PCB Design and Fabrication Concerns for MILLIMETER-WAVE CIRCUITS

Essential for mmWave applications, phase accuracy is affected by a host of variables. **by JOHN COONROD**

Applications for millimeter-wave (mmWave) circuits are growing rapidly, from collision-avoidance radar systems in autonomous vehicles to high-data-rate fifth generation (g5G) new radio (NR) cellular wireless networks. Many such applications are driving higher frequencies, above 24GHz, where wavelengths are smaller and the smallest attention to circuit design and fabrication can make the biggest differences in electronic product performance. Understanding the differences between PCBs at mmWave frequencies and lower frequencies can help avoid circuit manufacturing mishaps for many applications that are soon to require millions of double-sided and multilayer PCBs at those higher frequencies.

RF PCB Technologies Overview

Compared to lower frequency circuits, high-frequency RF/microwave circuits are sensitive to circuit materials and fabrication processes. Whereas some electrical circuit functions such as power lines and digital control may be well-supported with low-cost FR-4 circuit materials, RF, microwave and mmWave circuits require much higher performance circuit materials to minimize signal losses and distortion. Many multilayer mixed-signal PCBs with many different electrical functions are a blend of different types of circuit substrate materials, with materials selected according to behavior best suited for the types of circuit functions fabricated on that layer.

High-frequency PCBs are typically based on one of three common circuit configurations: microstrip, stripline, or grounded coplanar waveguide (GCPW) circuits **(FIGURE 1)**. The conductors and ground planes are configured differently for each circuit type, with electric (E) fields and current density depicted for each with single-ended transmission lines. The E fields are shown as coupled from the conductors to the ground planes. For differential circuits, two conductors are used. For a differential microstrip circuit, for example, the E fields would be coupled between two signal conductors on the top layer and the ground plane below. High-frequency circuits based on such transmission-line configurations are sensitive to circuit material parameters and PCB fabrication details, especially at higher frequencies.

The depictions of the three circuit types in Figure 1 are rough approximations and will appear differently with changes in frequency. At higher frequencies, current density will be thinner in a cross-sectional view due to skin effects, while the E fields will be more condensed. Electromagnetic (EM) waves generated by variations in each circuit's E and magnetic (M) fields (not shown) would propagate in a direction perpendicular to the two-dimensional circuit depictions, outward from the page.

The performance of all three types of high-frequency transmission lines depends on the dielectric material supporting the conductors. In the stripline case, the conductor is surrounded by dielectric material; for microstrip and GCPW circuits, in which the E fields extend beyond the dielectric material, the air surrounding the circuit contributes to the total dielectric environment of the circuit, so propagating waves in these circuits travel through media with a dielectric constant (Dk) that is a combination of the Dk of the substrate material and air, which is approximately 1. The resulting dielectric environment for microstrip and GCPW circuits is what is known as the effective Dk.

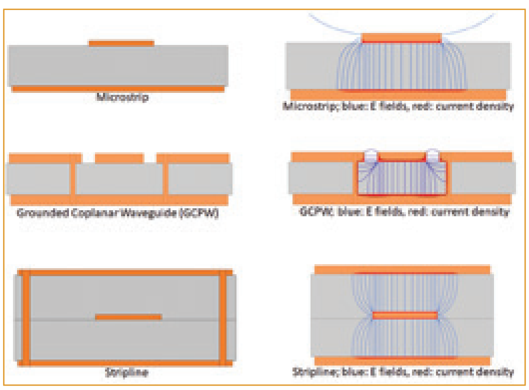


FIGURE 1. Cross-sectional views (left) for three common high-frequency circuit types, microstrip, grounded coplanar waveguide (GCPW), and stripline circuits, and corresponding electric (E) fields and current density for each circuit type (right).

The GCPW depicted in Figure 1 is tightly coupled, with small spaces between the ground planes and signal conductor on the top coplanar circuit layer. Larger spaces result in a more loosely coupled GCPW circuit. Tightly coupled GCPW have a greater percentage of E fields in air compared to loosely coupled GCPW, with the air contributing to a lower effective Dk for tightly coupled GCPW than for loosely coupled GCPW, where a greater percentage of the E fields is in the dielectric substrate material (with a higher Dk than air).

Available signal power tends to decrease with increasing frequency, requiring close attention to minimizing signal loss in high-frequency circuits. Maintaining an impedance-matched environment is critical for minimizing the loss of interconnected components in a high-frequency circuit or system, such as the transmission line between the signal generator and load in **FIGURE 2**. A passive component such as a high-frequency transmission line will exhibit some amount of insertion loss, typically due to conversion of signal energy to heat, even when impedance-matched to generator and load. But when it is not impedance-matched (Figure 2b), signal reflections at mismatched transmission junctions result in return loss, increasing the total loss of the transmission line from a nominal 3dB in the matched state to 6dB in the unmatched state. When signal power must be conserved, insertion loss and return loss must be minimized. They can be measured with a vector network analyzer (VNA) by making scattering (S) parameter measurements of S_{21} for insertion loss and S_{11} for return loss.

