HIGH FREQUENCY ELECTRONICS

Substrate Selection Can Simplify Thermal Management

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Substrate Selection Can Simplify Thermal Management

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Circuit materials formulated to dissipate heat can not only increase reliability; they can also increase power-handling capabilities.

Heat haunts many RF/microwave and power electronics circuits and can limit performance and reliability. The heat generated by a circuit is a function of many factors, including input power, active device efficiencies, and losses through passive devices and transmission lines. It is often not practical to disperse heat from a circuit by convection fan-driven cooling, and heat must be removed from sensitive components and devices, by creating a thermal path to a metal enclosure or heat sink with good thermal conductivity.

In many cases, however, such as miniature or multilayer electronic designs, it may not even be convenient or possible to attach a heat sink, and dissipation of excess heat must take place through the dielectric material of a printed circuit board (PCB) acting as a heat spreader, which can be accomplished through careful selection of circuit substrate materials. By using circuit materials formulated to dissipate heat, not only can circuit reliability be increased, but the power-handling capabilities of the circuits can be increased for the same or smaller-sized circuitry as standard circuit materials.

Thermal Stability

Active devices are not 100% efficient and some of the energy applied to those devices will be converted to heat. The temperature rise of an active device can be controlled by means of careful selection of circuit materials, using circuit materials capable of providing a thermal path for heat to flow away from the active device. In addition, a circuit board's metal ground plane or a metal heat sink attached to the circuit board provides thermal paths that allow heat to dissipate safely, without damage to a circuit's surface-mounted devices. In addition, by providing thermal stability, the effects of temperature on impedance can be minimized, since significantly elevated circuit temperatures can cause variations in the circuit's phase response.

Circuit materials are characterized by a number of standard parameters, including thermal conductivity (TC), dielectric constant (Dk), dissipation factor (Df), and coefficient of thermal expansion (CTE). Circuit materials for high-frequency and high-speed digital applications are typically composites formed of several materials, such as woven-glass and PTFE. Simple linear equations are available to compute the TC for a given type of material or composite material based on its thermal behavior as are software simulation programs for predicting the flow of heat through a particular type of material. The source of heat is often an active device, such as a power transistor in an amplifier. To ensure the long operating life of the amplifier (and the active device), it is beneficial to prevent it from self-heating.

In high-frequency single-layer designs, top-mounted circuitry consisting of microstrip or grounded-coplanar-waveguide (GCPW) transmission lines (Fig. 1) can yield high temperatures when handling sufficient power levels. The excess heat must flow away from the transmission lines, typically through a PCB's dielectric material, to a lower-temperature area on the bottom of the PCB, typically a heat sink. A cross-sectional depiction of this circuit arrangement (Fig. 2) shows how the heat flows from an area of higher temperature to an area of lower temperature, according to the simple relationship:

