Detailed Analysis of Impedance and Loss versus Frequency for Transmission Lines Made From Flexible Circuit Materials

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Abstract:
With the emergence of high speed, controlled impedance circuits requiring increasingly tight tolerances, there is a realization among designers and fabricators that more precise data is needed than the normal "data sheet" information given by materials companies. To meet this need, an extensive study has been conducted over the past year to closely evaluate flexible circuits in "real world" transmission line structures. The outputs of this study are clearly understood impedance and loss data that can be used as a basis for designs and fabricated structures.

The following structures will be evaluated:

-Microstrip Lines
-Covered Microstrip Lines
-Microstrip Lines with ENIG Finish

The following materials will be evaluated:

-Standard FR4 (100 um thick), Mid-Grade Glass Reinforced Epoxy (100 um and 50 um thick) and Low Loss Rigid Glass Reinforced Epoxy (100 um and 56 um thick)
-Adhesiveless Polyimide (50 um and 100 um thick)
-Fluoropolymer/Polyimide Composite (50 um, 75 um and 100 um thick)

Loss will be evaluated in terms of loss per unit length versus frequency at frequencies between 0.2 GHz to 25 GHz for long lengths. Impedance is measured utilizing typical TDR systems used by fabricators and compared to commercially available impedance calculation systems.

Motivation:
There have been significant efforts in recent years to better understand the electrical performance of flexible circuit materials. [1,2,3] This work has been driven by emerging needs of OEM's to have more demanding performance requirements for controlled impedance circuits. Many of these applications include flexible circuits, but there has been little analysis done on flexible circuit materials in high speed applications.

Loss tangent of flex materials is a misunderstood parameter. All polyimide (or "adhesiveless") flex clad has much lower dielectric loss than traditional adhesive based flex, but many designers and fabricators attribute higher loss values than actual to flex materials due to misunderstanding or lack of easily accessible data. In addition, there are new offerings of polyimide based materials that utilize a combination of fluoropolymer and polyimide to minimize both dielectric constant and loss tangent. Since these materials are new offerings, the amount of data available on them is limited. There is need to do further analysis to obtain a more complete understanding of electrical performance of flex materials, with special interest on new offerings.

Simple analysis of dielectric constant and loss tangent are insufficient to fully characterize interconnects. All "real life" circuits consist of both dielectric and conductor; hence they must be characterized together. It is also necessary to consider frequencies beyond 10 GHz. Companies involved in high speed system design have invested significant resources in better understanding these effects. [4]

Experimental Design:
The introduction of copper into the test matrix makes the analysis much more complex. The interactions between the conductor and the dielectric for thin clads is much more complex than one would intuitively expect from common experience with thick, rigid board design. Calculated models for loss do a pretty good job predicting behavior up to about 5-10 GHz. Beyond that, the models tend not to provide useful results for thin dielectrics. Designers typically turn to 3D simulation tools for analysis to understand behavior that empirical or closed-form equation-based models do not correctly capture. There is a significant trade-off between low loss performance and copper adhesion when considering properties of low-profile copper.

The principle of all the data collection and analysis in this work was to take an “apples to apples” approach. That is, test vehicles were made using the same artwork. Comparisons were made with like copper thickness, dielectric thickness and line widths. The same reusable connectors were used for all tests and all instrument measurements were conducted under the same calibration conditions.

We explored three figures of merit:

1. Impedance Performance – Is the permittivity what we think it is?
2. Loss Per Unit Length– Does the material show in a circuit the low loss performance we think it does? (Due to its low copper profile and low loss tangent.)
3. Can we see differences in the way it transmits digital signals?

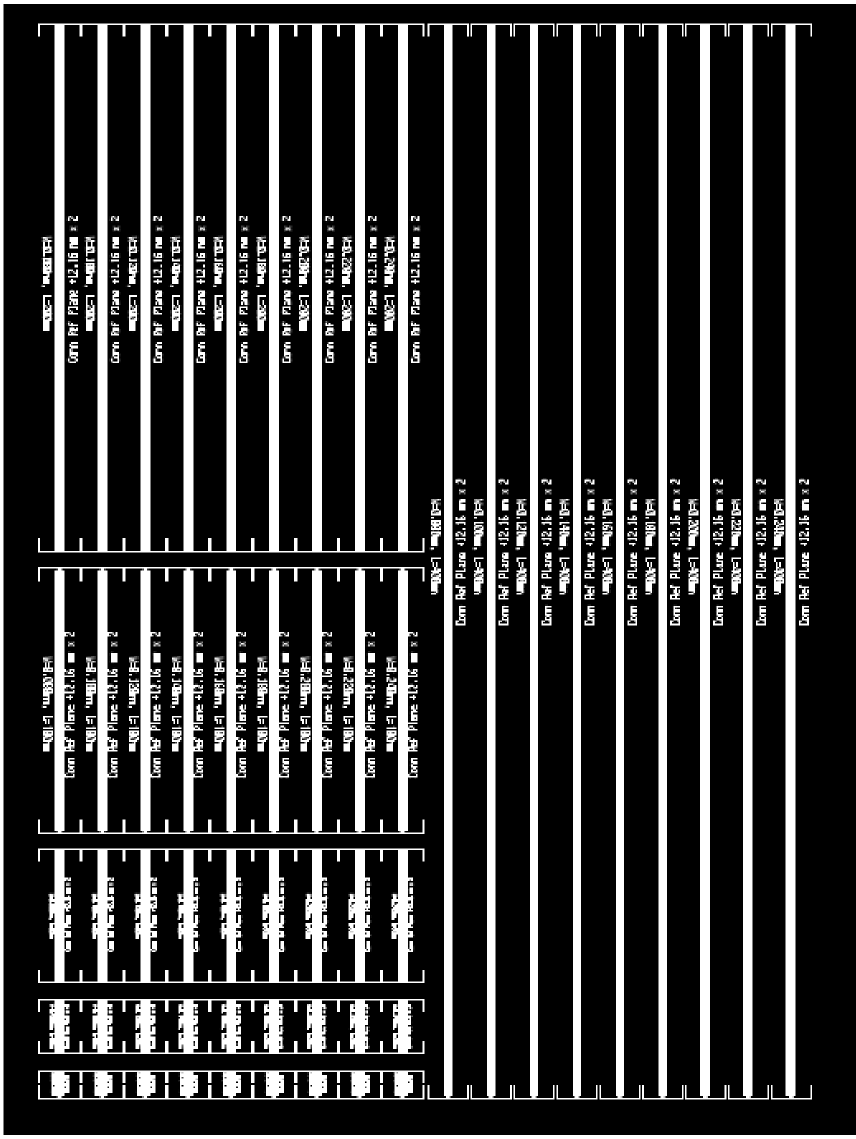
All samples were terminated with Southwest Microwave End-Lauched SMA connectors (Part Number 292-07A-5) that are valid up to 27 GHz.[5] Impedance performance is measured on a standard TDR commonly used by fabricators, Polar CITS system.[6] These were connected to the TDR using calibrated test cables and data is translated to time-base instead of length since the samples have different dielectric constants (hence different propagation speeds). Measurements were only performed on lines that had lengths of 100 mm or greater due to the resolution limits of the TDR.

Loss as a function of frequency is measured by the same connectors on line lengths of 20 mm, 50 mm, 100 mm, 200 mm and 400 mm for at least 5 different line widths. Then S-Parameters of each measured using a Vector Network Analyzer. Mismatch losses due to impedance differences are subtracted and the loss per unit length is determined. This is done by measuring several lengths, normalizing all loss measurements to these lengths and expressing the average of all of these measurements in dB/length.

Digital signal performance is determined using a Bit Error Rate tester with a Pseudo-Random Bit Stream. Lines with similar impedance are compared to each other and evaluated by how well the bits are transmitted through the data link. This analysis was performed on samples close to 50 ohms for only the 200 mm length lines.

Microstrip Test Structures:

The basic principle used to develop the test coupon was to make the signal lines representative of what is found in transmission line structures and allow for “apples to apples” comparison between different materials. The fundamental test coupon is illustrated in Figure 1. Shown is just the top layer. The bottom layer is solid copper ground plane with coverlay coating everything except ground openings for connector access.



18”x12” Panel
-Print and Etch
-No plated finish
(just bare copper)
for fundamental
comparison:
Black = Copper;
White = Etched

Five Line Lengths
400 mm, 200 mm,
100 mm, 50 mm,
20 mm

Nine Designed Line
Widths (Wart):
240 um, 220 um,
200 um, 180 um,
160 um, 140 um,
120 um, 100um,
80 um

NOTE: These are
ARTWORK widths, not
the actual fabricated
widths.

Figure 1 – Test Pattern Artwork

Microstrip Sample Identification:

A total of ten clads were manufactured for the basic microstrip test. All of the clad samples had 0.5 oz copper. The samples are identified as follows:

FR4-100	Standard FR4 material, Standard Profile ED Cu, 100 um thick dielectric
M4-100	Mid-Range Glass Reinforced Epoxy, RTF Profile ED Copper, 100 um thick dielectric
M4-50	Mid-Range Glass Reinforced Epoxy, RTF Profile ED Copper, 50 um thick dielectric
M6-100	Low Loss Glass Reinforced Epoxy, Ultra Low Profile ED Copper, 100 um thick dielectric
M6-50	Low Loss Glass Reinforced Epoxy, Ultra Low Profile ED Copper, 50 um thick dielectric
AP-100	Adhesiveless polyimide, Ultra Low Profile RA Copper, 100 um thick dielectric
AP-50	Adhesiveless polyimide, Low Profile RA Copper, 50 um thick dielectric
TK-100	Fluoropolymer/Polyimide Composite, Ultra Low Profile RA Copper, 100 um thick dielectric
TK-75	Fluoropolymer/Polyimide Composite, Ultra Low Profile RA Copper, 75 um thick dielectric
TK-50	Fluoropolymer/Polyimide Composite, Ultra Low Profile RA Copper, 50 um thick dielectric

Physical Analysis of Microstrip Samples:

A coupon was made for each line width on each test structure to analyze the physical dimensions of the etched lines. Cross section photos of the nominal line (W160) for each coupon are shown in Figure 2 (A-J). Table 1 details the cross section measurements for each microstrip line measured.

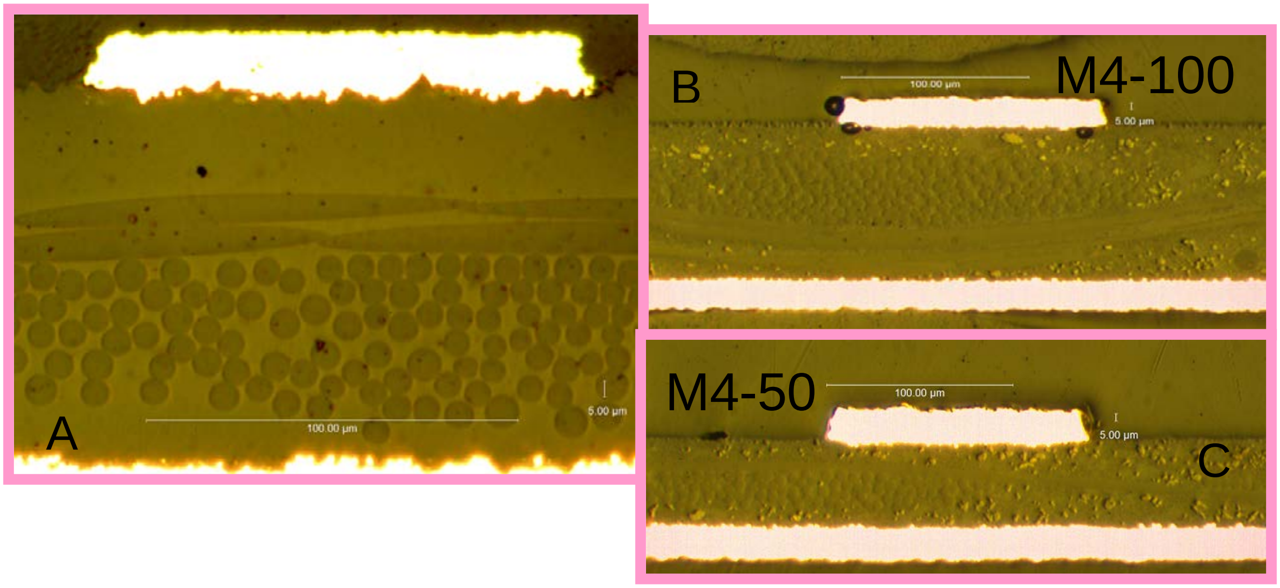
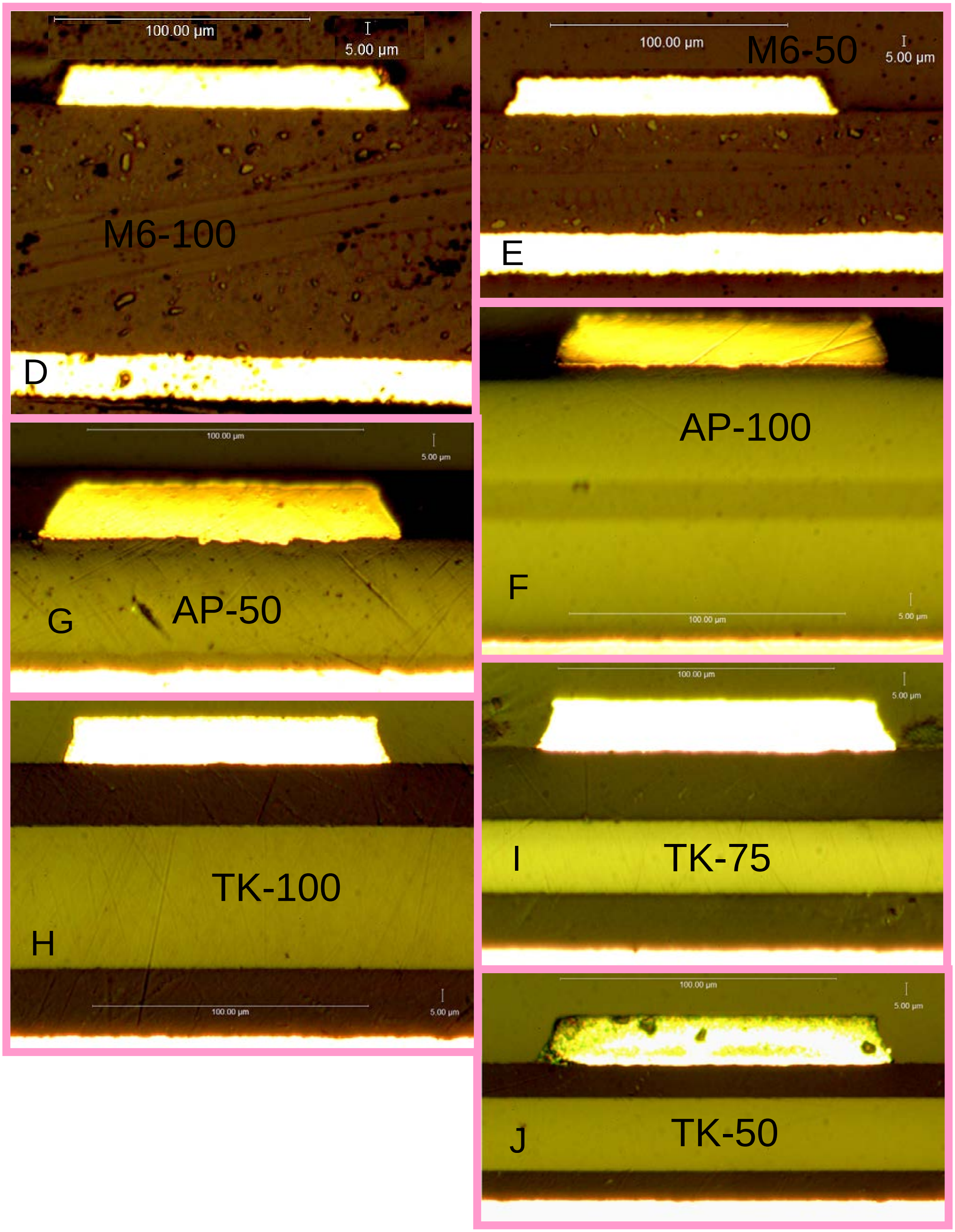


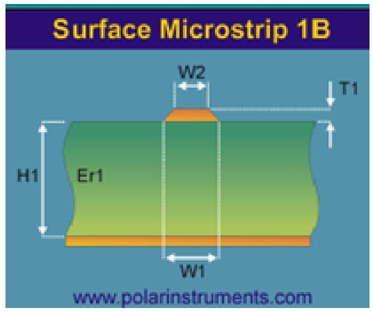
Figure 2 – Example Cross Sections of Each Line Sample (A-C)



100.00 µm
5.00 µm
M6-100
D
100.00 µm
M6-50
5.00 µm
E
AP-100
F
100.00 µm
5.00 µm
100.00 µm
5.00 µm
G
AP-50
100.00 µm
5.00 µm
I
TK-75
TK-100
H
100.00 µm
5.00 µm
100.00 µm
5.00 µm
J
TK-50

Table 1 – Physical Dimensions of Microstrip Lines Evaluated

Rigid Clads (dimensions in um)					
Clad	Wart	H1	T1	W1	W2
FR4-100	140	100	17	122	110
	180	102	16	166	155
	200	103	16	180	172
	220	101	17	210	199
	240	100	16	223	211
M4-100	160	97	18	144	133
	180	98	17	164	152
	200	96	17	190	180
	220	95	18	204	191
	240	98	17	227	209
M4-50	80	47	17	65	54
	100	46	18	84	77
	120	46	18	108	93
	140	45	18	126	113
	160	46	18	142	130
M6-100	160	48	18	127	113
	180	50	18	149	137
	200	48	19	165	152
	220	49	18	195	182
	240	47	18	212	201
M6-50	80	50	17	59	46
	100	50	17	75	63
	120	50	18	101	86
	140	50	17	116	102
	160	52	17	140	122



Note

Wart is the line width defined on the artwork. At least five different line widths times five line lengths were tested for each clad. One cross section measurement was made for each line width on each clad.