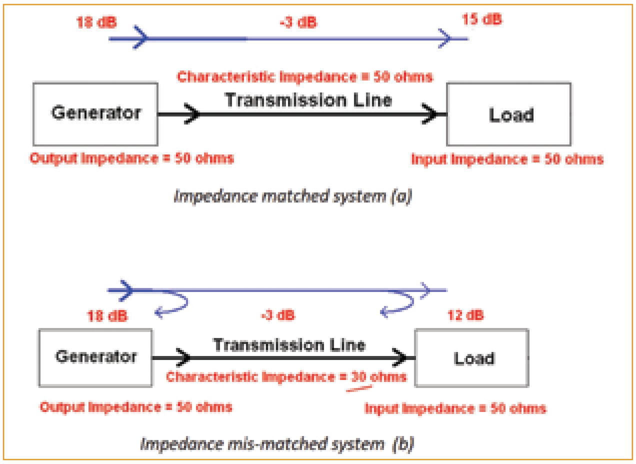


FIGURE 2. Less signal power will be lost between a generator and load with impedance-matched transmission line (a) than when using a transmission line not impedance-matched to the source and load (b).

The insertion loss of a high-frequency circuit is the sum of several different types of loss, including conductor loss (from the metal conductors), dielectric loss (from the substrate materials), radiation loss (from energy radiating away from the circuit), and leakage loss (from energy leaking between the copper planes). A reduction in any one of the four types of losses will result in less insertion loss for a high-frequency circuit.

Leakage losses are typically a concern for substrate materials with relatively low-volume resistivity, such as semiconductor materials, but not for high-frequency circuit materials that typically exhibit high-volume resistivity. Leakage loss can be an issue for high-power circuits but is usually not a concern for the signal power levels used in mmWave circuits. Radiation loss can be a concern at mmWave frequencies, and it can be modeled as part of any investigation of a circuit's total insertion loss, but for now the effects of conductor and dielectric losses are the main concern.

Conductor losses are more dominant for circuits with less dielectric material; i.e., circuits fabricated on thinner substrates where the copper planes are not widely separated. For thicker dielectric substrates, in which the copper planes are farther apart, conductor losses are a smaller percentage of the insertion loss compared to the greater amount of dielectric material in a thicker substrate. **FIGURE 3** shows how the conductor losses for a microstrip circuit decrease (compared to dielectric losses) as the dielectric substrate thickness increases.

Insertion loss testing in Figure 3 was performed on 50Ω microstrip transmission-line circuits using the same copper-clad laminates for identical circuits but with different dielectric substrate thicknesses. Test results are compared with modeled data[1] that predict the total insertion loss and the contributions of conductor and dielectric losses to the total insertion loss.

Figure 3 shows how conductor losses increase for thinner circuit substrates of the same dielectric material. The roughness of the copper at the interface of the dielectric substrate and the copper also plays a role in conductor loss, with a rougher copper surface yielding increased conductor loss compared to a smoother copper surface. Rougher copper conductor surfaces will also slow the EM wave propagation of high-frequency circuits such as microstrip and increase the phase angle of propagating EM waves as if the Dk of the substrate material is higher than its nominal value.

When a thin substrate is needed for a high-frequency design and low insertion loss is also a key requirement, the type of copper is an important consideration. Smoother copper will yield high-frequency circuits with lower insertion loss. For example, in Figure 3 high-profile electrodeposited (ED) copper was used for the conductors and ground planes. This type of copper contributes high conductor loss to the overall insertion loss of a circuit. Conductor loss can be reduced by using a circuit material with smoother copper. Similarly, insertion loss can be reduced by controlling dielectric losses. A thinner substrate will result in dielectric loss being a smaller percentage of a circuit's total insertion loss; selecting a substrate material with lower dissipation factor (Df), a material loss parameter, can also contribute to lowering a circuit's overall insertion loss. For example, the results shown in Figure 3 were achieved using a substrate with Df of 0.0037; dielectric loss (and insertion loss) is less using a substrate with Df of 0.0010.

Precise about Phase

Phase is a critical electrical parameter in many high-frequency circuits, especially in many emerging mmWave applications such as automotive radars and 5G wireless networks, where phase is the basis for many advanced modulation formats. High-frequency circuits must maintain consistent phase response so systems such as radars and wireless communications provide reliable information. A high-frequency circuit's phase response is usually characterized in terms of phase angle or phase velocity. For example, a circuit processing an ideal sine wave would have a 360° phase angle response. **FIGURE 4** shows the phase angle response for a reference microstrip circuit and several variations, with the reference designed to provide a 360° phase angle response, or physical

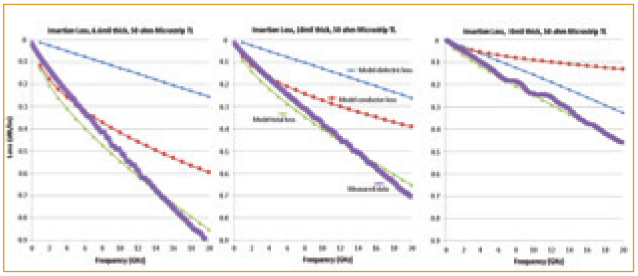


FIGURE 3. Conductor losses contribute less to the total insertion loss of a microstrip circuit for thicker dielectric circuit materials.

