High Frequency Printed Circuit Board Materials for use in Mobile Infrastructure Networks

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Base station designers for mobile infrastructure networks today have a large selection of high frequency printed circuit board materials and suppliers to choose from at the initial stage of their projects. The material is a critical component of the system and proper care must be taken when making this choice, since the success of the project could be greatly influenced by the printed circuit board (pcb) material. In the past, selection was done based on data sheet values and material price only. This basic method however is greatly flawed, as it does not take into account the variation in electrical performance outside of the lab where data sheet values were obtained nor does it consider the true cost of a pcb, meaning it does not consider the price of the finished circuit. When selecting the material, Performance, Reliability and Cost should be considered, and these themselves are made up of a series of critical items, some of which are listed below.

Performance: Dk tolerance/variation, Df, insertion loss, temperature stability,
Reliability: Operating temperature, PTH's, Pb-free solder processing, environmental effects
Cost: Material, fabrication, yield, supply

This paper will focus on one item per major area. This should not to be taken as the only or main items, but as examples of what a designer will need to consider in order to ensure the proper selection of the material that best captures the right mix of performance, reliability and cost in order to maximize the probability of a successful project.

Performance

Commercial high frequency PCB materials today are grouped into two categories based on the resin system. One grouping uses thermoplastic resins such as PTFE (polytetrafluoroethylene) while the second group uses a variety of thermoset resins. Both of these families of products combine the resin system with some type of reinforcement. Woven glass and or ceramic fillers are the most common choices. These composite laminates also come clad with surface metallization, copper foil being quite standard. Some materials (in particular those using PTFE) have the option of being available with thick metal cladding (typically used for mechanical structure and thermal management). Table 1 summarizes the low dielectric constant material options that designers most commonly use in commercial high volume wireless communications applications (like high power amplifiers) according to laminate supplier’s data sheets ;

	Dielectric Constant	Dissipation Factor	Thermal Co
			W/m/° K

PTFE/woven glass (low filler content)	3.5 ± 0.1 @ 1.9GHz	0.0018 @ 1.9GHz	0.24
PTFE/ceramic filler (high filler content)	3.5 ± 0.05 @ 10GHz	0.0017 @ 10 GHz	0.5
Thermoset/w.glass/ceramic filler	3.48 ± 0.05 @ 10GHz	0.0037 @ 10GHz	0.62

Table 1. Commonly used high frequency laminates for base station high power amplifiers

One word of caution when comparing material using data sheets, care must be taken that values being compared are taken under the same conditions. It is common for values to be presented at various frequencies or obtained by different test methods. A direct comparison should not be made because these variables can affect the property reported. Designers should always test materials being considered under identical conditions to get a real comparison of material performance.

When designing high power components, thermal management is an important factor. Two ways in which this can be done is one, keeping losses low and two, selecting materials with higher thermal conductivity. Insertion loss is made up of both dielectric losses and conductor losses. Dielectric losses are lower when working with materials with low dissipation factor (loss tangent) while working with copper with lower surface roughness assists in keeping conductor losses down. The impact of these parameters is also affected by the frequency of operation and the thickness of the substrate used.

One material property not often considered by electrical engineers, is thermal conductivity (Tc). Depending on the value of this property, sometimes a lower operating temperature can be achieved when selecting a material with higher Tc even if the dissipation factor or conductor roughness are higher. An example using 0.020” thick material with 1 oz ED copper at 2GHz is given below, using Hammerstead and Jensen equations (1)for microstrip insertion loss and simplified temperature rise estimates as listed in Rogers literature (2) ;

Material A: PTFE/ceramic filler Dk 3.5, Df 0.0018, Tc 0.24, RMS 1.0
Material B: Thermoset/woven glass/ceramic filler Dk 3.48, Df 0.0037, Tc 0.67, RMS 3.0
A: ad is 0.012 dB/inch, ac is 0.040 dB/inch ? power for temperature rise of 100°C is 110W
B: ad is 0.025 dB/inch, ac is 0.056 dB/inch ? power for temperature rise of 100°C is 201W
(a is the portion of insertion loss attributed to dielectric or conductor losses)

Although the PTFE based system has lower calculated insertion loss (0.052 dB/inch vs 0.081 dB/inch) compared to the thermoset material, due to the difference in thermal conductivity, the thermoset material can dissipate heat almost at 2X the rate and will therefore have a lower operating temperature. This is very critical, since lowering the operating temperature of the circuit can have a marked improvement in the MTBF of the components found on an amplifier.

