

Millimeter Wave Printed Circuit Board Developments - Improvements for Mechanical Packaging and Electrical Requirements

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Abstract- Millimeter applications place heightened and unique requirements on circuit board laminates used as transmission lines or as antennas. Historically, applications were low volume. Materials were either adapted from standard or semi-standard products that were not ideal for millimeter wave or the materials that were military grade in nature. Recent growth of millimeter applications, such as ACC (adaptive cruise control) and side lane changing sensors for standard, high volume, affordably priced vehicles or commercial millimeter communication systems, has driven circuit board laminate fabricators to innovate materials. This paper explores advancements in millimeter wave circuit boards and the technical requirements placed on materials.

I. INTRODUCTION

Millimeter waves offer many advantages associated with the higher operating frequency. This includes increased bandwidth, improved resolution and directivity (due to narrower beams) for a given antenna aperture. This can mean smaller, lightweight systems offering increased transmission capacity in the case of communication systems or improved resolution for radar or imaging systems. This assists in image recognition, or to help identify explosive materials by their spectroscopic signatures.

Millimeter waves also are prone to higher levels of attenuation due to atmospheric absorption of water vapor and O₂ [1]. This can be advantageous for covert communications, low probability of intercept signals (such as a clandestine aircraft altimeters) or for automotive adaptive cruise control systems which are designed to be limited in range to eliminate noise and interference.

II. MILITARY AND SATELLITE GRADE MILLIMETER LAMINATE REQUIREMENTS

Traditional millimeter wave applications were limited to high value, low volume military aircraft, satellite or highly valued communication applications. Applications included millimeter low-probability of intercept altimeters for low probability of intercept aircraft, covert communications or even millimeter Fire Control Radars with very low peak power, extremely low sidelobes and very low probability of intercept RF transmission, for Multi-role combat and attack helicopters and low altitude air vehicles, including aircraft.

The following chart (Fig. 1) highlights the author's interpretation of requirements placed on laminates used at millimeter frequencies within the high value, high

performance marketplace. These applications typically will value performance over cost for a component, if that component can deliver a higher level of systems performance, since the cost impact of the material is less than 1 or 2% of a systems cost. This higher level of performance can improve range or reduce power, decrease sidelobes, and improve target location accuracy.

Property	Technical Need
Low Dielectric Constant	≤ 2.20 , <i>small amount at 3.00</i>
Low Dielectric Loss	< 0.0013
Low Insertion Loss Copper	$\leq 0.40\mu\text{m RMS}$
Thickness	$\leq 0.381\text{ mm}$
Thickness Tolerance	$< 5\%$
Dielectric Constant Tolerance	$\leq 1\%$
Dielectric Consistency	$\leq 1\%$
Dielectric Constant Phase Stability	$< 15\text{ ppm}/^\circ\text{C}$
Costs	$\leq 250\text{ Euro}/\text{meter}^2$

Figure 1. Military/Satellite Technical Needs of mmW Laminate

Efforts to replace discrete resistors with embedded resistors have led to millimeter and K-Band packaging and reliability improvements. As a result, embedded resistor technology, such as Ohmega-Ply[®] or TCR[®] foils, is specified to provide the resistor function of Wilkinson power dividers in K-Band and mmW band applications. Ohmega Technologies describes their product as a thin-film, nickel-phosphorous (NiP) alloy that is electro-deposited onto the rough, or tooth, side of electrodeposited copper foil. 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 applications using such technology with PCBs. Thermal expansion mismatches between copper, resist layer, and dielectric can cause variance in the resist layer, especially with materials that have dimensional stability or registration stability issues. For multilayer or stripline circuits, pressures and temperatures for lamination can introduce further resistor variations.

