

## ADVANCED MICROWAVE MATERIAL DEVELOPMENTS FOR ELECTRONICALLY STEERABLE PHASED ARRAY RADARS

*Russell R. Hornung, John C. Frankosky, Alain Desire*

Arlon, LLC. Materials for Electronics Division  
1100 Governor Lea Road, Bear, DE, 19701, USA  
phone: + (01) 302-834-2100, fax: + (01) 302-834-2940, web: www.arlon-med.com  
email: rhornung@arlon-med.com, jfrankosky@arlon-med.com, adesire.arlon@free.fr

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### ABSTRACT

*Due to the complex nature of electronically steerable phased arrays, higher operating frequencies, increased density requirements, and wider operating temperatures, there has been increased focus on technology development with thinner microwave laminate substrates to create a multi-layer boards that are phase stable with temperature and compatible with embedded resistors utilized for Wilkinson Power Dividers. These laminates can range from 0.003" to 0.010" in thickness with frequencies well into the Ka Band. This paper explores technical advances and technical considerations placed on these materials as they are required for these advanced systems. This paper also discusses the processing limitations placed on existing materials and technical developments to overcome these deficiencies.*

### 1. MICROWAVE MATERIAL TECHNICAL NEED

The latest generation of advanced radars incorporate an active-element, electronically scanned array utilizing transmit/receive modules [1]. These systems do not use a gimbal/motor to scan for threats and targets, as these mechanical systems often caused reliability issues under the severe operating conditions of the aircraft [2]. By moving to electronic arrays, these radars are capable of changing the direction, power, and shape of the radar beam. They also have significantly faster scan rates than older generation gimballed antennas, so they can acquire target data while minimizing the chance their radar signal is detected or tracked. Key to these designs is the manifold feed that distributes RF energy. To accomplish this functionality, it is critical that energy is distributed as designed and the same from system to system. It is also critical that the system performs the same, independent of the wide range of temperature (-55°C to 150°C) and humidity levels (0 to 100%) [3].

The fourth-generation fire control radars, such as the APG-63(V)2, APG-77, APG-79, APG-80, APG-81 are technical marvels that utilize an active electronically scanned array (AESA). The demands placed on these long-range sensors include offering all-weather, standoff target detection, and low probability of intercept. The APG-81 (F-35 Lightning) system is being designed for a longer lifespan, well over

8,000 hours with MTBF in excess of 500 hours. The functionality of the APG-81 array incorporates a wide variety of advanced technology to utilize both a synthetic aperture radar (SAR) terrain mapping function for air-to-surface surveillance and targeting and inverse SAR (ISAR) mode used to detect and identify sea vessels.

Space-based radars (SBR) and RADINT (Radar Intelligence) have undergone vast technology and program changes in the past 7 years. The restructuring of SBR in a joint DoD and intelligence community (IC) program in 2005, resulted in a name change to Space Radar (SR). These systems are very sensitive to both weight and temperature, and they require an even higher level of reliability because making repairs in space is both costly and difficult. Technologies deemed necessary for space radar have been advancing since the Discover II STARLITE radar program, such that active electronically scanned arrays and synthetic aperture radar are considered standard designs for SBR. Therefore, materials will need to be both reliable and high-performance so that very high-resolution elevation data and highly accurate radar imagery can be achieved under all temperature situations.

### 2. FEED NETWORKS & MANIFOLDS

Electronically steered radars are using techniques to feed vertical and horizontal matrices to electronically control or steer the radar system. These stripline matrices feed networks of antennas via power divider networks, enabling each antenna element to be fed with both a different amplitude and phase (see Figure 1). As a result, the design and performance of the large power divider network is critical to the beamforming [4] properties of the radar antenna. New solid-state surveillance radars have been designed to use both horizontal and vertical phase and amplitude feed arrays to provide beamforming matrices for stacked-beam 3-D operation, or are scanned electronically in elevation by phase shifters or frequency-scan networks (and sometimes both).

