applications. Materials that pull heat away from the active components, through either the x/y-direction (heat spreading) or in the z-direction (typically to a heat sink), help reduce the maximum temperature seen on the board, especially around the power amplifiers. Figure 4 shows the heat spreading and heat reduction properties of a high TC laminate of 6.15 DK (TC = 1.1 W/m-K) compared to a conventional 6.15DK laminate (TC = 0.46 W/m-K), with which the same RF power FET transistors were mounted and operated on the same board design except for the difference of substrate thermal conductivity. It shows that the increase of thermal conductivity of the specially engineered, ceramic-filled high TC substrate reduced the maximum temperature from 82°C to 73°C on the FET's case and 78°C to 72°C at board bottom side.

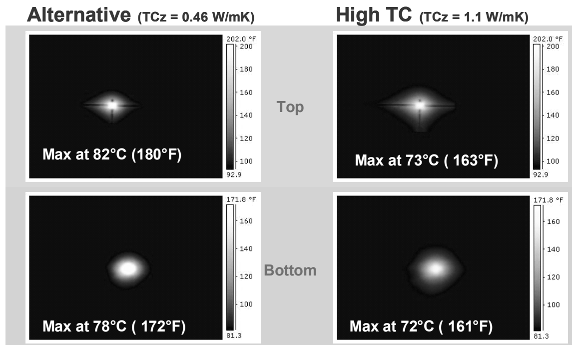

Figure 4. Thermal Images of Heat Dissipation around RF Power FET Transistors and Associated Max Temperature Reduction due to Higher Thermal Conductivity

Figure 5 shows the 8°C reduction in maximum temperature seen at the components by moving from a 0.35 W/m-K material to a 1.03 W/m-K material in the substrates of 3.50 dielectric constant range. These are two 47Ω power resistors connected in series under the same DC power conditions on different board materials of the same DK and thickness but different TC values. The heat spreading properties of the material can also visualized by the larger area of temperatures above 30°C thus reducing the severity of the temperature gradient within the circuit board. As shown in Table 1, the high TC 3.5DK laminate which is also a ceramic-filled PTFE-based substrate spreads the heat about 40% more areas across the board compared to the 3.5Dk laminate with the lowest TC under test.

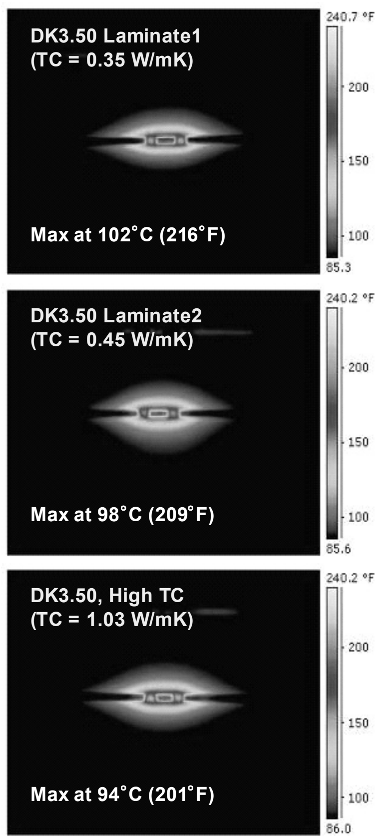

Figure 5. Thermal Images of Heat Dissipation around RF Power Resistors and Max Temperature Reduction due to Higher Thermal Conductivity at 3.5 DK

Table 1. Comparison of Heat Spreading Effects among 3.5DK Boards

RF Materials	TC (W/m-K)	Area > 30°C (86°F)
DK3.50 Laminate1	0.35	1.00
DK3.50 Laminate2	0.45	1.34
DK3.50 High TC	1.03	1.42

For RF power amplifiers, the desired gain, efficiency and linearity of power transistors will decrease when the junction temperatures in the transistor increase, since the higher temperature results in lower electron mobility in the p-n junctions or field junctions. It is evident that for the AlGaN/GaN power HFET transistors, if not properly designed for thermal dissipation they may result in high channel temperature and reduced device performance due to self-heating effects [6]. The material with higher thermal conductivity, such as the high TC laminates aforementioned, pulls the heat away from the "hot" spot as in the AlGaN/GaN power HFETs and allows it to be more efficiently dissipated. The reduced maximum temperature seen on the board keeps active devices, such as power amplifiers and transistors, operate at favorably lower temperature for higher efficiency with improved operating reliability and phase stability, and also helps reduce the maximum temperatures seen at solder joints or at plated through-holes (PTH), which are other areas critical for failure and fatigue due to thermal expansion behaviors closely following the maximum temperatures.

Reduced Thermal Expansion

Higher thermal conductivity reduces average temperature for the circuit board and its mounted components. In this example, any mismatch in expansion coefficients between the substrate and the components is mitigated. There is an additional benefit realized through these formulations. Use of ceramic fillers which promote thermal conductivity also typically reduces thermal expansion. Coefficients of thermal expansion in all three axes affect reliability of assembled printed circuit boards. Low substrate CTE, or even better in-plane CTE match, reduces stress on soldered joints to ceramic-based components. Maintaining lower temperature and lower z axis CTE improves plated through-hole reliability.

Figure 6 shows the z-direction expansion as a function of temperature for three types of PCB board materials – typical FR-4, traditional PTFE/Glass laminates and high TC laminates, while the high TC laminates have superior thermal expansion properties.

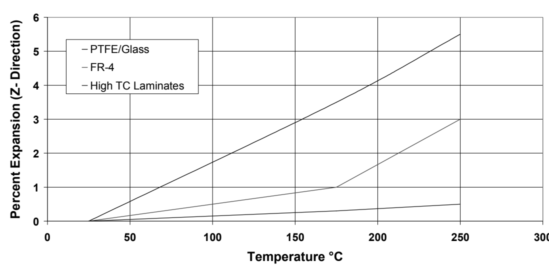

Figure 6. Expansion as a Function of Temperature

Many applications require not only mechanical reliability; they also require phase and impedance stability. Reduced temperature ranges and low expansion coefficients also help this effort to maintain electrical performance throughout operating conditions. Electrical length is critical for transmission lines and phase-matched components. Consistent line length is a function of conductor thermal expansion and dielectric constant thermal stability. Similarly, board height differences, which result from z-direction thermal expansion, can affect characteristic impedances in stripline and microstrip lines, and also change phase angle in microstrip because of the effects on effective dielectric constant.

Dielectric Constant Thermal Stability

For RF circuits, improved dielectric temperature stability directly translates into impedance and phase/frequency stability over temperature, with the benefits of reducing impedance mismatches around active components (such as power amplifier transistors), lowering device frequency/phase shift, reducing system bandwidth roll off and drift in "heated" operations, and thus improves efficiency and performance. Certain ceramic fillers in certain RF substrate materials promote both reduced thermal expansion and reduced dielectric constant change with temperature. As with thermal expansion, thermal conductivity is doubly beneficial in this aspect. As discussed in the last subject, phase stability or electrical length is affected by changes to mechanical length of transmission lines. Changes to dielectric constant also have strong influence. Thermally conductive substrates already reduce the operational temperature range. Use of substrates additionally designed for temperature stable dielectric constant assures phase stability throughout the temperature range.

