microwaves&rf

print | close

Thermal Design Begins At The Circuit Board

Microwaves and RF

John Coonrod

Wed, 2011-05-18 (All day)

Understanding different characterization parameters related to temperature can help when selecting a printed-circuit-board material for high-power RF/microwave applications.

PROPER THERMAL MANAGEMENT in an RF/microwave design starts with careful choice of electronic materials, and one of the most important of those materials is the printed-circuit board (PCB). In a high-power, high-frequency circuit such as a power amplifier, heat can built up around the amplifier's active devices. To prevent damage to the device junctions, nearby circuit components, or even the PCB material, the heat must be properly channeled away from the active devices and safely dissipated through device packages, circuit ground connections, heat sinks, equipment chassis, and ambient air. the choice of PCB materials can contribute a great deal to the overall thermal management of a high-power RF/microwave design.

A circuit material's power-handling capability is related to its capability to control temperature rises as a function of applied and dissipated power. As is the case with most electronic components, elevated operating temperatures translate into shorter operating lifetimes and, often, degraded electrical performance. Whether it is the environmental ambient temperature that is high, or the temperature of the circuitry and its components is elevated because of high-power operation, the results can be damaged and degraded performance at elevated temperatures. Depending upon the amount of power that a circuit must dissipate, maintaining that circuit at a lower temperature usually ensures improved reliability.

What happens to a PCB at elevated temperatures? As with most materials, it will expand and contract with changes in temperature, expanding in three axes (length, width, and thickness) as the temperature increases. The amount of this expansion for the change in temperature is characterized by a PCB material's coefficient of thermal expansion (CTE). Because a PCB is typically formed of a dielectric laminated with copper (to form transmission lines and a ground plane), the material's linear CTE in the x and y directions is usually engineered to match the CTE of copper (about 17 ppm/C). By doing this, the materials expand and contract together with changes in temperature, minimizing stress on the junction of the two materials.

The CTE in the z axis (the thickness) of the dielectric material is usually designed for a low value to minimize dimensional changes with temperature and maintain the integrity of plated through holes (PTHs). The PTHs provide paths from the top to the bottom of the circuit board as needed for ground connections, as well as for interconnecting multilayer circuit boards.

In addition to mechanical changes, temperature can also affect the electrical performance of a PCB. The relative dielectric constant of a PCB laminate, for example, varies as a function of temperature, as defined by a parameter known as the thermal coefficient of dielectric constant. The parameter describes changes in the dielectric constant (typically in ppm/C). Because the impedance of high-frequency transmission lines is determined not only by the thickness of the substrate material but also by its dielectric constant, changes in z-axis CTE and dielectric constant as a function of temperature can significantly impact the impedance of microstrip and stripline transmission lines fabricated on that material.

Microwave circuits, of course, rely on tightly matched impedances between components and circuit junctions to minimize reflections that can result in signal losses and phase distortion. In a power amplifier, impedance-matching circuitry is used to make transitions from the typically low impedances of a power transistor to the typically 50-Ω characteristic impedance of an RF/microwave circuit or system. Changes in transmission- line impedance due to temperature effects from high-power signals can alter the frequency response of a high-frequency amplifier, so those effects should be minimized as much as possible by careful choice of PCB laminate.

Numerous other parameters are helpful in selecting a PCB material that will help minimize the generation of heat at high power levels and frequencies. One of these is the temperature at which some materials can change states, known as the liquid-glass transition temperature or the glass transition temperature (T_g, for short). It can indicate a temperature at which dramatic changes take place in a material's CTE behavior, for example (Fig. 1). Because a material can undergo such a drastic change in CTE, it becomes mechanically and electrically unstable when operating above T_g, and should always be maintained below that temperature except for short-duration processing steps, such as solder reflow, that require the material to be at an elevated temperature as part of that processing step.

Another critical temperature-related parameter is a PCB's maximum operating temperature (MOT). The MOT is a rating which Underwriters' Laboratory (UL) will give a unique PCB construction made by a particular circuit fabricator site and using specific PCB materials. The MOT is the maximum temperature at which the PCB can be operated at for an indefinite period of time without significant degradation to critical performance attributes of the circuit. When a circuit is subjected to temperatures beyond the MOT for a long period of time, reliability risks become a concern. The MOT rating is meant to provide an indication of a safe high temperature for a PCB, although it does not necessarily include the effects of high levels of input power to the PCB.

A PCB material's thermal conductivity can be used as a relative indicator of a laminate's effectiveness in dissipating heat. This parameter essentially describes a PCB material's ability to conduct heat. It is measured in watts of power per meter of material per degrees Kelvin. Analogous to electrical conductivity and the flow of electricity through a material, thermal conductivity is used to predict the rate of energy loss as heat through a given material. The reciprocal of thermal conductivity is thermal resistivity, or the ability of a material to resist the flow of heat.

TRACKING THERMAL CONDUCTIVITY

Thermal conductivity depends on various properties of a material, such as its molecular structure. For example, glass is a poor thermal conductor, with an extremely low thermal conductivity of 1.1 W/(m-K). Copper, on the other hand, offers very low resistance to the flow of heat, with a very high thermal conductivity of 401 W/(m-K). Because the thermal conductivity of PCB dielectric materials is extremely lowthe thermal conductivity of high-T_g FR-4 circuit material is typically about 0.24 W/(m-K)heat can easily build up on the conductive traces of a high-power PCB which are typically formed of copper with its extremely low resistance to the flow of heat. But selecting a PCB material with a higher value of thermal conductivity allows for operation of a circuit at higher power levels.

