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Material Choices and Tradeoffs for Printed Circuit Board Antennas

Antenna designers must consider variations in dielectric constant and temperature coefficient of the PCB laminate

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Printed-circuit-board (PCB) antennas enable a wide range of wireless communications products. Properly designed, they can deliver excellent performance in extremely compact sizes. PCB antenna designers have a range of circuit materials from which to choose, and that choice can have significant impact on the performance of the final design. Before making a decision on PCB antenna materials, however, it may help to review some of the basic material properties important for PCB antennas as well as the various tradeoffs associated with some of the candidate materials.

PCB materials for wireless or RF/microwave antenna applications are differentiated by many of the same parameters used to evaluate such materials for standard planar circuits, including the dielectric constant or relative permittivity (ε_r) and the dissipation factor (Df), and key thermal characteristics, including the coefficient of thermal expansion (CTE) and the thermal coefficient of dielectric constant (TcDk). The dielectric constant, sometimes known as Dk, refers to the amount of energy that can be stored in a material by an applied voltage relative to the amount of energy that can be stored in a vacuum. Similarly, Dk is sometimes considered as the amount of capacitance possible from a capacitor that would be formed from a material relative to the amount of capacitance possible from a capacitor formed using a vacuum in place of the dielectric material. The dissipation factor, Df, is a measure of how much dielectric losses are associated with a particular PCB material.

The dielectric constant is a starting point for many PCB material selection processes. Although it can be measured in all three axes of a PCB material, the value in the *z*-direction at a particular test frequency, such as 10 GHz, is typically used for comparison in high-frequency RF/microwave applications. PCB materials with *z*-axis Dk values ranging from about 2 to 10 are most commonly used for RF/microwave circuit applications, and those materials with the lowest Dk values most often used for PCB antenna applications.

Because of manufacturing tolerances, the nominal Dk value of a particular PCB material can vary from one manufacturing lot to another. Depending upon the raw materials and the processes used to make the final PCB material, the nominal Dk value will usually fall within a known window. For example, a PCB material with a Dk tolerance of ±0.05 is considered quite good, although materials with even tighter Dk tolerances are available. For an antenna designer, the Dk is important because it relates to the center frequency of a PCB antenna; a tight Dk tolerance will result in less variability in the center frequency of PCB antennas fabricated with that material.

PCB materials with lower Dk values generally support circuits with higher center frequencies, although the thickness of a PCB material and the circuit pattern used for an antenna can also play parts in the final performance. PCB antennas such as those formed from microstrip radiators are wavelength dependent, so the physical dimensions of a PCB antenna's circuit features are directly related to the wavelengths of the frequencies of interest. But those dimensions are also a function of the Dk value: using a PCB substrate with a higher Dk value will enable smaller circuit features and allow reduced antenna size for a given frequency.

dk	Antenna radiator size			% area	50Ω Conductor Width
	Length (in.)	Width (in.)	area (in.^2)	reduction	Feed line (mils)
3	1.342	0.835	1.12057	baseline	76
4	1.162	0.747	0.868014	23%	62
6	0.952	0.632	0.601664	31%	45
10	0.742	0.504	0.373968	38%	29

TABLE 1
Microstrip patch antenna dimensions at 5 GHz, for several Dk values.

An antenna may be called upon to transmit (or radiate energy), or receive, or both. Its required functionality may also play a part in the type of circuit material used for a PCB antenna since materials with higher Dk values tend to radiate less than circuit materials with lower Dk values. As Table 1 shows, as a PCB material's Dk value increases, the physical dimensions of a microstrip patch radiator decrease for the same center frequency of 5 GHz in each case. At the same time, the increasing value of Dk results in smaller dimensions for the transmission lines serving as the feed line for the antenna pattern, where a characteristic system impedance of 50 ohms is being sought in each case. Any circuitry associated with the feedlines for the antenna can be significantly reduced by using a material with a higher Dk value, although other PCB material parameters, such as Df, will influence the overall performance of the design.

When fabricated on 30-mil-thick substrate materials with different values of dielectric constant (Dk), a microstrip patch radiator antenna pattern must use smaller dimensions with increasing Dk value to maintain a center frequency of 5 GHz. Similarly, the conductor dimensions are reduced with increasing Dk value to maintain the characteristic impedance of 50 ohms.

A PCB material's Df, for example, can affect the loss of the 50-Ω transmission lines that feed energy to and from an antenna's radiating elements. To maximize the amount of energy delivered to and from the antenna's resonant structure, the loss of the feedlines should be minimized, which usually suggests the use of a PCB material with low Df. While a PCB material with high Dk can help reduce the dimensions of the antenna's resonant structure, it will also result in a reduction of the width of the transmission lines that feed energy to and from the resonant structure (see Table 1), with corresponding increase in loss for those lines. Any attempt at miniaturizing an antenna's resonant structure by using a PCB substrate with high Dk value will also bring the tradeoff of narrower antenna feedlines and their associated higher losses.