Figure 7 shows the comparison of dielectric constant stability over temperature for typical FR-4, traditional PTFE/Glass laminates and DK3.5 high TC laminate. Using specialized ceramic filler choices in the DK3.5 high TC laminate not only leads to increased thermal conductivity (TC = 1.03 W/m-K), but also more sophisticated properties such as temperature stable dielectric constant (TCEr = -9 ppm/°C) and low thermal expansion (CTEx,y = 8 ppm/°C, CTEz = 17 ppm/°C).

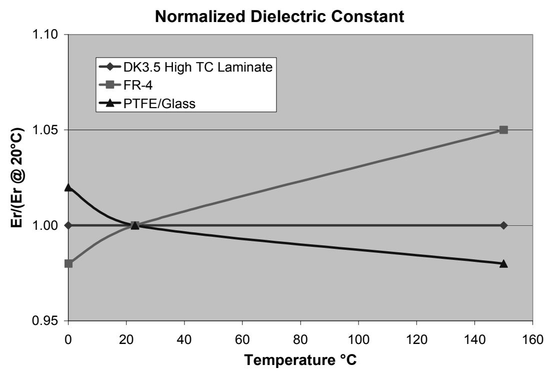

Figure 7. Change in Dielectric Constant over Temperature

Electrical Phase Stability

Thermal stable dielectric constant is very important for RF systems to avoid phase and frequency stability issue over temperature, especially in critical operations and wider temperature swings. As circuits are designed around a specific frequency, so physical circuit elements are designed around specific electrical lengths; these are measured by phase angle. Where temperature affects dielectric constant and mechanical dimensions, phase angle values of the circuit elements are also affected. The relationship between frequency or phase stability and dielectric constant drift can be illustrated in the following equations (where x represents the small change of DK or ε_r due to varying TCEr and CTE, while l is physical length of circuit elements and λ is the wavelength; c_0 and v_p are the wave phase velocity in vacuum and dielectric medium, respectively). Approximately, frequency or phase shift over temperature swing is close to half of the amount of DK drift or change, while it is readily to obtain that change of physical length affect frequency and phase stability in a 1:1 ratio.

$$\text{Frequency} \quad f = \frac{v_p}{\lambda} = \frac{c_0}{\lambda\sqrt{\varepsilon_r}} \tag{3}$$

$$\text{Phase} \quad \phi = \frac{l}{\lambda}\cdot 2\pi = \frac{2\pi\cdot f\cdot l\cdot\sqrt{\varepsilon_r}}{c_0} \tag{4}$$

$$\sqrt{1+x} \approx 1+\frac{x}{2} \qquad \frac{1}{\sqrt{1+x}} \approx 1-\frac{x}{2} \qquad \text{if } |x| << 1$$

$$\text{when } \varepsilon_r^{'} = (1+x)\cdot\varepsilon_r$$

$$f^{'} = \frac{1}{\sqrt{1+x}}\cdot f \approx \left(1-\frac{x}{2}\right)\cdot f \tag{5}$$

$$\phi^{'} = \sqrt{1+x}\cdot\phi \approx \left(1+\frac{x}{2}\right)\cdot\phi \tag{6}$$

Impedance Transformers are designed to provide a capacitive or inductive transformation to provide a better match with an active device in a desired bandwidth (see Figure 8). Optimization and trade-offs are made across the circuit frequency range to provide the best possible broadband performance. When the transformer's phase changes, it can be viewed as the transformation of rolling around a circle on the Smith Chart with different rotation of degrees of phase angle. This will result in a less than ideal impedance transformation and even a non-matched circuit. Signal integrity is also sacrificed as more signals are reflected. This results in lower gain (S21) and higher amounts of reflected energy and higher return loss (S11).

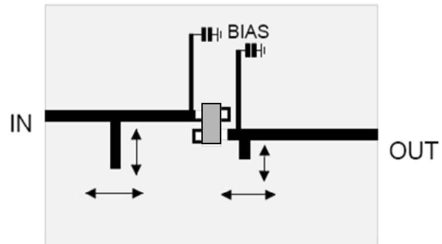

Figure 8. Power Amplifier Impedance Matching Networks

Selection of a material that is relatively insensitive to temperature provides a high degree of phase stability to the impedance matching networks, Wilkinson power dividers, quarter wave transformers, and etc. It also minimizes impedance changes in a transmission line when it is exposed to a changing temperature. Figure 9 shows how a standard RF material with a relatively high TCEr value responds to being heated. This is a TDR (time domain reflectometry) plot for impedance vs. time (or distance). The microstrip transmission line was exposed to 125°C source in the center of the board. As a result of the heat exposure, the dielectric constant was locally reduced and created an area of higher impedance (1.135 ohms higher). It also shorted the 5.8 nsec electrical length by 17.68 psec (see Figure 10).

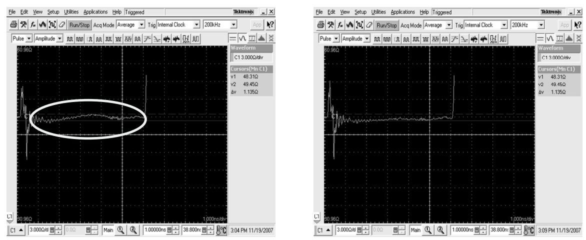

Figure 9. Transmission Line exposed to 125°C increases 1.135 ohms and Transmission Line after 5 minutes of Cooling

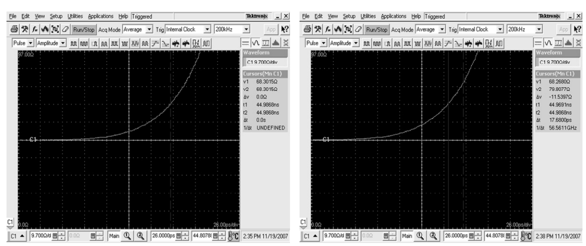

Figure 10. Electrical Length Before Heat Exposure and Electrical Length After Heat Exposure (17.68 psec shorter)

Conclusion

Thermally conductive substrates offer a wide variety of advantages over more traditional materials available for use as printed circuit board substrates. The obvious advantage of improved heat rejection is realized, increasing component life for active components which are sensitive to temperature. Other attendant advantages include component attachment and mechanical reliability for the assembled board and better electrical performance throughout the operating conditions.

Ironically, both performance requirements and cost sensitivity push power density and operating temperature limits. These technologies place a high demand on heat rejection to ensure component life and attachment reliability. This is particularly true where passive cooling is desired from cost, reliability, maintenance and size perspectives. Engineering focus for higher power designs has brought innovation and advancement to materials, such as Arlon's TC600 and TC350 substrates, which offer: low CTE (lower CTE offers better component attachment), low loss tangent (electrical loss creates additional heat) and high thermal conductivity (improved heat dissipation).

