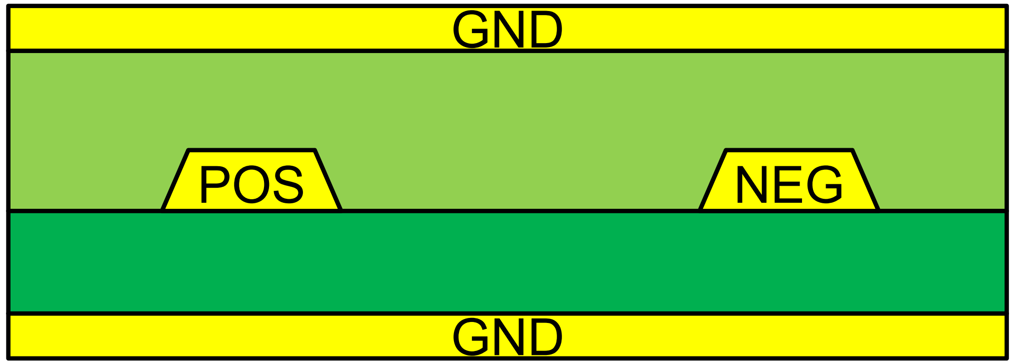
Mitigation of Fiber-Weave Effects by Broadside Coupled Differential Striplines

