DesignCon 2012

Comprehensive Analysis of Flexible Circuit Materials Performance in Frequency and Time Domains

Glenn Oliver, DuPont Electronics & Communications
glenn.e.oliver@dupont.com

Jim Nadolny, Samtec
jim.nadolny@samtec.com

Deepukumar Nair, DuPont Electronics & Communications
deepukumar.nair@dupont.com

Abstract

A thorough analysis of measured propagation properties in both frequency and time domain is presented for both flex and thin rigid transmission lines. This work is presented in three phases. The first phase is an "apples-to-apples" microstrip comparison of flex and thin rigid materials. Some of the variables analyzed are amount of fluoropolymer in the material (0%, 50%, 67%), type of Copper (RA, ED) and profile of Copper (standard ED, ultra-low ED, ultra-low RA). Design parameters like Er, Tan δ and Roughness are extracted and compared to simulated results utilizing equation-based methods and electromagnetic solvers. Two different approaches to parameter extraction are compared. The first method utilizes closed form equations and an electromagnetic field solver for microstrip structures. The second method utilizes Simbeor to extract parameters based on stripline structures. Both methods are verified by comparison of models to measured microstrip and stripline transmission lines. As an application example, the extracted design parameters are utilized to assess the performance differences between different materials in a Generation 3 PCI-Express application. Follow-on work was done to isolate and analyze the effects of Electroless Nickel-Gold (ENIG) surface finish and flexible dielectric coverlay on the loss properties.

Authors Biographies

Glenn Oliver - B.S. in Physics and his Masters in Engineering from North Carolina State University. His work background includes 8 years in Photonics research and development followed by 8 years in RF/Microwave development and applications. He is currently the principal engineer responsible for characterization of electrical properties of materials for high frequency applications. His other areas of focus are high speed flexible circuitry interconnect and high frequency applications support.

Jim Nadolny - Jim has an MSEE from the University of New Mexico and is the author of more than 20 publications on SI and EMI topics. He has more than 15 years in the connector industry and is a frequent contributor to DesignCon with paper awards in 2004 and 2008. At Samtec he leads Global SI efforts.

Deepukumar Nair - Holds two MSEE degrees, one in microwave engineering and another one in fiber optics and photonics as well as an MBA in general management. Has fifteen years of extensive; hands on experience in microwave and millimeter wave circuit and antenna design as well as program management, engineering management, and systems engineering. Currently responsible for applications development for millimeter wave materials at DuPont Electronic Technologies.

Introduction

Two trends are clear in high speed design; data rates are increasing and form factors are getting smaller. In general, these requirements must be met with no additions to loss budget. In response to this reality, designers have begun considering flex materials for high speed applications since these laminates are inherently thin. Flexible circuit materials differ significantly in terms of how they fit in to the requirements. Copper clad laminates that contain epoxy or acrylic based adhesives are not suitable for high speed due to their limited frequency response. On the other hand, a class of flexible copper clad laminates called "adhesiveless" materials is well suited for low-loss applications at higher frequencies. Over the past two years, great strides have been made in the characterization of dielectrics used in flexible circuit laminates. Polyimide(PI) is an industry standard material widely used for flex applications due to its superior mechanical and good electrical properties. Work presented at DesignCon 2010 and 2011 has shown that dielectric properties of PI laminates are significantly better at RF/Microwave frequencies than previously understood by conventional wisdom in the design community. [1,2] Electrical properties of PI based flex laminates can be further improved by forming PI-Fluoropolymer composites as in Pyralux® TK. These materials can perform equivalent to materials in the "low loss" categories of dielectrics. Initial results have been encouraging to the design community demonstrating the potential of flex circuits to expand further into high speed applications.

Of course, a flexible laminate consists of BOTH dielectrics AND conductor. Providing a dielectric constant/ loss tangent of the dielectric only is not sufficient for effective design work because conductor effects are often more significant than dielectric properties at speeds higher than 8 Gbits/s or frequencies higher than 4 GHz. This is especially true for flex interconnects where the dielectric thickness approaches or is less than the copper thickness. Recognizing this fact, a comprehensive study of Time Domain and Frequency Domain properties of flexible laminates was undertaken. Factors evaluated in this study also include effects of Copper profile, surface finish and the impact of adhesive covering.

This work is divided into three phases. Phase I focuses on differentiating basic performance properties of thin (50-100 um) clad materials using fundamental microstrip test structures and extracting basic properties like Er and Tan δ based on these measurements. In Phase II, a stripline construction is manufactured and parameters are extracted using Simbeor. In Phase III the extracted stripline parameters are applied to a real world application to determine impact on product performance.

Additional work will also be presented to isolate and analyze the effects of a flash Electroless Nickel Gold (ENIG) surface finish on the loss. Loss data will be compared directly to the results without any surface finish presented in Phase 1. The effect of flexible coverlay (Kapton® plus adhesive on one side) on loss will be analyzed in the same way and compared to baseline results. The time domain effects on the coverlay will also be analyzed in the same way as in Phase I by comparing eye patterns with the same stimulus with and without coverlay present.

Phase I – Rigid and Flex Clad Measurements

The approach taken in the first phase is to generate a standard test pattern and compare all materials on an "apples-to- apples" basis. The same artwork is used to produce a test board having 25 microstrip lines per test with 5 line widths (W = 100-200 um) and 5 line lengths (20 – 400 mm) which are characterized both in Time and Frequency domains. From this comprehensive data set, the following information can be directly evaluated:

- Dielectric Constant to Specify for Manufacturing (from TDR Impedance)
- Frequency Domain Transmission Loss per Unit Length (0.2 – 25 GHz)
- Time Domain Link Performance Improvement (from Eye Pattern)

The TDR waveform measurements are typical of what would be found in a circuit fabrication environment (t_r = 200 ps). The VNA measurements are two port S-Parameters measured between 0.2 – 25 GHz. The BERTScope measurements are eye patterns of 10.7 Gbit/s PRBS-31 signals.

The materials evaluated in Phase I include flex laminates designed specifically for high frequency/high speed applications. These materials are composites of polyimide and fluoropolymers. The percentages of fluoropolymer in the material are 0%, 50% and 67%. All of these materials have low profile Rolled-Annealed (RA) Copper and are compared to three grades of FR4 with both ultra-low and standard profile Electro-Deposited (ED) Copper. All of the materials evaluated are commercially available products.

From the direct observations of loss and impedance, design parameters like Dielectric Permittivity (Er), Dissipation Factor (DF) and conductor Roughness (Ra) can be extracted for designers and fabricators to utilize for simulation and prediction. These parameters will be validated using commercially available simulation software that are based on closed form empirical equations (Polar SI 9000), planar electromagnetic solvers (Sonnet) A detailed comparison of results will be presented.

Phase II – Simbeor Parameter Extraction

In Phase II, properties using alternate methods than those used in Phase I are compared. Fundamentally, the S-parameters of flex circuits will be measured to extract the Er and DF over a broad frequency range (300KHz -20 GHz). This method assumes the loss behavior follows a classic physics model of TEM propagation in lossy media. The data is fit to a causal model and values for Er and DF are derived. Simbeor, a commercial SI tool, is used for this parameter extraction. These extracted values are compared to both the parameters determined by fundamental test structures in Phase I. Also, a similar approach is taken using EM field solvers to verify that the parameters accurately predict circuit behavior. These results will also be compared to historical Er and Tan δ data presented in addition to the data presented in Phase I.

Phase III – Applications Example

The final phase quantifies the impact of improved materials in a real world application. We consider a flex assembly which consists of high density, microstrip style connectors married with a flex circuit. Using the material parameters obtained in Phase I and Phase II, we will determine its suitability for a mainstream PCIe Gen 3 application. A commercial tool, Agilent ADS, is used to simulate the PCIe Gen 3 environment including a multi-tap FIR equalizer on the transmitter and a CTLE filter with DFE on the receiver. This real world case study illustrates that low loss flex assemblies can be used at lengths to 20” for 8 Gbps applications.

Phase I – Description of Work

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, were fabricated and tested under similar conditions, and data analyzed in the same fashion. Comparisons were made with similar copper thickness, dielectric thickness and line widths. Space limitations of this paper format preclude a complete discussion of the test coupon, but these details have been published previously. [3]

All samples were terminated with Southwest Microwave End-Launched SMA connectors (Part Number 292-07A-5) that are valid up to 27 GHz.[4] Impedance waveforms were measured using a standard TDR commonly used by fabricators, Polar CITS system.[5] Five line widths were evaluated per clad. TDR waveforms of impedance versus time were measured for the 100 mm, 200 mm and 400 mm lengths for each line width.