Substrates

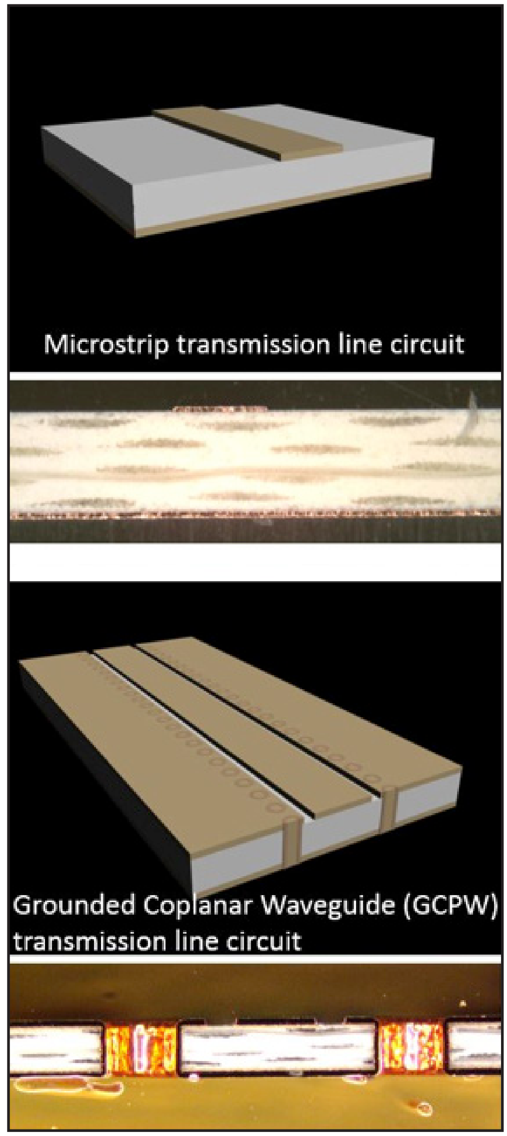

Figure 1 • Two popular high-frequency transmission-line technologies, microstrip and grounded coplanar waveguide (GCPW), employ circuitry on the top side of a PCB material, with a ground plane on the bottom.

$$H = kA(\Delta T/L)$$

where

H = the heat flow

k = the thermal conductivity

L = the distance between the two thermal areas, and

ΔT = the difference in temperature between the high-temperature area and the low-temperature area.

A thinner circuit material (smaller L) will provide a better heat flow through the z-axis or thickness of the circuit material, as will a higher value of k (TC). It also should be noted that TC applies to the x-y plane of a circuit material as well as through the thickness or z axis.

High-Frequency Circuits

In high-frequency and high-speed (digital) circuits or even power electronic circuits, the rise in temperature as a function of applied power is due to the combined losses through each circuit: the dielectric loss of circuit material, the insertion loss of the transmission lines, and TC (or thermal loss) of the circuit material. In active circuits where a source of power/heat, such as a discrete transistor or IC, may be mounted directly on the transmission lines, a high amount of thermal stress can occur at the interface between the active device and the circuit material.

The temperature rise of an active device can be moderated through the use of high-TC circuit materials, as well as through the fabrication of thermal vias connected through the substrate material to a high-TC material, such as a metal heat sink or ground plane (Fig. 3). An extreme temperature rise is to be avoided, since it can impact the loss characteristics of surface-mount components and high-frequency transmission lines, such as microstrip and grounded-coplanar-waveguide (GCPW) circuits, causing the phase angle of the transmission lines to vary with temperature from a nominal value. Circuit materials with high TC values can help avoid such a condition by flowing heat away from the source of the heat.