A PCB material's coefficient of thermal expansion (CTE) provides an indication of the dimensional changes in the material as a function of temperature. Since the material will be subjected to a certain amount of temperature cycling as part of normal circuit fabrication and assembly processes, a low CTE (less than 70 ppm/°C) helps minimize material expansion and contraction with changing temperature. Ideally, the CTE of a circuit dielectric substrate would match that of the copper conductors, which is 17 ppm/°C, so that both materials would expand and/or contract by the same amounts during thermal cycling. Although it is rare to formulate a PCB material with the same CTE as copper, a circuit material with CTE of 40 ppm/°C or less is considered quite good and typically provides reliable circuits even after the thermal cycling associated with production processes.

PTFE-based circuit materials offer excellent electrical properties for antenna applications, but some of these materials exhibit CTE values of greater than 100 ppm/°C, making them less than ideal for handling the thermal cycling of production processes. However, ceramic-filled PTFE circuit materials maintain many of the excellent electrical properties of PTFE-based materials, while using the ceramic filler for improved thermal stability.

Materials with higher CTE values will undergo

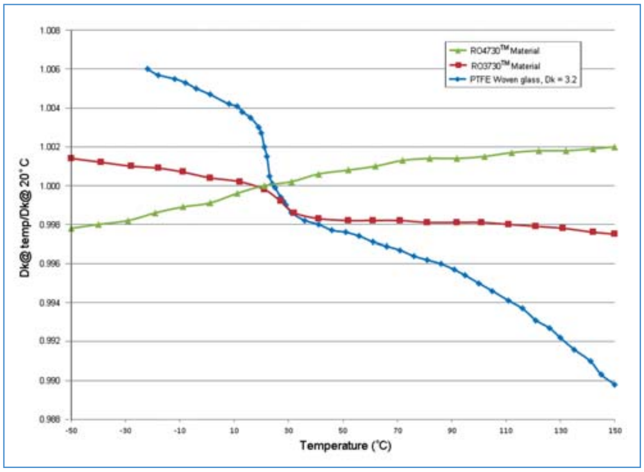

FIGURE 1
These three TcDk curves compare common high-frequency PCB antenna materials and their change in Dk versus change in temperature.

more stress due to thermal expansion and contraction when subjected to a thermal process than materials with lower CTE values. Such stress can affect the reliability of plated through holes (PTHs) used to make electrical connections between circuit layers in a multilayer-circuit construction. The solder reflow process normally used in circuit fabrication can also result in stress for materials with higher CTE values, with any dimensional changes resulting in changes to high-frequency responses.

In addition to dimensional changes as a function of temperature, the Dk value of a material will also change with temperature, a property known as thermal coefficient of dielectric constant, or TcDk. Sometimes even a small change in the value of a material's Dk can result in a change in the frequency response of a well-defined resonant circuit, such as a microstrip patch antenna. Some circuit materials offer excellent electrical properties but exhibit TcDk values of 200 to 400 ppm/°C, which can result in significant frequency shifts for antenna designs that must handle a wide range of operating temperatures. Materials with TcDk values of less than 50 ppm/°C are considered well suited to deliver consistent electrical performance with changing operating temperatures. Figure 1 shows a comparison of TcDk curves for three common PCB antenna materials.

Figure 1 plots TcDk behavior for three different PCB materials across a wide range of temperatures. As the curve for the PTFE woven glass material shows, PTFE-based materials undergo a distinct Dk transition at room temperature. The transition can be tempered by blending other materials into a PTFE-based PCB material formulation. The RO3730™ material is a ceramic-filled PTFE substrate material in which the TcDk behavior of the ceramic filler has dramatically dampened the PTFE transition. A different type of ceramic and material blend is used in the non-PTFE-based RO4730™ material that eliminates the TcDk room-temperature transition. These three PCB materials, PTFE woven glass, RO3730, and RO4730 laminates, exhibit TcDk values of approximately –94 ppm/°C, –19 ppm/°C and +21 ppm/°C, respectively, for the temperature range shown in Figure 1.

In terms of real-world effects, the TcDk values of these three materials will translate into shifts in the expected frequency of a PCB antenna based on its physical dimensions and wavelengths. Using data from Figure 1 and the microstrip patch antenna structure defined in Table 1, and based on the use of a PCB material with Dk of 3.0, the much different TcDk val-

Material TcDk TcDk (ppm/C)	Center Freq. (GHz)	Frequency Shift (MHz)
0	5.024	baseline
-78	5.048	24
-19	5.029	5
21	5.017	7

TABLE 2
Shift in center frequency for three values of Dk temperature coefficient, referenced to 0 ppm/°C.