S-Parameters were measured using an Anritsu Lightning Vector Network Analyzer swept from 0.2 – 25 GHz with a frequency step of 16 MHz. [6] A Short-Open-Load-Thru (SOLT) calibration was utilized for all S-Parameter measurements on all clads. SOLT was chosen since all clads have different dielectric constants. If a Thru-Reflect-Line (TRL) calibration method were chosen instead, it is likely that data would be less noisy but the results but the comparison between the clads would not truly be “apples to apples”. 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/cm. A rich data of loss per unit length measurements of 25 lines and an overall average is reported as a fit to a sixth-order polynomial curve. Transmission loss as a function of frequency is measured on line lengths of 20 mm, 50 mm, 100 mm, 200 mm and 400 mm for at least 5 different line widths. One set of these five line lengths is shown in Figure 1. This figure also shows the connectors used.

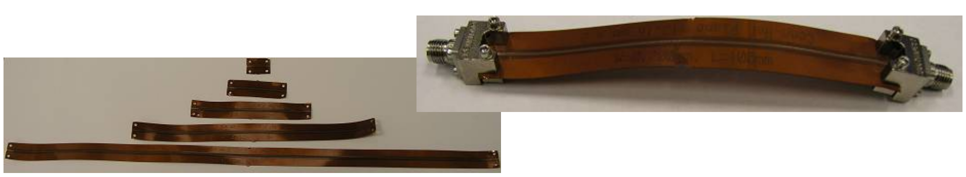


Figure 1 – Five of the 25 lines from a tested clad, one shown with connectors attached

Eye Patterns are measured using a Bit Error Rate test unit with an integrated pattern generator and error detector. [7] The generator and detector were matched to a 31 Bit Long Pseudo-Random Bit Stream (PRBS-31).with the Clock set to 10.7 Gbit/s. Lines with similar impedance are compared to each other and evaluated by how well the bits are transmitted through the data link. One line per clad is measured, the 200 mm long line closest to 50 ohms.

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

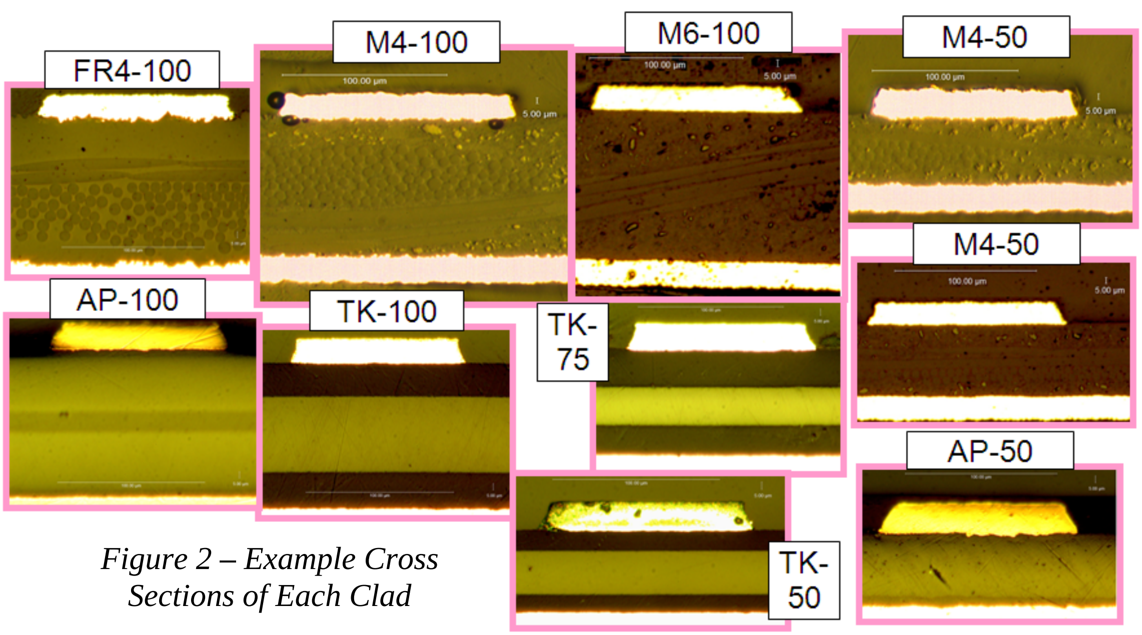
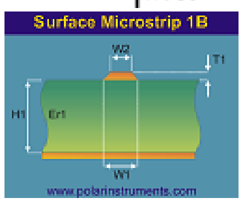


Figure 2 – Example Cross Sections of Each Clad

Phase I – Part A: Dielectric Constant Extraction from Impedance

Dielectric constant was determined from TDR measurements of each clad. Cross sections were made for each line width defined on all clads. This analysis was necessary since the same artwork was used for all the samples so the imaged width was used to label the line samples (W_{art}). Figure 2 shows a typical cross section for each clad evaluated. Physical measurements were made for each cross section. Specific measurements made were line width, copper thickness and dielectric thickness. This analysis was performed on five different line widths for each clad.

Flexible Clads (dimensions in um)					
Clad	Wart	H1	T1	W1	W2
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



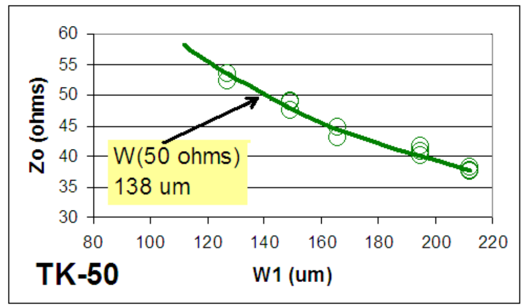


Figure 3 – Determination of 50 Ohm Line Width

Impedance was measured on the 400 mm, 200 mm and 100 mm long lines for each clad sample. The average TDR value for the center 50% of the waveform was determined to be the impedance value for each line. The line width in contact with the dielectric (W1) was then plotted against the measured impedance and a curve was fit to determine the 50 ohm line width. Figure 3 shows the detailed analysis used to determine the 50 ohm line width for the TK-50 clad sample. This same analysis was done for all clads, but the details are shown for this one example due to space limitations. The 50 ohm line width can be plotted versus dielectric constant using an impedance solver. [8] These plots are superimposed with the measured 50 ohm line widths to determine the dielectric constant experimentally. This analysis is summarized in Figure 4 where it is shown that Er(FR4-100) = 4.2, Er(M4-100) = 3.6, Er(M6-100) = 3.4, Er(AP-100)=3.1, Er(TK-100)=2.5, Er(TK-75) = 2.3, Er(M4-50) = 3.5, Er(M6-50) = 3.3, Er(AP-50) = 3.1 and Er(TK-50) = 2.5.