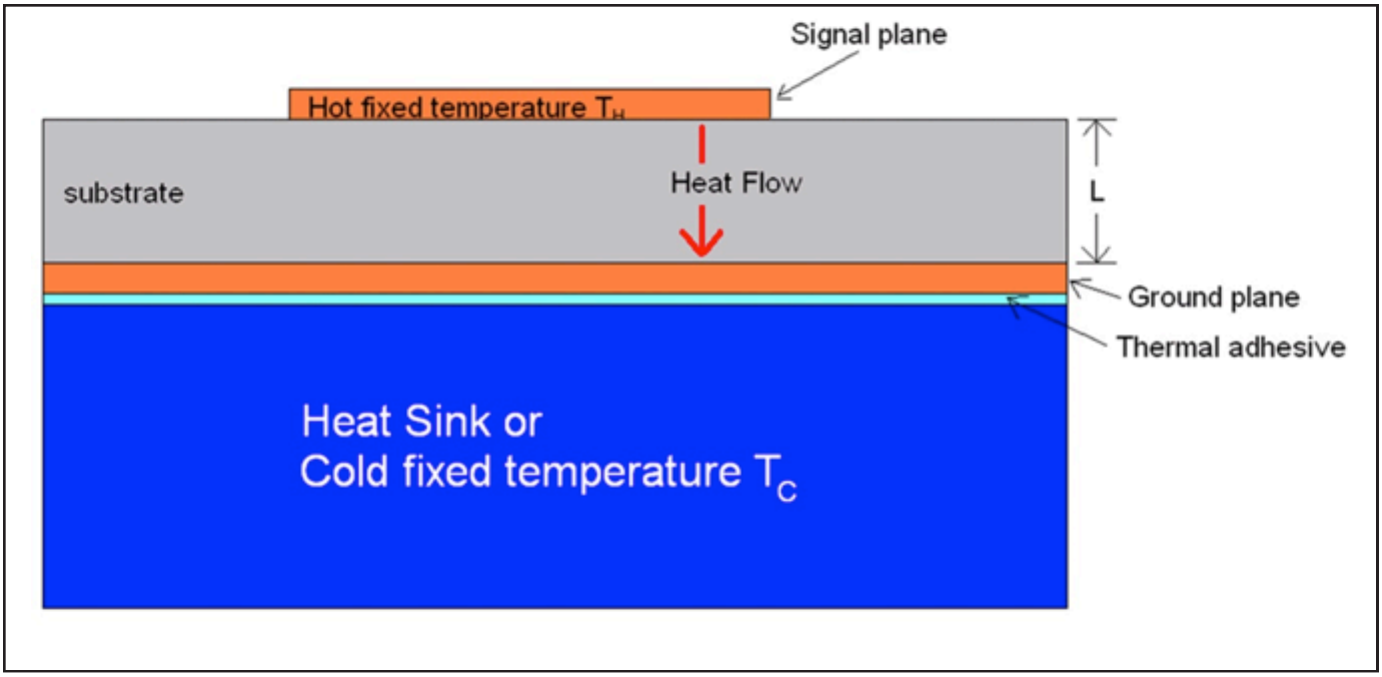

Figure 2 • The heat flow through a circuit-board substrate can be calculated for heat flowing from a top-mounted transmission line, such as microstrip, to a cooler region on the bottom of the circuit board.

Where it may not be possible to use a heatsink because of size and/or weight restrictions, the excess heat must be dissipated through the single dielectric layer or, in the case of a multilayer circuit, through additional circuit layers and/or surrounding structures. Fortunately, though an understanding of how various circuit material properties are affected and inter-related by temperature, it is possible to specify circuit materials with high TC capable of dependable thermal management at relatively high power levels, even without the use of a heat sink. Due to high TC and complementary material characteristics, such circuit materials can also enable the design and fabrication of circuits that can handle higher power levels in smaller footprints than circuit materials with lower TC values.

While the TC of most high-frequency PCB materials is relatively low compared to copper (which is 400 W/m-K), a PCB with TC of 0.5 W/m-K is considered acceptable for many lower-power applications. However, when increased thermal flow is required for a design, PTFE-based circuit materials such as RT/duroid® 6035HTC circuit laminates from Rogers Corp. offer values of TC (1.44 W/m-K) many times that of standard PTFE circuit materials for improved thermal flow at higher power levels, without sacrificing the excellent electrical characteristics of PTFE as an insulator. When the thermal dissipation or flow through a circuit laminate's dielectric material is insufficient, it can be aided by means of additional thermal pathways, such as provided by thermal vias to a heat sink. In comparing the TC values of different circuit materials, it should be noted that a given TC value is temperature dependent, and will be referenced at a specific test temperature.

MOT

One of the parameters used for circuit materials applications requiring the Underwriters' Laboratories (UL) rating is maximum operating temperature (MOT). In general, when the MOT of a particular circuit is not known, a safe rule of thumb is to use a MOT of +85ºC for that material.

Additional circuit material parameters related to TC and thermal management include dissipation factor (Df), conductor surface roughness, coefficient of thermal expansion (CTE), and, to a lesser degree, dielectric constant (Dk). The Df relates to the energy of a circuit lost to the dielectric material, in contrast to the conductor loss, which is energy lost to the conductors and conductive material. The Df, which is also known as the loss tangent, is a measure of a circuit material's tendency to absorb energy from an electromagnetic (EM) field to which it is exposed. Lower Df values correspond to lower dielectric loss, less EM energy absorbed, and less heat produced as a result of the absorbed energy. Two circuit material traits which combine for good thermal management (low generation of heat at higher power levels) are low Df and high TC; the combination is a good starting point in the selection of a circuit laminate for a higher-power RF/microwave circuit.