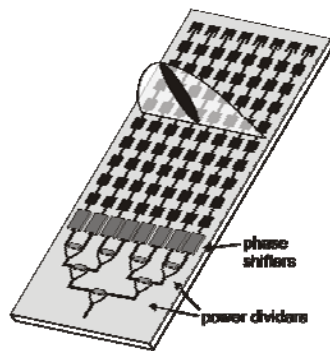


Figure 2. Phased Array mmW Antenna with Wilkinson Power Dividers (courtesy of Joerg Schoebel, Institute for High-Frequency Technology, Braunschweig University of Technology, Germany)

III. COMMERCIAL MILLIMETER LAMINATE REQUIREMENTS

Until the last 4 years, the commercial market did not exhibit volume consumption in millimeter wave applications. Today's automotive adaptive cruise control (ACC) systems have been exclusive systems subject to high manufacturing costs and a high price option for luxury class vehicles (ACC system costs the end customer about 1,500 to 2,500 Euros). Due to the relatively low volume of these applications, these systems are currently relying on specialty, expensive, material sets to achieve the desired performance requirements. Millimeter technology is also being utilized for collision and safety applications such as frontal assist for stopping distance reduction, Side lane changing assist or automatic activation of low beams with on-coming or closing-gap traffic.

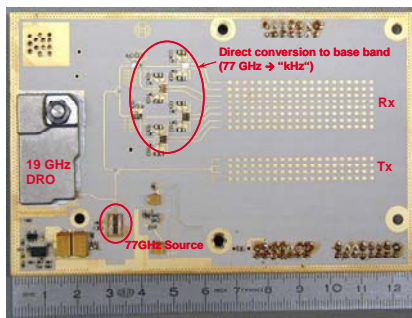


Figure 3. Phased Array on Laminate for 77 GHz Radar (Courtesy of Dr. Martin Schneider, RF & Microwave Engineering Laboratory, University of Bremen, Germany)

Efforts in the industry to consider future ACC or safety/collision systems as a affordable option are targeting < 300 Euros for system, < 50 Euros per sensor) [3]. Worldwide global platform, non-luxury class vehicles such as Honda Accord, Volkswagon Passat, Toyota Camry, Buick LaCrosse and Ford Mondeo are planning for adaptation as early as 2009-2010 model years. Very early developmental efforts and eventual introduction of such systems on Chery, Geely and GWM platforms, will quickly lead to rapid growth and legitimatization as a standard global product in 10 to 15 years.

To achieve the volume, cost and technical goal requirements of these growing and emerging applications,

innovation has been required to achieve both the manufacturing capacity as well as the technical and cost goals. Millimeter applications place heightened and unique requirements on circuit board laminates used as transmission lines or as antennas. Loss Tangent must be frequency frequency insensitive. Traditional materials fail in this category, both for being difficult to predict Dk at high frequency and for being too lossy.

The following chart (Fig. 4) highlights the author's interpretation of requirements placed on commercial automotive laminates used at millimeter frequencies based on customer interviews, IWPC forums [3] and consortiums and industry experts [4] [5].

Property	Technical Need
Low Dielectric Constant	≤ 3.00
Low Dielectric Loss	< 0.0015
Low Insertion Loss Copper	≤ 0.50um RMS
Thickness	≤ 0.381 mm
Thickness Tolerance	< 9%
Dielectric Constant Tolerance	≤ 1.5%
Dielectric Consistency	≤ 1%
Dielectric Constant Phase Stability	< 20 ppm/°C
Costs	≤ 100 Euro/meter ²

Figure 4. Commercial Technical Needs of mmW Laminate

IV. PROCESSING

Many millimeter requirements remove dielectric and place the chip directly onto a thermal and electrical ground (see Figure 5). Typically, this is accomplished through laser cutting and removing laminate material to expose a pocket.

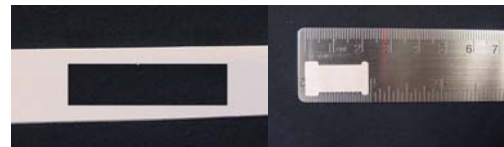


Figure 5. Laser Cut Outs

Materials that utilize high amounts of fiberglass cloth (especially heavy, non-uniform styles) become more difficult to cut with a laser. Materials that do not use fiberglass reinforcement (coated onto polyimide film and passed through an oven) face other challenges through fabrication and tend to have a gum-like nature when lazed. They also exhibit extremely high porosity levels and are subject to microvoids at the filler level. This creates a narrower processing window.

