# Design Considerations in the Selection of High Frequency Materials for PCB Base Station Antennas

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## Introduction

Antennas are a critical component in wireless communication infrastructure, and as such, careful consideration of key properties is needed. Designers of cellular base station PCB antennas have many choices when selecting high frequency laminates. This paper will provide the pros and cons of various laminate systems for use in PCB antennas. Comparison of electrical properties for these materials will be discussed. Insertion loss measurements will be presented as well as a detailed review of Passive Intermodulation testing and results for various laminates systems. Passive intermodulation (PIM) is the generation of unwanted frequencies due to non-linearities in the current-voltage relationship of passive elements. The most common source of PIM generation is usually at connections between devices. However, when the lowest PIM values are required in a planar circuit antenna system, the circuit laminate properties can play a significant role as well. In a high frequency circuit laminate, the copper foil roughness is a key variable. With the use of low profile copper foil, laminate PIM performance can be improved by 10 to15 dB, and consistent values of better than –153 dBc can be achieved. Due to the very low values of interest, development of a measurement system and understanding to the repeatability of the measurements is of major importance. This paper is aimed at base station PCB antenna designers, as a primer in the selection of materials.

## Laminate Options

Antennas used in base transceiver stations are, in concept, simple RF circuits when designed for a single frequency. These circuits today can be built out of coaxial cable and thin metal plates or out of printed circuit materials, PCB's (or a combination of both). However, today many antennas designed need to operate at multiple frequencies (due to air interphases, GSM, CMDA, WCDMA, LTE) and the complexity of these designs has increased in order to accommodate the various frequencies that can range from 700MHz to close to 2700MHz depending on the region of the world. Selecting an approach, metal/cable or PCB has many variables within performance, reliability, cost and time to market and which approach is best also depends on the organization and it's skill sets. In other words, no one right answer for everybody, and that is why we see both approaches used today in industry.

When following the PCB approach for antennas, one needs to select laminate materials that have the right electrical and mechanical properties and in the case of base stations, meet the cost targets in this very competitive market. Key electrical properties are;

Dielectric constant, Dk (< 3.5)
Dissipation factor, Df (< 0.003)
Passive Intermodulation, PIM (< -153 dBc)

When selecting a high frequency PCB material, designers today have two basic types of material options. The first is based on PTFE resin (thermoplastic) while the second option is based on thermoset hydrocarbon resin. PTFE based materials have the option of being reinforced with woven glass or with ceramic filler and woven glass. For the thermoset based materials, these all have both woven glass and ceramic filler (lower Dk versions have hollow ceramic filler particles). Figure A shows cross sections of four basic PTFE based Dk 2.97 – 3.0 materials 0.030" thick in the market today. Starting in the upper left corner and going in clockwise direction, the first sample is composed of layers of PTFE/ceramic with PTFE/woven glass, the second is entirely made of woven glass layers that have been coated with PTFE, the lower right hand corner shows a sample made of PTFE/ceramic resin coated on woven glass and the last example is made by combining layers of woven glass that has been coated with PTFE/ceramic and pure layers of PTFE. All samples have copper foil cladding on the outside.