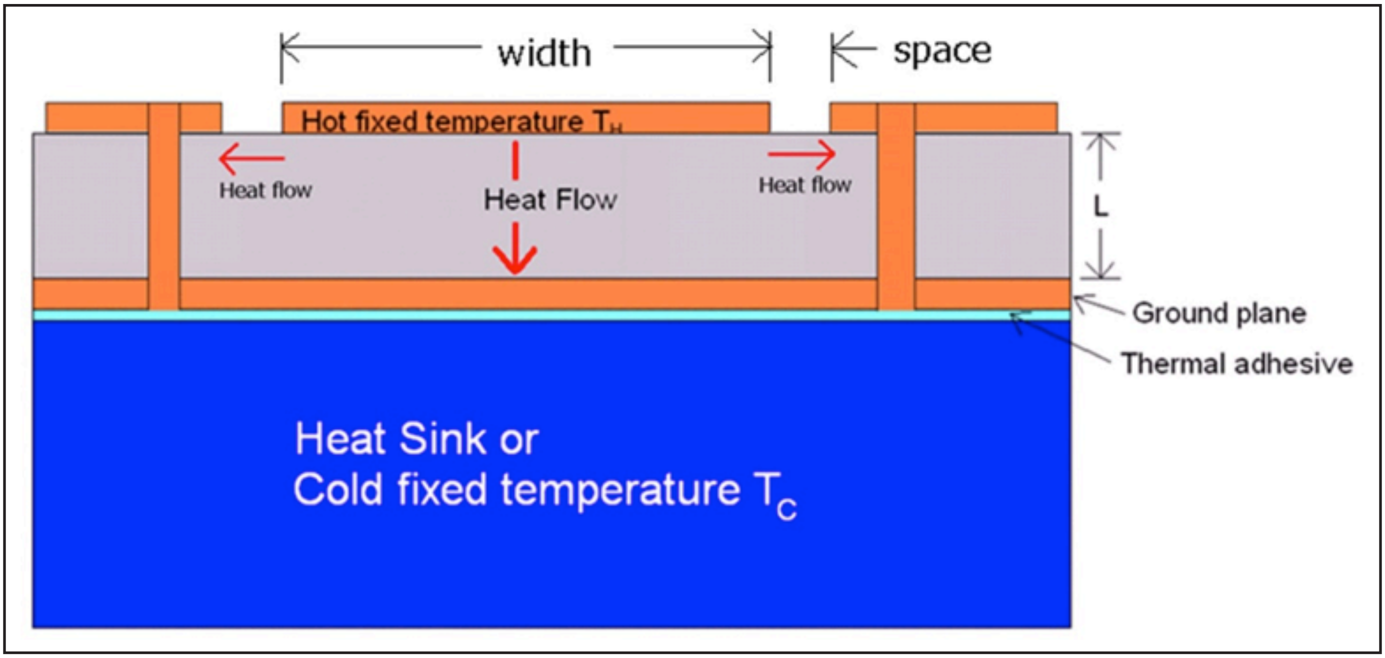

Figure 3 • Thermal vias provide the means of providing high-TC paths through a lower-TC dielectric material, transferring heat from a high-temperature region to a lower-temperature region on a circuit board.

Since the different forms of circuit loss will result in heat produced at higher operating power levels, conductor loss should be considered along with dielectric loss when selecting circuit materials for effective thermal management. Conductor loss is a function of the type of conductor material, with different loss characteristics for bare copper compared to copper plated with a more conductive metal, such as silver. The surface roughness of the copper used to form the conductors also contributes to loss, with minimal conductor surface roughness desired to minimize generation of heat from conductor losses.

CTE

CTE is a critical parameter to describe the mechanical changes of different materials due to temperature, especially at the interfaces between different materials such as in multilayer circuits. It essentially describes how much a material will expand for each degree temperature increase (measured in terms of ppm/°C). To avoid stress on those interfaces, the CTE differences should be as small as possible between the materials. Material interfaces include different types of devices, ICs, and packages mounted on circuit materials such as ceramics and ceramic- and glass-filled PTFE.

The CTE applies to the x, y, and z axes of a material and is typically not the same or isotropic in the two planes. In the x-y axes, CTE mismatches can result in excessive stress on mounted chip and packaged devices. In the z-axis or thickness of a circuit material, CTE mismatches can lead to stress on thermally or electrically conductive plated through holes at elevated temperatures. To minimize stress and provide high-reliability circuit conditions, differences among the CTEs of different circuit materials and their mounted components should be as small as possible. It is also important to note that CTEs are rarely linear and can change with temperature. The most accurate values of CTE are quoted in reference to a specific operating temperature or temperatures. The glass transition temperature (Tg) refers to the temperature of an amorphous material at which it changes from a glassy solid state to a softer, rubbery state. The CTE above the glass transition temperature is typically much higher than it is below the Tg. Therefore, the Tg is an important material property, with higher values typically resulting in better plated-through-hole reliability.