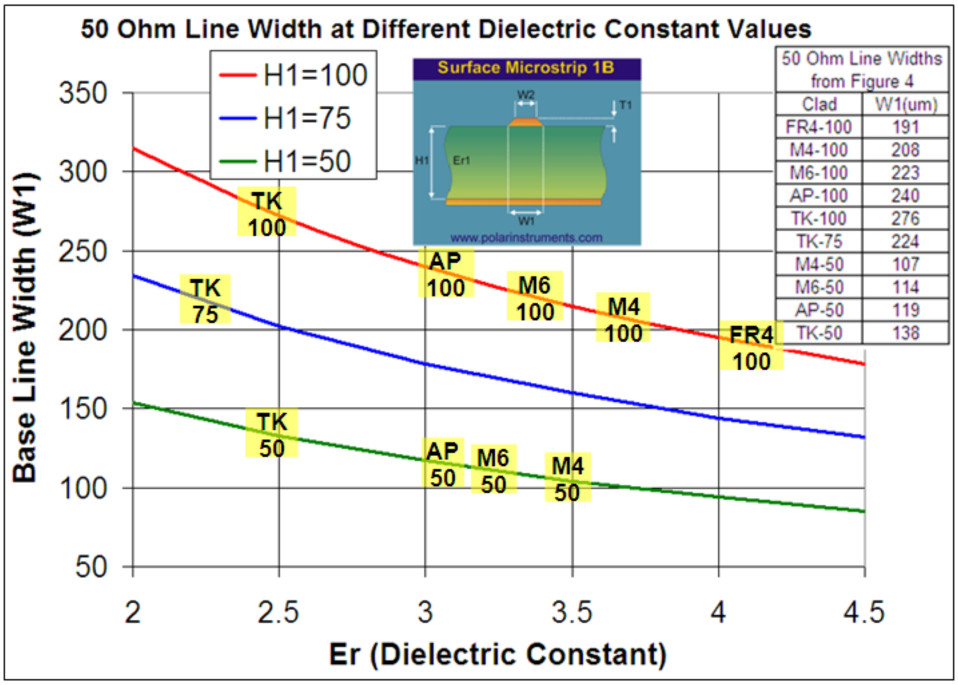


Figure 4 – Extracted Er Values from 50 Ohm Line Width Measurements

Phase I – Part B: Frequency Domain Loss per Unit Length

Since there are many material dependent variables that affect signal loss, the implementation of "apples to apples" comparison is especially critical to determine the differences between materials. Variables that are constant for each clad evaluated are copper thickness, line widths (artwork), and line lengths. Five of the materials evaluated had a dielectric thickness of 100 um so direct comparison could be done between these. Four of the samples evaluated had a dielectric thickness of 50 um so these could be compared directly. There was one sample that was 75 um thick, so this summary result was placed with the 50 um sample for reference instead of direct comparison. These results are summarized in Figure 5.

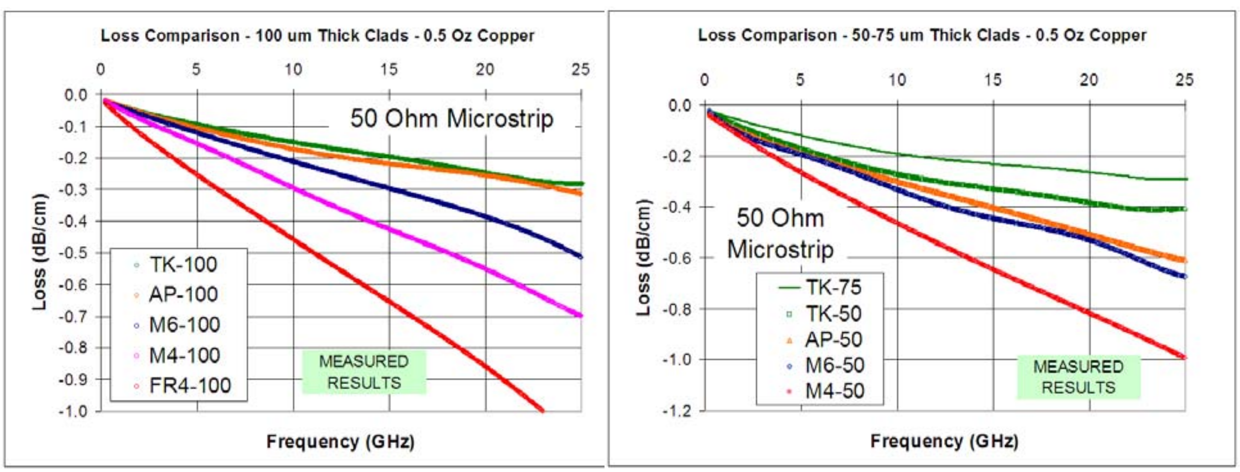


Figure 5 – Loss Comparison Microstrip Lines from 10 Different Clad Samples

Phase I – Part C: Eye Pattern Comparison at 10.7 Gbits/sec

Eye patterns were directly measured for each clad sample and compared. One sample from each clad was chosen. The 200 mm long line closest to 50 ohms was chosen as the sample. Figure 6 shows the test conditions and screen shots of two of the ten eye patterns measured. Parameters of each eye pattern are detailed in Table 1. All the results are compared relative to the two thickness of Megtron 6. Results are color coded for ease of comparison.

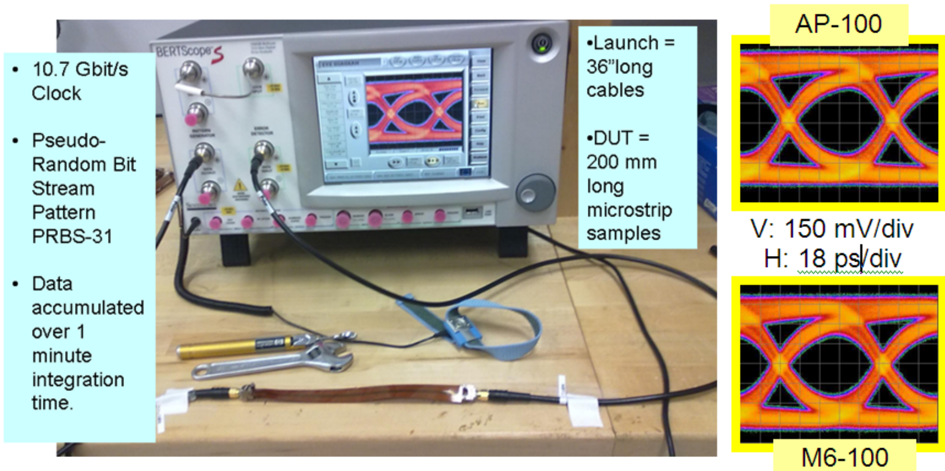


Figure 6 – Eye Pattern Test Setup and Example Eye Patterns

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps) Time (ps)	Rise Time (ps) % difference vs Megtron 6	Signal Amplitude (mV)	Signal Amplitude % difference vs Megtron 6	P-P Jitter (ps) (ps)	P-P Jitter (ps) % difference vs Megtron 6	Eye Height (mV) (mV)	Eye Height (mV) % difference vs Megtron 6	Eye Width (ps) (ps)	Eye Width (ps) % difference vs Megtron 6	Signal to Noise Ratio (dB)	Signal to Noise Ratio % difference vs Megtron 6
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

Table 1 – Detailed Data Extracted from Eye Patterns

Phase I – Extraction of Loss Tangent from Line Measurements

The key figure of merit that was desired to be extracted was dielectric loss tangent based on measured loss data. To do this, it is necessary to make some basic assumptions on some of the material properties. Part A of this phase of the study obtained values of dielectric constant. The two properties of copper that were needed to develop models were conductivity and roughness. Initially, conductivity was assumed to be the "textbook" value for copper of 5.7×10^{7} S/m. Using this value, extracted values of loss tangent for Megtron 6 came out to be 0.010 at 10 GHz, which is known to be incorrect. DC Measurements were made of all the clads to determine the actual conductivity for the microstrip lines. Since cross sectional dimensions were measured for all lines, it is a trivial exercise to determine the actual conductivity. All the copper clads had approximately the same measured conductivity of 4×10^{7} S/m. This value was used for all the models.

Roughness (Ra) of the copper surface in contact with the dielectric was determined directly for TK and AP samples since these were obtained directly from manufacturing. Ra values for these samples were between 0.3-0.4 um. The copper roughness of FR4 was determined empirically to be Ra=1.2 um since the loss tangent of this material is known to be about 0.015 at 10 GHz when this value was used in the model. The Megtron 6 roughness value was assumed to be equivalent to that of TK based on cross section observation and the stated estimates from the product data. The Megtron 4 roughness value was assumed to be 0.6 um based on observations made from cross sections.

Two sets of models for loss tangent were created for each clad evaluated. The first set of models developed is based on closed form calculations of loss. These calculations were performed using Polar Instruments SI-9000 Frequency Dependent Calculation [8] and Agilent Advanced Design System (ADS) MLIN and MSUB models [9] and were found to be equivalent. For each model, 50 ohm conditions were modeled based on the values determined experimentally. The only variable not assumed to be constant was loss tangent. Calculations were performed at loss tangent values that are overlaid against measured data to extract the loss tangent. These models were constructed for each of the ten samples evaluated in Phase I of this study. These models are shown in Figures 7-14 identified as "ADS" models.

