Insertion loss performance differences due to plated finish and different circuit structures

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Abstract

Many different final plated finishes are used in the PCB industry, each with its own influence on insertion loss. The impact of an applied finish on insertion loss is generally dependent upon frequency, circuit thickness, and design configuration. This paper will evaluate the effects of final plated finishes on the insertion loss of two popular high-frequency circuit design configurations, microstrip transmission-line circuits and grounded coplanar-waveguide (GCPW) transmission-line circuits. Data will be presented for loss versus frequency for six different plated finishes commonly used in the PCB industry, and opinions will be offered as to why the loss behavior differs for the different plated finishes and for the different circuit configurations. Because the insertion loss of high-frequency circuits is also dependent upon substrate thickness, circuits fabricated on substrates with different thicknesses will be evaluated to analyze the effects of substrate thickness on insertion loss using different plated thicknesses.

This report will also explore many different aspects of final plated finishes on PCB performance. The nickel thickness in electroless-nickel-immersion-gold (ENIG) finishes normally has some variations; data will show the effects of these variations on the RF performance of a PCB. Immersion tin is often used to minimize thickness variations and analysis will show the effects on RF performance for different thicknesses of immersion tin. The effects of plated finish on PCB performance can vary widely over frequency, and those effects will be shown for a wide range of frequencies, from 1 to 100 GHz.

Insertion Loss Overview

The insertion loss of a high-frequency PCB circuit can decrease the usable signal levels of a system, whether in a receiver or a transmitter. Details on insertion loss can be found in a previous IPC paper,[1] although, a simple review of insertion loss might be helpful prior to examining the data on PCB final plated finishes. The total insertion loss (α_T) is comprised of four loss components:

$$\alpha_T = \alpha_C + \alpha_D + \alpha_R + \alpha_L$$

where

α_C = conductor loss; α_D = dielectric loss; α_R = radiation loss; and α_L = leakage loss.

Leakage loss (α_L) is typically ignored when using high-frequency substrates due to the very high-level volume resistivity of the circuit material. If the material is semiconductor grade, where volume resistivity is not high, leakage losses may be a concern. Leakage loss is more of a concern for certain applications, although those are typically high-power circuits. The evaluations in the present paper are for low-power circuits.

Radiation loss (α_R) can be difficult to assess because it is dependent upon many factors. It will be ignored in the present paper because the circuits under study are relatively low in radiation loss. However, readers interested in radiation loss can learn more from a previous IPC report.[2]

To evaluate the effects of final plated finish on PCB performance, this study will focus on conductor loss and dielectric loss, as are graphically depicted in Figure 1.

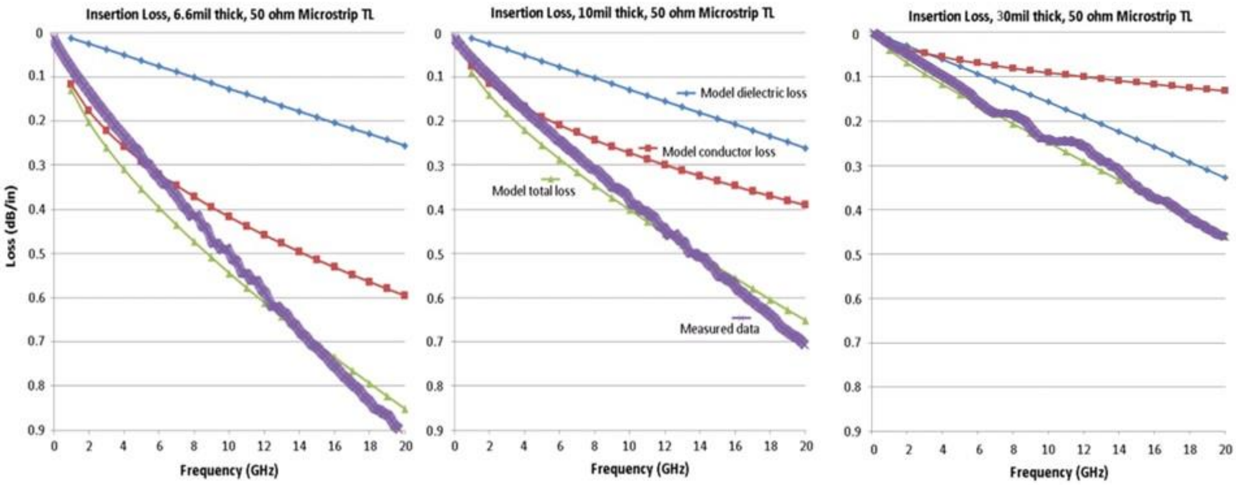


Figure 1. These plots of insertion loss versus frequency compare three sets of circuits on three different thicknesses of the same circuit material.

As Figure 1 shows, a circuit using a thinner substrate will have higher insertion loss than a circuit on a thicker substrate, largely due to conductor loss. For the 30-mil-thick circuit material at the far right (the thickest substrate), the insertion loss is relatively low and the dominant loss component is dielectric loss, largely due to the dissipation factor (Df) of the circuit material. In general, circuits fabricated on thinner substrates are more sensitive to differences in the conductor. Plated finishes will have an impact on a circuit's conductor loss. Thinner circuits will be more impacted by lossy plated finishes than thicker circuits (Fig. 2).