1. “Accurate models of microstrip computer aided design”, E. Hammerstad and O. Jensen, 1980 MTT-S International Microwave Symposium. Dig. pp. 407-409, May 1980
2. Design 3.3.2 “Temperature Rise Estimations in Rogers High Frequency Circuit Boards Carrying Direct RF Current”, Rogers Corporation, Revised 3/2003, Pub #92-332

Reliability

One of the many factors that need to be considered when evaluating the long term reliability of a RF circuit, is plated through hole (PTH) reliability. Often this has not been something that needed detailed consideration in RF circuit boards due to the simplicity of many designs, typically double sided boards where PTH’s were needed only for grounding purposes. However, newer designs require circuit technology that uses a multilayer approach to either reduce the overall circuit size or to integrate more functions into a single circuit board construction. There are two factors that need to be considered when performing PTH reliability analysis. The first is short term reliability. This in particular has to do with the behavior of the laminate’s coefficient of thermal expansion (CTE) and its effect on the PTH’s as it goes through high temperature exposures during printed circuit board (PCB) fabrication, like lead-free solder reflow (240°C to 260°C). The second is long term reliability. This mainly has to do with the circuit function once it is in the field. Newer base stations today are designed to be mounted outside of buildings. They no longer have the benefit of sitting inside an air conditioned shack and thus must be able to survive extreme environmental temperatures, in addition to operating temperatures.

To begin an analysis of good candidate materials, we must start with the CTE (in ppm/°C) of the materials being considered. Again, going back to the supplier’s data sheets for the materials listed in table 1, we find that the CTE’s are listed as follows;

1. PTFE/woven glass at 64 ppm/°C (from 30°C to 300°C)
2. PTFE/ceramic filler at 24 ppm/°C (from -55°C to 288°C)
3. Thermoset/w. glass/ceramic filler at 35 ppm/°C (from -55°C to 288°C)

Again, word of caution when comparing data sheet values, in particular with PTFE resins. PTFE goes through a significant increase in CTE between 17°C to 24°C and outside of those temperatures it levels off somewhat. Since a circuit board can see temperatures below 17°C in the field (in particular those cold winter places of the world), one should be concerned about the CTE at low temperatures too, not just

those above room temperatures.

When performing a test for PTH reliability, one should also take into account that high temperature exposures during the PCB fabrication process will also have an effect on the via for long term reliability. PCB's may undergo multiple solder reflow operations. This can cause stresses on the via's which may not be evident at this stage but could create a problem later in the field. The material selected should be one that can pass short term and long term PTH reliability tests. Detailed evaluations for PTH reliability were conducted on Rogers RO4350B™ high frequency laminate and RO4450B™ bonding prepreg (thermoset/woven glass/ceramic filler) using a daisy chained PTH test coupon. The via hole diameter ranged in aspect ratios from 3:1 to 18:1 and the total thickness of the PCB's ranged from 0.060" to 0.175". The test board is shown in figure 1.

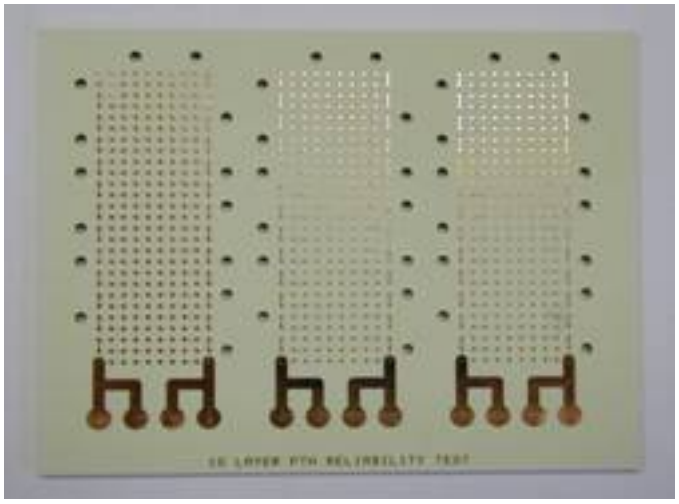

Figure 1. Test board for evaluation of PTH reliability: 0.060" to 0.175" with 3:1 to 18:1 aspect ratio vias

