KEEPING A GAUGE ON PCB THERMAL EFFECTS

IN THIS ISSUE:

Behavioral Modeling of a Broadband Microwave Receiver
Featured Products
New Products
Defense Electronics Products
High RF/microwave signal power applied to a high-frequency printed-circuit board (PCB) will inevitably generate some amount of heat due to loss through the circuitry and the circuit material. Quite simply, higher power levels through PCB materials with higher loss will produce higher levels of heat. Operating above certain temperature levels can cause problems. For example, PCBs are characterized by a parameter known as maximum operating temperature (MOT), and the performance and reliability of any PCB can be put at risk by operating above the MOT. By understanding the thermal properties of basic RF/microwave PCBs, with help of measurements and electromagnetic (EM) models, it is possible to avoid high-temperature-related performance and reliability problems with PCBs.

Understanding how insertion loss takes place through circuit materials can help to describe some of the critical tradeoffs that are associated with the thermal performance of high-frequency PCBs. To explore some of these tradeoffs, a common example will be used, a microstrip transmission line circuit. The losses associated with this double-sided PCB construction include dielectric, conductor, radiation, and leakage losses. The amounts of the losses can vary widely, with leakage losses typically low for high-frequency PCBs, although there can be exceptions. For this article, the leakage losses will be considered minimal and will be ignored.

Radiation Losses
Radiation losses depend on a number of different circuit parameters, including operating frequency, circuit substrate thickness, PCB dielectric constant (relative permittivity or $\varepsilon_r$), and various design aspects. Concerning this last item, radiation losses often stem from poor impedance transitions in circuits or differences in wave propagation that can take place in a circuit. Some of the areas for concern in circuit transitions include the signal launch area, stepped-impedance points, stubs, and matching networks. When properly designed, these circuit features will exhibit smooth impedance transitions with minimal radiation losses; still, there should be an awareness of the possibility of impedance mismatches (and their associated radiation losses) taking place at any kind of a circuit junction. In terms of operating frequency, radiation losses are typically more troublesome at higher frequencies.

Circuit material issues related to radiation loss are most often the dielectric constant and the thickness of the PCB material. Thicker circuit laminates tend to have more potential for radiation loss, while PCB substrates with lower $\varepsilon_r$ values will suffer more radiation losses than substrates with higher $\varepsilon_r$ values. In terms of material tradeoffs, the benefits of a thin circuit laminate sometimes offset concerns with using a lower $\varepsilon_r$ material. The thickness and $\varepsilon_r$ of a circuit laminate will affect performance as a function of frequency, and it is generally true that a circuit laminate with thickness of 20 mils or less will usually not suffer much radiation loss below 20 GHz. For that reason, most of this article will focus on circuit models and measurements below 20 GHz, and will not consider radiation loss a concern (as related to circuit thermal issues) below 20 GHz.

By neglecting radiation loss below 20 GHz, the insertion loss of a microstrip transmission-line circuit can be considered largely due to dielectric loss and conductor loss. The ratio of the
two losses comprising a microstrip circuit’s insertion loss is based on the thickness of the circuit substrate material. For thinner substrates, conductor losses dominate. But conductor losses can be difficult to predict for a number of reasons. For one thing, the surface roughness of a conductor can have a significant impact on wave propagation properties. Not only can the copper surface roughness alter the wave propagation constant of a microstrip circuit, it can also increase conductor losses. Due to skin effects, the impact of copper surface roughness has a frequency-dependent impact on conductor losses. Figure 1 compares the insertion loss of 50-Ω microstrip transmission-line circuits, fabricated on PCB materials with three different thicknesses: 6.6, 10, and 20 mils thick.