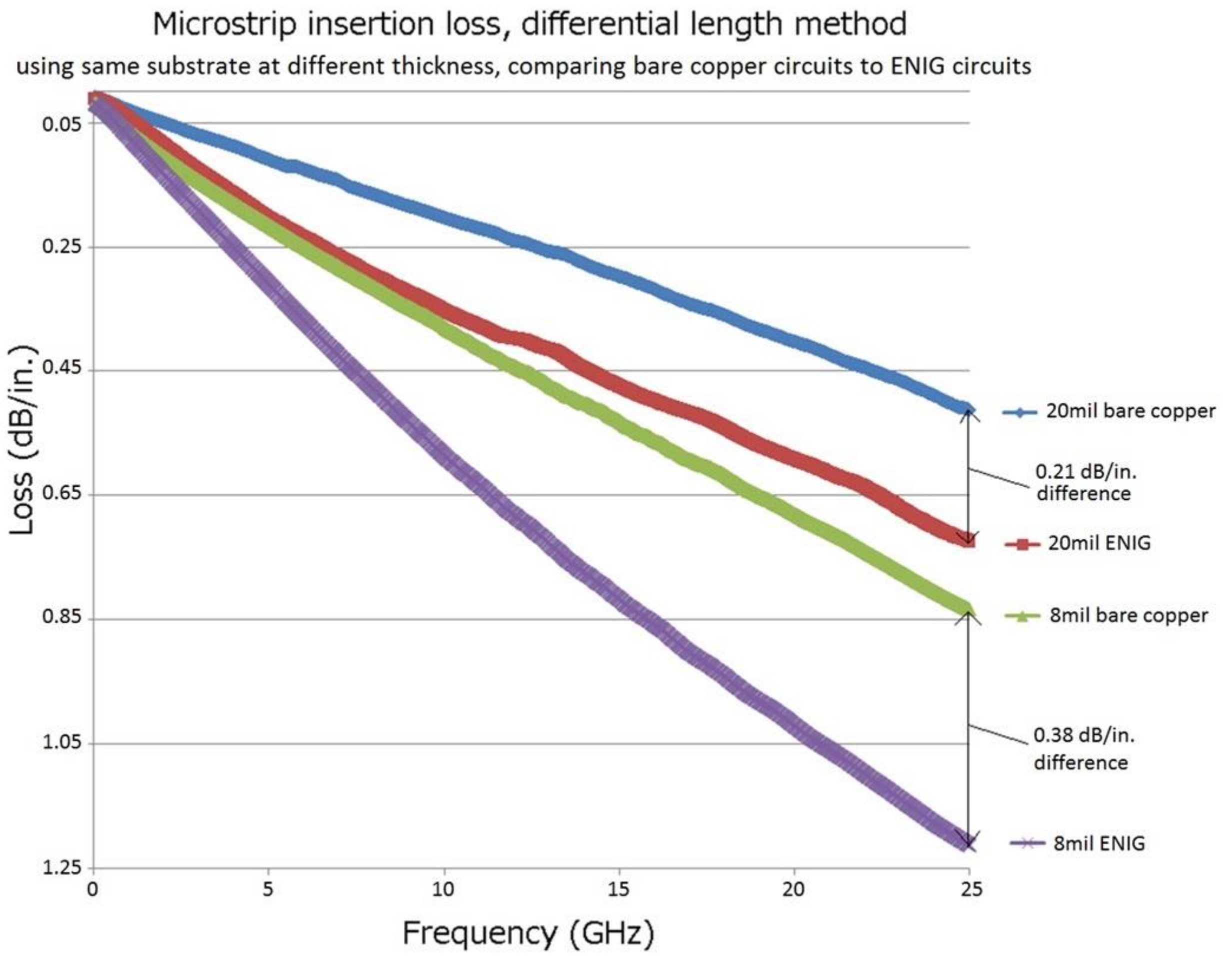


Figure 2. These plots of loss versus frequency for the same circuit material with different thicknesses and with and without ENIG finish show that circuits on thinner substrates are more impacted by loss than circuits on thicker substrates.

Figure 2 compares 50-Ω microstrip transmission-line circuits, using the same substrate at different thicknesses and comparing insertion loss of a circuit with bare copper conductor and the same circuit with ENIG finish. As the plots of loss versus frequency show, the difference in insertion loss between bare copper and ENIG is more dramatic for a thin circuit (an 8-mil-thick substrate) than for a thick circuit (20-mil-thick substrate). The ENIG finish results in additional conductor loss and a thinner circuit is more affected by differences in conductor loss than a thicker circuit.

Loss Mechanisms for Plated Finishes

Considering a cross-sectional view of a microstrip transmission-line circuit, the concentration of electric fields and the current density between the bottom edge of the signal conductor and the top edge of the ground plane can be readily visualized (Fig. 3). The opposing metal faces of the top copper (signal) plane and the bottom copper (ground) plane have a concentration of electric fields. However, there is also a high concentration of electric fields and current density to be found at the edges of the signal conductor as can be seen in Figure 3.

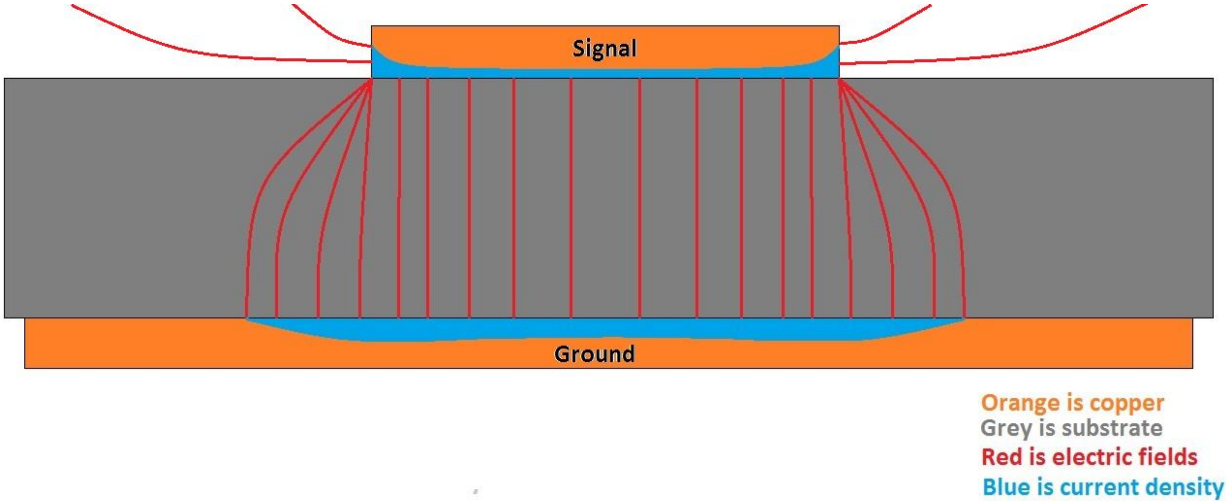


Figure 3. This cross-sectional view of a microstrip transmission line circuit shows the electric fields and current density between the two metal faces of the PCB.

The depiction of a microstrip transmission-line conductor in Figure 3 is not meant to be overly rigorous, although great care was taken to show the appropriate field lines and current density for a typical microstrip transmission line circuit. It is a general representation of the electric fields and current density for a microstrip circuit; the left sidewall and right sidewall of the signal conductor will have higher current density near the base of the conductor. Final plated finishes cannot penetrate the signal conductor and are typically applied to the three edges of the conductor other than the copper-substrate interface. The additional conductor loss from a lossy plated finish is typically an edge effect, coming from the left and right conductor sidewalls with the plated finish. Conductor losses will increase due to the finish having lower conductivity than copper. This lossy edge effect is accumulative: a circuit with short length will suffer minimal additional loss due to the plated finish while a circuit with long length will exhibit significantly higher loss as a function of length.

The increased loss due to final plated finish is also circuit design dependent, and a grounded coplanar-waveguide (GCPW) transmission-line circuit will suffer more loss due to a plated finish than a microstrip circuit with a plated finish. The GCPW configuration results in more of the lossy finish being part of the signal path than in a microstrip circuit (Fig. 4).

