Everything You Ever Wanted to Know About Laminates for Frequency Dependent Applications . . . But Were Afraid to Ask

By Chet Guiles

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 in "hard-wired" electronics. (Do you remember vacuum tubes?) Some of us can remember owning the early 9-volt battery-operated "transistor radios" with their little PWBs, 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. Figure 1 is a photo 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 determined by the frequency at which they operate and the requirements of their design.

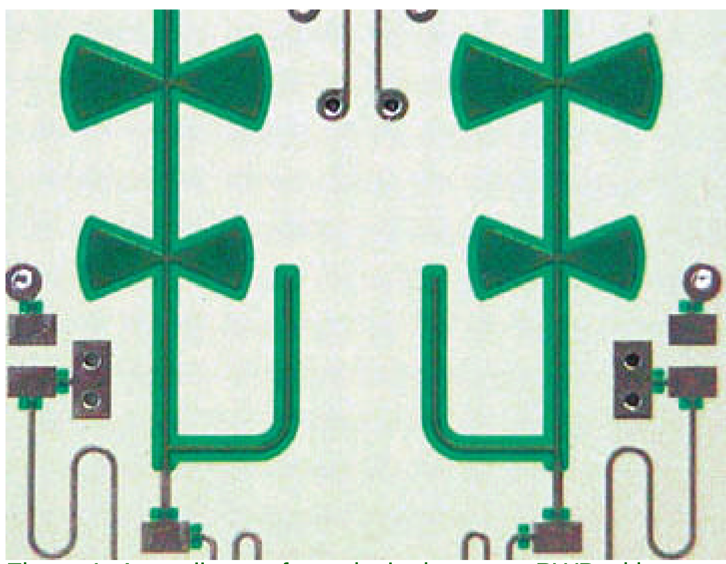

Figure 1. A small part of a typical microwave PWB with printed and etched active components.

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"
- 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 to 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
- PWBs must deliver controlled impedance (and thereby avoid problems with VSWR---which we will discuss later)

If you don't deal with any of the above issues every day (but your customers do), then this article is for you. It is intended to introduce anyone who makes, buys, or sells PWBs, 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 later must manufacture.

The Electromagnetic Spectrum

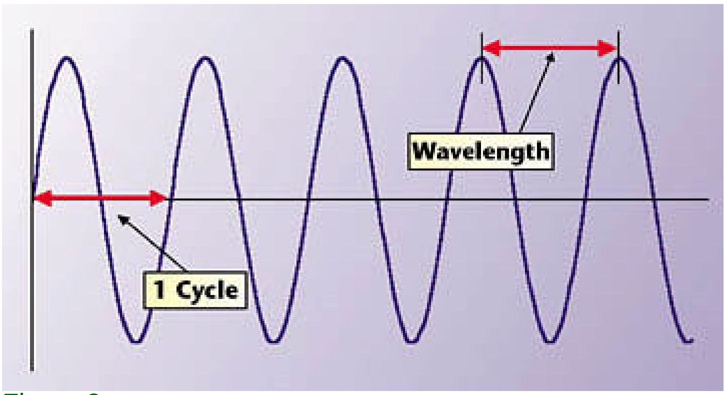

Figure 2.

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 Government-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 2.997952×10^{10} cm/sec, although with your kind permission we will round it off to 3×10^{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:

Equation 1:

$c_o = f\,\lambda$, where:

c_o is the speed of light in a vacuum (3×10^{10} cm/sec)

λ is the wavelength in cm

f is frequency in Hertz

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

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

Equation 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 (3×10^{10})

$\mathrm{sqrt}(\varepsilon_r)$ = the square root of the relative dielectric constant of the medium at that frequency

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.

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

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

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:

Equation 3:

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

For 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 (1.8×10^9 Hz)?

$$\lambda = 3 \times 10^{10} / (1.8 \times 10^9 * \mathrm{sqrt}(2.17)) = 11.3 \text{ cm, so } 8/4 = 2.83 \text{ cm}$$

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 Figure 3, illustrating common segments of the electromagnetic spectrum. What important characteristics of materials will impact the way they interact with electromagnetic signals?

