Surface Finish Effects on High-Speed Signal Degradation

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***Abstract*—In high-speed circuits, skin effects and dielectric properties are important factors for signal degradation considerations, especially in the microwave frequency region. When surface finishes are applied to prevent traces from oxidation, the electrical properties of traces are affected. In this work, experimental study and finite element method (FEM) based full wave simulation are used to investigate the effects of hot air solder leveling (HASL) and its alternatives on signal integrity. Classical interconnect structures, microstrip line, and differential mode coupled microstrip lines subjected to different finishes are investigated. Our work reveals that the net conductor loss that results from surface finishes is the dominant factor in signal degradation when the clock frequency is within the microwave frequency region. For microstrip line, the influence of surface finishes on signal distortion is negligible; for differential mode coupled microstrip lines, however, the surface finish effects, especially those with high resistivity, can lead to significant signal distortions. These findings are expected to have strong implications when designing high-speed circuits that meet strict timing requirements.**

***Index Terms*—Interconnect, signal degradation, signal integrity, surface finish.**

I. Introduction

THE INCREASING demand on higher data transfer rate drives the printed circuit board (PCB) industry to use higher clocking speed signals. For example, a PCI Express × 8 data bus may deliver a 40 Gbps throughput at clock speed 2.5 GHz. As the clock speed increases, the electrical properties of materials become more pronouncedly frequency dependent. With increasing operating frequency, the conductor loss increases due to the skin effects, and the dielectric loss increases. Consequently, transmitted high-speed signals in traces are subject to dispersion and attenuation leading to potentially significant signal distortion at the receiver.

Surface finish is a coating used to protect the exposed copper land areas in PCBs. This protective coating, which is soldered on top of the exposed copper, acts as a barrier to oxidization. In the production of printed circuit boards, the selection of surface finish is the result of balancing several demands. Cost, performance, and material compatibility, all need to be carefully reviewed when choosing appropriate surface finish. Hot air solder leveling (HASL) is the most widely used surface finish in the market. However, the financial burden, technological limitations, environmental issues and safety factors surrounding the HASL process continue to grow. A variety of surface finish alternatives to HASL have been developed, which present the circuit designer, board fabricator, and component assembler with some interesting and challenging options. Electroless nickel/immersion gold (ENIG), organic solderability preservatives (OSP), immersion silver, electrolytic tin, and lead-free HASL are important alternatives available in the market.

As frequency increases, signal degradation through the traces increases because of the skin effects, increased dielectric loss and dispersion. High-speed signal degradation is a combination of both signal attenuation loss and dispersion. The electrical properties of traces applied with surface finishes are affected by the combination of both the trace conductors and coatings. Consequently, the signal integrity behavior at high frequencies is subject to complicated combination of attenuation loss and dispersion due to the components combination. It was noticed that the electrical properties of trace coatings may become the highest priority while selecting surface finishes [1], [2].

Previous experimental studies considered the effects of surface finishes and substrate dielectric materials on signal loss of microstrip line circuitry up to 18 GHz [3]. These earlier investigations showed that, for microstrip line, the substrate material dependence on frequency had the most profound effect on signal loss. Surface finishes were found to have little effects on signal loss. For a coupled interconnect structure such as differential pair, the coupling between traces will be reduced when surface finishes are applied [4]. The reduction of coupling needs to be considered for high speed interconnects design.

In this paper, we first briefly review the surface finishes techniques in Section II. In Section III, we investigate the effect of surface finish on two interconnect structures: a single microstrip line and a differential mode coupled microstrip lines. This analysis will be carried out using Ansoft HFSS full wave finite element method (FEM) simulator. Physical measurements are conducted to characterize the signal loss arising from the application of the surface finish, thereby validating the numerical simulations. The full-wave analysis results are then fed into a time-domain SPICE circuit simulator to predict the behavior of a pulse propagating through the interconnect. In Section IV, signal dispersion and loss induced by surface finishes are discussed based on physical considerations. Section V concludes with a summary and key recommendations that are important for designers of high-speed digital.

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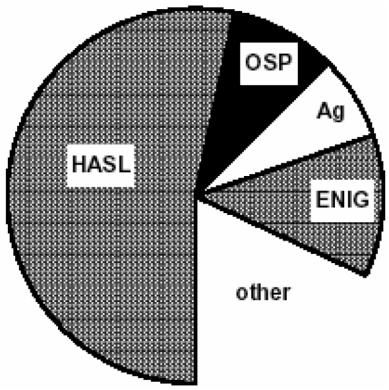

Fig. 1. Surface finishes usage in 2002.