Table 2 summarizes the conditioning and test results performed on the multilayer PCB. There were two components of the pass/fail criteria, electrical and mechanical. If the value of the resistance of the daisy chained vias increased by more than 10% during the heating cycle in the environmental chambers, it was considered a failure. For the mechanical criteria, this was based on visual inspection of the cross sectioned vias. Evidence of cracked plating in the hole wall was considered a failure.

PTH Test Board Conditioning	Electrical Test	Mechanical
Short Term Tests		
10 times exposure to 60 second 288° C solder pot float	Pass	Pass
60 minute conditioning in pressure pot, followed by 60 second solder pot float	Pass	Pass
100 hours at 85° C/85% relative humidity, followed by	Pass	Pass

60 second solder pot float		
24 hours immersion in 25° C water tank followed by 60 second solder float test	Pass	Pass
Long Term Tests		
10 times through Pb-free solder reflow oven with 260° C peak temperature, then 1000 cycles from -55° C to 125° C	Pass	Pass
10 times through Pb-free solder reflow oven with 260° C peak temperature, then 500 cycles from -55° C to 150° C	Pass	Pass
10 times through Pb-free solder reflow oven with 260° C peak temperature, then 25 cycles from 0° C to 225° C	Pass	Pass

Table 2. PTH reliability testing of RO4350B high frequency laminate

As can be seen from the results of this evaluation, PTH reliability for this material set is quite high. Designers have selected this product in many designs because of this reason. Although there are several options when working with PTFE based materials, their different CTE properties mean they behave in a different manner from each other when performing PTH reliability testing. Some PTFE based laminates have also proven to be as reliable as RO4000® materials, in particular those that have high ceramic filler content (driver for low CTE). Again, PTH performance is only one of many reliability factors that need to be carefully addressed. Designers should conduct careful electrical and mechanical evaluations to determine the material and design combination fitness for use over the entire life of the end product.

Cost

In today's designs, system costs are greatly scrutinized. The benefit/value relationship is constantly being re-evaluated as the competitive landscape changes and subscriber expectations evolve. Under this scenario, one can understand why some designers might focus on minimizing the bill of materials (BOM) of the amplifier or the microwave radio for example. However, this approach is flawed, because it does not take into account the total cost of the system. One could select the lowest cost PCB material and components, but if the cost to fabricate the populated circuit is higher and has a lower yield, the low cost BOM option could very likely be the more expensive solution. Some materials might require more costly processing. For example, PTFE based materials require special hole wall preparation prior to plating. This is an added cost compared to thermoset resin based laminates. If the design is a multilayer board, using thermoset prepregs are less costly than thermoplastic bonding films in two ways. The first, being that the PCB industry is setup on processing epoxy/glass laminates (FR-4) and as one moves away from this process depending on material selection, higher costs are incurred and passed on to

the customer. Thermoplastic bonding films usually require lamination temperatures that exceed those of FR-4 prepreg, while thermoset high frequency prepregs are designed to be laminated at the same temperatures. The second reason, if the design requires multiple laminations, thermoplastic bonding films can re-melt in those layers previously bonded. This will cause registration issues and could greatly reduce yield. Thermoset bonding prepregs do not have this problem, sequential lamination is a common occurrence. One should also consider the cost and yield implications of the material selected on the assembly of the populated board.

There is no high frequency material that is considered the best option in all three areas of performance, reliability and cost. This work needs to be done by the designer. As no two designs are identical, a solution that best fits one project may not necessarily be the right option for another. Designs are becoming more complex and the work in selecting the best fit material can't all be done by the designer. Just as there are three areas to consider when selecting the material, a designer should work with the PCB facility and laminate supplier to keep in mind best in class practices in DFM (design for manufacturability). Maximizing the benefit/value proposition of today's systems starts with a good foundation, and this foundation can many times be the high frequency material which carries the load from the lab to the field.

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