

Application Notes

Ambiguous Influences Affecting Insertion Loss of Microwave Printed Circuit Boards

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oftware design programs often assist RF/ microwave engineers in creating high-frequency printed circuit boards (PCBs). A multitude of commercial software tools are available, from electromagnetic (EM) simulation programs to circuit layout and complete system simulators. Both engineers and software tools try to forecast the effects of various circuit- and material-based parameters, but some factors may be overlooked or simply not well enough understood to be properly accounted for in a software simulation of a PCB design. This article intends to help RF/microwave PCB designers better understand the different influences affecting high-frequency PCB loss performance, such as copper roughness, solder mask, plated finishes, and circuit configurations, and how to more accurately predict their effects on final PCB insertion-loss (IL) performance.

Solder Mask Effects

The use of solder mask is typically avoided in sensitive microwave circuitry, although there may be some cases where it is necessary. Solder mask, which has traditionally been added to PCBs to prevent solder from forming unwanted connections between conductors, is relatively lossy at microwave frequen-

Digital Object Identifier 10.1109/MMM.2012.2197145 Date of publication: 11 July 2012 cies, high in moisture absorption, and contributes to dispersion effects. In addition, the thickness of solder mask can vary widely, depending on the specific circuit design and the type of process in which it is applied. To further complicate matters, one type of solder mask may exhibit a considerably different relative dielectric constant (ε_r) and dissipation factor than another solder mask type. Some solder masks are based on acrylic chemistry, whereas others are epoxy based. Due to these chemical differences and purposeful formulation differences, for certain applications there are different ε_r values as well as dissipation factor for many solder masks. In this study, a very common epoxy-based solder mask used in the PCB industry was employed.

To understand the effects of solder mask on highfrequency PCBs, a simple study was performed with commercial circuit laminate material. Various microstrip structures were fabricated on the laminate and solder mask applied, with the loss performance of the microstrip circuits then measured. A microstrip transmission line was used to achieve a wideband response, while an edge-coupled bandpass filter was used to represent a narrowband response. A commercial epoxy-based solder mask was used in the study, applied by means of a standard screen-printing process. The commercial laminate was RO4350B substrate, a 0.51-mm (20-mil) thick) dielectric with 0.5-oz electrodeposited (ED) copper conductor layer. Figure 1 shows the effects of the solder mask on microstrip circuit loss, for a broadband microstrip transmission line and a narrowband, edge-coupled bandpass filter.

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The increase in dispersion resulting from the addition of solder mask to a circuit can affect performance.

Figure 1(a) shows that the broadband microstrip circuit with the solder mask exhibits 15–20% more insertion loss, depending on frequency, than the same circuit without solder mask. Figure 1(b) reveals that the edge-coupled filter with solder mask suffers about a 10% increase in insertion loss in its passband region compared to the same filter circuit with bare copper (without solder mask). For the frequency range covered by the bandpass filters, the simple microstrip transmission line with solder mask has an increase in insertion loss of about 16% compared to the microstrip line without solder mask.

The higher loss for the edge-coupled filter resulting from the solder mask might be expected, since the lossy solder mask material is covering and between coupled circuit features. But it might be surprising to learn that the effects of the solder mask on the loss of the simple microstrip transmission line are more significant. Although not shown here, this same study included a filter design with twice as many (eight) coupled elements, and the effect of the solder mask on that more complex filter resulted in higher insertion loss, about 16% more due to the solder mask or an increase that was comparable to the effects of the solder mask on the simple microstrip line. This shows that the increases in loss from the use of solder mask are highly dependent on the complexity and type of circuit design. Some designs, in fact, may benefit from some solder mask effects, such as its increase in the effective dielectric constant of the circuit board, which may cause electric fields to be more concentrated between resonant filter elements, resulting in increased coupling between elements.