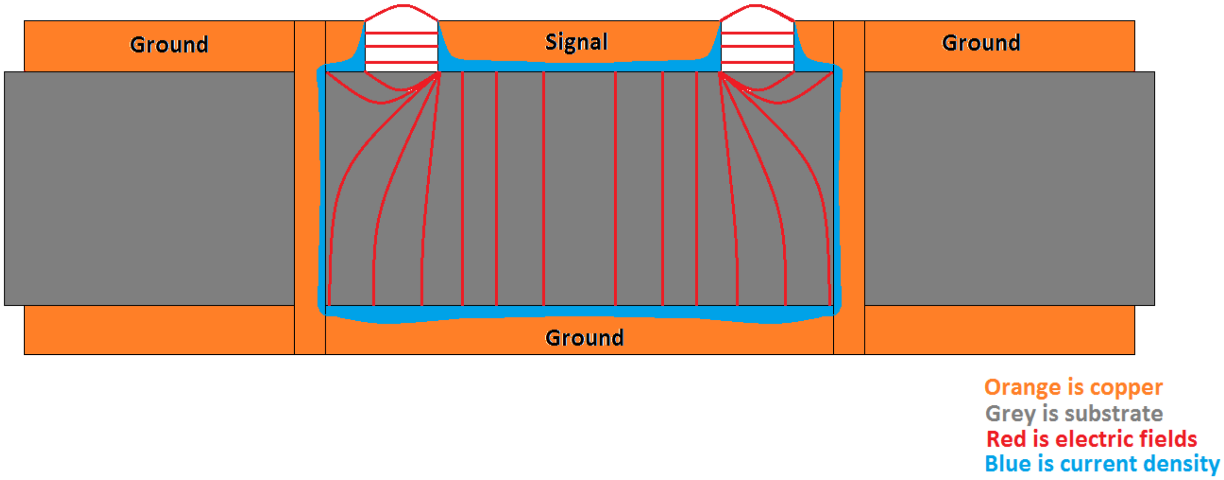


Figure 4. This cross-sectional view of a GCPW transmission-line circuit shows its electric field lines and current density.

As with the image in Figure 3 for microstrip, the drawing of GCPW in Figure 4 may not be exact, but much diligence was applied to show the appropriate electric field and current density configurations for a typical GCPW circuit. As was the case for the microstrip circuit, the final plated finish cannot impact the copper-substrate interface; however, the coplanar sidewalls will be plated with the finish. In the case of a GCPW circuit, there are four sidewalls where the plated finish will be applied and significant current density occurs in those areas. A lossy plated finish will cause a more-significant increase in conductor loss for a GCPW circuit as compared to a circuit based on microstrip transmission lines.

The GCPW circuit in Figure 4 is considered tightly coupled. This means that the space between the ground-signal-ground (GSG) plane on the coplanar layer is relatively small compared to the substrate thickness. If a loosely coupled GCPW (with large GSG coplanar spacing) was drawn, there would be much less current density along the sidewalls. The impact of final plated finish on this circuit configuration would be considerably less than on a tightly coupled GCPW circuit configuration. In general, the loss of a microstrip transmission-line circuit will be less impacted by the final plated finish than a GCPW circuit, as illustrated by Figure 5.

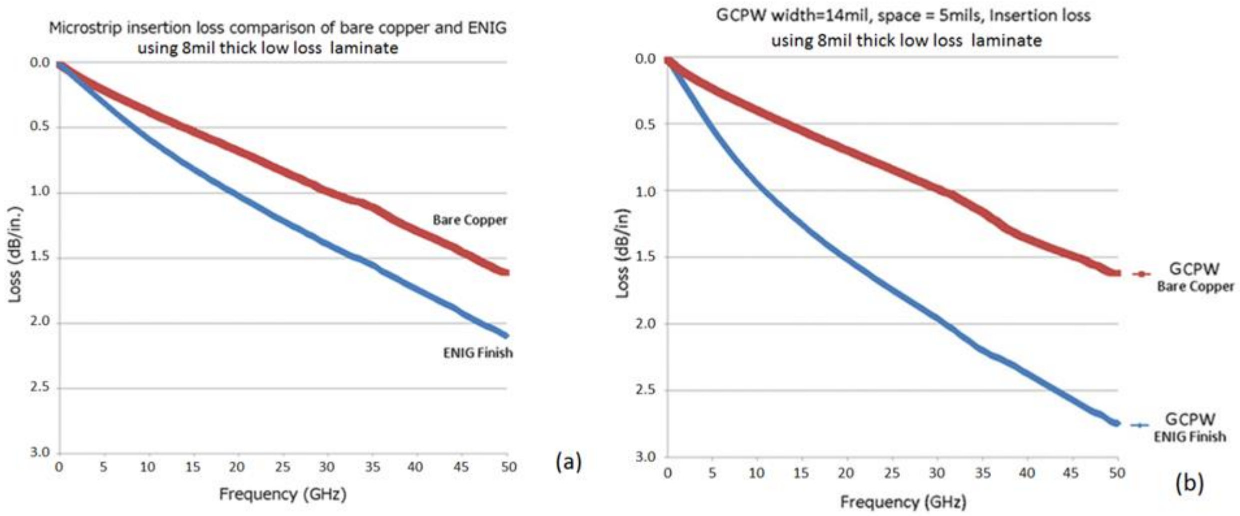


Figure 5. For the same circuit laminate, the differences in loss can be seen for bare copper conductors and conductors with ENIG plated finish for (a) microstrip and (b) GCPW circuits.

As can be seen in Figure 5, the increase in insertion loss due to a lossy (ENIG) plated finish is greater for a GCPW circuit than for a microstrip circuit. In this case, the comparison is between a tightly coupled GCPW circuit (Fig. 5b) and a microstrip circuit (Fig. 5a). If the comparison had been between a loosely coupled GCPW circuit and microstrip, the results would have been somewhere between the microstrip and GCPW responses shown in Figure 5. A very loosely coupled GCPW circuit can behave very much like a microstrip circuit in terms of loss behavior.

Trying to account for the losses of a final plated finish as a function of frequency can be rather difficult, because many loss mechanisms for these circuits are frequency dependent, as is the loss impact of the final plated finish.