An additional benefit of higher thermal conductivity laminates can result in improved phase stability over temperature, provided the proper choice of ceramic fillers. The proper combination of ceramics not only increases thermal conductivity, but, it also dampens the dielectric constant changes due to both the density and mechanical changes when exposed to extremes of heat. For most electronics, this at least means extremes from ambient 21°C to operating temperatures of 125°C. For space, military or avionics applications, this range can easily expand to a -55°C to 150°C and beyond.

RF materials had traditionally been thermal insulators; finding the optimal balance of material properties is critical for device reliability, cost and performance.

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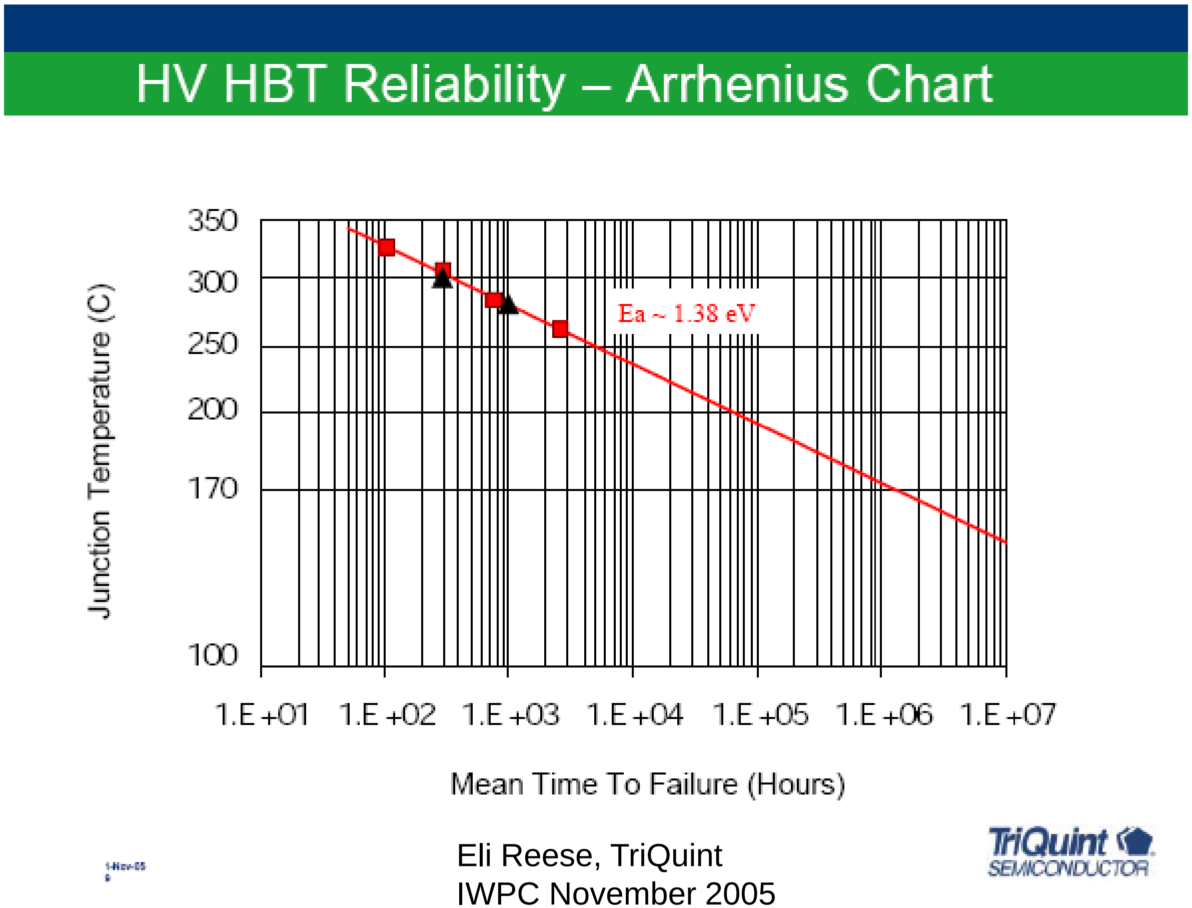
Arlon, Inc.,
Materials for Electronics Division,
1100 Governor Lea Road, Bear, DE 19701, USA

Agenda

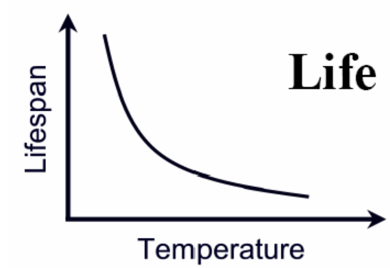
- Importance of Thermal Management
- Substrate Materials for RF and Microwave Applications
- Increased Thermal Conductivity and Product Reliability
- Benefits of Reduced Thermal Expansion
- Dielectric Constant Thermal Stability
- Electrical Phase and Frequency Stability for Performance and Efficiency
- Conclusion

Why is Thermal Management Important?



Reliability of components follows a first order Arrhenius equation:

10° C increase doubles failure rate



Even 1° C matters

Thermal Management Challenges

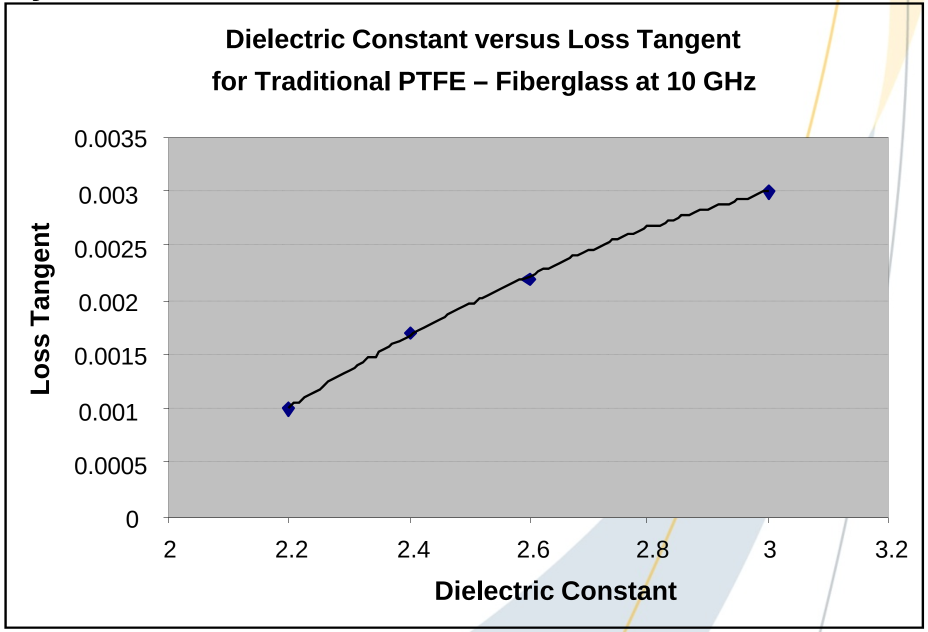
- Power density continues to increase
- Packaging getting smaller & hotter
- Higher temperatures reduce component reliability
- Tower mounted & outdoor electronics increase environmental exposure while requiring higher reliability
- Complex waveforms decrease amplifier efficiency, more energy lost to heat