V. RESISTANCE TO MOISTURE INGRESSION AND CONTAMINATION

Older PTFE/ceramic laminate technologies have an Achilles heal resulting from microvoids at the PTFE/ceramic interface. Many are made through the calendaring of a PTFE/ceramic slug onto a polyimide film (Kapton®). The calendared layers are layed up either with or without a PTFE only coated woven fiberglass membrane. 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 affect, PTFE laminate samples were exposed to a 500 PPM, BASF X-70 Black Colourant dissolved in acetone (Figure 6). In legacy materials, the black die readily penetrated the material, demonstrating the potential impact of contamination from PCB fabrication on circuit performance.



Figure 6. Exposure to Low Surface Tension Contaminant

VI. IMPEDANCE CONTROL

A. Dielectric Constant Tolerance

Dielectric constant tolerances become even more aggressive with higher frequencies. A 10 GHz signal, in a vacuum, is roughly 3.0 cm in wavelength.

$$\lambda = c / (f \sqrt{\epsilon_r})$$

At 24 GHz, a wavelength, in a vacuum, is 1.25 cm and at 79 GHz, the wavelength is 0.38 cm. In a 3.00 dielectric constant microstrip, a 79 GHz signal is 0.22 cm in wavelength, making a 0.055cm quarter wavelength. A result of the high frequency and the square root effect of the dielectric constant, small differences in dielectric constant become a much larger factor in phase angle in a millimeter wave system.

With the use of Phased Arrays into the millimeter designs, these systems become even more sensitive to changes in dielectric constant across temperature cycling. Each element is designed to achieve a different phase and amplitude to electrically steer the array. Unpredictable changes in dielectric constant will provide higher error rates as well as inaccurate data.

B. Thickness Tolerance

Typically, millimeter wave systems are based on stripline or microstrip based circuit designs circuitry using thin materials (assume 0.13mm to 0.380 mm). Because of cutoff frequency limits, thinner materials need to effectively transmit at shorter wavelengths. Line widths are chosen to achieve a certain impedance (assume 50 ohms). In addition

to the importance of dielectric constant, transmission line impedance is also driven by circuit geometry, including thickness of the dielectric. Where thickness varies, non-ideal impedance is a result. In turn, this can cause higher order insertion loss (S21) and higher amounts of reflected energy and higher return loss (S11). In phased array systems that depend upon a phase fed antenna (Fig. 2 and 3), this can cause degradation of the system performance.

C. Variability across Transmission Line

Most material testing requirements place a requirement on the batch-batch test requirements and do not evaluate, study or understand the effects of inter-panel variability, either from a thickness or a dielectric constant standpoint. As highlighted in section B., this can affect impedance. If impedance varies down the length of the transmission line, it incurs much higher reflected energy, higher return loss (S11) and finally higher insertion loss (S21).

VII. THERMAL STABILITY OF DIELECTRIC CONSTANT

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 7, where the center of the board was placed on a heat source of 125°C. This local area increased 1.135 ohms.

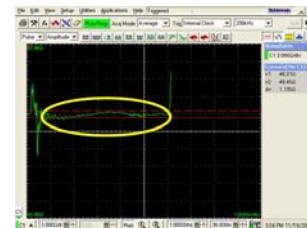


Figure 7. Transmission Line exposed to 125°C increases 1.135 ohms

VIII. THERMAL CONDUCTIVITY

Circuit board thermal conductivity can greatly improve thermal stability of the dielectric constant, as heat is better spread through the laminate and areas of maximum heat (and thus maximum impedance mismatch) are minimized. The following image (Fig. 8) represents a thermal image of two different microwave circuits of the same dielectric constant and thickness. The thermal conductivity of the left material is 0.46 W/mK, compared to 1.1 W/mK. The increase of thermal conductivity reduced the maximum temperature from 180°C to 163°C. The heat spreading properties of the material can also visualized by the larger area of temperatures above 92.9°F thus reducing the severity of the temperature gradient within the circuit board.

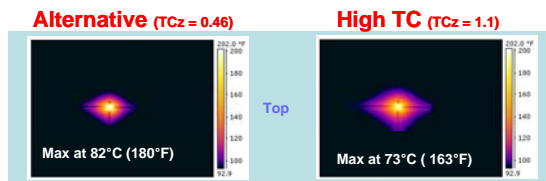


Figure 8. Thermal Images of Heat Dissipation and Associated Max Temperature Reduction due to Higher Thermal Conductivity

The material with higher thermal conductivity pulls the heat away from the "hot spot" and allows it to be more efficiently dissipated.

