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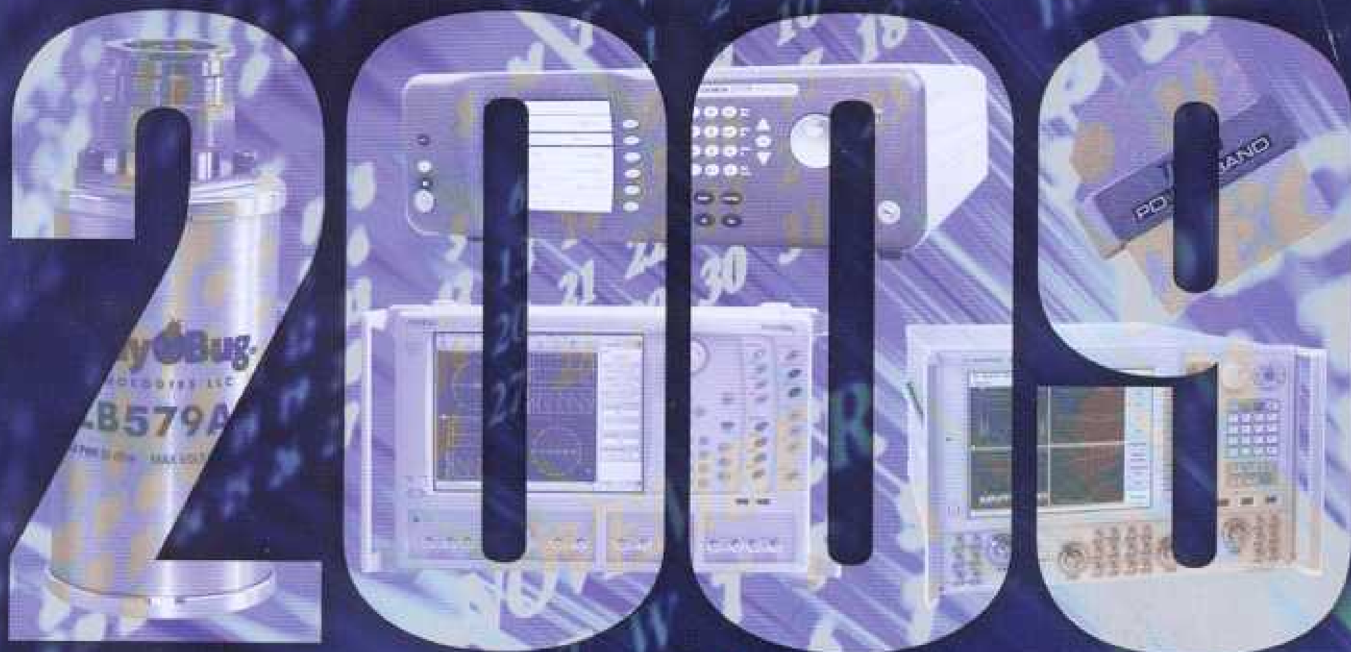

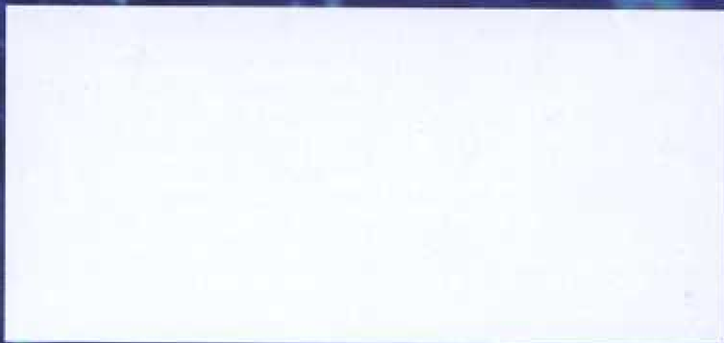

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Microwave Materials Lay Foundation For PAs

Understanding key material parameters can help power-amplifier designers to choose the optimum high-frequency laminate in support of their circuits.

