# Everything You Ever Wanted to Know About Laminates for Frequency Dependent Applications ... But Were Afraid to Ask (Part I)

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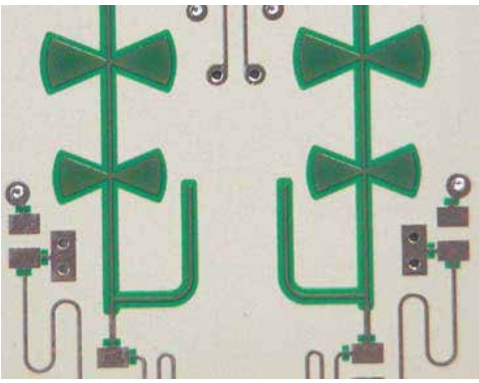
Arlon Materials for Electronics

**INTRODUCTION:**



In the earliest generations of printed wiring boards the etched circuits were little more than neatly laid out replacements for the tangles of wire that connected all the pins of the components (Do you remember vacuum tubes?) in "hard-wired" electronics. Some of us can remember owning the early 9-volt battery-operated "transistor radios" with their little printed wiring boards and generally scratchy reception of AM radio stations. In the latest "radios," many of which we know as "cellular phones" or "base stations," printed wiring is no longer simply a way to provide voltage bias or carry current from one place to another. In many cases the circuitry actually includes or is a part of active functional elements including amplifiers, power dividers, couplers, filters and antennas. This photo (left) is of a small part of a typical microwave PWB with printed and etched active components. At RF frequencies these active (and passive) components interact with the substrate material on which they are fabricated in ways that are determined by the frequency at which they operate and the requirements of their design. For instance:

- Circuit lines can become unintentional "antennas" for ambient signals and noise, especially if their length is close to the wavelength of a harmonic of the primary frequency;

— Closely spaced transmission lines may need to be "shielded" from one another to avoid coupling, or "cross-talk"[1];

— High-speed digital data transmission requires that wavefronts (consisting of an infinite number of harmonics of the primary frequency) remain coherent -- in other words the whole square wave signal gets where it's going at one time;

— Boards have capacitance and inductance that can distort signals both in-plane (in transmission lines) and as they go from one layer to another through plated vias;

— Circuit element size is inversely proportional to the square root of the relative dielectric constant of the PWB material;

— Etched antennas may be subject to Passive Intermodulation Distortion;

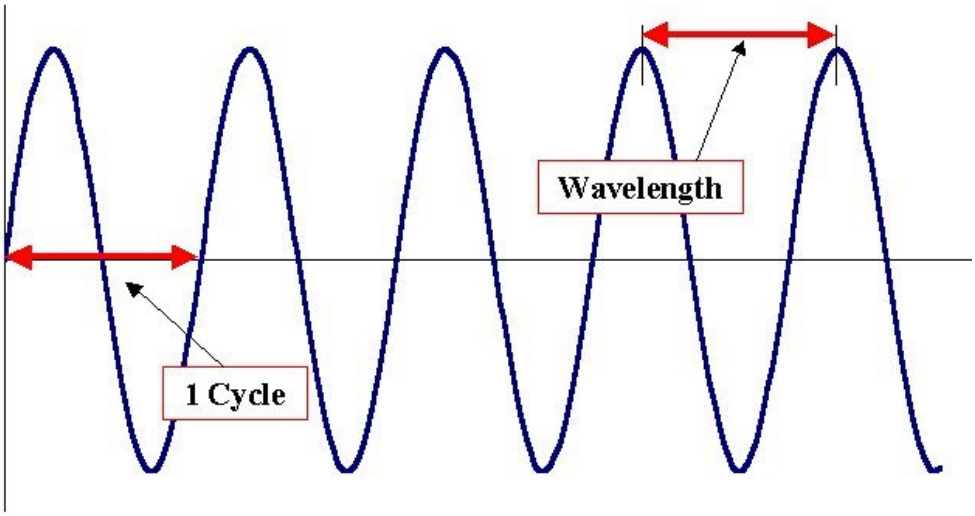
-- PWB's have to deliver controlled Impedance (and thereby avoid problems with VSWR -- about which we will disclose additional information later);

— And much, much more…

If there are any of the above that you don't deal with every day (but your customers do), then this article is for you. It is intended to introduce anyone who makes, buys or sells PWB's, but isn't a microwave design engineer, to the basics of RF/microwave signals and how those basics impact the laminate materials choices that are made in frequency dependent circuitry. With this information at hand you will not only better understand why your customers (or your engineers) are selecting the materials they do, but you will hopefully be better able to partner with them during their design process, when you can still impact the produceability of the product you will later have to manufacture.

**The Electromagnetic Spectrum**

For our purposes the electromagnetic spectrum is best surveyed in terms of frequency. The word "spectrum" as I use it here refers to the whole range of frequencies represented by the electromagnetic spectrum. In Gov-Speak, "spectrum" is tiny little bits of that range of frequencies that have been auctioned off by the governments of various countries, on the assumption that the government "owns" the right




to their use, for enormous amounts of money to companies that as a result can't afford to do anything with them.

If you envision a sine wave alternating between positive and negative values in a regular fashion (creatively called "alternating current?"), and if you count the number of times it goes back and forth through one complete cycle every second, you have frequency. The term used to characterize frequency is the Hertz -- named after Heinrich Hertz, the German physicist who first observed electromagnetic radiation in 1886. One Hertz is one cycle per second. Wavelength is the spacing between consecutive cycles. If you stuff twice as many cycles in the same space (i.e. double the frequency), the wavelength of each cycle will be half as long as the original.

**The Basic Mathematics of Electromagnetic Signals**

Frequency, wavelength and propagation velocity are all interrelated and this brief section will be the only one in which some simplified mathematics will be employed to explain how the interrelationship works.