The second set of models utilized an industry standard method of moment EM simulation tool Sonnet. [10] This tool takes a significantly different approach since it performs full Electro-Magnetic simulation of the test structures to capture any details that may be omitted by closed form equation based solvers like ADS. The 3D microstrip geometry is meshed to a large number of elemental volumes and Maxwell's equations are solved using Method of Moments imposing the general boundary conditions and material properties within each element. To keep the simulation geometry relatively simpler so as to reduce computational time, a 1 mm long microstrip line is assumed for all test cases. It is then scaled to a 1 cm line for the S parameters without losing any generality to do a direct comparison to the experimental data. Sonnet provides sophisticated options to handle various metal and dielectric layers. Specific "thick" copper metal model with roughness was used in these simulations. S parameters were calculated in the frequency range 1 to 25 GHz and the loss tangent of the dielectric is kept as a parameters varying through appropriate ranges. For the comparison purposes only the transmission parameter S21 is considered. These models are shown side-by-side to the closed form calculated models in Figures 7-14 identified as "Sonnet" models.

There is an additional model shown for each of the "TK" samples (Figure 11). In each of the Sonnet models, the dielectric is assumed to be homogeneous. Since Sonnet allows for multiple dielectric layers in a composite structure, only the loss tangent of the internal Kapton® layer is assumed to be in question. The Teflon® has a very low dielectric loss tangent of about 0.0005 assumed to be constant. This was done in attempt to explain the loss performance at frequencies higher than 10 GHz. It is assumed that the Teflon® in close proximity to the signal line partially explains the lower than expected loss observed at frequencies higher than 10 GHz.