II. Printed Circuit Board Surface Finishes

HASL, ENIG, immersion silver, and OSP are the most popular surface finishes used in the PCB industry. As reported by the IPC Technology Marketing Research Council [5], HASL is the most dominant with approximately 52% of the entire surface finishes volume, followed by ENIG at 15%, OSP at 13%, and Ag at around 8%, as shown in Fig. 1.

HASL was initially introduced as a reliable method to apply solder to the copper surfaces after solder mask is applied. A thin layer of eutectic solder is deposited onto the exposed copper by passing the boards through a hot molten wave (or pot) of solder and subsequently blasting the excess solder from the boards using high velocity hot air. This process is currently under scrutiny due to environmental and safety concerns (hazardous waste/lead exposure), technological limitations (fine-pitch device assembly), and equipment maintenance expenses. HASL use is also limited by highly variable topography that results from HASL application. The thickness of a HASL coating varies from 100 μin to 1000 μin.

ENIG is a two-layer metallic coating over catalyzed copper. The top layer of gold provides low contact resistance, excellent shelf life and good wetting. The nickel layer acts as a barrier layer to prevent copper and gold inter-diffusion. Electroless nickel is an auto-catalytic process using a precious metal catalyst and internal reducing agent for continuous deposit as long as the chemistry is maintained in an active state. Due to the nature of the electroless process, the nickel deposit may be engineered to a variety of specified thickness, but deposits of $100 \sim 250$ μin are typical. In contrast, immersion gold is deposited in an exchange reaction. As the nickel plated part is introduced into the gold solution, a chemical exchange occurs replacing nickel on the surface with a thin layer of pure gold. The reaction stops when all of the exposed nickel is replaced with gold, thus an upper limit of approximately 8 μin is found with the process.

OSP is a thin organic coating that is applied in vertical or conveyorized chemical processes. The two predominant OSP compounds in the industry are benzotriazole and substituted benzimidazole. Materials based on benzotriazole provide a monomolecular layer, which is extremely thin (<0.5 μin). Air reflow, handling issues and shelf-life considerations prevent these thin materials from being a true alternative for HASL. Substituted benzimidazole based chemistry, which can achieve coating thickness ranging from 5 to 20 μin, provides excellent protection against oxidation of the copper surface due to moisture and oxygen penetration. The substituted benzimidazole compounds have advantage of withstanding multiple heat cycles typically found in mixed technology PCB assembly operations (surface mount and through hole soldering). Consequently, the substituted benzimidazole becomes a leading HASL alternative. Since the coating is not conductive, OSP is not normally used for contact functional circuitry.

Immersion silver consists of a very thin (8–20 μin) coating of nearly pure silver. Organic materials are typically codeposited within the silver for prevention of tarnish and electromigration. The metal coating is deposited via a relatively simple and inexpensive conveyorized or vertical chemical process. Silver consists of only the outermost coating on the conductor, which is the most conductive element in nature.

When surface finishes are applied to an exposed copper trace, the thickness of the trace and the material compounds of the trace are changed. For high-frequency signal propagation, the electrical properties of the compounds and the increased thickness could introduce extra distortion, which is frequency dependent. In this work, we will focus our investigation on the effects of HASL, ENIG, and OSP on high-frequency signal degradation.

III. Surface Finish Effects on High-Speed Signal Propagation

In high-frequency digital circuits, the degradation of transmitted signals is a combination of attenuation and dispersion. The attenuation distortion can be characterized by insertion loss, which represents the energy dissipation per unit length in an interconnect. Insertion loss is defined as

$$\text{Insertion loss} = -20\log(|S_{21}|)/L(\text{dB/in}) \tag{1}$$

where L is the length of trace. The scattering parameter, S_{21}, denotes how much energy will be transmitted from the source to the load, is given by

$$S_{21} = \frac{\text{Power delivered to a } \mathrm{Z_0 load}}{\text{Power available at a } \mathrm{Z_0} \text{ source}}. \tag{2}$$

If there is no loss in the interconnect, S_{21} is unity and the insertion loss is 0 dB/in. If all the energy is dissipated in the interconnect, then S_{21} is 0, and the insertion loss approaches infinity. So the insertion loss is always greater than or equal to 0. The bigger the insertion loss is, the higher energy dissipation.