Flexible Clads (dimensions in um)					
Clad	Wart	H1	T1	W1	W2
AP-100	160	99	16	110	91
	180	99	16	144	124
	200	100	17	168	151
	220	99	16	189	173
	240	99	18	205	189
AP-50	160	48	18	115	91
	180	47	19	151	129
	200	47	19	167	146
	220	48	17	197	183
	240	48	18	217	197
TK-100	160	96	18	110	99
	180	98	18	148	136
	200	99	17	172	162
	220	100	18	191	177
	240	99	18	209	195
TK-75	160	71	18	113	99
	180	73	19	169	150
	200	70	21	172	159
	220	72	19	195	186
	240	70	18	215	204
TK-50	160	49	18	115	100
	180	50	18	149	137
	200	48	19	165	152
	220	49	18	195	182
	240	47	18	212	201

Impedance and Propagation Time Data Analysis:

Each line 100 mm or longer was measured with a TDR using connectors (not probes). Each line was tested from both directions and the impedance versus time was saved as a waveform. Instead of using the default setting for time-base assuming FR4 (DK=4.2), the output waveform was converted into propagation time in picoseconds. This is because each clad tested has a different dielectric constant and the propagation speed will not be the same in all the materials.

Since the length of each line is known, propagation speed was measured experimentally by measuring the propagation time (half the round-trip time of the TDR measurement). The termination point (end of the line) was determined by evaluating the 2^{nd} derivative of impedance with respect to time and observing the impedance discontinuity. Once the propagation time was determined; the impedance of each microstrip line was determined by taking the average impedance over the center of the line. That is, the impedance values were averaged between 25% and 75% of the propagation time. Figure 3 provides an example of how impedance and propagation time were determined for each line measurement.

Figure 3 – Examples Showing How Impedance and Propagation Time are Determined

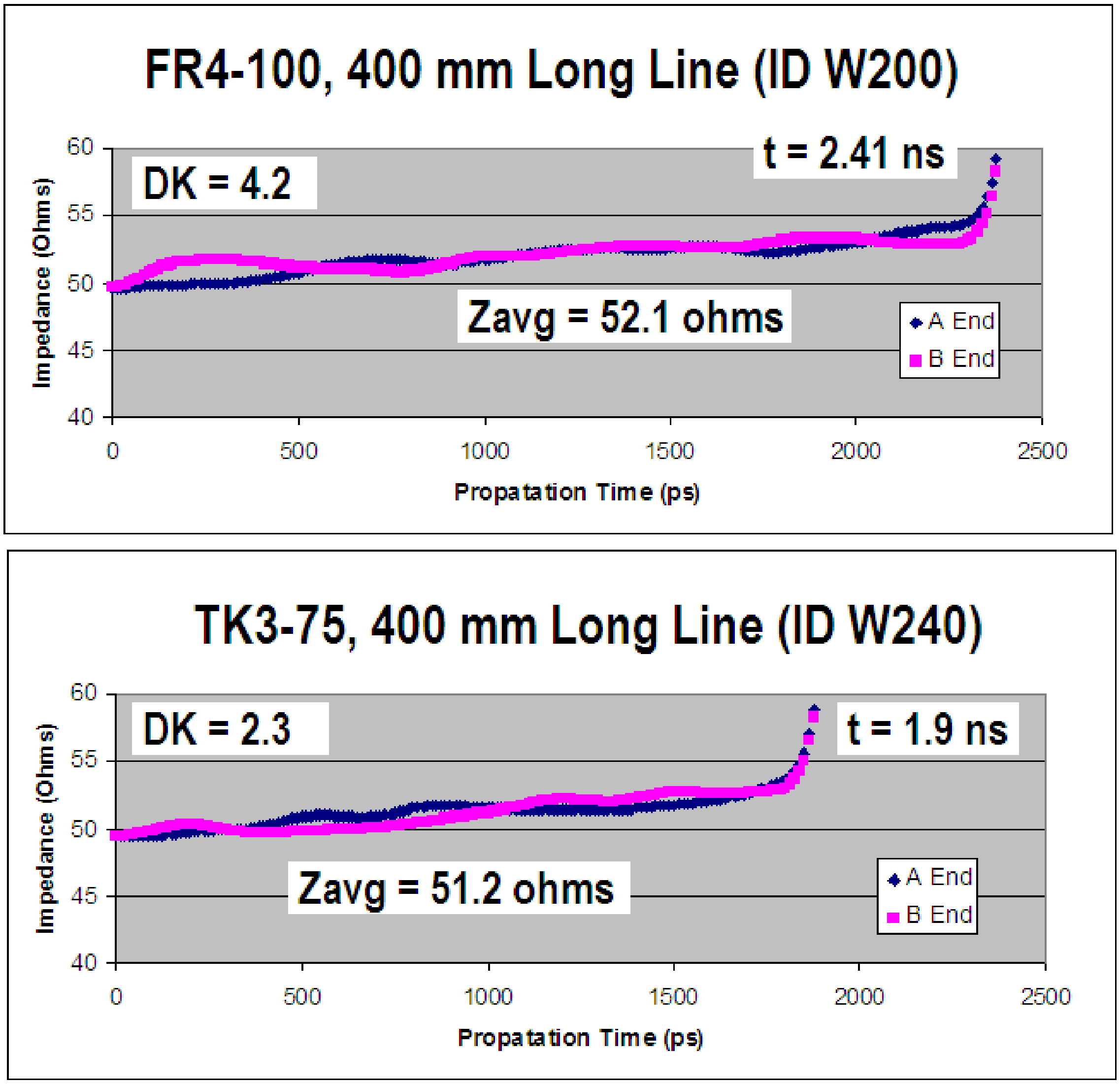


Figure 3 – Examples Showing How Impedance and Propagation Time are Determined

Average propagation speed (Vavg) is determined by dividing the known length of the line by the measured propagation time. The average and standard deviation of this figure of merit are reported. Units for this quantity are expressed in mm/ns simply to represent the speed values as whole numbers. The impedance and propagation speed are shown for each clad in Figure 4. The clads are compared to each other and to values calculated using the Polar Instruments SI-9000 analysis tool. [7] This comparison is summarized in Figure 5. Propagation speed is calculated by taking the calculated time delay from SI-9000 and converting this delay to an equivalent speed by inverting the value. Note, that the values of Dielectric Constant for the various clads are discernable from this analysis. One must assume a slightly higher Dielectric Constant in the propagation speed analysis, but the trends are the same for all the materials. Due to the inherent low resolution of the propagation speed analysis, the values determined from impedance measurements (top half of Figure 5) are considered more accurate and valid.

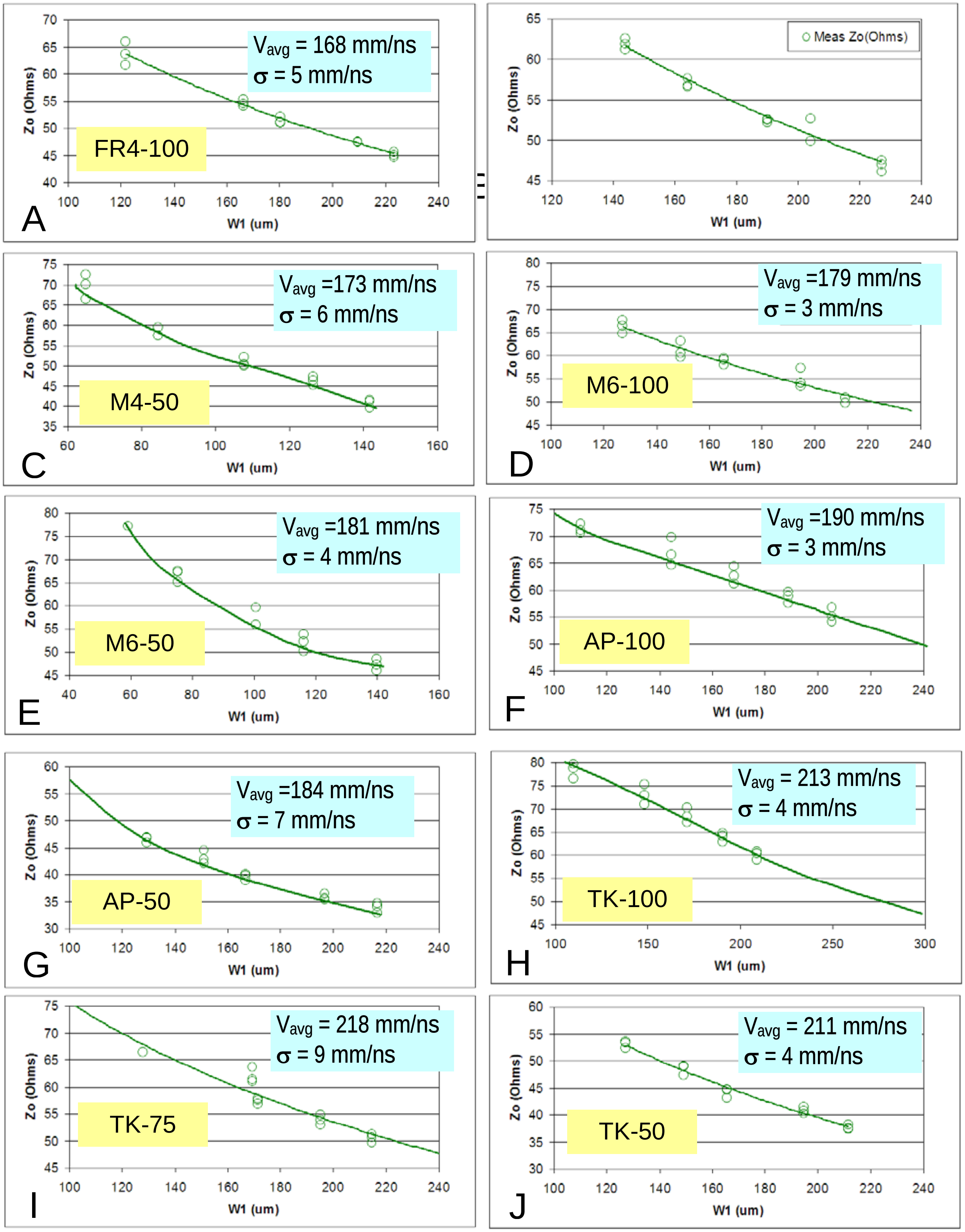


Figure 4 – Propagation Speed and Impedance as a Function of Line Width

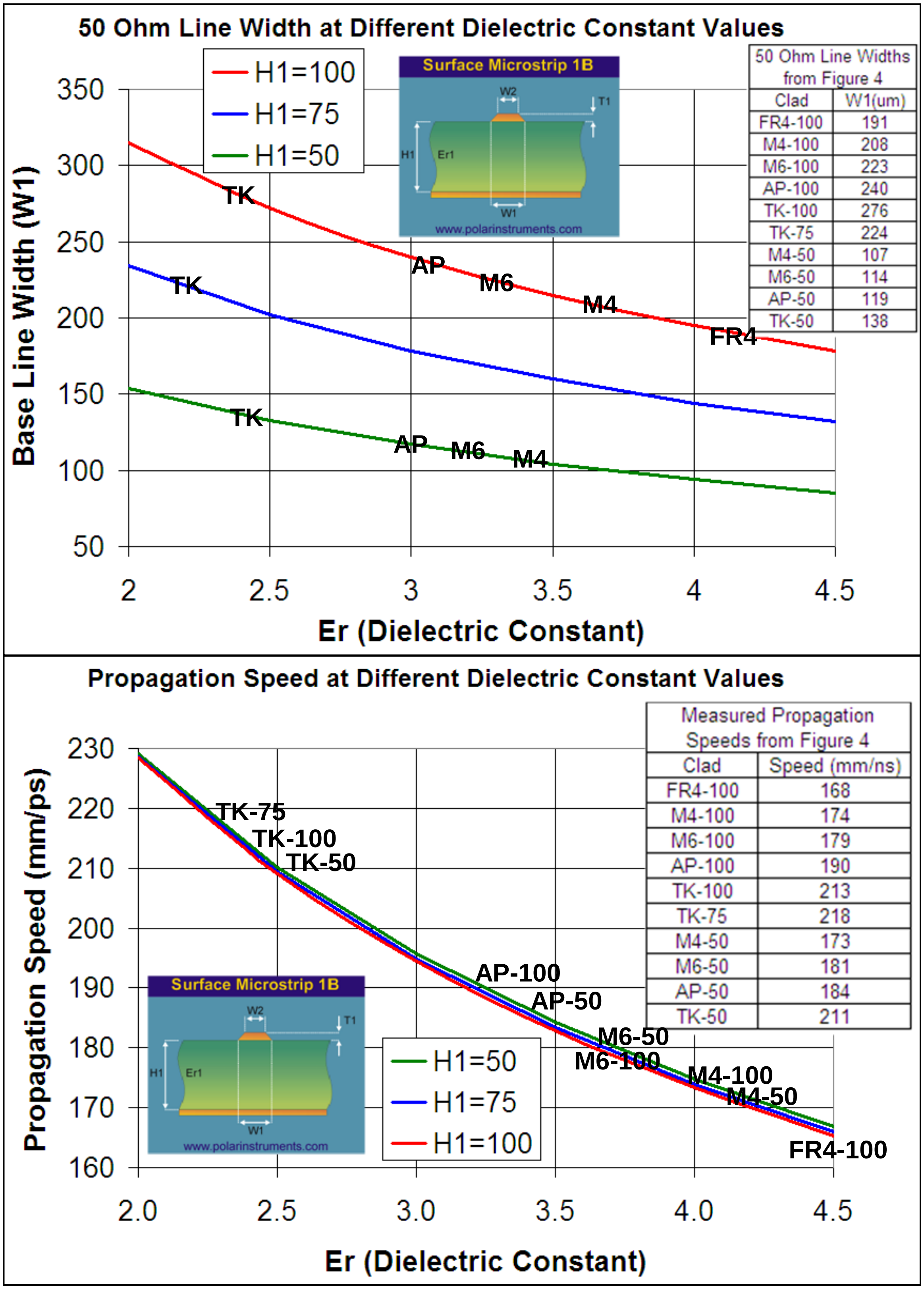


Figure 5 – Measured versus Calculated Line Width (um) and Propagation Speed (mm/ns)

Loss versus Frequency Analysis for All Microstrip Samples:
To compare microstrip loss between clads, a useful figure of merit is loss per unit length. This is determined by measuring S-Parameters and isolating transmission loss by subtracting off mismatch loss. Since the same connectors are used for all measurements, loss attributable only to the microstrip line can be determined by subtracting transmission loss from a longer length from a shorter length. Loss per unit length can simply be determined by dividing the loss difference by the appropriate length difference. Since the connectors are common to both measurements, the effects of the connectors are subtracted out.

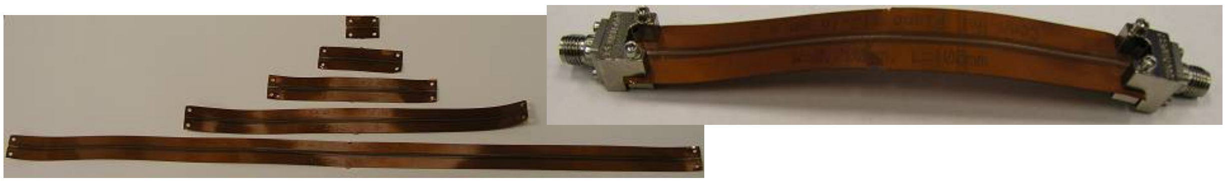


Figure 6 – One Set of Microstrip Lines (5 out of 25), One Enlarged Shown with Connectors

Specifically in this experiment, loss measurements were done with an Anritsu Lightning Vector Network Analyzer swept from 0.2 – 25 GHz. [8] The calibration performed was a standard SOLT calibration using a load and connectors verified up to 27 GHz. As stated previously, all microstrip lines are tested using end-launched connectors. Figure 6 shows one set of five microstrip lines and the connectors used. A total of 25 lines are measured per clad (five line lengths x five line widths).