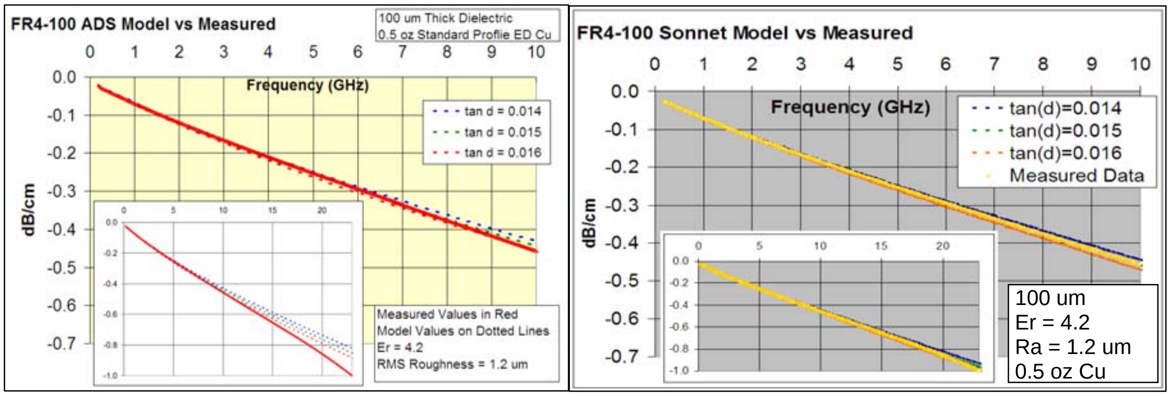


Figure 7 – FR4-100 ADS and Sonnet Models of Loss Tangent

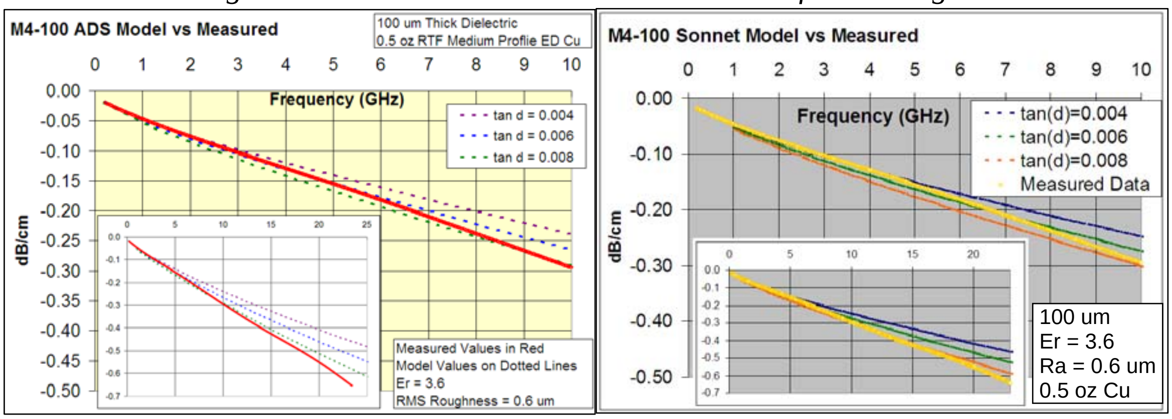


Figure 8 – M4-100 ADS and Sonnet Models of Loss Tangent

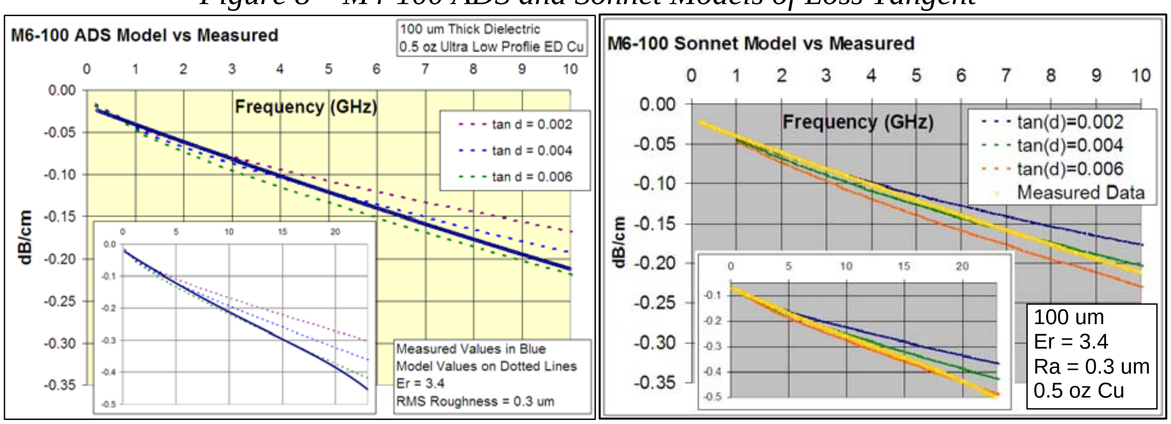


Figure 9 – M6-100 ADS and Sonnet Models of Loss Tangent

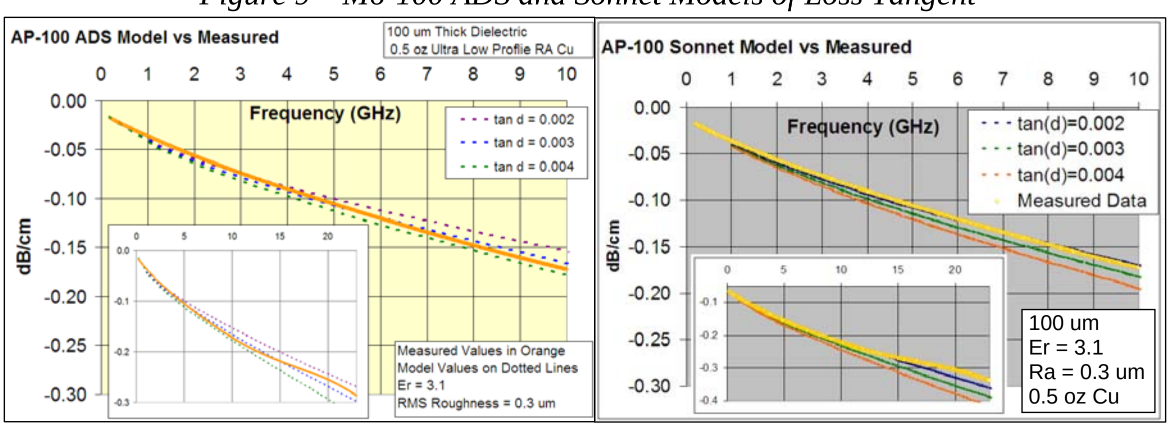


Figure 10 – AP-100 ADS and Sonnet Models of Loss Tangent

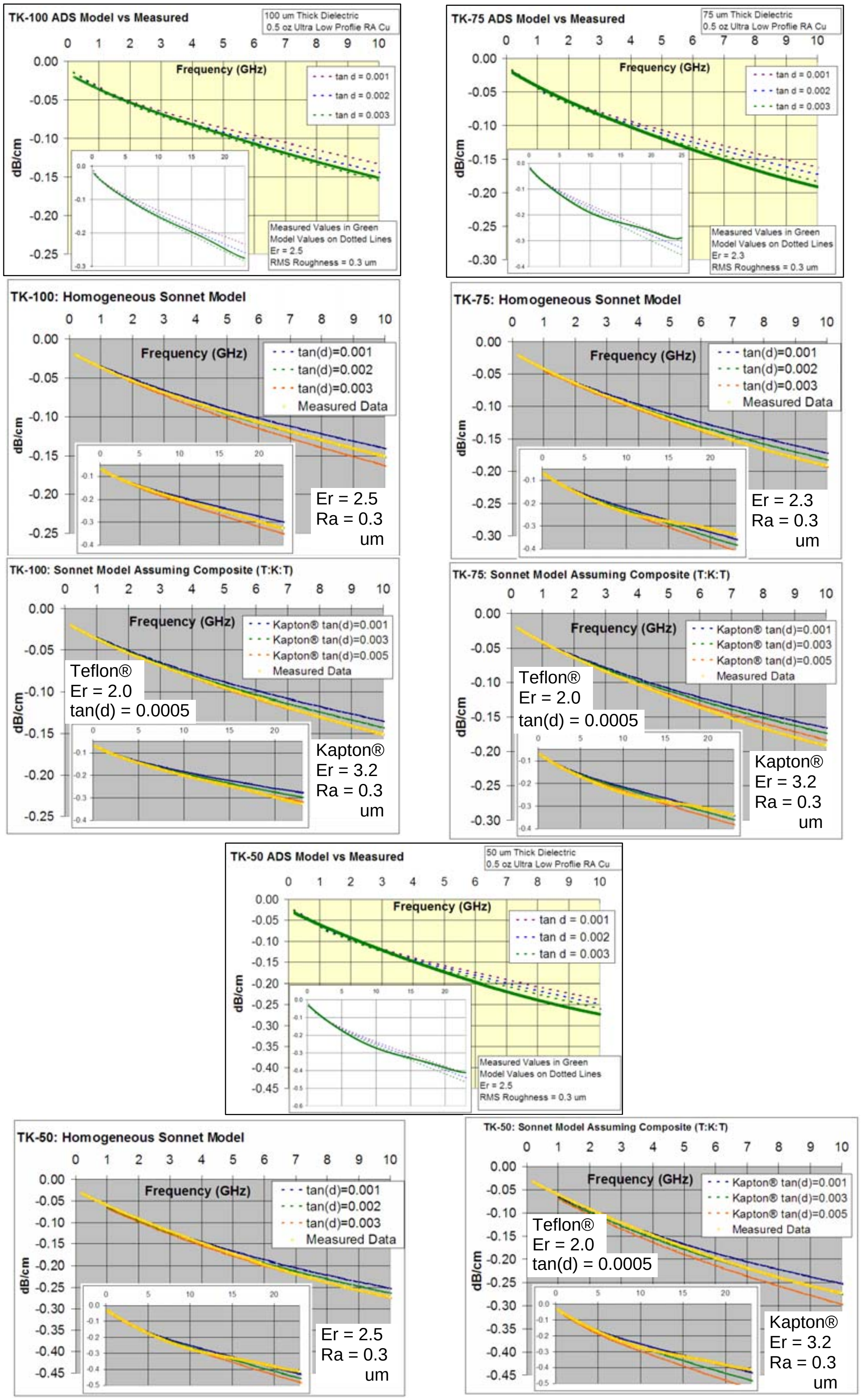


Figure 11 – All TK Loss Models Considering Homogeneous and Composite Cases

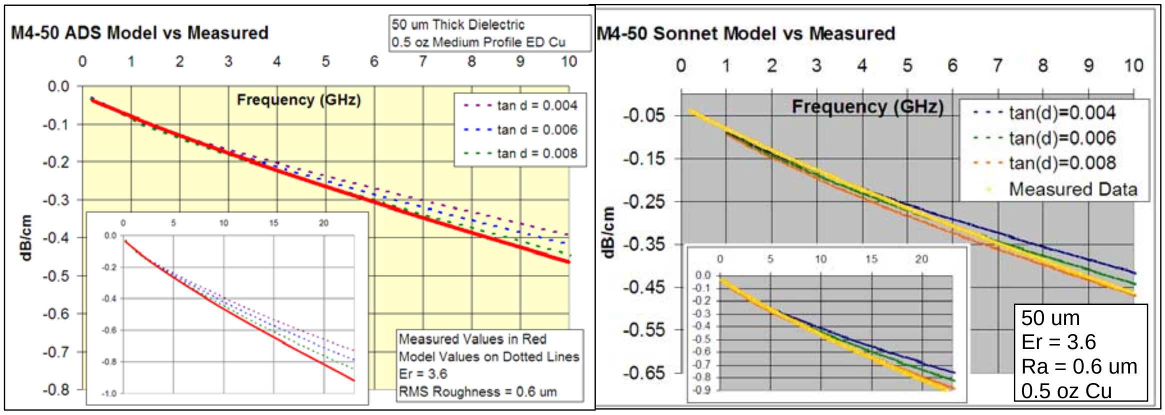


Figure 12 – M4-50 ADS and Sonnet Models of Loss Tangent

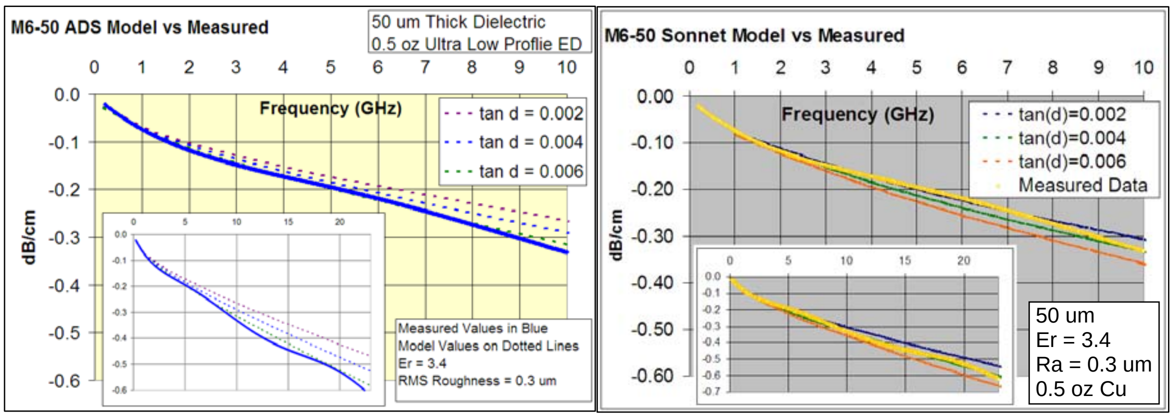


Figure 13 – M6-50 ADS and Sonnet Models of Loss Tangent

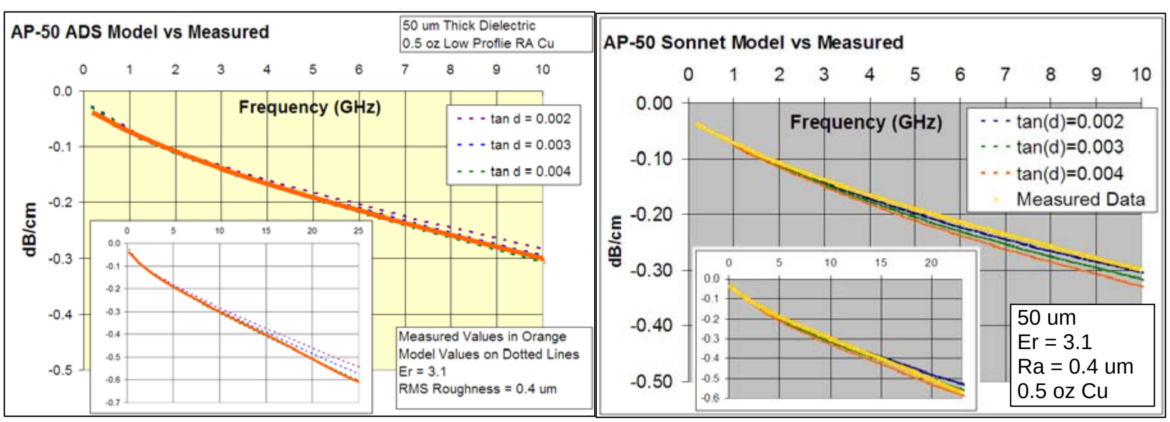


Figure 14 –AP-50 ADS and Sonnet Models of Loss Tangent

Phase II – Description of Work

A model based approach can also be used to derive material parameters. In this method a model of a structure is developed based on a known geometry. Model parameters are adjusted until the modeled response matches the measured response. The material parameters in the model which results in the best match are then used as the derived values.