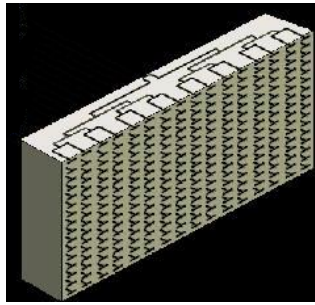


Figure 1 – Feed Network

### 3. LIMITATIONS OF PTFE ON MULTI-LAYER BOARDS

Polytetrafluoroethylene (PTFE) is a near ideal material for microwave circuit boards. It is recognized for providing outstanding electrical properties at high frequencies. It withstands both very high and very low temperature; it is chemically inert and resistant to UV radiation. Its dielectric constant and loss tangent are among the lowest values for solid materials.

However, difficulties with PTFE laminates arise in manufacturing multilayer boards. PTFE has a relatively high coefficient of thermal expansion (CTE). Electrically, fiberglass reinforced PTFE-based laminates such as Arlon DiClad 880 or CuClad 217, Taconic TLY-5, and Rogers RT/duroid 5880 provide extremely low loss characteristics. These laminates have very high amounts of PTFE and relatively low amounts of either woven fiberglass cloth or random glass fiber reinforcement.

PTFE is a relatively soft dielectric with a low bulk modulus. However, in-plane constraint from fiberglass reinforcement (either woven or nonwoven) forces thermal expansion to occur mostly in the z-axis. This characteristic affects plated through-hole (PTH) reliability. Typical z-direction CTE values for laminates described above are on the order of 200 ppm/°C; in comparison to copper PTH expansion of about 18 ppm/°C, this can result in less reliable multilayer boards.

For finished circuit boards exposed to wide temperature range cycling, plated through-holes are subject to tensile and compressive stresses, as the dielectric material expands and contracts at a significantly higher rate than copper. As temperature cycles continue, copper work hardens and eventually fails through fatigue in barrel cracking of plated through-holes.

Another characteristic that presents limitations in printed circuit design is dielectric constant change over their temperature (see Figure 2). While these PTFE-based composites are considerably better than epoxy resin-based counterparts, demanding microwave frequency applications often require absolute phase stability. As the dielectric constant of the substrate changes, electrical length of transmission elements changes, too, reducing efficiency.

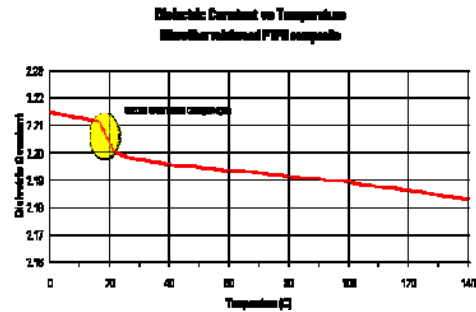


Figure 2: Dielectric constant temperature profile of PTFE composite

Many conventional PTFE-based substrate materials have a thermal coefficient of dielectric constant (TCER) on the order of -150 ppm/°C. It is interesting to note that the TCER is a negative number. For PTFE, as material expands, its density decreases, which helps explain this result. This is in contrast to TCER values for epoxy (FR-4)-based materials around +600 ppm/°C. Molecular interactions in epoxy resins contribute to its rising dielectric constant with temperature. These same interactions are also responsible for its higher electrical loss over all frequencies.

### 4. PTFE PHASE CHANGE (MOLECULAR STRUCTURE)

PTFE is well characterized and especially notorious for a second-order phase change that occurs at about 19°C. As temperature increases or decreases through this value, there is a second-order phase change to the PTFE molecule.

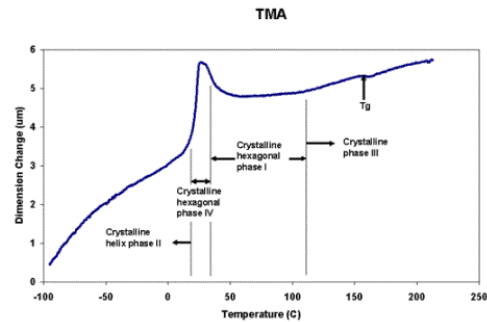


Figure 3: Phase order changes of PTFE

As temperature increases through 19°C, the helical structure of PTFE “relaxes” slightly and induces an abrupt volume expansion of about 1.5% (see Figure 3). This has implications to mechanical and electrical properties of the dielectric. Thermal expansion rates are higher at this temperature, affecting physical lengths and dimensional stability of circuits. The volume change to PTFE also sharply reduces dielectric constant.