All of the clads are analyzed in the same way. To illustrate how data is collected and summarized, the complete raw data details of the TK-75 clad are shown. Space allotted in this format does not allow for complete raw data to be shown for all ten clads. Figure 7 summarizes the insertion loss measurements as a function of frequency for each of the 25 microstrip lines. These results are expressed in dB using the same scale for clarity and ease of communication. In general, the forward (S21) and reverse (S12) insertion loss are roughly equivalent. For purposes of this study, insertion loss is defined as the average of the forward and reverse insertion loss for each line. Figure 8 illustrates the mismatch loss of the same sets of lines. This quantity is calculated from averaging the forward (S11) and reverse (S22) return loss and is expressed in dB. The same scale is shown for both insertion loss and mismatch loss for ease of analysis.

Note that the widest line has the lowest mismatch loss. This is consistent with this line being closest to 50 ohms. This is consistent with the observation for the same clad in Figure 4, Plot I which is the analogous case for impedance analysis. For each line, the Mismatch Loss is subtracted from the Insertion Loss to obtain the Transmission Loss used to determine Loss per Unit Length. Figure 9 shows overlay plots of loss per unit length of seven of the line combinations normalized to the same units (dB/cm).

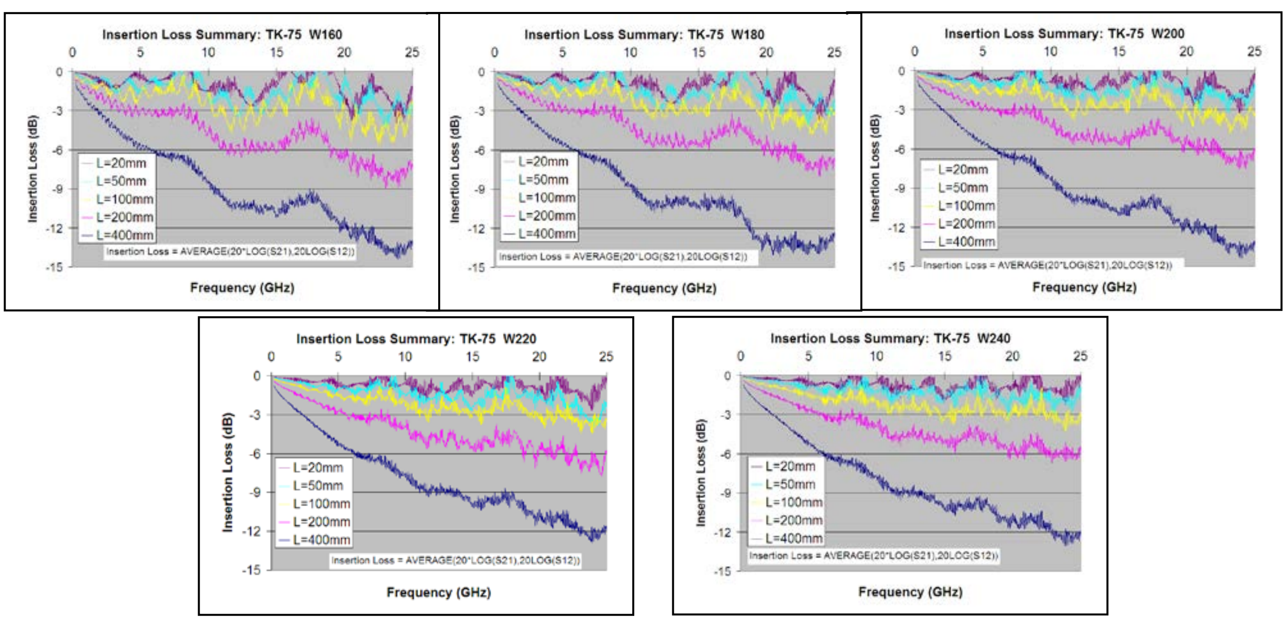


Figure 7 – Raw Insertion Loss Measurements for the 25 TK-75 Lines

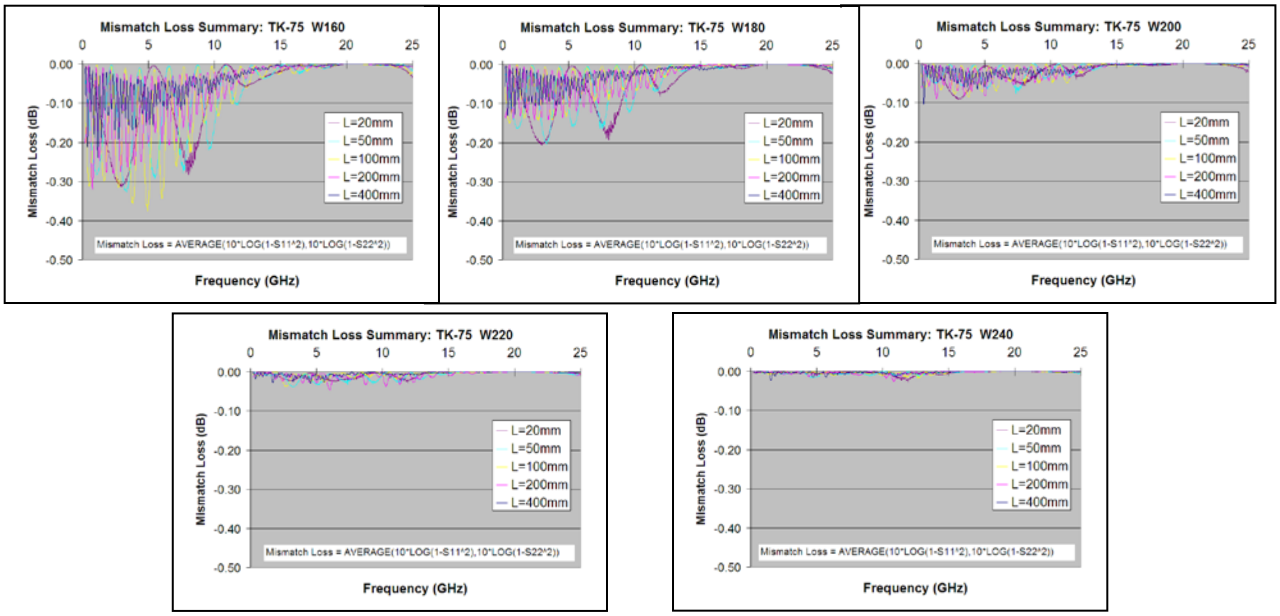


Figure 8 – Raw Mismatch Loss Measurements for the 25 TK-75 Lines

The following seven line combinations were averaged to obtain the summary data to normalize all results to dB/cm:

[Loss (400 mm) – Loss (200 mm)] * (1/20)
[Loss (400 mm) – Loss (100 mm)] * (1/30)
[Loss (200 mm) – Loss (100 mm)] * (1/10)
[Loss (400 mm) – Loss (50 mm)] * (1/35)
[Loss (400 mm) – Loss (20 mm)] * (1/38)
[Loss (200 mm) – Loss (50 mm)] * (1/15)
[Loss (200 mm) – Loss (20 mm)] * (1/18)

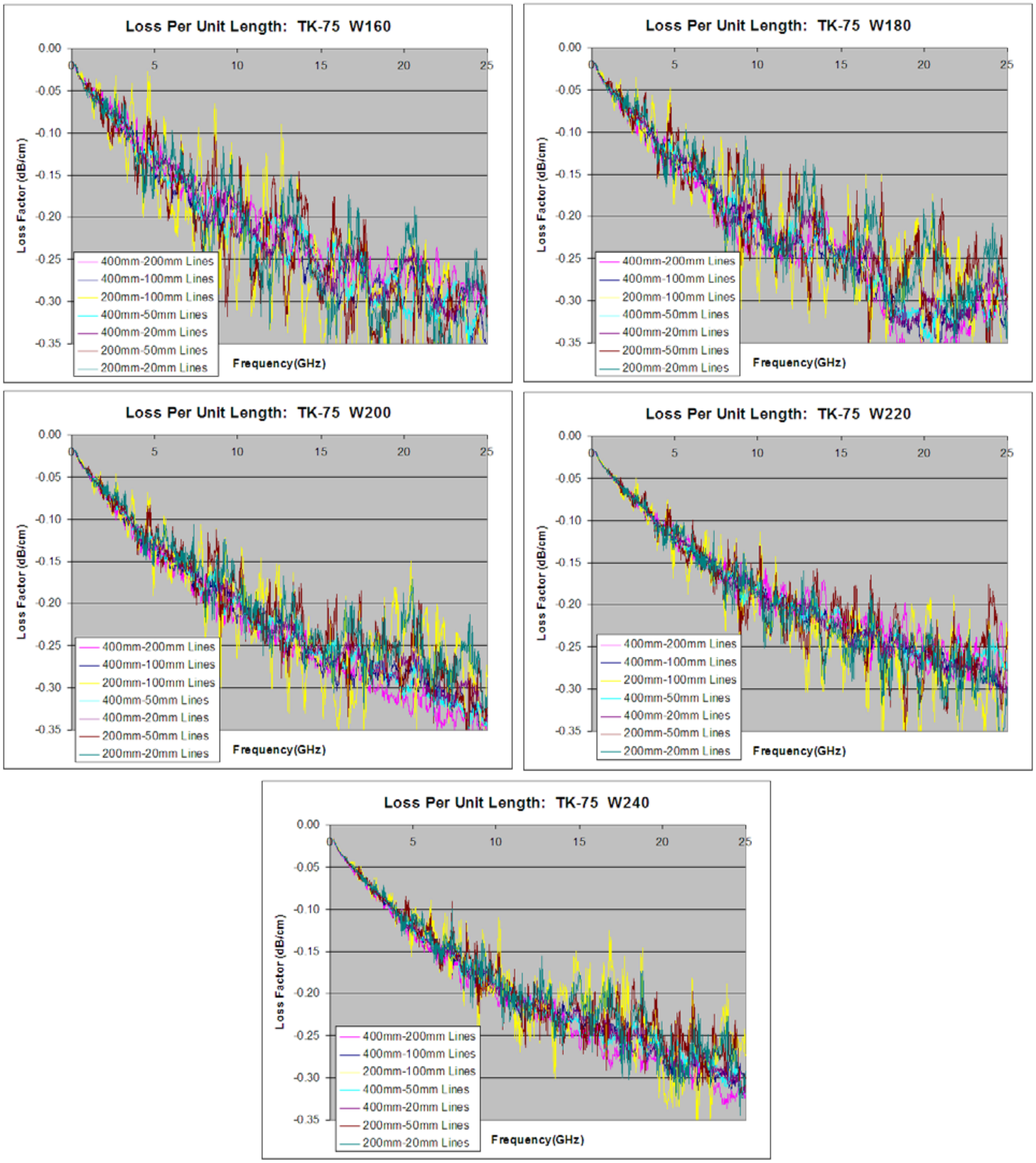


Figure 9 – Loss per Unit Length for the 25 TK-75 Lines

Even though the loss per unit length data is very “noisy” at frequencies above 5 GHz, there is a great deal of consistency to the data. It is useful to average the results to show trends at the higher frequencies. Figure 10 illustrates the average of all the plots shown in Figure 9. In addition, Figure 10 shows that the summary data is coarsened for easier viewing of the trends.

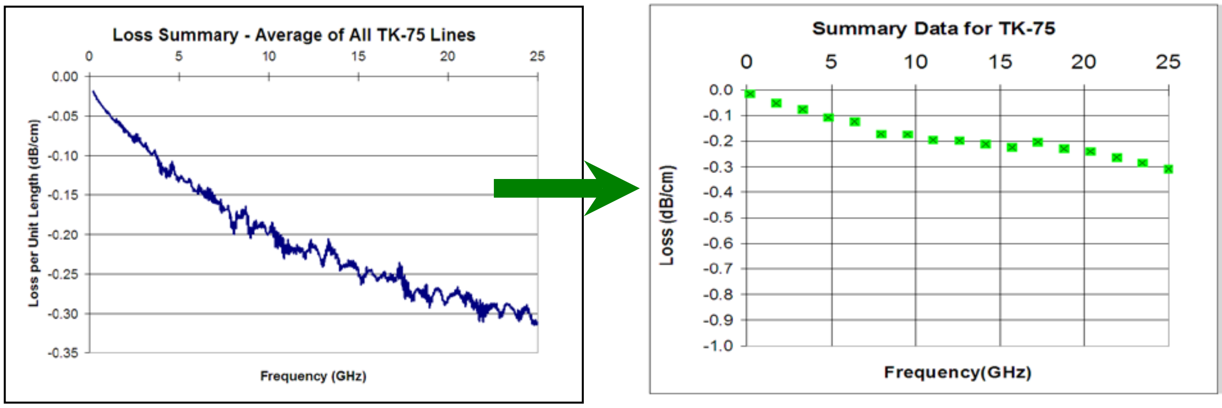


Figure 10 – Development of Summary Plots for the TK-75 Clad

The final summary data is shown in Figures 11 and 12. Keep in mind that each set of data in the summary plot is actually a summary of 25 microstrip line measurements. Specifically, the 10 sets of data between the two plots are summaries of 250 individual line measurements. Although the raw data is quite noisy, the trends are clearly resolvable above the noise and are quite repeatable. The reason so many lines had to be measured was the high level of noise inherent to these measurements. Averaging such a large number of measurements enables trends to be observed above this noise.

