The Impact of Conductor Surface Profile (R_{rms}) on Total Circuit Attenuation in Microstrip and Stripline Transmission Lines.

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Abstract — **Transmission line attenuation is known to be influenced by conductor surface profile (R_{rms}), an effect that worsens as frequency increases. Using microstrip transmission lines, copper conductive losses are characterized from 0.03 – 30 GHz in low loss materials incorporating various copper types and tracewidths. Differing copper types are also evaluated in stripline structure using the Bereskin method. Such comparison allows the relationship between R_{rms} and conductor loss to be quantified. The advantages of packaging low loss materials with low profile copper foil are discussed.**

I. INTRODUCTION

Signal attenuation in microwave transmission lines is a frequency dependent response that has significant influence on circuit performance. Low loss substrates are one of the key tools that the designer has in high performance microwave and high speed digital applications.

In the laminates industry much attention is given to dissipation factor (DF), the dielectric loss, which is a function of material's polarizing response to a magnetic field. Since dielectric loss generally increases proportionally to frequency, flattening this frequency response is an important material design consideration. In the case of polytetrafluoroethylene (PTFE), low DF is a result of the lack of polarizability of the carbon-fluorine bonds branching from the polymer backbone. In addition to PTFE composites, other low loss formulations are available in the marketplace.

Loss in transmission lines is actually a combination of dielectric, radiative and conductor losses. In printed circuit boards, the conductor is supplied as copper foil which is laminated to the material. For adhesion purposes the underside (treatment side) of the foil is made to have a surface profile. Several grades of profile are available, see Fig. 1.

There are two main classes of foil, rolled annealed and electrodeposited (ED), both provided in differing weights corresponding to thickness. The most common foil thicknesses are ½ oz, 1 oz and 2 oz. Rolled and ED foils types also differ in grain structure as well as surface morphology. While rolled foil has a long history in microwave laminates, current design trends along with global copper supply issues are driving the microwave PCB industry into using a diversity of ED foil types.

Electrodeposited foils are manufactured using a galvanic copper deposition process. Surface roughness is engineered into the foil for purposes of conductor adhesion. The mechanical strength of the dielectric/conductor interface has significant influence on thermal stability and reliability of finished PCB structures. Thus, copper adhesion is an important parameter subject to rigid industry specified requirements. The tradeoffs associated with foil roughness and conductor loss must be balanced with the need for mechanically robust packaging requirements. Designers of low loss dielectric laminates are forced to balance these needs, optimizing conductor loss while maintaining foil adhesion.

The relationship between conductor surface profile and loss is well documented; the general relation is as follows:

$$\alpha_c = \frac{R_S}{Z_0 W} \quad \text{(Np/m)} \qquad (1)$$

Thus conductive losses are dependent on these three parameters; surface resistivity (R_s), the impedance of the transmission line (Z_o), and trace width (W). Surface resistance is a material property, partially governed by surface roughness in conductors. Trace width (W) and Z_o are both design parameters, with much attention given to proper impedance matching and characterization. The width of the trace has influence on radiative losses, particularly in microstrip structures where transmission lines act as antennas.

Conductive losses are directly proportional to surface resistance in a general sense. However conductor loss must be corrected for the skin affect, as signals travel at the conductor surface at differing depths depending on W, Z_o and frequency.

Equation 2 relates conductor losses to the root mean square of surface roughness (R_{rms}). Skin depth (δ) (equation 3) is inversely proportional to the square root of the product of frequency, material permeability, and material conductivity.

$$\alpha_{cond,rough} = \alpha_{conductor}\left(1 + \frac{2}{\pi} a\tan\left(1.4\left(\frac{R_{RMS}}{\delta_s}\right)^2\right)\right) \qquad (2)$$

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (3)$$

The previous equations relate to both microstrip and stripline structures. In the case of stripline transmission lines, the roughness of both the treatment side and the "shiny" side of the conductor foil influences loss. In most PCB stripline designs, the inner layer undergoes microetching of the external conductor before subsequent lamination. For this reason, design considerations of conductor roughness can be limited to treatment profile for both microstrip and stripline structures.

One convenient method for evaluating the influence of conductor roughness in stripline configurations is the Bereskin Method. This test method is primarily employed as a measurement of dielectric loss. Fig. 2 shows the fixture design.