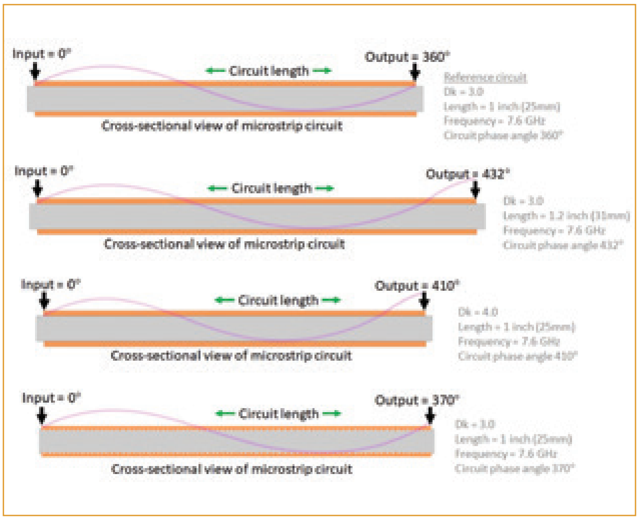


FIGURE 4. The reference microstrip circuit design (top) has a phase angle response of 360° or one wavelength at 7.6GHz. Changes in circuit length and substrate characteristics result in changes in phase angle response.

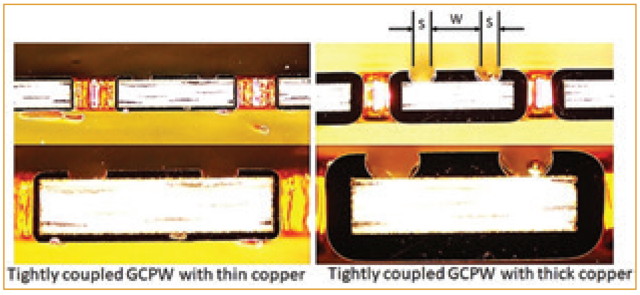


FIGURE 5. These micro-section images illustrate tightly coupled GCPW circuits with thin (left) and thick (right) copper plating on a circuit.

length equal to one wavelength, at 7.6GHz for a particular type of circuit material (with Dk of 3.0).

As Figure 4 illustrates, phase angle response can be affected by small changes in circuit design and circuit material characteristics. The microstrip reference circuit is designed with a physical length of 1" (25.4mm) for a phase angle response of one wavelength or 360° at 7.6GHz. Since wavelength decreases with increasing frequency, the same reference circuit has a phase angle response of two wavelengths or 720° at twice the frequency (15.2GHz). For two wavelengths at 7.6GHz, the reference circuit requires a physical length of 2" (50.8mm).

High-frequency circuit design is often based on supporting specific frequency bands and ranges, such as for communications channels, and the physical features of a circuit are very wavelength-specific, even involving the use of circuit features with fractional wavelengths such as quarter- and half-wavelength features. Given that one wavelength for the reference circuit in Figure 4 is 1" at 7.6GHz, and that wavelength decreases with increasing frequency, it is easy to see how circuit dimensions can become almost microscopic for circuits at mmWave frequencies.

Various circuit material parameters can impact a circuit's phase angle response, such as Dk and copper roughness. For example, for a 1" microstrip circuit fabricated on a substrate with Dk = 4.0 (the third circuit in Figure 4), the phase response increases to 410° at 7.6GHz. Similarly, the phase response decreases in wavelength with decreasing circuit material Dk value. Compared to smooth, low-profile copper, rougher copper results in slower wave velocity and an increase in the phase angle response (as the bottom circuit in Figure 4 approximates).

For mmWave circuits based on phase responses to function properly, the phase angle consistency is a key performance parameter. While a 1" microstrip circuit may exhibit a phase angle response of 360° at 7.6GHz, a microstrip circuit with that physical length on a substrate material with Dk = 3.0

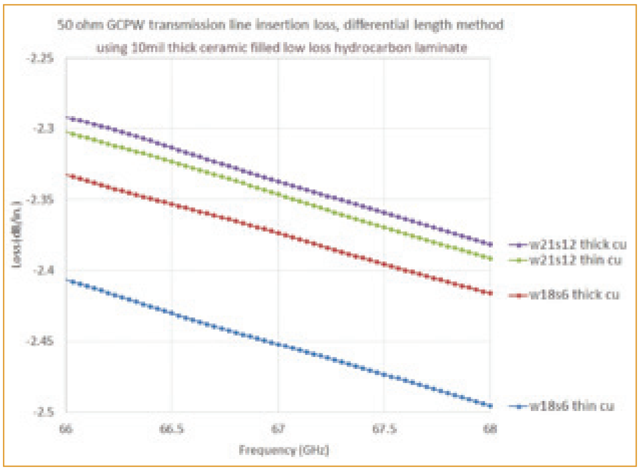


FIGURE 6. Insertion loss comparisons of circuits built on the same sheet of material, but with thin and thick copper and loosely coupled (w21s12) and tightly coupled (w18s6) GCPW circuits.