The effects of solder mask on a given PCB are dependent on a number of different parameters, including the circuit design itself, the substrate thickness, the relative dielectric constant (ε_r) of the substrate, the copper conductor layer thickness, the solder mask thickness, and various other factors. If solder mask is necessary for a particular RF/microwave circuit design, several issues should be considered. Solder mask varies in thickness from PCB to PCB, and can impact electrical performance as a function of thickness. Also, a circuit with solder mask will yield different performance in a humid environment than in a dry environment, due to a typically high value for the moisture absorption properties of solder masks, which can impact loss and impedance. Additionally, the increase in dispersion resulting from the addition of solder mask to a circuit can affect performance, particularly in wideband applications.



Figure 1. The solder mask can impact microstrip loss, as shown for (a) a broadband microstrip transmission line and (b) a narrowband, four-element edge-coupled bandpass filter.

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The following are a few quick side notes regarding the insertion loss testing shown throughout this article. All testing is using a differential length method, which yields loss in units of dB/unit-length. This method is derived from a paper [1] regarding differential phase length measurements for acquiring accurate effective dielectric constant from microstrip transmission lines of differeant lengths. The assumption is to use the same connectors, same signal launch for the circuit design and different lengths of microstrip transmission lines, with everything kept the same except for the length of the circuits and subtracting the loss per length for each circuit. This yields an insertion loss curve in units of dB/unit-length, and the reactance's due to the connectors and signal launch are minimized to being insignificant. Another important issue to consider is radiation loss, and, for the testing done in this article, radiation loss was less than 18% of total loss for any measurement. This was found by using a free impedance and loss calculation software, MWI-2010 [2] and uses closed form equations from well-known Hammerstad and Jenson [3, (26)-(38)]. The microstrip loss calculations are augmented for radiation loss from Wadell [4] and given here:

$$\alpha_r = 60 \left(\frac{2\pi h}{\lambda_0}\right)^2 F(eff), \qquad (1)$$

$$F(eff) = 1.0 - \frac{\varepsilon_{eff} - 1}{2.0\sqrt{\varepsilon_{eff}}} \log\left(\frac{\sqrt{\varepsilon_{eff}} + 1.0}{\sqrt{\varepsilon_{eff}} - 1.0}\right),$$
(2)

where *h* is the substrate thickness, λ_0 is the wavelength in free space, and ε_{eff} is the microstrip effective dielectric constant. An example output is shown in Table 1 with the loss versus frequency for the 20 mil RO4350B microstrip transmission line shown in Figure 1(a) for the bare copper curve.

Surface Finish

Another PCB ingredient that can affect electrical performance is surface finish, such as electroless nickel immersion gold (ENIG), silver, tin, and solder. ENIG has excellent shelf life but can suffer drawbacks in terms of IL performance. The nickel portion of such a finish is relatively thick compared to the gold portion. The nickel thickness is typically 1.91-7.62 µm (75-300 µin), compared to a gold thickness of generally around 0.08-0.20 µm (3-8 µin) The nickel used in an ENIG process is actually an alloy, which can vary in composition, depending on ENIG supplier and process. The nickel alloy is much less conductive than copper and is generally assumed to be about one-third the conductivity of copper. Nickel also has a high permeability value, about 500, compared to copper, which is near unity. This is one of the reasons that the suppliers of ENIG surface finishes alter the nickel in order to reduce the permeability of the ENIG to a value near copper.

The increases in loss from the use of solder mask are highly dependent on the complexity and type of circuit design.