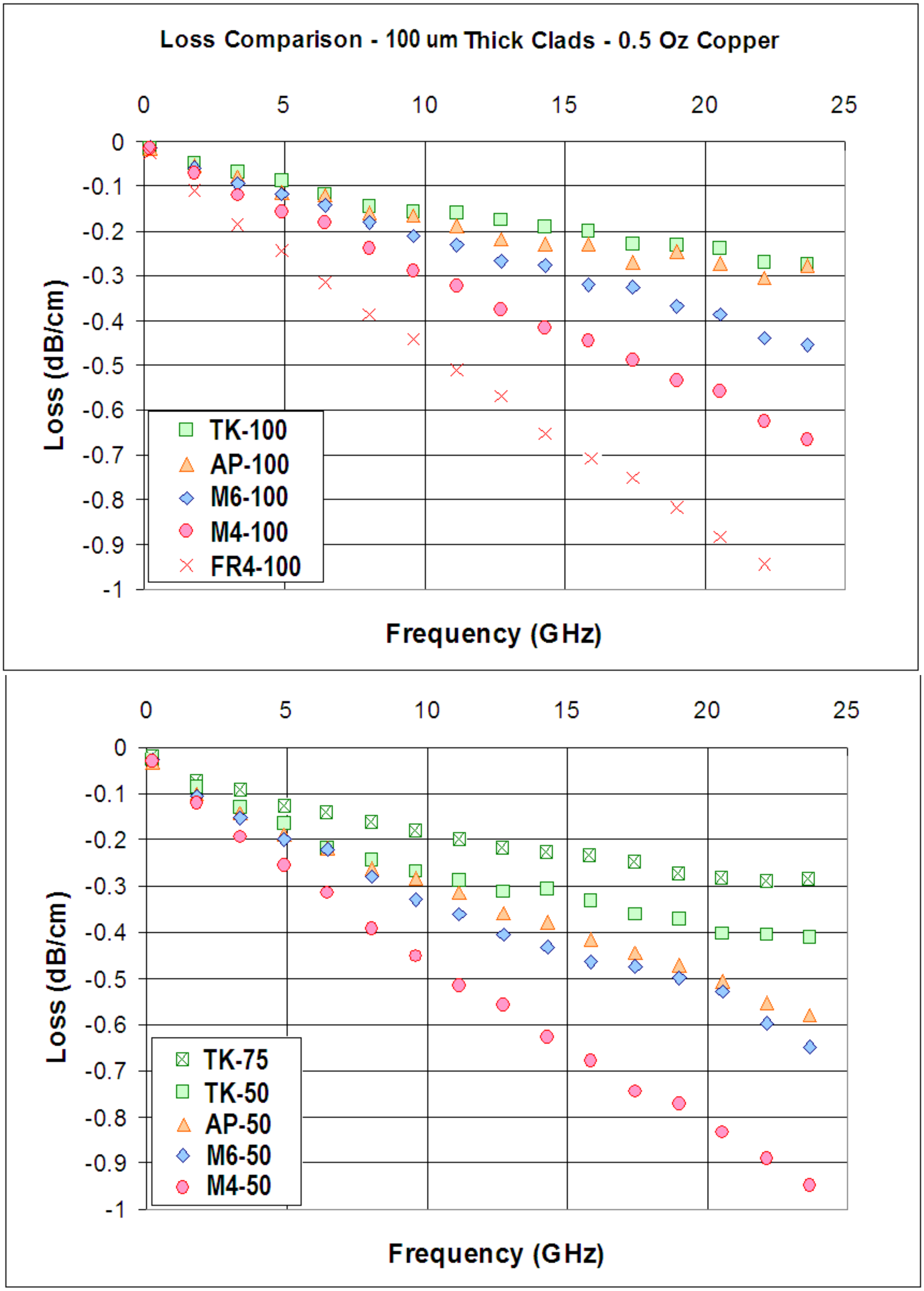


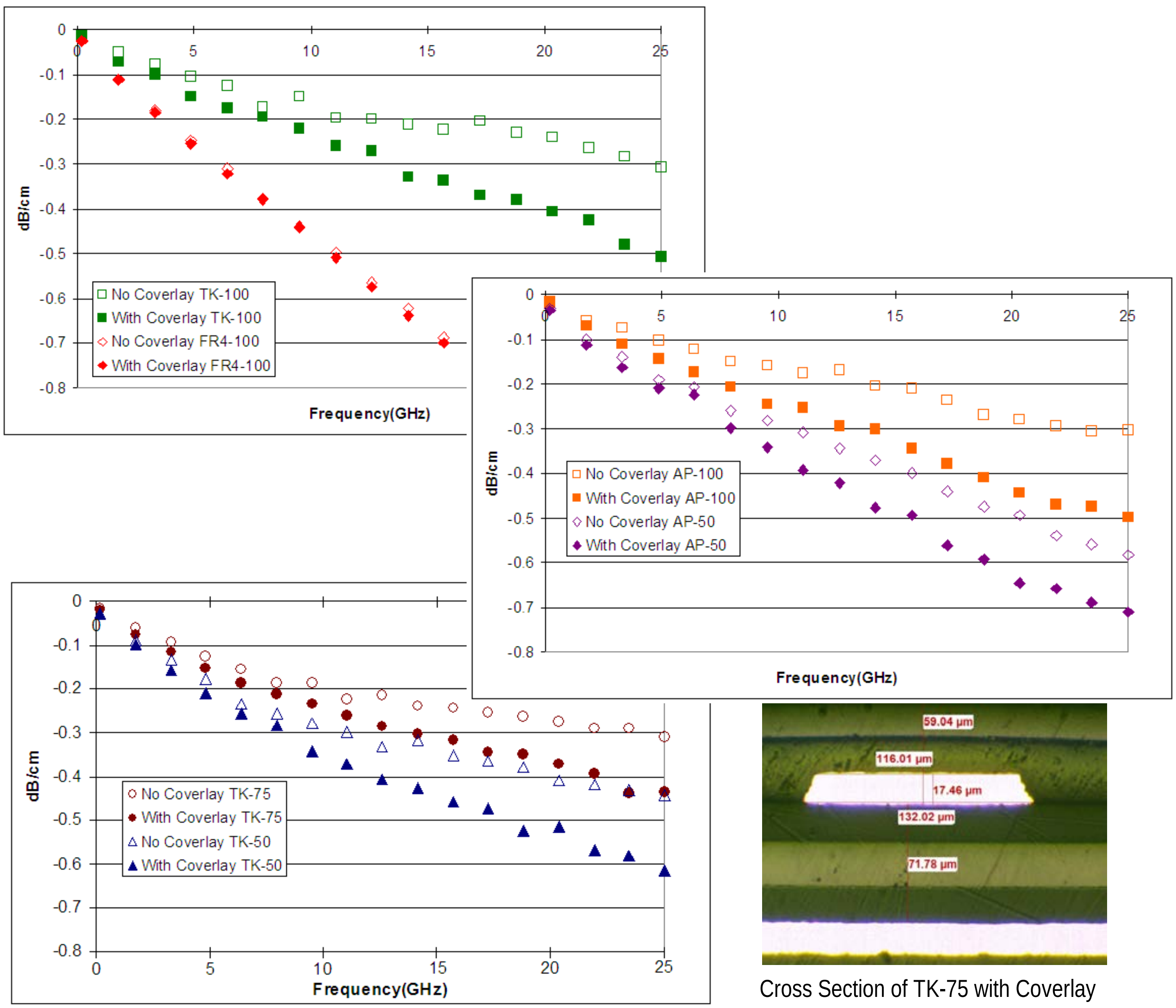
Figure 11 – Summary of Loss Measurements for 100 um Thick Microstrip Samples

Effect of Coverlay on Microstrip Loss:
With a thorough baseline of data to clearly understand the loss performance of different microstrip lines, it is possible to determine effects of more complex structures.

Covered microstrip is only slightly more complex than microstrip, so it is reasonable to isolate the effect of the coverlay independent of the clad. This can be done by measuring the same test structure with the only variation being the addition of coverlay. In this case, a coverlay with 25 um of acrylic adhesive coated to 25 um of polyimide was laminated to the flex materials and one of the rigid materials for comparison. Specifically, this experiment was performed on the following clad samples:

*FR4-100
*AP-100
*AP-50
*TK-100
*TK75
*TK-50

The same thorough analysis was performed on the covered microstrip lines that were conducted on the regular microstrip lines discussed previously. While the impedance slightly decreases by the addition of the coverlay, this will not be discussed in this forum for sake of space constraints. The loss impact is far more significant and of greater value for designers to understand thoroughly.



Cross Section of TK-75 with Coverlay

Figure 13 – Effect of Coverlay on Loss in Covered Microstrip Structures

Figure 13 summarizes results directly comparing microstrip to covered microstrip for each of the five flex clads and one FR4 rigid clad. While the coverlay does not have a very large impact on loss up to about 5 GHz, beyond this frequency the negative impact on loss is quite significant. This impact also increases with frequency. For instance, at about 10 GHz, the coverlay has about a 0.05 dB/cm impact on loss for the flex clads. At 25 GHz, the impact is about four times more (0.2 dB/cm). It is interesting that the coverlay has more of a negative effect for thicker clads than for thinner clads. This is likely due to more electric field passing through the coverlay than the clad dielectric when the thickness is higher. Finally, the coverlay does not have a significant impact on the FR4 clad. This is likely due to the fact that the dielectric loss in the FR4 is higher than the loss of the coverlay, so the impact is masked by the higher loss of the FR4 dielectric.

Effect of ENIG on Microstrip Loss:

Often an Electroless Nickel-Gold (ENIG) flash plated coating is applied to surfaces to prevent oxidation of the copper, especially for samples that are to be tested at high frequency. While this is appropriate on features like probe-pads and connector launches, it is not a good idea to plate long spans of transmission line with ENIG due to the fact that Nickel has relatively poor conductivity and does not have very good properties at high frequencies. To show this phenomenon, the same microstrip boards were made on four flex clads and one FR4 clad. (The data for AP-100 is not available at the time of publication.) Loss is measured and compared directly to the baseline microstrip boards made without any copper finish. Figure 14 summarizes these test results.

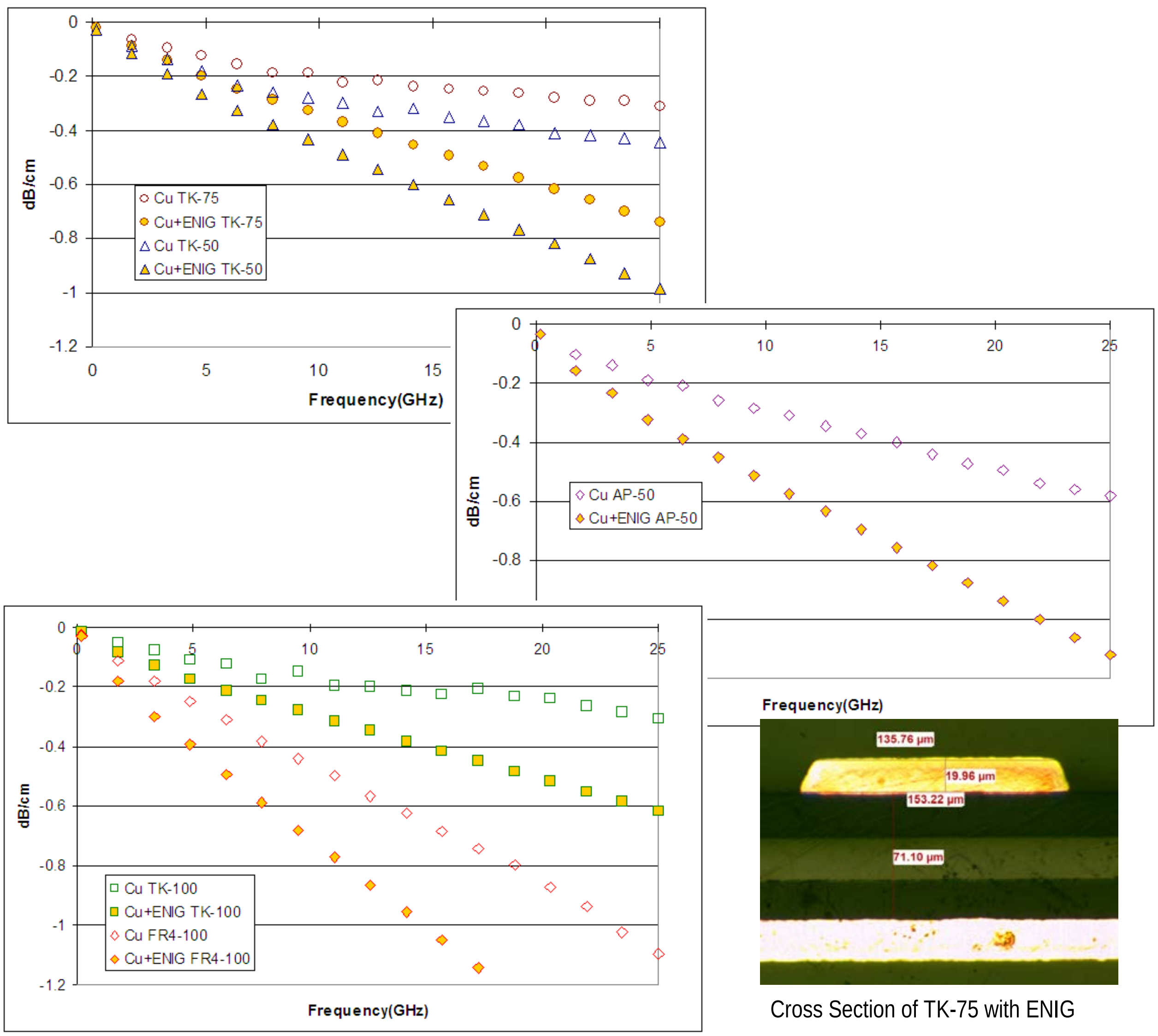


Figure 14 – Effect of ENIG on Loss in Microstrip Structures

The effect of the ENIG is different from the effect of the coverlay in two ways. First, the ENIG has a much larger negative impact on signal than coverlay at all frequencies, for all boards. In general, the effect is two to three times that of the effect of the coverlay. Also, the negative impact of the ENIG occurs at all frequencies while the impact of the coverlay was mostly a problem at frequencies higher than about 10 GHz.

Eye Pattern Analysis:

Usually eye pattern results seen presented for materials are based on models plugged into a circuit simulator and eye patterns are generated based on material data. In this case, eye patterns are generated directly from covered microstrip examples. One covered rigid microstrip line and five covered flex microstrip samples are tested.

The same settings were used for all eye pattern tests. A Tektronix BERTScope® S unit was used for all testing. [9] The generator and detector were matched to a 31 Bit Long Pseudo-Random Bit Stream (PRBS-31). The Clock set to 10.7 Gbit/s. The vertical scale shown on all eye patterns is 150 mV/division. The horizontal scale is 18 ps/division.

Six, 200 mm long lines were evaluated. All lines were compared to the FR4-100 covered microstrip as a baseline. Table 2 shows a summary of the instrument measurements of eye height and eye width improvement compared to the baseline. In addition, the eye patterns and the associated cross section of the sample are shown in Figure 16.

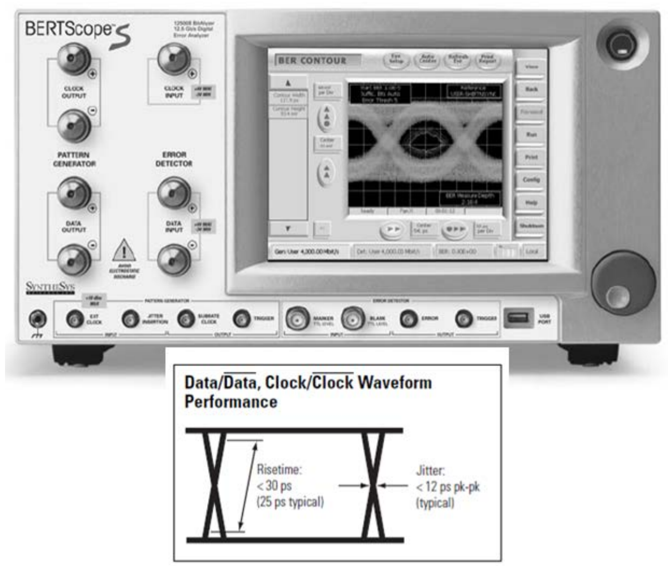


Figure 15 – Test Equipment for Eye Pattern Testing

Table 2 – Summary of Eye Pattern Measurements

200 mm Lengths For All	Eye Height (mV)		Eye Width (ps)		Signal to Noise Ratio	
	(mV)	% improvement vs FR4	(ps)	% improvement vs FR4	(dB)	dB improvement vs FR4
FR4-100: 48 ohms	210.0		57.6		2.5	
AP-100: 55 ohms	398.6	90%	73.0	7.3%	4.5	+2.0
TK-100: 55 ohms	450.0	114%	77.7	9.6%	5.3	+2.8
TK-75: 52 ohms	411.4	96%	74.1	7.9%	4.7	+2.2
AP-50: 48 ohms	240.0	14%	58.6	0.5%	3.1	+0.6
TK-50: 50 ohms	248.6	18%	63.8	3.0%	3.3	+0.8

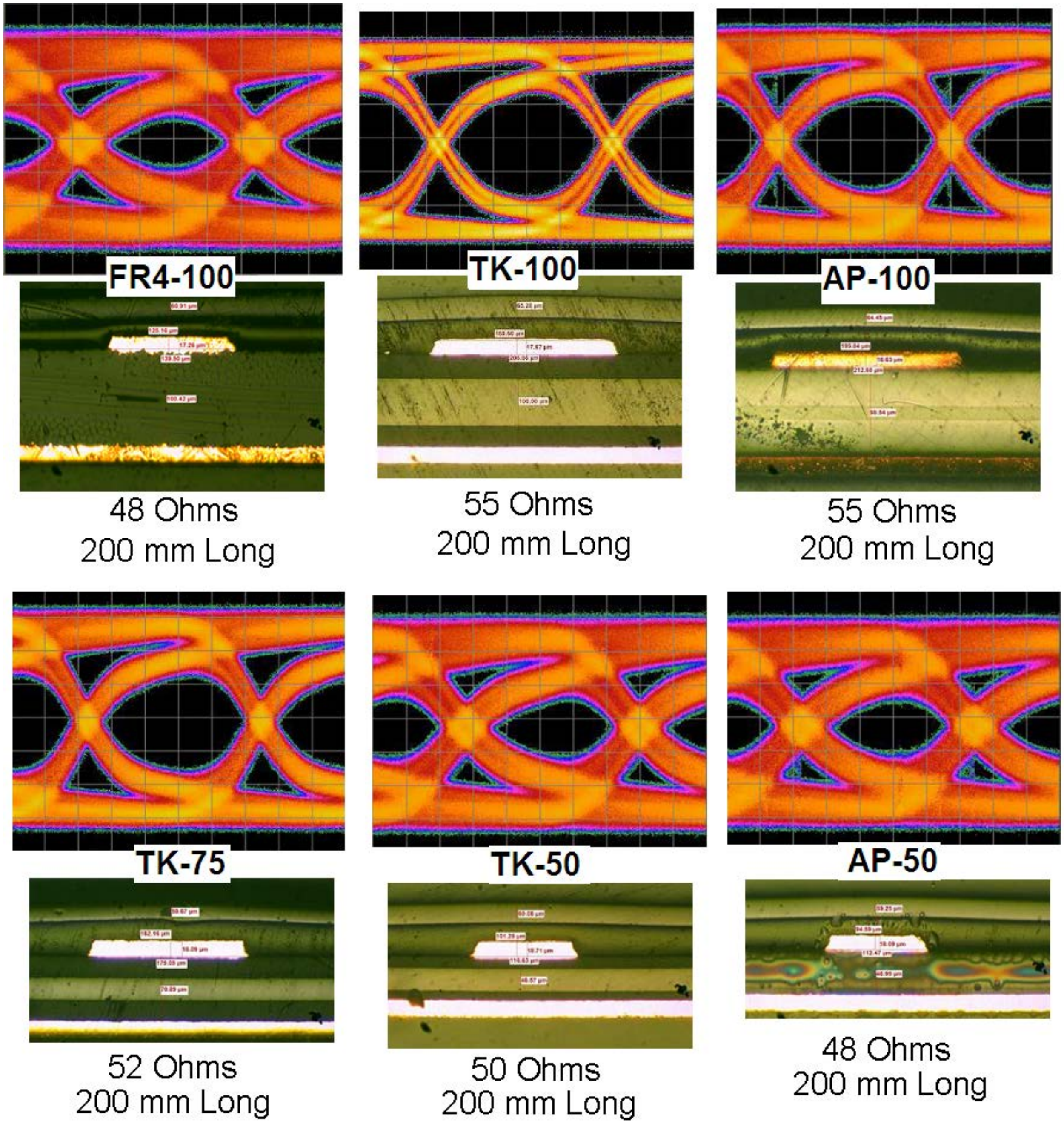


Figure 14 – Effect of ENIG on Loss in Microstrip Structures

Conclusions and Take Aways:

- When using thin layers to make controlled impedance structures, one valid concern is consistently defining line widths that have impedance high enough to meet the specification. There are lower dielectric constant options available to allow designers and fabricators to meet impedance requirements for thin structures. Data shown in this report confirm that the dielectric constant is actually as low as claimed in data sheets. Typical dielectric constant values for Fluoropolymer/Polyimide composites are 2.3-2.5. For adhesiveless polyimides, typical dielectric constant values are around 3.1. For epoxy-based rigid materials, dielectric constants are typically higher (3.6-4.2).