The table offers a comparison of typical PCB laminate materials, including a relative newcomer, RT/duroid 6035HTC laminate material from Rogers Corp. As the table shows, it has a considerably higher thermal conductivity than FR-4 and even several lowloss, high-frequency laminates. It consists of a ceramic-filled PTFE composite dielectric available with standard or reverse-treated, electrodeposited (ED) copper foil. The material, with its high thermal conductivity, has been engineered for effective thermal management in microwave amplifiers operating at hundreds of watts of power. It has a relative dielectric constant of 3.50 at 10 GHz in the z-axis which is maintained within a 0.05 tolerance across a board to maintain consist impedance in transmission lines. The CTE in the x and y axes is 19 ppm/C, closely matched to that of copper.

Of course, proper thermal management in a circuit design is not simply a matter of selecting a circuit laminate with the best thermal properties. Many other factors can affect the temperature of a circuit operating at a given power level and frequency. For example, circuit materials are characterized by dissipation factor, which is the loss attributed to the dielectric material. There is also loss through the conductive transmission lines, such as microstrip or stripline circuits, with higher insertion losses resulting in more heat being generated in the transmission lines at higher power levels. The roughness of the copper conductor on a PCB can contribute to increased insertion loss, especially at higher frequencies.

Continue on Page 2

Page Title

In addition, the choice of a PCB material's dielectric constant will determine the size and density of an RF/microwave circuit, since the dimensions of microwave transmission-line structures are based on the wavelengths of the signals to be handled. At higher relative dielectric constants, the dimensions of the transmission lines needed to achieve a given impedance grow smaller, and a PCB's power-handling capabilities will be limited to an extent by the width and insertion loss of its conductors, as well as by the ground-plane spacing. For an amplifier circuit, by way of example, choosing a PCB material with a lower relative dielectric constant can lead to wider transmission lines for a given impedance, for improved thermal flow. Using a PCB material with a higher relative dielectric constant results in finer transmission-line dimensions and a more densely spaced circuit, which may create thermal hotspots in high-power circuits. In addition, selecting a material with low dissipation factor can help minimize the insertion loss of the transmission lines and optimize the gain of an amplifier circuit.

With the help of the free MWI 2010 Microwave Impedance Calculator software, the behavior of several different PCB laminates was simulated for use at high power levels, based on MOT as a key parameter in determining the highest amount of RF power that each material could practically handle. The MOT for each material was assumed to be +105C. An ambient temperature of +25C (room temperature) was used in each calculated case, and the rise above ambient was predicted for different power levels. The same 20-mil-thick, 50-Ω microstrip test circuits were fabricated on each of the materials, using 2-oz. copper as the conductive laminate. When a high-Tg FR-4 laminate was compared with RO4350B laminate from Rogers Corp., the predicted differences in powerhandling capability for a comparable rise in temperature at 800 MHz were decidely noteworthy (Fig. 2). The FR-4 exhibited a temperature rise above ambient of about +75C for an RF power level of about 40 W. The RO4350B laminate rose about +77C above ambient as a result of almost 250 W RF power.

When the RT/duroid 6035HTC laminate was added to the MWI 2010 simulation at a higher frequency of 2 GHz, assuming the same circuit and material (2-oz. copper) conditions as the 800-MHz simulation, the FR-4 actually projected lower-handling capability (about 25 W) for a temperature rise above ambient approaching +90C while the RO4350B showed a temperature rise approaching +85C for RF power of about 150 W at 2 GHz (Fig. 3). The RT/duroid 6035HTC, engineered for high-power use, projected a thermal rise above ambient of just over +80C for more than 350 W RF power at 2 GHz in these MWI 2010 simulations. These simulations not only reinforce the expected capability of the RT/duroid 6035HTC laminate at high power levels, but the frequency dependency on powerhandling capabilities for the other two materials.

When the same three materials were tested with the same test circuits, but with each fed with test signals at the same frequency and power levels, the high-Tg FR-4 exhibited the highest rise in temperature above ambient, jumping to +109C (+229F) or a rise of +84C above ambient. The RO4350B laminate exhibited a +56C rise above ambient, increasing from +25C to +82C (+180F). The RT/duroid 6035HTC rose only +36C above ambient (from +25C to +62C) under the same test conditions.

Further testing on RO4003C laminate from Rogers and RT/duroid 6035HTC with 1-oz ED copper and 2-oz. ED copper, but otherwise all other test conditions the same, revealed interesting results for the influence of the copper surface. For tests at 800 MHz (Fig. 4), a temperature rise of +80C above ambient for all three laminates occurred at about 280 W for the RO4003C laminate, about 700 W for the RT/duroid 6035HTC with 2-oz. copper, and almost 800 W for the RT/duroid 6035HTC with 1-oz. copper. When tested at 2 GHz (Fig. 5) for the same increase in temperature, the RO4003C's power-handling capability dropped to about 140 W, while the RT/duroid 6035HTC with 2-oz. copper handled about 380 W and the RT/duroid 6035HTC with 1-oz. copper handled more than 400 W. The improved performance of the RT/ duroid 6035HTC with 1-oz. copper over the same dielectric with heavier cladding is attributed to the smoother copper surface (and lower associated insertion loss) for the RT/duroid 6035HTC with 1-oz. copper.

As these tests show, temperature rises will occur in all PCB materials as a result of high RF power levels. But different materials, and even copper cladding options, can affect the power-handling capability of a circuit. If considering a prudent MOT in order to ensure a PCB laminate and high-frequency design with long operating lifetime, then the choice in material should factor in low loss, high thermal conductivity, and stable mechanical characteristics with temperature.

Source URL: http://mwrf.com/materials/thermal-design-begins-circuit-board