One frequency related issue is skin depth and that is how much of the conductor will be used by the RF current at a given frequency. When the frequency increases, the skin depth will get thinner and that will naturally cause more conductor loss. Skin depth is also impacted by the conductivity of the metal conductor. Copper has excellent conductivity, but most final plated finishes have less conductivity than copper. The following function gives a reference to the skin depth formula and the conductivity of different metals:

Skin depth (δ)

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

f = frequency
μ = permeability
σ = conductivity

Approximate conductivities (σ) of metals

Silver	6.301 x 10^7 S/m
Copper	5.817 x 10^7 S/m
Gold	4.520 x 10^7 S/m
Nickel	1.500 x 10^7 S/m
Tin	0.870 x 10^7 S/m
Solder	0.700 x 10^7 S/m

As the skin depth formula suggests, an increase in frequency results in a decrease in skin depth. A decrease in conductivity will cause an increase in skin depth. Finally, an increase in permeability results in a decrease in skin depth.

The effects of a lossy plated finish on the composite conductivity of the sidewalls of a signal conductor can be difficult to estimate, especially considering changes with increased frequency and how skin depth decreases with frequency. But it can be remembered that at lower frequencies (less than 500 MHz), the composite conductivity at the sidewalls of a signal conductor is a combination of copper-nickel-gold. As frequency increases, the skin depth will decrease and the composite conductivity at the sidewalls will be a combination of nickel-gold. At much higher frequencies, with very thin skin depth, the composite conductivity will be dominated by the gold. So far, the plated finishes for PCBs have been referred to as "lossy plated finishes" because they increase the loss of a copper conductor beyond its unplated performance. A plated finish that would not be considered lossy would be one that does not increase the loss of a copper conductor, such as immersion silver (with conductivity higher than copper).

For ENIG, nickel exhibits about one-quarter the conductivity of copper; since it is less conductive than copper, it will suffer greater conductor losses. The presence of nickel can cause a doubling or even a tripling effect on conductor losses. For one thing, the nickel will cause more conductor loss due to its conductivity being less than copper. For another, with increased skin depth in nickel, the RF current will use more nickel, resulting in greater loss. A third factor has to do with the ferromagnetic nature of nickel and how it will normally suffer some amount of magnetic loss in combination with the other two loss components.

The potential ferromagnetic effects of nickel are difficult to quantify. In general, ferromagnetic properties change dramatically with frequency, from lower microwave frequencies to a few GHz. The higher relative permeability (μ_r) of nickel will result in some decrease in skin depth, somewhat offsetting the increased skin depth of nickel due to poor conductivity. In addition to these complications, the nickel used in ENIG is not pure nickel but is typically doped with phosphorous. Suppliers of ENIG will adjust different characteristics of the nickel alloy for different reasons. Due to the many issues associated with the magnetic properties of nickel, it can make a correlation between models (for simulation) and measurements less accurate.

Measured Results and Discussion

The author has conducted several studies on plated finishes over the past few years with the cooperation of two ENIG suppliers and a PCB fabricator (referenced in the acknowledgments). Before reviewing some of the measurement results of those studies, it may be helpful to detail the test vehicle used for the measurements. The preferred test vehicle consisted of a 50-Ω microstrip transmission-line circuit on a selected circuit material as the device under test (DUT), with measurements made per the differential length method[3]. The microstrip circuits were fabricated on thin, low-loss substrates with smooth copper. These material characteristics help minimize dielectric losses while exaggerating any conductor loss differences among different plated finishes used on the DUTs. It should be noted that all copper foils used in the PCB industry have some normal surface roughness variations which result in variations in conductor losses from one circuit to another when using the same circuit laminate. By using smooth rolled copper, the surface roughness variations were minimized as much as possible

Microstrip circuits were used in the measurements instead of GCPW, even though GCPW might have been thought to be more sensitive to loss differences among circuits with different plated finishes. But studies have shown[1] [4] that GCPW suffers more performance variability due to PCB fabrication processing and normal copper plating thickness variations, and conductor trapezoidal effects can cause significant loss variations from circuit-to-circuit when using the same substrate, making it more difficult to separate the effects of final plated finishes from the fabricated circuits. Microstrip circuits are less impacted by PCB fabrication variables, making microstrip a more suitable choice of transmission-line format to study the effects of plated finishes on circuit loss.

Initial studies were performed using 50-Ω microstrip transmission-line circuits based on 5-mil-thick ceramic-filled PTFE laminate, with a Dk of 2.94, Df of 0.0012, and rolled copper with an average surface roughness of 0.35 µm RMS. Multiple plated finishes were used, with a summary of the insertion-loss curves for the different finishes provided in Figure 6.