- Some flexible circuit materials have very good high frequency loss performance. Materials utilizing high quality, adhesiveless polyimide have low loss due to both the quality of the dielectric and ultra-low profile RA copper. Fluoropolymer/Polyimide composites have exceptionally low loss due to the presence of the fluoropolymer in the dielectric in addition to still lower profile copper used in the adhesiveless clads.

- One significant challenge in utilizing flexible circuit materials at high frequencies for microstrip structure is the presence of the coverlay adhesive material. The adhesive material is lossy and has a negative impact on loss as frequencies increase. However, the loss impact is not significantly detrimental until frequencies increase to about 10 GHz. It is also possible that copper surface preparation for coverlay adhesion may increase the copper roughness and have a negative impact on loss. This surface treatment effect is sometimes attributed to the coverlay and may make the loss of the coverlay seem higher than it actually is. Regardless, adhesive materials that have lower dielectric loss are significant development needs for future wide adoption of flex circuit use at high frequencies.

- More significant than the impact of the coverlay is the effect of metal finishes like ENIG. Data from this study shows that extensive use of ENIG on signal lines can have a strong negative impact on the loss performance at high frequencies.

- Flex circuit materials are viable options for high speed digital interconnect applications. Data showing transmission of digital signals through flex transmission lines show significant performance improvement over materials like FR4 even if the thickness of the dielectric is cut in half.

Acknowledgements:
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References:

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[7] Polar Instruments. SI-9000 Signal Integrity Analysis Tool. www.polarainstruments.com.

[8] Anritsu. Lightning 37000 Model Vector Network Analyzer. www.anritsu.com.

[9] Tektronix. BERTScope® S 12500A Bit Error Rate Tester. www.tek.com.

Detailed Analysis of Impedance And Loss Versus Frequency for Transmission Lines Made from Flexible Circuit Materials

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Scope and Overview

- Apples to Apples Test Results - Microstrip
  - Cross Section Measurements
  - Impedance
  - Loss (dB/cm)
  - Digital Signal Performance

- Additional Analysis of Loss
  - Lines after Coverlay – Direct Comparison to Microstrip

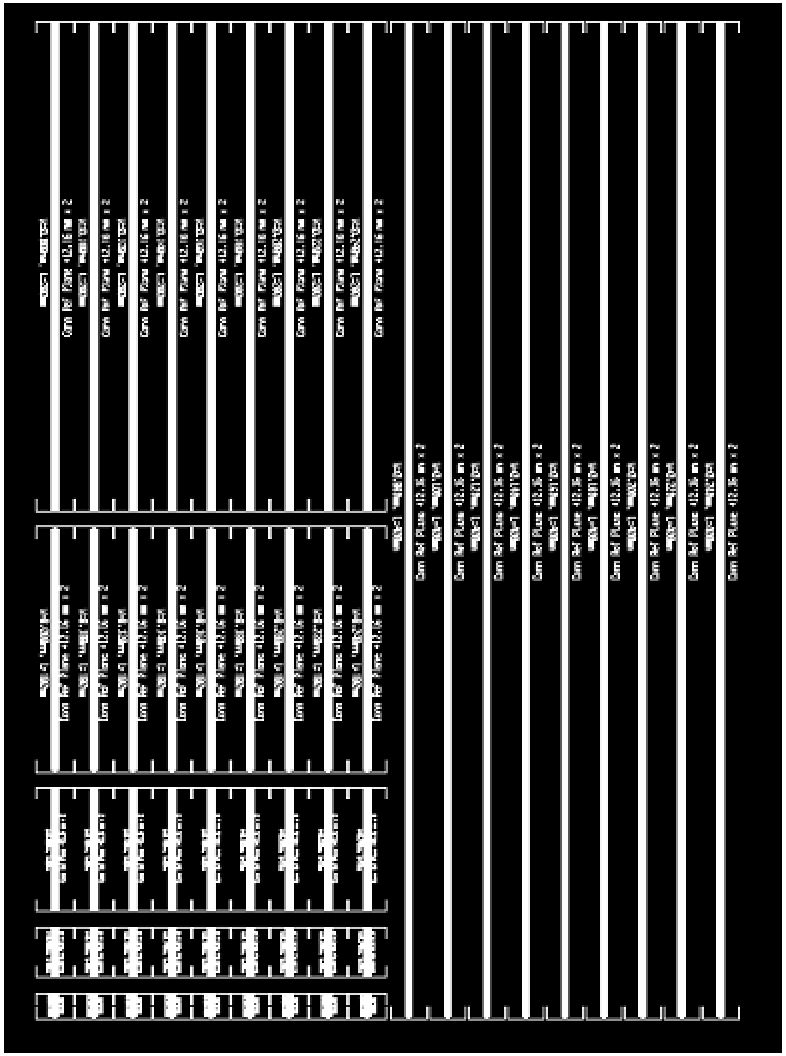
Motivation for Work

- Need thin materials to meet form factors and have better electrical performance.
- Not a lot of good data on high frequency performance of flex materials.
- DK and DF measurements are not enough.
- Simple structures so conclusions can be made and directly compared to well known materials.
- Lots of data must be collected since loss measurements are somewhat noisy.

Basic Approach

- Simple test pattern with five lengths and a range of line widths.
- Same artwork used for all samples.
- TDR done on 10, 20, 40 cm lengths.
- VNA 0.2-25 GHz done on all lines.
- Can extract loss per unit length by subtracting loss of longer lines from shorter lines and normalizing to length.

Test Vehicle Design



18"x12" Panel
- -Print and Etch
- -No plated finish (just bare copper) for fundamental comparison
- Black = Copper; White = Etched

Five Line Lengths
- 400 mm, 200 mm, 100 mm, 50 mm, 20 mm

Nine Designed Line Widths (W_{art}):
- 240 um, 220 um, 200 um, 180 um, 160 um, 140 um, 120 um, 100um, 80 um

NOTE: These are ARTWORK widths, not fabricated widths.

Materials Tested – 0.5 oz Cu Clads

- Glass Reinforced Materials
  - **FR4-100:** Standard FR4 - 100um, standard ED Cu, high dielectric loss
  - Mid Grade – RTF ED Cu, moderate dielectric loss
    - **M4-50:** 50um, 1067 Glass, 66% Resin, RTF H/H Cu
    - **M4-100:** 100um, 3313 Glass, 57% Resin, RTF H/H Cu
  - Low Loss – Ultra Low Profile ED Cu, low dielectric loss
    - **M6-50:** 50um, 1035 Glass, 65% Resin, BF-HFI-LP2 H/H Cu
    - **M6-100**: 100um, 3313 Glass, 54% Resin, BF-HFI-LP2 H/H Cu

- Adhesiveless Polyimide
  - **AP-50:** 50 um, Ultra Low Profile RA Cu, low dielectric loss
  - **AP-100:** 100 um, Ultra Low Profile RA Cu, low dielectric loss

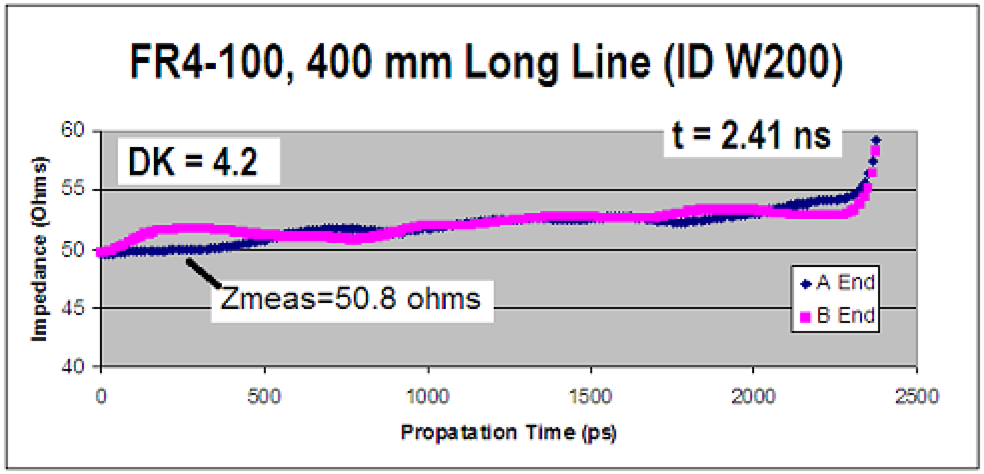
- Fluoropolymer/Polyimide Composite
  - **TK-50:** 50 um, Ultra Low Profile RA Cu, 50% PI:50% Fluoropolymer
  - **TK-75:** 75 um, Ultra Low Profile RA Cu, 33% PI:67% Fluoropolymer
  - **TK-100:** 100 um, Ultra Low Profile RA Cu, 50% PI:50% Fluoropolymer

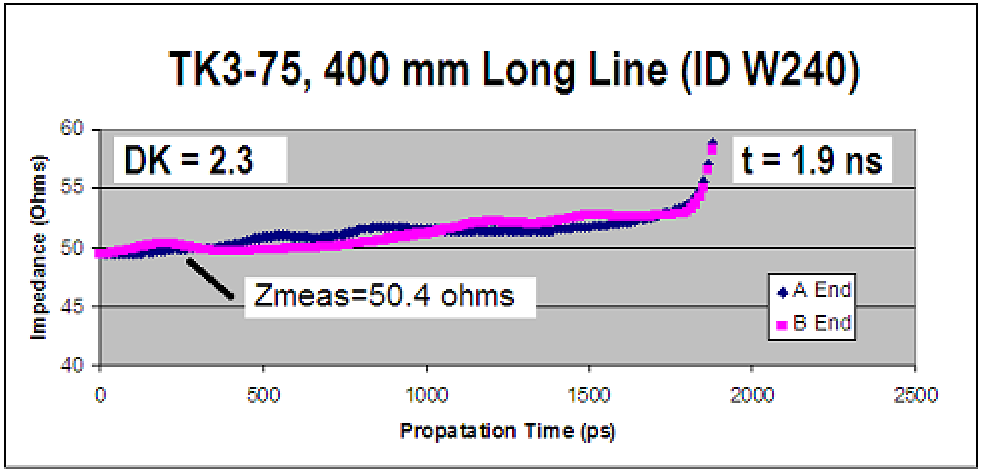
Connectors and Line Measurements

- High frequency SMA connectors used…good up to 27 GHz
- 100, 200 and 400 mm length lines tested for impedance.
- The shorter lines (20 and 50 mm) are only tested for loss since TDR can not resolve these lines.

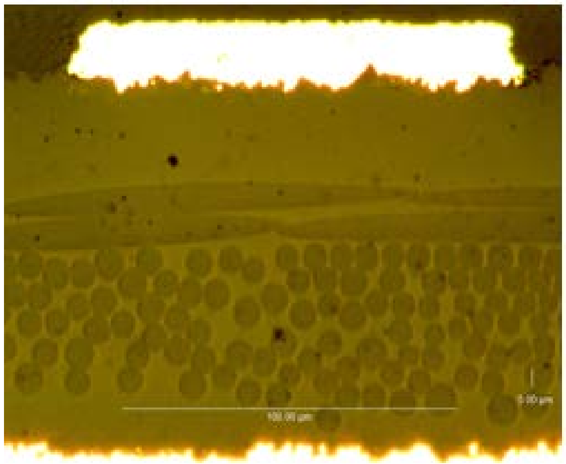
Impedance and Propagation Time

- Time scale is propagation time (½ round trip time). Propagation time determined by evaluating end discontinuity point.
- Impedance value is measured at the after the waveform stabilizes past connector (250 ps).
- **This is different from the method in the published paper. The method here reflects more conventional impedance measurement techniques.**
- Propagation time converted to speed since length of line is known.
- Can clearly see the effect of lower dielectric constant on propagation speed in TDR waveforms.



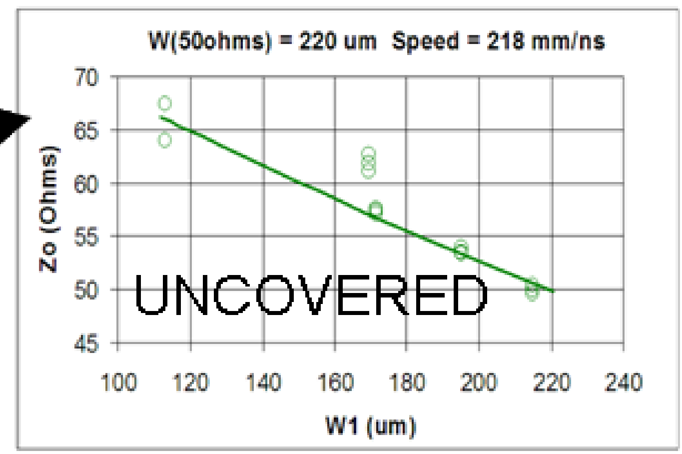


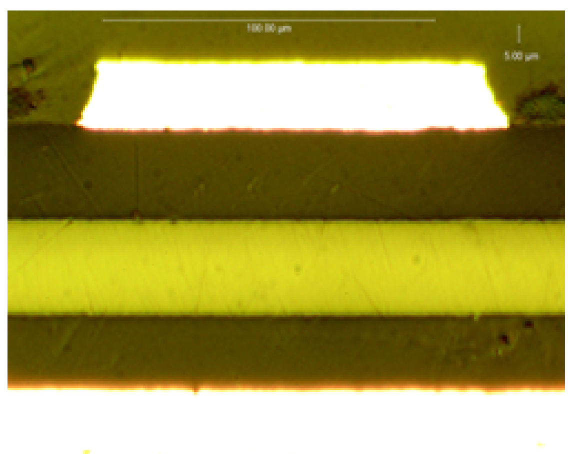
FR4-100



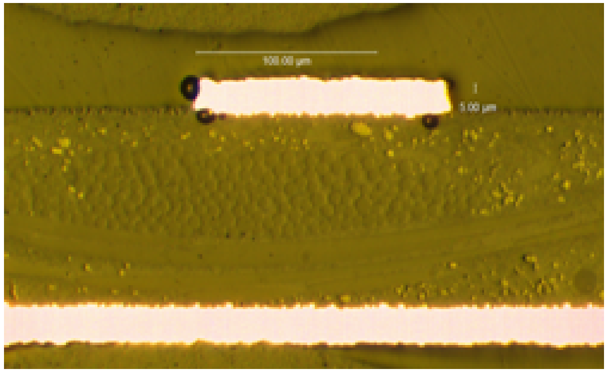

W(50ohm) = 188 um   Speed = 168 mm/ns
Zo (Ohms)
65
60
55
50
45
40
100
120
140
160
180
200
220
240
W1 (um)
UNCOVERED

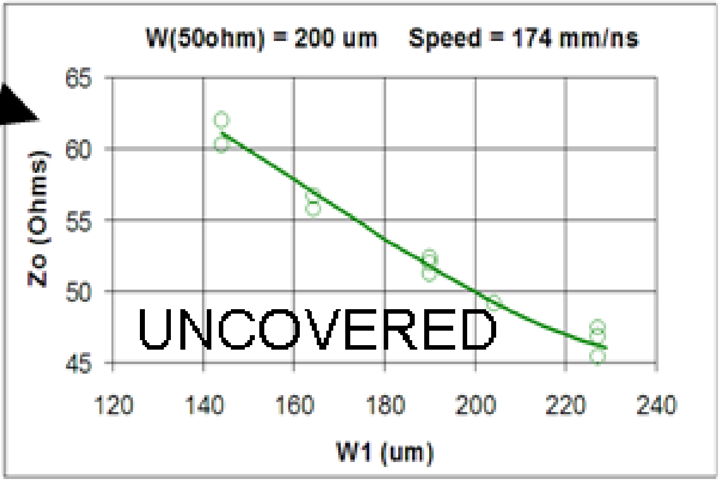
TK-75

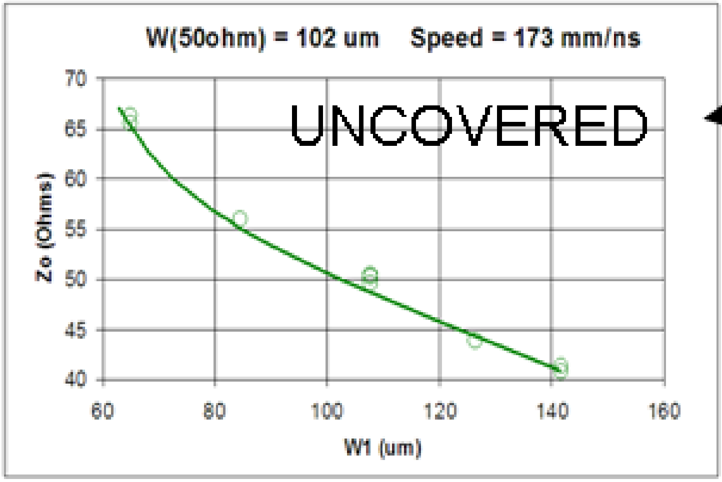

W(50ohms) = 220 um Speed = 218 mm/ns
Zo (Ohms)
70
65
60
55
50
45
100
120
140
160
180
200
220
240
W1 (um)
UNCOVERED



