Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Overview

- Broadside coupled striplines can reduce mode conversion due to fiber-weave effects in PCB.
- We have confirmed its principle, performance, and potential risks by simulation and measurements.

Edge-Coupled Striplines

Broadside Coupled Striplines
Outline

• Background
• Principles
• Implementation Issues
• Evaluation Results
• Summary
Outline

- Background
- Principles
- Implementation Issues
- Evaluation Results
- Summary
Fiber-Weave Effects in Conventional Edge-Coupled Striplines

- Propagation speed of electrical signal is inversely proportional to square root of Dk (Dielectric Constant)
- Dk of glass is higher than Dk of resin
  → Distribution of glass causes intra-pair skew of a differential pair signal
Intra-pair Skew and Mode Conversion

- Intra-pair skew of a differential pair signal
  - Mode conversion at high frequency
  - Differential insertion loss at high frequency

\[
P_{21dd} = \frac{(P_{21} + P_{43} - P_{41} - P_{23})}{2}
\]
\[
P_{21cd} = \frac{(P_{21} - P_{43} + P_{41} - P_{23})}{2}
\]
\[
P_{21cc} = \frac{(P_{21} + P_{43} + P_{41} + P_{23})}{2}
\]

Simulation Model

30cm

SE Port 2, Port 4
MM Port 2d, Port 2c

SE Port 1, Port 3
MM Port 1d, Port 1c

Cross section

- $\Delta Dk = 0.00$ (ideal)
- $\Delta Dk = 0.05$ (skewed)

$Dk = 3.42$

- $-\Delta Dk$
- $+\Delta Dk$

Dk = 3.42

Frequency-Domain Resp.

Single End Impulse Resp.

Mixed-Mode Impulse Resp.

Intra-pair Skew 27ps

Two Peaks

P21dd, P21cc: + +

P21cd: + –

S21dd has a glitch

S21cd has a peak at \(1/(2*27\text{ps}) = 18.5\text{GHz}\)

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
A Prior Scheme Against Fiber-Weave Effects

• **Scheme:** Rotate traces against glass-fiber yarn
  - By rotating the entire panel, or
  - By drawing traces with some angle

• **Principle:** Dk is averaged over the entire trace, and equalized between POS and NEG traces
  - Hence, the intra-pair skew, as well as mode conversion, can be minimized

• **Drawbacks:**
  - Increase material cost (if rotating the entire panel)
  - Increase design complexity (if drawing angled traces)
  - Insertion loss has a glitch, because impedance periodically goes up and down
    • The glitch frequency may be increased by increasing the rotation angle
      - Increase material cost or design complexity further
Outline

• Background
• **Principles**
• Implementation Issues
• Evaluation Results
• Summary
Stronger Coupling: Tight Edge Coupling or Broadside Coupling

- Coupling can be made stronger with tight edge coupling, or strongest with broadside coupling.

- Q: Does stronger coupling help to mitigate fiber-weave effects?

- A: It depends on coupling mode. Yes for capacitive or inductive coupling. No for neutral coupling.

Conventional
Loosely Edge-Coupled Striplines

Tightly Edge-Coupled Striplines

Broadside Coupled Striplines

Weak coupling

Stronger coupling

Strongest coupling
# Overview of Capacitive / Inductive / Neutral Coupling

<table>
<thead>
<tr>
<th>Coupling mode</th>
<th>Capacitive</th>
<th>Inductive</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Dominant coupling by electric field</td>
<td>Dominant coupling by magnetic field</td>
<td>Equal capacitive and inductive coupling canceling each other</td>
</tr>
<tr>
<td>Homogeneity of dielectric material</td>
<td>Non-homogeneous</td>
<td>Non-homogeneous</td>
<td>Homogeneous</td>
</tr>
<tr>
<td>$D_{Kdiff}$ vs $D_{Kcom}$</td>
<td>$D_{Kdiff} &gt; D_{Kcom}$</td>
<td>$D_{Kdiff} &lt; D_{Kcom}$</td>
<td>$D_{Kdiff} = D_{Kcom}$</td>
</tr>
<tr>
<td>Propagation speed</td>
<td>$Diff &lt; Com$</td>
<td>$Diff &gt; Com$</td>
<td>$Diff = Com$</td>
</tr>
<tr>
<td>Reduction of mode conversion</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Neutral Coupling in Homogenous Dielectric Material