Thermal Management Strategies

- **Removing the Heat** – focus on tools for increased heat dissipation, such as increased PCB thermal conductivity
- **Beating the Heat** – focus on materials and components that are tolerant of higher operating temperatures
- **Surviving the Environment** – requires an understanding of operating environment and a focus on materials tolerant of thermal cycling
- **Reducing the Heat** – uses higher efficiency, lower power or lower loss materials to reduce heat generation

RF and Microwave Laminates

- **PTFE-based Laminates**
  - Low loss and high performance
  - Woven and non-woven fiberglass enforced
  - Relatively high thermal expansion and TCEr
- **Thermoset Material**
  - Low cost and easy to fabricate PCB boards
  - Higher loss compared to PTFE materials
  - Thermal aging, stability and reliability issues
- **Ceramic-filled Materials**
  - Increase dielectric constant
  - Low loss tangent
  - Thermal conductivity
  - Thermal expansion
  - Thermal stability of TCEr



TC for Common RF Substrates

Substrate	TC (W/m-K)
Typical PTFE/Glass	0.2 – 0.3
Normal Ceramic Filled PTFE/Glass or Thermoset	0.3 – 0.6
High TC Laminates	**1.0 – 1.4**
LTCC (Low Temperature Co-fired Ceramics)	2.0 – 3.0

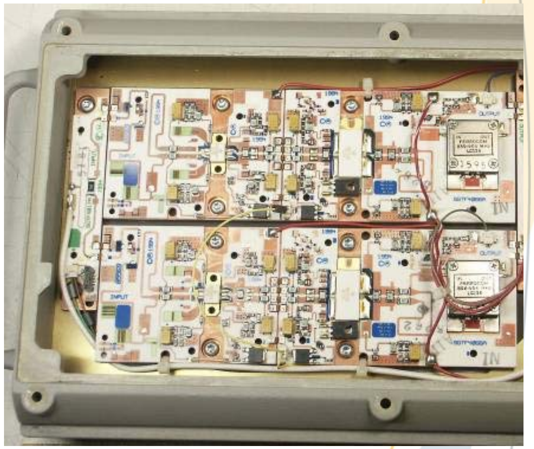
Benefits of Laminate Thermal Conductivity

- Component and Solder Joint Reliability improvements would drive down warranty costs
- At constant heat rise, the improvement in heat transfer can be used to increase power handling 5-30%
- Thermal Stability of Dielectric Constant (i.e. low TCEr) reduces *"Dead Bandwidth"*, increases phase stability, power efficiency and performance over temperature, reduces design limits & complexity
- Compliments all other alternative sources of thermal heat extraction …. ***Doesn't cost you anything!!!***
- Or potentially simplifies or lowers costs of other thermal solutions ***(i.e. cast vs. machined heat sinks, reduction in copper plate thickness from 3mm to 1mm lowers weight and cost.)***
- Ultimately increase the MTBF figure for electronics, and thus improve product reliability.

Sources of Heat

- **Extrinsic Heat** – Active Components, such as RF Power Amplifiers

$$\eta_{PAE} = \frac{P_{RF\_Out} - P_{RF\_In}}{P_{DC}} \times 100\%$$



$$P_{Diss} = P_{DC} - \left(P_{RF\_Out} - P_{RF\_In}\right) = P_{DC}\left(1 - \eta_{PAE}\right)$$

- **Intrinsic Heat** – Dielectric and Conductor Losses

$$\alpha = \alpha_c + \alpha_d$$

Example – RF Power Amplifier

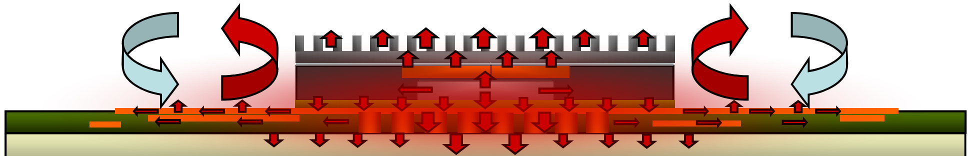
20dB gain, 43dBm (20W) output @1.6GHz with PAE ~35%

RFin = 43dBm-20dB = 23dBm = 200mW (i.e. 1W=30dBm)

RFout-RFin = 20W-200mW = 19.8 W (added RF power)

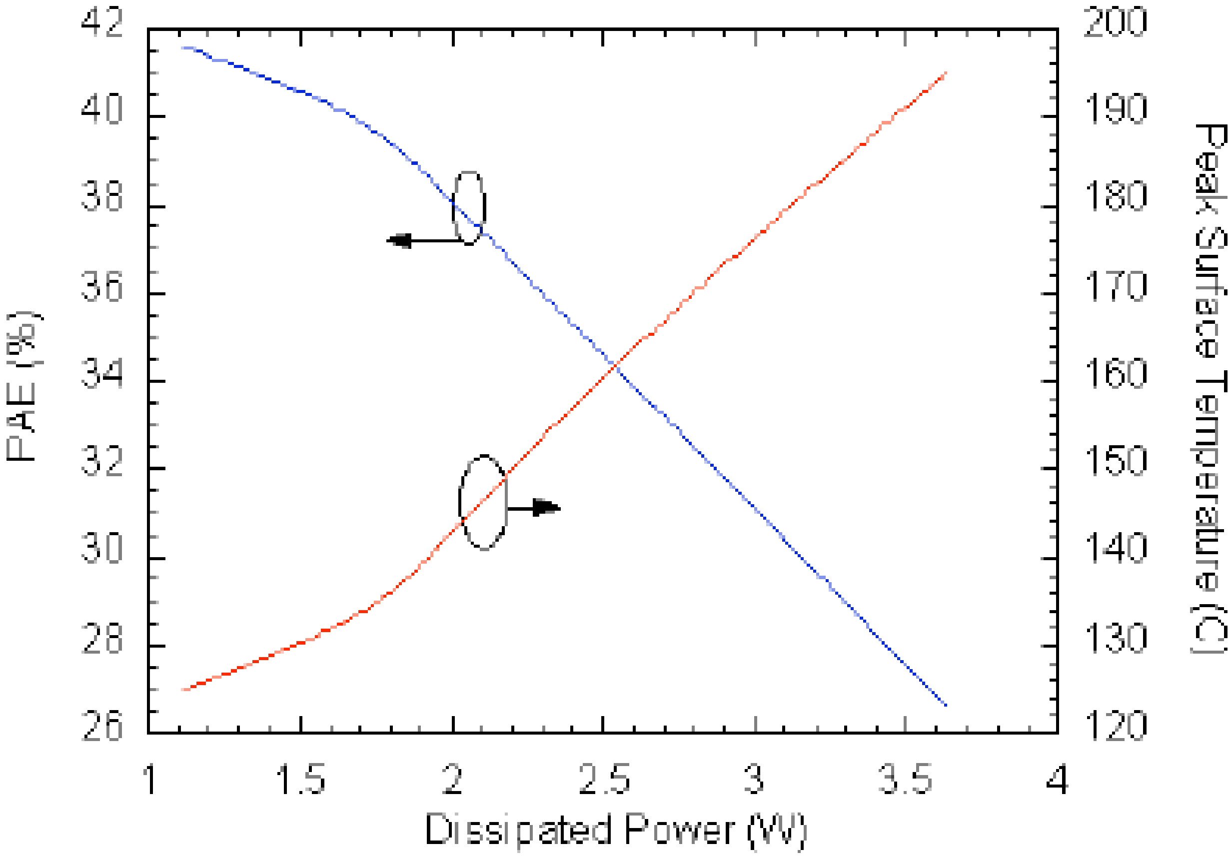
DC Power = (RFout-RFin)/PAE = 19.8/0.35 = 56.6 W