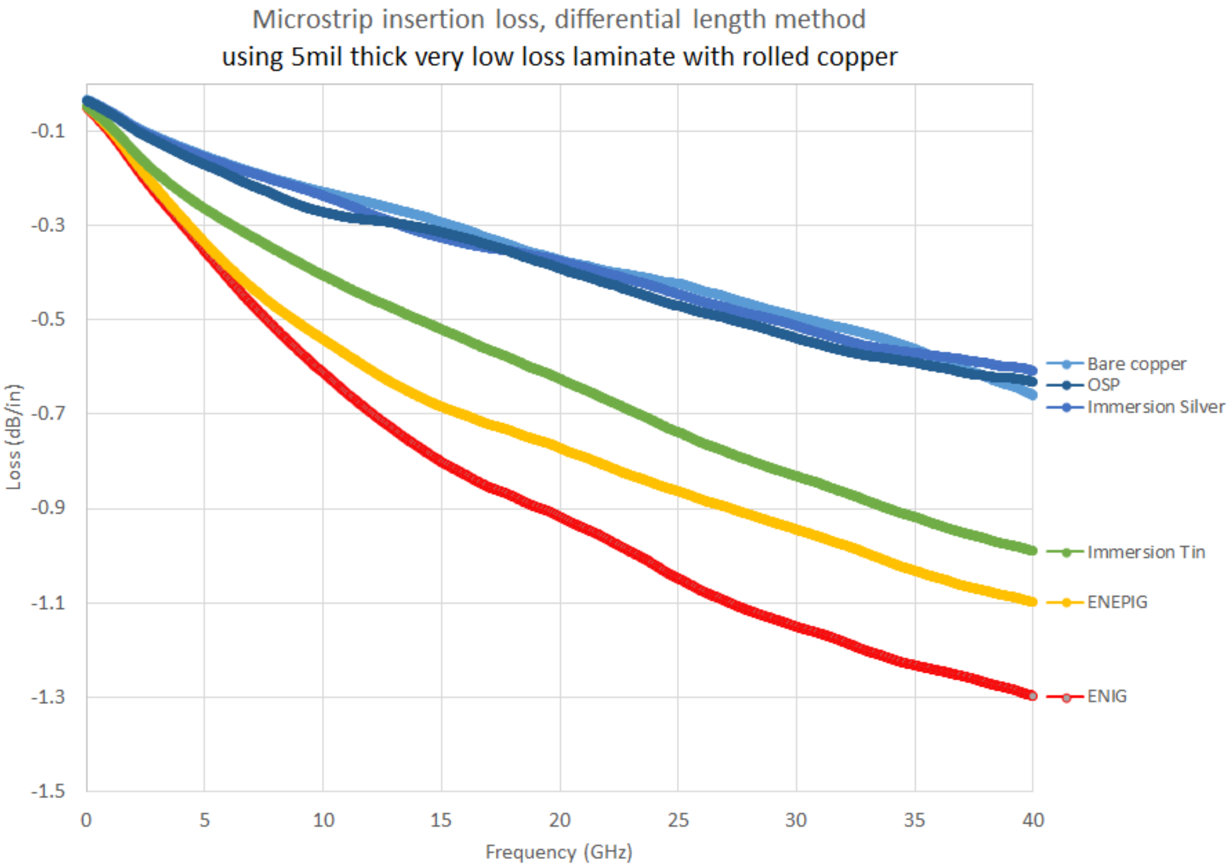


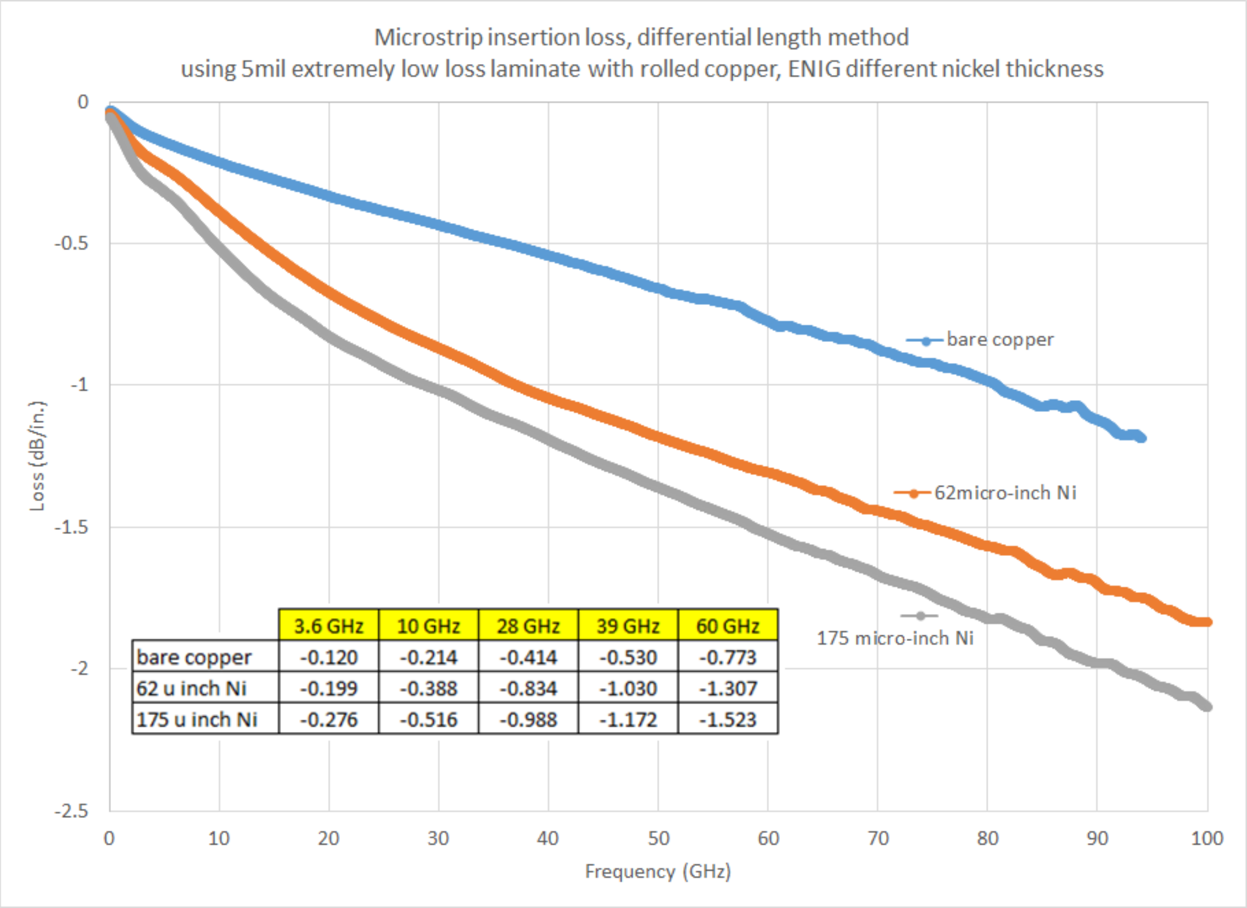
Figure 6. Insertion loss curves of multiple final plated finishes using the microstrip differential length method

The reference (top) curve in Figure 6 is for a microstrip circuit with bare copper. As can be seen, the loss curves for the OSP and immersion silver finish are approximately equivalent to the circuit with bare copper. Other studies have shown similar results, where OSP and immersion silver do not significantly influence the insertion loss. The ENIG plated finish shows the greatest amount of loss, and these results have been confirmed in other studies of this nature. The electroless nickel electroless palladium immersion gold (ENEPIG) plated finish has less loss at higher frequencies; however, at lower frequencies this finish and ENIG exhibit similar effects on loss. Other studies have confirmed this trend. A plausible reason for the frequency-loss relationship is that ENEPIG finishes uses thinner nickel than ENIG finishes.

Since conductivity is a composite effect and changes with frequency, there is a range of frequencies where the composite conductivity of ENEPIG and ENIG are basically the same due to the skin depth using about the same amount of copper-nickel-gold; or at slightly higher frequencies, the same thickness of nickel-gold. Once the frequency increases to the point where the nickel is contributing less for ENEPIG, the nickel will still be a significant factor for the ENIG because ENIG has thicker nickel.

As Figure 6 shows, finishes with ENEPIG and ENIG both have more loss than a finish with immersion tin. About the metal conductivities presented earlier, it would be expected that immersion tin would have greater loss than these other finishes. The insertion-loss relationship between ENEPIG and ENIG has been confirmed by other studies; it has been assumed that the added magnetic losses of nickel used with ENEPIG and ENIG finishes makes them lossier than an immersion-tin finish. However, it is possible that the loss differences are related to thickness and/or skin-depth effects; immersion tin is extremely thin and skin-depth effects would not be significant until much higher frequencies. Microstrip circuits have other components of loss which result in increased loss with increasing frequency, and these loss components can make it difficult to separate the effects of immersion tin on loss. Some of the loss components not related to plated finish include the fact that the Df of the substrate material increases with increasing frequency and the radiation loss increases and the electric fields condense more at higher frequencies. Condensed fields will cause a narrower ground return path which increases the conductor loss, adding to the total loss behavior of the circuit at higher frequencies.