- No (effective) coupling occurs at far end in homogenous dielectric material
  - Differential-mode and common-mode propagates at the same speed
- For this reason, FEXT does not occur for stripline in homogeneous dielectric material

<table>
<thead>
<tr>
<th>Input Port</th>
<th>Coupled Striplines</th>
<th>Output Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Same Dk</td>
<td>P2</td>
</tr>
<tr>
<td>P3</td>
<td>Same Dk</td>
<td>P4</td>
</tr>
<tr>
<td>P1–P3/2</td>
<td>Same speed</td>
<td>P2–P4/2</td>
</tr>
<tr>
<td>P1+P3/2</td>
<td>Same speed</td>
<td>P2+P4/2</td>
</tr>
</tbody>
</table>

Pulse: P1
None: P3
Differential-mode: P1–P3/2
Common-mode: P1+P3/2

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Capacitive Coupling in Non-homogenous Dielectric Material

- Capacitive coupling occurs when $\text{DK}_\text{diff}$ is higher than $\text{DK}_\text{com}$
  - Differential-mode propagates slower than common-mode
  - Coupled pulse at P4 has first a positive peak, then followed by a negative peak, and its integral is zero
  - Current flows in the same direction in the signal conductors at the forefront of the pulse

Input Port

| P1 | Pulse
|----|---
| P3 | None

Output Port

| P2 | Pos pos
| P4 | Pos neg

Coupled Striplines

- Differential-mode
  - $\frac{P1-P3}{2}$
  - Slow
- Common-mode
  - $\frac{P1+P3}{2}$
  - Fast

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Inductive Coupling in Non-homogenous Dielectric Material

- Inductive coupling occurs when DKdiff is lower than DKcom
  - Differential mode propagates faster than common mode
  - Coupled pulse at P4 has first a negative peak, then followed by a positive peak, and its integral is zero
  - Current flows in the opposite directions in the signal conductors at the forefront of the pulse

**Input Port**
- P1
  - Pulse
- P3
  - None

**Output Port**
- P2
  - Pos
- P4
  - Pos
  - Neg

**Coupled Striplines**
- High DKcom
  - P1
  - Slow
- Low DKdiff
  - P3
  - Fast
- High DKcom
  - GND
  - Slow

**Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines**
### Reduction of Mode Conversion by Capacitive Coupling

#### Neutral
- **DK1 = DK2**
  - DK2 = 3.42
  - P21 = (P21 + P43) / 2
  - P21cd = (P21 - P43) / 2

#### Capacitive
- **DK1 > DK2**
  - DK2 = 3.32
  - P21dd = (P21 + P43 - P41 - P23) / 2
  - P21cd = (P21 - P43 + P41 - P23) / 2

#### Strong Capacitive
- **DK1 >> DK2**
  - DK2 = 3.22
  - P21dd = (P21 + P43 - P41 - P23) / 2
  - P21cd = (P21 - P43 + P41 - P23) / 2

#### Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines

- Smaller P21cd
  - Separated peaks
  - Larger P41, P23
  - Larger inter-mode skew

- Reduced S21cd gain
  - Reduced S21cd freq.
Reduction of Mode Conversion by Inductive Coupling

<table>
<thead>
<tr>
<th>Neutral</th>
<th>DK1 = DK2</th>
<th>DK2 = 3.42</th>
<th>+0.05</th>
<th>-0.05</th>
<th>+0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK1 = 3.42</td>
<td></td>
<td>±0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DK2 = 3.42</td>
<td>-0.05</td>
<td>+0.05</td>
<td>-0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inductive</th>
<th>DK1 &lt; DK2</th>
<th>DK2 = 3.42</th>
<th>+0.05</th>
<th>-0.05</th>
<th>+0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK1 = 3.32</td>
<td></td>
<td>±0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DK2 = 3.42</td>
<td>-0.05</td>
<td>+0.05</td>
<td>-0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong Inductive</th>
<th>DK1 &lt;&lt; DK2</th>
<th>DK2 = 3.42</th>
<th>+0.05</th>
<th>-0.05</th>
<th>+0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK1 = 3.22</td>
<td></td>
<td>±0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DK2 = 3.42</td>
<td>-0.05</td>
<td>+0.05</td>
<td>-0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
P21_{dd} = \frac{(P21 + P43 - P41 - P23)}{2}
\]
\[
P21_{cd} = \frac{(P21 - P43 + P41 - P23)}{2}
\]
\[
P21_{cc} = \frac{(P21 + P43 + P41 + P23)}{2}
\]

P21dd, P21cd, P21cc

- Larger P21 P43 and P41 P23
- Separated peaks
- Larger inter-mode skew
- Reduced S21cd gain
- Reduced S21cd freq.

