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

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Outline

- Motivation for Work
- Overview of Testing and Analysis
  - Phase I
  - Phase II
  - Phase III
- Phase I Test Results and Analysis
- Phase II Test Results and Analysis
- Phase III Analysis
- Additional Results Compared to Phase I Baseline
**Motivation**

- Mobile network connection speeds will increase 10-fold by 2015 from 2010 Levels*
- Global mobile data traffic will increase 26-fold between 2010 and 2015*
- Two-thirds of the world’s mobile data will be video by 2015*

- Data transmission at high speeds used to involve very specialized circuitry that was concentrated near the processor.

- High speed signals are no longer restricted to thick packages. There are many more applications for thin dielectrics.
Thin vs Thick Copper Clad Laminates

For thin transmission lines at higher frequencies, many more factors influence signal loss than simply the dielectric loss tangent.

Each Example is 50 Ohms
How to Evaluate Thin Dielectrics?

Three Phase Plan:

- Phase I – “Apples to Apples” comparison of microstrip lines made from copper clads made from 100um and 50um thick dielectrics.
  - Five Rigid Clads versus Five Flexible Clads
  - Directly Measure Impedance, S-Parameters and Eye Patterns
  - Extract Permittivity from Impedance Measurements
  - Analyze Loss Tangent from Transmission Loss Measurements
  - Evaluate Time Domain Effects from Eye Patterns

- Phase II – Utilize specially designed connectors to obtain measured stripline results. Use Simbeor Methodology to extract parameters (Dk and Df) from stripline transmission lines.

- Phase III – Apply extracted parameters to a PCIe-Gen3 application. Compare to parameters extracted from traditional flex used as incumbent material.
Phase I - Apples to Apples Comparisons

All samples had 0.5 oz copper with dielectric between 50-100 um thick

- **Rigid Copper Clads:**
  - FR4-100  FR4 material, Standard Profile ED Cu, 100 um thick dielectric
  - M4-100  Mid-Range Glass / Epoxy, RTF Profile ED Cu, 100 um dielectric
  - M4-50  Mid-Range Glass / Epoxy, RTF Profile ED Cu, 50 um dielectric
  - M6-100  Low Loss Glass / Epoxy, Ultra Low Profile ED Cu, 100 um dielectric
  - M6-50  Low Loss Glass / Epoxy, Ultra Low Profile ED Cu, 50 um dielectric

- **Flexible Copper Clads:**
  - AP-100  Adhesiveless PI, Ultra Low Profile RA Cu, 100 um dielectric
  - AP-50  Adhesiveless PI, Low Profile RA Cu, 50 um dielectric
  - TK-100  Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 100 um dielectric
  - TK-75  Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 75 um dielectric
  - TK-50  Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 50 um dielectric
Phase I – Common Test Pattern

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

Five Line Lengths
  400 mm, 200 mm, 100 mm, 50 mm, 20 mm
  (plus X-section samples)

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

One set of lines used for cross section.

NOTE: These are ARTWORK widths, not final fabricated widths.
Representative X-Sections

- FR4-100
- M4-100
- M4-50
- M6-100
- AP-100
- TK-100
- M6-50
- TK-50
- AP-50
- TK-75
Compile 15 measurements and plot to obtain 50 ohm line width from curve-fit.

15 lines per clad (3 Lengths x 5 Widths)

This example shows measurement of one line width for one clad.

<table>
<thead>
<tr>
<th>Flexible Clads (dimensions in um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clad</td>
</tr>
<tr>
<td>TK-50</td>
</tr>
<tr>
<td></td>
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</table>

100 mm Line TK-50 W160

200 mm Line TK-50 W160

400 mm Line TK-50 W160

W(50 ohms) = 138 um
Loss Analysis Method

- 25 Lines Measured for Each Clad
  - 5 Lengths x 5 Widths
  - High Frequency Connectors Attached

- Vector Network Analyzer (VNA) Measurements
  - SOLT Calibration, Anritsu Lightning VNA
  - 0.2 – 25 GHz, 1601 Points

- 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.
From Raw to Summary Data

- 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 Data – Loss 100 um Clads

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

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
Summary Data – Loss 50-75um Clads

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

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

Delta M6 at 10 GHz:
TK    +0.06 AP    +0.02 M4    -0.13
Lessons Learned from Loss Measurements

- Thickness of dielectric has a HUGE impact.
- The differences between 100 um thick and 50 um thick versions of the same dielectric are LARGER than any differences between different types of low-loss dielectrics of the same thickness.
- Loss differences get larger as frequency increases
  - Differences about double at 10 GHz versus 5 GHz
- dB per cm versus Frequency is roughly a linear function between 5 GHz and 25 GHz (once skin effect becomes dominant).
Extraction of Loss Tangent

- Roughness (Ra) estimated from measurements of treated side of Cu (flex samples) and estimated from cross sections (rigid samples).

- Conductivity measured by measuring DC resistance and back-calculating from cross sectional dimensions of lines. Found to be approximately $4 \times 10^7$ S/m. Same value used for all models.

- Loss Models Developed:
  - Used Agilent ADS and Polar SI9000 to calculate loss/cm up to 25 GHz. Determined to give virtually the same results.
  - Sonnet EM solver with thick metal model with roughness.
    - For composite dielectric, models are generated that assume:
      - Homogeneous (averaged) dielectric properties
      - Composite – individual dielectrics considered separately
Tan d between 0.014 – 0.016 at frequencies <10 GHz and >0.016 at higher frequencies.
Tan d is between 0.004 – 0.006 at frequencies <5 GHz, 0.006 – 0.008 between 5-10 GHz and >0.008 at higher frequencies.
Tan d is 0.002 at frequencies <5 GHz, 0.002 – 0.004 between 5-10 GHz and >0.004 at higher frequencies
Tan d is 0.002 at frequencies <5 GHz, 0.002 – 0.003 between 5-10 GHz and 0.003 – 0.004 between 10-20 GHz
If considered as composite:

Teflon® $\tan\delta = 0.0005$
Kapton® $\tan\delta = 0.003-0.005$ up to 20 GHz

If considered as a homogeneous structure:

Tan $\delta$ is 0.002 at frequencies up to 20 GHz
If considered as composite:
A little better agreement between model and measured, but does not explain loss behavior > 15 GHz. Theory: Teflon® is under-represented in the composite model.