The speed of light in a vacuum (designated $c_o$) is considered a fundamental physical constant and is given as 2.997952 x $10^{10}$ cm/sec although with your kind permission we will round it off to 3 x $10^{10}$ for ease of doing a few sample calculations. All electromagnetic waves travel at this velocity in vacuum regardless of their frequency. Please stick with me on the use of the standard metric units for this stuff, but it makes the examples much easier than translating into miles per hour, or furlongs per leap year. For a quick perspective, consider that the speed of light in a vacuum is 670,641,862.4 miles per hour.

How Are Velocity, Frequency and Wavelength interrelated?

Now here comes some of that math. Frequency and wavelength are related to the speed of light by the equation:

Eq. 1. $c_o = f\lambda$, where:
$c_o$ is the speed of light in a vacuum
$\lambda$ is the wavelength in cm
$f$ is frequency in Hertz

Example: What is the wavelength of a 10 GHz radar signal in deep space?

$\lambda = c_o/f$ (3.0 x $10^{10}$ / 10 x $10^9$) = 3.0 cm

When the electromagnetic signal is not traveling in the vacuum of space then its speed is slowed in inverse proportion to the square root of the dielectric constant of the medium in which it is traveling. In other words "stuff" slows down electromagnetic signals.

Eq. 2. $c = c_o/\mathrm{sqrt}(\varepsilon_r)$, where:
c = velocity of the signal in a transmission medium (your PWB) $c_o$ = velocity of light in vacuum (3 x $10^{10}$)
$\mathrm{sqrt}(\varepsilon_r)$ = the square root of the relative dielectric constant of the medium at that frequency

Example: What is the propagation velocity of a signal traveling in an FR-4 circuit ($\varepsilon_r$ = 4.5)?

$c=c_o/\mathrm{sqrt}(4.5)=3.0\mathrm{x}10^{10}/2.12=1.42\mathrm{x}10^{10}$ cm/sec (less than half of $c_o$)

Note however that in terms of highway speeds this is still a blistering 317 million miles per hour.

Analogously the wavelength will be reduced by the same factor since the wavelength in a transmission medium is determined by the signal speed in the medium:

Eq. 3. $c_o/\mathrm{sqrt}(\varepsilon_r)=\lambda f$ from which we derive

Eq. 4. $\lambda=c_o/(f * \mathrm{sqrt}(\varepsilon_r))$

Example: An etched antenna element is designed to be a quarter wave in length ($\lambda/4$). If an antenna is etched on a piece of woven glass reinforced PTFE laminate of dielectric constant 2.17, what will the length of the antenna element be if the system is designed to operate at 1.8 GHz (1.8 x 109 Hz)?

8 = 3 x $10^{10}$/(1.8 x 109 * sqrt(2.17)) = 11.3 cm, so $\lambda/4$ = 2.83 cm

With those simple relationships you can easily determine the velocity of a signal in a transmission medium (read "printed circuit board") and can calculate the wavelength at any frequency for that material. Thus endeth the math lesson. Take a quick look at common segments of the electromagnetic spectrum (Figure 3):

**A BRIEF SAMPLING FROM THE ELECTROMAGNETIC SPECTRUM**

**Definitions**: Hz = Hertz (Cycles/Second), KHz = Kilohertz = 1000 Hz, MHz = Megahertz = 1,000,000 Hz, GHz = Gigahertz = 1,000,000,000 Hz

**60 Hz** -- The Frequency of the electricity in your wall sockets

**1070 KHz** -- CBS Affiliate Station KNX 1070, AM Radio Los Angeles ("Traffic and Weather Every Six Minutes")

**88 MHz** -- The Low End of the FM Radio Band

**900 MHz to 1800 MHz** (**0.9 to 1.8 GHz**) -- Cellular Phone Transmissions

**Example**: CDMA (Code Division Multiple Access) is allocated two bands of frequencies: 824 to 849 MHz (Transmit) and 869 to 894 (Receive)

**9 GHz** (In the So-called "X-Band") -- AWACS airborne radar

**25-50 GHz** (Also referred to as Millimeter Wave because its wavelengths are below 1 mm in length) -- Local Point-to-Point or Point-to-Multipoint transmission systems

**75-90 GHz** -- Automotive Collision Avoidance Radar Systems

**500,000 to 1,500,000 GHz** -- "Light" Spectrum (The high frequency of light is why so much data can be carried on optical backchannels)

**And beyond** -- X-Rays and Gamma Rays

## What important characteristics of materials will impact the way they interact with electromagnetic signals?

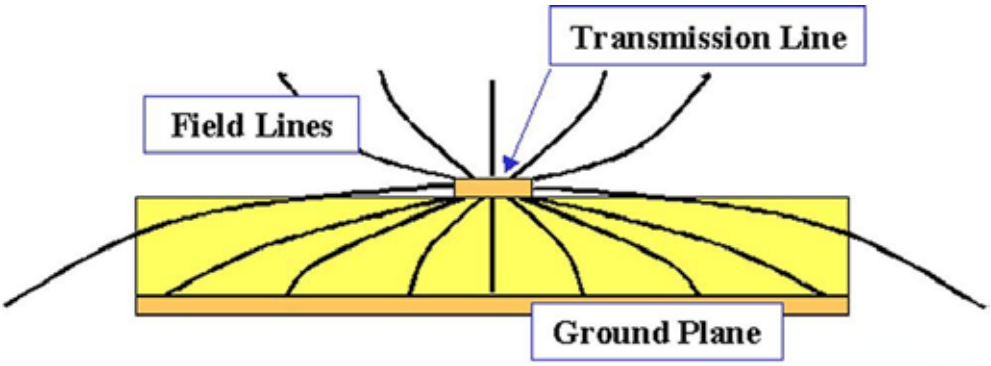
### *Dielectric Constant*

As we have already seen, the dielectric constant of a transmission medium affects the speed at which an electromagnetic signal travels in that medium. It does so because while we normally think of the "signal" as traveling in the copper transmission line (the etched circuit line on our circuit board) the truth is that signal has a radiating electromagnetic field associated with it that is "grounded" in a ground plane on the opposite side of the board (using a simple microstrip example). There is a well-established principle called the "skin effect" that says an electromagnetic signal travels at the very surface of the conductor. That means that the "footprint" of that electromagnetic signal has to run along in the higher dielectric constant of the printed circuit board that limits it to the speed it can travel in that medium.