**Measured and Simulated Response**

The curves of Figure 1 include measured and simulated responses, with the simulations produced by means of the MWI-2010 Microwave Impedance Calculator software from Rogers Corp. The MWI-2010 software uses closed-form equations from a well-known paper on microstrip computer modeling. The measured data shown in Figure 1 are from a microwave vector network analyzer (VNA) using the differential length measurement method. Relatively good correlation can be seen in Figure 1 between the total loss curves from the software models and the measured data. As the plots show, a thin circuit (the left curve based on 6.6-mil-thick material) has conductor losses that dominate the total insertion loss. A thicker circuit (the plots on the right for the 20-mil-thick circuit) shows that dielectric and conductor losses tend to be more balanced and combine to form the total insertion loss.

The models and circuits measured in Figure 1 are based on circuit material with a dielectric constant of 3.66, dissipation factor of 0.0037, and high-profile copper with a surface roughness of 2.8 µm RMS. When this same material is used with low-profile (smoother) copper, the conductor losses can be reduced significantly for the 6.6- and 10-mil circuits shown in Figure 1, but there is less benefit for the 20-mil circuits. Figure 2 shows mea-
Figure 2 • These plots compare microstrip transmission lines using the same material type, but with different dielectric thicknesses and copper roughness.
sured data of this same material with high-profile copper, which is standard RO4350B™ circuit material from Rogers Corp. and this same material with low-profile copper, which is RO4350B LoPro™ material from Rogers Corp.

Figure 2 shows the benefits of microstrip circuits fabricated on copper with a smoother surface, where the thinner laminates have a greater impact on reducing insertion loss. The 6.6-mil laminate on the left has an improvement in insertion loss of 0.30 dB at 20 GHz with the smoother copper. The 10-mil laminate has an improvement of 0.22 dB in insertion loss at 20 GHz using the smooth copper, while the 20-mil laminate (on the right) is improved by about 0.11 dB in insertion loss at 20 GHz using the smoother copper.

As shown in Figures 1 and 2, thinner circuits tend to suffer higher insertion loss, which means that they will generate more heat when sufficient RF/microwave signal power is applied. Tradeoffs to consider when addressing thermal concerns is that although a thinner circuit may generate more heat at higher power levels than a thicker circuit, it can be kept relatively cool by means of a more efficient heat flow path to a heat sink because of the thinner circuit.

For managing thermal issues, an ideal thin circuit would be based on circuit material with low dissipation factor, smooth copper, low εᵣ, and high thermal conductivity. The low εᵣ allows the use of a wider conductor than when using higher εᵣ circuit material, which can result in reduced conductor loss. In terms of circuit thermal management, thermal conductivity is an important parameter, although most circuit substrates used in the high-frequency PCB industry are more thermal insulators than conductors, with very poor thermal conductivity.

A great deal of detail regarding the thermal conductivity of circuit laminates was reported in an earlier article, and some of the information from that report will be presented here. For example, the following equation and Figure 3 are helpful in understanding the tradeoffs associated with PCB material thermal issues. In the equation, k is thermal conductivity (in W/m/K), A is area (m), TH is the temperature (K) of the hot reservoir, TC is the temperature (K) of the cold reservoir, and L is the distance (m) between the hot and cold reservoirs.

\[ H = -k \cdot A \cdot \left( \frac{T_H - T_C}{L} \right) \]

**Thermal Model**

The equation with Figure 3 is a simple representation of a thermal model for a microstrip circuit. The circuit would have the signal plane as the top conductor layer and a ground plane as the bottom conductor with the dielectric substrate between these two planes. The thermal model of Figure 3 assumes that heat is generated on the signal plane and this plane serves as the hot reservoir. This is acceptable for a simple thermal model, although the heat generation in a microstrip circuit is much more complicated in reality. In the thermal model of Figure 3, the substrate serves as the thermal conductor to transfer heat from the signal plane to the ground plane, assuming that the ground plane has a heat sink and acts as a cold reservoir. In reality, the circuit substrate acting as the thermal conductor is a poor thermal conductor. To illustrate, the thermal conductivity of a good thermal conductor, copper, is about 400 W/m/K. In comparison, the thermal conductivity of most commercial PCB substrate materials is much worse (less), only about 0.2 to 0.3 W/m/K.