This general approach relies on several assumptions:

1. It is assumed that the geometry is known
2. It is assumed that the model accurately approximates all physical effects in the measurement

Applying this approach to flex circuits can work well but care must be taken to avoid violating the basic assumptions. [11,12] The approach that works best is to simplify the geometry as much as possible so that we avoid problems with assumption 1. For assumption 2 we actually need a fairly sophisticated model to approximate all physical effects in a flex circuit.

Phase II - Simplifying the Geometry

To test a flex circuit probes of some type are required to interface instrumentation to the sample. For this study, custom SMA connectors were designed and fabricated to permit a consistent connection with optimized return loss characteristics on a flex circuit. Figure 16 shows a picture of this custom connector. The SMA interface is ideal for interfacing to a vector network analyzer (VNA) but they are still problematic. If a standard SOLT calibration is performed on the VNA, the reference plane will be at the SMA interface and the measurement will include the SMA to flex circuit transition.

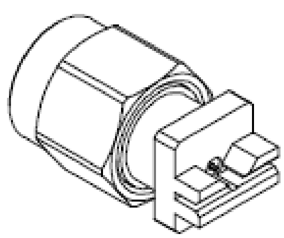


Figure 15 - Customized SMA Connector for Flex Assembly Testing

The problem arises when we try to model the flex circuit with the needlessly complex SMA transition. Methods exist to de-embed these launch effects from the measured data so that our modeling efforts can focus on the flex circuit. Simbeor, an electromagnetic signal integrity software tool, can easily de-embed the launch effects. [13] By reducing the measured geometry to a simple transmission line we can more accurately derive the material parameters.

Phase II - Approximating Physical Effects

Our current understanding of transmission line loss is that there are 5 physical mechanisms:

1. Dielectric Loss
2. Conductor Loss
   2a. Ohmic loss
   2b. Skin Effect loss
3. Reflection Loss
4. Crosstalk
5. Radiation

We assume that radiation loss is small and our sample design minimizes crosstalk, these terms are ignored in the modeling process. Reflection loss is accounted for in the Simbeor parameter extraction [13]. Dielectric loss is modeled using a frequency dependent loss tangent which preserves causality. Conductor loss is modeled using a constant conductivity and a Modified Hammerstad Correction Coefficient model for surface roughness.

Phase II - Results

The cross section for the TK flex samples is shows in Figure 16. Note that 2 different bondplys are used in the construction with slightly different characteristics. The extracted values will be the effective parameters for the composite structure.

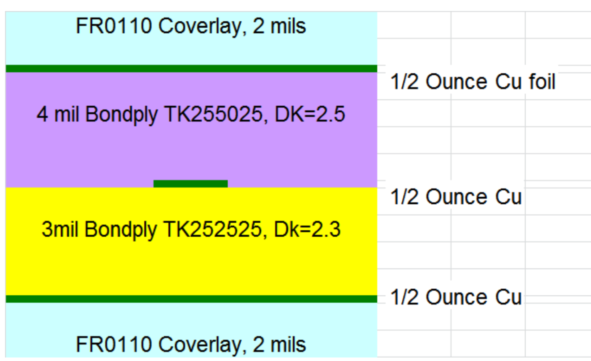


Figure16 - TK Flex Sample Cross Section

By adjusting model parameters in Simbeor the computed insertion loss is compared to the measured insertion loss. After only a few iterations very good correlation was achieved and is shown in Figure 17. In the model, there are actually 2 variables and only 1 known which means there can be many combinations which result in good correlation. The insertion loss is known but the copper conductivity and loss tangent are both unknowns. The classic value of copper conductivity is 5.8×10^7 S/m but this is not accurate for copper traces on flex circuits. For these simulations a value of 4.25×10^7 S/m is used based on physical measurements of conductivity.

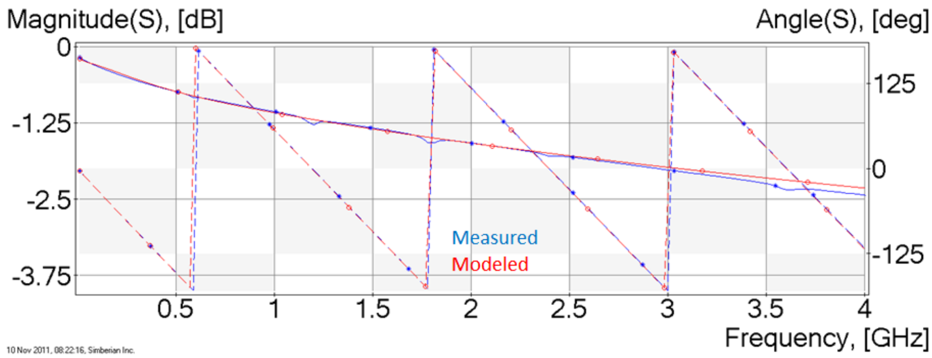


Figure 17 - Measured and Modeled Insertion Loss of TK Flex Circuit

The extracted values for Er and Df are shown in Figures 18.

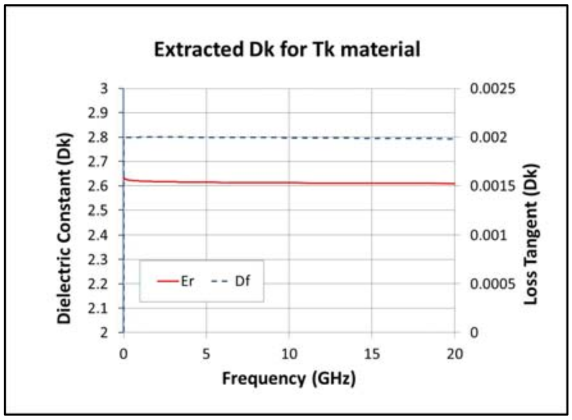


Figure 18 – Extracted value of Er and Df

Overall these values correlate very well with measurements obtained in Phase I of this study as shown in Table 2

	Simbeor Extraction	Phase 1
Er	2.62	2.5
DF	0.002	0.002

Table 2 - Comparison of Material Parameter Values

Phase III

The low loss properties of modern flex circuit interconnect are an advantage in high speed digital applications. The lower loss translates into improved system performance on existing designs or allows for longer interconnect lengths on new designs. To quantify the improvement, consider a PCIe Generation III design that operates at 8 Gb/s. [14]

The approach will rely on simulations of high density flex circuit assemblies ADS 2011.05 is the simulation environment and will combine models of the flex circuit and high density connectors.   The analysis is part of an ADS design template developed specifically for PCIe Gen III and uses behavioral models of PCIe Gen III drivers, receivers, chip packages and equalization.   PCIe Gen III uses a 3 tap FIR filter in the driver and a 2 pole CTLE filter with a 1 tap DFE in the receiver.

The flex circuit assembly includes the flex circuit and a Samtec ERM8/ERF8 connector. This combination is referred to as an ERDL2 assembly. The connector was modeled in CST microwave studio and the resulting S-parameter models are used in the analysis.

The first step is to compare the flex material in the absence of any connector discontinuities. The flex circuit is modeled in ADS using the multilayer T-line model which performs a 2D analysis of the cross section. The generic term “Kapton” is used to refer to Pyralux FR bondply and coverlay which is widely used at Samtec in production applications.   Figure 19 shows the stackups used and the resulting insertion loss for an 18” length of flex circuit.