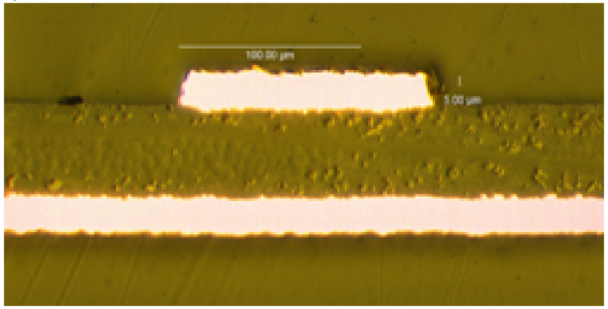
M4-100


100.00 µm
5.00 µm

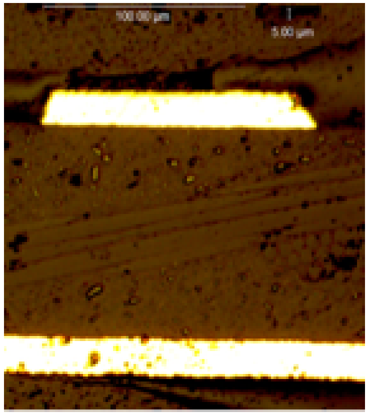

W(50ohm) = 200 um Speed = 174 mm/ns
Zo (Ohms)
W1 (um)
UNCOVERED
65
60
55
50
45
120
140
160
180
200
220
240

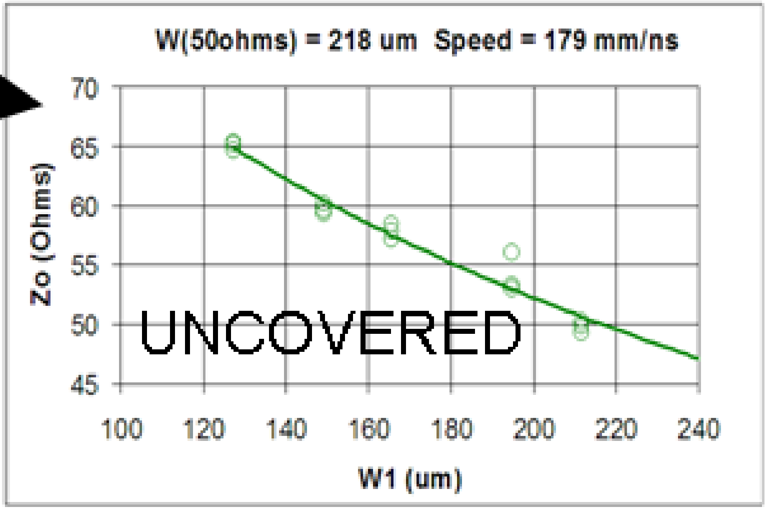

W(50ohm) = 102 um Speed = 173 mm/ns
Zo (Ohms)
W1 (um)
UNCOVERED
70
65
60
55
50
45
40
60
80
100
120
140
160

M4-50

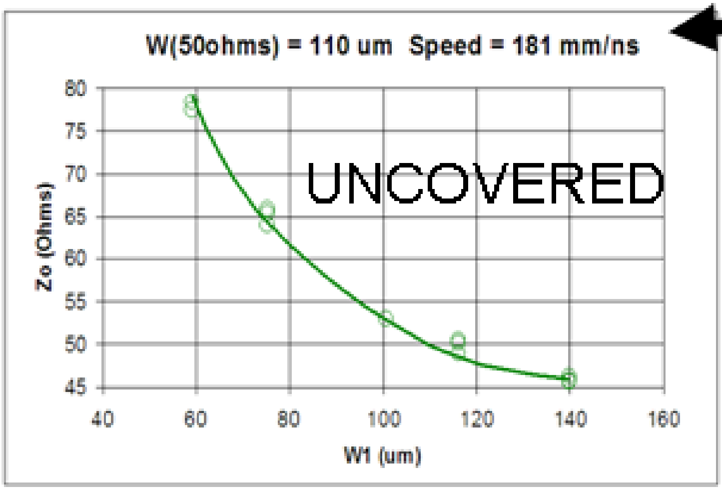

100.00 µm
5.00 µm

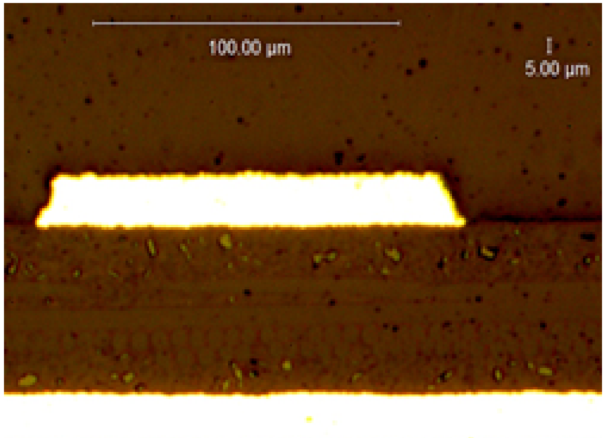
M6-100


100.00 µm
5.00 µm


W(50ohms) = 218 um Speed = 179 mm/ns
Zo (Ohms)
W1 (um)
UNCOVERED
70
65
60
55
50
45
100
120
140
160
180
200
220
240

M6-50


W(50ohms) = 110 um Speed = 181 mm/ns
Zo (Ohms)
W1 (um)
UNCOVERED
80
75
70
65
60
55
50
45
40
60
80
100
120
140
160


100.00 µm
5.00 µm

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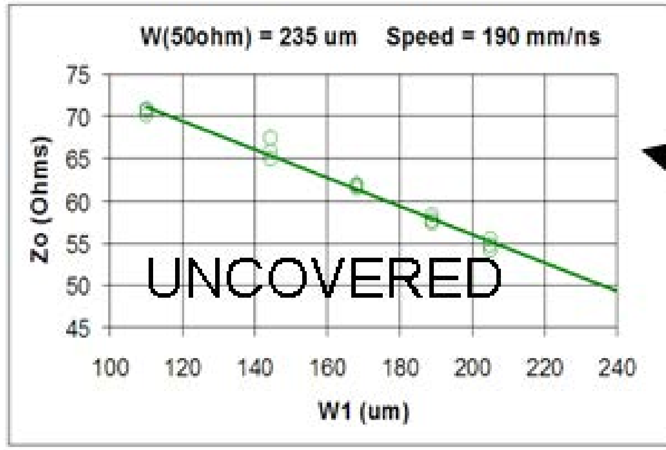
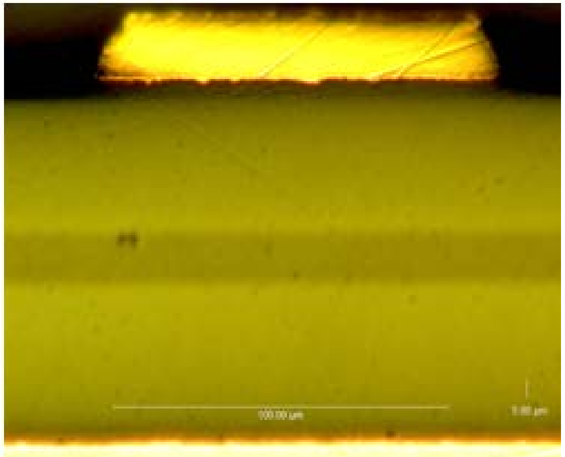
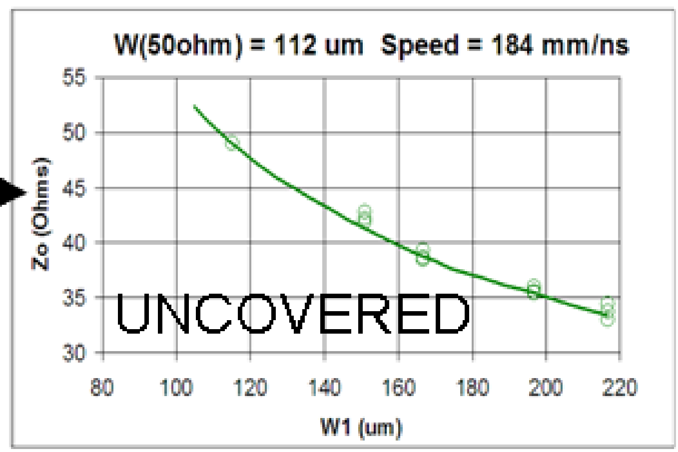
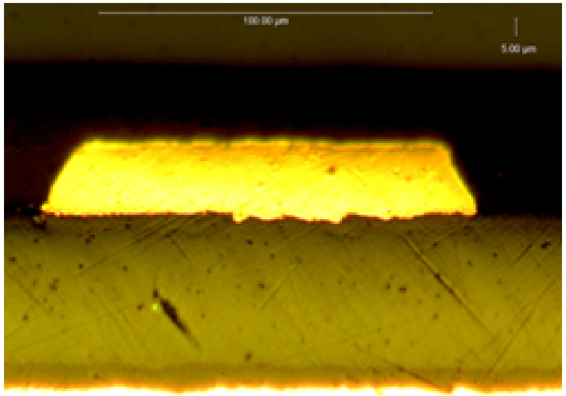


AP-100

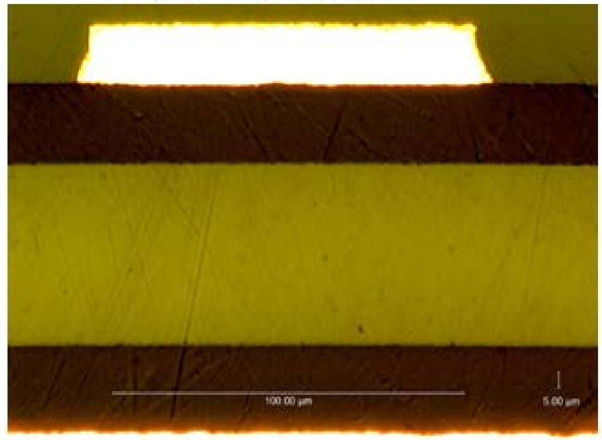




AP-50

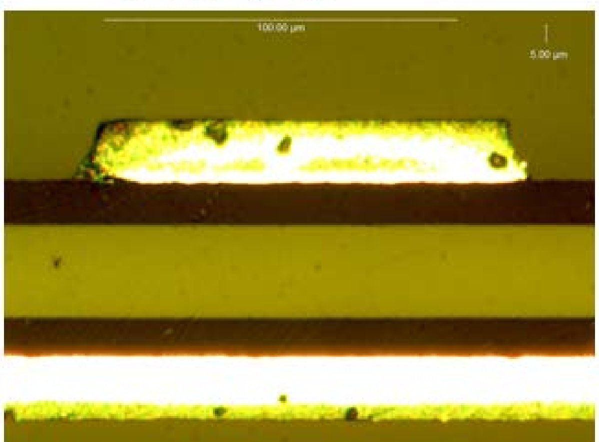


TK-100


100.00 µm
5.00 µm


W(50ohms) = 272 um Speed = 214 mm/ns
Zo (Ohms)
80
75
70
65
60
55
50
45
140
160
180
200
220
240
260
280
W1 (um)
UNCOVERED

TK-50


100.00 µm
5.00 µm


W(50ohms) = 132 um Speed = 206 mm/ns
Zo (Ohms)
60
55
50
45
40
35
30
100
120
140
160
180
200
220
W1 (um)
UNCOVERED

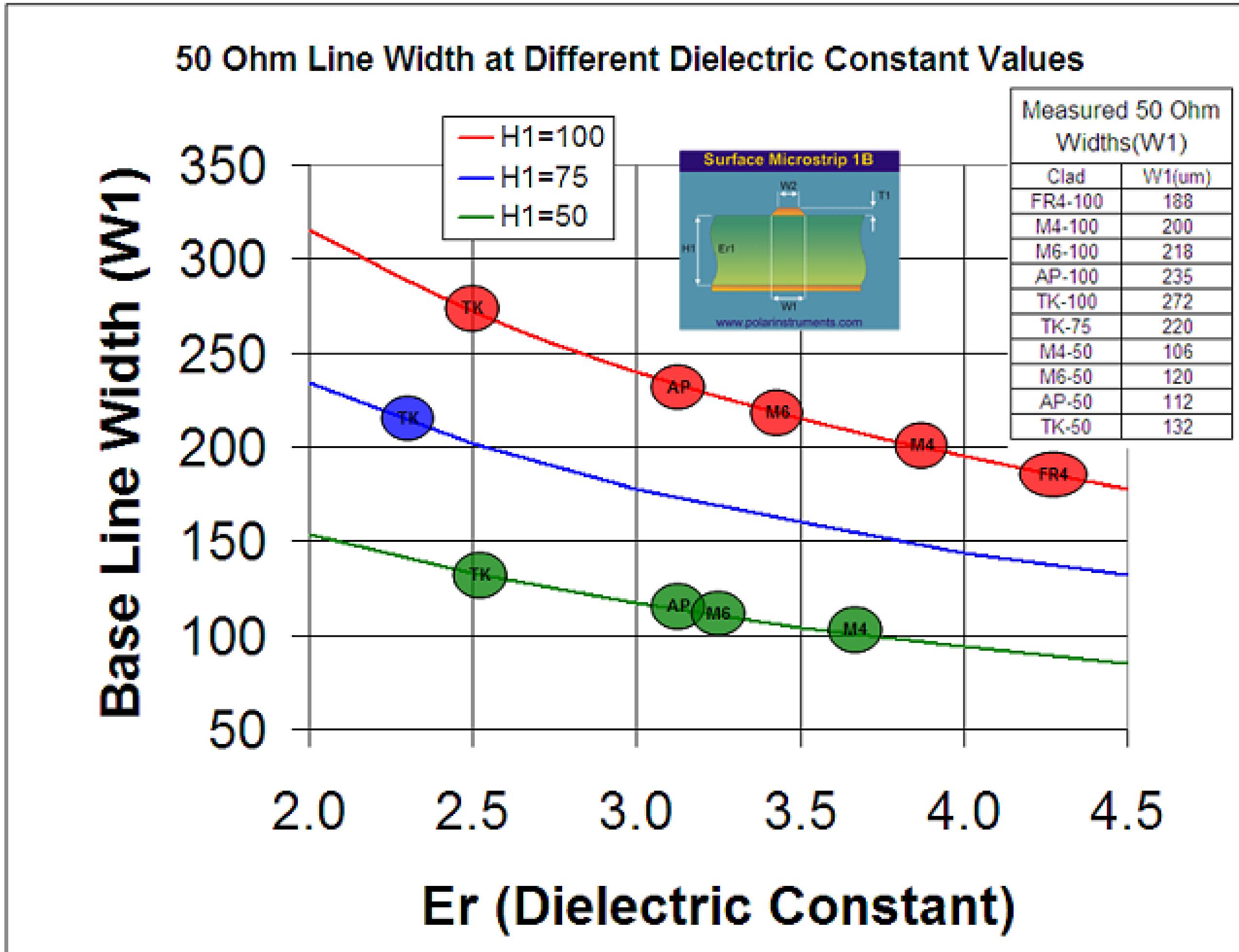
Key Result – Line Width and Er

- Clear differences. Can distinguish different types of materials.

- Shows benefit of Low Er to Design and Manufacture

- Verified with physical measurements. Good objective Er analysis.