The heat flow equation explains why a thinner circuit (with smaller L) has improved heat flow and can achieve cooler operation under higher power levels. A substrate with improved thermal conductivity (k) will exhibit increased heat flow compared to a circuit material with poor k, providing the potential to achieve cooler operation under higher power levels.

The amount of power that can be applied to a high-frequency PCB is usually determined by knowing how hot the circuit will become with an applied RF/microwave power level. Circuit materials rated to Underwriters’ Laboratory (UL) can also receive a rated thermal index (RTI), which is the maximum temperature that the PCB material can handle for an indefinite period of time without degradation of critical PCB performance parameters. When a substrate material is made into a circuit, other variables must be considered in terms of thermal management. For example, a circuit can receive an MOT rating for the maximum temperature to which it can be exposed for an indefinite period of time without degradation of critical circuit parameters. A circuit’s MOT is
always less than the RTI of the same circuit’s PCB material.

The amount of RF/microwave power that can be applied to a PCB is based on the MOT as well as the operating environment. If the applied RF/microwave power does not heat the PCB above the circuit’s MOT, it is acceptable. Still, applied power will result in circuit heating and will increase the temperature some amount above the ambient temperature. If the ambient temperature is +25°C, the heat generated by the applied RF/microwave power may not violate the MOT. But if the same power is applied to the same circuit at an ambient temperature of +50°C, it may violate the MOT and be a problem in that higher-temperature environment. As this example demonstrates, the amount of power that can be applied to a high-frequency PCB is somewhat dependent upon the operating environment.

Tradeoffs

To better understand tradeoffs in thermal issues for PCB materials, a study was conducted with 50-Ω microstrip transmission-line circuits similar to the constructions used in Figures 1 and 2. Circuits were fabricated on the same types of PCB materials but with differences in thickness and copper roughness. In addition, a circuit was evaluated on a higher-loss PCB material, as well as a tightly coupled grounded-coplanar-waveguide (GCPW) transmission-line circuit using the same low loss material as one of the other microstrip circuits. The applied RF/microwave power varied from 5 to 85 W. At 3.4 GHz, the return loss for all circuits was better than 18 dB, and all circuits were laminated to a 0.25-in. copper plate to be used as a heat sink. Circuits were laminated to the heat sinks by means of COOLSPAN® Thermally & Electrically Conductive Film. This thermoset adhesive material exhibits a thermal conductivity of 6 W/m/K.

As part of the study, an infrared (IR) camera was used to record the heat patterns of the circuits with applied power. To ensure accurate measurements, consistent color was used on all circuits and surfaces in the view of the camera. The color was a black paint with a known emissivity which the IR camera adjusts for accurate thermal imaging. Unfortunately, application of the black paint increased the insertion loss of the transmission lines, so the recorded heat rise is considered a worst-case scenario. In addition, the insertion loss (and heat rise) of the GCPW circuit was impacted to a greater degree than the microstrip circuits, since the black paint filled the gaps in the coplanar ground-signal-ground (GSG) area, which is an area of high current density.

Table 1 shows the circuits, material types and properties, insertion loss, and heat rise results of this multiple circuit/material study. It offers a great deal of information for comparing thermal effects on different circuit materials. For example, it allows a comparison of two
circuits based on the same circuit substrate but with two different types of copper, one with rough copper surface (circuit ID 3) and one with smooth copper surface (circuit ID 4). As expected, the circuit with smoother copper surface has lower insertion loss than the circuit with rougher copper surface, with less heat rise for the circuit with smoother copper surface than for the circuit with rougher copper surface.

Comparing circuit ID 1 with circuit ID 3 reveals the differences in heat rise with a change in PCB material thickness. These two circuits use the same material and copper type and are the same except for the thickness. Circuit ID 1 is thinner, with higher insertion loss than the thicker circuit ID 3. As noted earlier, higher insertion loss usually means higher levels of heat generated when high-enough levels of RF/microwave power are applied. However, as Table 1 shows, the thinner circuit ID 1 was actually cooler than the thicker circuit ID 3, and this is due to the shorter heat flow path, represented by parameter L in the equation with Figure 3.