In addition to signal speed (the inverse of which is called "propagation delay") the relative dielectric constant of a material affects the characteristic impedance (Zo) of a transmission line. Matching characteristic impedance between different sections and components of a high frequency system is very important. When there is a mismatch in Zo between components or sections, part of the signal can be reflected back along the transmission line which results in a.) added "noise" in that section of the line and b.) less signal strength going on down the line. The degree of this mismatch in Zo is sometimes referred to in terms of a ratio called the Voltage Standing Wave Ratio, or VSWR. So when somebody says your VSWR is out of synch, please don't get insulted -- first go check your impedance assumptions.[2]

Impedance is a function of laminate (and or prepreg pressed) thickness, etched copper trace width and height (cross sectional area) and, as you might expect from the above equations, the inverse square root of the dielectric constant of the transmission medium (your laminate). Variability in any of these will impact the absolute value of impedance and it involves print and etch precision, lamination conditions and the as-received laminate thickness and dielectric constant. Interestingly in most cases because the impact of dielectric constant is an inverse square root relationship, its effect even when it varies is usually less than that of the other components of impedance.

This is as good a time as any to talk about the fact that unlike the speed of light in a vacuum, dielectric constant really is not a constant, which is why we refer to a relative dielectric constant ("relative" is what the little subscript "r" stands for in ($\varepsilon_r$). Dielectric constant can vary markedly as a function of frequency as well as test method and conditioning. Dielectric constant of most materials will also vary with the temperature of the material, although some laminate products are produced that compensate for temperature and have a relatively flat TC$\varepsilon_r$ (Thermal Coefficient of Dielectric constant). One significant additional contributor to dielectric constant (and loss) variability may also be absorbed water -- since water has a dielectric constant of about 70 and a relatively small amount can make a measurable change in many



dielectric laminate materials. Good test protocols call for making measurements after drying and desiccating to ensure that water does not impact test results. But remember that in real life (your circuits out there and in use) it can, and will affect performance.

With all that in mind, let's jump back to the subject of what impact the dielectric constant of your laminate material has on the design of those high frequency circuits you are building. We have mentioned propagation velocity (or its inverse, propagation delay) and impedance. The other important aspect of dielectric constant on FR and microwave design is circuit geometry! Like the antenna we mentioned in the wavelength and frequency example above, virtually all frequency dependent circuit elements have specific geometries determined by the wavelength of the signal in the transmission medium (laminate). As long as the material is the right dielectric constant for the frequency and the design -- all is well. But if the dielectric constant is wrong, or changes excessively due to temperature, or if the etched circuit elements are not the right length and width, then the circuit may not behave properly:

A bandpass filter will pass some of the wrong frequencies. A resonator will resonate at the wrong center frequency. An antenna may "receive" some spurious signals. Or impedance of a long transmission line will change and result in VSWR problems. Remember that etched circuits are active elements, not just "printed wires."

***Dissipation Factor (Loss Tangent)***

In addition to the dielectric constant, a second and very important characteristic of any dielectric medium is its loss characteristic. Dielectric loss refers to the part of a signal that is lost in the dielectric medium. As high frequency signals (which are all alternating current, so they switch rapidly back and forth between positive and negative -- like that sine wave we looked at earlier) pass through a dielectric, the molecules of the dielectric attempt to orient themselves with the electromagnetic field of the signal. (Note: this orientation is analogous to the orientation of a magnetized compass needle in the earth's magnetic field -- remember when we talk about the electromagnetic spectrum that there is a magnetic field associated with it as well. Remember the old "Mr. Science" experiment in which you make and break a magnetic field next to a coil of wire and lo and behold, an electric current flows in the wire.) Torque is applied by the signal to the molecules of the dielectric, and while they actually do not fully "orient themselves" because for the most part the molecules in the resins in dielectric materials are "cured" or "crosslinked" and thereby relatively immobile, work is nonetheless exerted by the electromagnetic field in trying to orient these molecules. That work is dissipated as heat. Molecules such as PTFE that are inherently non-polar, that is that have no large relative positive and negative regions in the molecules, have little tendency to orient themselves in an electric field, and therefore have inherently low loss values. (We'll discuss PTFE in more detail later.)

Example: FR-4 Epoxy ($\varepsilon_r$ =4.5), using a relatively polar epoxy resin, has a typical loss value at 1 GHz of about 0.025, while a PTFE Laminate with Er=2.17 can have a loss as low as 0.0009.

The loss tangent of any given material, like its dielectric constant is dependent on frequency and test method. Loss can sometimes change significantly with frequency and it is not uncommon to see loss vary in a somewhat sinusoidal pattern as a function of frequency within a range. As a general rule over a range of frequencies, we expect to see loss become greater at higher frequencies because of the higher energy level of those frequencies.

Loss in power in a transmission line (which we call attenuation) is usually expressed in dB/inch and is the result of losses in the copper as well as in the laminate material. We ought to pause and go through one more brief mathematical exercise to define dB. Then we will give a couple of simple examples after which you'll never have to worry about the math again.3 The expression dB (decibel) is a measure of the ratio of the power out vs. power in (in this instance, a measure of signal attenuation, although gain, which has to do with signal amplification, can also be expressed in dB).

