Conductor Profile Effects on the Propagation Constant of Microstrip Transmission Lines

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Abstract—We experimentally show that the increase in conductor loss due to roughness is larger than the factor of two predicted by the most widely used roughness factor models. This is consistent with a recent numerical study of the effect of random roughness on conductor loss. The data also show that, for thin substrates, increasing the conductor profile substantially slows the effective velocity of propagation and also increases dispersion, independent of the composition of the dielectric material. Measurements are compared with results from a new conductor model as used in a 3-D planar EM analysis that includes an excess inductance related to the conductor profile. It is shown that this accounts quantitatively for both the insertion loss and phase constant effects.

Index terms – Conductors, dielectric measurements, microstrip, electromagnetic analysis, roughness, transmission line measurements

I. INTRODUCTION

IN 1949, S. P. Morgan [1] numerically modeled the effect of regular triangular and square patterned grooves in a conductor surface on conductor loss. As the skin depth of the signal approaches the height of the grooves, conductor loss increases. With grooves with an aspect ratio of about 1:1, the maximum increase of a rough conductor is a factor of two for a signal traveling perpendicular to the grooves.

The Morgan model was adapted into an automated microstrip insertion loss and impedance calculation described by Hammerstad and Jensen [2] (H&J). The model is a multiplicative correction factor K_{SR} to the attenuation constant calculated for a smooth conductor.

$$\alpha_{\text{cond, rough}} = \alpha_{\text{cond, smooth}} \cdot K_{SR} \qquad (1)$$

where $\alpha_{\text{cond, smooth}}$ is the attenuation constant calculated for a smooth conductor and

$$K_{SR} = 1 + \frac{2}{\pi}\tan^{-1}\left(1.4\left[\frac{R_{RMS}}{\delta}\right]^2\right)$$

where R_{RMS} is the RMS value of the conductor roughness and δ is the skin depth. Both $\alpha_{\text{cond, smooth}}$ and K_{SR} are functions of frequency. When the ratio of R_{RMS}/δ is small, as with a smooth conductor or at low frequencies where the skin depth is large, the value of K_{SR} is close to one. As the value of R_{RMS}/δ
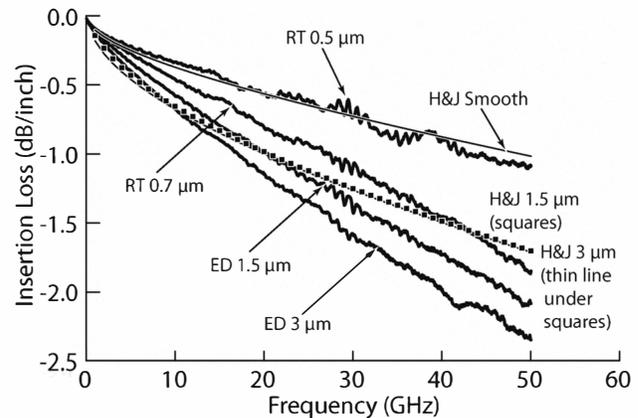

Fig. 1. Insertion loss of 50Ω transmission lines on 0.004" thick LCP dielectric with copper foil RMS profile as a parameter [8].

increases, the value of K_{SR} approaches 2. This model predicts a "saturation effect," i.e., that the maximum effect of the conductor roughness would be to double the conductor loss. This result also implies that the conductor loss for a lower profile foil eventually approaches that of a rough foil as frequency increases. Typical results are shown in Fig. 1. Groisse et al [3] describe a similar factor for correcting conductor loss for surface roughness that also saturates at high frequency and predicts a maximum increase in conductor attenuation of a factor of two.

Historically, these models have shown reasonable agreement with measured data. However, Tsang et al [4] have performed numerical and analytical simulations that show that for multiscale rough surfaces (rather than the periodic surfaces treated by Morgan), saturation does not occur and increases of greater than a factor of two in conductor loss can occur.

