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The Effects of PCB Fabrication on High-Frequency Electrical Performance

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Achieving optimum high-frequency printed-circuit-board (PCB) performance is not simply a matter of specifying the best possible PCB material, but can be significantly impacted by PCB fabrication practices. In addition to appropriate circuit materials and circuit design configurations to meet target performance goals, a number of PCB material-related issues can affect final performance, including the use of soldermask, the PCB copper plating thickness, the conductor trapezoidal effect, and plating finish; understanding the effects of these material issues can help when fabricating high-frequency circuits for the best possible electrical performance.

Many PCB applications use soldermask as a thin coating to prevent the adhesion of solder to different sections of a PCB, although it may be surprising to those not working with PCBs at higher frequencies to find that these circuits are formed without soldermask, or that it is used only sparingly for high-frequency PCBs. High-frequency PCBs are often multilayer constructions employing a combination of materials and circuit configurations. For high-frequency PCBs, it is not uncommon to have outer copper circuit layers consisting of microstrip circuits or grounded coplanar circuit constructions as shown in figure 1.

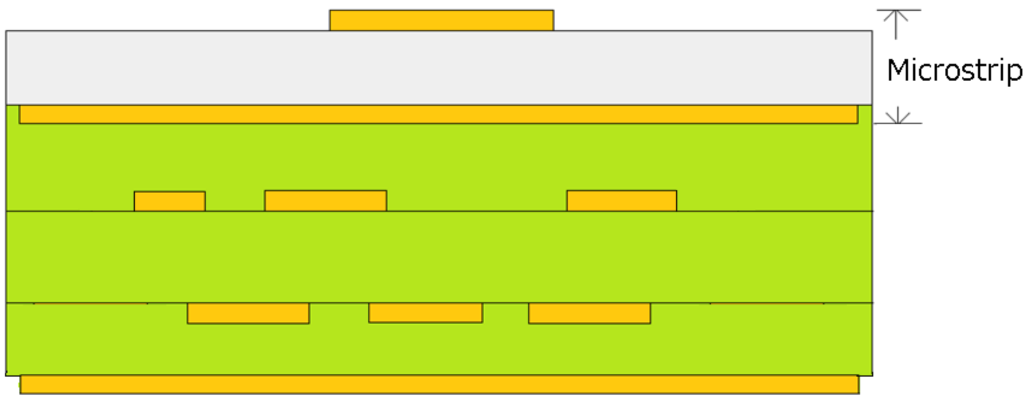


Figure 1. A hybrid multilayer PCB assembly is formed with different circuit materials, with the top two copper conductor layers used in a microstrip circuit configuration for RF signals.

The electromagnetic (EM) energy in the microstrip portion of this circuit consists of electric and magnetic fields propagating through the PCB material and the air around it. Because the air is a medium with the lowest possible loss, the microstrip circuitry benefits from that portion of its EM energy that propagates through the air. The total loss through the microstrip circuitry, α_T, is actually comprised of four different loss components as shown in Eq. 1:

$$\alpha_T = \alpha_C + \alpha_D + \alpha_R + \alpha_L \qquad (1)$$

where α_C is the conductor loss, α_D is the dielectric loss, α_R is the radiation loss, and α_L is the leakage loss. For high-frequency RF/microwave circuit applications, the leakage loss, with a few exceptions, is typically insignificant. The radiation loss is typically dependent upon a particular circuit design, with some circuit configurations more prone to radiation loss than others. Dielectric and conductor losses are typically dependent upon the choice of PCB material, although these losses can also be impacted by circuit fabrication practices. Figure 2 presents measured and modeled data showing how the insertion loss in PCBs is comprised of dielectric and conductor losses and how the loss can vary for different thicknesses of the same PCB material.

