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Calculation of the Differential Impedance of Tracks on FR4 Substrates

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Abstract
There is a discrepancy between calculated and measured values of impedance for differential transmission lines on FR4. This is especially noticeable in the case of surface microstrip configurations. The anomaly is shown to be due to the nature of the substrate material. This needs to be considered as a layered structure of epoxy resin and glass fibre. Calculations, using Boundary Element field methods, show that the distribution of the electric field within this layered structure determines the apparent dielectric constant and therefore affects the impedance. Thus FR4 cannot be considered to be uniform dielectric when calculating differential impedance.

Introduction
In a previous paper[1], the authors described an accurate and economical method for the calculation of the controlled impedance of PCB tracks. This method was adapted for the calculation of the impedance of single track and differential tracks in stripline, surface microstrip, and embedded microstrip configurations[2]. To test the accuracy of the software, several panels, each containing test coupons for 27 differential tracks on FR4 substrates, were manufactured. There were three different track widths at three different track spacings. Each width was repeated three times. Panels were made for stripline, surface microstrip and embedded microstrip. The differential impedance of each track was measured and the tracks sectioned and their cross-sectional dimensions determined. The impedance was calculated using these dimensions and compared with the measured values. As reported previously[1], good correlation between the calculated and measured differential impedances of stripline and embedded microstrip, was obtained using a dielectric constant of 4.2. However to obtain reasonable correlation between calculated and measured impedance for the surface microstrip examples, a dielectric constant of 4.8 was required. Figure 1 shows an error graph for the calculated and differential impedance of a typical surface microstrip panel (panel 19).

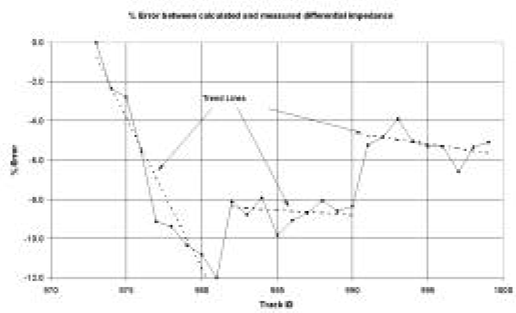

Figure 1 - Error Between Calculated and Measured Differential Impedance for Surface Microstrip Samples

The calculated impedance is used as reference in this figure and all other similar figures. The points are for each track, represented by an ID number. On close examination, the error falls into three distinct trends, one for each track width. For each width the magnitude of the error increases with increasing track separation. These trends are shown in Figure 1. Other surface microstrip panels exhibit the same trend. These trends are thus real and not due to random manufacturing variations. A mechanism to explain these variations is described below.

The panels containing stripline and embedded microstrip tracks also show some of these trend lines, particularly for the narrower tracks. However the trends are not so great as those for surface microstrip.

FR4 Substrate
These substrates are manufactured from several basic unit layers as shown in Figure 2.

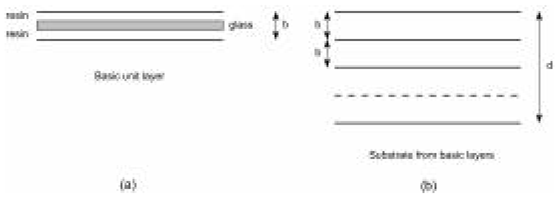

Figure 2 - Basic Substrate Construction

For our purposes the woven fibre glass can be considered to be a solid layer of glass of uniform thickness, surrounded by epoxy resin. The number of basic units depends on the thickness of the substrate. Figure 3 shows schematically the paths of the electric field for single-ended tracks and differential tracks. For single-ended tracks, Figure 3a, the field lines are approximately perpendicular to the layers. For differential tracks the field lines are approximately parallel to the layers, Figures 3b and 3c. Figure 3c shows that as the track separation increases, the electric field penetrates more layers. This variable penetration means that the average dielectric constant is variable.