The present authors found only two recent papers directly addressing the effects of conductor profile on the phase constant. Ding et al [5] have conducted modeling of wave propagation in a randomly rough parallel plate waveguide and find an increase in the phase constant for rough conductors, though the magnitude of the effect is not quantified. Deutsch et al [6] measured the relative dielectric constant, ε_R, of 0.0025" and 0.010" thick samples of FR4 laminate clad with rough and smooth copper foil using the "full sheet resonance" test method [7]. The calculated ε_R of the thin substrate clad with the rough foil was approximately 15% higher than that of

the same thickness substrate with smooth foil. The increase in calculated ε_R of the thin substrate clad with the smooth foil was considerably lower. Modeling with a 3-D full-wave electromagnetic field solver and a 2-D solver that includes the detailed profile of the conductors confirmed the approximate magnitude of the measured results. The authors attribute the increase in calculated ε_R to an increase in inductance caused by the conductor profile.

Horn, III et al [8] present insertion loss and phase length data on 50 Ω microstrip transmission lines on a LCP (liquid crystal polymer) dielectric with a wide range of conductor profiles that show results similar to those predicted in [4] and [6]. EM modeling [9], [10] also shows that adjusting the conductor model to account for an increase in inductance due to conductor roughness simultaneously quantitatively matches the increase in insertion loss and the increase in K_{eff} (effective dielectric constant).

In the present work, we review the results of [8] and extend the measurements to another dielectric material and present results for a new model of the effect of conductor profile.

II. SAMPLES AND EXPERIMENTAL METHODS

A. Microstrip laminate and copper foil samples

Fifty-ohm microstrip transmission lines were photo-lithographically etched onto copper foil clad Rogers ULTRALAM® 3850 LCP (liquid crystal polymer) laminates of thicknesses of 0.004" to 0.020". The LCP laminate makes an excellent test vehicle for circuit properties. This material is a glass fabric-free, pure resin circuit substrate that relies on the inherently low CTE (coefficient of thermal expansion) of the oriented LCP film to achieve a good in-plane CTE match to copper foil. Since the LCP substrate consists of a single pure substance, the variation in the dielectric properties is inherently low. The dielectric constant, ε_R, at X-band of the LCP material is 3.0 and DF is 0.002 (loss tangent). The samples were made in thicknesses increments of 0.004" from 0.004" to 0.020" by plying up 0.004" sheets and laminating them to copper foils with a range of profiles from 0.4 μm to 3 μm RMS as discussed below.

A similar set of samples of thicknesses from 0.004" to 0.020" was also prepared using Rogers RO4003C® and RO4350B® substrates. These are silica-filled hydrocarbon (HC) laminates that are widely used in commercial high frequency systems. The RO4350B laminate is flame retardant (HC-FR). The ε_R of the HC laminate is 3.55 and that of the HC-FR material is 3.66 when tested at 0.020" thickness by the "full sheet resonance" method (IPC-TM-650 2.5.5.6). The foils were treated with about 8 μm of an adhesive that exhibits an ε_R of 2.5. The ε_R of the laminate itself is expected to decrease as the laminate thickness decreases since the lower ε_R adhesive comprises a larger portion of the overall thickness.

There are two main types of copper foil that are commercially produced for the purpose of planar circuit substrate conductors. Rolled-annealed (RA) foil is literally rolled from a solid copper ingot. After the rolling process, both sides of the foil exhibit a low profile (about 0.1 to 0.2 μm RMS). When destined for planar circuit applications, the foil manufacturer plates a treatment on the shiny foil that increases the profile to 0.4 to 0.5 μm RMS.

Electrodeposited (ED) foil is made by plating from a copper sulfate bath onto a slowly rotating stainless steel drum. Historically, the ED foil manufacturers plated additional treatments on the rough side of the foil, resulting in RMS profile values of 1.0 to 3.0 μm. More recently, as demand for lower profile foils increases, ED foil manufacturers have developed "reverse-treated" (RT) foils, by producing low profile bath side base foils and plating the "drum side." RT copper foil profiles are typically 0.5 to 0.7 μm RMS.

In the present study, samples were clad with one type of RA foil with an R_{RMS} of 0.4 μm, three grades of RT foil with R_{RMS} values of 0.5, 0.6 and 0.7 μm, and two grades of ED foils with R_{RMS} values of 1.5 and 3.0 μm.

B. Experimental methods

The surface profiles in the current work are characterized using a Veeco Metrology Wyko® NT1100 optical profiling system based on white light interferometry. This non-contact method generates a three dimensional image of the surface topography with a resolution of 1 nm in a 1 mm square area.