## 5. ADDITION OF CERAMICS

Earlier, the mechanical considerations for conventional PTFE/fiberglass composite dielectrics were discussed. Among other considerations are changing electrical characteristics related to the second-order phase change of PTFE. As it applies to microwave printed circuit boards (PCBs), this is known to cause decreasing electrical length over temperature (phase shift). This change in the material is highlighted in Figure 3 at 19° C.

To mitigate both mechanical and electrical effects, laminate manufacturers have incorporated microdispersed ceramic in some newer PTFE-based laminates. This drives a significant reduction in z-axis expansion. With material expansion now on the same order as copper, PTH reliability is dramatically improved.

## 6. REDUCING TEMPERATURE COEFFICIENT OF DIELECTRIC CONSTANT

Products that employ the addition of phase stable ceramics to reduce "dielectric constant change with temperature" or  $TCE_r$  include Rogers RT/duroid® 6002, Arlon CL TE and now CLTE-XT. They were developed to provide consistent dielectric constant not only near the PTFE phase change but also throughout a much wider operating temperature range. In addition to dielectric constant stability, CLTE has a reputation for greater dimensional stability (registration), especially in thinner laminates. However, this stability has been at the expense of higher loss tangent than competitive products.

As circuits are redesigned 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.

Dielectric constant across temperature needs to be consistent to avoid phase stability issues. For antenna designs, a significant shift in Resonance Frequency and bandwidth roll off at specific frequencies, results in lower gain performance. 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, etc. It also minimizes impedance changes in a transmission line when it is exposed to a changing temperature. This can be seen in Figure 4, where the middle of a 50 ohm trace of a -75 PPM/°C board was exposed to a heat source of 125°C. At the location of the heat source, the impedance increased 1.135 ohms.

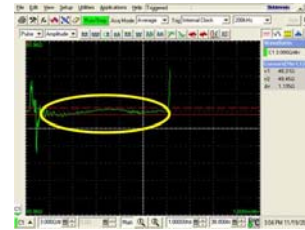


Figure 4. Transmission Line exposed to 125°C increases 1.135 ohms

It is interesting to note that PTFE-based laminates generally exhibit negative coefficients of dielectric constant change over temperature (as temperature increases, dielectric constant decreases). As dielectric constant increases, electrical length decreases. Thermomechanical expansion coefficients are typically positive and electrical length increases with mechanical length. For conventional materials described earlier, temperature dependent dielectric constant coefficients are large in comparison to their mechanical counterparts, so these competing influences on electrical length are only partially offsetting.

For ceramic-filled PTFE-based materials, temperature coefficients for both mechanical expansion (10-12 ppm/°C for CLTE) and dielectric constant (-13 ppm/°C) are relatively small. The opposite signs and similar scale of these coefficients promote mutually counteractive effects with regard to electrical length, and provide a substrate material that is stable both electrically and mechanically across temperature and frequency.

## 7. PERFORMANCE AS A FUNCTION OF DIELECTRIC CONSTANT TOLERANCE

A phase network is designed around an effective dielectric constant. Dielectric constant is a key criterion and is used to design quarter-wave transformers as well as power dividers. As with temperature-induced change, variation in dielectric constant affects not only insertion loss but also the phase of the signal. More energy is reflected (higher S11), less energy is transmitted (S21), and relative differences in phase are a result. Designers have focused on reducing or eliminating this variable from system performance because of the degree of impact it can have on a finished circuit. As a result, tighter tolerances are demanded of materials, because the materials continue to be a major contributor or driving force in the overall system performance.