Heat = 56.6-19.8 = 36.8 W



Thermal Management ISSUE

Power Transistors P.A.E. vs. Temperature



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Thermal Testing - MOSFET Transistors

Alternative (TCz = 0.46 W/mK)

High TC (TCz = 1.1 W/mK)

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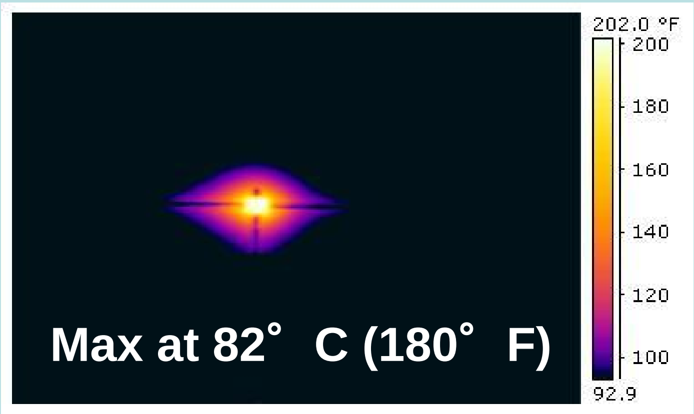
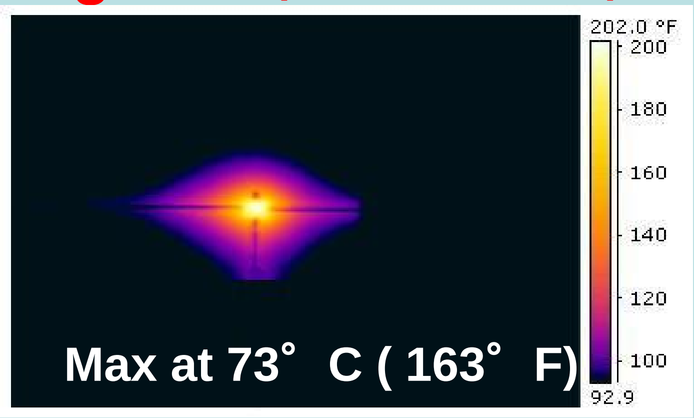
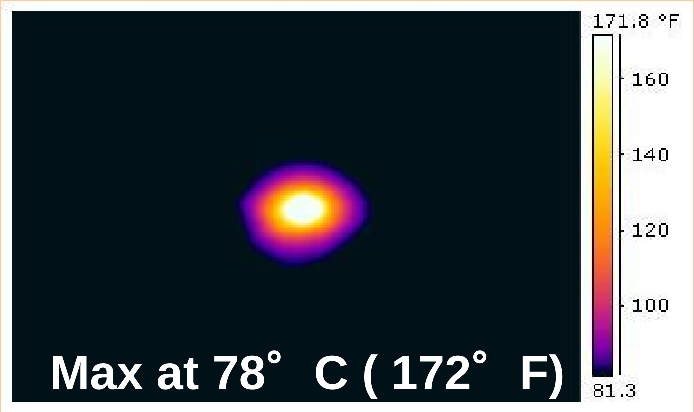
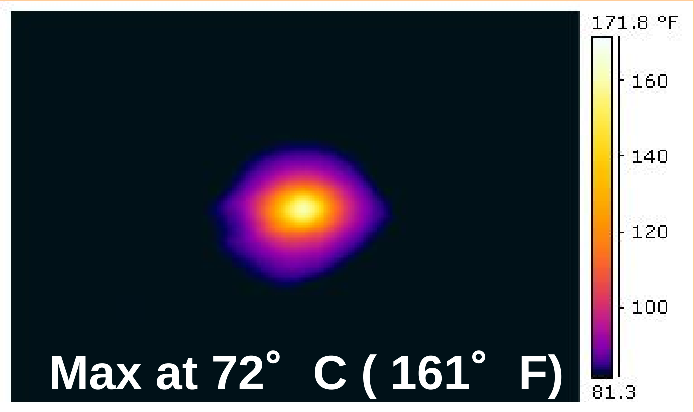