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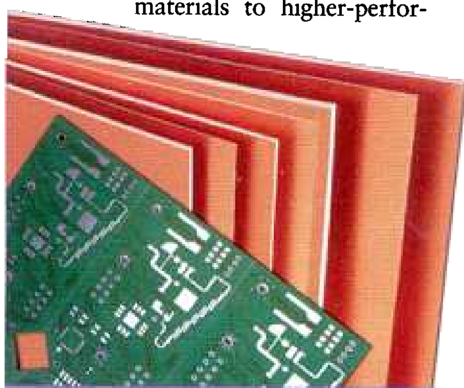
Power-amplifier designers typically create a circuit based on specific active devices for the output stage. While the choice of transistor determines the ultimate performance of an amplifier, printed-circuit-board (PCB) materials can also play a major role in an amplifier design. Selecting optimum substrate materials for an amplifier can improve gain and stability, and enable the maximum output power possible for a design.

High-frequency amplifier designers have a wide array of PCB materials from which to choose, from lower-cost FR-4 and thermoset-resin dielectric materials to higher-performance (and higher costing) dielectric materials based on polytetrafluoroethylene (PTFE) reinforced by woven glass or ceramic filler (*Fig. 1*). Understanding the electrical and mechanical properties of those materials and how they impact amplifier performance can help guide an amplifier designer through the materials selection process.



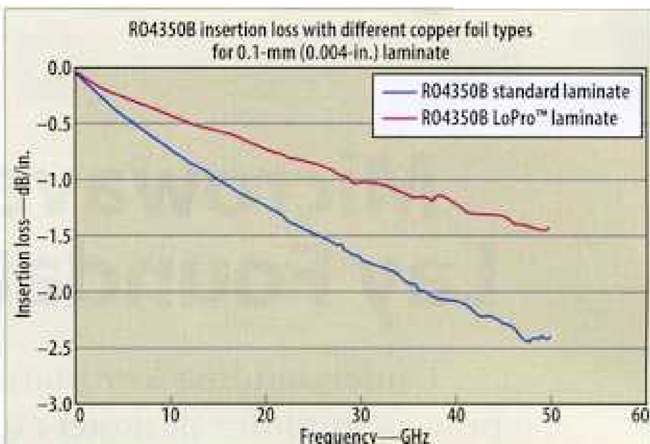
1. Amplifier designers have a wide array of laminates from which to choose. Understanding key materials parameters can simplify the selection process.

All substrate materials are defined by their permittivity (ε). The parameter describes the capability of a material to act as an insulator of electrical charges as well as by its capability to store charges. Substrate materials are typically defined by measuring their permittivity relative to that of a vacuum, which is unity or 1. Because it is referenced to a vacuum, the relative permittivity (or dielectric constant), ε_i, of a substrate material is always greater than 1. For most high-frequency circuits, vendors offer substrate materials with dielectric constants from about 2 to 10 as measured in the z-axis of the material (or through the thickness of the material).

The basic trade off in substrate materials with lower versus higher values of dielectric constant is the levels of insulation provided by the materials. Materials with lower relative dielectric constants provide excellent isolation for lower-frequency signals, particularly in dense circuits with closely spaced conductive lines. Materials with higher relative dielectric constants provide a means by which a circuit can be reduced in size and are usually used in lower frequency applications or where the size of a board needs to be minimized.

Since conductive transmission lines must be formed on a dielectric substrate material to create a circuit, materials suppliers generally offer their products in the form of laminates, with different available thicknesses of copper foil or thick metal cladding on the surfaces of the dielectric material. For an amplifier, the dielectric constant, the thicknesses of the dielectric material and the copper conductors will impact the final size and performance of a design.

Various characteristics of a substrate's relative dielectric constant can be critical to a power amplifier circuit, such as consistency across the laminate, lot-to-lot uniformity, and stability with changes in temperature. For example, variations in the dielectric constant across the length (x direction), width (y direction), and thickness (z direction) of a laminate can result in changes in the impedance of a transmission line formed on that substrate, causing signal reflections and frequency deviations. Laminate suppliers typically characterize their



2. This plot compares the insertion loss for RO4350B and RO4350B LoPro laminates using 0.1-mm-thick (0.004-in.-thick) circuit boards.

products in terms of tolerance values for the relative dielectric constant in the z direction as well as providing data regarding the relative dielectric constant over a defined temperature range, usually referenced to the value of the relative dielectric constant at room temperature (+25°C). Lower tolerance values translate into more predictable results from the design stage to the production stage, especially for amplifiers subject to temperature extremes, such as in an outdoor cellular communications tower. Tighter tolerances support closer agreement between modeled and measured performance when designing an amplifier with computer-aided-engineering (CAE) simulation software.