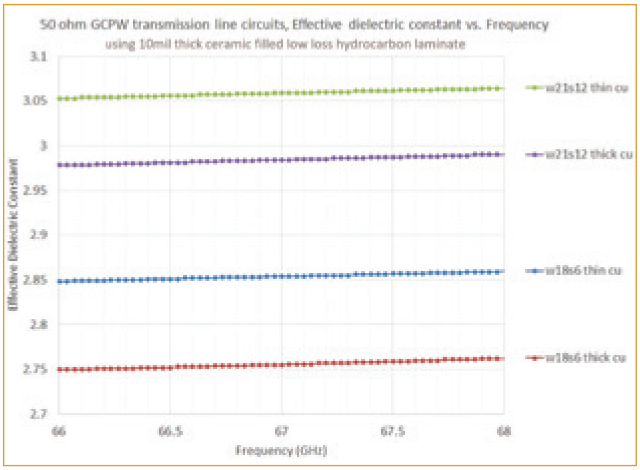
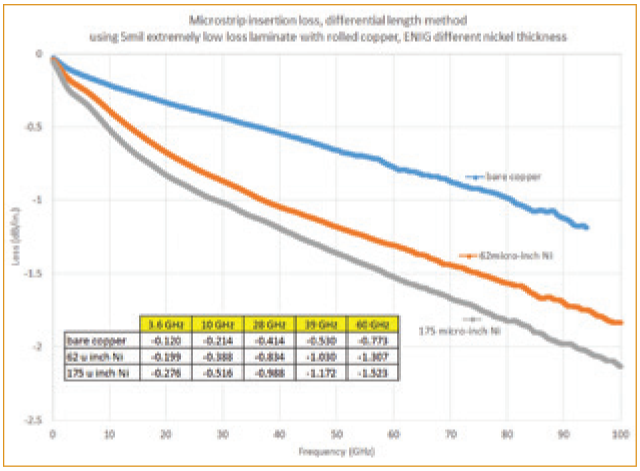


FIGURE 7. The effective Dk values are compared here for circuits built on the same sheet of material, but with thin and thick copper and tightly coupled (w18s6) compared to loosely coupled (w21s12) GCPW circuits.



	3.6 GHz	10 GHz	28 GHz	39 GHz	60 GHz
bare copper	-0.120	-0.214	-0.414	-0.530	-0.771
62 u inch Ni	-0.199	-0.388	-0.834	-1.030	-1.307
175 u inch Ni	-0.276	-0.516	-0.988	-1.172	-1.523

FIGURE 8. The insertion loss of microstrip transmission-line circuits was compared through mmWave frequencies with different Ni plating thicknesses, using bare copper circuits as reference.

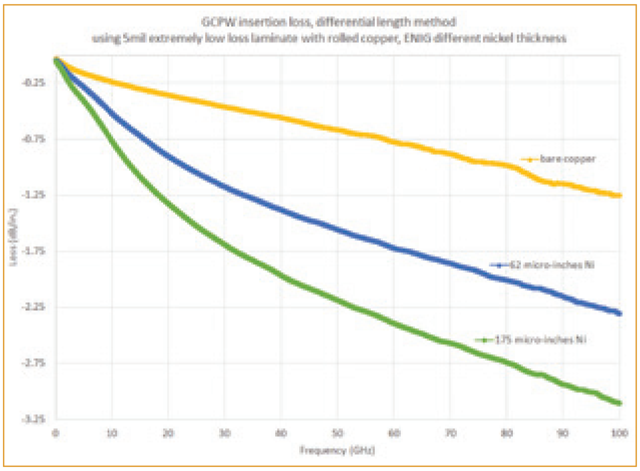


FIGURE 9. The insertion loss of GCPW transmission-line circuits was compared through mmWave frequencies with different Ni plating thicknesses, using bare copper circuits as reference.

may have a phase angle response of greater than 4,000° for a 77GHz radar, and phase angle variations of as little as ±30° can result in errors in radar detection (such as in automotive collision-avoidance systems). For mmWave circuits at lower frequencies, such as the 26GHz and 28GHz frequency bands used in 5G NR systems, phase response is also important for maintaining accuracy in phase-modulated networks, but with the lower frequencies and longer wavelengths, those circuits are less sensitive to variations in phase angle.

Designing PCBs for mmWaves

Many variables affect the performance of a PCB at the small wavelengths of mmWave frequencies, starting with how high-frequency signals are launched onto the PCB from a connector interface. An impedance anomaly generally exists at that interface, and a variation in impedance can cause signal reflections, elevated return loss and distortion. The junction of a high-frequency connector to the PCB may be an extremely short distance, and the impedance anomaly may only affect a physical distance of about 0.1" (2.54mm), but that length can equal a significant fraction of the wavelength at mmWave frequencies and can cause distortion of the wave. For example, at 40GHz, the wavelength is 0.18" (0.46mm). Such an impedance anomaly is less of a concern at lower frequencies where the wavelengths are much longer and less affected over that short distance.

Impedance anomalies at fractional wavelengths can impact mmWave circuit performance. How much is too much? An impedance anomaly of one-half wavelength will typically impact wave performance. A one-quarter-wavelength anomaly may also wreak havoc on mmWave circuit performance, but not as much as the one-half-wavelength anomaly. Generally, impedance anomalies of one-eighth wavelength or longer will influence wave behavior, and anomalies should be kept to one-tenth wavelength or shorter to minimize circuit performance problems at mmWave frequencies.