It is important to keep in mind, however, that the insertion loss only explains the magnitude attenuation but not phase-related dispersion. In high-speed digital interconnects, signal skew is a primary concern. The signal skew is related to the signal shape after it has propagated through the interconnects. In this work, we use the S parameters obtained from the full-wave simulation and feed them directly into a time-domain SPICE circuit simulator. This allows efficient time-domain response of the excitation pulse as it propagates through the interconnect.

In this section, we study the surface finish effects on high-speed signal propagation in interconnects experimentally and using numerical simulation. We focus on two widely used types

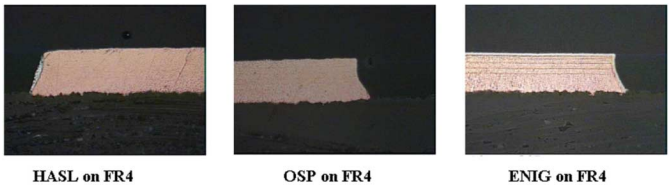

Fig. 2. Cross section of microstrip line with surface finishes.

of interconnects, namely, the microstrip line and the differential microstrip pair.

A. Signal Distortion in a Microstrip Line

Microstrip line is one of common interconnects in PCB. The fundamental mode of propagation in a microstrip line is a quasi-TEM mode. In this work, we consider a 50-Ω microstrip line on a FR4 substrate with selected surface finishes applied. The microstrip is 0.035 in wide and 0.002 in thick. The substrate is 0.02 in thick. The cross-sectional photographs of the fabricated microstrip line with coatings are shown in Fig. 2. The surface finishes applied to the microstrip transmission line are as following.

1) OSP: Two panels of each material are processed through a horizontal OSP line. Preparation consisted of preclean and micro-etch. The thickness of OSP is as thin as 5 μin.
2) HASL: Two panels of each material are processed in a Gyrex vertical HASL machine. Preparation consisted of micro-etch/preclean followed by a surface activator. Panels are post baked after solder coating. The thickness of HASL varies from 200 μin to 300 μin.
3) ENIG: Two panels each are process through a vertical dip immersion nickel/gold line with agitation. Nickel thickness is targeted at 200 μin. XRF equipment is used to verify the mean nickel thickness 197.5 μin. On this sample set, mean gold thickness is determined to be 4.9 μin.

An HP8510 vector network analyzer (VNA) with time domain reflectometry (TDR) is used to collect full two-port S-parameters and accounts for the contribution of the test apparatus. The measurement system is calibrated using a 3.5-mm calibration kit. Each test specimen is mounted in a test apparatus and connected to the measurement system. The testing apparatus is shown in Fig. 3.

Corresponding test specimens are simulated using the HFSS finite element 3-D full wave solver. The finite thickness of the conductor is accounted for in the FEM circuit model to allow for skin effects. The insertion loss versus frequency of the microstrip line with HASL and ENIG is shown in Fig. 4. The experimental measurements are observed to be in very good agreement with the FEM based numerical simulation. It is important to note that the insertion loss increases exponentially with respect to the frequency increase. This is because the substrate dielectric loss is the dominant factor for electrical short transmission lines, which is proportional to the frequency at gigahertz level.

Having verified the numerical finite element model, we now proceed with confidence in testing other structures which can be more susceptible to surface finish effects. Fig. 5 shows the comparison between the bare copper microstrip line and microstrip

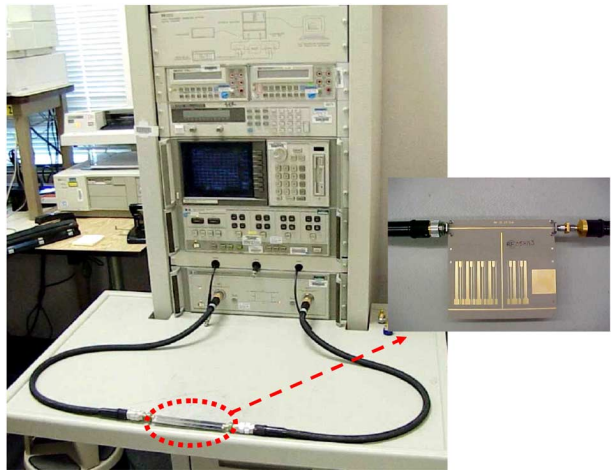

Fig. 3. Measurement apparatus showing the use of the VNA.