Changes in the dielectric constant of a circuit-board material as a function of temperature are described by a parameter known as the thermal coefficient of dielectric constant. In order to minimize the effects of temperature variations, substrate suppliers employ a variety of fillers for their dielectric materials, in addition to traditional glass-based fillers. The thermal coefficient of dielectric constant is defined in terms of changes in the dielectric constant in parts per million (PPM) per change in temperature in degrees Celsius (°C).

As an example, RO4350B laminate from Rogers Corporation (www.rogerscorp.com) is a circuit-board material with dielectric constant of 3.48 ± 0.05 measured in the z-axis. This represents a typical variation of only ±1.4 percent in the relative dielectric constant. For fabricating the impedance-matching networks needed for amplifier designs, the thickness of the material is tightly controlled within ±8 percent for a 20-mil-thick substrate.

The material, which is suitable for both low-noise and high-power RF/microwave amplifiers, has a thermal coefficient of dielectric constant of +50 PPM/°C when evaluated with a short-term exposure test over ambient temperatures from -50° to +150°C, indicating an increase of 50 PPM in the value of the relative dielectric constant for every one-degree Celsius rise in temperature. Of interest to power-amplifier designers, RO4350B laminates utilize RoHS-compliant, flame-retardant technology for applications requiring UL 94V-0 certification.

RO4350B material is mechanically stable and uses a thermoset resin laminate reinforced by a combination of glass and ceramic fillers. It is engineered to be used in fabrication processes similar to those used with low-cost epoxy/glass FR-4 PCB materials and does not require specialized preparation (as needed by PTFE substrates) when fabricating the plated through holes (PTHs) used to interconnect different circuit layers in multilayer circuit designs. In addition, multilayer boards can be fabricated at FR-4 temperatures with the use of the RO4400 family of prepregs.

Depending upon the power levels and efficiency of the design, high-frequency power amplifiers can generate enough heat to cause variations in the dielectric properties of a laminate material. A printed circuit's power-handling capabilities are usually de-

termined by the width and insertion loss of its conductors as well as by the ground-plane spacing. But a dielectric material parameter—the dissipation factor—can also play a major role in determining the ultimate output power available from a given amplifier design. The dissipation factor, which is also known as the loss tangent, is the ratio of the material's loss to its capacity. All laminates suffer some loss; in a power amplifier, the loss results in added generation of heat, dictating the use of a laminate material with the lowest dissipation losses possible to minimize thermal effects. Low-loss materials can also ensure maximum gain from an amplifier design. As an example, RO4350B laminate has a low dissipation factor of 0.0031 at 2.5 GHz for low insertion loss in both low-noise and high-power amplifiers.

Moisture absorption is a material parameter that can affect the value of a laminate's relative dielectric constant, since most resin-based dielectrics will absorb small amounts of water under conditions of high humidity. Since water has a dielectric constant of about 73, absorption by a low-dielectric-constant substrate material can raise the relative dielectric constant, leading to variations in impedance for conductors. Laminate moisture absorption can also increase leakage current, and create reliability problems in high-power amplifiers or require the use of an expensive package to protect the circuitry from moisture absorption, leading to increased dielectric losses and overall deterioriation in performance. The dissipation factor of the material can also be affected by moisture. Depending upon the expected environmental conditions for an application, amplifier designers generally select a material with low moisture absorption. For RO4350B material, for example, the moisture absorption is extremely low, at 0.06 percent when tested with 48 hours emersion in water at +50°C.

Two other laminate parameters related to high-power capabilities are thermal conductivity and coefficient of thermal expansion (CTE). The thermal conductivity is a measure of the amount of heat that passes through a unit area of a laminate of unit thickness, with higher values indicating a better capability of conducting heat away from the copper transmission lines and through the dielectric material. The thermal conductivity is defined in terms of watts of power per meter of laminate material per degrees Kelvin. For RO4350B laminate material, for example, the thermal conductivity is 0.62 W/m/K measured at +100°C.