Eq. 5. dB = 10*log(Power Out/Power In)

Example: A signal of 1 Watt is attenuated to 0.5 W through an entire system. Express the power loss in dB.

dB = 10*log(0.5/1) log(0.5)= -0.30 10(-0.30) = -3.0 dB

3 dB of loss is referred to as the half power point, at which 50% of the power of a signal is attenuated.

In our examples we have referred several times to laminate materials based on PTFE. The one burning question that undoubtedly has been gnawing at you for several minutes now is: Why are these guys always talking about PTFE for high frequency circuitry applications? There are (as there always have been) laminate materials that are cheaper than PTFE, and some now have properties that appear to be almost as good as PTFE. So why is PTFE laminate still being used? There are some very good reasons for that that tie back to the fundamentals we have already discussed about properties and performance.

A few of the important properties of PTFE (polytetrafluoroethylene, or Teflon® if you prefer) should indicate why laminates based on this versatile resin are going to be around for a long time, and why they will continue to be the performance standard by which potential lower cost substitute materials will be evaluated and assessed.

1. PTFE is essentially non-polar. With no strong positive or negative sites on the molecule it's not going to be oriented in an electromagnetic field, and hence will not absorb much energy from the signal associated with that field. The loss characteristic

of pure PTFE (i.e. without a glass substrate) is less than 0.0004 -- and that's about as good as it gets. (Of course if our design for a copper-clad laminate with an air dielectric could get past the few remaining technical hurdles, we would really see a low dielectric constant and loss.)

2. PTFE has an inherently low dielectric constant (for pure PTFE it's about 2.1 at 10 GHz) that is stable over a wide range of frequency, so a low loss PTFE-based laminate can be and is used at frequencies well up into the millimeter wave range and beyond for such applications as automotive radar (75 GHz+) and millimeter wave point to point and point to multipoint data transmission systems.

   The coherent wave-front for a square-wave that we mentioned earlier depends heavily on the frequency independence of the transmission medium. This is optimal in PTFE because of the relative frequency independence of its dielectric constant.

3. PTFE is hydrophobic -- it has very low water absorption, which means that it is not subject to dramatic change in loss or dielectric constant as a function of relative humidity and temperature fluctuations. (Remember that water is highly polar and has a dielectric constant of about 70!) Materials that are highly susceptible to moisture uptake may be limited in their application.

4. PTFE melts somewhere above 700˚F and so it will be unlikely to be affected even as solder temps go higher. Other materials also have low dielectric constant and loss characteristics, materials such as polyethylene and polypropylene, but they are relatively low melting materials that will not survive the soldering and reflow processes that are part of PWB manufacture. With new lead-free solder technology coming into play, those solder temperatures could creep up by anywhere from 0 to 40˚C (depending on who you believe).

5. PTFE is essentially non-flammable (in any environment less than a 95% pure oxygen), chemically inert and non-toxic. You probably cook in PTFE (Teflon®) every day.

6. PTFE is a very versatile material from a compounding perspective, and can be combined with a variety of reinforcements and ceramic fillers to provide tailored properties all the way from Er=2.17 to Er=10, while still retaining the dielectric stability over frequency that is important to microwave and RF design engineers.

That said, PTFE is not being used in all elements of microwave and RF systems, and as we look at some of the components of a typical transceiver in the second part of this article, we will see that the "best" material is not needed in all areas, and that in some cases plain old FR-4 (or one of the PPO -- polyphenylene oxide -- modified epoxy systems that have proliferated in the last few years) can do the job perfectly well. Most cellular infrastructure systems contain a hodge-podge of materials, depending on the functional requirements of their subcomponents.

Now that you have absorbed the fundamentals of electromagnetic signals, in the second half of this article we will look in some detail at several high frequency applications, the laminate materials that are available, and why different materials might be selected for various applications.

**Everything You Ever Wanted to Know About Laminates for Frequency Dependent Applications … But Were Afraid to Ask (Part 2)**

Up to this point you've enjoyed some electro-magnetic appetizers, so-to-speak -- but now it's time for the main course. Which is to say that we are going to look at some actual RF applications, the material choices available, and why a designer might select one material rather than another based on the fundamental principles we discussed in the first part of the article. For those of you for whom much of this is already "common knowledge" read on -- you may learn something new and you will certainly read some of the subliminal propaganda for Arlon Materials for Electronics, which I have incorporated.

As a framework, we will refer to a simplified block diagram of a cellular transceiver, although you are probably aware that copper-clad laminates are used in a wide variety of other RF and high speed digital circuitry in applications from military radar to optoelectronics.

**What Important Properties of Designed Circuits Depend on Laminate Properties?**

This is sort of a trick question because designers have a plethora of options in terms of available materials, and because certain material properties (notably dielectric constant) can be "worked around," while others (notably loss) probably cannot as easily. The properties and characteristics of finished PWB's are dependent both on the intrinsic properties of the dielectric material and on the design and processing of the finished PWB.

**Characteristic Impedance and VSWR**

Characteristic Impedance (Zo) is critical in frequency dependent circuits, and more and more, impedance characteristics are often specified as part of the PWB purchase order. Impedance is critical when a signal is transmitted through the various elements of a system since, when there is a mismatch in impedance, part of the signal may be lost in the transition from one section to another. In fact that "lost" part of the signal isn't really lost at all -- most of it is reflected back along the original transmission line where it adds to the baseline "noise" in the system. Microwave engineers have coined two terms that characterize the degree of mismatch in characteristic impedance -- VSWR, or Voltage Standing Wave Ratio (pronounced "vizzer") and "Return Loss," which is a sort of inverse of VSWR the mathematics of which is well understood but beyond the scope of this introductory article. If you remember that a VSWR of 1.0 is perfect (no Return

Loss) while 1.3 to 1.5 is a typical design target, and very high VSWR ratios (10:1 or more) are so "leaky" that not enough signal is coming out at the far end to be of any earthly good[4], you will know enough not to be confused when you see it referred to in the literature.