## 8. DIELECTRIC CONSTANT VARIABILITY WITHIN THE SUBSTRATE

Circuits are also designed around specific impedance values; let us assume 50 ohms. When dielectric constant is not as expected, impedance is no longer 50 ohms. As dielectric constant increases, impedance decreases. As dielectric constant decreases, impedance increases. Transmission lines that vary more (see Trace A in Figure 5) will not perform as well as a lines that vary less (see Trace B), despite the fact that they have the same relative impedance. More energy will be re-

flected with Trace A, resulting in higher S11 (reflected energy) and lower S21 values (through energy). Variation in line width (etching) is a contributor, but in this paper we will view it as a non-variable, to simplify the discussion. Thus, materials that have significant within-panel variability become troublesome in high-performance RF and microwave circuit designs.

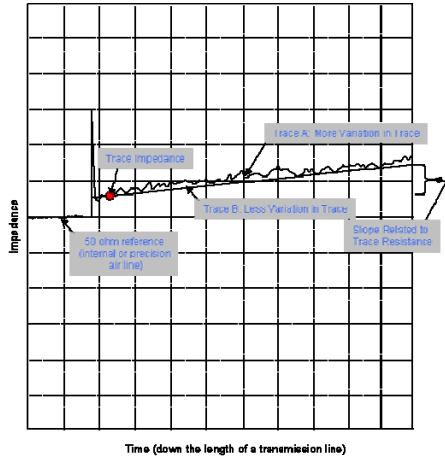


Figure 5: TDR trace of down-length impedance variability

Within-panel variability may not be a major factor on raw laminates before they are processed. If the material contains microvoids or is prone to absorbing low-surface-tension liquids, such as alcohol (which is used as a neutralizer after sodium etch surface treatment), an unpredictable event can occur. The alcohol can pull along board processing chemistry that remains in the board, even after drying. This could be a contributing factor to dielectric constant variability within a panel that is not present before processing, which is very difficult to predict and even more difficult to identify.

**9. MOISTURE INGRESSION AND PROCESSING CHEMICAL ABSORPTION**

The lowest-loss-tangent materials do not always make ideal laminates, because processing and fabrication can influence laminate performance in ways that would not be reflected in loss tangent measurements associated with standard IPC test methods. Moisture and processing chemical absorption play a critical role in insertion loss. A material that is viewed as low loss because of a low loss tangent may in fact have issues with moisture absorption, or ingress. Designs with many through-holes or routed areas can quickly become high-loss boards if moisture ingress/absorption is an issue.

It is also not fit for use if the resin has high moisture absorption or does not provide a robust resin-to-reinforcement interface that prevents moisture absorption. (Typical reinforcements include woven or non-woven glass.) The resin-to-reinforcement interface is critical and can be compounded by the speeds and processes associated with application of the resin to the reinforcement.

Other contributing factors include choice, composition, and treatment of any ceramics complementing the resin, and the sizing or treatment of reinforcements that can interfere with resin interface and complicate moisture absorption.

A common area for moisture ingress is through poor-quality holes that disturb resin-to-reinforcement or layer-to-layer interfaces. Some laminates have a broader window than others when it comes to their sensitivity to processing. Moisture ingress and processing chemical absorption can also have a role in delamination or blistering if the laminate is exposed to rapid temperatures during post etching processes. The rapid increase in laminate temperature of more than 100° C causes accelerated evaporation of embedded moisture, which results in expansion stresses that cause separation between laminate layers or, in severe cases, cracks in the board. The integrity of the laminate after fabrication also factors into design performance and impacts insertion loss beyond the typical equations or reported datasheet values. Due diligence on final design and materials is again warranted to achieve a desired design optimum.

Porosity with ceramic PTFE laminates at a microscopic level creates performance constraints in applications exposed to high humidity, such as in an F-18E/F on the deck of an aircraft carrier in the Mediterranean, South Pacific, or Arabian Sea. Microvoids existing at the filler-PTFE interface are areas where the smaller water vapor molecules (1/200 the size of water droplets) can permeate into a laminate. Water vapor will have a great effect upon the overall performance of the circuit, especially affecting loss tangent and insertion loss of the board (see Figure 6). Low-surface-tension liquids such as organic solvents and surfactant laden aqueous solutions will penetrate pores and cause similar loss issues.