IX. DEVELOPMENTS

Requirements placed on millimeter wave and K-band circuit board laminates has driven product development and basic technological research and innovation. Two results of this work, have been CLTE-XT and CLTE-AT. CLTE-XT has been developed for high precision, military-focused applications that require very low loss, highest level of thickness and dielectric constant consistency, and highest level of phase stability. As a result, its performance is "Best-in-Class" for Phase Stability, Low Loss and a range of mechanical properties. CLTE-AT uses common technologies developed for the high precision, military-focused CLTE-XT. However, there are some non-trivial changes to make the product more affordable for the commercial market. Differences include a marginally higher dielectric constant and some impact on loss, processing performance, higher moisture absorption, limits on product options and lower peel strength. Its performance still place it as "Best-in-Class" for performance of a commercial laminate for Phase Stability and Low Loss and a range of mechanical properties. To maintain its lower cost base, CLTE-AT adheres to a standardized approach. It is offered with fewer options for copper style and panel sizes.

CLTE-XT has excellent Electrical Phase Stability vs. Temperature (-9 ppm/°C), Tightest Dielectric Constant (2.94±0.03) as well as very tight Thickness Tolerance. It also has the lowest moisture absorption, critical for contamination resistance and dielectric constant variability.

CLTE-AT also has excellent Electrical Phase Stability of -10 ppm/°C (Fig. 9), High Thermal Conductivity (0.64 W/mK) and Tight Dielectric Constant (3.00±0.04) as well as very good Thickness Tolerance. CLTE-AT has good low moisture absorption properties and contamination resistance.

CLTE-AT was developed with a very low dielectric loss tangent of 0.0013 via IPC 2.5.5.5 test method. CLTE-AT has been qualified to use smoother copper styles with average surface roughness (Rz) of 4.0µm, compared to competitive offerings using the rougher 9-10 µm copper.. This reduces insertion loss due to the increased transmission line resistance as a result of skin effect, while still maintaining peel strength required for thin traces on thin laminates (6.5 pounds per linear inch, 1.2 N/mm).

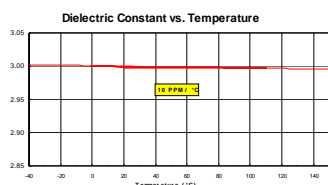


Figure 9. Dielectric Constant Stability with Temperature for CLTE-AT

CLTE-XT and CLTE-AT is a micro dispersed ceramic PTFE composite utilizing a woven fiberglass reinforcement to provide the highest degree of dimensional stability without impacting inter-panel dielectric constant stability, even at millimeter wave frequencies. Both products have registration consistencies 1/10th that of incumbent materials when utilizing thin dielectric laminates (i.e. 0.005" and 0.010"). This is the result of not only the inclusion of a microfine woven reinforcement, but, also the choice of raw materials chosen for stability, and product sensitive process parameters used during lamination of the raw laminate. As a result, Impedance mismatches are minimized and maximum power transfer is achieved at the correct phase angle.

X. CONCLUSION

Millimeter applications place heightened and unique requirements on circuit board laminates used as transmission lines or as antennas. These parameters include: low dielectric loss (loss tangent), low insertion loss (includes copper and copper interface), capability to make and control dielectric constant and thickness variability for (especially) thin laminates, phase stability and thermal conductivity.

This has required a three year product development and basic technological research and innovation to achieve a cost effective, technically advanced material. The resultant, CLTE-XT and CLTE-AT achieves the technical needs of the millimeter applications for the precision military market and the cost sensitive, high volume commercial markets.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and support of the GSMM2008 Steering and Technical Programme Committee as well as the Engineering and Analytical Testing Support Team at Arlon. Special acknowledgement to Dr. Martin Schneider, RF & Microwave Engineering Laboratory, University of Bremen, Germany, and Joerg Schoebel, Institute for High-Frequency Technology, Braunschweig University of Technology, Germany for providing both pictures and editorial review.

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