Ensuring circuit features such as substrate thickness and conductor width are less than one-tenth wavelength at a frequency of interest can prevent performance problems, such as unwanted resonances, at mmWave frequencies. For example, a mmWave circuit fabricated on a circuit substrate with one-half-wavelength thickness at the operating frequency will exhibit resonant conditions between the signal plane and the ground plane due to the thickness of the substrate. A conductor width equal to one-half wavelength at the operating frequency will also cause resonant conditions across the width of the circuit's conductors. By keeping the substrate thickness and conductor widths at one-tenth wavelength or less of the operating frequency, unwanted resonant conditions can be avoided.

Proper PCB Fabrication

The fine dimensions of mmWave circuits require well-controlled PCB fabrication processes to achieve circuits with repeatable, high-quality performance. Variations in copper plating thickness and the final plated-finish placed on copper surfaces can impact the performance of a mmWave circuit, and both processes must be tightly controlled for success with mmWave circuit fabrication. For laminated circuit materials, variations in the thickness of the raw copper on the laminates are typically held to a tolerance of ±10%. But for circuits using plated through-hole (PTH) technology for circuit interconnections, the base copper on a laminate will be thicker in support of the PTH process. The copper plating process yields normal variations related to circuit design and the type of fabrication process. Copper is typically plated thinner in the middle of a processed circuit panel and thicker closer to the edges of the panel, but such variations in copper thickness can be a source of performance variations at mmWave frequencies. For

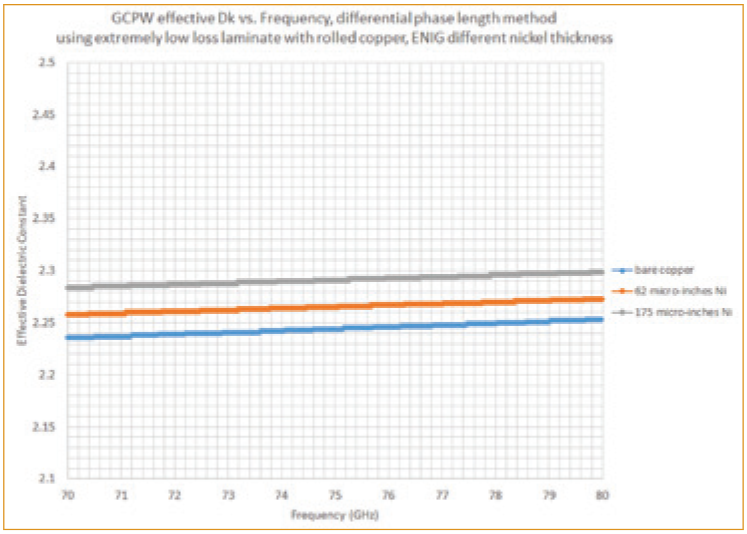


FIGURE 10. With a bare copper circuit as a reference, the effects of ENIG with different nickel-plated thicknesses on the effective Dk of GCPW transmission-line circuits were mapped from 70 to 80GHz.

mmWave circuits manufactured in large volumes, for example, variations in copper thickness can result in circuit-to-circuit variations in insertion loss and phase response. GCPW circuits and most circuits with coupled circuit features can be affected by the circuit material's variations in copper thickness.

A study[2] performed years ago based on 10 mil-thick hydrocarbon-based circuit material evaluated several circuits with different copper thicknesses that were fabricated on the same sheet of material to minimize dielectric material variations. Starting with a 24 x 18" (610 × 457mm) panel of circuit material, it was cut in half, and the halves of circuit material were processed with thin and thick copper plating. Each half panel had the same circuits fabricated on them, consisting of microstrip, tightly coupled GCPW, and loosely coupled GCPW transmission-line circuits. The circuits with thinner copper plating had total conductor thickness of 1 mil, while the circuits with thicker copper plating had total conductor thickness of 3 mils. A 3 mil difference in copper thickness that occurs in even a small percentage of millions of circuits as part of a high-volume manufacturing process can be costly.

Among the different circuits fabricated on these panels, single-ended microstrip transmission-line circuits showed little difference between circuits with thin and thick copper. The circuits with thicker copper had slightly lower insertion loss and lower effective Dk than the same type of circuits fabricated with thinner copper. The thicker copper conductors produced more fringing E fields in the air, with its low Dk, causing the effective Dk to drop and insertion loss to decrease. But at mmWave frequencies, microstrip transmission-line circuits with thicker copper can experience a greater number of wave interference problems than microstrip with thinner copper, due to the increase in surface waves with thicker conductors at such small wavelengths.

In contrast, tightly coupled, single-ended GCPW transmission-line circuits revealed significant differences **(FIGURE 5)**; loosely coupled, single-ended GCPW transmission-line circuits were also evaluated in the study, but the results are not shown here. The circuits were named according to a convention that lists signal conductor width (w) and space (s) between conductors and neighboring ground planes, such as w18s6 for a tightly coupled circuit with signal conductor width of 18 mils and coplanar spacing of 6 mils. A loosely coupled circuit, as an example, had dimensions according to w21s10.