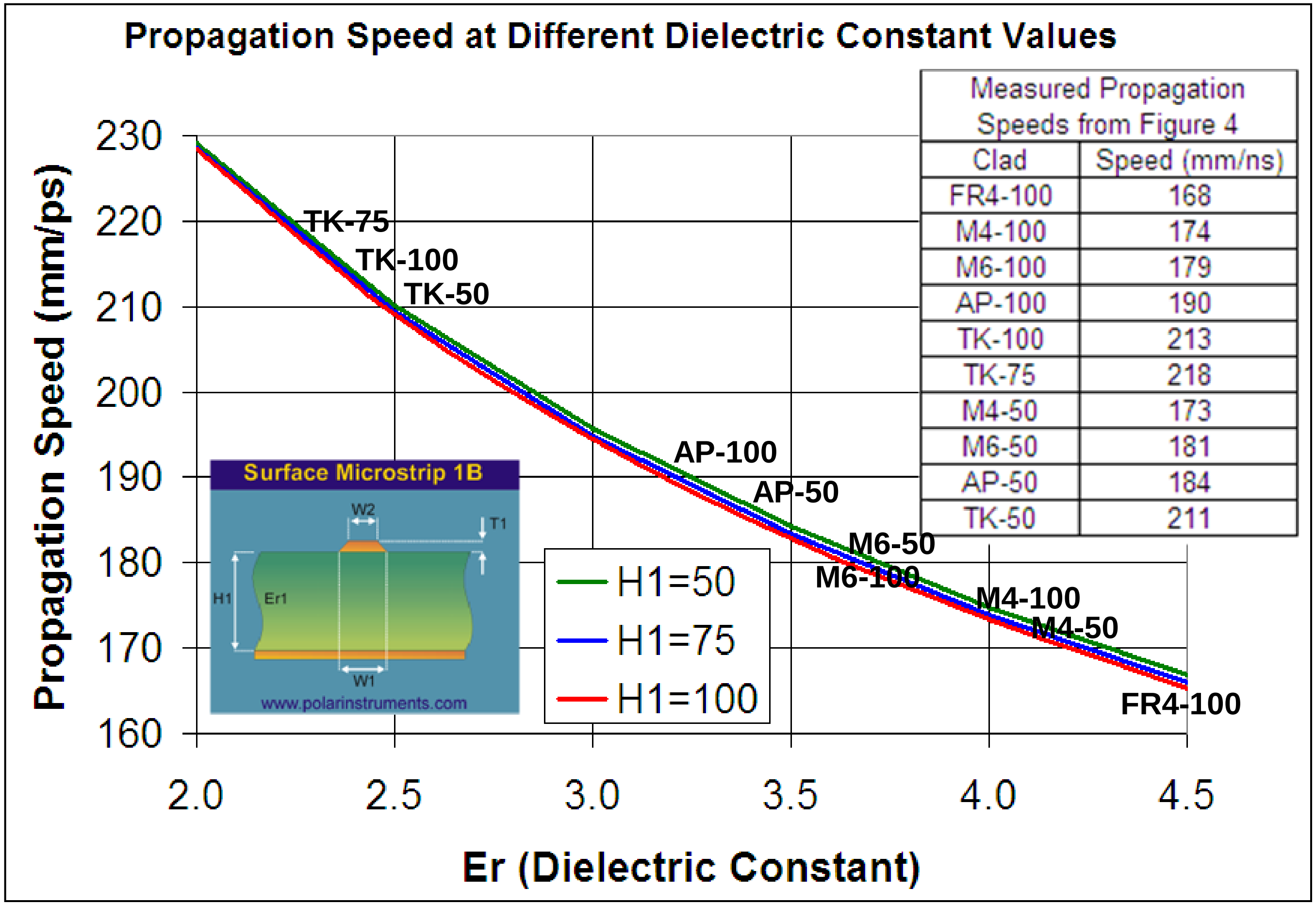
- Slight difference from published paper (Er +0.1) due to updated impedance analysis.



Measured 50 Ohm Widths(W1)	
Clad	W1(um)
FR4-100	188
M4-100	200
M6-100	218
AP-100	235
TK-100	272
TK-75	220
M4-50	106
M6-50	120
AP-50	112
TK-50	132

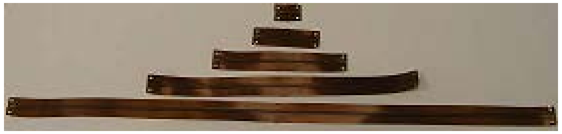
Key Result – Speed and Er

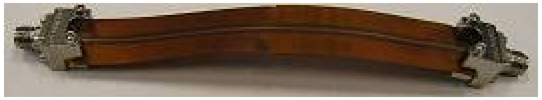
- Similar result to impedance analysis. Lower Er materials propagate signals faster.
- Result is more valuable for comparison than for determining Er since Polar TDR is a coarse measurement tool for speed measurements.



Measured Propagation Speeds from Figure 4	
Clad	Speed (mm/ns)
FR4-100	168
M4-100	174
M6-100	179
AP-100	190
TK-100	213
TK-75	218
M4-50	173
M6-50	181
AP-50	184
TK-50	211

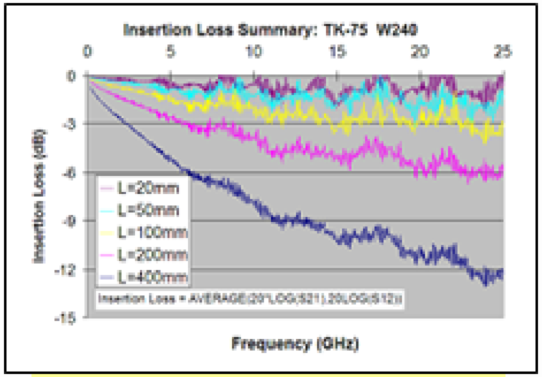
Loss Measurement - Method





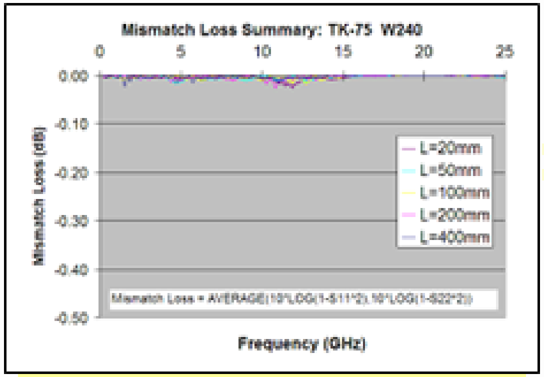
- 25 Lines Measured for Each Clad
  - 5 Lengths x 5 Widths
  - High Frequency Connectors Attached
- Vector Network Analyzer (VNA) Measurements
  - SOLT Calibration
  - 0.2 – 25 GHz
- Since all lines were not 50 ohms, mismatch loss is subtracted out to isolate only the signal loss that is due to transmission.
- Since five different lengths are measured, effects of connectors can be subtracted off by looking at the DIFFERENCE in loss divided by the DIFFERENCE in length.
- The next slide details the full analysis of one clad just for purposes of illustration

Determination of Loss/Length



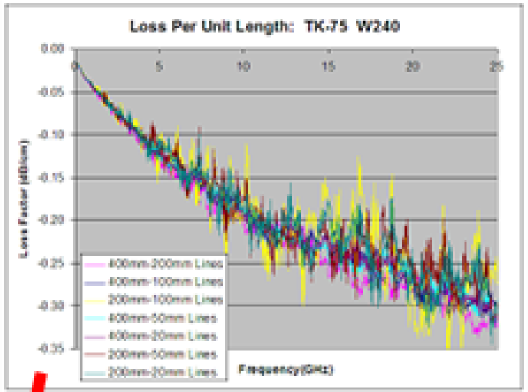
Insertion Loss from S21 and S12 of one width (5 lines)

−

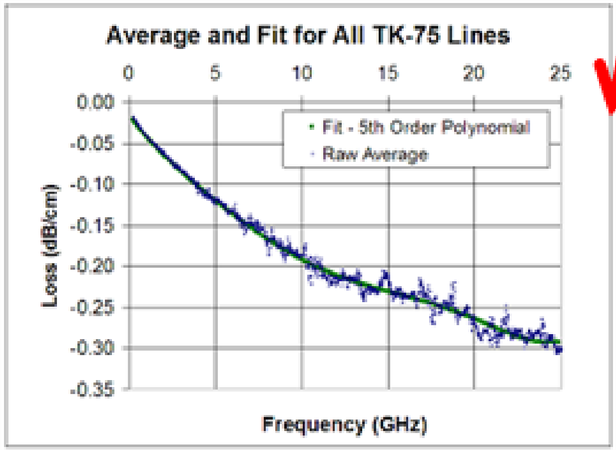


Mismatch Loss from S11 and S22 of same lines

=

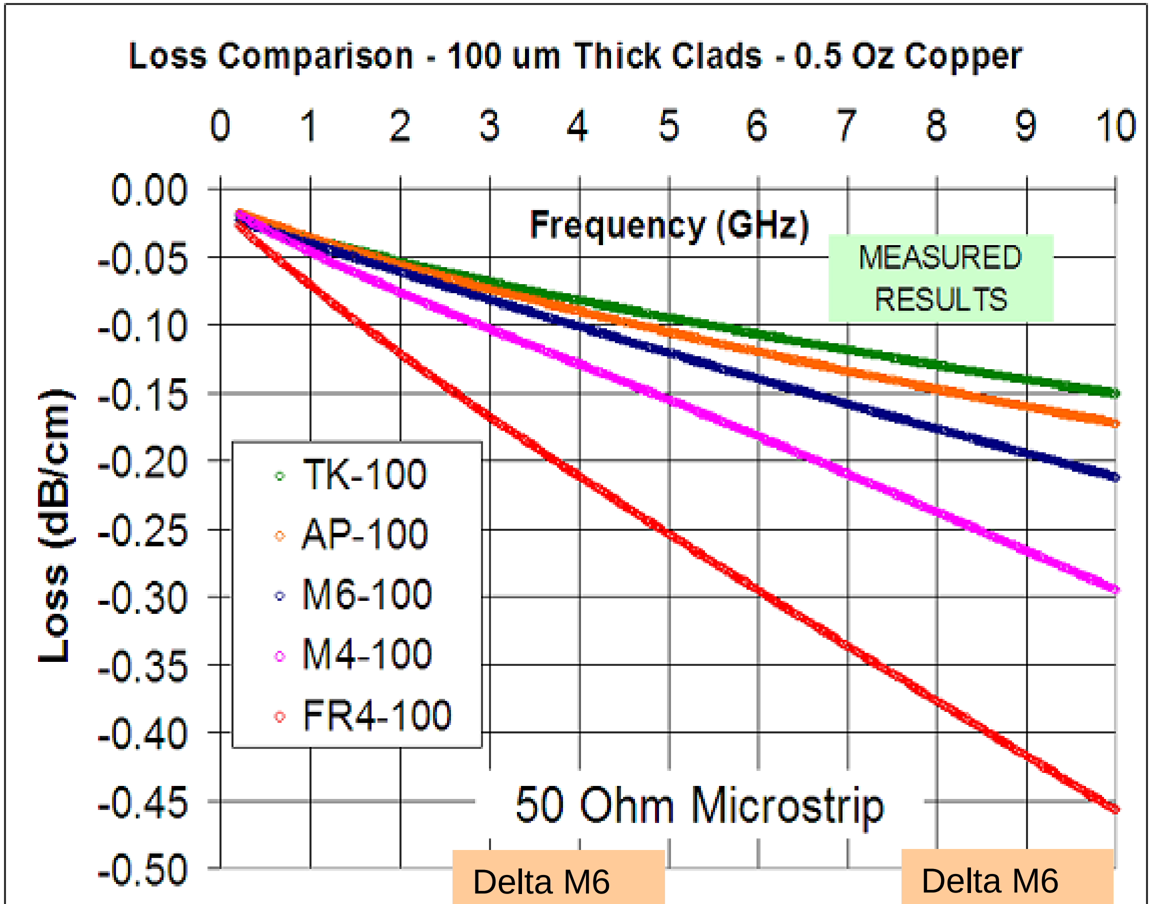


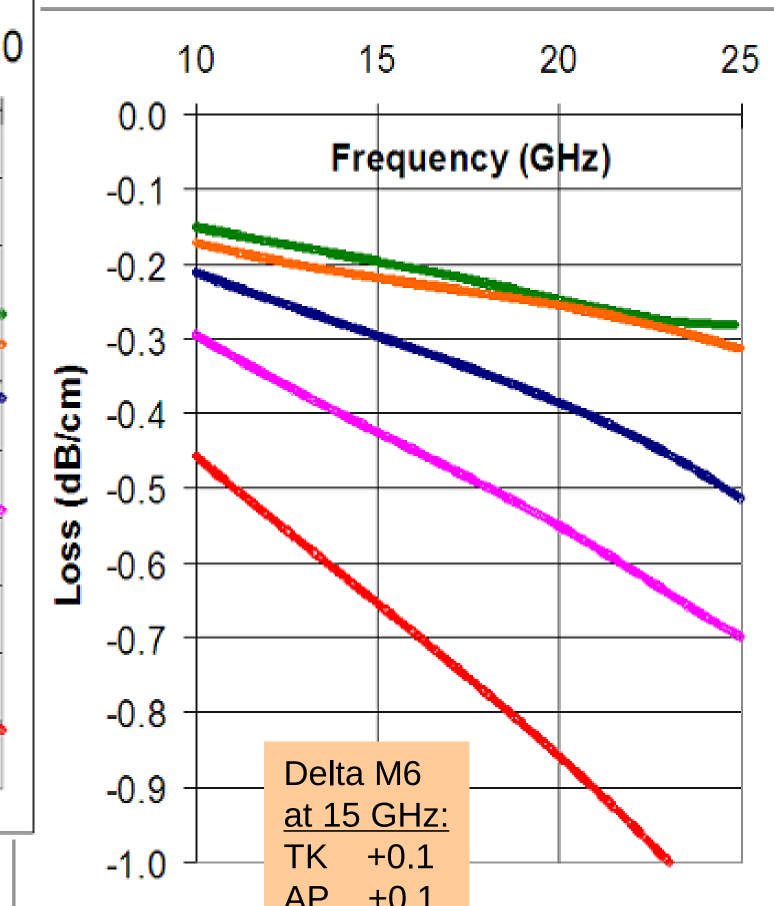
Loss/Length for each case length difference 100 mm or more



Average of 25 lines (five lengths x five widths) from the TK-75 clad

Summary Results – 100 um Clads





Delta M6
at 5 GHz:
TK +0.03
AP +0.01
M4 -0.04
FR4 -0.14

Delta M6
at 10 GHz:
TK +0.06
AP +0.04
M4 -0.08
FR4 -0.25

Delta M6
at 15 GHz:
TK +0.1
AP +0.1
M4 -0.1
FR4 -0.4

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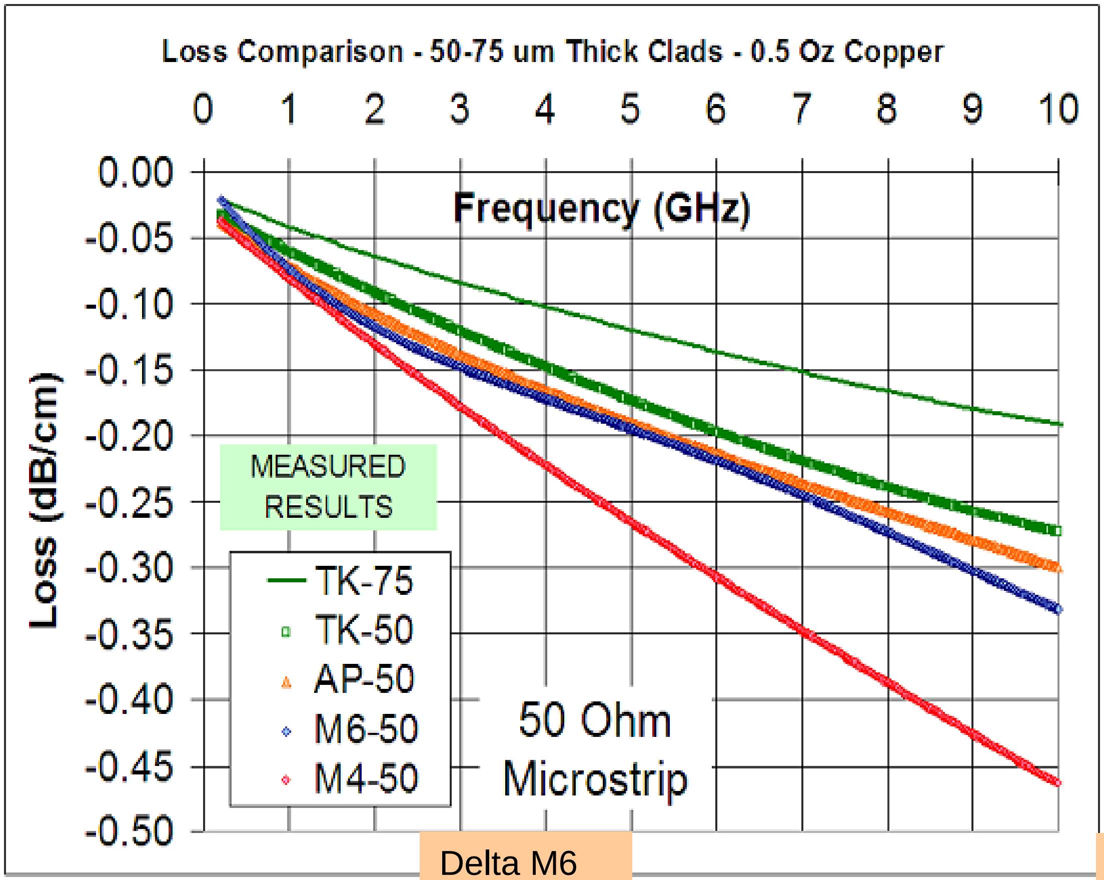
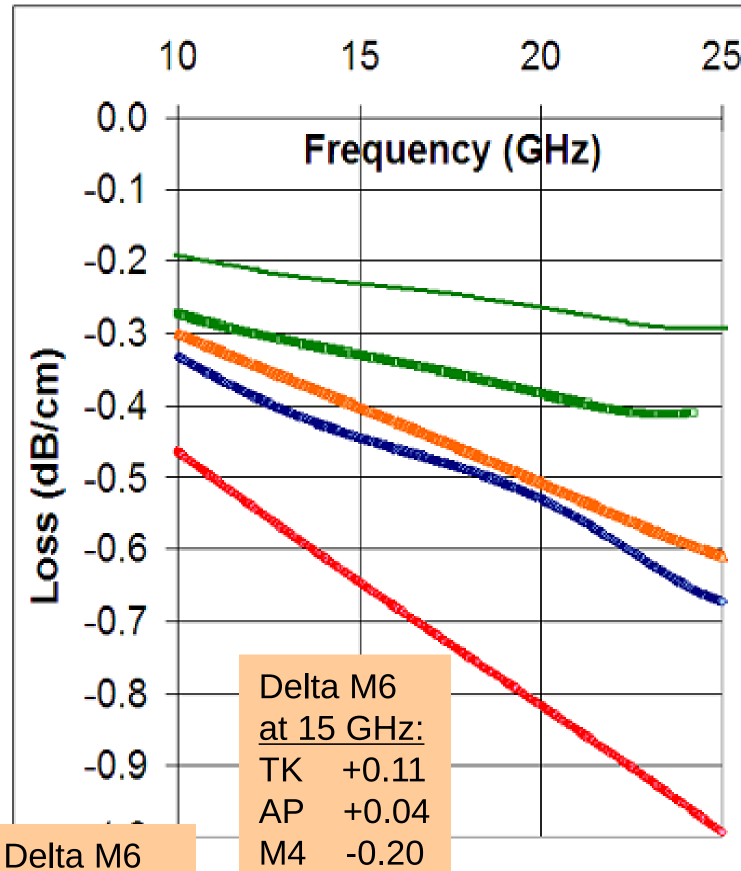
Summary Results – 50-75 um Clads