### *Line Attenuation*

Anytime you see the word "attenuation" in a discussion of RF and microwave signals it means the signal is being made progressively weaker. It is the opposite of "gain" and "amplification" and while sometimes attenuation is necessary and desirable, we usually think of it as a signal "take-away." Impedance mismatch results in signal attenuation as the result of signal loss at a connector or interface, much like "pressure drop" occurs in a water line when the water passes through a ball valve or adapter.

Line attenuation is the continuous reduction in the strength of a signal as it travels down an etched line on a PWB. There is attenuation in shielded cables as well -- as much as 50% of the power is lost (remember -3 dB) as a signal is cabled from a base station up to the top of an antenna tower. This is one reason we hear a lot of talk about "tower top electronics." Line attenuation results from signal loss into the dielectric material itself (we discussed the electromagnetic "footprint" that has to drag along in the material) and resistance in the copper trace. The smaller the area of the copper that a signal has to travel along the greater the copper attenuation (electrical resistance gets greater as that area is smaller) so as designers start to try to conserve space by making their lines thinner and narrower, guess what, they impact their signal attenuation. Attenuation is typically expressed in terms of dB/in. To give you an idea of the impact of material, here are examples of attenuation in a 50-ohm transmission line in two different materials:

FR-4 (Er = 4.5, loss = 0.025)
at 1 GHz = 0.19 dB/inch
at 10 GHz = 1.27 dB/inch

PTFE-Glass (Er = 2.17, loss = 0.0009)
at 1 GHz = 0.067 dB/in (very close to the loss of the copper alone)
at 10 GHz = 0.22 dB/inch

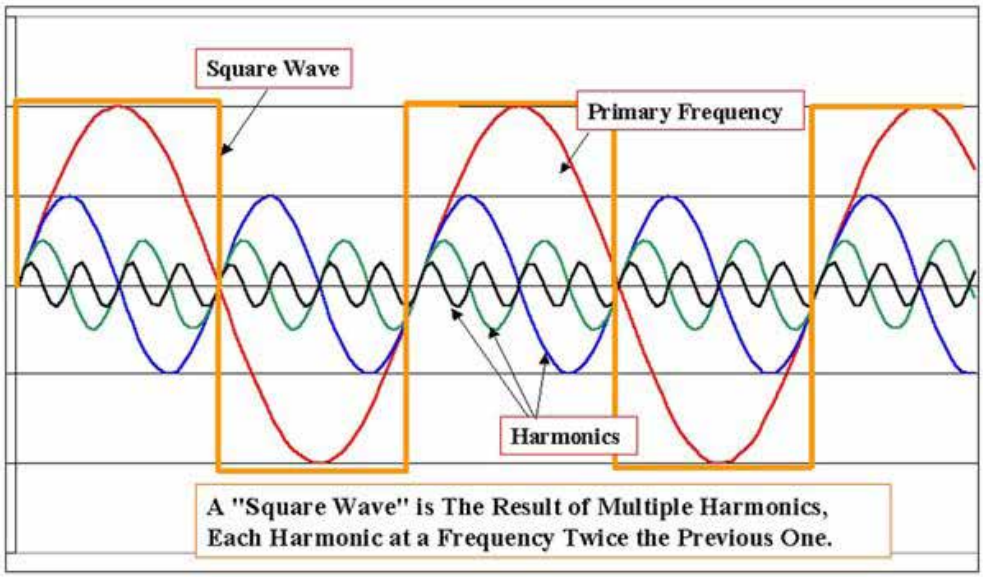
Signal attenuation can be minimized in design in different ways. The designer can simply try to minimize the run lengths for every critical trace, and when it is possible to do this without otherwise overcomplicating the design, lower loss (and lower cost) materials can be used in the designs. The alternative is to design with a material such as a PTFE laminate with very low dielectric loss, which is the preferred method where line lengths must be long, such as in high gain antennas.

### *Signal Integrity*

The signal has to get from where it originates to where it is headed without being lost in the noise floor (excessive attenuation, see above)) and without being distorted or otherwise modified in the process. One good example of that is in the area of high-density digital data transmission where the preferred form of the signal is a "square wave." Since mathematically (and physically) a square wave is the mathematical sum of the primary signal and its odd numbered harmonics, when this signal travels along a transmission line it is necessary for all the harmonics (each of which is at a different -- and higher -- frequency) to travel at the same speed. But if you recall we indicated that the speed of transmission was related to the dielectric constant, and the dielectric constant was related to the frequency. So if a 10 GHz signal with harmonics at 20 GHz and 40 GHz are all traveling down a transmission line, how can we be sure they will all get there at the same time, maintaining the square wave and avoiding a "fuzzy wave front?" We will hopefully choose a material, probably PTFE-glass, in which the frequency dependence of the dielectric constant is very low.

### *Passive Intermodulation Distortion*

Another signal integrity issue is Intermodulation Distortion. Passive intermodulation distortion (PID) occurs when two or more signals are present in a transmission line at the same time and the system becomes nonlinear (such as at the high end of a power curve). The 3rd and 5th harmonics of the two signals can in such a case interfere with a signal being handled at a nearby frequency. Often in a GSM phone system the center frequency of the transmit (high power) signal is very close to the frequency of the much lower powered receive signal. The intermod products act as "noise" and can overwhelm the much lower powered receive signal.