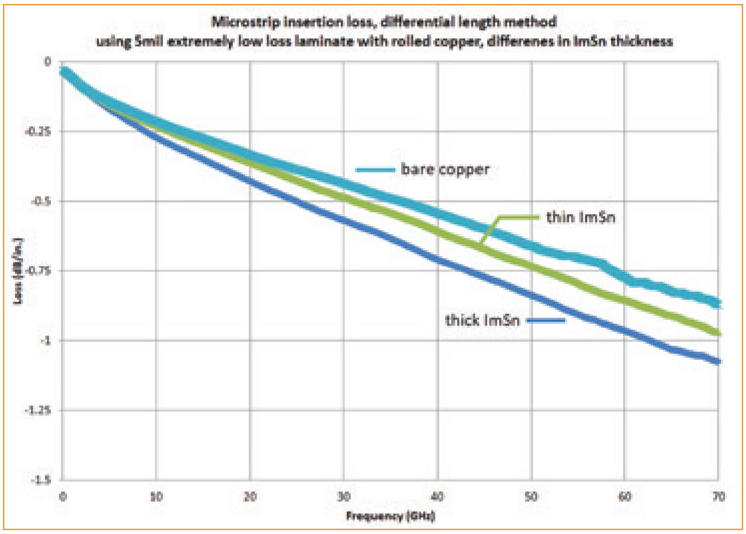


FIGURE 11. Microstrip circuits were evaluated across a wide frequency range to compare the effects of different thicknesses of ImSn plated finishes on rolled copper using a low loss, 5mil circuit material.

In addition to GCPW circuits with thicker copper conductors having more E fields in the air than GCPW circuits with thinner copper conductors, the thicker copper results in conductors with more of a trapezoidal shape than thinner copper with conductors that have more of a rectangular shape. The differences in conductor shapes impact the behavior of the E fields and affect mmWave performance according to the copper conductor thickness.

FIGURE 6 offers a comparison of insertion loss for tightly coupled and loosely coupled GCPW transmission-line circuits with thin and thick copper conductors. The GCPW circuit with conductor width of 21 mils and spacing of 12 mils (w21s12) with thick copper had the lowest insertion loss due to having more E fields in air with its low Dk value and having a wider signal conductor with reduced conductor loss. The GCPW circuit with 18 mil conductor width and 6 mil spacing (w18s6) on thin copper had the highest insertion loss because of having the lowest percentage of E fields in the air and a narrower signal conductor with its increased conductor loss. The frequency range (66GHz to 68GHz) chosen for evaluation was a band where all circuits had return loss of better than 15dB.

The circuits were also evaluated for phase response, with phase angles measured at different frequencies. The effective Dk of each circuit was determined by the differential phase-length method, where a known difference in the physical length of a transmission line corresponds to a known difference in phase angle. In this test method, phase angles are measured for two circuits built side-by-side on the same circuit material panel, with the circuits identical except for transmission lines with different physical lengths. The effective Dk is determined by a simple formula that relates the difference in measured phase angle to the difference in physical length.

FIGURE 7 shows the GCPW circuits with the lowest effective Dk are those with 18 mil-wide conductors and 6 mil spacing (w18s6) with thick copper. With their tight coupling, these circuits have increased E fields in the coupled areas (and in air). The thick copper contributes to tall, coupled conductor sidewalls with more E fields in air. The GCPW circuits with the highest effective Dk are those with 21 mil conductor widths and 12 mil spacing (w21s12) with thin copper, since fewer E fields are in air (with their low Dk value).

Because many mmWave circuits, such as 5G NR small cells and radar systems, rely on maintaining consistent and precise phase responses, phase-angle response deviations must be held within acceptable limits according to frequency and to the requirements of an application. For 77GHz radars, for example, circuits may have total phase lengths of thousands of degrees, so a phase deviation window of 50° (or ±25°) may be acceptable. Depending on design requirements and frequencies, some radar systems may operate acceptably with even larger phase deviations, while some may require a phase deviation window as tight as ±10°. Designers and fabricators of PCBs for these applications should keep in mind how circuit material characteristics and PCB production techniques can impact the phase response of a circuit, especially at the small wavelengths of mmWave frequencies. For example, the difference in effective Dk of 0.1 shown in Figure 7 translates to an approximate phase angle difference of 60° in the 67GHz band. This much of a phase angle difference is attributed to variations in circuit copper thickness alone, with many other variables, including dielectric material thickness variations, Dk variations, and even the type of final plated finish of the copper, affecting the phase angle response. Since copper thickness variations can significantly impact coupled circuits such as GCPW, other circuit configurations, such as microstrip, which are less affected by copper thickness variations, are typically used at mmWave frequencies.

The final plated finish applied to a circuit's copper is usually evaluated in terms of its effect on insertion loss. But at mmWave frequencies, plated finish can also play a role in a circuit's phase angle response. Generally, the effect of plated finish on performance will depend on the type of circuit, such as single-ended or coupled circuits, and the influence of skin depth at different operating frequencies.

FIGURE 8 shows how plated finish can make a difference in the insertion-loss performance of microstrip transmission-line circuits. It compares loss for circuits with rolled copper and different thicknesses of nickel (Ni) plating, using electroless nickel immersion gold (ENIG) plating. The ENIG process normally undergoes some amount of nickel thickness variations, and those variations can impact the insertion loss and phase response of high-frequency circuits at mmWave frequencies.