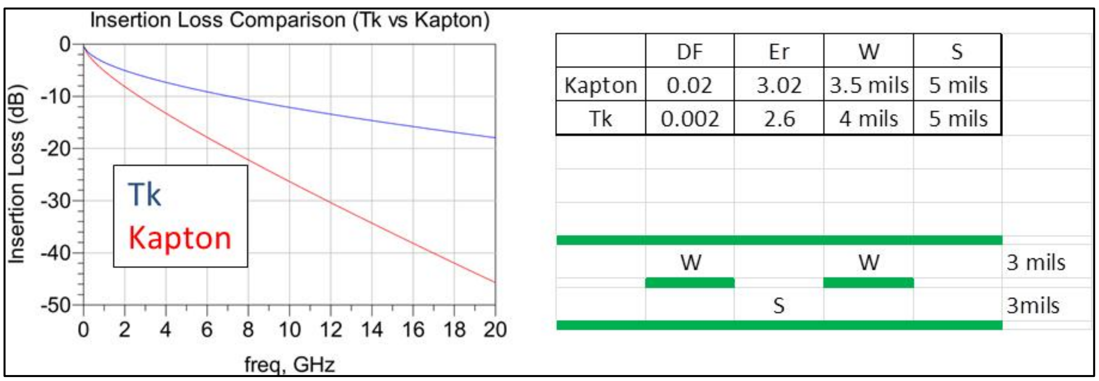


Figure 19 - Insertion Loss Comparison between Tk and Kapton Flex Circuits (Length =18”)

The next step is to include the effects of the ERM8/ERF8 connectors. At frequencies above 6 GHz the connectors begin to have an impact on the insertion loss of the assembly.   The insertion loss of the flex circuit assemblies are shown in Figure 20.

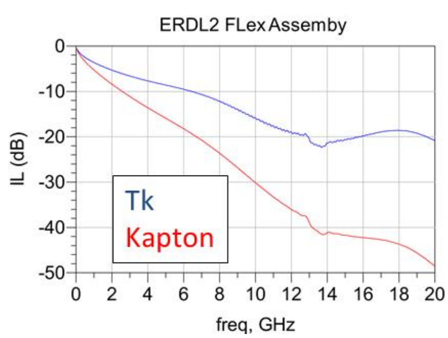


Figure 20 - Insertion Loss Comparison between Tk and Kapton Flex Circuit Assemblies (Length =18”)

The next step is to simulate the flex circuit assembly using a custom PCIe Gen III simulation environment. This simulation environment includes multiple crosstalk aggressors, Tx/Rx package parasitics, and equalization. Figure 21 shows the resultant eye patterns at the receiver for one specific set of equalization settings.

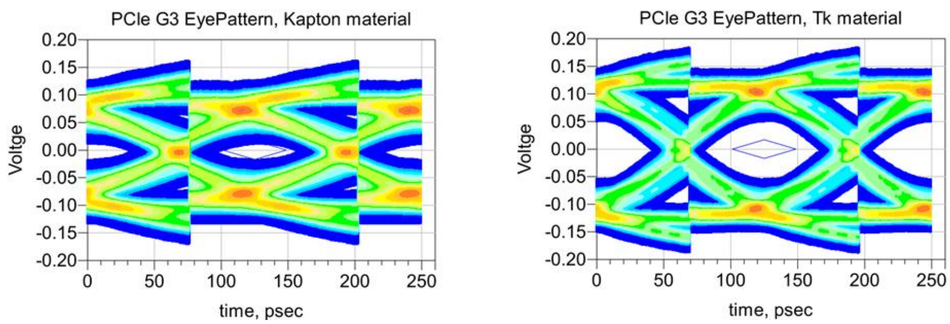


Figure21 - PCIe G3 Eye Pattern Comparison (Kapton – Left, Tk – Right), CTLE=6dB

There are multiple equalization settings that can be used for PCIe Gen III. One of the most critical settings is the CTLE gain which compensates for insertion loss. It is possible that adjusting a simple gain setting on this equalizer will correct for the additional losses associated with the Kapton material. Figure 22 shows that this is not the case. By performing batch simulations in ADS we can generate graphs of eye metrics versus a specific parameter such as CTLE gain. Figure 22 shows that for this length flex circuit assembly the Kapton material is not able to meet the required eye height even with equalization whereas the Tk material meets the specification with margin.

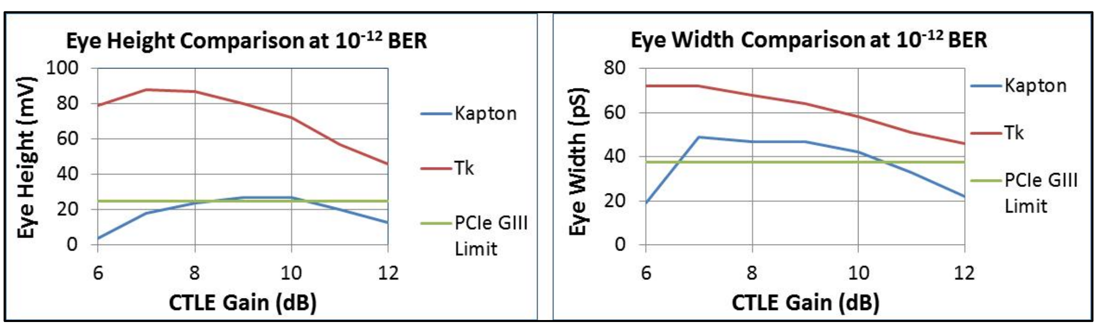


Figure 22 - PCIe G3 Eye Metric Comparison, CTLE=6-12 dB

Additional Work

Some follow-on work has already been done building on the foundation created in Phase I. Identical test coupons of all the flex materials evaluated were created with the only differences being the effects of surface finish and dielectric coatings. FR4 was done as a control for these additional cases.

Figure 23 shows the results of the loss testing of the baseline case in Phase I with the only difference being a flash finish of Electroless Nickel Gold (ENIG). This flash finish was applied to the signal lines and the bottom ground plane where it interfaces with the connectors. Coarsened points of the baseline data is shown for comparison so that the differences can be seen more clearly in this format.

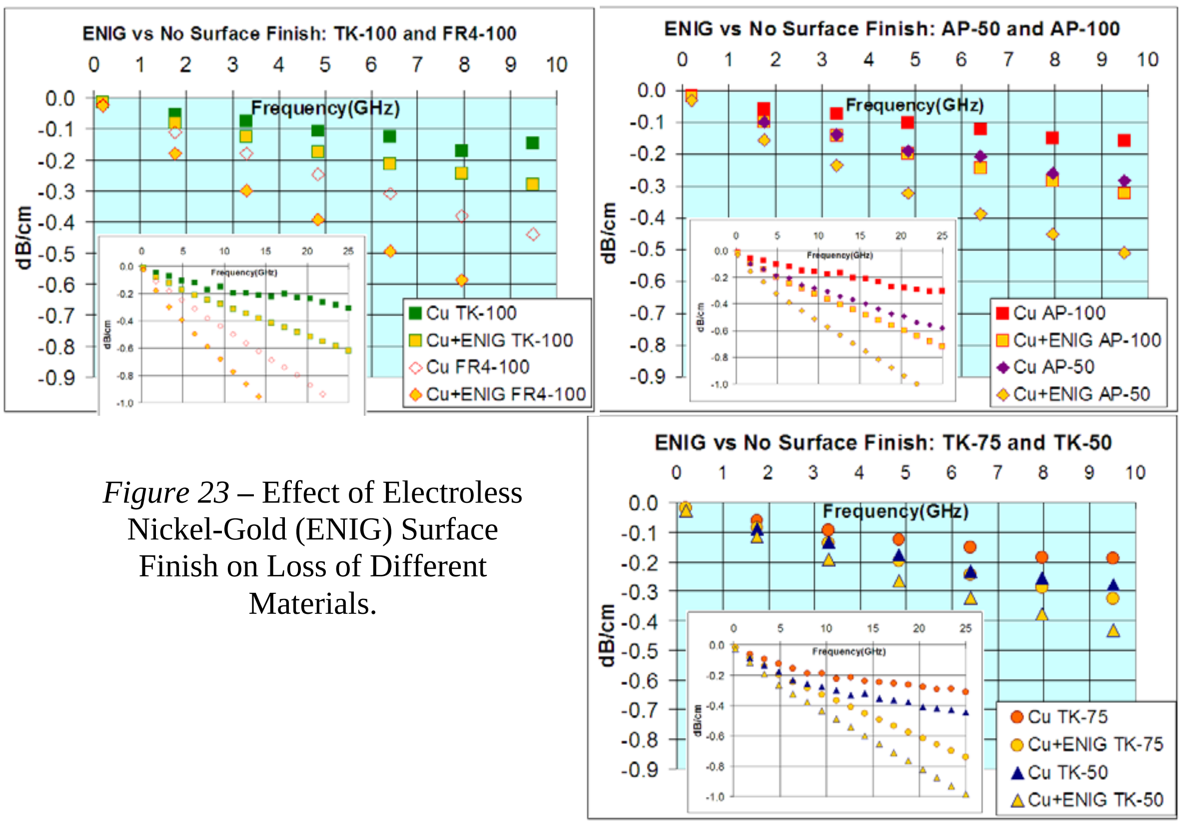
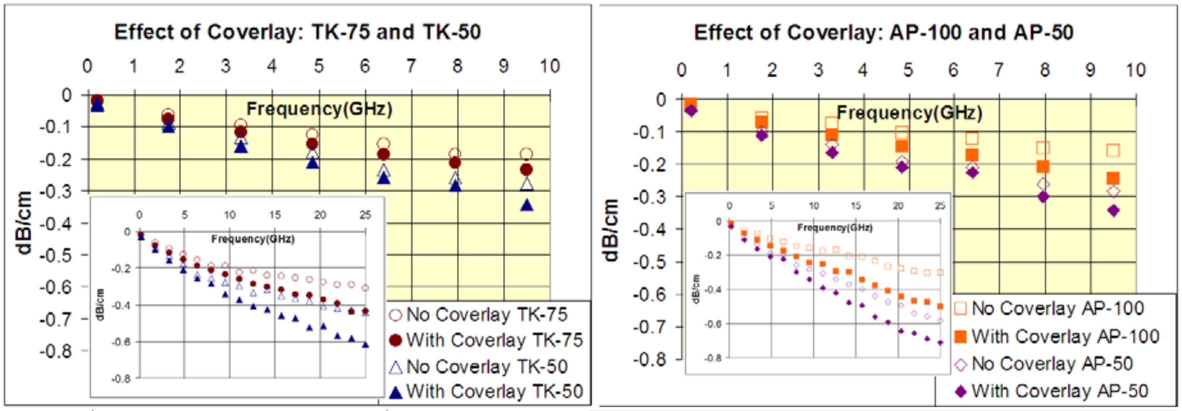