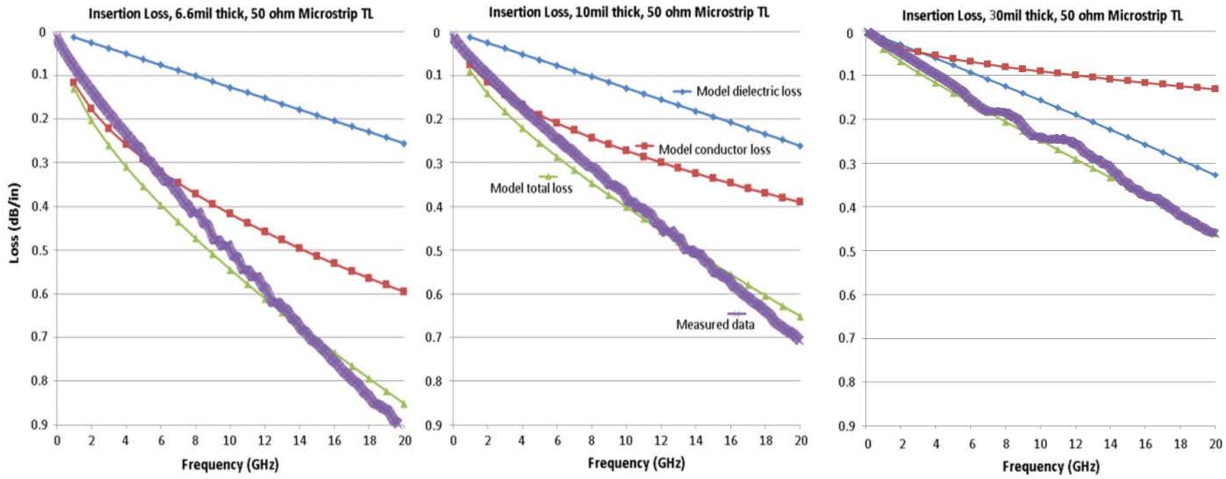


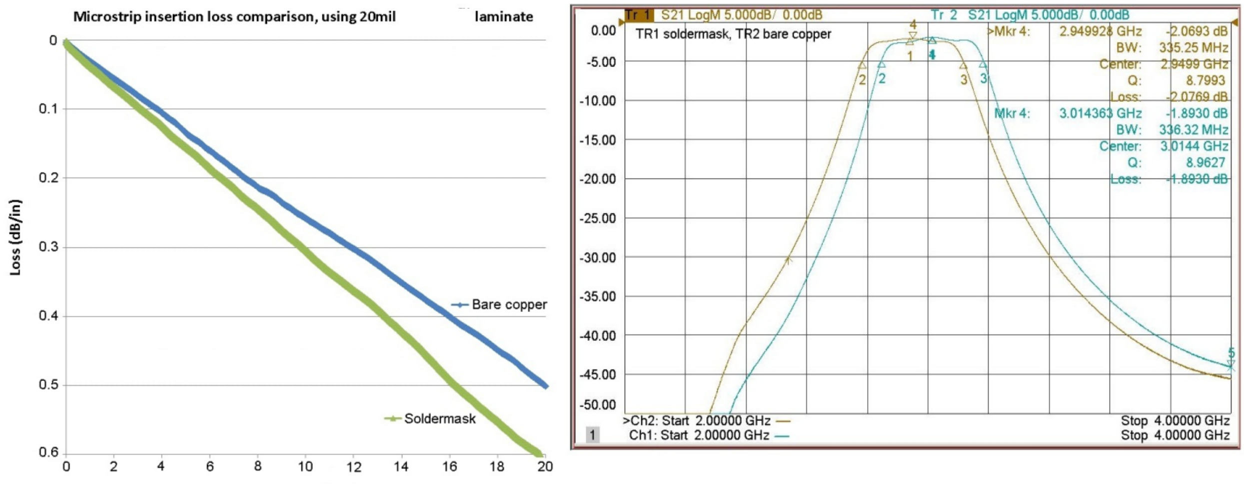
Figure 2. These plots compare measured and modeled components of PCB insertion loss for three circuits of different thicknesses, using the same circuit-board material.

For simplicity, radiation and leakage losses have been ignored in the comparison of PCB losses in figure 2. The model data for these plots was generated using a software program available for free download from the company. (www.rogerscorp.com). The software performs modeling of impedance and circuit loss for microstrip transmission lines using closed-form equations.[1] The circuits are based on a commercial PCB material of different thicknesses--6.6, 10, and 30 mils thick from left to right as indicated in figure 2--but with the same dielectric constant of 3.66.

The middle chart in figure 2 depicts the loss data for the 10-mil-thick PCB material. The total loss predicted by the model is quite close in value to the measured results, so the model appears to be valid. In addition to predicting the total loss, the model is capable of dissecting the PCB's loss into components of dielectric loss and conductor loss. For the 10-mil-thick PCB material, the model predicts higher conductor loss than dielectric loss. In comparison, for the loss of the 30-mil-thick PCB material plotted on the right-hand side of figure 2, the dielectric loss (the blue curve) is greater than the conductor loss. The thinnest of the three circuits, the 6.6-mil-thick PCB material on the left-hand side of figure 2, shows insertion loss which is dominated by the conductor loss. As a general rule, insertion loss in thinner circuits is dominated by conductor loss while insertion loss in thicker circuits is more due to dielectric losses.

To reduce the insertion loss of a thinner circuit material, such as the 6.6-mil-thick PCB material, methods are needed to reduce the conductor loss, which is the dominant loss component for thinner PCB materials. Conductor loss can be reduced by using a smoother copper conductor, since smoother copper conductor surfaces yield lower conductor losses than rougher copper conductor surfaces, resulting in lower insertion loss for that PCB material. For a thicker circuit material, such as the 30-mil-thick PCB material, switching to a smoother copper conductor surface will have less effect on the total insertion loss since the conductor losses of this thicker PCB material amount to less of the material's total insertion loss. For the thicker PCB material, dielectric losses are a larger portion of the material's total insertion loss, and the dielectric losses must be reduced by selecting a circuit material with lower dissipation factor (Df) and lower dielectric loss. For the 20-mil-thick circuit material, a model-measured chart of its loss components would show that its total insertion loss is about equally divided between conductor and dielectric losses (ignoring radiation and leakage losses).

Soldermask applied to the signal side of a microstrip transmission-line circuit will increase the dielectric loss of the circuit. When solder mask covers the signal layer, some of the EM fields that might have propagated through low-loss air will propagate instead through some thickness of soldermask, which typically exhibits relatively high Df of around 0.02. Addition of soldermask adds to the dielectric loss of the PCB material and ultimately the insertion loss of that material. As figure 3.a. shows for measurements of microstrip circuits using the same commercially available PCB materials, one with bare copper conductor and the other with soldermask over bare copper, the loss for the soldermask increases with frequency, with a significant difference between the two circuits at 20 GHz.



a b

Figure 3. The plots compare (a) the insertion loss of microstrip circuits with bare copper and with soldermask as well as (b) S_{21} forward-transmission S-parameters for edge-coupled filters fabricated on the same circuit material, with bare copper and with soldermask.