The microstrip samples are held in an Intercontinental Microwave W-7000 Universal substrate fixture that provides a rapid set-up, low return loss transition from coax to microstrip and is SOLT calibrated to the cable ends. The S_{11}, S_{21}, and phase length of 3.5" and 7.0" long samples were measured using an Agilent PNA-L 50 GHz network analyzer. S_{11} is generally less than –20 dB over the frequency range recorded. The S_{21} values and phase length values of the short samples were subtracted from those of the long samples and divided by the difference in length to yield the transmission line's insertion loss and differential phase length.

III. RESULTS

Insertion loss results up to 50 GHz for copper foils with profiles of 0.5, 0.7, 1.5, and 3.0 μm for the 0.004" thick LCP dielectric material are shown in Fig. 1. The measured data for the 0.5 μm profile foil match the smooth foil H&J results, [2]. The H&J insertion loss calculated for the conductor profile of 1.5 μm is substantially higher than the measured data above 20 GHz. For the 3.0 μm profile, measured loss is substantially higher than calculated above 10 GHz.

Note that the calculated insertion loss for the 1.5 and 3.0 μm profile conductors are essentially identical beyond about 15 GHz, while the measured data show that the 3.0 μm profile

foil has substantially higher loss at all frequencies. The increase in loss for the 3.0 μm profile foil compared to the smooth foil is close to the factor of three predicted by [4]. These data show that saturation does not occur; at least up to frequencies of 50 GHz and that the effect of conductor profile is larger than predicted by the Morgan model above 10 GHz.

Fig. 2 shows the profound effect of conductor profile on the substrate dielectric constant, K_{sub}, calculated by the method of [2], from the measured differential phase length and the circuit dimensions of the same samples. The authors emphasize that the conductor profile is not changing the ε_R of the substrate, but that the higher profile increases the phase constant.

The magnitude of the effect of the conductor profile on the phase constant is highly dependent on the thickness of the microstrip circuit. The average K_{sub} calculated from 5 to 35 GHz for the LCP samples ranging in thickness from 0.004" to 0.020" clad with 0.4 and 3.0 μm profile foil is plotted against the substrate thickness in Fig. 3. Fig. 3 shows that there is an apparent 12% increase in the calculated K_{sub} as thickness decreases with 3.0 μm RMS foil, while there is minimal apparent change for the samples clad with 0.4 μm foil.

The same effects of laminate thickness and copper foil profile are seen in Fig. 4 for the HC and HC-FR materials clad with 0.5 and 3.0 μm RMS profile foils. On these materials, there is a slight decrease in K_{sub} as laminate thickness decreases due to the increasing proportion of the lower ε_R adhesive layer on the samples clad with the 0.5 μm profile foil. The effect of the adhesive, however, is overwhelmed by the 3.0 μm profile foil, which also exhibits an approximate 12% increase in K_{sub} as the laminate thickness decreases from 0.020" to 0.004".

IV. MODELING

Clearly the simple model of [2] is inadequate for predicting the effect of conductor profile on either insertion loss or phase constant. It is well known that skin effect in a good conductor affects the phase constant as well as the attenuation [10]. The simplified model of [2] ignores the imaginary part of the skin effect surface impedance. More advanced skin effect models, [10], do account for this effect.

In addition to the attenuation correction factors of [2] and [3], a common method of modeling the loss caused by conductor roughness is to reduce σ, the conductivity, to match measured insertion loss. The measured insertion loss of 50 Ω transmission lines on 0.004" LCP are compared with three curves simulated by Sonnet® [9], using the measured physical dimensions of the actual circuits, an ε_R value of about 3.0, and tan(δ) of 0.002 for the LCP dielectric, Fig. 5. The "Model-smooth Cu" curve uses σ = 5.8×10⁷ S/m (ideal copper) and matches the measured loss for the 0.4 μm RMS foil. If we try to match the higher frequency insertion loss values of the 3.0 μm RMS foil sample by decreasing the value of the
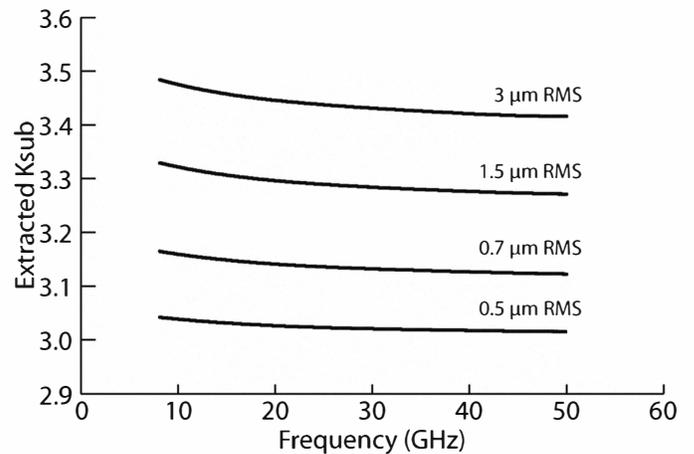