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Figure 2 shows a cross-sectional view of a microstrip circuit with ENIG plating. Some microwave applications with ENIG finish on the copper conductors can exhibit increased insertion loss. The higher loss comes from the skin effects of having a significant amount of nickel alloy as part of the PCB's conductor along with increased current density at the base of the conductor. The loss attributed to this phenomenon is dependent on frequency, circuit design, and substrate thickness. The general relationships that help illustrate the influence of nickel conductivity on conductor losses are shown in (3)–(5):

$$z_s = R_s + j\omega L_i$$
 Internal impedance of conductor, (3)

$$R_s = \frac{1}{\sigma \delta}$$
 Surface resistivity, (4)

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad \text{Skin depth}, \tag{5}$$

where σ is conductivity, μ is permeability, ω is frequency, and L_i is internal inductance. The internal inductance is defined from [5], which analyzes rectangular conductors at microwave frequencies. The decreased conductivity of the nickel alloy results in an increase in skin depth and, depending

TABLE 1. The output of MWI-2010 program displaying loss prediction for bare copper microstrip curve shown in Figure 1.

Loss (dB/in) Versus Frequency (GHz)							
Frequency	Dielectric Loss	Conductor Loss	Radiation Loss	Total Loss			
1	-0.009	-0.037	0	-0.047			
2	-0.018	-0.056	-0.001	-0.077			
3	-0.028	-0.071	-0.004	-0.103			
4	-0.037	-0.083	-0.007	-0.128			
5	-0.047	-0.093	-0.011	-0.152			
6	-0.056	-0.103	-0.016	-0.176			
7	-0.066	-0.111	-0.022	-0.201			
8	-0.076	-0.119	-0.029	-0.225			
9	-0.085	-0.127	-0.037	-0.251			
10	-0.095	-0.134	-0.046	-0.276			
Conventional Microstrip, MWI-2010, Rogers Corporation Using 0.020-in O4350B circuit materials; conductor width = 0.042 in; impedance = 49.57 Ω ; effective dielectric constant (dk) = 2.8961							

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ENIG plating has more impact on the insertion loss of the simple microstrip transmission line than on the filter.

on the frequency, more nickel may be used as the conductor. The lower conductivity of nickel will also increase the surface resistance, resulting in increased conductor losses. Figure 3 shows the insertion loss characteristics of two microstrip (broadband and narrowband) circuits, with and without ENIG plating.

It can be seen that ENIG plating has more impact on the insertion loss of the simple microstrip transmission line than on the filter. The filter design is less affected by the ENIG plating due to the dual-mode operation of the edge-coupled filter. The filter in this ENIG plating study is the same design as shown in Figure 1, with four resonant elements. The increase



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Figure 2. Cross-sectional view of a microstrip circuit at (a) high magnification and (b) lower magnification. The high magnification picture of part (a) shows an ENIG finish on a copper conductor. By the nature of high-frequency EM fields, the current density will be high at the bottom edge and bottom corner of the conductor.



Figure 3. These plots compare the effects of ENIG plating on two microstrip circuit designs: (a) a simple, broadband microstrip transmission and (b) a narrowband edge-coupled microstrip filter.

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in insertion loss for this filter as a result of the ENIG plating was about 26%, while the increase in insertion loss for the simple microstrip transmission line as a result of the ENIG plating was between 30% and 40%, depending on frequency. When the more complex eight-element filter was evaluated, the increase in insertion loss as a result of the ENIG plating was found to be about 70%.

For each RF/microwave application, the benefits of ENIG plating for a high-frequency PCB must be weighed against the impact of the ENIG plating on IL performance. When the impact of the added loss is significant, there may also be an issue with the difficulty of achieving good circuit-to-circuit repeatability because of the variability of the ENIG plating process. The thickness of nickel for a given ENIG process can vary widely, and a range of thickness of more than 2.54 µm (100 µin) across a few circuits from the same process is not unusual. For a circuit operating at microwave frequencies, where the skin depth for the frequencies of interest is equal to the nominal thickness of the nickel plating, variations in the nickel thickness can cause the skin depth to use more or less of the nickel from one circuit to another, resulting in variations in IL performance when comparing multiple circuits of the same design.