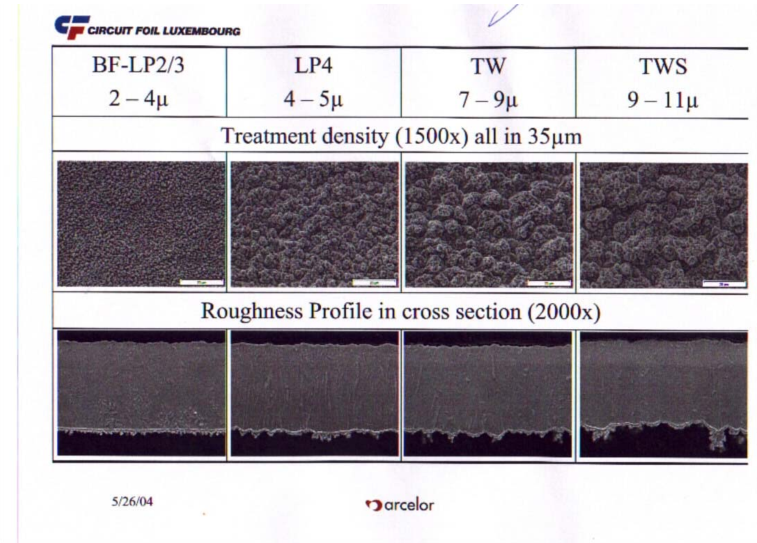

Figure 1: SEM images of several grades of copper foil available from Circuit Foil Luxembourg. Units shown are for R_z in microns (μ).

II. METHODS

For testing of microstrip structures, Taconic test laminates were manufactured at thicknesses of 16 and 28 mils with various copper types and panelized. Materials were tested for dielectric constant using the Bereskin method. From these results, AppCAD™ v3.0.2 from Agilent Technologies was used to design 50 Ω microstrip lines.

Microstrip transmission lines were mechanically routed using an LPKF Protomat 93S circuit plotter and accompanying CircuitCAM v 4.0 and BoardMaster v 4.0 software. For each material, a 12" long microstrip was fabricated. S – Parameter measurements were done on an Anritsu 37369 Vector Network Analyzer following full 12 term calibration using a customized microstrip end-launch fixture from Intercontinental Microwave Inc. The microstips were characterized over a frequency domain sweep spanning 0.04 – 30 GHz for acceptable return loss (S11) and complex impedance to ensure 50Ω transmission line continuity across the bandwidth.

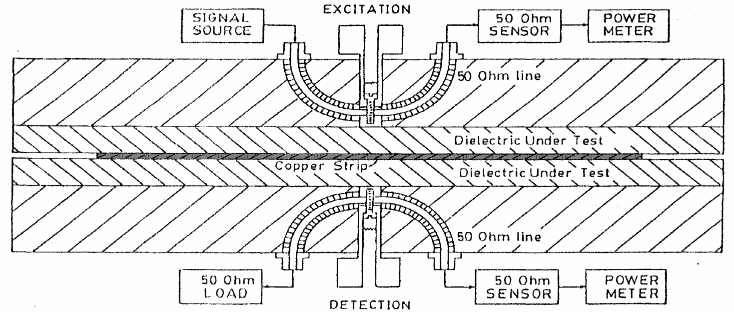

Figure 2: Side view of the fixture design used for Bereskin measurements. A copper strip conductor is sandwiched between two laminate samples, to which a microwave signal is incident through the z-axis of the structure, creating a cavity resonator.

Attenuation (S21) for each microstrip was measured at four different lengths, 12", 8", 4" and 1", across the 0.04 – 30 GHz bandwidth. The trend in attenuation vs. length was then used to calculate the loss due to the fixture in each sample/fixture combination. Fixture loss was subtracted out and attenuation (dB/inch) was derived for each material.

Copper foil samples were analyzed for R_{rms} profile using a contact mechanical probe analyzer. Measurements were in accordance with IPC-TM-650 2.2.17A Surface Roughness and Profile of Metallic Foils Contacting Stylus Technique. A Mitutoyo Surftest-212 profilometer was used. Each copper type was measured at 1" intervals across the 38" width of the foil roll. Roughness was reported as R_{rms}, the root mean square of all the measurements of surface profile depth.

For the Bereskin analysis, conductor strips were cut from sheets of foil. The sample/fixture combinations depicted in Fig. 2 were put together with each conductor sandwiched between the same laminate samples of Taconic laminate.

III. RESULTS

The copper foils used in this analysis were measured for surface profile and reported in microinches (μin); results are shown in Table 1.

For attenuation measurements, impedance matching was ensured by both S11 response and by Smith Chart. Fig. 3 depicts a typical S11 response of test laminates at 16 mils.

Due to fixture related losses and reflections, the bandwidth of the microstrip S21 measurements limited to 30 GHz. Fig. 4 shows the attenuation of 16 mil test laminates with various coppers.