Fig. 2. Extracted K_{sub} of 50 Ω transmission lines on 0.004" thick LCP dielectric with copper foil profile as a parameter [8].
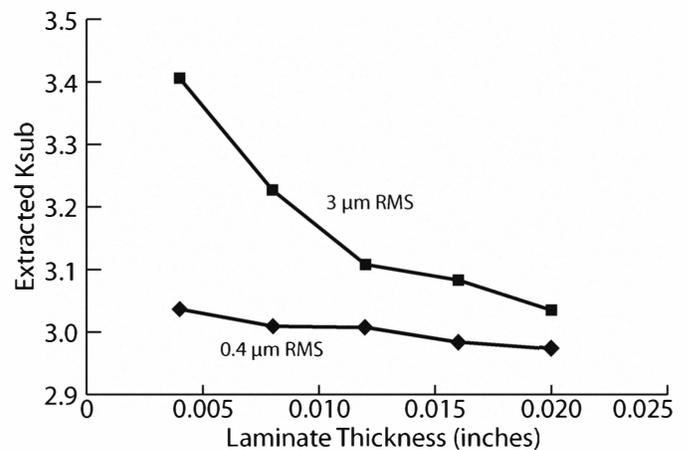

Fig. 3. Extracted K_{sub} (avg. 5-35 GHz) vs. thickness for 50 Ω transmission lines on LCP clad with 0.4 and 3.0 μm profile foils [8].

conductivity by a factor of 0.12 times that of copper, poor agreement is still observed. At low frequency, the error approaches 100%. In the third simulation, we use the new roughness model, which includes the effect of the 3.0 μm RMS profile. The new roughness model represents measurements nearly perfectly.

If we ignore the high values of insertion loss at lower frequency in Fig. 5 and use the same decrease in to model the effective dielectric constant, K_{eff}, of the microstrip lines, the agreement is even worse, Fig. 6. Simply decreasing conductivity to fit insertion loss does not increase K_{eff} nearly enough to match measurements. However, the same conductor model used to fit insertion loss (Fig. 5) provides an excellent fit to the K_{eff} data (Fig. 6) as well.

The new roughness model invokes more surface inductance than expected from smooth surface skin effect. The reason for this is that the incident electric field (Fig. 7) forms a voltage source that excites a current loop formed by the depression in the conductor. All the magnetic field enclosed by the indicated loop increases the surface inductance.
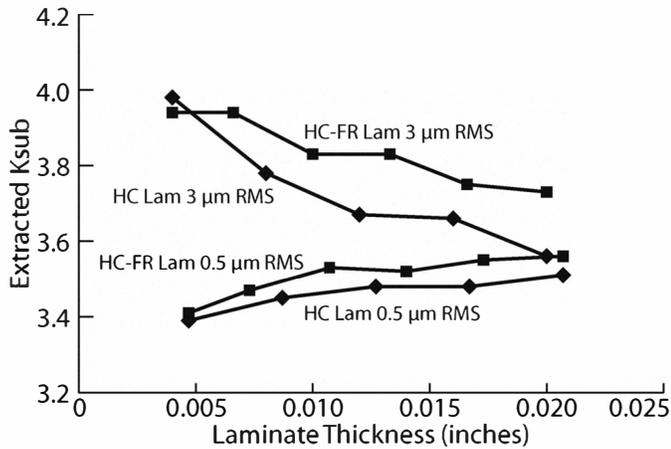
Fig. 4. K_{sub} versus thickness for 50Ω TLs on HC and HC-FR laminates clad with 0.5 and 3 μm profile copper foils.
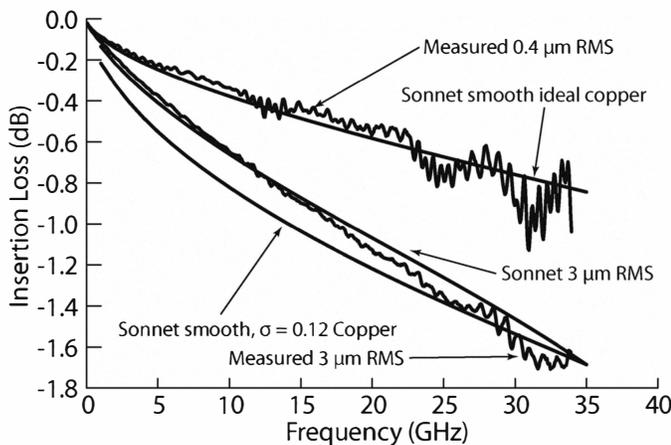