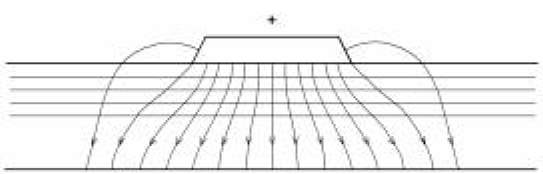

Figure 3a - Single Track: Essentially Parallel Fibre Layers

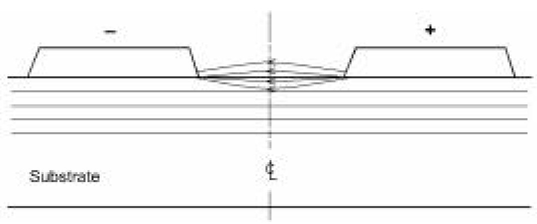

Figure 3b - Close Spacing: Field Largely Just Above and Just Below the Surface (Lower e_R)

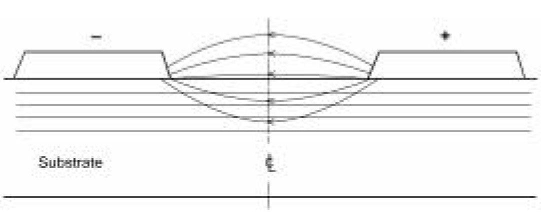

Figure 3c - Moderate Spacing: Field Now in Several Layers

Figure 4 shows the layer arrangement between two capacitor plates, which can be used to estimate the average dielectric constant.

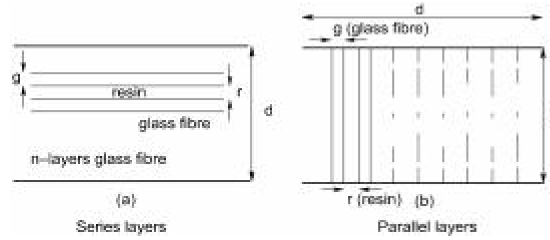

Figure 4 - Layer Arrangement to Determine Average Dielectric Constant

Figure 4a represents the single-ended case and Figure 4b represents the differential case. For the series layers shown in Figure 4a, the average dielectric constant is

$$e_g = \frac{e_{res} e_g}{e_g - \frac{ng}{d}\left(e_g - e_{res}\right)} \quad (1)$$

For the parallel layers shown in Figure 4b, the average dielectric constant is

$$e_p = e_{res} + \frac{ng}{d}\left(e_g - e_{res}\right) \quad (2)$$

In both cases the volumetric fraction of epoxy resin is:

$$f_r = \frac{d - ng}{d} \quad (3)$$

In these equations, ε_g and ε_{res} are the dielectric constants of glass fibre and epoxy resin respectively.

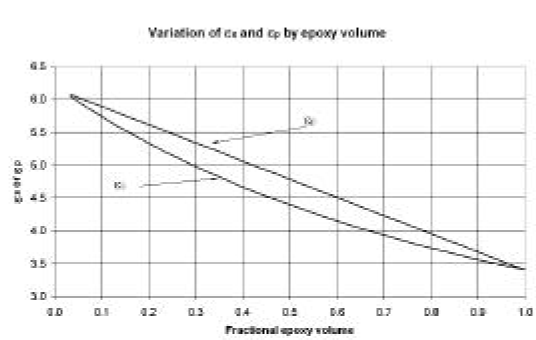

Figure 5 - Variation of e_S and e_P by Epoxy Volume

Figure 5 shows the variation of ε_s and ε_p for different volumetric fractions of epoxy, when ε_g = 6.11 and ε_{res} = 3.40. The curve of ε_s is similar to that given by Wadell[3]. For a given volumetric fraction of epoxy, the values of ε_p are greater than those for ε_s. For a fraction of 0.6, ε_s is 4.2, and ε_p is 4.5. That is an increase of about 7%. In Figure 1, ε_s was used in the calculation. If ε_p had been used in the calculation the magnitude of the error would be less. However, using ε_p would not explain the trend curves of Figure 1.

Differential Tracks: Field Distribution

Figures 3b and 3c show schematically, that the electric field between the tracks spreads out unevenly in the glass and epoxy layers as the track separation increases. To examine the field distribution in more detail, the electric field on the centre line of the representative tracks shown in Figure 6 and Table 1, was calculated using a boundary element method (BEM)[4]. The dielectric constant of the substrate was 4.2 and assumed to be uniform. Figure 7 shows the E-field distribution. A normalised position of 0.0 is the ground plane, and 1.0 is the substrate surface. All the electric field values have been normalised so that the maximum for each track is 1.0. In all cases, the peak of the field is in the air just above the surface.