The impact of variations within the plated finish on loss must also be considered. The nickel layers used in ENIG finishes can suffer large circuit-to-circuit thickness variations: it is possible for the nickel layer to vary from 50 to 250 µin. (1.27 to 6.35 µm). A study targeted finishes with low and high nickel thickness and everything else remaining the same. The test vehicle remained the same for this study, but a different material was used, with low loss and rolled copper. The material was a ceramic-filled PTFE laminate, with a Dk of 3.0, Df of 0.001, and copper surface roughness of 0.35 µm.



	3.6 GHz	10 GHz	28 GHz	39 GHz	60 GHz
bare copper	-0.120	-0.214	-0.414	-0.530	-0.773
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 7. These insertion loss curves compare microstrip circuits with bare copper to microstrip circuits with ENIG finishes with different nickel thicknesses.

The microstrip insertion loss curves shown in Figure 7 depict significant differences in insertion loss with variations in nickel thickness that is within the thickness range which could occur from one circuit build to another. ENIG is typically not used above 60 GHz; however, as can be seen in the table of Figure 7, there are significant differences in loss at lower frequencies as well.

As designers transition from applications operating at microwave frequencies to circuits at higher, millimeter-wave frequencies, they often consider the use of GCPW to replace microstrip transmission lines. The benefits of using GCPW at millimeter-wave frequencies include less dispersion, less radiation, and the possibility to suppress spurious wave propagation modes more effectively. However, there are several PCB-related issues which impact the consistency of RF performance for GCPW circuits. With this in mind, it seemed prudent to show the same information in Figure 7 but using a test vehicle that is a GCPW transmission-line circuit. This comparison is shown in Figure 8.

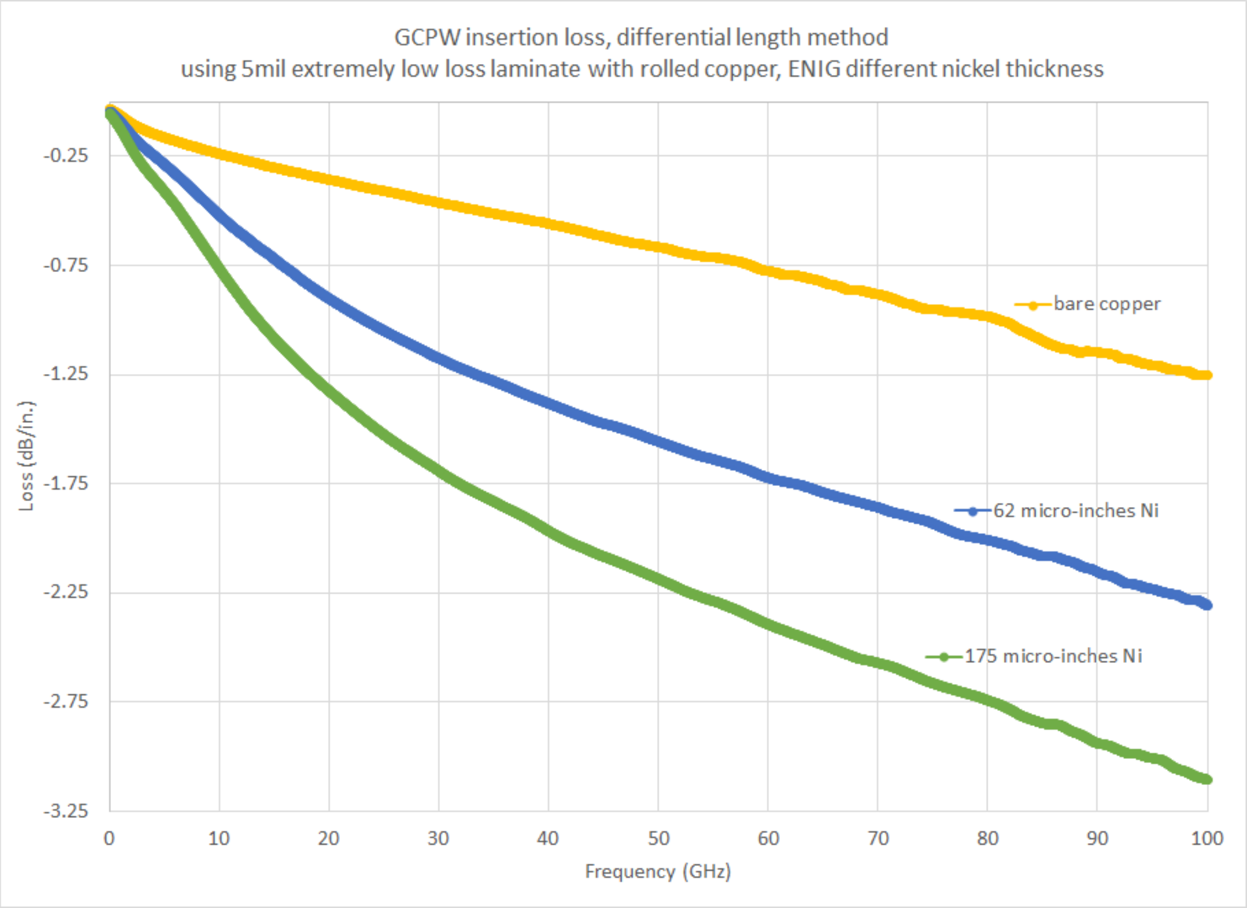


Figure 8. These insertion loss curves for GCPW transmission-line circuits compare circuits with bare copper conductors to circuits with ENIG finishes with different nickel thicknesses.

Several things should be considered when comparing Figures 7 and 8. Different y-axis scales are used for insertion loss in the two graphs, and the curves for GCPW depict much greater losses than the curves for microstrip. Another item of interest is the differences between the insertion loss for circuits with thin nickel compared to circuits with thicker nickel.

Plated thickness variations for immersion tin will have less impact on variations in insertion loss because the immersion tin is very thin. It is applied by means of a self-limiting process and the typical immersion tin thickness is about 8 µin. (0.2 µm). With such a thin layer, the tin does not have a significant influence on the composite copper-tin conductivity at the sidewalls of the microstrip signal conductor until well into the millimeter-wave frequency range. The copper-tin composite conductivity is difficult to estimate because it is only an edge effect for the microstrip signal conductor and the composite conductivity changes with frequency as does other aspects of the microstrip circuit. A simple way to think about the RF effects of the tin thickness, which is on average 0.2 µm, is to consider the skin depth of bare copper (which can be estimated relatively accurately). For copper to have a skin depth equal to 0.2 µm, the frequency must be 110 GHz. The composite conductivity of copper-tin will cause this 0.2-µm skin depth at a lower frequency, roughly about 90 GHz.   A study was performed to examine variations of insertion loss due to varying the thickness of immersion tin and a summary is given in Figure 9.