Cu type	Treatment R_{rms} (μin)
Control-smooth	8
1 oz. RA	9
½ oz. RA	12
½ oz. RFT ED	19
1 oz. RFT ED Hi-Perf.	20
1 oz. DSTF	20
1 oz. VLP ED	20
2 oz. ED	21
½ oz. ED	23
½ oz. Hi-Perf.	23
½ oz. ED	26
1 oz. ED	41
2 oz. ED	42

Table 1: Roughness R_{rms} values for the foils used in this study expressed in microinches (μin). Foil samples from 6 different suppliers were tested. Abbreviations are as follows: RA = Rolled Annealed; RTF = Reverse Treat Foil; ED = Electrodeposited; Hi-Perf = High Performance; DSTF = Drum Side Treated foil; VLP = Very Low Profile.

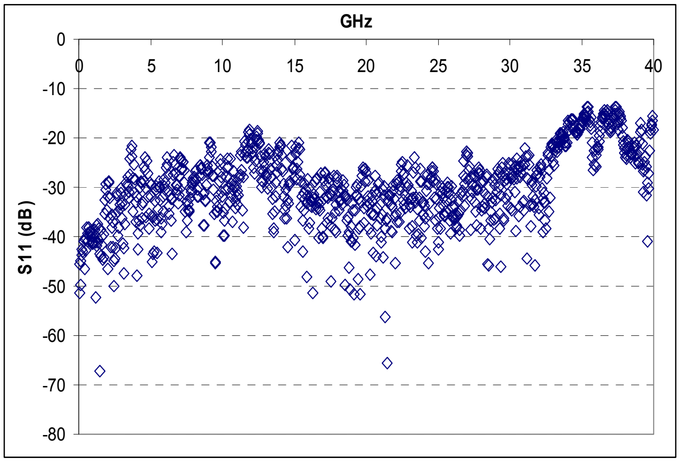

Figure 3: Typical S11 response of the microstrips tested in this study.

Similarly, microstrip attenuation was measured for test laminates at 28 mils thick using various coppers. Fig. 5 shows these results.

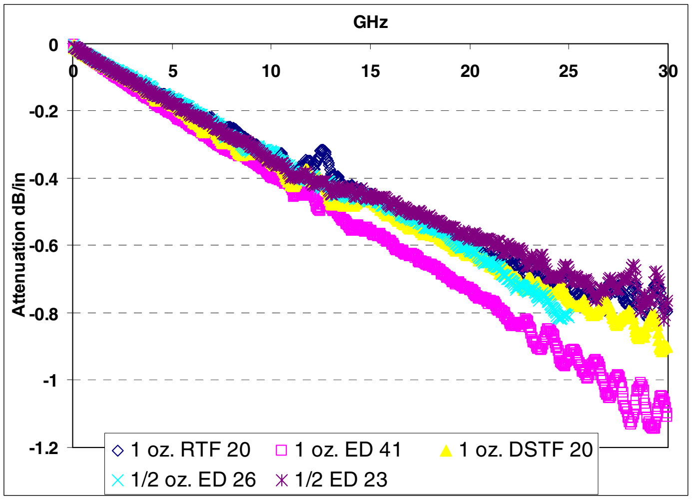

Figure 4: Attenuation S21 of 50 Ω microstrips on 16 mil test laminates with various copper types. The numbers in the legend correspond to R_{rms} values. Also see Table 1.

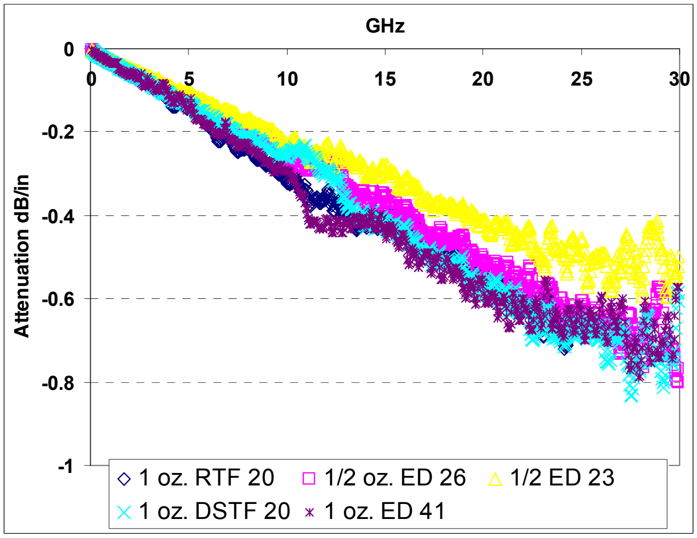

Figure 5: Attenuation S21 of 50 Ω microstrips on 28 mil test laminates with various copper types. The numbers in the legend correspond to R_{rms} values. Also see Table 1.