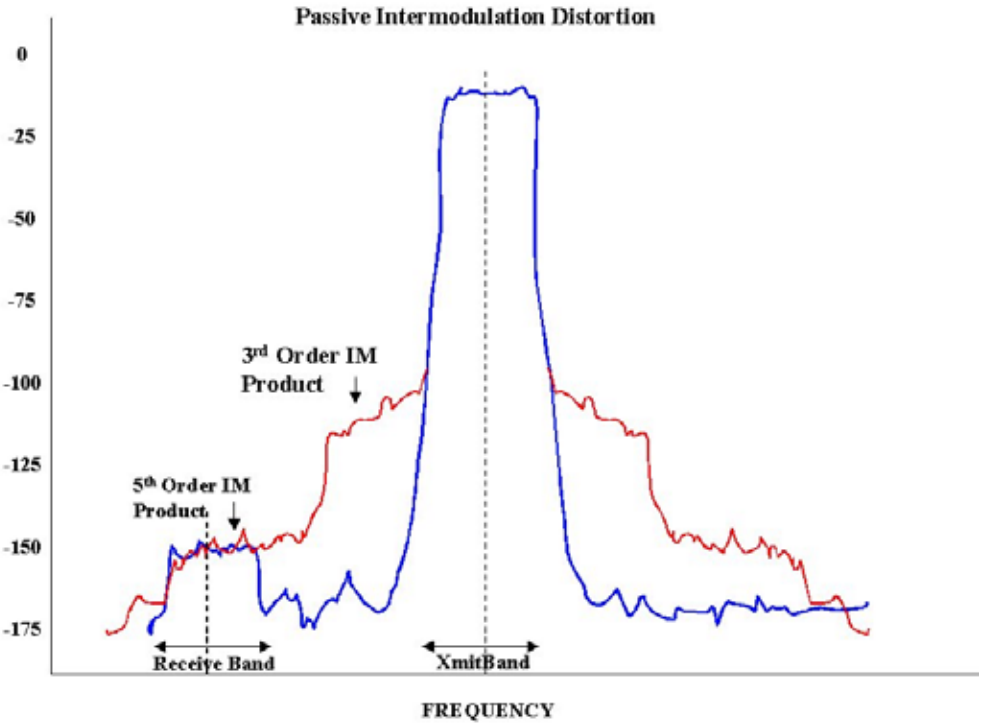
This illustration of PID shows this clearly. If you remember how close the send and receive frequencies are for the CDMA bands, you can easily imagine that a strong intermodulation effect in the 5th harmonic from the transmit band could overwhelm a weak incoming signal. All well and good if you are talking on the phone and a word or two drops -- you can almost always figure out what was being said. But if high volume digital data is interrupted too often or for too long, it becomes a steady stream of dubious digital drivel, or it requires a lot of extra bandwidth to resend lost data. While most PID results from problems with metal-to-metal connections, and is worst in the nonlinear portion of the power curve, the laminate industry has been able to design copper clad laminates that minimize the impact of PIM and are permitting etched PTFE antennas to be used for more demanding 3G cellular systems where digital data transfer will require much better signal integrity. Requirements for Passive Intermodulation Distortion below -155 dBs are typically desired in antennas for digital data transmission in 3G systems.

***High Dielectric Constant and Thermal Conductivity***

I'm including these together, and treating high dielectric constant as a separate subject because in many cases the two are related. The most salient example is the use of high dielectric constant copper clad materials (dielectric constant 10) in high power base station amplifiers for cellular infrastructure. Such products are generally produced by loading PTFE with a high dielectric constant ceramic powder. The use of a high dielectric constant material allows the designer to shrink the circuit patterns substantially because, as you will remember from Microwave 101 the higher the dielectric constant, the smaller the wavelength, and therefore, the smaller the circuit elements need to be.

There are additional benefits. The base station's size can be reduced significantly which will make all the local zoning boards who want cellular phone service but don't want to have to actually SEE the equipment that is broadcasting the signal in their community (it's OK if the next town has the big tower and the 200 pound gorilla amplifier) happy, and will make it easier for the installation and repair guys to haul it around. Equally important, because high Er materials normally have higher thermal conductivity (one of the side benefits of loading them with ceramic fillers) they manage the dissipation/diffusion of the heat generated by this 50 Watt+ amplifier better than the lower Er material without the filler.

There is a whole subcontinent of discussion we could have about the use of so-called soft substrates (to which I am referring in this article) vs. ceramic substrates (to which I am not) and the degree to which there is interchangeability, cost advantage and technical tradeoffs to be considered, but that's for another time…



| | Low Er Low Loss PTFE | Low Cost PTFE Grades | Stable Er PTFE -40 to +140C | High Dielectric Constant PTFE | Low Cost Low Loss Thermoset | FR-4 Epoxy Laminate 4.5 |
|---|---|---|---|---|---|---|
| Dielectric Constant (1 GHz) | 2.17 | 3.2 | 2.98 | 10 | 3.38 | 4.5 |
| Dissipation Factor (Loss) | 0.0009 | 0.003 | 0.0025 | 0.003 | 0.0025 | 0.025 |
| CTEr | -160 | -100 | nil | -233 | -25 | +200 |
| Thermal Conductivity (W/m-K) | 0.25 | 0.3 | 0.5 | 0.65 | 0.5 | 0.25 |
| CTE (ppm/C) X-Y | 25 to 35 | 9 to 12 | 10 to 12 | 14 to 16 | 15 to 18 | 16-18 |
| CTE (ppm/C) Z | 250 | 70 | 40 | 37 | 55 | 60 |
| Peel Strength (1 oz.) lb/in | 12 to 15 | 12 to 15 | 5 to 8 | 4 to 6 | 4 to 6 | 8 to 10 |
| Arlon Example | DiClad 880 | AR-320 | CLTE | AR-1000 | 25N | 45N |
| Note(s) | High PTFE % Woven Glass | Heavy Glass Reinforced | Ceram Filled PTFE | Ceram Filled PTFE | Ceram Filled FR Avail | Multifunctional Epoxy |

### *Now I'm a Graduate of Microwave 102 — So What?*

We characterize materials in terms of properties that are relevant to several "audiences:" a.) the electronics designer (who is chiefly interested in the electrical properties of the finished PWB); b.) the reliability guys, who would like to be sure that when received and after a reasonable period of use, the circuits still function as designed c.) the Cost Containment Contingent, of whom from this vendor's perspective there seem to be more than there are electrical designers; and d.) the PWB manufacturer (who would like to have a material that can pass through a complex system of mechanico-chemical processes and meet the specifications handed to them by a.), b.) and c.) above with 97%+ process yields.