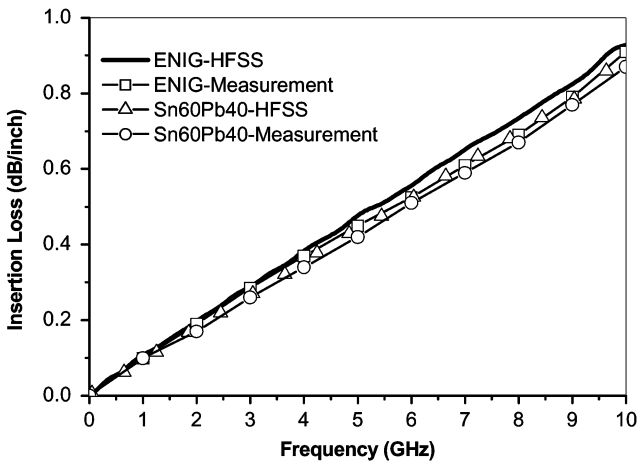

Fig. 4. Simulation and measurements of the microstrip line with HASL and ENIG applied.

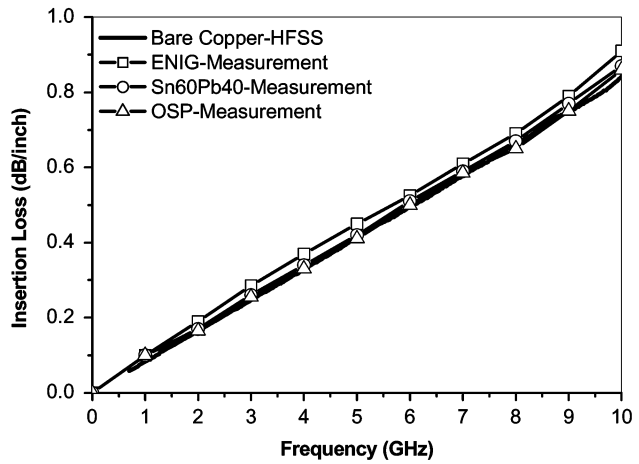

Fig. 5. Insertion loss of a bare copper trace and trace with surface finishes.

line with surface finishes. With the increase of the frequency, the signal losses of the microstrip with surface finish increase. For the microstrip circuitry, the maximum loss is the trace plated with ENIG, which has about 0.9 dB/in insertion loss at 10 GHz. Compared with the bare copper microstrip line at 10 GHz, the

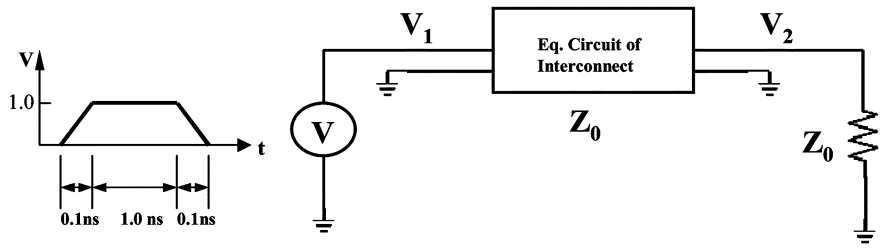

Fig. 6. Network with equivalent circuit of investigated microstrip line.

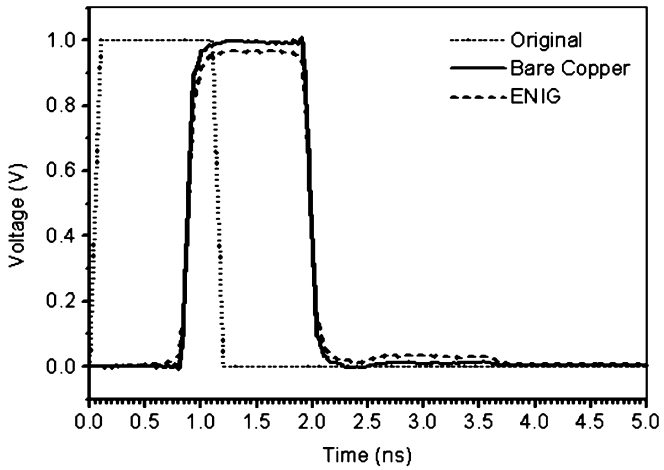

Fig. 7. SPICE Simulation of the pulse response on the investigated 50-Ω microstrip line on a FR4 substrate with selected surface finishes applied. Microstrip is 0.035 in wide and 0.002 in thick. Substrate is 0.02 in thick.