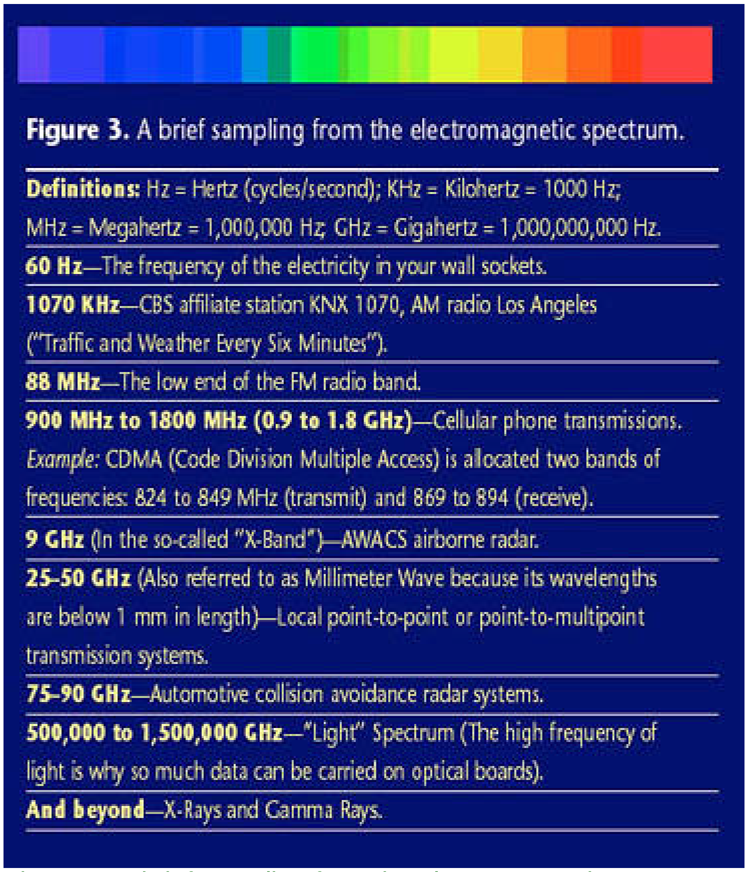

Figure 3. A brief sampling from the electromagnetic spectrum.

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 boards).

And beyond—X-Rays and Gamma Rays.

Figure 3. A brief sampling from the electromagnetic spectrum.

Dielectric Constant

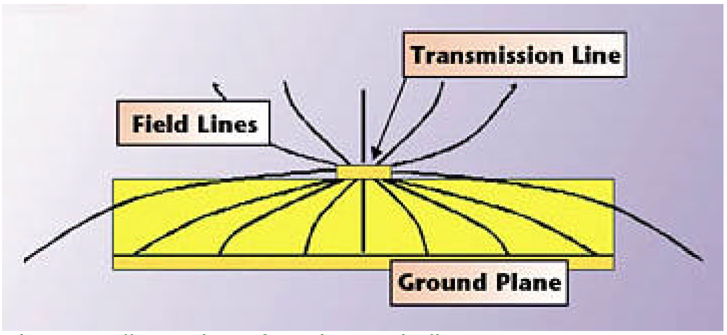

Figure 4. Illustration of a micro-strip line.

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 added "noise" in that section of the line, as well as 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 (VSWR). So when somebody says your VSWR is out of sync, please don't get insulted-first go check your impedance assumptions.

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 subscript "r" stands for in ε_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
- 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.)

For example, FR-4 Epoxy (ε_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 ε_r = 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.

Equation 5:

$$dB = 10^{*} \log (\text{Power Out}/\text{Power In})$$

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).

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 that tie back to the fundamentals we have already discussed about properties and performance.

PTFE Properties

A few of the important properties of PTFE (polytetrafluoroethylene, or TeflonR if you prefer) should indicate why laminates based on this versatile resin will 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 as a result 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 degrees 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 30-50 degrees 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 (TeflonR) 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 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. See you next month for Part II.

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