The S_{21} forward-transmission S-parameter loss curves in figure 3.b. are based on the same circuit configuration and circuit material as for figure 3.a., but depicting an edge-coupled bandpass filter, to show the effects of using soldermask compared to a microstrip circuit with bare copper conductor. The center frequency of the bandpass filter with soldermask has shifted to the left, or lower in frequency, compared to the bandpass filter with bare copper conductor, because the addition of soldermask is also an addition to the dielectric constant of the PCB material, and frequency is inversely related to dielectric constant. The loss of the bandpass filter in the passband region is 1.89 dB for the bare copper circuit and 2.08 dB for the circuit with soldermask. The filter's center frequency is about 3 GHz and such small relative differences in loss between circuit materials with bare copper conductors and with soldermask are typical for that frequency.

Variations in copper plating thickness are to be expected in commercial circuit materials, and these variations can cause subtle differences in the insertion-loss performance of some high-frequency circuits, resulting in circuit-to-circuit variations for the same design. Variations in copper thickness generally have less impact on microstrip circuits than on edge-coupled circuitry such as grounded coplanar waveguide (GCPW) circuit structures. To better understand the effects of variations in copper plating thickness on high-frequency circuits, a study was performed in which the copper plating thickness was purposely varied and different circuits were fabricated and evaluated for insertion loss and phase response. Two types of circuits, both employing two copper layers, were evaluated: microstrip and GCPW circuits. Microstrip features a top signal layer and bottom ground plane separated by a dielectric layer. GCPW has a solid bottom ground plane but incorporates a top conductor coplanar layer fabricated in a ground-signal-ground (GSG) configuration. The signal conductor lies between two ground planes in the GSG configuration, and these top-layer ground planes are electrically connected to the GCPW bottom-layer ground plane by means of plated-through-hole (PTH) viaholes as shown in figure 4.

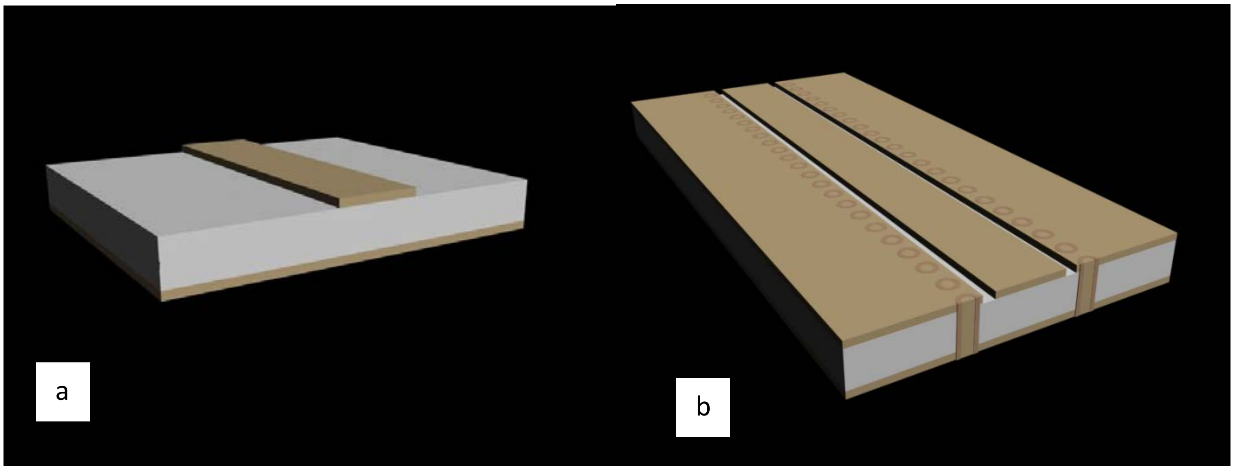


Figure 4. A microstrip transmission-line circuit (a) features a top-layer signal conductor and bottom-layer ground plane separated by a dielectric layer while a grounded coplanar waveguide (GCPW) circuit (b), which is also called a conductor-backed coplanar waveguide (CBCPW) circuit has top- and bottom-layer ground areas.

The study on copper plating thickness variations used commercial, 10-mil-thick, high-frequency PCB material, circuit material from the company. The insertion-loss characteristics of this material, when used for RF/microwave microstrip transmission-line circuits, can be seen in the middle curve of figure 2. As part of the study, microstrip transmission-line circuits were formed on circuit material with thin as well as thick copper plating, and two types of GCPW circuits were fabricated, both loosely and tightly coupled, in reference to the amount of electric field coupling between the coplanar GSG circuit sections on the GCPW circuit's top copper layer. For tightly coupled GCPW circuits, the space between the ground, signal, and ground metal traces was 6 mils. For the loosely coupled GCPW circuits, the space between the ground, signal, and ground traces was 12 mils. The widths of the conductors were tuned appropriately in the loosely and tightly coupled GCPW circuits to maintain 50-Ω impedance for the transmission-line circuits. Figure 5 shows microphotographs of some of the circuits used in this study.