ENIG coated microstrip line, which has the maximum insertion loss increment, has less than 10% loss increment; the OSP coated microstrip line has less than 3% loss increment; and the HASL coated microstrip has 5% loss increment. Therefore, it can be concluded that the signal attenuation caused by the surface finishes in the microstrip circuitry are negligible.

The signal waveform behavior of the interconnection is investigated by using a matched load as a termination as illustrated in Fig. 6. In most digital applications, a trapezoidal pulse is a sufficient model for a pulse. Although the energy spectrum of a trapezoidal pulse is spread over a very wide range, most of the signal energy is concentrated near the low-frequency region and decreases rapidly with the increase in frequency. The desired maximum frequency $f_{\max}$ and t_r (rise/fall time) can be expressed as

$$f_{\max} = 1/t_r. \tag{3}$$

As a result, the desired maximum frequency 10 GHz corresponds to a pulse with rise/fall time 0.1 ns. The SPICE simulated pulse response through a 5.12-in-long microstrip line interconnect without coating, and with ENIG coating is given in Fig. 7, respectively. This pulse response clearly confirms that the surface finishes generate negligible signal distortion for a microstrip line structure.

B. Signal Distortion in Differential Mode Coupled Microstrip Lines

Coupled microstrip lines are two conducting strips placed side by side on a dielectric substrate. When the two strip lines

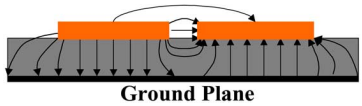

Fig. 8. Field distribution in the differential mode (odd mode) in coupled microstrip lines.

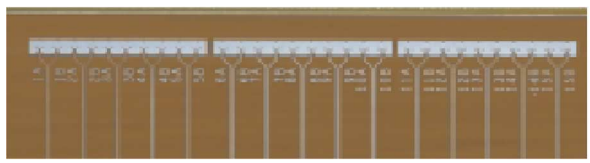

Fig. 9. Test samples of differential pairs.

are sourced with an equal magnitude and a 180° phase shift between them, the excitation is referred to as differential mode (odd mode) and the coupled microstrip lines carrying differential mode signals as a differential pair. Differential mode propagation in the coupled microstrip lines is robust since it is less susceptible to external common mode noise and the opposite current flows in the pair result in significant reduced electromagnetic interference [6]. A major feature of the differential mode configuration is the current which tends to concentrate near the two inner edges of the copper traces. The electric field and magnetic field configuration of the differential pair is sketched in Fig. 8. The energy in the differential pair stripline configuration are less confined in the dielectric substrate than those in a single microstrip line. Based on the distribution of the field lines, a higher concentration of the field would be present within the surface finish. Therefore, it is expected that the unique field distribution for each interconnect configuration would leads to a unique effect on the signal quality.

Two sets of differential pairs, 85 Ω pair and 100 Ω pair on a FR4 substrate, were fabricated. The 85-Ω pattern is designed as a pair of 6-mil-wide microstrips separated by 8 mil, and the 100-Ω pattern is designed as a pair of 4-mil-wide traces separated by 5 mil. (HASL was not experimentally tested because in high-speed PCB manufacturing, the process of HASL without soldermask results in a 0.5–1.5 mil thick coating on the copper trace, which is comparable to the thickness of the trace itself.)

The test samples are shown in Fig. 9. The surface finishes are applied as followings.

- OSP: Four coupons for each matrix element are processed through a vertical type prototype line using MacDermid's M-Coat Plus chemistry. Preparation consists of preclean, microetch and appropriate rinsing. The OSP thickness measured on a specifically designated rate panel was determined to be 0.18 μm (0.007 mil).

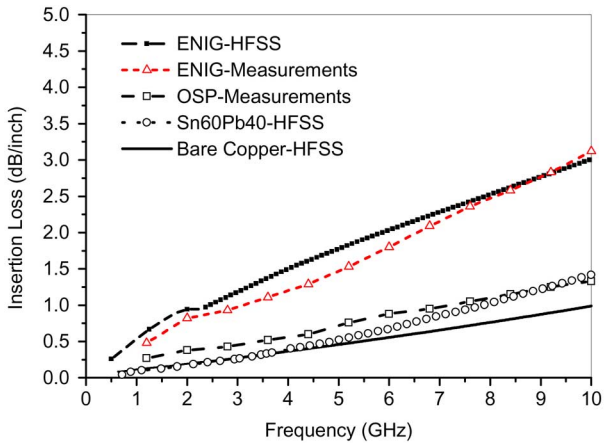

Fig. 10. Simulation and measurements of differential pairs with ENIG and OSP finishes applied.

