



MATERIALS FOR ELECTRONICS DIVISION

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INSERTION LOSS and LOSS TANGENT

When Selecting Low-Loss Microwave Laminates, Loss Tangent Is Only 25% Of The Story

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Introduction

The optimal selection of a Low Loss Microwave Laminate requires much more due diligence than the comparison of reported Loss Tangent ($\tan\delta$) or Dissipation Factor values (Df) of various competitive materials. The shortcoming of reported values are due to the fact that they measured under idealized conditions which neglects moisture and processing affects on material performance and omits the importance of conductor losses (and the choice of the copper profile). Experienced Microwave Engineers report that they prefer to understand the Insertion Loss of the material, especially in a circuit representative of their application. This approach is a much more insightful measurement that takes much more into consideration all the variables that impact a design than just laminate dielectric loss and result in designs optimized for high performance applications.

Although loss tangent is good starting point, determining the highest performance, lowest loss microwave laminate would require further analysis. For example, a comparison of all IPC-4103/06 style laminates reveal a range of Loss Tangent Values from 0.0012 to 0.0025. One would expect the 0.0012 laminate to have the lowest insertion loss, but various independent tests have shown that the material with the 0.0025 loss tangent resulted in the lowest insertion loss in its class despite having higher dielectric loss than alternative products. Based on our own evaluations, the performance differences can be attributed to lower moisture absorption, improved fabrication to resist processing chemicals and lower conductive loss. With this example, utilization of special low profile copper combined with a unique resin formulation, provides lower conductive loss, while still providing excellent copper bond. Although the same copper could theoretically be used for all laminates (*thus equalizing conductive loss*), copper bond strength could be sacrificed to the point where fabrication is no longer feasible. Therefore, in practice, this results in a higher conductive loss that ends up offsetting the lower loss tangent advantage.

Insertion Loss

Insertion loss is a combination of multiple sources of loss, which include: Dielectric Loss (related to Df or Loss Tangent), Connector Losses, Impedance Mismatches (Reflections), Conductor Losses and Radiation Losses. From a design perspective, the primary sources for insertion loss to consider in terms of laminate performance are the dielectric loss and the conductive losses. At moderate frequencies with very low loss materials (loss tangent around 0.0009), conductive loss might dominate dielectric loss 3 to 1. As frequencies increase, the conductive loss and dielectric loss ratio will change to a point where they could be similar in value depending on the material performance across frequencies.

Dielectric Loss

Dielectric loss is due to the effects of finite loss tangent, $\tan\delta$, in which the losses rise proportional over the operating frequency. For common microwave substrate materials like glass reinforced PTFE with a loss tangent less than 0.0009 like Arlon's DiClad 880 example given above, dielectric loss is only a fraction of the total loss with conductor losses being significantly larger in value. For materials with a higher dielectric loss, such as a ceramic filled PTFE material with a loss tangent of 0.0025, dielectric loss still might only be roughly equivalent to the conductor loss.

Moisture and Solvent Ingression is frequently overlooked in the early choice of materials. The nature of the test methods utilized for testing loss tangent of a microwave material requires conditioning of the sample to remove moisture and etchants. Since water is very lossy (assume distilled water has a loss tangent of 0.157 @ 3 GHz), a laminate with higher moisture absorption can quickly become a much higher loss laminate after processing in solvents or exposed to a damp or humid environment. Testing a circuit representative of the application allows a Designer to expose the circuit board to the solvents, chemicals and thermal cycles used in the processing of boards. Moisture absorption also becomes more critical to designs where board operating temperatures do not drive out moisture or were it frequently cycles through wide temperature ranges. As a result, the loss seen by a circuit is not just that of the virgin laminate, but rather it sees a dielectric composed of the virgin laminate and any moisture, chemicals or solvents that it acquires during processing. The relationship between dielectric loss and loss tangent can be seen in the following formula:

Dielectric Loss:

$$\alpha_d = \frac{\epsilon_r}{\sqrt{\epsilon_{r_{eff}}}} \cdot \frac{\epsilon_{r_{eff}} - 1}{\epsilon_r - 1} \cdot \frac{\pi}{\lambda_0} \cdot \tan \delta_d$$

Under idealized conditions, the material under test is isolated from moisture and processing chemicals (or heated for a period of time to remove trapped moisture). This minimizes (and idealizes) the dielectric loss and thus the calculated (and reported) $\tan \delta_d$ of the material. This typically does not represent the material in use.