Comparing circuit ID 1 and circuit ID 2 shows the use of the same circuit materials, but with different circuit configurations. Circuit ID 2 is a GCPW circuit, which is tightly coupled and with plated-through-hole (PTH) vias very near the coplanar ground-signal edges. Figure 4 shows the configurations for the microstrip and GCPW transmission-line circuits being compared.

**Insertion Loss**

The tightly coupled GCPW configuration has thermal benefits compared to the microstrip circuits. The GCPW circuit (circuit ID 2) employs a space of about 5 mils on the coplanar layer between the signal conductor in the middle and the adjacent grounds, and very near this are repetitive ground PTH vias holes. These vias holes are copper and behave as thermal paths to efficiently transfer heat from the signal plane to the ground plane. As can be seen in Table 1, the difference in insertion loss between the microstrip (circuit ID 1) and GCPW circuits (circuit ID 2) is significant. Since both of these circuits are fabricated on the same-thickness material, the circuit with the higher insertion loss should heat up much more. While the GCPW circuit does heat more than the microstrip circuit, it is not nearly as much of a difference due to the thermal benefits of the repetitive ground vias holes.
Finally, comparing circuit ID 3 and circuit ID 5 from Table 1 pits two circuits with the same 20-mil thickness, but with many other differences. Circuit ID 5 is based on low-cost FR-4 circuit material not truly intended for use at microwave frequencies, and the insertion loss for circuit ID 5 is significantly higher than that for circuit ID 3. As a result, the heat rise with applied power is much higher for circuit ID 5 than for circuit ID 3. Circuit ID 5 also suffers several shortcomings related to thermal performance, including poor dissipation factor, low thermal conductivity, and higher $\varepsilon_r$, which results in the conductor for the 50-Ω transmission line to be more narrow and with higher conductive loss than the conductor for the circuit ID 3 material with lower $\varepsilon_r$ value.

For any circuit thermal study, signal launch can be an issue in attempting to transfer RF/microwave energy as efficiently as possible from an input connector to the circuit under test. For this study, all subjects used 3.5-mm end-launch connectors from Southwest Microwave (www.southwestmicrowave.com) which performed very well. As well as the circuits were designed for good signal launch, some RF/microwave energy will be lost around the signal-launch area, resulting in higher heat generated in that area. Since the connector is a good thermal conductor, some heat will be pulled away from the connector besides being drawn into the heat sink. As thermal imaging can reveal, under high-power conditions, the signal launch area for one of these test circuits tends to be hotter than the body of the microstrip circuit.

Figure 5 shows the thermal image for such a case, for a circuit not part of the study in Table 1.

Figure 5 shows the thermal image of a 12-mil-thick, 50-Ω microstrip transmission-line circuit, which exhibited 0.23 dB/in. insertion loss after the black paint was applied for thermal imaging. The highest temperature in the signal launch area of this circuit was +127°F, reaching +119°F in the body of the circuit. Although this does not appear to be a large difference in temperature, it is worth noting since the signal launch area of the circuit has more heat sinking than the body of the circuit.

Conclusion

Reviewing the different components of insertion loss as well as this simple thermal model and several key circuit material properties can be useful in understanding the heating effects of high-power RF/microwave signals on high-frequency PCBs. Quite simply, a circuit material that is relatively thin, with good thermal conductivity, smooth copper and low dissipation factor, can provide the behavior needed for diminishing the heating effects of high-power RF/microwave signals on high-frequency PCBs.

About the Author:

John Coonrod is Market Development Engineer for the Advanced Circuit Materials Division of Rogers Corporation, Chandler, AZ. He can be reached at john.coonrod@rogerscorp.com.

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