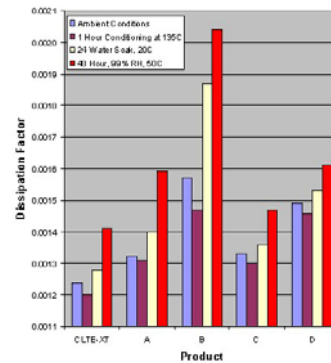


Figure 6: Moisture effects on various laminates

Older PTFE/ceramic laminate technologies have an Achilles heel resulting from microvoids at the PTFE/ceramic interface. Many are made through the calendaring of a PTFE/ceramic/microfine glass then applying a multiple calendaring process. Or, calendaring a PTFE/ceramic and coating it onto a polyimide film (Kapton®). The calendared layers are placed on top of each other, either with or without a woven fiberglass membrane that is coated only with PTFE. The multiple calendaring process both fibrillates and work

toughens the PTFE and aligns more glass in the calendaring direction. To achieve lamination, very high pressures must be utilized which has been known to move the ceramic particles into low spots in the laminate. Inherently, this process is reported to contain at least a 5% volume porosity with microvoids exist at filler-PTFE interface. Low Surface Tension Liquids such as organic solvents and surfactant laden aqueous solutions will penetrate pores. Alcohol (which is used as a neutralizer after sodium etch surface treatment), has been known to introduce permeation of contaminants which affects circuit performance. The alcohol can pull along board processing chemistry or contaminants that remains in the board, even after drying. This is a contributing factor to dielectric constant variability within a panel that is not present before processing and increased loss. To demonstrate this effect, PTFE laminate samples were exposed to a 500 PPM, BASF X-70 Black Colourant dissolved in acetone (Figure 7). In legacy materials, the black die readily penetrated the material, demonstrating the potential impact of contamination from PCB fabrication on circuit performance.



Figure 7. Exposure to Low Surface Tension Contaminant

## 10. CONSISTENCY OF EMBEDDED RESISTORS

With multilayer boards, discrete resistors are a packaging and reliability issue. As a result, embedded resistor technology, such as Ohmega Technologies Ohmega-Ply<sup>®</sup> or Ticer Technologies TCR<sup>®</sup> foils, is frequently used to provide the resistor function of Wilkinson power dividers. These embedded resistors are also known as planar resistors, buried resistors, or integral resistors. Ohmega Technologies describes their product as a thin-film, nickel-phosphorous (NiP) alloy. They apply this at about 0.1 to 0.4 microns thick. The alloy is electro-deposited onto the rough, or tooth, side of electrodeposited copper foil. Visually, you would see copper on one side of the laminate and a darker resistive layer exposed on the other. The foil comes in various resistance values; the most common values are 25, 50, and 100 ohms per square.

The resistor-conductor composite foil is laminated with the resistive side against the dielectric laminate during manufacturing. PCB manufacturers etch copper to its final patterns and then use a second chemistry to etch away unwanted portions of the exposed resistor layer, defining resistor values and placement within conductor traces.

Consistency with embedded resistors is a key performance requirement for microwave PCBs in multilayer designs. Thermal expansion mismatches between copper, resistor layer, and dielectric can cause variance in the resistor layer. Among the challenges faced by resistor foil manufacturers and circuit board substrate laminators is to develop materials that enhance each other's performance and withstand the ~700° F and >400 psi lamination cycles needed for PTFE.

Printable resistors have also been developed using ruthenium oxide (RuO<sub>2</sub>) and carbon. Cabot Corporation also offers a nanoparticle nickel and other inorganic inks to print resistors directly onto the laminate. Development in selective, additive, plated embedded resistor technology offers loss advantages over traditional resist foils as the higher loss resist layer is not present between the copper foil and laminate. MacDermid offers one such technology called M-Pass. Because PTFE has such low surface energy (nothing wants to stick), sodium etch or plasma treatment is required prior to plating to change the surface morphology and increase surface energy. These materials have less exposure to PTFE/ceramic-based laminates, but continued investigation seems to be warranted.