If considered as a homogeneous structure:
Tan $d$ is 0.002 – 0.004 up to 10 GHz then goes down to 0.001 at around 15 GHz.
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A little better agreement between model and measured, but does not explain loss behavior > 15 GHz. Theory: Teflon® is under-represented in the composite model.
Eye Pattern Testing

First a disclaimer

I am not a digital signaling expert. This is new to me.

This was done on the “Apples to Apples” principle.

- 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
- V: 150 mV/div
- H: 18 ps/div
- M6-100
- AP-100
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.
A second method was used to extract dielectric constant (Dk) and dissipation factor (Df) values.

- Flex assemblies were manufactured by Samtec.
- Custom SMA connectors with optimized footprints were developed.
- VNA measurements were made and Dk and DF values extracted using Simbeor, a commercial tool.
The samples in Phase II differed from Phase 1
- An offset stripline topology was evaluated rather than a microstrip
- Only the TK family of materials was tested
- Simbeor method requires only two samples of differing lengths to be characterized
- Launch discontinuities must be “the same” for both test samples
Phase II – Parameter Extraction

By adjusting the surface roughness, copper conductivity, Dk and Df, a model is developed which approximates the measured insertion loss.

- Copper conductivity = $4.25 \times 10^7$ S/m
- Roughness = 1.2um (surface roughness)

Note: Roughness is considered differently in Simbeor than in ADS or Sonnet.
Phase II – Results of Extraction

The extracted values have minor frequency variation as required for causality condition.
Again, the samples used in the Phase II Simbeor extraction differed slightly from the Phase 1 samples

- Offset stripline vs microstrip (Phase 1)
- Overall the correlation is good

<table>
<thead>
<tr>
<th></th>
<th>Simbeor Extraction</th>
<th>Phase 1</th>
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</thead>
<tbody>
<tr>
<td>Dk</td>
<td>2.62</td>
<td>2.5</td>
</tr>
<tr>
<td>Df</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Consider a flex assembly based channel for PCI Express, Generation III (PCIe G3) applications

- 8 Gb/s data rate
- Equalization
  - 3 tap FIR de-emphasis equalization
  - 2 pole CTLE filter
  - 1 tap DFE
- Tx/Rx package models

Analyze two different channels

- Pyralux® FR Bondply (Kapton®)
- Pyralux® TK (Teflon®/Kapton®)
Phase III – Flex Performance Comparison

- The lower Dk results in wider trace widths for TK materials resulting in better loss performance.
- Lower Df for TK results in better insertion loss.
- Analysis below is for 18” trace length.

Insertion Loss Comparison (TK vs FR)

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Dk</th>
<th>W</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>0.02</td>
<td>3.02</td>
<td>3.5 mls</td>
<td>5 mls</td>
</tr>
<tr>
<td>TK</td>
<td>0.002</td>
<td>2.6</td>
<td>4 mls</td>
<td>5 mls</td>
</tr>
</tbody>
</table>
Samtec Edge Rate™ ERM8/ERF8 Series connector models are added to the 18” flex model to form an ERDL2 Series Flex Circuit Assembly.
Phase III – ADS Simulation Environment

- A PCIe G3 simulation environment was developed in ADS
- Batch simulation of different trace lengths
- Parameter sweeps for the different equalization setting
- Multi-aggressor crosstalk effects included
- PCIe G3 Tx/Rx package effects
- Tx jitter modeled
- Eye mask templates included
- Results correlated to SEASIM

- The ERDL2 Series Flex Circuit Assembly was modeled in this simulation environment
Phase III – PCIe G3 Results

The lower loss in the ERDL2 Series Flex Circuit Assembly with TK material easily meets the G3 eye mask.
Phase III – PCIe G3 Results

By sweeping the CTLE gain, we can optimize the PCIe G3 equalization settings for a particular channel.
Phase III – Summary

- Material parameters extracted match the DuPont results
  - Different samples/structure
  - Different test lab
  - Different measured data post processing method

- Lower Dk and Df of TK material results in improved performance at the flex assembly level
  - A PCIe G3 example was shown for an 18” flex assembly length
Effect of ENIG is slightly greater than cutting dielectric thickness in half.

Ferromagnetic properties of ENIG is the principal culprit for this effect.
Additional Work – 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.

TK-75 Example

Effect of Coverlay: TK-75 and TK-50

Effect of Coverlay: TK-100 vs FR4-100

Effect of Coverlay: AP-100 and AP-50
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.

Degradation in eye height consistent with loss degradation shown in previous slide.

Coverlay effect is more significant as overall stackup thickness decreases.
Transmission results reported instead of just bulk dielectric properties.

- Flex copper clad laminates have desirable properties versus thin rigid, especially at frequencies >10 GHz
  - Lower Permittivity
  - Lower Loss
  - Wider Eye

- Dk and Df data is reliable, having been tested using different samples and techniques. Separate labs report the same values

- PCIe G3 channel simulations of flex assemblies show the advantage of improved materials in an 8 Gbps application

- Effects of surface finishes and coverlay also must be considered
  - ENIG has a large impact on loss
  - Coverlay has a significant impact on loss and eye pattern
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