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Summary of Principles

• Mode conversion is reduced by capacitive or inductive coupling, but not by *neutral* coupling
  – Coupling is capacitive (inductive), when DKdiff is higher (lower) than DKcom
    • As the difference between DKdiff and DKcom increases, the coupling becomes stronger, mode conversion is reduced more effectively, and the inter-mode skew between differential mode and common mode increases
  – Coupling is *neutral*, when DKdiff and DKcom are equal
    • When DKdiff and DKcom are equal, the inter-mode skew between differential mode and common mode is zero

• For broadside coupled striplines, we can easily control DKdiff and DKcom by choice of DK of each layer
  – For edge-coupled striplines, DKdiff and DKcom are always similar, and coupling mode is always *neutral* under normal PCB process

• For broadside coupled striplines, glass-weave effects of center dielectric layer using 1-ply cloth is small
  – Glass-weave effects of center dielectric layer using 1-ply cloth are symmetric against the top and bottom strips

• Risks
  – Large impedance variation
    • Broadside-coupled striplines have been considered only for low-speed applications due to large impedance variation
  – Non-causal-like response with capacitive coupling
    • Capacitive coupling may have non-causal-like response, because differential response is preceded by common-mode response
  – Thickness of center dielectric layer
    • Center dielectric layer using 1-ply cloth may be too thin, but its glass-weave effects may be significant if we use 2-ply cloth
  – Far-end crosstalk
    • Stronger coupling will increase far-end crosstalk between adjacent differential signals
Outline

• Background
• Principles
• Implementation Issues
• Evaluation Results
• Summary
### Implementation Issue 1: Location of Core and Prepreg

<table>
<thead>
<tr>
<th>PCP stack</th>
<th>CPC stack</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="PCP Stack Diagram" /></td>
<td><img src="image2.png" alt="CPC Stack Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small misalignment error between two sides of a core</td>
<td>DK1 (core) is likely high → Likely capacitive coupling → P21dd may look non-causal</td>
</tr>
<tr>
<td>DK1 (prepreg) is likely low → Likely inductive coupling → P21dd always looks causal</td>
<td>Large misalignment error between two laminated cores</td>
</tr>
</tbody>
</table>
Implementation Issue 2: Common-Mode Impedance

- To make common-mode impedance 25 ohm and differential impedance 100 ohm, H2 must be half of H1.
- If we use 1-ply cloth for DK1, available H1 will be limited such as up to 125um.
- Then, H2 will be up to 62.5um, and trace width will be too narrow (such as less than 50um).

- To avoid manufacturing issue, we choose thick DK2 and compromise common-mode impedance.
- Common-mode impedance will be 40~50 ohm when differential impedance is 100 ohm.

![Diagram showing DK1, DK2, H1, H2, and Virtual GND.]
Implementation Issue 3: Intra-pair Skew at Differential VIA

- Intra-pair skew to access different layers from board surface
  → Compensated by an intentional offset of the escape trace
Simulation Results of Skew-Compensated Differential VIA

Without Skew Compensation

With Skew Compensation

Phase

Phase Delay

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Outline

• Background
• Principles
• Implementation Issues
• **Evaluation Results**
• Summary
Overview of Test Board

Test Board

16 Circuits per board

Cross Section w/o GND Shield

Cross Section with GND shield

Unit Circuit

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
## Stack-up Parameters of Test Board