When these integral resistors are incorporated in a multilayer design, there are several stages of manufacture where dielectric materials play a critical role. In contrast to lamination of dielectric substrates, where copper foil cladding is continuous, multilayer designs use inner layers that purposefully have had most of the copper removed through print and etch processes.

Resistors that are defined by print and etch processes are also vulnerable through this process. Because it has always offered continuous fiberglass reinforcement, CLTE is known to provide the most consistent performance for resistors etched into Ohmega-Ply foils and incorporated in multilayer PCB structures.

An approach that uses resistive ink has similar considerations mechanically, in that they also benefit from the mechanical stability provided by woven fiberglass reinforcement. These ink systems also face temperature limitations, so a adhesive choices for multilayer lamination are limited, as well.

## 11. DIMENSIONAL STABILITY

With multilayer boards, dimensional stability is critical. Registration and dimensional stability in the XY direction become even more critical as packages get denser, plated through-hole density increases, and stricter electrical requirements are placed on materials. Stresses inherent to some materials can also allow circuits to wander or create laminates that bow when most of the copper is removed from one side.

Boards frequently go through sequential lamination processes as they are built up into final multilayer packages. Materials that lack dimensional stability or predictable movement that can be compensated become a major processing issue as "things end up not being where they're supposed to

be." Multiplied poor yield values could result in a very difficult and very expensive board to manufacture.

## 12. CONCLUSION

Ideal laminates for military and space systems require careful consideration in order to deliver system performance and reliability. This includes well-known laminate properties, such as low dielectric loss, low thermal expansion, and low temperature sensitivity of the dielectric, but also includes other material considerations such as dimensional stability, moisture and processing sensitivity, and interaction with other technology such as embedded resistors.

To address the needs of the marketplace for phase-stable low-loss laminates for multilayer microwave PCB applications, Arlon invested in the development of a new generation of CLTE. This next generation, CLTE-XT, is an ideal product for high-performance designs in antenna networks, radar manifolds, tactical radio, and navigation systems in which thermal stability of dielectric constant is critical. This includes aerospace and other temperature-sensitive applications where electrical performance is the critical issue in design.

Improving on the original CLTE product, CLTE-XT has the lowest absolute value for TCER at -9 to -10 ppm/°C for improved phase stability in design and exceptionally low X, Y, and Z thermal coefficients of expansion (8, 8, and 20 ppm/°C respectively). This makes CLTE-XT suitable for mounting leadless ceramic chip carriers, as well as for ensuring a high degree of confidence in the reliability of plated through-holes due to the very low z-direction expansion. The total z-direction CTE from -55 to 150°C is a remarkable 0.4%.



Fig. 8 20 Layer Board of CLTE-XT and SPEEDBOARD® C

In addition to these improved electrical and mechanical properties, testing has shown that CLTE-XT offers reduced water absorption (0.02%) in conventional water immersion.

There is corresponding resistance to exposure to high-temperature and high-humidity conditions. CLTE-XT also resists absorption of other processing fluids, in particular alcohols that are used to neutralize and rinse after sodium etch PTH processing. And in extensive testing of several thicknesses of laminate, Ohmega-Ply resists etches on CLTE-XT show very consistent, tight tolerances. NASA (Goddard Space Flight Center) has completed outgassing testing per ASTM E-595 on CLTE-XT; it has received the agency's approval for space applications, exhibiting very low mass loss, very low water vapor regain and no residual collected

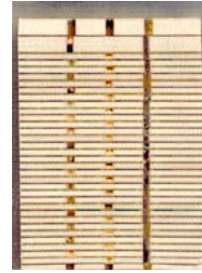


Fig. 9 68 Layer Board, ~1.5" Thick, CLTE Based, GlobalStar RF Beam Forming Network

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