The high-frequency circuits in Figure 8 exhibit the edge effects of each final plated finish. Microstrip circuits have high concentrations of RF current and E fields on the left and right edges of their signal conductors. When the edges of the conductors of a high-frequency circuit are coated with a metal finish that is not as conductive as copper, the conductor losses will increase, adding to the overall insertion loss of the circuit. In a GCPW circuit, however, with a conductor structure consisting of four edges, the effects of a plated finish that is not as conductive as copper will be much greater than in a microstrip circuit with two conductor edges. **FIGURE 9** shows test results for tightly coupled GCPW circuits and how they are more significantly impacted by plated finish than the microstrip circuits of Figure 8.

Reference circuits in Figures 8 and 9 use bare copper without plated finishes for comparison to the circuits with plated finishes. Often, circuit designers will perform simulations on circuits using a material with specific characteristics, such as its values of Dk and Df, but will not include the effects of a plated finish on their modeled circuits. Those plated finish effects may be difficult to model, but they can affect the performance of both microstrip and GCPW circuits, with increased insertion loss at mmWave frequencies.

FIGURE 10 shows how PCB plated finishes affect the effective Dk, and thus the phase angle response, of tightly coupled GCPW circuits from 70 to 80GHz. Circuits with thin and thick Ni plating exhibit a difference of about 0.02 in effective Dk. The larger difference in effective Dk for tightly coupled GCPW circuits with plating thickness difference compared to microstrip circuits means those circuits will experience greater deviations in phase angle response as a function of plating thickness variations compared to microstrip circuits. A 0.02 difference in effective Dk translates to a phase angle difference of about 60° from 70 to 80GHz. Such large phase angle response deviations can be significant for many mmWave applications requiring consistent phase performance, including radar systems and 5G NR cellular wireless networks.

To minimize the insertion loss of the plating finish at higher frequencies, most mmWave circuits avoid the use of ENIG finish. The variations in Ni-plated thickness of ENIG finishes can also cause excessive variations in phase angle response. As low-loss alternatives, immersion tin (ImSn) and immersion silver (ImAg) plated finishes are more commonly used for mmWave PCBs. In addition, some organic solderability preservative (OSP) finishes with low loss and long shelf lives are used for circuits at mmWave frequencies. ImSn finishes will add some insertion loss and small variations in phase angle response to a mmWave circuit, but because they are so thin, the thickness variations are minimal compared to ENIG finishes, with little effect on the insertion loss and phase response of a mmWave circuit.

Data shown in **FIGURE 11** extend from DC to 70GHz, although data were collected through 110GHz. Data for those higher frequencies were not plotted because of the poor return loss for the test circuits above 70GHz. The high return loss can degrade the accuracy of insertion-loss measurements, so only the results to 70GHz are shown. At 70GHz, the difference in insertion loss between microstrip circuits with thin and thick ImSn plating finish is about 0.12dB/in., which is considerably less than the difference of 0.25dB/in. at 70GHz for the ENIG thickness variations shown in Figure 8 for microstrip test circuits. Although not shown, the difference in ImSn plating difference for microstrip circuits at 70GHz translates to a phase angle difference of slightly less than 3° at 70GHz.

Staying in Shape

Due to the small features of mmWave circuits, circuit etching must be accurate and repeatable. For example, conductors should be formed with ideal rectangular shapes, and trapezoidal conductor shapes should be minimized not only for coupled circuitry such as GCPW but in microstrip circuits as well. Conductor shape variations will have more impact at higher frequencies, with trapezoidal-shaped conductors altering circuit performance at 77GHz, but have little effect on

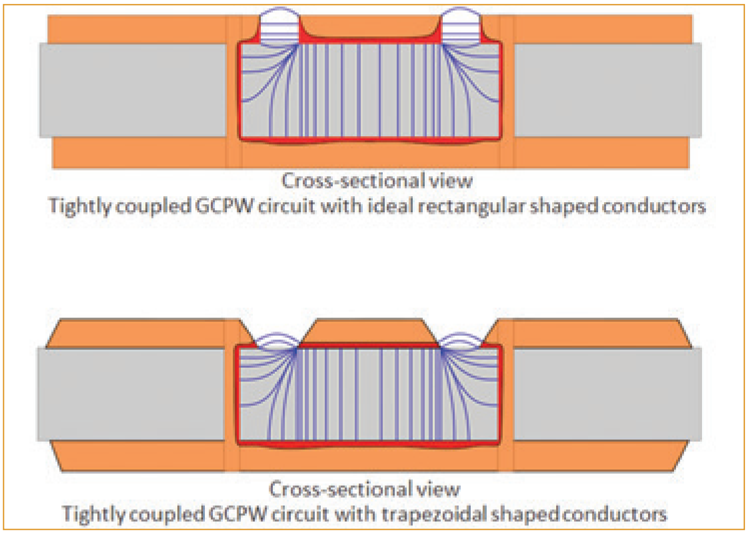


FIGURE 12. These cross-section views show how differences in GCPW conductor shapes can affect a circuit's E field patterns, with rectangular-shaped conductors in the top view and trapezoidal-shaped conductors in the bottom view.

circuits operating at 24GHz. Most circuits designed for 77GHz are based on the use of thinner circuit laminates, such as 4 or 5 mils in thickness, to avoid unwanted resonances. Thinner substrates will use narrower signal conductors than thicker circuit materials, and trapezoidal shapes will have more impact on narrower conductors compared to wider conductors. At lower frequencies, such as 24GHz, thicker laminates are typically used. They have wider conductors in which trapezoidal conductor shapes have less impact on high-frequency performance.