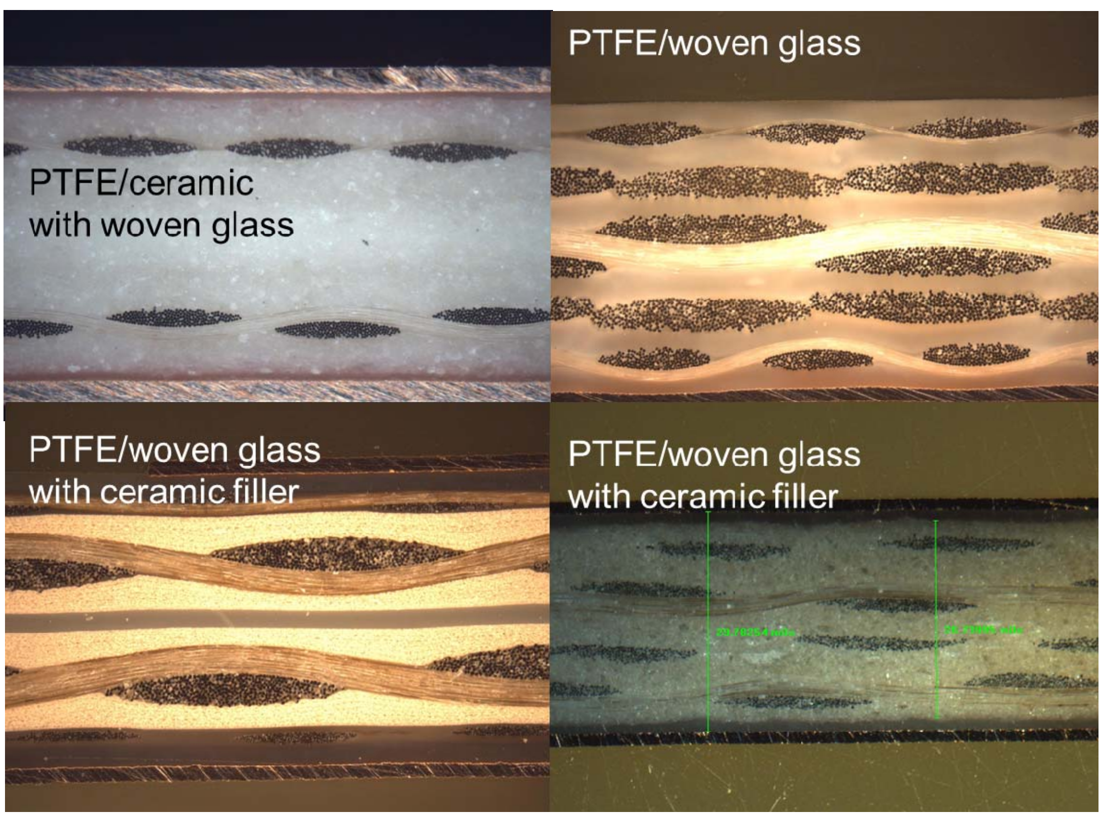


Figure A. Four basic constructions for PTFE based Dk 3.0 materials (0.030")

The range of Dk and Df for these materials is summarized in table I based on published data sheet values from the top four major suppliers of high frequency materials. When comparing properties among materials based on data sheet values, one needs to be careful because not all are tested using the same method or at the same frequency. Some are tested at 10 GHz while others are tested at 2.5GHz or 1.9GHz. The Df value can vary significantly depending on the frequency selected. The designer should always consult the individual data sheet for a particular material and ultimately perform their own testing to understand how that material will perform in the specific application. In the market today, the vast majority of designs for base station antennas are using PTFE based materials that fall in the 2.5 – 2.65 or 2.97 – 3.0 Dk range. Thermoset materials are newer products that offer a cost advantage over PTFE materials and are beginning to gain ground in newer designs.

| | **Dk various frequencies** | **Df (various frequencies)** | |
|---|---|---|---|
| **PTFE/woven glass** | 2.2<br>2.50 – 2.65<br>3.0<br>3.2 | 0.0009<br>0.0016 – 0.0021<br>0.0023<br>0.0024 | |
| **PTFE/woven glass, ceramic** | 2.5 - 2.65<br>2.97 – 3.0<br>3.2 | 0.0012 – 0.0017<br>0.0012 – 0.0020<br>0.0032 | |
| **Thermoset/woven glass, ceramic** | 2.55<br>3.0<br>3.30<br>3.40 | 0.0022<br>0.0023<br>0.0020<br>0.0022 | |

**Table 1. Data sheet property values for antenna grade materials**

In general, if low loss tangent is the primary concern of the designer, PTFE based materials have more options with lower Df. However, the real measure of the loss performance of the PCB needs to also take into consideration the effect of conductor loss. A better measure of the true performance of the substrate is a comparison of the insertion loss. Such comparison was made with several Dk 2.97 – 3.0 Dk materials. To start, measurements using IPC-TM- 650 2.5.5.5.1 type B were made to characterize the Dk and Df under the same test method and frequency (2GHz), then insertion loss measurements were made on 50Ω microstrip 0.030" samples using differential length method. Table 2 shows first, no matter what might be printed on a data sheet, Dk and Df values will vary based on the conditions of the test. Second, not all materials that appear to be interchangeable by comparing data sheets are truly interchangeable. And third, when comparing insertion loss, one finds that materials with higher loss tangent (as is the case for the thermoset laminate) are not necessarily the ones with higher insertion loss, due to the use of smoother copper to reduce conductor losses (and PIM, as will be discussed in the next section). Figure 2 shows cross sections of the conductor/substrate interphase and demonstrates the difference in roughness between 3 of the 5 samples characterized.