Just a few of the critical properties that we look at (not necessarily in order of importance, since that varies with the application) are:

— Dielectric Constant (aka permittivity)

— Dielectric Loss (aka loss tangent, tan-beta and dissipation factor)

— Thermal Coefficient of Dielectric Constant ($TC\varepsilon_r$)

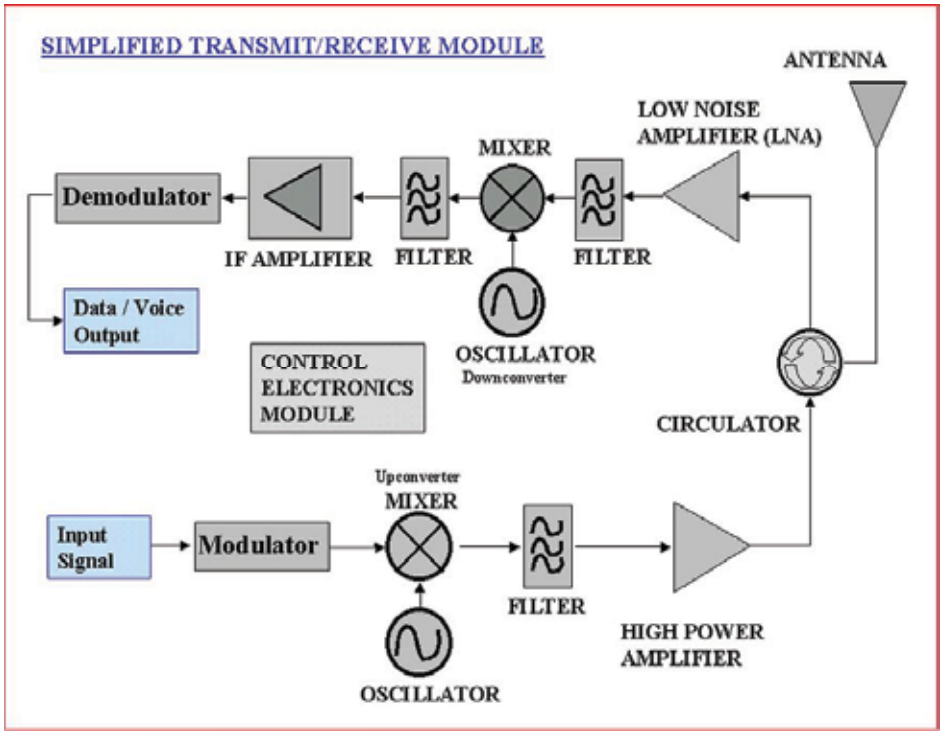
— Coefficient of Heat Transfer (W/m-°K)

— Coefficient of Thermal Expansion -- X, Y and Z (ppm/°C)

— Peel Strength -- How well the copper is bonded to the resin (lb/in)

And many more including process details, but the purpose of this article is to give you guiding principles, not detailed data sheets, which you can find at www.arlonmed.com and other fine websites situated at designated exit ramps along the information superhighway.

Materials for frequency dependent applications come in a wide variety of shapes and sizes and there are several suppliers of such materials. The following is a short chart that lists a number of material types, mostly based on PTFE, that are widely used in the RF and microwave world with a couple of non PTFE "reference materials" that represent either lowest cost and standard processing (FR-4) or Low Cost Low Loss options (thermoset olefinic materials). Although I have mentioned specific Arlon products as examples, other suppliers of PTFE materials often have functionally equivalent or alternative products that serve similar end applications.



**A Microwave Transceiver. What Materials Might be in it and why?**

Pictured above is a simplified GSM transceiver that we will now use to try to put "rubber to the road" in terms of how to choose materials for various applications based on their properties and the requirements of the design.

To "keep it simple" we are going to look only at a few key elements of the system, but those represent a variety of demands and requirements that will let us see how many of the available materials can be and are being used. Some of the subsystems of a GSM base station might include:

— Antennas

— Amplifiers and Filters

— IF Systems

— Modulation/Demodulation

— Control Electronics

Some very critical elements of any cellular base station are the receiving antenna and the LNA (low noise amplifier) and filter(s) immediately inboard of the antenna. Because the signal coming into a base station is very low powered (your cellular phone probably generates around 0.1 watt of power (compare that with 50 Watts or more that the same system sends out at the transmit end) it needs to be handled with TLC to avoid getting lost in the noise floor. Designers of high gain receive antennas normally will want a material with very low loss tangent. A PTFE laminate with loss under 0.001 at 1.8 GHz is an ideal choice for such an application, and, since such material is sold in large volume for antenna applications, it also represents a surprisingly economical approach. For some newer designs in which antennas are being combined on single boards with filters or even LNA's, the low loss characteristics are even more important.

On the other hand while the transmit antenna way well also want to be a low loss material for maximum radiating efficiency and to mitigate the impact of passive intermodulation distortion, the amplifiers and filters on the transmit side may well be made with a commercial grade of PTFE or with a low loss thermoset material. Here the higher loss of the products is offset by the available power on the transmit side, and can represent a significant cost savings over traditional PTFE products.