Figure 23 – Effect of Electroless Nickel-Gold (ENIG) Surface Finish on Loss of Different Materials.

Figure 24 shows the results of the loss testing of the baseline case in Phase I with the only difference being the addition of a laminated flexible coverlay. This coverlay is a layer of Kapton® coated with acrylic adhesive commonly used in flexible circuits. Specifically, the thickness of each layer was 25 um for the Kapton® and 25 um for the adhesive. This coverlay encapsulates the microstrip line with only a small opening to enable intimate contact with connector pins. Just as in the baseline case, 25 microstrip lines were measured per clad evaluated and the loss and length combinations were averaged together to obtain the final data set. Coarsened points of the baseline data is shown for comparison so that the differences can be seen more clearly in this format.



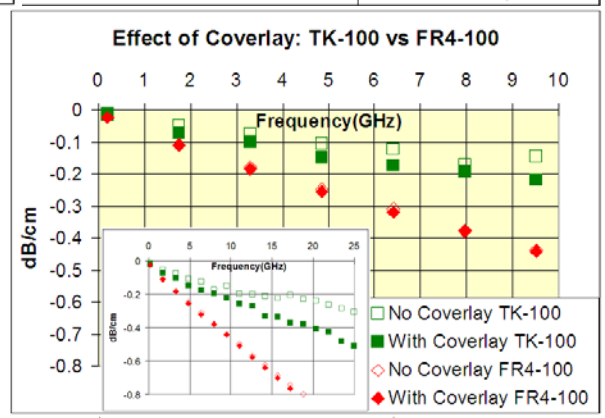


Figure 24 – Effect of Flex Coverlay on Loss of Different Materials.

The 200 um long coverlay study samples closest to 50 ohms were selected for comparison of time domain properties by evaluating eye patterns. The exact same settings used for the measurements were used as for the baseline case presented in Phase I. Recall that the original eye pattern results were analyzed relative to the properties of the best-performing rigid material. In this case, the intent is to isolate the effect of the coverlay dielectric. The results shown in Table 3 are compared to the data in Table 1 for this purpose. The odd result for TK-100 is explained by the impedance for the baseline case (from Table 1) was 60 ohms. The coverlay case for this sample has a better impedance match and has a higher signal amplitude as a result.

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps) Time (ps)	% diff with coverlay	Fall Time (ps) (ps)	% diff with coverlay	Amplitude (mV)	% diff with coverlay	P-P Jitter (ps) (ps)	% diff with coverlay	Eye Height (mV) (mV)	% diff with coverlay	Eye Width (ps) (ps)	% diff with coverlay	Signal to Noise Ratio (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

Table 3 – Eye Pattern Data of Microstrip Lines with Coverlay
Refer to Table 1 for Baseline (Uncovered) Data

Summary and Conclusions

A detailed study directly comparing key performance parameters of rigid to flexible copper clad laminates (50-100 um thick) was presented. The flexible materials evaluated had desirable properties compared to the rigid materials. The flexible materials showed improved permittivity, loss and eye patterns. The work presented went to great lengths to present this analysis as close as possible to the performance properties observed in real transmission links. The rich data set generated was compared to loss models generated from closed form equations and electromagnetic solvers. Estimates of loss tangent versus frequency were presented for each material evaluated.

Experts in design and fabrication of flexible circuits for interconnect applications built test vehicles to characterize stripline data links with new flexible material offerings versus traditional flexible dielectrics. Material parameters were successfully extracted utilizing a method with wide acceptance in the design community. These results were applied to the design of a PCIe Gen III link. Where traditional flexible material would not be able to meet the specification, a link made out of TK flex material has the properties needed to meet the link requirements.

One attractive feature of the approach taken in this study is the ability to isolate the effects of factors beyond just the properties of the copper clad laminate. By direct comparison, the effects of a surface finish like ENIG could be successfully evaluated. Likewise, the effects of flexible coverlay could also be isolated. Even though simple and seemingly minor factors like a flash surface finish or a coverlay may seem insignificant, the results of this study shows these effects could be as large as the base material at high frequencies.

Acknowledgements

Gerry Sinks, Jim Parisi and Ahmed Camacho performed countless hours of testing in the lab at DuPont to make these results possible.

Justin McAllister was instrumental in fabricating and testing the samples for Phase II, while Kieran Kelly performed the material parameter extraction. Finally, Rick Crabtree and Steve Hillerich were essential in fabricating the Phase II samples. Without their efforts, this contribution would not be possible.

References

[1] G. Oliver. "Characterization of Flexible Circuit Dielectrics for High Speed Applications". DesignCon 2011. www.designcon.com.

[2] G. Oliver. "Electrical Characterization of Flexible Circuit Materials at High Frequency". DesignCon 2010. www.designcon.com.

[3] UBM Media/DuPont "High speed? High frequency? And flexibility? Now you can have it all!" Webinar presented December 2011. www.dupont.com/tk

[4] Southwest Microwave. End Launched Connectors. Female SMA connectors with 5 mil diameter pin tested up to 27 GHz. www.southwestmicrowave.com.

[5] Polar Instruments. Controlled Impedance Test System (CITS). www.polarainstruments.com.

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

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

[8] Polar Instruments. SI-9000 Impedance Calculation Tool. www.polarainstruments.com.

[9] Agilent Technologies. Advanced Design System (ADS). www.agilent.com.

[10] Sonnet Software, Inc. Sonnet Suites™. www.sonnetsoftware.com.

[11] Yuriy Shlepnev, Alfred Neves, Tom Dagostino, Scott McMorrow, "Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR-4 board for 6-20 Gbps Applications" DesignCon 2009, February 2009

[12] Yuriy Shlepnev, Alfred Neves, Tom Dagostino, Scott McMorrow, "Practical Identification of Dispersive Dielectric Models with Generalized Modal S-parameters for analysis of Interconnects in 6-100 Gb/s Applications" DesignCon 2011, February 2011

[13] Simbeor Software, Simberian Inc.

[14] PCI Express Base Specification Revision 3.0, Version 0.9, August 10, 2010