- ENIG: Four coupons for each matrix element are processed through a vertical prototype line using MacDermid's Planar 2.0 electroless nickel immersion gold chemistry. Preparation consists of preclean, microetch, catalyst, acid dip, and appropriate rinsing. Nickel thickness is targeted at 5.0 μm (0.200 mil). XRF equipment is used to verify the mean nickel thickness of the actual samples to be 5.4 μm (0.213 mil). The mean gold is measured at 0.095 μm (0.004 mil).

Electrical measurements are conducted at Intel's Signal Propagation Laboratory in Hilsboro, OR. For measurements, a 450-μ in pitch Cascade Probe (GGB 40A-GS-450-EDP) attached to an Agilent 8722ES vector network analyzer via low loss Gore cables is used to probe each end of the differential pair to collect S-parameters.

In the FEM HFSS simulation, only the odd mode is excited to ensure differential signaling. The HFSS simulation results and the averaged measurements of ENIG are shown in Fig. 10. The simulation results are consistent with the measurements. With the validated simulation process, two other cases are modeled for comparison purpose: the bare copper differential pair case and the HASL coating (Sn60Pb40) case. The insertion loss of these two cases is also shown in Fig. 10.

As seen in Fig. 10, as the frequency increases, the signal loss increment between the traces with finishes and the naked trace increase. For differential pairs plated with ENIG, at 10 GHz, the insertion loss is 3.1 dB/in. Compared to the bare copper differential pairs, the insertion loss increment with ENIG surface finish is higher by 200%. The insertion loss of differential pair plated with OSP or HASL is very close to each other. At 10 GHz, the insertion of OSP or HASL is about 1.3 dB/inch, compared with the noncoated differential pairs, the insertion loss increment is higher by 30%.

A circuit network, as shown in Fig. 11, is used to demonstrate the signal integrity of a pulse through a 2.0-in-long differential pair coated with surface finishes. In the network, the loads Z_a, Z_b are obtained from the following relationships [7]:

$$Z_{\text{comm}} = \frac{Z_b}{2}, Z_{\text{diff}} = 2Z_bZ_a/(2Z_b + Z_a) \tag{4}$$

where, Z_{comm} is the common mode (even mode) impedance, and Z_{diff} is the differential mode (odd mode) impedance of the coupled microstrip lines, respectively. The signal responses of differential pair plated with HASL, ENIG, and differential pair without coating, as seen in Fig. 12, show that ENIG generates significant distortion on a transmitted signal.

The simulation results and measurements show that the coupling can be significantly reduced at high frequency when the high resistivity surface finish, ENIG, is applied. The increase of the resistivity of the trace due to the electroless nickel coating generates significant reduction of the coupled fields between the traces. For a nonconductive surface finish (OSP) or low resistivity surface finish (HASL) applied on the differential pairs, the resulted signal distortion is much less than that of ENIG.

IV. Discussion

In Section III, we have shown that significant surface finish effects have been found on differential pair lines whereas little effects have been found on microstrip lines. In this section, a brief discussion based on the physical distortion mechanism is given for these effects.

An interconnect structure consists of metal parts and dielectric parts. The metal parts provide boundaries to guide the transmitted fields, and the dielectric parts provide media for fields to be transmitted through. The signal distortion, regardless of proximity and parasitic effects, has two distortion mechanisms: dispersion and attenuation. The attenuation includes both dielectric loss and conductor loss. When surface finishes are applied to traces, the two distortion mechanisms will both be affected, depending on the materials used in surface finishes.

A. Dispersion Distortion

Waves of component frequencies that travel with different phase velocities cause the dispersion distortion in the signal wave shape. In a microstrip line structure, pure TE or TM modes cannot be supported. The insertion of a center strip in microstrip line structure causes currents to flow both in the transverse direction and the longitudinal direction on this strip. These currents serve to couple the transverse modes and longitudinal modes so that the final mode propagating in the microstrip line structure is hybrid, which is called quasi-TEM mode. The hybrid mode of propagation along microstrip (quasi-TEM mode) leads to the signal dispersive distortion.