Fig. 6. Comparison of modeled and measured K_{eff} data on 50 Ω TLs on 0.004" LCP. All figures will be redone in this format for the final paper.

Fig. 5. Comparison of measured and modeled insertion loss data on 50 Ω TLs on 0.004" LCP.

Fig. 7. Magnetic field encircled by the surface current flowing on a rough conductor and excited by the incident electric field results in substantial surface inductance, above and beyond that generated by the smooth surface skin effect.

VI. CONCLUSION

Surface roughness in conductors is experimentally shown to have substantial effect on both transmission line insertion loss and velocity of propagation that is at substantial variance to previous metal roughness models. These effects are most prominent in the very thin substrates now being used for high frequency and high speed work. Results from a new model that includes an excess inductance reproduces the effects of roughness nearly exactly.

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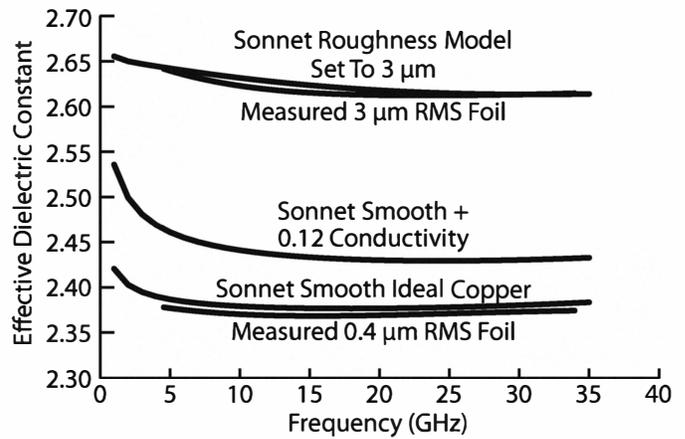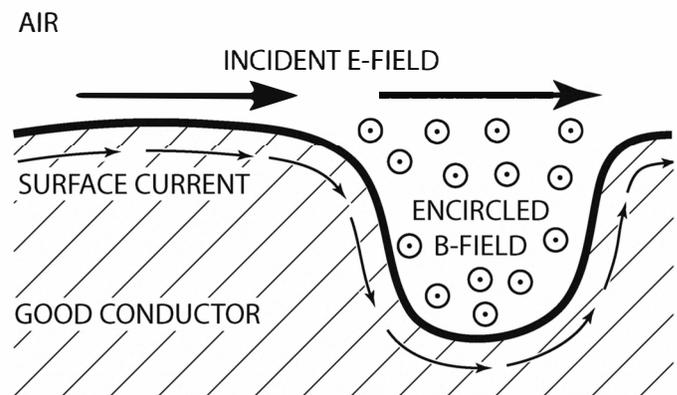[3] S. Groisse, I. Bardi, O. Biro, K. Preis, and K. R. Richter, "Parameters of lossy cavity resonators calculated by the finite element method," *IEEE Trans. on Magnetics*, vol. 32, no. 3, pp. 894–897, May 1996.
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