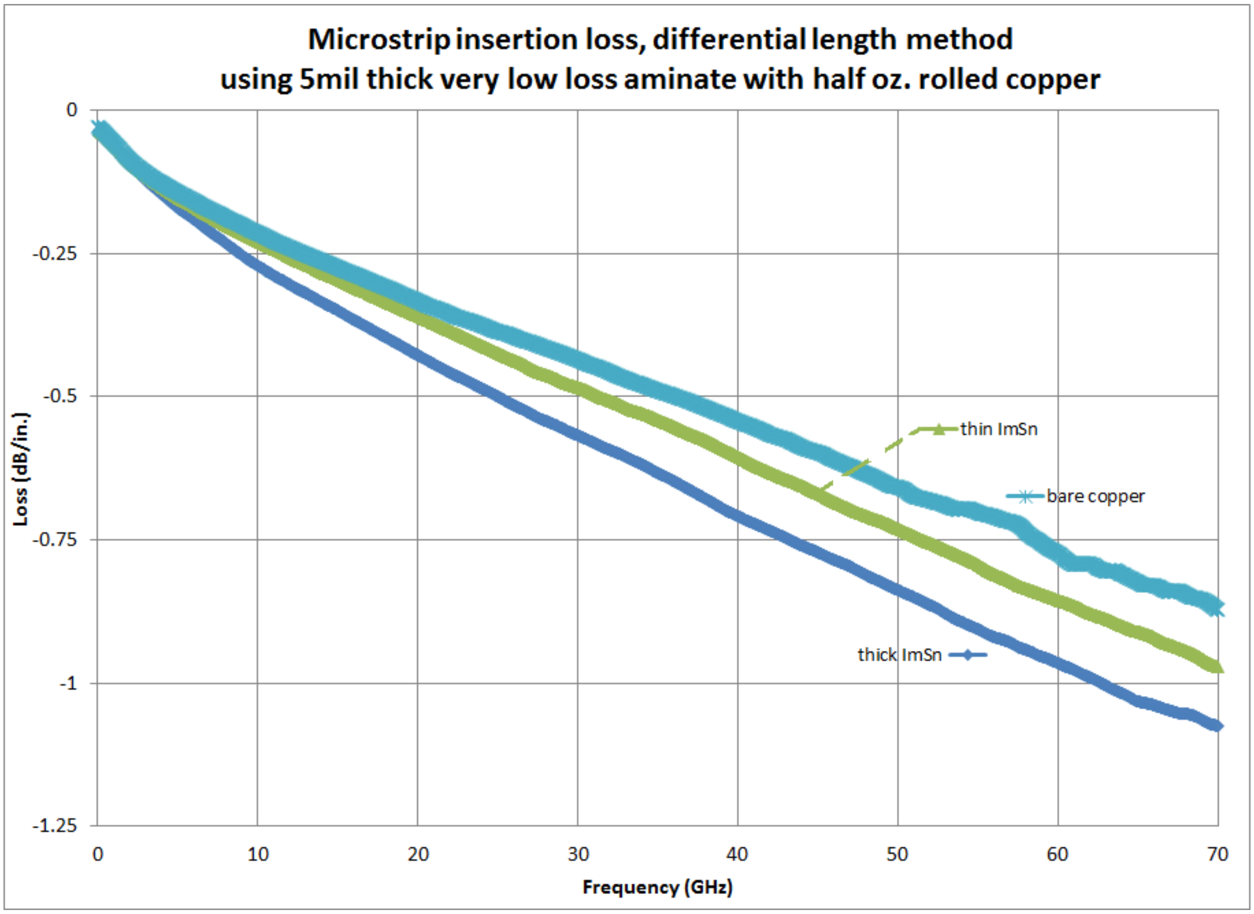


Figure 9. The microstrip insertion loss curves compare circuits with bare copper conductors to circuits with immersion tin (ImSn) finishes with different tin thicknesses.

Figure 9 used the same test vehicle as used for Figures 7 and 8, but with different thicknesses of immersion tin. As is evident, the immersion tin thickness variation has some impact on insertion loss at higher frequencies, but not as much as the impact of ENIG finishes with varying thicknesses of nickel.

Another study has looked at an electroless palladium immersion gold (EPIG) plating which does not have nickel. The same test vehicle was used as for the other finishes, and EPIG plated finish shows an improvement in insertion loss compared to the other finishes. However, a different substrate material was used in the EPIG study, a material with a Dk of 3.2, Df of 0.0033, and copper surface roughness of 0.9 µm RMS. With this material, the bare copper circuit will have more losses than in previous studies in which bare copper circuits have been mentioned. However, the comparison between the bare copper circuit and the EPIG finish is still noteworthy (Fig. 10).