Intermediate Frequency (IF) subcomponents and modulator and demodulator blocks are often able to use a lower cost low loss product, although as TX/RX (transmit/receive) frequencies get higher and higher as in point to point and point to multipoint data distribution systems, it will become desirable to have lower loss materials to minimize power drain and signal deterioration, especially if the signal has to be upconverted and amplified through numerous steps. The diagram I have used assumes a simple one step up-conversion and down-conversion, using a 500 MHz local oscillator/mixer to bump a 400 MHz IF signal up to a broadcast frequency of 900 MHz. In reality multiple steps may be used in some systems and no real system is as simple-minded as I have made this one appear to be.

Control electronics will normally be made of FR-4 -- conventional epoxy. These circuits provide instructions to the rest of the system concerning what to do, when and how, and provide control voltages as required, but are not directly in the signal processing path so do not have to have the "microwave" properties needed for the other components.

For each component of a system the designer needs to determine what is critical and what is not and assign them some kind of relative cost-performance weighting. Designers and Cost-Containment Engineers look, not at raw material (laminate) cost, but at finished PWB pricing. As a supplier of PWB's you can influence the designers to make the best choices of materials by understanding the basis by which he chooses his materials, and by being flexible in your ability to process and work with the various alternatives. Your experience in many cases can help a designer make the right choice without having to be concerned that his boards will be functionally problematic. In many cases the selection of a "low cost" product is offset by the need for the OEM to use expensive and laborious mechanical or laser to "tune" his circuits one at a time to bring them into spec. If a somewhat higher priced raw material can reduce that "tuning time" because it is tighter in thickness or dielectric tolerance, it may well be the real "low cost option" after all, something you as a board supplier can influence based on your own experience and expertise.

**To summarize some of the key points:**

Quo Vadis? Where are we Headed?

Nothing stands still, and this is as true of the laminate materials industry as any other. As the top end wireless service providers struggle to make efficient use of their very expensive spectrum (billions have been spent on frequency spectrum in the US and Europe) we are hearing people talk much more about optoelectronics, the combining of RF and optical components on single PWB's. To handle high GB/s (gigabit per second) digital data transfer rates, many are talking about processing at 10 GHz or higher, and that certainly will shift upward all the requirements for materials that are frequency stable in dielectric constant in addition to adding complexity in terms of processing and manufacture as some boards have to become micro-optical benches in addition to high frequency circuit boards.

To handle immense amounts of digital data we believe that many PWB's that have to operate at high frequency will also be HDI (high density interconnect) boards with narrow lines and spaces and very high interconnect density levels. In addition to low loss and dielectric constant, such materials will require improved dimensional stability (for improved layer to layer registration)

| ISSUES AND ANSWERS -- Selecting the Right Laminate for Frequency Dependent Applications | |
|---|---|
| **Requirements** | **Laminate Solutions** |
| Low Loss is a Must | PTFE Grades are available with loss as low as 0.0009 |
| Temperature Stability is Critical | Ceramic-filled Temperature stable grades are available |
| Low Propagation Delay is Critical | PTFE Laminates are available with Er as low as 2.17 |
| Circuit Miniaturization is Needed | Laminates with Er of 6 and 10 are readily available |
| Thermal Conductivity is Needed | Ceramic-filled laminates have higher thermal conductivity |
| Cost is the Issue | Commercial PTFE and Thermoset products are available |

for use in large optoelectronic backplanes. Even FR-4 may not be dimensionally stable enough for these applications, and laminate products based on Thermount®, a nonwoven aramid reinforcement with lower dielectric constant, capable of high speed laser microvia formation, with outstanding registration stability will almost certainly find their way into low-loss applications including backplanes, BGA's and others.

In Closing…

If there is a lasting message to be found in this discussion of materials for high frequency electronics, it may be that you, as the suppliers of microwave PWB's, will continue to become more involved in understanding the basis for the selection of board materials so you can discuss the subject of material and process intelligently with designers. Why? So they can design circuitry that not only will work elegantly in terms of its electronic sophistication, but so that you can produce it in acceptable yields and make a buck making them (and you) happy!

Every time designers and board producers sit in the same room to talk about design and manufacturing, part of the discussion may be over the board producer's head (the esoteric scientific design stuff) and part may be somewhat mysterious to the designers (the incredible mystical process of board-making). In the end as the group as a whole becomes better informed, we will all understand one another's needs, concerns and issues and work together better to produce a final product. If this article has helped in any way to facilitate understanding and some interaction, it will have accomplished a great deal.

**About the Author…**

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Additional information about Arlon, including the text of "Everything You Ever Wanted to Know…" can be found at www.arlonmed.com. You can contact Chet directly by e-mail at cguiles@Arlon-med.com

## REFERENCES


1. Weisman, Carl J.: The Essential Guide to RF and Wireless, c. 2000, (Prentice-Hall PTR, Saddle River, NJ)

   This little volume is a great introduction to the functional elements of FR and Wireless systems. I found it invaluable in developing a sense of what all those gizmatches you see in a wireless block diagram really represent. Recommended reading for anyone who is peripheral to the wireless world but really wants enough information to be dangerous.

2. Gipprich, J., and Stevens, D.: A New Via Fence Structure for Crosstalk Reduction in High Density Stripline Packages, 2001 International Microwave Symposium Digest, IEEE (Phoenix, AZ -- May 2001)

   This article is a real-life example of how the properties of materials influence and affect the design of microwave and RF circuits in ways that would not have been imagined in strictly traditional "printed wiring" applications.


*Teflon® and Thermount® are trade names of the Dupont Company, Wilmington, DE*


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