To characterize the dispersion of a microstrip line structures, a frequency dependent effective microstrip permittivity (dielectric constant) $\varepsilon_{\text{eff}}(f)$ can be defined as [8]

$$\varepsilon_{\text{eff}}(f) = \left(\frac{c}{v_p(f)}\right)^2 \tag{5}$$

where c is the light speed, and $v_p(f)$ is phase velocity, which is a function of frequency (f). Since some of the fields are inside the substrate and some of are in the air, so the effective dielectric constant is in the range $1 \sim \varepsilon_r$.

Besides the substrate dielectric constant, the conductor thickness and the cross-section geometry are other important factors for dispersion of microstrip line structures. As reported in [9], at

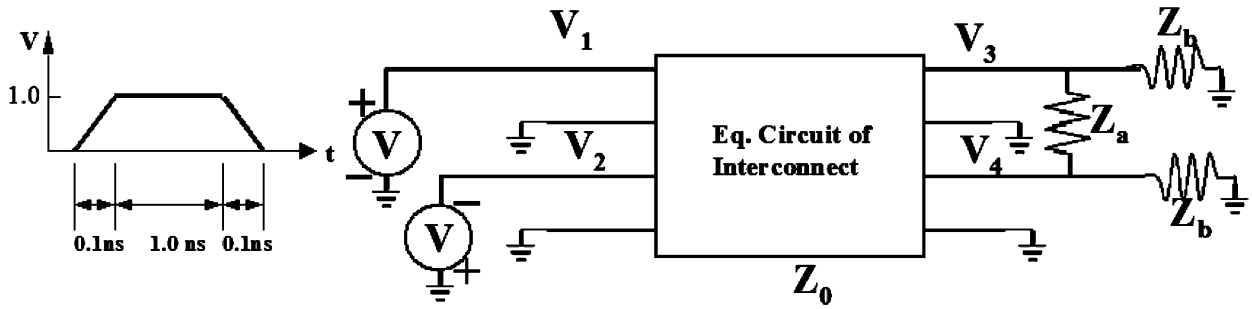

Fig. 11. Network with equivalent circuit of investigated differential pair interconnect.

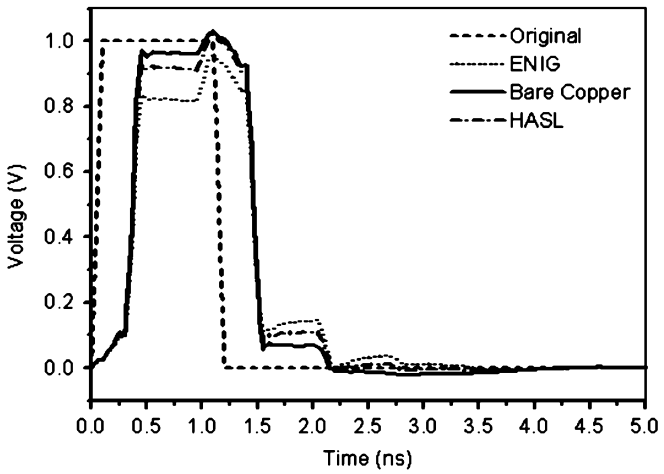

Fig. 12. SPICE simulation of the pulse response on the investigated 85-Ω differential pair. The 85-Ω pattern is designed as a pair of 6-mil-wide microstrips separated by 8 mil.

5.0 GHz, when conductor thickness increases from 0.01 to 0.5 mm, the effective dielectric constant decreases approximately 15%. This also showed that with a thicker conductor, the average phase velocity of the EM wave becomes greater than the case with the thinner conductor microstrip, which makes the effective dielectric constant smaller. As a result, the portion of EM energy traveling outside of the substrate is higher in the thicker conductor microstrip structure.

When a conductive surface finish applied to a trace, the thickness of the trace is significantly increased. For instance, HASL and ENIG coatings may result in a layer on top of a copper trace, which is as thick as the bare trace. The effective dielectric constant, due to the finite thickness effects, is less than that of the bare trace without coatings, which result in higher dispersion than that of the one without coatings.

A nonconductive coating, OSP, which has a dielectric constant of 3.7–5.4 [10], adds a dielectric layer on top of the bare trace conductor. Since the thickness of the OSP coating is less than 10% of the trace thickness, the dispersion effects caused by this layer is negligible.

B. Attenuation Distortion

The attenuation of signal results from conductor loss and dielectric loss. In interconnect designs, when the surface finish effects are not considered, the dielectric loss can be ignored because the conductor loss is dominant [11], [12].