Moisture Ingression and Processing Chemical Absorption

The lowest loss tangent materials do not always make the ideal laminate because processing and fabrication can influence the performance of the laminate that would not be reflected by loss tangent measurements associated with the standard IPC test methods. Moisture and Processing Chemical absorption will 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 ingression. Board designs with many thru-holes or routed areas can quickly become high loss boards if moisture ingression/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 (typical reinforcements include woven or non-woven glass) interface that prevents moisture absorption. 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. Sizings and reinforcement treatments also play a vital role. A typical woven glass sizing such as starch, can be carbonized or vaporized at the high temperatures required to sinter coated reinforcements or laminate low loss laminates. This could potentially leave a void along the fibers that could result in a prime root cause of wicking.

Other factors can contribute to such as choice, composition and treatment of any ceramics complimenting the resin, or the sizing or treatment of reinforcements that can interfere with resin interface and complicate moisture absorption.

A common area for the moisture ingress is the through poor quality holes that disturb resin-to-reinforcement or layer-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 create a role in delamination or blistering if the laminate is exposed to rapid temperatures during post etching processes. The rapid increase in laminate temperature well above 100°C causes accelerated evaporation of embedded moisture, which result 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 in to 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.

Conductor Loss

The next consideration in understanding insertion loss performance is Conductor Loss. Hammerstad and Jensen developed the following equation for the Conductive Loss:

$$\alpha_c = \frac{R'}{Z_L \cdot W} \cdot K_r \cdot K_i$$

with

$$R' = \frac{\rho}{\delta} = \sqrt{\rho \cdot \frac{\omega \cdot \mu}{2}} = \sqrt{\rho \cdot \pi \cdot f \cdot \mu}$$

$$K_i = \exp\left(-1.2 \left(\frac{Z_L}{Z_{F0}}\right)^{0.7}\right)$$

$$K_r = 1 + \frac{2}{\pi} \arctan\left(1.4 \left(\frac{\Delta}{\delta}\right)^2\right)$$

whereas

R' sheet resistance of conductor material (skin resistance)

ρ specific resistance of conductor

δ skin depth

K_i current distribution factor

K_r correction term due to surface roughness

Δ effective (rms) surface roughness of substrate

Z_{F0} wave impedance in vacuum

It is necessary to account for the surface roughness of the substrate interface (see Figure 1) is because of the asymptotic increase seen in the apparent surface resistance with decreasing skin depth. This effect is considered by the correction factor K_r . The current distribution factor K_i is a very good approximation provided that the strip thickness exceeds three skin depths ($t > 3 \delta$). The impact of copper foil roughness on conductor loss is due to increase in transmission line resistance as a result of skin effect. The skin effect is the tendency of an alternating electric current to distribute itself within a conductor so that the current density near the surface of the conductor is greater than that at its core. It causes the effective resistance of the conductor to increase with the frequency of the current. This skin depth reduces inversely with the square root of frequency and translates into a resistance that increases with the square root of frequency.

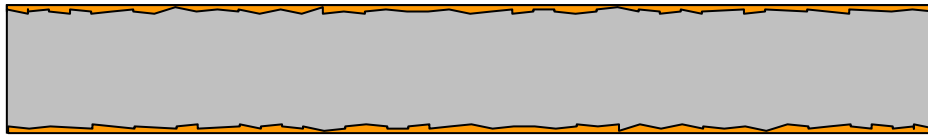


Figure 1. “Overemphasized” Roughness Interface Profile between Laminate and Copper

Conductor Surface Profile (R_{rms} or R_z)

Hammerstad and Jensen account for the effects in Conductor Surface Profile (seen as Δ in their formula) through the use of the correction factor K_r in their equation.

Smoother surface roughness of the copper cladding provides for lower conductor losses, but, usually at the sacrifice of the copper bond to the laminate. Extremely low loss resin formulations that require rougher surface profiles (higher tooth structure) to provide an acceptable copper bond, compete well on paper with their low D_f value, but, are mediocre (or even disappointing) in the field with their high conductive loss. This is especially true with “low-loss” thermoset laminates where copper adhesion is extremely difficult and requires a high surface roughness copper.

Microwave laminates can vary in roughness range from roughly 15 to 130 microinches using the root mean squared method for measuring surface roughness (R_{RMS} or R_z). FR-4 and polyimide copper styles are an order of magnitude rougher and considered not “fit-for-use” for microwave laminates. Due to difficulties in measuring this value, a head-to-head comparison of laminate or copper supplier surface roughness measurements is usually not very meaningful because of variations in test methods and equipment. Contact gauges test a very small physical area and the stylus can plow through the treatment or skip over valleys depending on the weight and size of the stylus. Optical chromatic aberration techniques are very promising as they are non-contact and have higher precision but these methods are not well known in the industry and have not been evaluated for their use in correlations used in the above equations. This leaves direct comparisons of copper-clad laminates as the best method for understanding loss performance.