<table>
<thead>
<tr>
<th>Evaluation Phase</th>
<th>1st Phase</th>
<th>2nd Phase</th>
<th>Previous Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label</td>
<td>A5</td>
<td>B4</td>
<td>C5</td>
</tr>
<tr>
<td>Type</td>
<td>CPC</td>
<td>PCP</td>
<td>CPC</td>
</tr>
<tr>
<td>Coupling Mode</td>
<td>Inductive</td>
<td>Capacitive</td>
<td>Inductive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Prepreg</td>
<td>Core</td>
<td>Prepreg</td>
</tr>
<tr>
<td>Resin / Glass</td>
<td>Megtron 6 / NE</td>
<td>Megtron 6 / NE</td>
<td>Megtron 6 / NE</td>
</tr>
<tr>
<td>Cloth</td>
<td>#1078 * 1 ply</td>
<td>#2116 * 1 ply</td>
<td>#1035 * 2 ply</td>
</tr>
<tr>
<td>Thickness</td>
<td>118um</td>
<td>125um</td>
<td>148um</td>
</tr>
<tr>
<td>Dk@1GHz</td>
<td>3.13</td>
<td>3.40</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Core</td>
<td>Prepreg</td>
<td>Core</td>
</tr>
<tr>
<td>Cloth</td>
<td>#1035 * 2 ply</td>
<td>#1035 * 2 ply</td>
<td>#1035 * 2 ply</td>
</tr>
<tr>
<td>Thickness</td>
<td>120um</td>
<td>148um</td>
<td>120um</td>
</tr>
<tr>
<td>Dk@1GHz</td>
<td>3.35</td>
<td>3.13</td>
<td>3.13</td>
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</tr>
</tbody>
</table>

- **DK1**
- **DK2**

- **Mitigation of Fiber-Weave Effects by Broadsided Coupled Differential Striplines**

<table>
<thead>
<tr>
<th></th>
<th>1st Phase</th>
<th>2nd Phase</th>
<th>Previous Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Prepreg</td>
<td>Core</td>
<td>Prepreg</td>
</tr>
<tr>
<td>Resin / Glass</td>
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<td>Megtron 6 / NE</td>
<td>Megtron 6 / E</td>
</tr>
<tr>
<td>Cloth</td>
<td>#1078 * 1 ply</td>
<td>#2116 * 1 ply</td>
<td>#2116 * 1 ply</td>
</tr>
<tr>
<td>Thickness</td>
<td>118um</td>
<td>125um</td>
<td>125um</td>
</tr>
<tr>
<td>Dk@1GHz</td>
<td>3.40</td>
<td>3.13</td>
<td>3.71</td>
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</tr>
</tbody>
</table>

- **# of measured traces**
- **# of measured boards**

- **Previous Project**
  - M1A (Reference)
  - Edge Coupled
  - Neutral
Intra-pair Skew (X) vs Differential Insertion Loss (Y)

- With BSC SL, differential insertion loss (Y) does not necessarily increase as intra-pair skew (X)

A5 (CPC, inductive, 1-ply DK1):
- Loss increases randomly

B4 (PCP, capacitive, 1-ply DK1):
- Weak quadratic function

M1A (edge coupled, neutral):
- Strong quadratic function

C5 (CPC, inductive, 2-ply DK1):
- Loss increases randomly

B8 (PCP, strong cap., 1-ply DK1):
- Loss does not increase

Trace Length
- A5/C5/B4: 314.37mm
- B8: 343.11mm
- M1A: 305.30mm
Inter-mode Skew (X) vs Differential Insertion Loss (Y)

- Differential insertion loss (Y) generally decreases as magnitude of inter-mode skew increases (X)
  - Magnitude of inter-mode skew indicates the coupling strength, and its sign indicates the coupling mode, i.e. inductive or capacitive

A5: Inter-mode skew < 0

B4: Inter-mode skew > 0

M1A: Inter-mode skew ~ 0

C5: Inter-mode skew < 0

B8: Inter-mode skew > 0

Trace Length
A5/C5/B4: 314.37mm
B8: 343.11mm
M1A: 305.30mm
Insertion Loss to Mode-Conversion Ratio (X) vs Differential IL (Y)

- IMCR (=|S21dd| / |S21cd|, insertion-loss to mode-conversion ratio) shows margin for mode conversion
- Lower side of IMCR looks bounded for B4 (down to – 4dB) and B8 (down to 0dB)

A5 (CPC, inductive, 1-ply DK1): IMCR lower bound – no clear limit

B4 (PCP, capacitive, 1-ply DK1): IMCR lower bound ~ – 4dB

M1A (edge coupled, neutral): IMCR lower bound – no clear limit

C5 (CPC, inductive, 2-ply DK1): IMCR lower bound – no clear limit

B8 (PCP, strong cap., 1-ply DK1): IMCR lower bound ~ 0dB

Trace Length
A5/C5/B4: 314.37mm
B8: 343.11mm
M1A: 305.30mm
Effective DKdiff (X) vs Effective DKcom (Y)

- Confirmed that A5 and C5 are inductive, B4 and B8 are capacitive, and M1A is weak inductive.