| Material type | Dk (2GHz) | Df (2GHz) | Ins Loss @ 2GHz |
|---|---|---|---|
| **PTFE/ceramic, woven glass** | 2.94 | 0.0009 | 0.024 |
| **PTFE/woven glass, ceramic** | 2.91 | 0.0018 | 0.029 |
| **PTFE/woven glass** | 2.92 | 0.0024 | 0.034 |
| **Thermoset/woven glass ceramic** | 2.99 | 0.0026 | 0.034 |
| **PTFE/woven glass, ceramic** | 3.0 | 0.0023 | 0.036 |

**Table 2. Electrical comparison of various Dk 3.0 materials.**

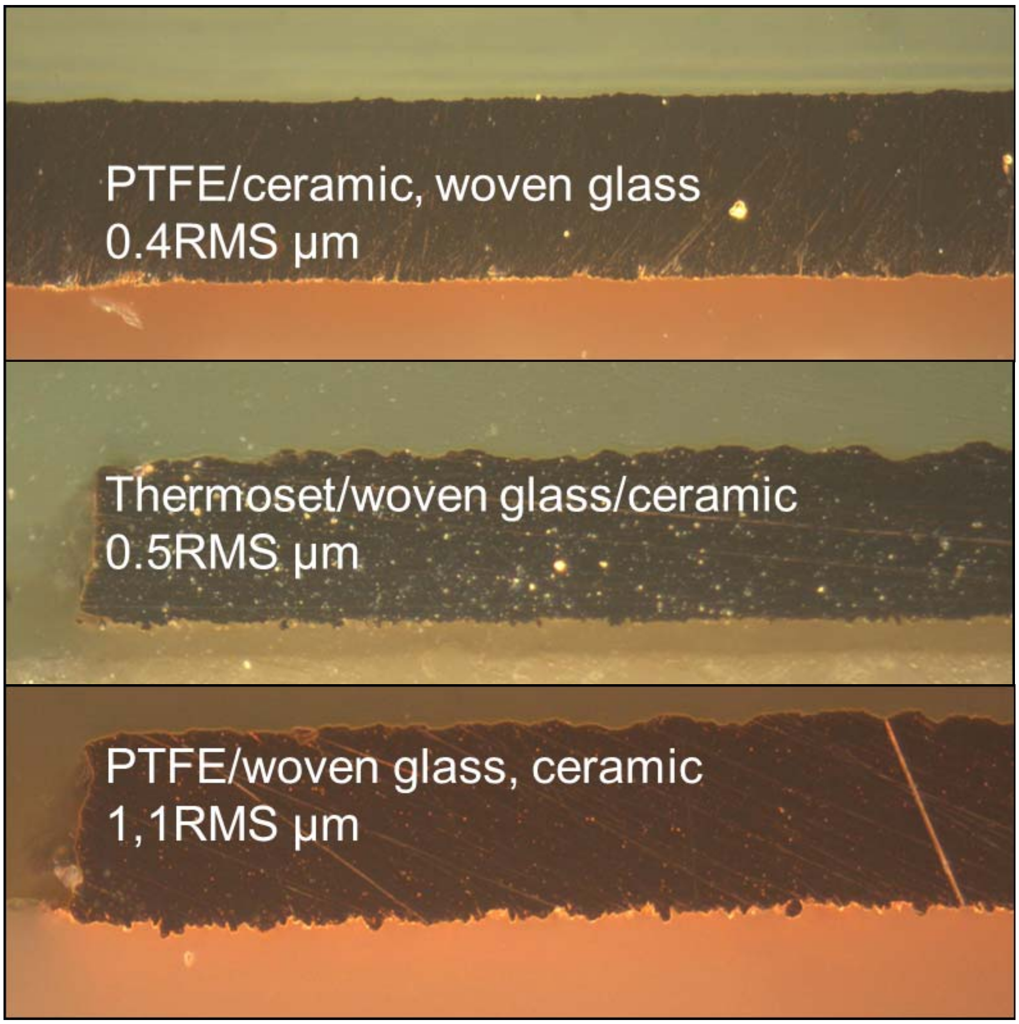


**Figure 2. Comparison of conductor/substrate roughness interphase**

Thermoset materials have shown to have the largest advantages over PTFE based materials in the area of multilayer board (MLB) designs. Usually this is not an area that antenna designer paid much attention to, since designs were mainly microstrip. Advances in design approaches have led to future systems integrating both the antenna and the amplifier in one common structure. This requires materials that not only are compatible with each other in MLB's but that are cost effective too. Thermoset RF materials have met the electrical and financial needs of power amplifier MLB designs for well over a decade. Now they also offer a unique solution to antenna designers today as they integrate amplifiers in the antenna housing.