Delta M6
at 5 GHz:
TK +0.02
AP 0
M4 -0.07

Delta M6
at 10 GHz:
TK +0.06
AP +0.02
M4 -0.13

Delta M6
at 15 GHz:
TK +0.11
AP +0.04
M4 -0.20

Thickness Effect at 5 GHz:
M6(50)-M6(100) = -0.07
M4(50)-M4(100) = -0.02
AP(50)-AP(100) = -0.08
TK(50)-TK(100) = -0.08

Thickness Effect at 10 GHz:
M6(50)-M6(100) = -0.12
M4(50)-M4(100) = -0.01
AP(50)-AP(100) = -0.13
TK(50)-TK(100) = -0.12

Thickness Effect at 15 GHz:
M6(50)-M6(100) = -0.16
M4(50)-M4(100) = -0.01
AP(50)-AP(100) = -0.17
TK(50)-TK(100) = -0.12

Discussion of Loss Results

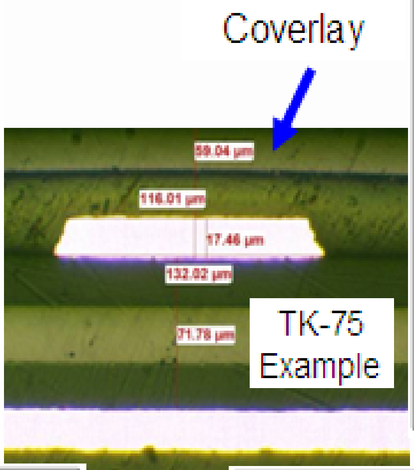
- Rigid board materials perform as expected.
  - Dielectric and Copper Profile have significant impact on loss performance.
  - Note that material with fluoropolymer based resin systems were not tested, these would have even lower loss than the materials tested her.
- All Polyimide flex materials have lower loss all than epoxy-based rigid materials tested
- Fluoropolymer/Polyimide composites had the lowest loss of all samples tested.
- There is inherent increase in loss from the Physics of going thin. The lower dielectric constant and presence of fluoropolymer helps keep loss low as thickness decreases.

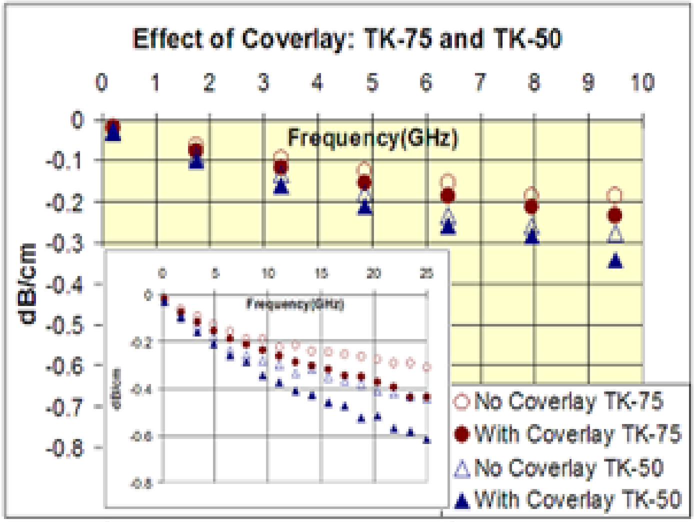
Effect of Coverlay

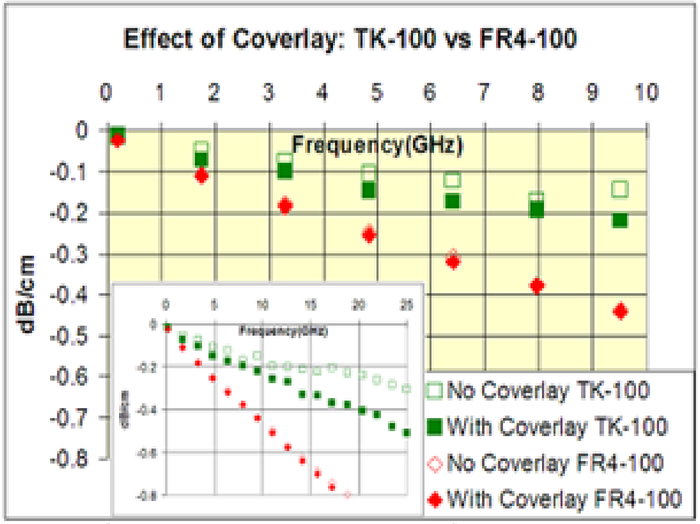
- Covering of signal lines is necessary in most cases.
- We explored the effect of the same flex boards as evaluated before, but covered
  - 25um adhesive / 25um polyimide coverlay.
- Same flex materials as in baseline case, with a standard FR4 as a control.
- Same analysis method for loss as baseline case.

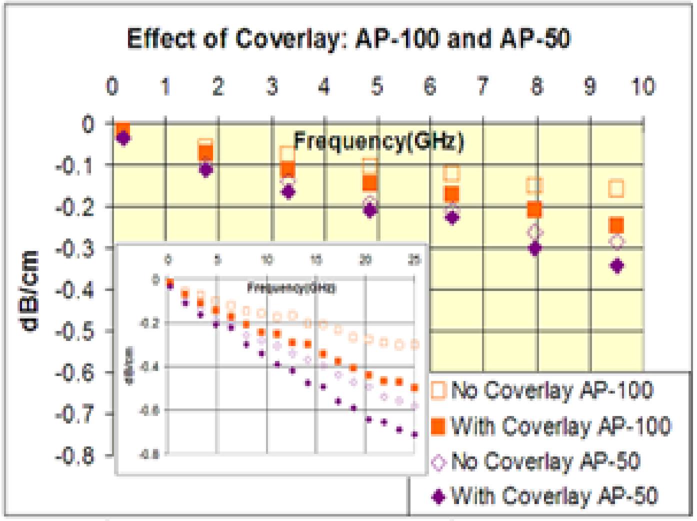
Summary – Loss from Coverlay

- Effect of coverlay is significant and has more of an impact for thinner clads.
- Even though relatively thin, the effect must be considered.







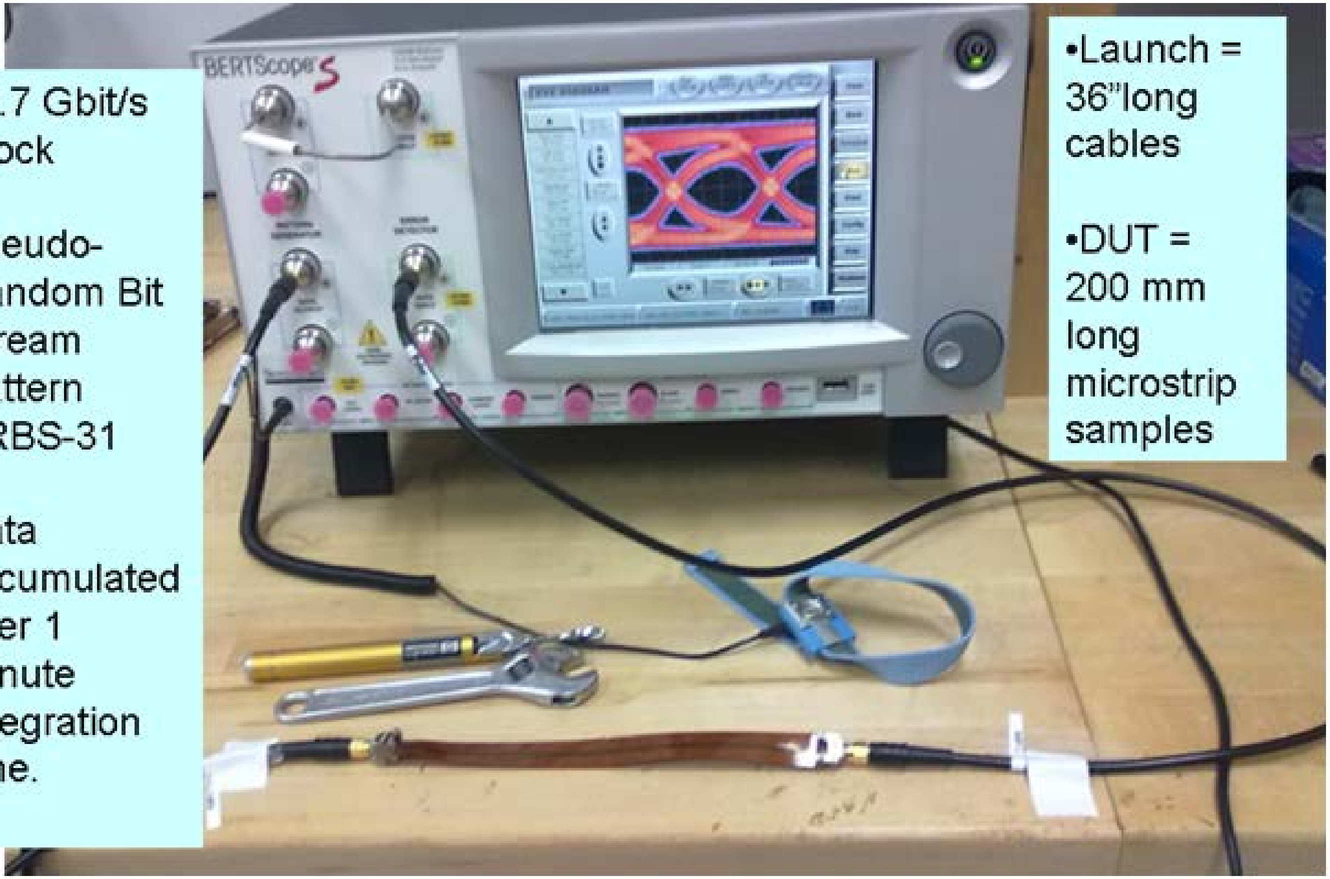


Discussion on Coverlay Loss

- Not a huge effect at lower frequencies (<5 GHz).
- Becomes more significant as frequencies increase to 10 GHz and above. The dominant factor is the acrylic adhesive in the coverlay.
- Not a big impact on FR4 material since epoxy has even higher loss than the coverlay acrylic.
- Effect can be exaggerated at higher frequencies since fabricators often roughen the copper surface to promote coverlay adhesion. A rougher surface will also increase loss at high frequencies.
- Although the coverlay effect was not as bad as expected, an adhesive with a lower dielectric loss is an area in which new materials are needed if low loss is of primary importance at high frequency.

Digital Signal – Eye Patterns

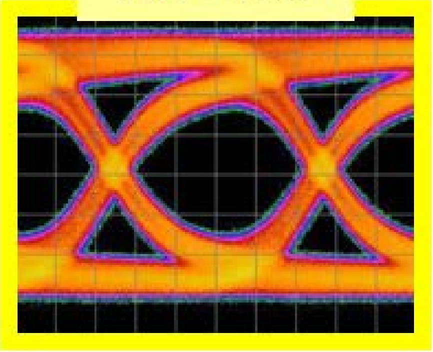
- 10.7 Gbit/s Clock
- Pseudo-Random Bit Stream Pattern PRBS-31
- Data accumulated over 1 minute integration time.



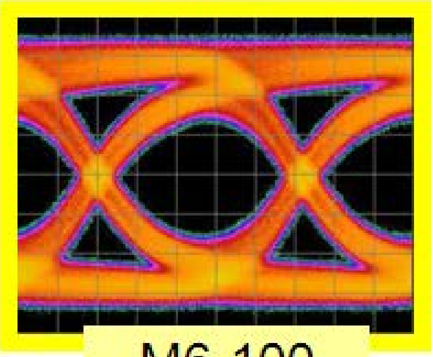
•Launch = 36"long cables

•DUT = 200 mm long microstrip samples

AP-100



V: 150 mV/div
H: 18 ps/div



M6-100

Eye Pattern Results - Microstrip

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps) Time (ps)	% difference vs M6	Signal Amplitude (mV)	% difference vs M6	P-P Jitter (ps) (ps)	% difference vs M6	Eye Height (mV) (mV)	% difference vs vs M6	Eye Width (ps) (ps)	% difference vs vs M6	Signal to Noise Ratio (dB)	% difference vs vs M6
2x36"cables+2cm Thru	30.4		882.9		12.5		701.8		81.3		7.5	
100um FR4: 51 ohms	52.9	8%	739.3	-8%	34.4	65%	241.1	-45%	60.4	-17%	3.1	-1.5 dB
100um M4 51 ohms	52.3	7%	785.7	-2%	25.4	22%	362.9	-18%	68.6	-6%	4.0	-0.6 dB
100um M6 50 ohms	49.1		800.0		20.8		440.0		72.8		4.6	
100um AP: 55 ohms	47.4	-3%	817.5	2%	19.8	-5%	463.9	5%	74.9	3%	5.0	+0.4 dB
100um TK: 60 ohms	46.8	-5%	822.9	3%	18.4	-12%	478.9	9%	75.2	3%	5.1	+0.5 dB
75um TK: 50 ohms	49.3		823.9		20.4		447.9		73.7		4.8	
50um M4: 51 ohms	53.7	1%	730.0	-4%	37.7	19%	222.9	-30%	56.0	-11%	2.9	-0.8 dB
50um M6: 52 ohms	53.3		757.2		31.7		320.0		63.3		3.7	
50um AP: 50 ohms	50.9	-5%	754.3	0%	26.8	-16%	334.3	4%	67.4	6%	3.9	+0.2 dB
50um TK: 49 ohms	52.9	-1%	782.2	3%	24.1	-24%	366.4	15%	70.2	11%	4.3	+0.6 dB

- Attempted to compare 50 ohm examples of each. The TK-100 was the lowest impedance line available.
- Lower Er for flex materials leads to less jitter and improved eye width.
- Lower loss for flex materials leads improved eye height.

Eye Patterns – Covered Microstrip

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps)		Fall Time (ps)		Amplitude		P-P Jitter (ps)		Eye Height (mV)		Eye Width (ps)		Signal to Noise Ratio	
	Time (ps)	% diff with coverlay	(ps)	% diff with coverlay	(mV)	% diff with coverlay	(ps)	% diff with coverlay	(mV)	% diff with coverlay	(ps)	% diff with coverlay	(dB)	dB diff with coverlay
2x36"cables+2cm Thru	31.0		29.7		884.3		12.5		704.3		80.9		7.5	
100um FR4: 48 ohms	54.8	4%	53.0	2%	727.2	-2%	39.3	14%	218.6	-9%	54.5	-10%	2.8	-0.3 dB
100um AP: 55 ohms	48.9	3%	48.3	3%	788.6	-4%	21.3	7%	425.7	-8%	72.5	-3%	4.6	-0.4 dB
100um TK: 55 ohms	50.6	8%	49.9	9%	830.0	1%	21.4	17%	434.3	-9%	72.8	-3%	4.6	-0.5 dB
75um TK: 52 ohms	52.5	6%	51.6	7%	794.3	-4%	24.4	20%	402.9	-10%	70.3	-5%	4.5	-0.3 dB
50um AP: 48 ohms	51.9	2%	51.6	1%	715.7	-5%	32.7	22%	268.6	-20%	61.0	-9%	3.3	-0.6 dB
50um TK: 50 ohms	53.8	2%	52.7	0%	761.4	-3%	33.1	37%	274.3	-25%	61.4	-13%	3.4	-0.9 dB

- Coverlay had a more negative impact on jitter than expected. This is likely due to the dielectric constant mismatch between the coverlay and the clad dielectric. Mismatch is larger with the composite clads.

- Reduction in eye height consistent with loss degradation shown in loss summary.

- Coverlay effect is more significant as overall stackup thickness decreases.

Overall Conclusions

- Lower dielectric constant options are attractive
  - Wider Lines
  - Signal Travels Faster

- All Polyimide Flex and Fluoropolymer / Polyimide Composites offer significant advantages for thin transmission lines.
  - Lower Dielectric Constant
  - Lower Loss
  - No Glass

- Digital signal analysis shows simple flex interconnects can be viable options for high speed transmission.

- Coverlay adhesive does increase loss and slightly degrades eye performance.

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