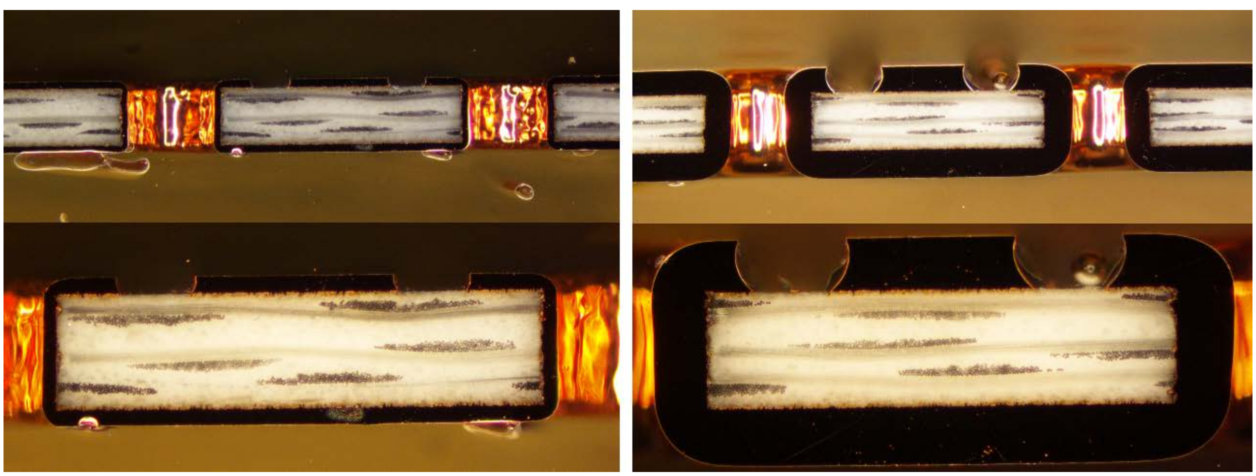


Figure 5. The top and bottom pictures on the left show tightly coupled GCPW circuits with thin copper plating while the pictures on the right show the same circuit configuration with thick copper plating.

Circuits in the study were evaluated for insertion loss and effective dielectric constant, using a differential-length test method.[2,3] Measured differences in insertion loss were relatively small, but statistically valid and in line with loss values suggested according to theory. Since the differences in insertion loss were small, experimental results are shown over a narrow band of frequencies where the return loss was good, where dispersion was at a minimum, where the loss curves were well behaved, and where a fine-enough scale can be used to discern the differences in insertion loss among the circuit configurations. Figure 6 compares the insertion loss levels for different tightly and loosely coupled GCPW circuits with thin and thick copper.

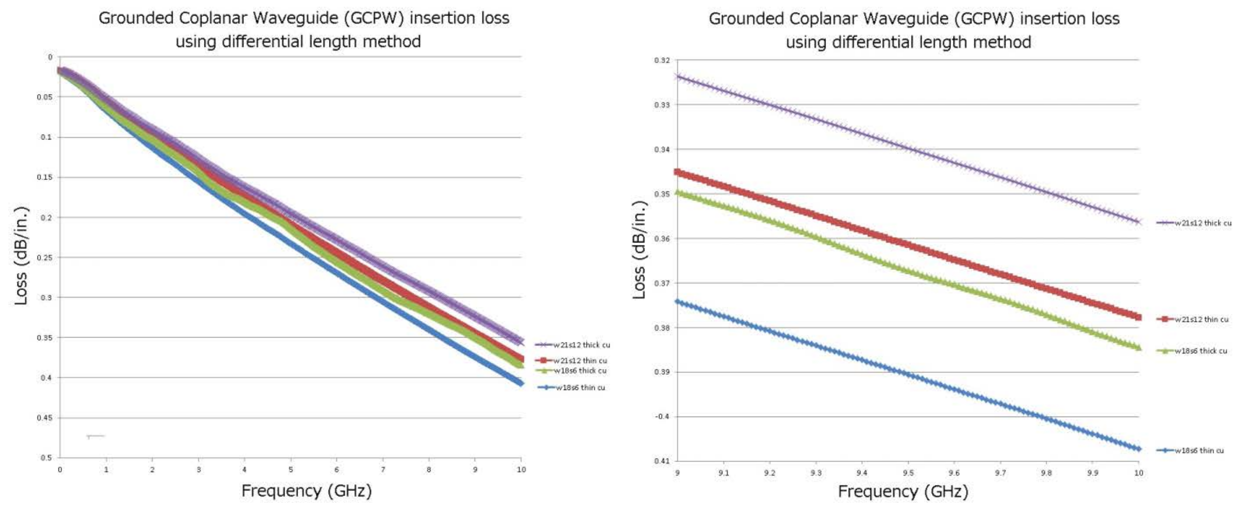


Figure 6. These plots compare the insertion loss of GCPW tightly and loosely coupled structures with thin and thick copper plating thicknesses.

The lowest-loss GCPW circuit in figure 6 is the w21s12 material with thick copper plating, a GCPW circuit formed with 21-mil-wide copper signal conductor and 12-mil spacing between the signal conductor and the adjacent ground planes on the top coplanar layer of the two-copper-layer circuit material. The highest-loss circuit in figure 6 is the w18s6 configuration with thin copper plating. The total copper thickness for this thin copper circuit is only 1 mil compared to a copper thickness of 4.1 mils for the thick copper circuits.

In evaluating the insertion loss of the different GCPW circuits, some things should be kept in mind. Since the circuit under study is relatively thin, at 10 mils thick, conductor losses will be more significant than for a thicker circuit material, and a circuit with wider signal conductor will have less conductor loss and lower insertion loss than a circuit with narrower signal conductor. Also, the electric fields between the ground-signal-ground metallization propagate through air, which is the lowest loss medium. For circuits with thicker copper plating, the sidewalls of the conductors will be taller with more electric field propagating through air between the signal and ground metallization. In considering these factors, it is believable that the lowest-loss GCPW circuit, the w21s12 thick copper circuit material, also had the widest conductor and the thickest copper. The circuit with the next lowest loss was the w21s12 thin copper circuit material, which benefitted from the wide conductor. Next in terms of loss was the w18s6 thick copper circuit material, with a narrow conductor but with thick copper. The material with the highest insertion loss, the w18s6 thin copper circuit material, had the narrowest conductor and the thinnest copper, using less air for its electric fields.