**Laminate PIM Measurement**

While the International Engineering Consortium has published general guidelines for the testing of PIM (IEC Document 62037), no organization has a test method specifically directed to testing PIM generated in the laminate itself. Using a commercially available Summitek SI-1900b PIM tester, Rogers Corporation has developed a laminate test method, with the assistance of Summitek personnel following the IEC guidelines.

The standard sample consists of a 12" (300mm) long, 50 ohm transmission line printed and etched on a 0.060" (1.5 mm) thick laminate. The test samples are bonded to a 0.060" (1.5 mm) thick piece of FR-4 to increase the rigidity. Cutouts (figure 3) in the FR-4 allow DIN 7/15 low PIM coax-to-microstrip connectors to be soldered directly to the signal trace and ground plane. Four test samples are prepared on each laminate.

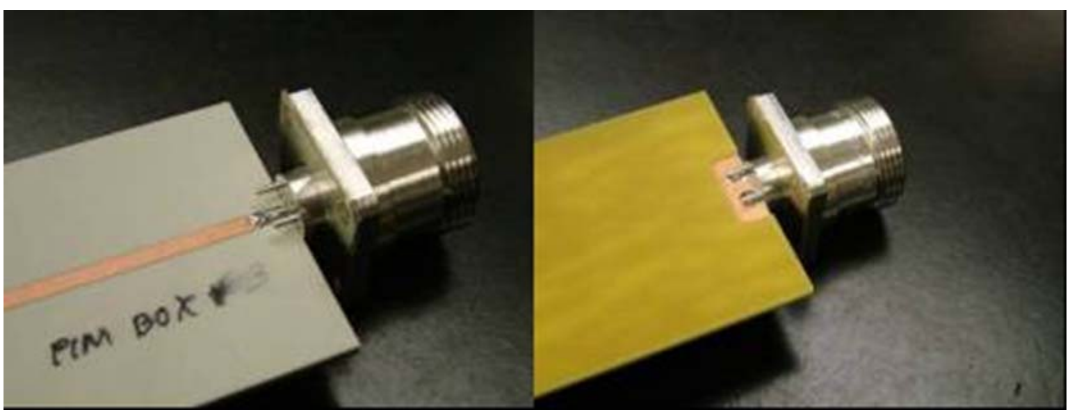


**Figure 3. Substrate PIM test coupon**

The reflected PIM measurements are made with two swept 43 dBm tones. The PIM values are reported as dBc (dB below the primary tone power level). Any particulate contamination is removed from the connectors with clean compressed air. The sample is connected directly to port 1 of the Summitek instrument and port 2 of the sample is connected to a low PIM load. The connectors are adjusted until the lowest stable PIM versus swept frequency output is achieved and the PIM value for that sample is recorded. The PIM values for the four samples are averaged. The procedure is repeated in a second measurement session on another day, and all eight values are averaged to yield the reported PIM value for that laminate.

The results of a repeatability study consisting of over 800 individual PIM measurements at PIM levels from –175 dBc to –125 dBc are shown in figure 4. The lowest PIM values were measured on the low PIM load connected directly to port 1. The approximate –125 dBc values were measured on experimental laminates that had been purposely contaminated with 5 wt. % of iron powder in order to generate a reliable high PIM sample. “Measurement 1” is the average PIM of the four samples measured on the first day and “measurement 2” is the average of the same four samples measured on the second day. With an ideal measurement system, a plot of measurement 2 versus measurement 1 would comprise the y = x line. Clearly, at PIM values of –140 dBc and higher, the measurements are quite repeatable. However, at PIM values of –150 dBc and lower, the 95% confidence limit for the average of a set of 4 measurements is ±6 dBc. Clearly, many repeated measurements are required to understand the differences in PIM levels generated in laminates.

