# Minimizing Signal Transmission Loss in High-Frequency Circuits

By: George Milad

*National Accounts Manager for Technology, Uyemura*

## Introduction

The amount of information transferred on wireless networks has increased dramatically with the growth of internet access, mobile phones, and other handheld devices.

The transmission of a high-speed RF signal is increasingly required in PCBs to handle massive data in electronic systems. The transmission speed of signals propagating inside the system is also increasing.

RF signal loss, i.e. insertion loss, is the degradation of signal power resulting from the insertion of a device in a transmission line or optical fiber. Expressed in decibels (dB), insertion loss becomes significant on a PCB in the higher GHz frequencies. Insertion loss can lead to rising edge degradation of signals, higher rate bit errors and other issues.

All PCB materials have both conduction and dielectric RF signal losses. Conduction losses are resistive and are caused by the conductive copper layer used in the board. Dielectric losses are associated with the PCB substrate (insulating material). This paper explores resistive conduction losses by the board's copper layer.

The study of transmission loss requires plotting the electrical behavior (scattering matrix), measured in dB, of linear electrical networks when undergoing various steady-state stimuli by electrical signals versus increasing signal frequency (GHz).

Transmission loss, aka insertion loss, is the additional loss produced by the introduction of the device under test (DUT) between the two reference planes of the measurement. This extra loss may be due to intrinsic loss in the DUT and/ or mismatch. In case of extra loss, the insertion loss is defined to be positive. The negative of insertion loss expressed in dB is defined as insertion gain.

## Skin Effect

Unlike DC or AC current that flows through the entire conductor trace, RF current does not penetrate deeply into electrical conductors, but flows along their surfaces; this is known as the skin effect. Signal loss in the conductive copper layer is directly related to this phenomenon. Skin depth is the depth of the conductor the RF current uses. Basically, less of the conductor is used as the frequency increases. Figure 1.

Two phenomena that directly impact insertion loss due to the "skin effect" are the degree of copper roughness (Figure 1) and the nature of the surface finish.

Surface finishes that contain electroless nickel, including electroless nickel immersion gold (ENIG) and electroless nickel electroless palladium immersion gold (ENEPIG), show greater insertion loss due to the resistive properties of the electroless nickel as compared to copper.

Newer finishes like electroless palladium immersion gold (EPIG) and immersion gold electroless palladium immersion gold (IGEPIG) are the preferred finishes for minimum insertion loss in high-frequency applications.

**Copper Surface Roughness**

Copper surface roughening is done to enhance adhesion of the conductor to the dielectric in multilayer structures. Roughening is accomplished by chemical or mechanical means, creating anchoring sites for the resin.

This has worked well for non-RF current applications, and it would also work well for RF signals propagating at lower frequencies. However, as the frequency increases to 10 GHz and above, the skin depth is reduced. When the skin depth is equal to or less than the copper surface roughness (Figure 1), the roughness increases the resistivity of the trace, and impacts the conductor loss and the phase angle response of the circuit.

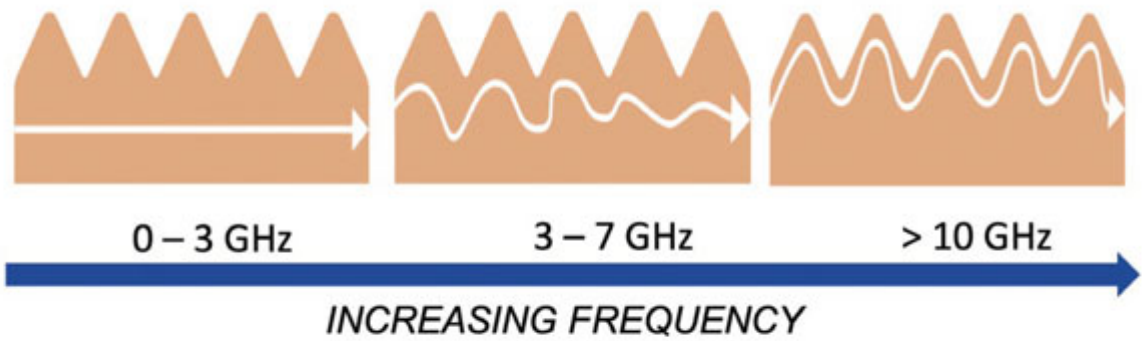



Figure 1: Copper conductor skin effect.

As signal frequency increases, electrical signals run closer to the copper conductor surface. This leads to increased resistance and transmission loss.

Circuits using copper with a rougher surface will have more conductor loss than circuits using copper with a smoother surface. More specifically, the copper surface at the substrate-copper interface is the concern for surface roughness in relation to conductor loss. Recent advancements that increase adhesion in multilayer boards go beyond the standard roughening produced by black and brown oxides.

Today, most inner layers rely on chemical etching to micro-roughen the traces for maximum bonding. However, micro-roughening is not the answer to minimizing conductor signal loss. Chemical bonding is becoming the choice for adhesion for traces carrying high-frequency RF signals; it is also highly effective for smooth copper surfaces.