Silver is sometimes used in microwave circuits as a plating finish for copper conductors. Most silver plating for PCB fabrication is performed by means of an immersion process, which is self-limiting, resulting in relatively uniform, fixed thickness of silver plate, as it relates to the thickness of the deposited silver. Like the immersion gold used in ENIG plating processes, immersion silver is applied in a very thin layer, with a typical thickness of 0.13–0.30 µm (5–12 µin). Silver has higher conductivity than copper and is sometimes used as an ENIG-replacement finish where conductor losses must be minimized. Even though silver has better conductivity than copper, the added silver will typically result in increased losses for microwave PCBs compared to those using bare copper conductors.

The additional losses are low, typically less than 3% and mostly due to three causes.

- The immersion silver is not pure silver. Although its conductivity is better than that of copper, it may not be 8% better as a nominal value of pure silver would suggest.
- The silver coating is extremely thin and the contribution of this higher conductivity may have minimal impact on reducing surface resistivity.
- Even though the silver is thin, it will have an impact on skin depth since the silver is on the outer part of the conductor where the current density is higher. The higher conductivity of

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the silver in the high current density area of the conductor will reduce the skin depth, and the RF current will use less of the conductor overall. The added loss of the silver is typically so low that it may not be measurable by the microwave test system used to evaluate circuit losses.

Figure 4 provides a comparison of the effects of solder mask, ENIG plating, and silver plating on microstrip insertion loss, showing only slight differences between bare copper conductors and those with silver plating.

Copper Surface Roughness

Copper surface roughness, which is known to cause conductor losses, is yet another material parameter that must be included in any model representing a PCB material. These conductor losses are frequency dependent due to a number of factors, notably the ratio of the skin depth to copper surface profile. A number of technical references [6]–[10] have addressed this topic, including an excellent paper available for free download [11]. This article summarizes the effects of copper surface roughness and reviews appropriate models and the influence of copper surface roughness on the effective dielectric constant of PCB material. Figure 5, which is an excerpt from [11], demonstrates the impact of copper



Figure 4. These curves compare the effects of solder mask, ENIG plating, and silver plating on microstrip insertion loss.

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It is common for two of the four copper-substrate interfaces to have much different values of copper surface roughness.

surface roughness on the insertion loss of thin microstrip transmission-line circuits.

Figure 5 plots IL characteristics for simple 50- Ω microstrip transmission-line circuits fabricated on a thin, 100-µm (4-mil) substrate. The thin substrate was chosen so that the dominant portion of the microstrip insertion loss would be due to conductor losses. By using the same homogeneous substrate material for all of these circuits, any variations in copper surface roughness from substrate to substrate should appear with good resolution as differences in IL performance. The values for copper surface roughness are shown in units of microns and as root-mean-square (RMS) values. For example, a substrate with ED copper with rough surface finish has a value of 3 μ m, while a substrate with smooth copper surface finish has a value of 0.5 µm. From the curves, it can be seen that a substrate with smooth copper (RTF 0.5 µm) will exhibit significantly less loss than one with rough copper (ED 3.0 µm).

The curves shown in Figure 5 refer to predictions from a computer program based on the work of

Hammerstad and Jenson [3] (H&J) to model characteristic impedance and insertion loss. It uses closedform equations to determine microstrip insertion loss and is augmented by a routine from Morgan [6] to account for copper surface roughness. The H&J models are relatively accurate at lower frequencies but provide better results for some circuit configurations rather than others. Better models for microstrip insertion loss with copper surface roughness have been developed, including those from Sonnet Software [11]

The copper surface roughness, which can be seen in Figure 2 at the copper-substrate interface, is a concern in a microwave PCB. This side of the conductor typically has much greater surface roughness than the other three sides in order to achieve improved adhesion with the substrate. While the simple microstrip circuit of Figure 5 revealed clear correlations between increased copper surface roughness and increased loss, not all circuit types will necessarily show a trend of improved loss characteristics with smoother copper. For example, a microwave stripline circuit has three conductive layers and four coppersubstrate interface planes. It is common for two of the four copper-substrate interfaces to have much different values of copper surface roughness. In such a case, it may be difficult to assess the true effect of the copper surface roughness unless the circuit configuration is very well understood and a model is able to accommodate these differences. The losses associated with different plating finishes and solder mask