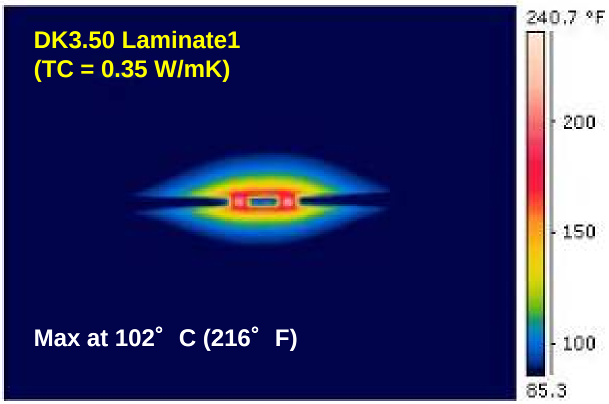


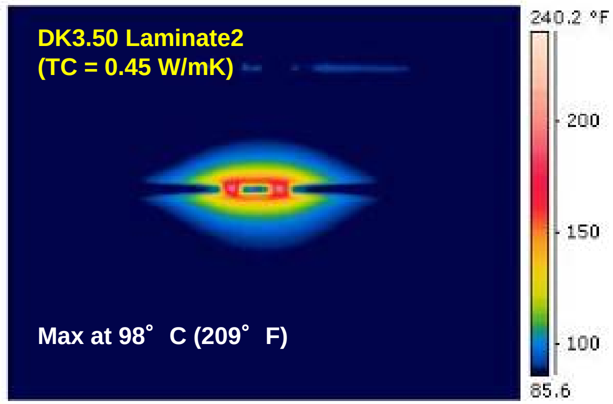
Bottom

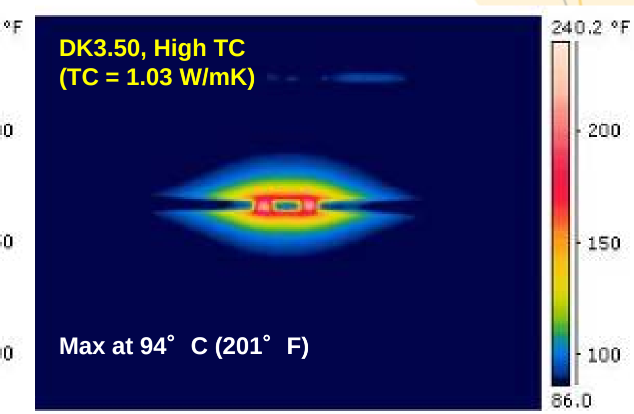




Thermal Testing - Power Resistors

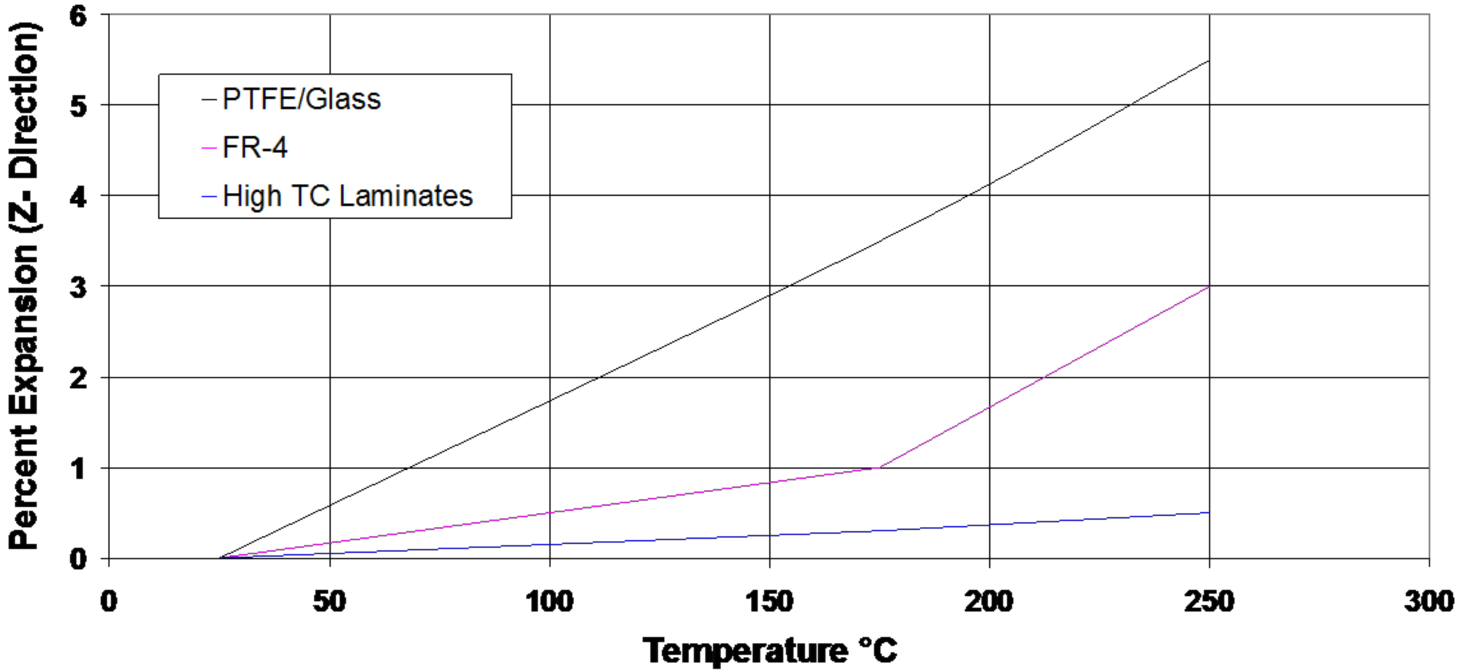






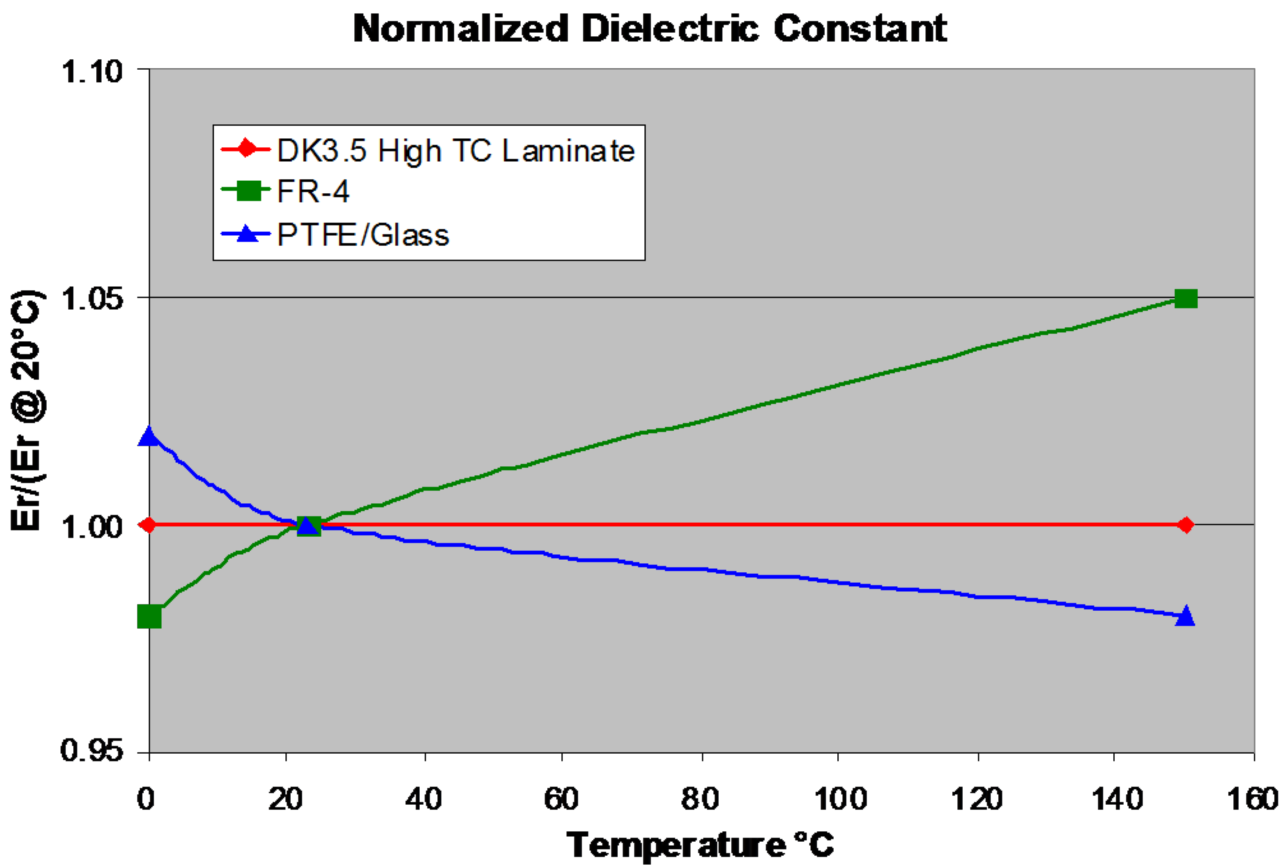
RF Materials	TC (W/m-K)	Area > 30° C (86° F)
DK3.50 Laminate1	0.35	1.00
DK3.50 Laminate2	0.45	1.34
DK3.50 High TC	**1.03**	**1.42**