For the microstrip circuits, the differences in insertion-loss characteristics for the materials with thin and thick copper were less dramatic than for the GCPW circuits; in general, the microstrip circuits with thicker copper exhibited slightly less loss. This is likely due to the fact that the circuits with thick copper plating have fringing electric fields using a greater percentage of air for propagation, resulting in lower insertion loss for the microstrip circuits with thick copper plating.

As part of this circuit study, the phase responses of the different circuits were evaluated, essentially by calculating the effective dielectric constant of the GCPW circuits through the application of the differential phase length method.[2,3] This method uses short and long circuits, identical in every way except for physical length. Phase measurements are made for each circuit, and the effective dielectric constant is found at that frequency. With an incremental increase in frequency, the effective dielectric constant is found at the next frequency, and so on. The phase response formula (eq. 2) is altered to account for two circuits of different lengths (ΔL) and the difference in the two circuits' phase angles is ΔΦ. The basic formulas follow, with the alteration to include two circuits of different length (eq. 3) and then rearranging the equation for determining the effective dielectric constant (eq. 4):

$$\Phi = 2\,\pi\,f\,\frac{\sqrt{\mathrm{Eff\_}\varepsilon_r}}{c}\,L$$

(2)

$$\Delta\Phi = 2\pi f \frac{\sqrt{Eff\_\varepsilon_r}}{c} \Delta L \tag{3}$$

$$Eff\_\varepsilon_r = \left(\frac{\Delta\Phi \ c}{2 \pi f \Delta L}\right)^2 \tag{4}$$

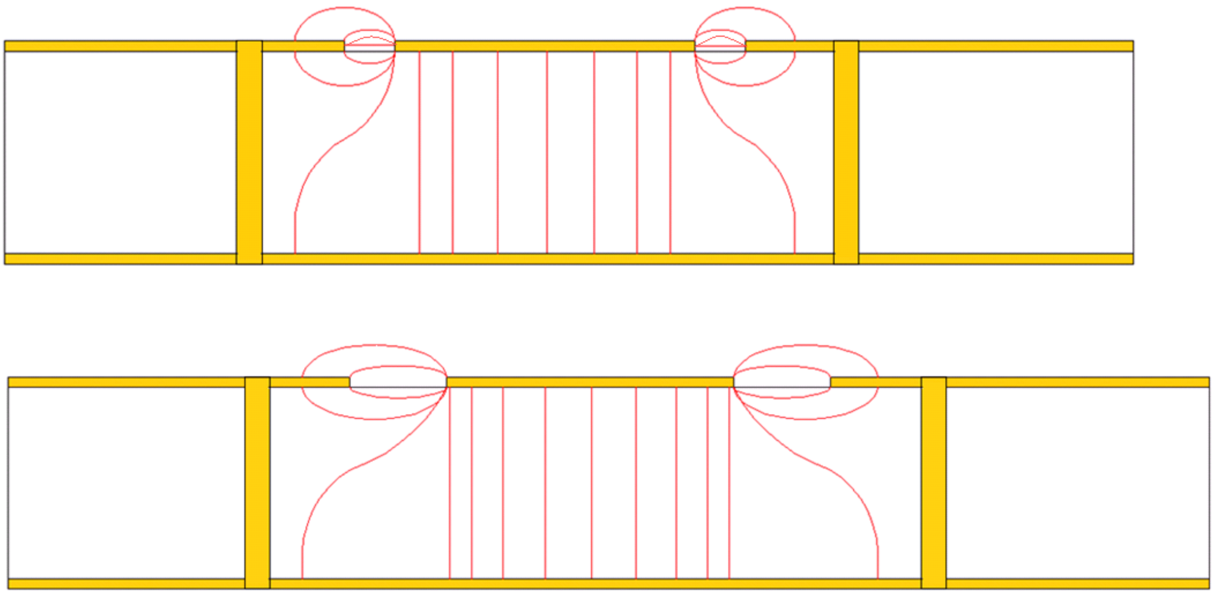


Figure 7. These simple illustrations depict the electric fields for the tightly coupled GCPW circuit (a.) and the loosely coupled GCPW circuit (b.).

The current density will be more highly concentrated along the sidewalls of the coplanar GSG conductors in the tightly coupled GCPW circuit than in the loosely coupled version. As a result, less of the electric field will propagate through the substrate material and more through the surrounding air, with the effective dielectric constant lowered due to the greater use of air for EM propagation in the tightly coupled GCPW circuit than in the loosely coupled GCPW circuit. In addition, if the copper plating for the circuit material is thicker, a greater portion of the electric field will propagate through the air, which will also contribute to a lowering of the effective dielectric constant for the circuit material. As figure 7 attempts to show, less of the electric field occurs in the substrate material for the tightly coupled GCPW circuit than for the loosely coupled GCPW circuit, so it should have a lower effective dielectric constant. As the plots of figure 8 illustrate, the combination of thicker copper plating and tightly coupled GCPW circuitry yields the lowest effective dielectric constant for the different combinations of circuit configurations and circuit materials.