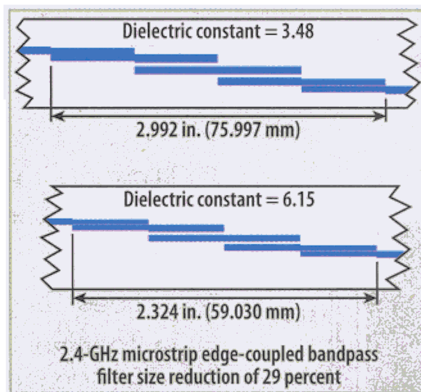
The CTE characterizes physical changes in a laminate material with changes in temperature. In the x and y directions, the CTE of a dielectric substrate is usually engineered to match the CTE of copper, so that expansion and contraction of copper conductors and dielectric material occur at the same rate. The CTE of copper is typically 17 PPM/°C. In contrast, Rogers RO4350B laminate has CTE values of 14 and 16 in the x and y directions, respectively, and CTE of 35 in the z direction when measured from -55 to +288°C, to closely match the thermal expansion and contraction of copper traces formed on its surfaces. For multilayer designs, the z-axis CTE is of interest to ensure the reliability of PTH connections. Low values of CTE usually result in excellent dimensional stability for a laminate used in amplifiers or other high-frequency circuits.

Related to a laminate's CTE is its glass transition temperature, Tg. This is the temperature at which the CTE makes a drastic change from a low value to a much higher value, corresponding to a change in phase for the laminate's resin system. Because such a change in CTE can result in unpredictable or unstable electrical performance, amplifier designers usually specify laminates with the highest possible Tg, to withstand the temperature extremes of soldering and other production processes. As an example, the Tg of RO4350B laminate is more than +280°C, considerably higher than most other organic substrates.

DesignFeature

With the increasing use of digital modulation in wireless communication systems, amplifier designers must minimize the amount of distortion exhibited by their circuits. Particularly in systems relying on multitone signal formats, intermodulation distortion (IMD) can be a limiting factor in bit-error-rate (BER) performance. To minimize the substrate as a source of passive intermodulation (PIM), amplifier designers can specify laminates specifically engineered for low PIM. For example, RO4350B LoPro laminate from Rogers Corporation is essentially a variant of the firm's RO4350B material, using reverse-treated copper foil in place of "a more standard" electrodeposited (ED) copper (***Fig. 2***). The dielectric properties of the RO4350B LoPro material remains the same as that of RO4350B material, but with lower insertion loss and improved PIM performance (typically -150 dBc). The LoPro technology results in a laminate with smooth copper surface, reducing conductor losses.

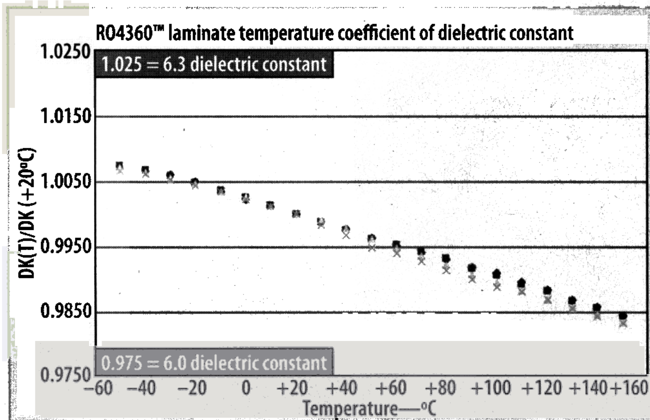
High-frequency power-amplifier designers have traditionally used laminates with dielectric constants from 3.0 to 3.5. But increasing demands for miniaturization in both commercial and military systems has many amplifier designers seeking laminates with higher dielectric constants, since such materials can allow circuit dimensions to shrink while maintaining required impedances. For example, for amplifier designers accustomed to RO4350B laminates with a dielectric constant of 3.48, the use of RO4360 laminates from Rogers Corporation, with a dielectric constant of 6.15 ± 0.15 in the z direction (at both 2.5 and 10.0 GHz), can result in a considerably smaller amplifier circuit without sacrificing performance (***Fig. 3***) or cost.



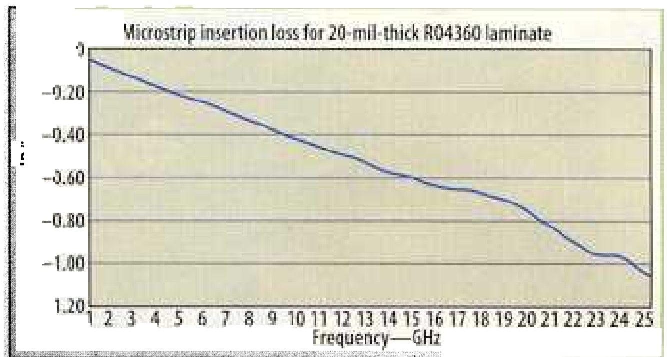
3. The size of a 2.4-GHz microstrip bandpass filter can be reduced by 27 percent using a laminate with relative dielectric constant of 6.15 (bottom) instead of 3.48 (top).