Reduced Thermal Expansion



- PTH reliability
- Impedance control
- Phase and frequency stability

Dielectric Constant Thermal Stability



- **Impedance control**
- **Phase and frequency stability**
- **System performance, efficiency and reliability**

Temperature Sensitivity of Phase/Frequency

Frequency $f = \frac{v_p}{\lambda} = \frac{c_0}{\lambda\sqrt{\varepsilon_r}}$

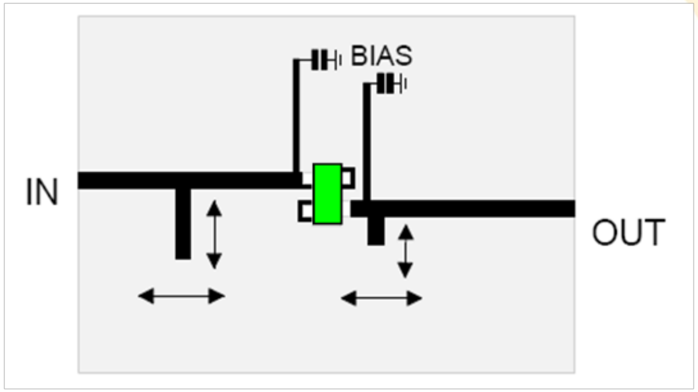
Phase $\phi = \frac{l}{\lambda} \cdot 2\pi = \frac{2\pi \cdot f \cdot l \cdot \sqrt{\varepsilon_r}}{c_0}$

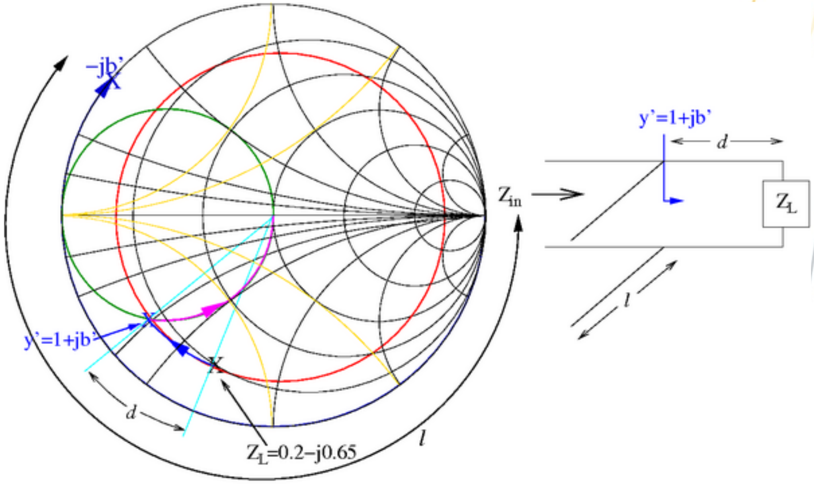
$\sqrt{1+x} \approx 1 + \frac{x}{2}$ $\frac{1}{\sqrt{1+x}} \approx 1 - \frac{x}{2}$ if $|x| << 1$

when $\varepsilon_r^{'} = (1+x) \cdot \varepsilon_r$

$$f^{'} = \frac{1}{\sqrt{1+x}} \cdot f \approx \left(1 - \frac{x}{2}\right) \cdot f$$

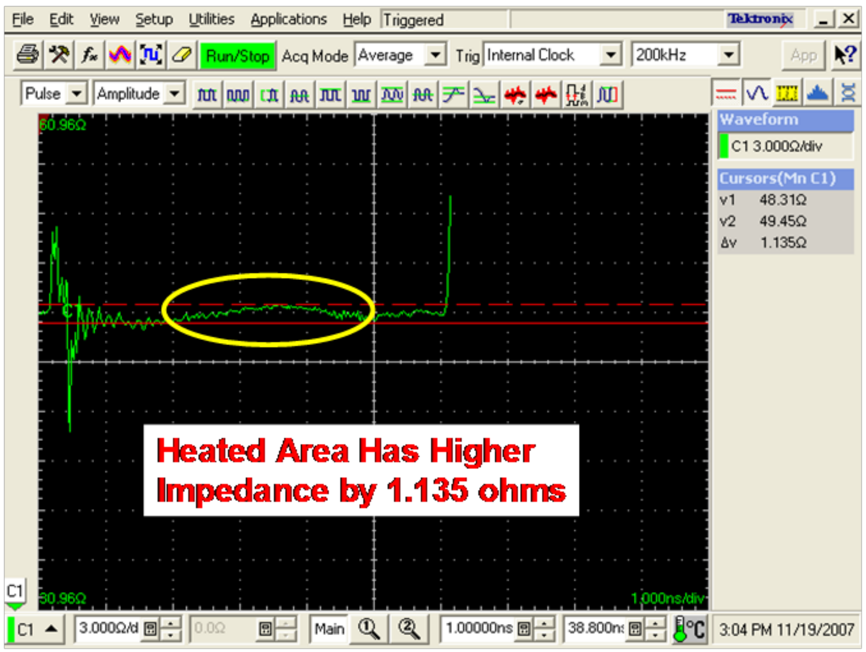
$$\phi^{'} = \sqrt{1+x} \cdot \phi \approx \left(1 + \frac{x}{2}\right) \cdot \phi$$