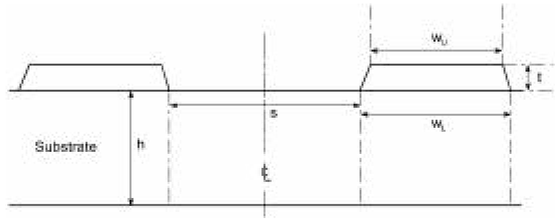

Figure 6 - Illustrating Surface Microstrip Parameters

Table 1 - The Field Distribution

Track ID	Separation s, μm	Differential Impedance, Ω	Lower Track Width w_L, μm	Upper Track Width w_u, μm
975 977 980	132 258 372	130.95 163.83 183.98	118	90
982 986 989	190 376 740	133.27 165.79 201.97	184	152
992 995 998	256 500 1000	136.18 167.52 202.72	244	216

Note: Substrate height, h, 1450 μm
Track thickness, t, 48 μm

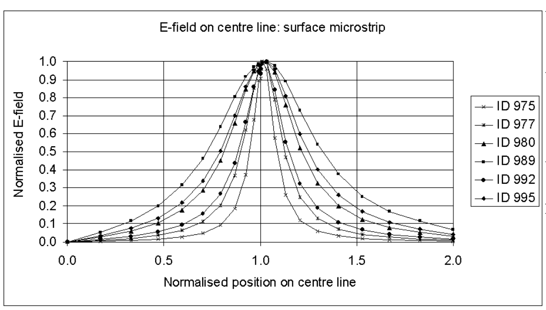

Figure 7 - Electric Field Distribution Across Centre Line Between Two Differential Microstrip Tracks

Referring to tracks 975, 977, and 980, Figure 7 shows that as the track separation increases, the spread of the E-field increases. The other curves show that the spread with separation, is slightly greater for wider tracks. For the substrate used, the normalised width of a glass fibre layer is 0.08. This distance is shown in Figure 8. For the narrower track separations, this glass width is similar to the width of the E-field distribution. So the actual position of the glass fibre relative to the substrate surface is expected to have a major effect on the field distribution and hence the value of impedance.

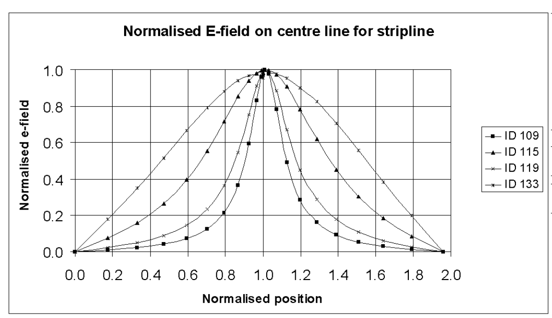

Figure 8 - E-Field Distribution on Centre Line for Differential Stripline Tracks

Figure 8 shows the electric field distribution of some stripline differential tracks. As the separation between the tracks increases so does the width of the distribution of the field on the centre line. In fact, at the widest separation (ID 133) the spread is so wide that it suggests that some of the electric field from a track terminates on the ground plane. This means that the layer structure of the substrate will be less of a problem. Since some of the electric field lines will now cross the layers as suggested in Figure 3a; this might explain the reasonable agreement between the measured and calculated impedances[1] for stripline.

Differential Impedance with Layers

In order to assess the effect of alternating layers of epoxy and glass, the BEM was used to estimate the differential impedance of surface microstrip. Figure 9 shows the general arrangement.