One chemical bonding system available today is immersion tin, followed by a treatment with a silane coupling agent. The treatment is usually carried out in horizontal conveyorized equipment and results in excellent adhesion between conductor and dielectric.

According to one source [1], “studies have shown that copper foil types of varying degrees of roughness have a direct effect upon the insertion loss of a stripline structure. New treatments targeted at conductor insertion loss and surface roughness minimization are being offered by chemical suppliers.”

**Insertion Loss and Surface Finish**

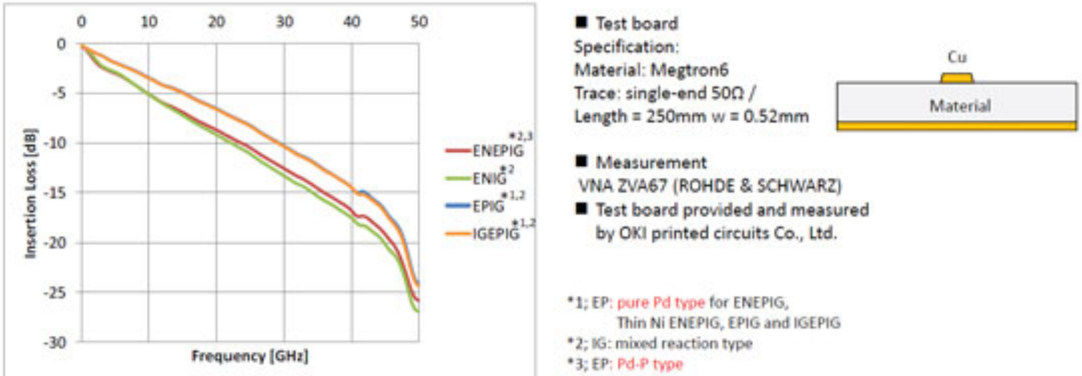
Handheld devices are a key driver for miniaturization by circuit designers: fine lines and spaces are being normalized for many applications. In addition, the need for wire bonding focuses attention on nickel gold (ENIG) and nickel palladium gold (ENEPIG).

These finishes are approaching their limits when it comes to high (10 and 10+) GHz RF signal transmission. The electroless nickel layer is an integral part of the surface of the conductor. There is a transmission loss associated with the skin effect of the electroless nickel as compared to copper.

Newer surface finishes for high-frequency RF transmission are now available. These finishes eliminate or reduce the use of EN. The most common among them is electroless palladium immersion gold (EPIG). I discussed EPIG in a column published in PCB Connect 007. Here, the focus is on insertion loss.

Figure 2 includes a plot of the scattering parameter (S-parameter) as the vertical axis versus the signal frequency on the horizontal axis. With S-parameters, scattering refers to the way in which the traveling currents and voltages in a transmission line are affected when they meet a discontinuity caused by the insertion of a network into the transmission line.

A baseline is first established, and a new plot is then measured with the introduction of the DUT. The difference is the transmission loss or insertion loss, measured in dB.




| Insertion loss [dB] | Normal ENEPIG*2,3 | Normal ENEPIG*1,2 | ENIG*2 | Thin Ni ENEPIG*1,2 | EPIG*1,2 | IGEPIG*1,2 |
|---|---|---|---|---|---|---|
| 10 GHz | -5.1 | N.D. | -5.1 | N.D. | -3.4 | -3.5 |
| 20 GHz | -8.6 | N.D. | -9.1 | N.D. | -6.5 | -6.6 |
| 30 GHz | -12.5 | N.D. | -13.3 | N.D. | -10.3 | -10.4 |

Figure 2: Comparison of the insertion loss of surface finishes with nickel, reduced nickel, and no nickel.

Figure 2 compares the insertion loss of surface finishes with nickel (two variations of ENEPIG and one for ENIG), reduced nickel (thin nickel ENEPIG), and no nickel (EPIG and IGEPIG). Thin nickel ENEPIG has as little as 4.0 µins (0.1µm) of electroless nickel.

IGEPIG is a variation of EPIG. EPIG uses an immersion palladium catalyst on the copper surface to initiate electroless palladium deposition; IGEPIG uses an immersion gold layer as the catalyst for the deposition of electroless palladium.

The different finishes were deposited on a single end 50Ω transmission trace (250 mm in length, 0.52 mm in width). Insertion loss measuring equipment was VNA 2VA67 (Rhode and Schwartz). As shown in the graph and summarized in the table (Figure 2), the low nickel and nickel-free gold surface finishes produce significantly less insertion loss compared to thick (120–240 µin or 3–6 µm) nickel gold finishes.

As the industry continues down the path of massive data transfer and miniaturization, RF signal transmission frequencies will continue to move higher. As 10 and greater GHz RF frequencies become more common in PCBs, steps must be taken to minimize transmission losses associated with copper roughness and the surface finish used.

**References**

1. S. Hinaga, A. Rakov, M.Y. Koledintseva, & J.L. James, “Insertion Loss Reduction Through Non-Roughening Inner Layer Surface Treatments,” Proceedings of IPC APEX EXPO, March 2014.

*George Milad is the national accounts manager for technology at Uyemura. To read other materials published by Milad, click here.*

*This column originally appeared in the “Plating Forum” column in IConnect-007.*