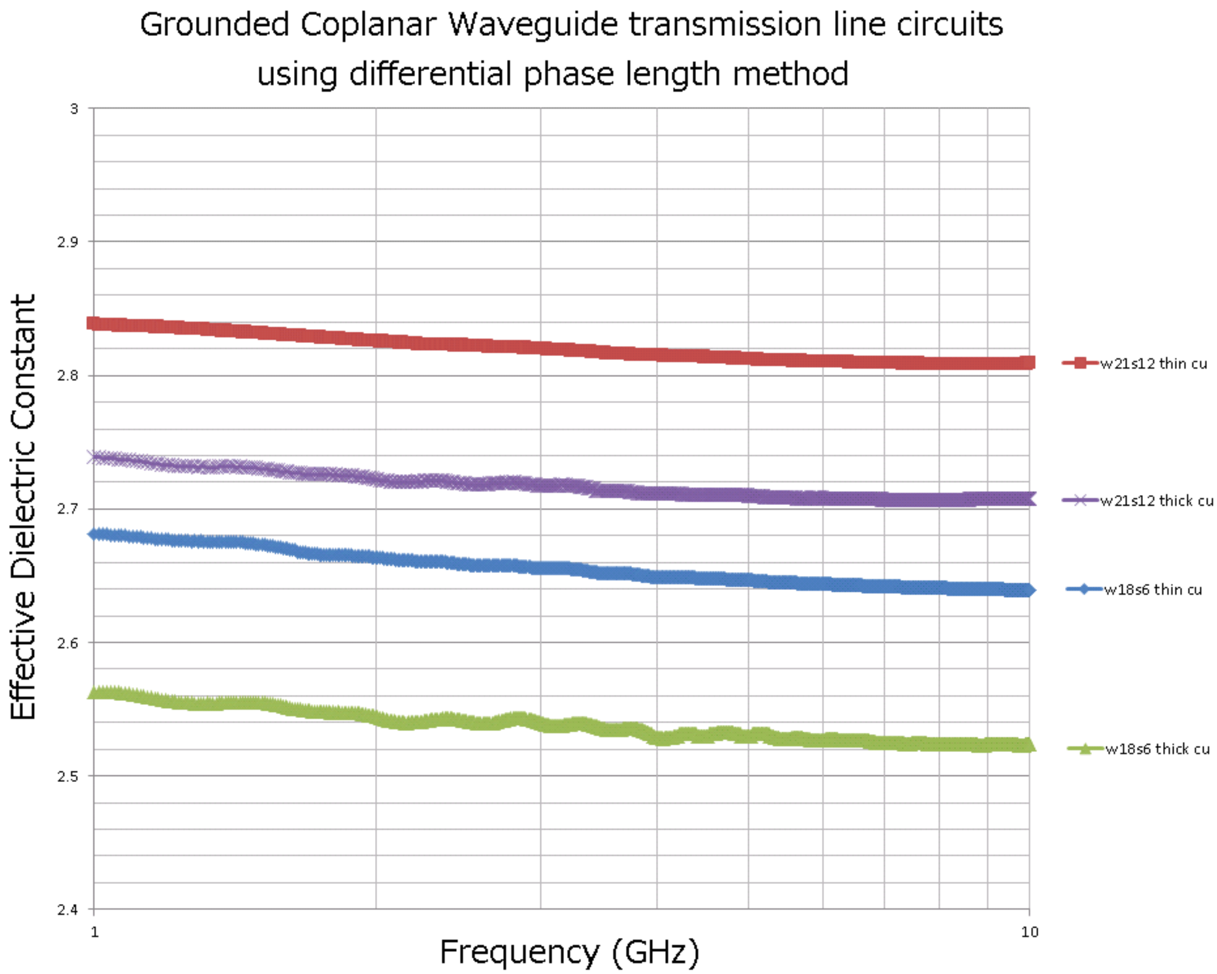


Figure 8. These curves compare the values of effective dielectric constant for tightly and loosely coupled GCPW circuits with thin and thick copper plating.

As the comparisons of the GCPW circuits in figure 8 show, the tightly coupled circuit with the thickest copper (w18s6 thick cu) has the lowest effective dielectric constant. Above that in value of effective dielectric constant is the tightly coupled circuit with thinner copper, followed by the loosely coupled GCPW circuitry with thicker copper. The loose coupling allows more of the electric field to travel through the substrate material, but the thicker copper balances that by enabling more of the electric field to travel through the air around the circuitry. The highest value of effective dielectric constant belongs to the circuit material with the thinner copper and the loosely coupled GCPW circuitry.

For many EM modeling software tools, the cross-sectional geometry of the conductors for a microstrip or GCPW circuit is often assumed to be rectangular in shape. But, as figure 5 illustrates, this is often not the case. Circuits with thinner copper are closer to achieving a conductor shape that is slightly trapezoidal in shape, which is common for PCB technology. The circuits on the right-hand side of figure 5 with thicker copper plating do not form rectangular conductors, and their variations in conductor shapes can result in variations in current density and electric fields for circuits formed on those materials. The trapezoidal shape causes greater variations with GCPW circuit designs than with microstrip configurations. The fields between the coplanar GSG circuit configurations are sensitive to the parallelism of the conductor sidewalls and when the sidewalls are parallel there will be a maximum amount of coupling electric fields. When the same circuit design has angled sidewalls, variations can occur in the electric fields with resulting variations in loss and impedance. Such variations are difficult to predict and model, but current density mappings of EM simulation software programs will show that these variables are valid. Variations of the conductor sidewalls is a normal PCB occurrence which should be considered when designing and fabricating GCPW circuits.

The final plating finish of a PCB material can also contribute to the insertion-loss performance of that material. Several different types of plating finish are used with commercial PCBs, including immersion silver, tin, electroless nickel-immersion gold (ENIG), and hot air level soldering (HASL). For example, ENIG is a popular final plated finish for many high-frequency circuits although it can cause an increase in the circuit's insertion loss. Nickel exhibits about one-third the conductivity of copper resulting in higher conductor losses. The effects of the plated nickel will also be frequency dependent due to the skin depth of the plated nickel finish. Because plating finish impacts a PCB's conductor loss, the significance of that impact will depend on the substrate thickness, with thinner circuit substrate materials more dominated by conductor losses than thicker circuit substrate materials.