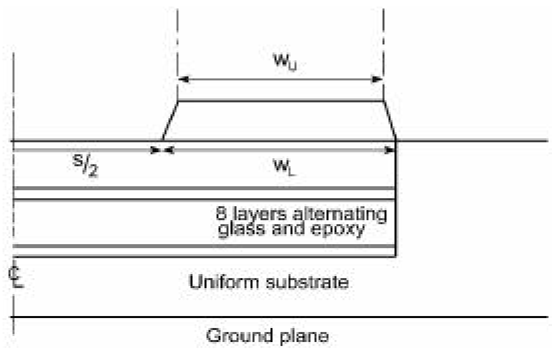

Figure 9a - Showing the Layer Structure for Calculation

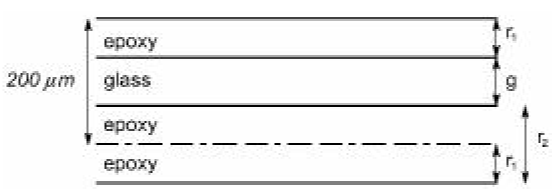

Figure 9b - Details of Layer Dimensions

To limit the size and length of the calculation, only 8 layers, either epoxy or glass, were used within the substrate as shown. This is equivalent to 4 basic FR4 unit layers. The individual layers only extend to the far end of the track. The dielectric constant of each epoxy or glass layer was used respectively. The rest of the substrate was assumed to be uniform with a dielectric constant of 4.2. Figure 10 shows, for a few representative tracks, the errors compared to the impedance calculated assuming a uniform substrate with a dielectric constant of 4.2. Figure 10 also shows the practical results for the same tracks.

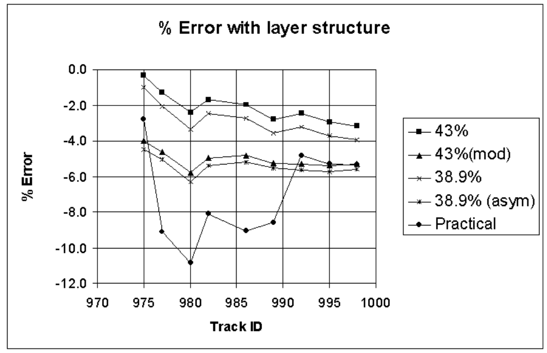

Figure 10 - Effects of Layer Structure on Differential Impedance of Surface Microstrip

A basic FR4 unit layer, code 7628, has a thickness of 200µm and a resin content of 38.9%. This means that in Figure 9b, g = 122µm. When the glass is in the centre then r_1 = 39µm and r_2 = 78µm. These values give the curve labelled 38.9%. If the glass is nearer the air surface an asymmetric layer is obtained. The curve labelled 38.9%(asym) has r_1 = 20µm. The other dimensions remain unaltered. The curve labelled 43% has g = 114µm, r_1 = 43µm, and r_2 = 86µm. The curve labelled 43%(mod) has r_1 = 0, so that the glass fibre is on the air interface.

In Figure 10, all the curves exhibit the trend referred to in section 1. This shows that the layer structure does modify the value of the differential impedance from that calculated assuming a uniform substrate. As the track separation increases, the spread of the electric field between the tracks increases, so that the field now passes through more layers of epoxy or glass. When the glass fibre is offset from the centre of the basic FR4 unit layer, there is approximately a 4% increase in the magnitude of the error. This offset could happen in the manufacture of a substrate from several basic units.

In the calculation each basic layer was identically affected. In practice each unit layer in the substrate may be different. This manufacturing variability might explain why the practical results differ from those calculated using a modified layer structure.

These calculations show that the layer structure and its variability, can be an important factor in determining the value of the differential impedance particularly for surface microstrip differential tracks. As a compromise, at least for surface microstrip configurations, the value of the dielectric constant can be increased by approximately 14% in differential impedance calculators[2] to average the effect of the layers.

Conclusions

It has been shown that the glass-fibre/epoxy-resin layer structure can have an important influence on the value of differential impedance particularly for surface microstrip tracks. This influence depends on both the track width and track separation, and the actual layer arrangement between the epoxy resin and glass fibre. To compensate for the layer effects, it is recommend that a larger value for the average dielectric constant, particularly for surface microstrip, is used in differential impedance calculators.

References

1. Burkhardt, Andrew J., Gregg, Christopher S., Staniforth, J. Alan – Calculation of PCB Track Impedance.
2. Proceedings of the Technical Conference IPC Expo '99, Long Beach, Mar 14-18, 1999, pages S19-5-1 to S19-5-6.
3. CITS25 – Differential Controlled Impedance Calculator.
4. Polar Instruments Ltd. http://www.polar.co.uk
5. Wadell, Brian C. – Transmission Line Design Handbook, Artech House 1991, p438
6. Brebbia, C. A. – The Boundary Element Method for Engineers, Pentech Press 1978.