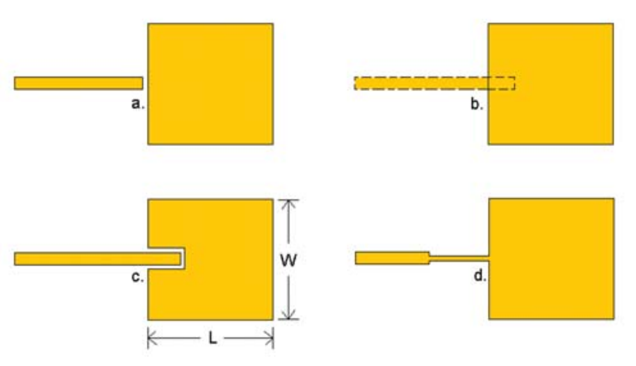

FIGURE 2
Some common microstrip patch designs (top view of circuit pattern) showing different feed networks; (a) loosely gap coupled,(b) bottom layer feed, (c) tightly gap coupled, and (d) quarter-wave transformer.

ues of the three materials from Figure 1 will result in different center frequencies for the same physical microstrip patch resonator structure. Using an operating temperature range of +25 to +150°C and TcDk values of –78, –19 and +21 ppm/°C for the PTFE woven glass, RO3730, and RO4730 PCB materials, respectively, Table 2 shows how the TcDk behavior of the different materials affects the center frequency of the antenna's resonant structure relative to an ideal, 0 ppm/°C baseline condition.

These shifts in frequency were calculated by commercial EM simulation software for a microstrip patch resonator element as defined in Table 1 using PCB material with Dk of 3.

Compared to other antenna technologies, microstrip patch antennas are relatively simple to fabricate and low in cost. They feature thin profiles for ease of integration, can be formed into more complex arrays as needed, and support simple addition of other components when necessary. Of course, they are limited in bandwidth and suffer relatively low efficiency compared to other antenna structures. Also, the radiation loss of the feed lines can be excessive and proper polarization can be difficult to achieve.

Microstrip patches are formed from simple geometric shapes, such as a square patch. The key to a successful design is the effective coupling of energy from the nearby circuit to the antenna's resonant structure or patch. A number of methods are available to couple the feed line to the antenna patch, as shown in Figure 2.

The width (W) and length (L) of the rectangular patch for these microstrip patch antennas were determined with the following simple formulas:

$$W = \frac{c}{2f_r} \cdot \sqrt{\frac{2}{Dk+1}}$$

and,

$$L = \frac{\lambda}{2 \cdot \sqrt{Dk_{eff}}} - 2\Delta L$$

where Dk_{eff} is the effective dielectric constant of the microstrip structure and ΔL is the added length due to fringing fields (calculated with the MWI-2010 microwave impedance calculator software, available for free download from Rogers Corporation). To calculate variations in center frequency as a result of shifts due to TcDk, the microstrip structures were analyzed using rev. 13.54 of the three-dimensional (3D) planar EM software from Sonnet Software (www.sonnetsoftware.com).

A major design tradeoff of microstrip patch antennas regards optimizing the feed line and the radiating element simultaneously. A more efficient radiating element typically requires a thicker substrate, although this can result in increased radiation loss for the feed line as well as feedline spurious propagation. The requirements for the two antenna sections are in conflict: it would be best for the feedline to use a thin substrate with high dielectric constant and a thick substrate with low dielectric constant for the radiating structure.

Various approaches are available to achieve a solution to this apparent compromise, including the use of a more complex PCB structure, such as a multilayer structure. For example, the feedline layer may be stripline that is optimized for low loss and then coupled to a top-layer patch through an aperture etched in the inner layer copper pattern between buried stripline and surface microstrip layers. Figure 2b shows the basic concept, although the actual construction is much more complicated and fabrication of the circuit can be considerably more challenging.

Multilayer structures used for PCB antennas are not routine or easy since the materials for the different layers must be considered in terms of their CTE characteristics for reliability with temperature. A multilayer structure will require the use of material with lower CTE for good circuit fabrication yields as well as robust reliability when enduring the thermal cycling from the soldering process. Any multilayer construction in which the PCB materials have been selected for optimum performance of the feedlines and radiating elements will typically have different substrate materials in the mix, with numerous concerns about how those different materials behave across the wide range of temperatures faced in multilayer PCB manufacturing. Many of these concerns have been detailed in an earlier report [1].

In conclusion, PCB antenna designers have many tradeoffs to consider, some related to the choice of substrate materials. PCB materials with higher Dk values result in smaller antennas, although at some cost to antenna efficiency. But using a PCB material with low Dk value for the antenna radiator element can have drawbacks for the feedline, and it may be more effective to adopt a multilayer hybrid design approach to optimize the feedline as well as the antenna elements. Evaluating a PCB material's different attributes, including its thermal characteristics, can lead to the best choice of material for a particular PCB antenna design.

Reference

1. John Coonrod, "High frequency PCBs using Hybrid and Homogenous Constructions," *PCB West* 2010, September 2010.

Note: RO3730 and RO4730 are licensed trademarks of Rogers Corporation.

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