Figure 5. These curves show the effects of copper surface roughness on the IL characteristics of thin microstrip transmission-line circuits. (Reprinted from [11] with permission.)

can make the task of gauging the effects of copper surface roughness on insertion loss even more difficult. ()

In addition to microstrip, one of the more common double-conductor microwave circuit configurations is conductor backed coplanar waveguide (CBCPW). Because of how CBCPW functions, the benefits of smooth copper may not be so obvious. For tightly coupled CBCPW, the effects of copper surface roughness are diminished due to an increase in current density in the coupled region, which lessens the current density at the copper-substrate interface. Another practical consideration with CBCPW is that conductor walls are often not perpendicular to the substrate and can be trapezoidal

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in shape. When the conductor walls lack a true parallel configuration due to trapezoidal effects, the current density shifts from the walls down to the base of the conductor, and the copper surface roughness will have a greater impact. Figure 6 provides cross-sectional views of the three CBCPW circuits to show these differences.

CBCPW circuits are often used in applications where higher frequency operation is required, where radiation losses must be reduced, and where suppression of spurious modes of wave propagation is critical. CBCPW transmission lines offer many performance benefits but will typically suffer higher losses than microstrip transmission lines. In addition, the normal variations in PCB fabrication processes and the conductor trapezoidal effect can make it difficult to achieve good circuit-to-circuit consistency with CBCPW-based microwave designs.

To evaluate the impact of different values of copper surface roughness on different types of transmissionline circuits, a well-known, high-performance microwave circuit laminate, RT/

duroid 5880, material was used as the common starting point for the different circuits, which included variations of microstrip and CBCPW transmission lines. Three different types of copper conductor with three different values of copper surface roughness (0.4, 1.8, and 2.8 µm RMS) were used, always with 0.254-mm-thick (10-mil-thick) RT/duroid 5880 dielectric material. All of the circuits fabricated for the study were $50-\Omega$ transmission lines. The microstrip transmission lines had a conductor width of 0.762 mm (30 mil). The tightly coupled CBCPW featured a conductor width of 24 mil with 5 mil spacing. The moderately coupled CBCPW has a conductor width of 26 mil and spacing of 8 mil. The loosely coupled CBCPW was fabricated with a conductor width of 28 mil and 12 mil spacing. Table 2 compares the copper surface roughness values for the different types of circuits, while Table 3 provides a summary of the IL characteristics for the different transmission-line types at 5 GHz.

This study revealed that the tightly coupled CBCPW circuit had more loss than the microstrip

This study revealed that return-loss performance is much improved with all CBCPW designs compared to microstrip.



Figure 6. Cross-sectional views showing (a) ideal tightly coupled CBCPW, (b) ideal loosely coupled CBCPW, and (c) common trapezoidal conductor shapes for tightly coupled CBCPW.

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circuit, as might be expected, although the CBCPW circuit was also less responsive to differences in copper surface roughness than the microstrip circuit. A reason why tightly coupled CBCPW might be preferred over microstrip is for enhanced bandwidth. This study also revealed that return-loss performance is much improved with all CBCPW designs compared to microstrip.

In Figure 7, drawings of the different transmission lines are given. A magnified view is shown for the CPW launched microstrip (CPW microstrip). All of

TABLE 2. Overview of a study using different copper roughness and circuit configurations.					
Copper Surface Roughness (µm, RMS)					
Microstrip	0.4	1.8	2.8		
CPW launch microstrip	0.4	1.8	2.8		
CBCPW tightly coupled	0.4	1.8	2.8		
CBCPW moderately coupled	0.4	1.8	2.8		
CBCPW loosely coupled	0.4	1.8	2.8		

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the circuits had the same circuit geometry in the signal launch area regarding the conductor width and taper. The same connectors were used and were 2.4 mm end launch connectors model 1492-04A-5 from Southwest Microwave Inc. also shown in Figure 7. Additionally the frequency where the return loss (RL) was worse than –15 dB is shown in this figure as well.