A circuit configuration will also determine the amount of insertion loss for a given circuit material at a given frequency for a plated finish. For example, the addition of an ENIG plated finish will have a greater effect on the insertion loss of a GCPW circuit than on a microstrip circuit. The ENIG plating finish only affects the fringing fields at the corners of the microstrip conductors but, as shown in figure 9, the electric fields on the coplanar GSG circuitry of the GCPW circuit will use four layers of the ENIG plated finish, adding to the conductor loss of that circuit in the process.

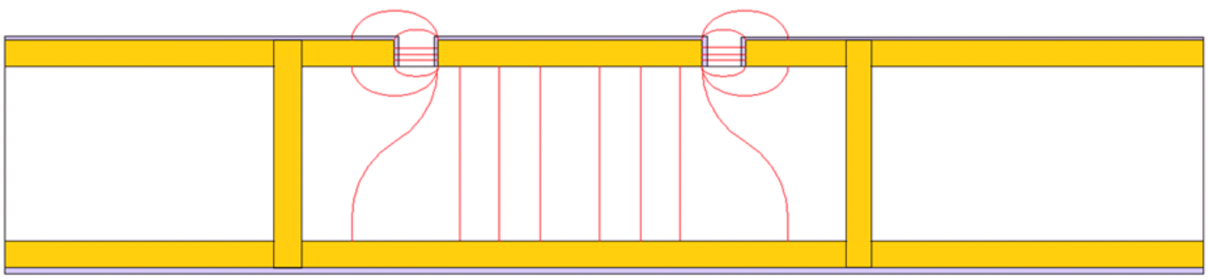


Figure 9. This diagram illustrates how the electric fields of a GCPW circuit use four layers of ENIG plated finish, where the ENIG layer is shown in grey.

In a tightly coupled GCPW circuit, the electric fields will be highly concentrated in the coplanar GSG area of the circuit, with higher losses associated with a ENIG plated finish than for a loosely coupled GCPW circuit with the same ENIG plated finish. Figures 10-12 depict the different effects that ENIG plated finishes can have on both microstrip and GCPW circuits on different types of circuit materials. As figure 10.a. portrays, the ENIG finish causes about a 0.5 dB/in. increase in insertion loss for the microstrip circuit and, as shown in figure 10.b., the ENIG finish increases the insertion loss by about 1.2 dB/in. for the tightly coupled GCPW circuit.

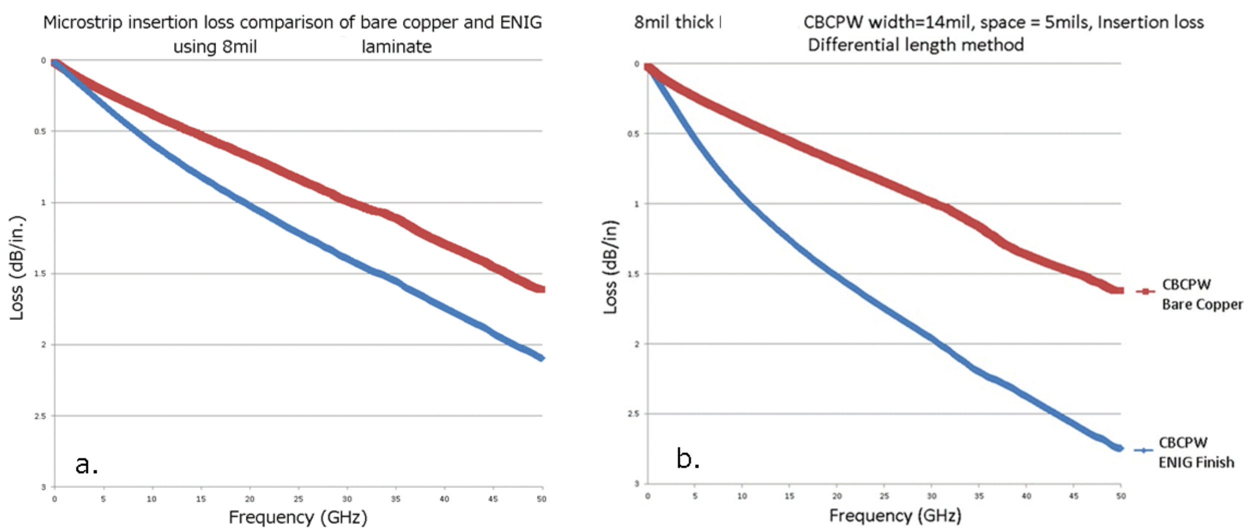


Figure 10. These plots compare the insertion loss of a microstrip circuit using bare copper to a microstrip circuit with ENIG plated finish (a.) and also compare the insertion loss of a tightly coupled GCPW circuit (also known as CBCPW) with bare copper to a tightly coupled GCPW circuit with ENIG finish (b.).

When considering GCPW circuits only, the differences between the insertion loss of a circuit material with bare copper conductors and a circuit material with ENIG finish will depend on the amount of coupling for the circuit. As figure 11 shows, a tightly coupled GCPW circuit will exhibit a greater increase in insertion loss when moving from a circuit with bare copper conductor to a circuit with ENIG plated finish than a loosely coupled GCPW circuit making a move from a circuit with bare copper conductor to a circuit with ENIG plated finish.