DesignCon 2015

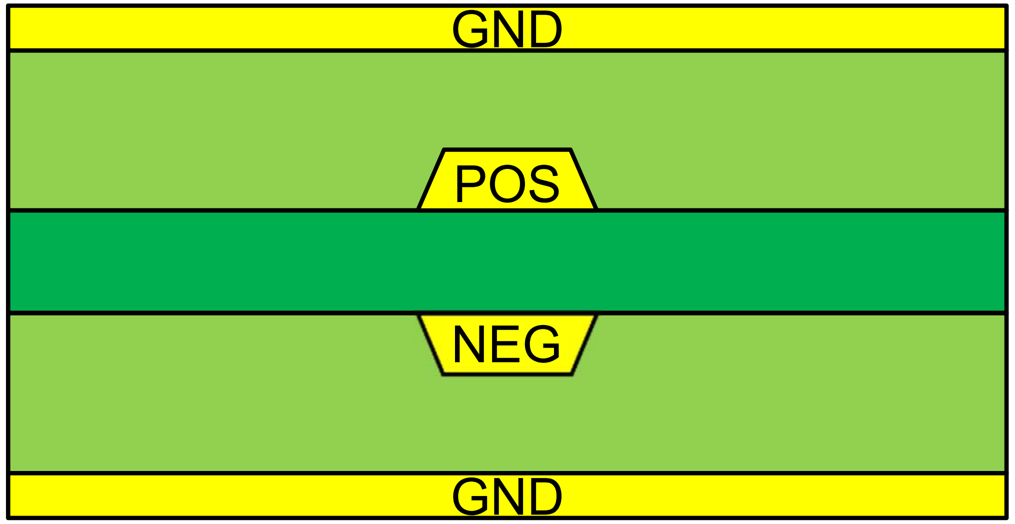
Overview

- 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
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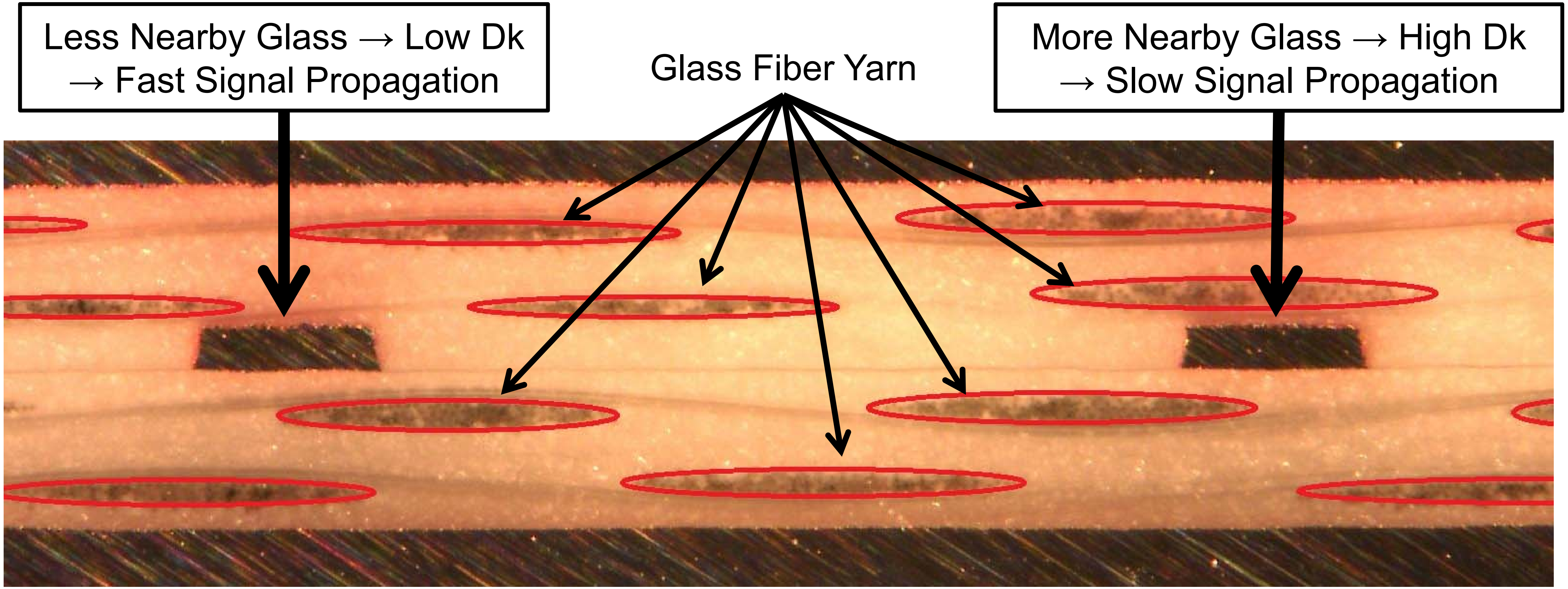
Fiber-Weave Effects in Conventional Edge-Coupled Striplines

- 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

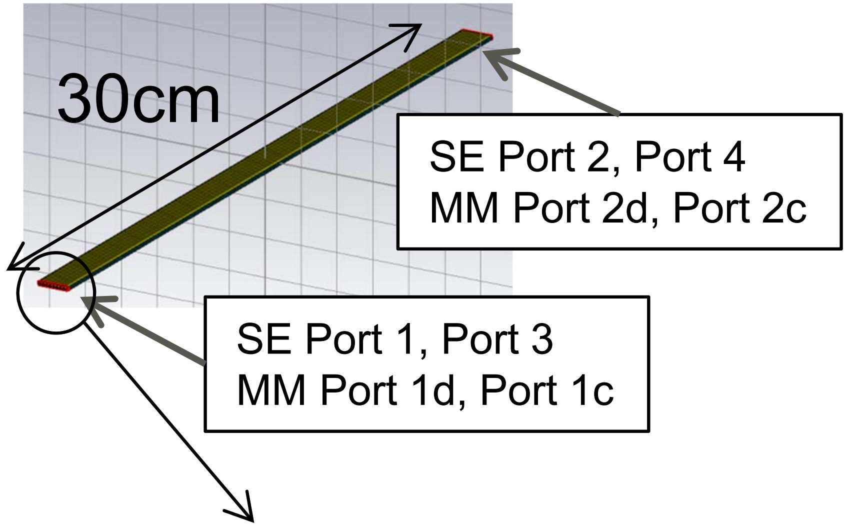


Intra-pair Skew and Mode Conversion

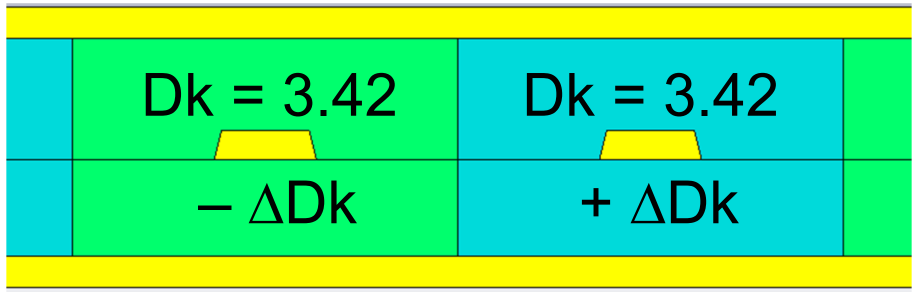
- Intra-pair skew of a differential pair signal
  → Mode conversion at high frequency
  → Differential insertion loss at high frequency