Of course, shrinking an amplifier's circuitry can lead to challenges in dissipating the heat generated by the active devices. The thermal conductivity of RO4360 laminates is somewhat higher than that of RO4350B material, at 0.8 W/m·K versus 0.64 W/m·K, to support the higher power densities of smaller amplifier circuitry. At the same time, the CTE performance for the two materials is comparable. The CTE values for RO4360 laminates are about 17, 15, and 30 PPM/°C in the x, y, and z directions, respectively, compared to CTE values of 14, 16, and 35 PPM/°C in the x, y, and z directions, respectively, for RO4350B laminate. The RO4360 material has a thermal coefficient of dielectric constant of -120 PPM/°C in the z direction when evaluated in a short-term test from -50 to +150°C (***Fig. 4***), compared to a value of about -160 PPM/°C for other commercially available laminates with relative dielectric constant of about 6.

Because of the increased power densities of newer device technologies, including silicon-carbide (SiC) and gallium nitride (GaN) transistors, even the most advanced laminate materials require careful thermal design



4. The temperature coefficient of dielectric constant for RO4360 is plotted here from -60° to +160°C.

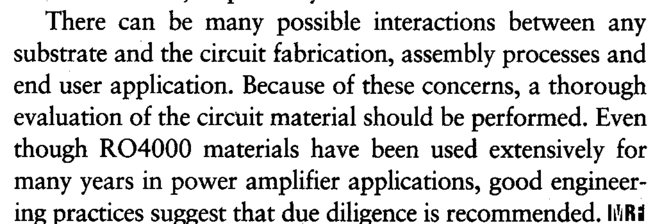


5. The insertion loss of a microstrip line is plotted here through 26 GHz for 20-mil-thick RO4360 laminate.

when creating a compact amplifier with either RO4350B or RO4360 materials. Heat generated by an active device must follow a low-resistance thermal path from the device and the laminate to either a dedicated heatsink or metal package flange serving as a heatsink. In extreme cases, forced-air cooling may be required to ensure that any active devices do not exceed their rated junction temperatures.

The RO4360 material is based on the same proven technology as RO4350B material, but with a higher dielectric constant. It is a glass-reinforced, ceramic-filled thermoset laminate that can be processed with the ease of low-cost FR-4 material. It is suitable for use with lower-dielectric-constant materials in multilayer designs. Normally, an increase in dielectric constant implies an increase in the dielectric-constant tolerance as well. But for the RO4360 laminates, the tolerance for the relative dielectric constant is ±0.15 or ±2.4 percent of the full value of relative dielectric constant, which is tightly controlled for a material with this value of relative dielectric constant.

For laminates with higher relative dielectric constants, the dissipation factor will usually be higher than for materials with lower values of relative dielectric constant. For the RO4360 material, however, the dissipation factor is nearly the same as that of RO4350B material, 0.0038 in the z direction at 10 GHz for RO4360 material versus 0.0037 in the z direction at 10 GHz for RO4350B material, resulting in low insertion loss for the stripline and microstrip matching circuits used for power amplifiers (***Fig. 5***). Of interest to amplifier designers is the improvement in thermal conductivity for the RO4360 material versus RO4350B laminate, an improvement of 22 percent by merit of thermal conductivity of 0.80 W/m-K. In addition to reducing the size of an amplifier circuit, the higher relative dielectric constant of the RO4360 material helps to reduce radiation losses in a design. Similarly, RO4360 laminate provides CTE performance that is comparable to that of RO4350B laminates. The RO4360 material exhibits CTE of about 17 PPM/°C in the x direction, 15 PPM/°C in the y direction, and 30 PPM/°C in z direction, compared to x, y, and z values of 14, 16, and 35 PPM/°C, respectively for RO4350B laminate.



There can be many possible interactions between any substrate and the circuit fabrication, assembly processes and end user application. Because of these concerns, a thorough evaluation of the circuit material should be performed. Even though RO4000 materials have been used extensively for many years in power amplifier applications, good engineering practices suggest that due diligence is recommended. MRF