The copper types analyzed in Table 1, were also tested in the Bereskin setup. Each copper type was substituted in the fixture using the same laminate sample. This test method is suited for measuring the Quality factor (Q) of the system for each resulting stripline circuit. In the Bereskin test, Quality factor equates to the difference in frequency of the ½ power points around resonance, divided by the resonant frequency in GHz. Results for Q vs. frequency and R_{rms} are shown in Fig. 6.

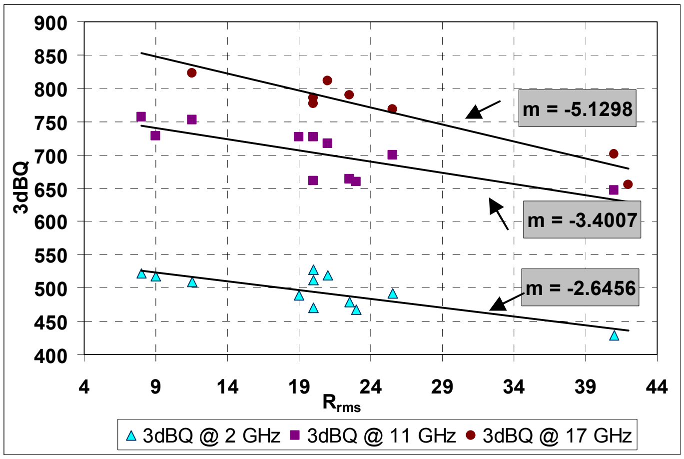

Figure 6: Quality factor Q at 3 dB from resonant frequency for laminate/conductor combinations using the Bereskin test method. The value m represents the slope of each line respectively.

IV. CONCLUSION

These data illustrate the influence of conductor roughness over loss in both microstrip and stripline configurations. The dielectric in each test was kept constant, providing an adequate control for evaluating conductor losses in each case.

By way of a contact stylus technique, a diversity of copper types and vendors were evaluated for this study. Other studies have utilized a non-contact method which can provide different values. In our case the contact method is shown to provide relative results for R_{rms}. Each of these foil types were tested in the Bereskin test for transmission loss. For the microstrip experiments, only a subset of the coppers in table 1 was tested.

Figs. 4 and 5 show the attenuation of test laminates using different coppers at both 16 and 28 mils thickness. In fig. 4 a significant delta is seen between R_{rms} values around 20 and 40 μin. The difference in attenuation is shown to increase with frequency. At 30 GHz the difference in attenuation is approximately 0.3 dB/inch between R_{rms} values of 23 and 41 μin. The three types in the 20 μin range are all grouped, showing little difference. The best material combination here uses ½ oz. ED foil at 23 μin R_{rms}, showing a slight advantage over the RTF and DSTF types. This suggests that conductor properties other than roughness alone also contribute to loss. These may include grain structure, treatment chemistry or other variables in foil manufacturing.

The attenuation 28 mil microstrips shows a different behavior. Here the trend over frequency with R_{rms} is also present; however the difference is less drastic. In these samples, the copper types rank in the same order as those in fig. 4. The larger dielectric thickness yields a lower attenuation for all copper types. This result is expected from equation 1. Conceptually this effect can be described as a more complete distribution of the field lines through the dielectric. The larger spacing between the trace and ground plane allows a better field distribution which leads to an averaging of conductor roughness effect.

In a stripline configuration, R_{rms} is shown to influence attenuation in a similar way, see fig. 6. Here the effect is quantified as a lowering of Q as R_{rms} increases. As was the case in microstrip attenuation, conductor loss is shown to increase with frequency. The change in Q vs. R_{rms} roughly doubles from 2 GHz to 17 GHz, as shown by the slope values of the trend lines in fig. 6.

This analysis highlights the advantages of using low profile conductors in microwave PCB applications. The techniques used prove to be convenient for this analysis. In both microstrip and stripline structures, copper type is shown to dramatically influence the attenuation of transmitted microwave signals. Being more dramatic on thinner dielectrics this effect poses difficult design challenges for thin core/multilayer microwave architectures. Emerging high Speed digital applications are also subject to these conductor influences. Also as operating frequencies move to higher bandwidths, the choice of conductor types becomes a primary concern. To meet these requirements, the laminates industry must design materials which optimize both the dielectric and conductor losses while maintaining a mechanically reliable substrate.

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