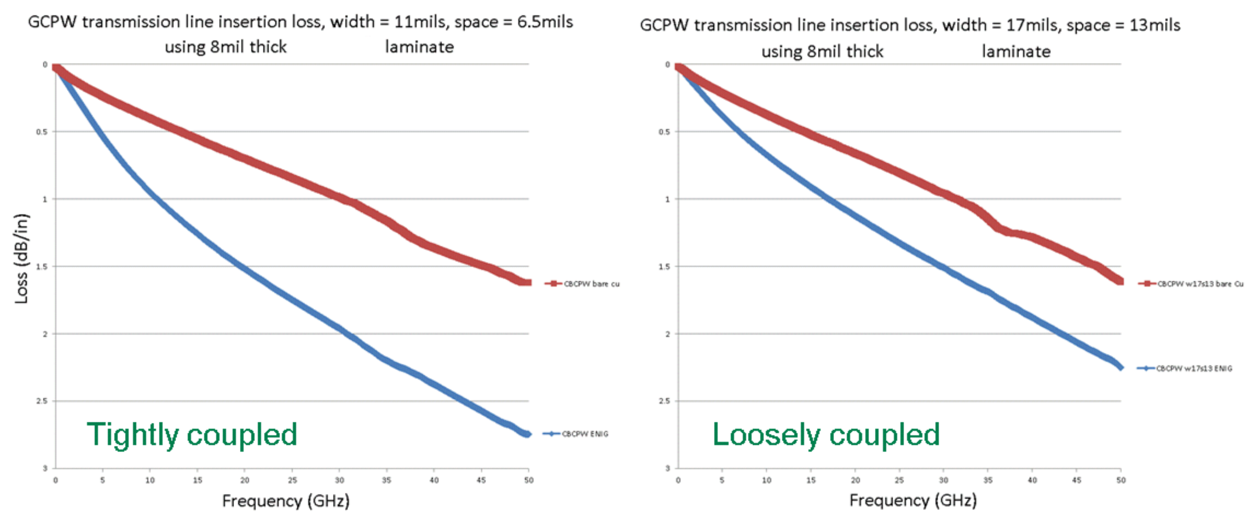


Figure 11. These traces compare insertion loss for tightly and loosely coupled GCPW circuits with bare copper conductors and with copper conductors having ENIG finish.

It is important to remember that the characteristics of a circuit will change as a function of thickness. A thinner circuit will be more dominated by conductor losses than a thicker circuit. When ENIG is part of a circuit conductor, the nickel adds to the conductor loss. But, as shown in figure 12, this added conductor loss will have greater impact on a thinner circuit, which is more dominated by conductor losses, than on a thicker circuit.

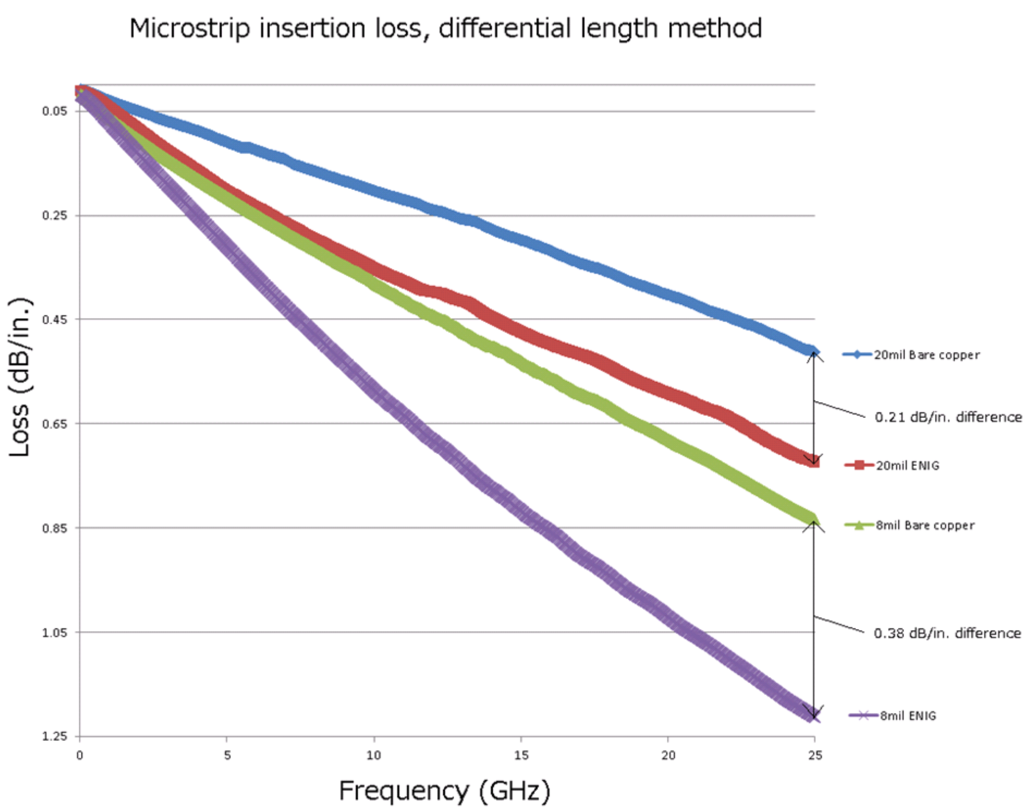


Figure 12. These curves of insertion loss versus frequency compare circuits with bare copper and ENIG for microstrip transmission-line circuits fabricated on different thicknesses of the same circuit material.

References

[1]E. Hammerstad and O. Jenson, “Accurate models of microstrip computer aided design,” 1980 MTT-S International Microwave Symposium Digest, May 1980, pp. 407-409.

[2] Nirod K. Das, Susanne M. Voda, and David M. Pozar, “Two Methods for the Measurement of Substrate Dielectric Constant,” IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-35, No. 7, July 1987.

[3] John Coonrod, “Understanding the Variables of Dielectric Constant for PCB Materials Used at Microwave Frequencies,” European Microwave Week, 2011.