When considering the dielectric loss, if the non-conductive surface finish (OSP) is applied, earlier work showed that the substrate dielectric loss is much more significant than that of the surface finish [3]. In OSP coating, the portion of EM energy confined in the coating and the dissipation factor of the coating determine how much energy is dissipated. The dissipation factor of the OSP compounds is in the range of 0.013 $\sim$ 0.021 [10]. In a single microstrip line structure, the field is mostly confined in the substrate. For an odd mode coupled differential pair, the fields are strongly coupled between the edges of the traces, which leads to higher loss in the coating than the single microstrip line. However, as the thickness of the OSP coating is less than 10% of the trace thickness, and the electromagnetic energy are mostly concentrated in the substrate, only little dielectric loss is expected to be caused by OSP. From the experiments and simulation results in Section III, the dielectric loss results from the OSP coating is not significant.

The conductor loss from conductive coatings is much higher than that of the dielectric loss from nonconductive coating. The conductor bulk resistivity and skin effect are important factors of the conductor loss. At high frequency, the current flowing in a conductor will migrate toward the periphery of the conductor. This phenomenon causes variations of the resistance and the inductance of a conductor with frequency. For a good conductor, the skin depth is given by [7]

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}} \tag{6}$$

where, δ denotes skin depth, μ is the conductor's magnetic permeability, σ is the bulk conductivity, and f is frequency.

The losses in the conductor can be approximated using the dc (bulk) resistance and the skin effect (ac) resistance [11]

$$R_{\text{ac}} \approx \frac{1}{\sigma p \delta}$$
$$R_{\text{bulk}} = \frac{1}{\sigma A} \tag{7}$$

and, the total resistance per unit length

$$R_{\text{total}} \approx \sqrt{R_{\text{bulk}}^2 + R_{\text{ac}}^2} = \frac{1}{\sigma} \sqrt{\frac{1}{A^2} + \frac{\pi \mu \sigma f}{p^2}} \tag{8}$$

where, p = effective perimeter with respect to skin depth, A = bulky cross-sectional area. Therefore, as frequency in-

TABLE I
RESISTIVITY OF PCB METALS

Metal	Resistivity (μΩ•cm)
Silver	1.4
Copper	1.7
Gold	2.4
Nickel	7.4
Tin	10.9
Sn60Pb40 Solder	17.0
Electroless Nickel/Phos.	55.0~90.0

creases, the total conductor loss will increase, and as the bulk conductivity decrease, the total conductor loss will increase as well.

When applying a conductive surface coating, whose thickness is larger than the skin depth, it can result in significant conductor loss increase. The resistivity of widely used conductive PCB coating materials are listed in Table I, [12]. Compared with the resistivity of copper, the resistivity of HASL (Sn60Pb40 Solder) is about 15 times higher than that of copper, and the resistivity of the Electroless Nickel is about 50 times higher that of copper. At high frequency, the thickness of coating can be up to hundreds of microns, which is much bigger than the skin depth. Consequently, with a high resistivity conductive coating, such as ENIG, the total resistance is significantly increased and high signal distortion is expected as demonstrated in Section III.

V. CONCLUSION

In this work, the effects of surface finishes on high-speed signal degradation were investigated. Two typical interconnect structures, microstrip line circuitry and coupled microstrip line circuitry with HASL and its alternatives were fabricated and tested. A finite element method full wave simulator, Ansoft HFSS is also employed to model the surface finish resulted degradation. The numerical simulation results are consistent with the measurements. Time-domain pulse response through investigated interconnects is studied using SPICE modeling. From this work, we conclude that:

The surface finishes increase the signal loss compared to a bare copper trace without coating. Conductive surface finish has higher loss than the nonconductive surface finish. The signal loss is frequency dependent: as the frequency increases, the signal loss increment becomes higher. The signal loss in differential pairs is much higher than that in a single microstrip line with same surface finish.

For the noncoupling interconnects, such as microstrip line, surface finishes do not have significant effects on signal losses; for strong coupling dependent interconnects, such as coupled microstrip lines, the signal degradation from ENIG is significant and may cause false switching if not well considered. The effects of OSP and HASL on coupled microstrip lines also need to be considered in high-speed digital design. Therefore, the electrical performance analysis is necessary when selecting surface finishes for coupling based high-speed interconnects and devices.

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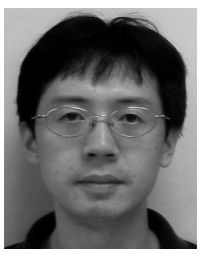

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