Given the DiClad 880 laminate example provided earlier, and choosing a very low profile copper, Arlon has been able to reduce conductive losses by up to 50% at 10 GHz by using very low profile copper. Figure 2 shows three identical circuits made on 0.0031” laminates. The circuit design was a 50 ohm serpentine microstrip transmission line on a 18” x 24” panel. The

“Lowest Profile” copper had a 30 microinch (Rz) value, the “Low Profile” copper had a 46 microinches (Rz) value and the “Standard Profile” was on the order of 75 microinches (Rz).

Selection of the “Lowest Profile” copper could result in a 25% lower Insertion Loss over “Standard Profile” copper but this will sacrifice the copper-laminate bond because the lower profile copper has less tooth structure (less surface area) as an interface to the laminate. Higher peel strengths are critical for narrow line widths and more aggressive circuitry. Therefore, there is a constant trade-off to achieve the lowest conductor roughness profile while maintaining reasonable bond strengths.

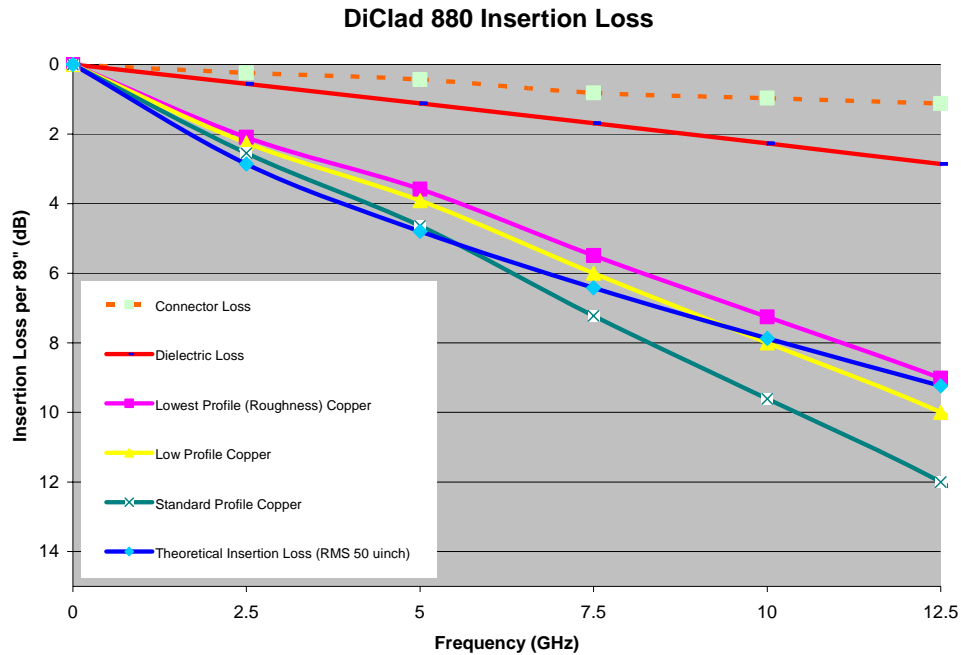


Figure 2. DiClad Insertion Loss for Various Copper Roughness Profiles

Conclusion

Loss Tangent is an important screening tool in selecting a laminate, but, does not provide the insight provided by Insertion Loss Testing. Materials that test for a low loss tangent, might require higher profile (rougher) copper profiles to achieve good bond strength between the copper and dielectric. Due to the skin effect of conductors, this higher surface roughness between the dielectric and the copper cladding increases the conductive losses of the laminate.

Moisture absorption and processing solution exposure will also negatively impact the dielectric loss of a laminate. This is not revealed in loss tangent testing, as the test methodology requires a “conditioned” sample (baked to remove moisture). This is an idealized condition and may not represent the material in a real environment or subject the laminate to the degree (and variety) of processing solvents it will see in a realistic processing environment.

Insertion Loss tells a more complete story of the “fitness-for-use” of the laminate. It takes into account the copper-laminate interface as well as any changes in the material due to absorption. Experienced microwave designers recommend developing test methodologies that reveal insertion loss under conditions that are representative to their circuit design. Mechanical robustness, dimensional stability, thermal stability and thermal conductivity are also critical properties that need to be evaluated to insure that the idealized laminate is chosen.

Design optimization is a risky proposition if you base your decision making criteria on comparing datasheets alone. There needs to be a conscience effort in choosing a laminate and experienced engineers promote doing your due diligence. Selecting a laminate solely on the loss tangent and dielectric constant extracted from a data sheet can oversimplify the complexity of material performance and lead to sub-optimized performance and increased costs. Expenses, resources and time can be compounded (*and careers limited*) when the problems arise after the design cycle, when product is in production and there is little time or tolerance for problem solving.

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