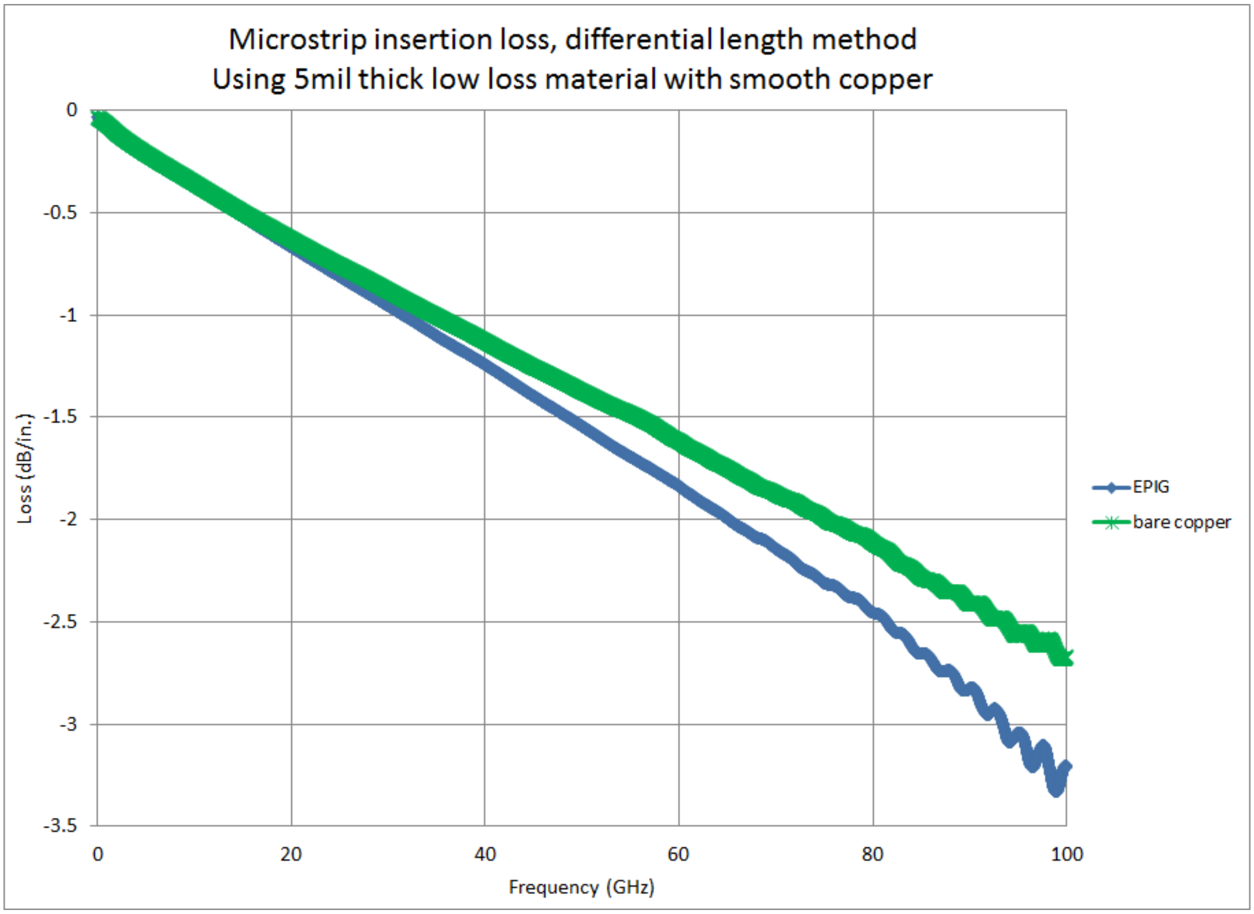


Figure 10. These curves show the insertion loss of microstrip circuits using a gold final plated finish which does not have nickel.

Since the test vehicle was using a slightly higher loss material and the copper surface was slightly rougher, the bare copper circuit loss in this study of EPIG finish is higher than for the bare copper shown in previous studies in this paper. The copper was a low-profile, reverse-treated copper with minimal surface roughness variation. The insertion loss difference between the bare copper circuit and the EPIG circuit has the least difference of any other gold finishes shown in this study.

Even though this paper was focused on insertion loss, it seemed judicious to mention a slightly different issue which can be important in material characterization and is related to the plated finish study. Microstrip ring resonators are commonly used to characterize materials at microwave and sometimes millimeter-wave frequencies, however if ENIG is applied the nickel variation can have an impact on the capacitance in the gap coupled area of a ring resonator. An evaluation was done, in parallel to the evaluation shown in figures 7 and 8, where gap coupled ring resonators were evaluated using the same sheet of laminate to make the circuits and it was found that nickel thickness variation does impact the resonant frequency of a ring resonator. Which means if this structure was used to calculate the Dk of the material, which is common, the extracted Dk would be altered due to nickel thickness variation. A summary of this information can be seen in figure 11.

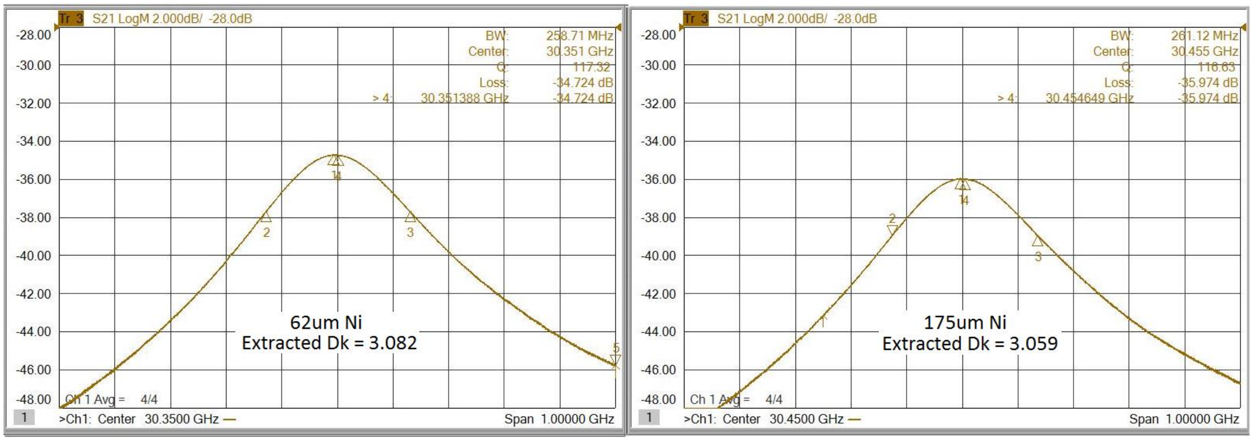


Figure 11. Comparison of Dk extraction using microstrip ring resonator with ENIG plating and having different nickel thickness.

The materials used to make the microstrip ring resonators were made from the same large sheet of material, cut in half. One half panel had circuits made with thinner nickel for the ENIG and the other half panel had circuits made with thicker nickel for ENIG.   The nickel variation makes some small differences in the loss, Q and bandwidth, but makes a pretty significant difference in the center frequency and the extracted Dk. By using the same large sheet of material, that will minimize material differences and yet there is an extracted Dk difference of 0.023.   The ring resonators having different nickel thickness were measured for circuit dimension differences and nothing significant found. The thicker nickel will impact the capacitance in the gap coupled area. Thicker nickel decreases the conductivity in the gap coupled area, which is seen as a decrease in capacitance, that will shift the frequency up which relates to a lower extracted Dk. Additionally, if Df was extracted, there the ring resonator with the thicker nickel would report a falsely higher Df than the ring resonator using the thinner nickel; again, while using the same sheet of material.

In summary, conductor loss is one of the components of PCB insertion loss, and it can be impacted by the final plated finish used for a circuit. In fact, there can be a substantial increase in insertion loss due to the final plated finish. This study explored the effects of final plated finish on circuit insertion loss. Thin substrates were used to achieve good resolution among the different plated finishes used with the test vehicle, although if a thicker circuit was used, the magnitude of the curves shown in this study would be less. As a reference, that effect (of substrate thickness) can be seen in Figure 2. Designers should consider the effects of final plated finish on insertion loss when predicting and simulating circuit performance during the design phase of a circuit development and choose final plated finishes according to performance requirements.

Acknowledgments

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