Dielectric constant (Dk) is one of the first circuit material parameters usually checked by engineers when in the process of selecting a circuit material for a particular design. For many high-frequency and high-speed circuit designs, materials with lower Dk values of about 3.0 to 4.5 provide manageable circuit dimensions at a typical 50-Ω impedance at RF/microwave frequencies. Commercial polymer-based (soft) circuit materials such as those using PTFE with various fillers are available with reasonably good TC values and low Dk values.

Selection of circuit materials with high TC is one step towards achieving thermal management. For example, epoxy-based 92ML™ circuit materials from Rogers Corp. have an in-plane thermal conductivity of 3.5 W/m-K (Fig. 4). With a Tg of **+160°C** and low z-axis CTE, these materi-

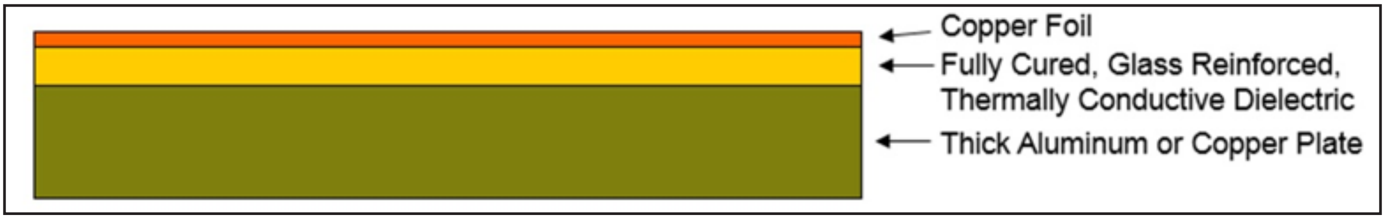

Figure 4 • Through the use of a thick ground-plane layer, 92ML™ circuit materials in effect provide an integral heat sink for the purpose of enhancing heat slow away from heat sources.

als are engineered for consistent thermal flow in high-power applications. Many of those same material traits that favor effective thermal management can also be found in RT/duroid 6035HTC circuit material, also from Rogers Corp., which uses PTFE with ceramic filler to achieve a composite with much higher TC than standard PTFE circuit material. The material exhibits a Dk of 3.50 in the z axis at 10 GHz. It provides an impressive TC of 1.44 W/m-K at +80ºC, supported by low z-axis dissipation factor (Df) of 0.0013.

Measurements and Modeling

Measurements and modeling are essential for achieving the best thermal management solution for a given circuit material and circuit design. Standardized measurements for TC include ASTM D5470 ("Standard Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials," which measures the thermal impedance of various types of materials, including liquids), in which the z-axis TC of a material is measured. In laser flash test ASTM E1462 ("Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules"), the thermal diffusivity is measured, which can then be used to calculate the z-axis and the x/y-axis TC. Electromagnetic (EM) simulation software, such as Ansys HFSS and Sonnet Software, is often used for planar or three-dimensional (3D) analysis of thermal flow through and away from a structure. In addition, Ansys IcePak includes a large number of thermal models, including macro devices, such as PCBs, heat sinks, packages, and heatpipes for modeling purposes, and allows users to create their own models. Also, FloTHERM® thermal modeling software from Mentor allows users to experiment with different materials and the interfaces between them when modeling thermal management at the PCB, device, and package levels. In addition, Energy2D is an open-source, free thermal modeling software from Thermtest (www.thermtest.com) that provides thermal analysis of many standard materials.

For further reading

Allen F. Horn III, Chris Caisse, and James R. Willhite, "Measurement and modeling of the effect of laminate thermal conductivity and dielectric loss on the temperature rise of HF transmission lines and active devices," Proceedings of DesignCon 2012.

John Coonrod, "An Overview of Various Critical Thermal Issues for Microwave PCBs," Proceedings of the 2015 IEEE MTT-S International Microwave Symposium (IMS 2015), San Francisco, CA.

ASTM International, "Standard Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials," standard D5470-12, www.astm.org.

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