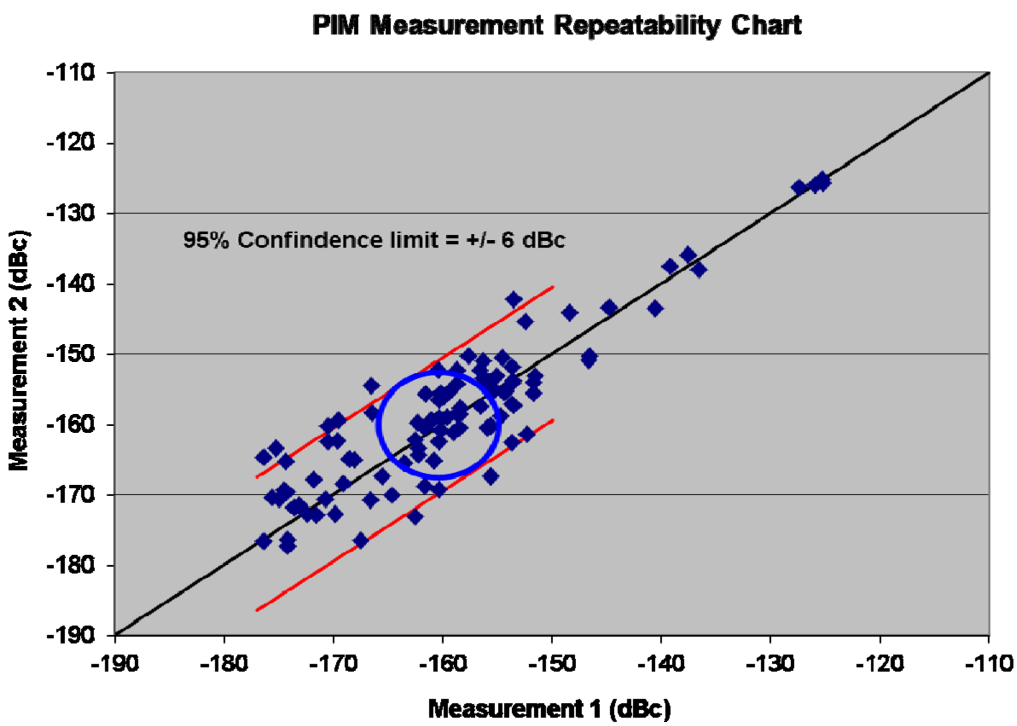


**Figure 4. PIM measurement repeatability for high frequency materials**

If consideration is limited to low loss dielectric materials and high purity copper foil without a nickel treatment, the major laminate variable that affects PIM is the copper profile. Although data scatter can be relatively large, it is Rogers experience that increasing foil roughness results in a significant increase in PIM.

Staying with Dk 3.0 materials, a study was conducted to compare various materials PIM measurements using the test method described here. Although many factors outside of the PCB material can and do contribute to PIM generation (e.g., connectors, solder connection), this evaluation serves as a guideline to understanding PIM in the substrates in a relative way (comparing materials tested at the same time and in similar conditions). Based on these results, one can see that one should not make a general characterization that PTFE based materials always have better PIM than thermoset based materials. Some do and some don't. What is important to note is there can be significant variation in the measurement for a particular product grade and ultimately, this property should always be verified by designers. Historically, PIM variation, lot to lot, has routinely affected quality control at base station antenna OEM's. Selecting a material for best PIM performance does not only reside in working with a substrate that yielded good values during design qualification, it is just as important to select a supplier that offers consistent performance over time.

| **Material type** | **Average PIM, dBc** | **PIM Range, dBc** |
|---|---|---|
| **PTFE/woven glass** | -168.8 | -160.2 to -172.9 |
| **PTFE/ceramic, woven glass** | -165.7 | -162 to -169.1 |
| **Thermoset/ceramic, woven glass** | -160.3 | -153.2 to -168.9 |
| **PTFE/woven glass, ceramic** | -154.8 | -152.9 to -156.7 |

Table 3. PIM measurements for various Dk 3.0 antenna grade materials.

## Conclusion

Wireless high speed communication access has become an everyday occurrence in many parts of the world today. The networks needed to provide this access require mode demanding antenna designs that maximize efficiency and minimize size and cost. To assist designers in achieving these goals, there are many design paths and material choices. Selecting the right approach is not just about electrical properties; it is also about partnering with the supplier base to provide consistent performance lot to lot and to work together to meet cost targets in this ever demanding market of wireless communications networks.