For large-volume production, variations in trapezoidal-shaped conductors can cause variations in the performance of GCPW circuits but also affect microstrip circuits due to circuit-to-circuit variations in the fringing fields. As more or less of the fringing fields propagate in air, the low Dk of air alters the effective Dk of each circuit. Signal conductors with more pronounced trapezoidal shapes will have less E fields in air, resulting in less lowering of the effective Dk due to the low Dk of air compared to more ideal rectangular-shaped conductors with more of the E fields in air. The circuit-to-circuit variations in conductor shapes are exhibited as variations in phase angle response, which will impact the performance of phase-sensitive circuits at mmWave frequencies, particularly more for coupled circuits such as GCPW than microstrip circuits **(FIGURE 12)**.

Conductors are often produced with trapezoidal shapes due to thick copper or a fast-etching process in which an insufficient amount of copper is etched away to form the more ideal rectangular conductor shape. The fast-etching processes typically used in high-volume PCB manufacturing can leave behind copper dendrites on the left and right edges of a high-frequency conductor, and these added copper flakes can cause phase distortion in microstrip and GCPW circuits. Conductors that are more rectangular-shaped (with less circuit-to-circuit phase angle response variations in high-volume production) than trapezoidal-shaped can be produced using thinner copper and better controlled (although typically slower) copper etching processes.

Solder mask used in the production of PCBs can raise the insertion loss and phase deviations of high-frequency circuits and must be removed, especially from mmWave circuits. Liquid photoimageable (LPI) solder mask is typically used in manufacturing high-frequency microstrip and GCPW PCBs. If not removed from the conductors of a microstrip circuit, for example, the E fields normally in air will be in the solder mask with its higher loss and Dk than air, resulting in increased insertion loss and phase angle for that circuit. For coupled circuits such as GCPW, solder mask on the conductors will cause even greater degradation of insertion loss and phase angle response.

Depending on wavelength, it may be possible to use small amounts of solder mask, such as for solder damming, without significantly degrading the performance of a mmWave circuit. As in the case of circuits with impedance anomalies, the solder mask does not affect a portion of the circuit that is more than one-tenth wavelength at the operating frequency. For a 77GHz circuit, one-tenth wavelength is about 10 mils. At lower frequencies, a solder mask patch can have a much greater length without having deleterious effects on circuit performance. For example, at 24GHz, one-tenth wavelength is about 33 mils, and a solder mask patch with that physical length will not pose resonant conditions or significantly affect the circuit's wave properties.

The copper surface roughness at the substrate-copper interface has an impact on PCB phase response at mmWave frequencies. Unfortunately, copper foils used in PCB manufacturing will exhibit a certain amount of roughness, with variations in the amount of copper roughness from sheet to sheet and even within the same sheet. For example, ED copper with an average copper surface roughness of 2µm RMS (also known as Rq or Sq) may have a copper surface roughness that varies from 1.7 to 2.3µm. Circuits produced with that range of copper surface roughness will exhibit significant variations in phase angle response and insertion-loss performance, especially at mmWave frequencies.

The copper may be part of the laminate manufactured by a circuit material supplier, or a foil is used by a PCB fabricator to build a PCB. Generally, copper with a smooth surface will have fewer variations in surface roughness and will yield fewer variations in phase response than copper with a rougher surface. Rolled copper is a type of copper with little variation in surface roughness (and phase response), with average surface roughness of 0.35µm RMS (compared to the average surface roughness of 2µm RMS for ED copper). It is extremely smooth with very low conductor loss, contributing to circuits with less insertion loss than those with ED copper.

In general, mmWave PCBs rely on precise fabrication of circuit features and positioning of components due to the small wavelengths and how physical size variations translate into phase variations over the nominal mmWave frequency range of 30 to 300GHz. A growing number of applications will rely on mmWave signals and PCBs, from autonomous vehicle radars to 5G wireless networks, and phase accuracy is essential for those applications whether for radar target detection (for collision avoidance) or for phase-modulated communications.

The phase performance of a PCB can be affected by many design and fabrication variables, including substrate Dk variations, copper surface roughness variations, substrate thickness variations, copper plating thickness variations, final plated finish variations, etching consistency, conductor trapezoidal shape variations, the moisture absorption properties of the circuit material, and the circuit material's thermal coefficient of Dk (TCDk). For GCPW circuits, variations in the locations of PTHs that connect top and bottom ground planes can cause variations in mmWave phase response. The consistency of lead-free solder-reflow processes and the choice of final plated finish can also affect the phase performance and loss performance consistency of PCBs when they are intended for mmWave frequency ranges, which many applications in need of additional frequency bandwidth will reach. ❑

REFERENCES

1. Circuit simulations were used to compare test results in Figure 3 for different components of microstrip insertion loss for thin and thick circuits at microwave frequencies.
2. Rogers Corp. study shows copper thickness variations for GCPW circuits based on 10-mil-thick RO4350B circuit material.

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