A5 (CPC, inductive, 1-ply DK1)
- Mostly inductive

C5 (CPC, inductive, 2-ply DK1)
- All inductive

B4 (PCP, capacitive, 1-ply DK1)
- Mostly capacitive

B8 (PCP, strong cap., 1-ply DK1)
- All capacitive

M1A (edge coupled, neutral)
- All weak inductive
A Successful Case of Inductive Coupling (A5)

- While intra-pair skew is large, inductive coupling successfully suppressed mode conversion.
A Successful Case of Capacitive Coupling (B4)

- While intra-pair skew is large, capacitive coupling successfully suppressed mode conversion.
Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines

A Failure Case of 2-ply Glass Cloth for DK1 (C5)

• Mode conversion was not suppressed well, because DK1 was inconsistent between POS and NEG traces
Differential Impedance

- A5 (CPC stack) has large impedance variation due to large horizontal offset of CPC stack
- B4 and B8 (PCP stack) has small impedance variation comparable to conventional edge coupling

<table>
<thead>
<tr>
<th>Stack up type</th>
<th>CPC</th>
<th></th>
<th>PCP</th>
<th></th>
<th>Edge Coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label</td>
<td>A5</td>
<td>C5</td>
<td>B4</td>
<td>B8</td>
<td>M1A</td>
</tr>
<tr>
<td>Cloth Style</td>
<td>#1078x1 (DK1)</td>
<td>#1035x2 (DK1)</td>
<td>#2116x1 (DK1)</td>
<td>#2116x1 (DK1)</td>
<td>2 ply (Core)</td>
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<tr>
<td></td>
<td>#1035x2 (DK2)</td>
<td>#1035x2 (DK2)</td>
<td>#1035x2 (DK2)</td>
<td>#1035x2 (DK2)</td>
<td>2 ply (PP)</td>
</tr>
<tr>
<td>Trace Width</td>
<td>DF</td>
<td>DF</td>
<td>DF</td>
<td>DF</td>
<td>DF</td>
</tr>
<tr>
<td>Random Variation</td>
<td>60~100um</td>
<td>6.74Ω/σ</td>
<td>313</td>
<td>1.07Ω/σ</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>84um</td>
<td>6.82Ω/σ</td>
<td>76</td>
<td>0.95Ω/σ</td>
<td>44</td>
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<tr>
<td></td>
<td>100um</td>
<td>6.09Ω/σ</td>
<td>77</td>
<td>0.88Ω/σ</td>
<td>44</td>
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<tr>
<td></td>
<td>120~140um</td>
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<tr>
<td>Average</td>
<td>60~100um</td>
<td>106.92Ω</td>
<td>111.32Ω</td>
<td>113.07Ω</td>
<td>109.95Ω</td>
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<tr>
<td></td>
<td>84um</td>
<td>102.22Ω</td>
<td>106.90Ω</td>
<td>108.50Ω</td>
<td>105.51Ω</td>
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<tr>
<td></td>
<td>100um</td>
<td>92.74Ω</td>
<td>97.26Ω</td>
<td>98.55Ω</td>
<td>95.61Ω</td>
</tr>
<tr>
<td></td>
<td>120~140um</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

DF: Degree of Freedom
Horizontal Offset between Top and Bottom Traces

- Horizontal offset was one order of magnitude worse with the CPC stack than PCP stack.
  - This is the cause of the large impedance variation that has been commonly seen for broadside coupled striplines.

Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines
Far End Crosstalk vs S21dd without Shield

- With trace pitch 500um, B8 has less margin than B4
- With trace pitch 1000um, B4 and B8 have similar margin
Far End Crosstalk vs S21dd with Shield

- With shield VIA pitch 5.0mm, B4 and B8 have similar margin
- With shield VIA pitch 2.5mm, B8 has slightly more margin than B4
Summary

- Mode conversion is reduced by capacitive or inductive coupling using broadside coupled striplines
  - The coupling mode (inductive or capacitive) and its strength is controlled by choice of dielectric constant of each layer
    - Coupling is capacitive (inductive) when $\text{DK}_{\text{diff}}$ is higher (lower) than $\text{DK}_{\text{com}}$
  - While the mode-conversion is reduced, the intra-pair skew (as single-end signals) remains, and the inter-mode skew increases

- Takeaways
  - Use the PCP stack configuration (i.e. core for the center dielectric, and prepreg for the top and bottom dielectric)
    - CPC stack will result in large impedance variation
  - Use 1-ply glass cloth for $\text{DK}_1$ (center dielectric)
    - 2-ply cloth for $\text{DK}_1$ introduces inconsistent $\text{DK}_1$ values between POS and NEG traces
  - May need to compromise high common-mode impedance
    - It may be 40~50 ohm for differential 100 ohm
  - Use IMCR ($=|S_{21dd}|/|S_{21cd}|$, insertion loss to mode conversion ratio) as the figure of merit for mode-conversion loss
    - Intra-pair skew is a useless metric for broadside coupled striplines
  - FEXT (far-end cross talk) slightly increases as the coupling gets stronger

- For future study
  - Use different resin material for $\text{DK}_1$ and $\text{DK}_2$
    - Will reduce variation of coupling strength as glass-weave effects of $\text{DK}_1$
    - May realize inductive coupling with PCP stack
Appendix 1: Calculation of Loss-Compensated Delay

Hilbert Transform was implemented by DFT as follows:
1. \( R(-f) = R(f) \); get the R value for negative frequency by mirroring the positive frequency value
2. \( CR(t) = \text{ifft}(R(f)) \); get cepstrum of R by inverse DFT
3. \( CX(t) = CR(t) \ast \text{sign}(t) \); get cepstrum of X by multiplying CR with sign of time
4. \( X(f) = \text{fft}(CX(t)) \); get the X value that is the Hilbert Transform of R by DFT
Appendix 2: Calculation of Effective Dk for each mode

- **S21**
  - S-parameter
  - Loss Compensated Delay
  - Average Delay for 5~15GHz: 1877.63ps
  - Effective DK (length = 314.37mm): DKpos: 3.2061
- **S43**
  - S-parameter
  - Loss Compensated Delay
  - Average Delay for 5~15GHz: 1879.08ps
  - Effective DK (length = 314.37mm): DKneg: 3.2111
- **S21dd**
  - S-parameter
  - Loss Compensated Delay
  - Average Delay for 5~15GHz: 1874.74ps
  - Effective DK (length = 314.37mm): DKdiff: 3.1963
- **S21cc**
  - S-parameter
  - Loss Compensated Delay
  - Average Delay for 5~15GHz: 1889.58ps
  - Effective DK (length = 314.37mm): DKcom: 3.2470

**Single-Bit Pulse Response (56Gbps)**

**Mitigation of Fiber-Weave Effects by Broadsided Coupled Differential Striplines**
Appendix 3: Calculation of Effective $D_k$ for each layer

- Approximation of effective $D_k$ for each mode from effective $D_k$ for each layer

\[
\begin{bmatrix}
D_{Kpos} \\
D_{Kneg} \\
D_{Kdiff} \\
D_{Kcom}
\end{bmatrix}
\approx
X
\begin{bmatrix}
D_{K1} \\
D_{K2top} \\
D_{K2btm}
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
3/8 & 4/8 & 1/8 \\
3/8 & 1/8 & 4/8 \\
4/6 & 1/6 & 1/6 \\
0 & 1/2 & 1/2
\end{bmatrix}
\]

- Approximation of effective $D_k$ for each layer from effective $D_k$ for each mode

\[
\begin{bmatrix}
D_{K1} \\
D_{K2top} \\
D_{K2btm}
\end{bmatrix}
\approx
Y
\begin{bmatrix}
D_{Kpos} \\
D_{Kneg} \\
D_{Kdiff} \\
D_{Kcom}
\end{bmatrix}
\]

\[
Y = (X^tX)^{-1}X^t = \begin{bmatrix}
0.3101 & 0.3101 & 1.1512 & -0.7713 \\
0.3101 & 1.1512 & -0.7713 & 0.3101 \\
1.5504 & -1.1163 & -0.2442 & 0.8101 \\
-1.1163 & 1.5504 & -0.2442 & 0.8101
\end{bmatrix}
\]