In comparing these differences between CBCPW and microstrip, there are also the effects of copper surface roughness on insertion loss to consider when choosing a transmission-line approach. To better appreciate the trends in insertion loss and copper surface roughness with increasing frequency, Table 4 lists differences in loss for the different transmission lines with RMS surface roughness values of 0.4 and 2.8 μ m at 5 and 10 GHz. To simplify a comparison of different transmission lines and copper roughness, Figure 8 shows two extreme cases as functions of frequency.

Summary

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Microwave circuit designers usually associate insertion loss with dielectric, conductor, radiation, and leakage losses, and try to account for these when choosing a circuit laminate material. When predicting or modeling performance for a given circuit and material, however, other factors that can affect loss, including solder mask, ENIG finish, and copper surface



Figure 7. (*a*) Drawing of the top view of different transmission line designs used in this study, (b) magnification of the CPW Microstrip signal launch area, (c) picture of the 2.4 mm end launch connectors used, and (d) RL frequency where the RL was worse than –15 dB for each circuit.

TABLE 3. Comparing IL results at 5 GHz for different circuit types built on the same-thickness dielectric substrate with different copper surface roughness values (shown in µm RMS).

	Insertion Loss (db/in) at 5 GHz			Fractional Pov	Loss Increase (%)	
	RMS = 0.4 μ m	RMS = 1.8 μ m	RMS = 2.8 μ m	RMS = 0.4 μ m	RMS = 2.8 μ m	RMS = 0.4–2.8 μm
Microstrip	-0.072	-0.109	-0.139	0.016	0.031	192%
CPW Launch Microstrip	-0.079	-0.111	-0.148	0.018	0.034	186%
CBCPW tightly coupled	-0.112	-0.143	-0.169	0.025	0.038	150%
CBCPW moderately coupled	-0.073	-0.106	-0.136	0.017	0.031	185%
CBCPW loosely coupled	-0.068	-0.104	-0.131	0.016	0.030	191%

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TABLE 4. Comparison of different circuit configurations and copper roughness in regards to insertion loss change from 5 to 10 GHz.

	Insertion Loss (db/in) at 5 GHz		Insertion Loss (db/in) at 10 GHz		Power Loss Increase (%)	
	RMS = 0.4 μ m	RMS = 2.8 μ m	RMS = 0.4 μ m	$\text{RMS}=\text{2.8}~\mu\text{m}$	$\text{RMS}=\text{0.4}\;\mu\text{m}$	RMS = 2.8 μ m
Microstrip	-0.072	-0.139	-0.120	-0.250	166%	178%
CPW Launch Microstrip	-0.079	-0.148	-0.121	-0.257	152%	171%
CBCPW tightly coupled	-0.112	-0.169	-0.163	-0.281	145%	164%
CBCPW moderately coupled	-0.073	-0.136	-0.113	-0.231	154%	168%
CBCPW loosely coupled	-0.068	-0.131	-0.106	-0.227	155%	171%

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Figure 8. Comparing the insertion loss for microstrip and the tightly coupled CBCPW fabricated on circuit laminates with smooth and rough copper.

roughness effects, must also be included in any material or circuit model. Some of the finishes used for PCB conductors can generate more loss, such as ENIG. The losses associated with ENIG can be worse with certain structures such as edge coupled filters. Additional copper surface roughness is known to have an impact on conductor losses. However, it was shown that the impact is different on different structures; when considering the impact of rougher copper surfaces, the microstrip transmission line had more loss than a tightly coupled CBCPW transmission line. Microwave circuit material suppliers are very aware of these issues and readily invite designers to engage them with their projects. This interaction is optimum for the advancement of our industry and technology.

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