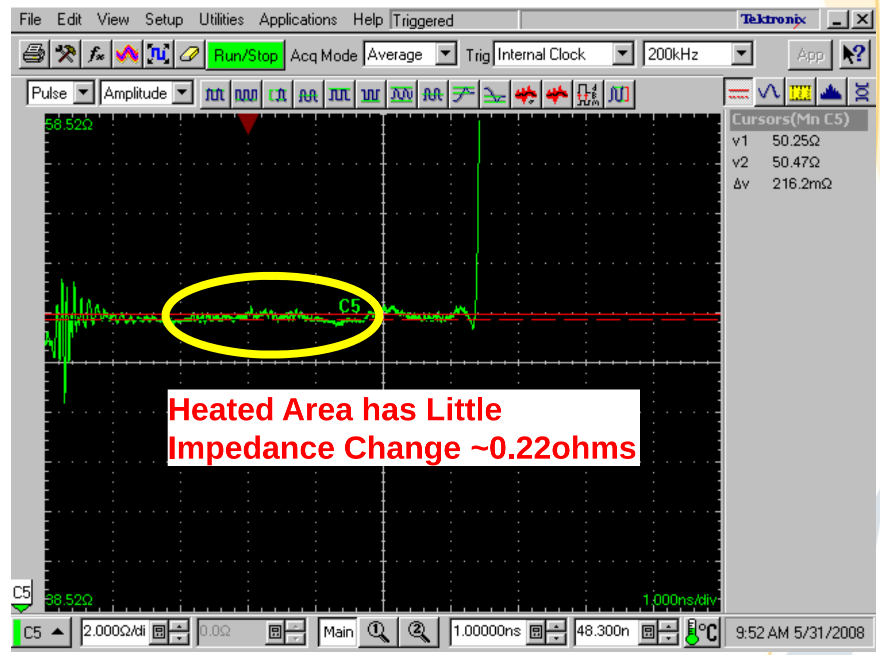


Impedance Change due to Temperature

TDR (Time Domain Reflectometer) Results:

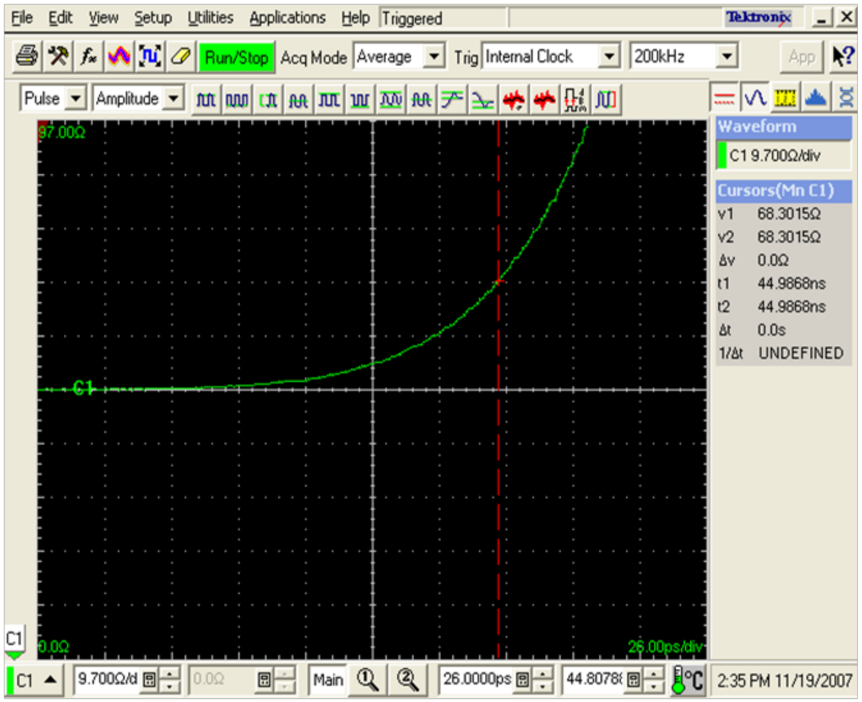


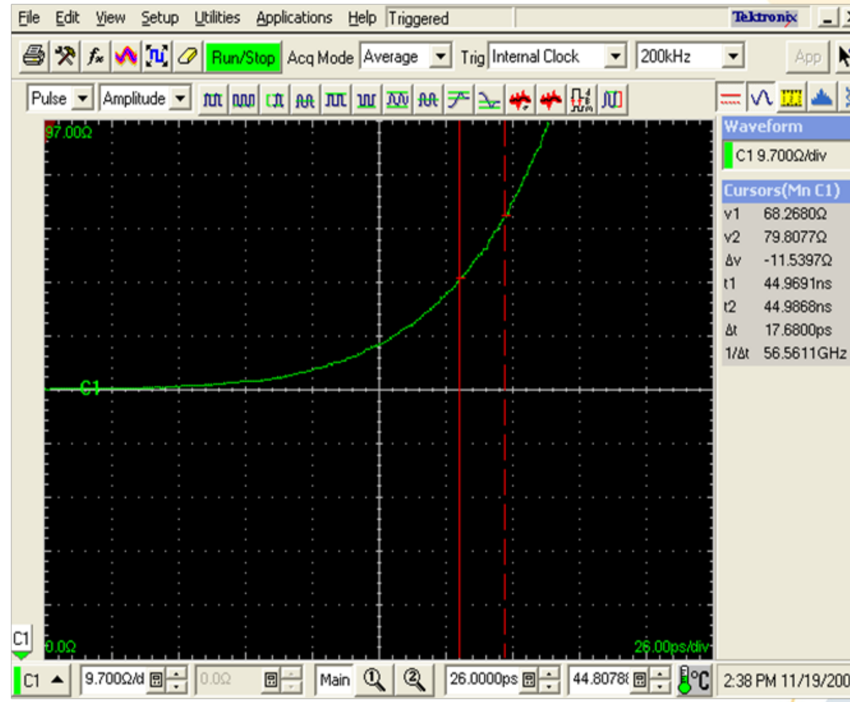
Temperature Effects on Impedance of a Standard **-150 ppm/° C** DK3.5 Material **at 125° C**



Temperature Effects on Impedance of **High TC** DK3.5 Laminate (-9 ppm/° C) **at 125° C**

Phase Angle Change due to Temperature





Electrical Length Before Heat Exposure and Electrical Length After Heat Exposure at 125° C (with 17.68 psec shorter in 5.80 nsec microstrip line on the Standard laminate)

Key Properties for High TC Laminates

Key Properties	DK3.50 High TC	DK6.15 High TC
Dk (@ 10 GHz)	**3.50**	**6.15**
Df (@ 10 GHz)	**0.0020**	**0.0020**
Df (@ 1.8 GHz via Circular Cavity)	**0.0018**	**-**
TCEr (*ppm/° C*)	**-9**	**-75**
Thermal Conductivity (*W/mK*)	**1.0**	**1.1***
CTEx,y (*ppm/° C*)	**7**	**9**
CTEz (*ppm/° C*)	**23**	**35**
Copper Peel (*lbs/in*)	**7**	**8**
Moisture Absorption(%)	**0.05**	**0.02**

* For DK6.15, TCz is 1.1W/mK and TCx,y is 1.4 W/mK.

Conclusion

- Thermally conductive substrates offer a wide variety of advantages over traditional materials available for RF and microwave applications, such as better heat dissipation, product reliability and efficiency.
- Arlon’s TC600 and TC350 substrates offer: a) low CTE for better component attachment and PTH reliability; b) low loss tangent for less additional heat; and c) high thermal conductivity for improved heat dissipation.
- High thermal conductivity laminates with reduced CTE and thermally stable dielectric constant TCEr can result in improved phase stability over temperature, thus improve system performance and efficiency.
- RF materials had traditionally been thermal insulators; finding the optimal balance of material properties is critical for device reliability, cost and performance.