P21dd = (P21 + P43 – P41 – P23)/2
P21cd = (P21 – P43 + P41 – P23)/2
P21cc = (P21 + P43 + P41 + P23)/2

Simulation Model



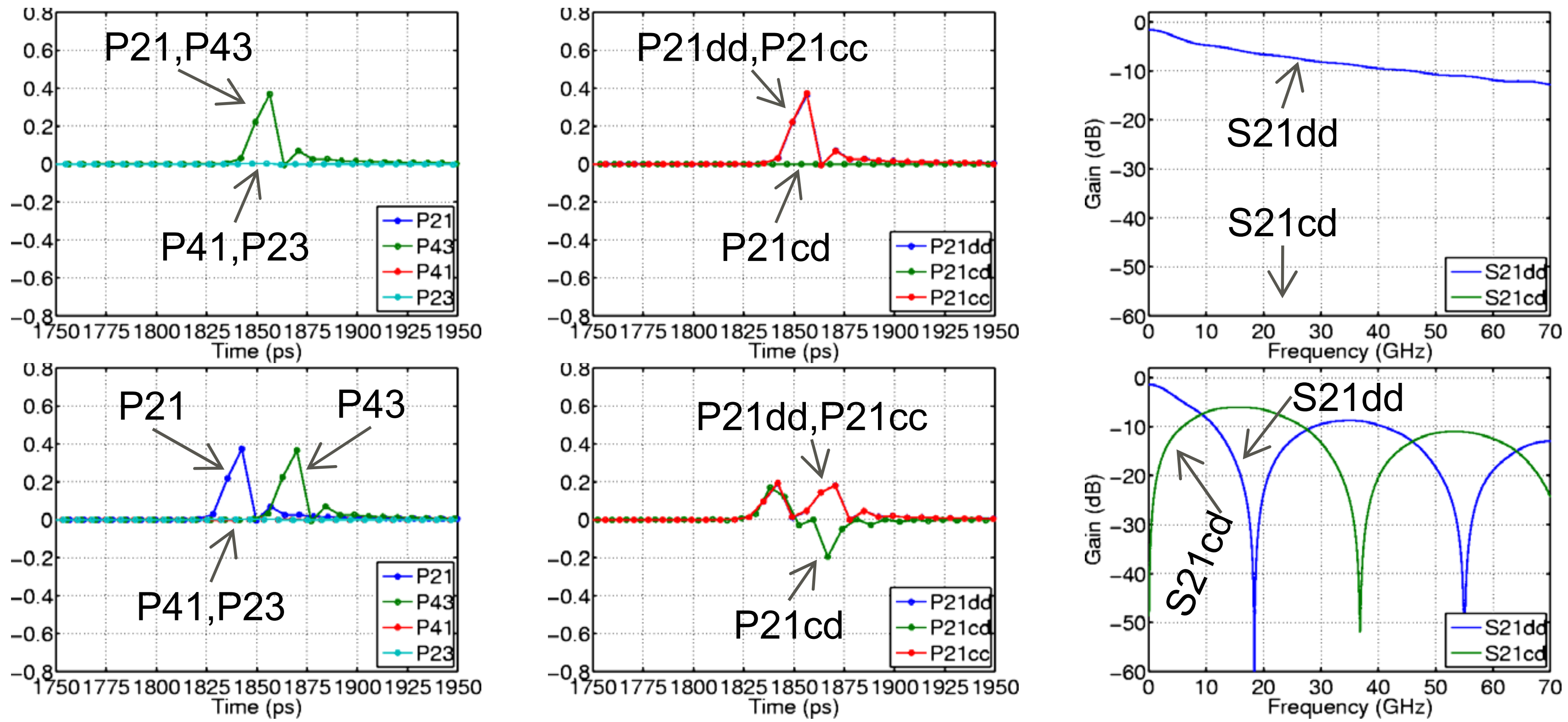
Cross section



Single End Impulse Resp. | Mixed-Mode Impulse Resp. | Freq-Domain Resp.

ΔDk=0.00 (ideal)

ΔDk=0.05 (skewed)



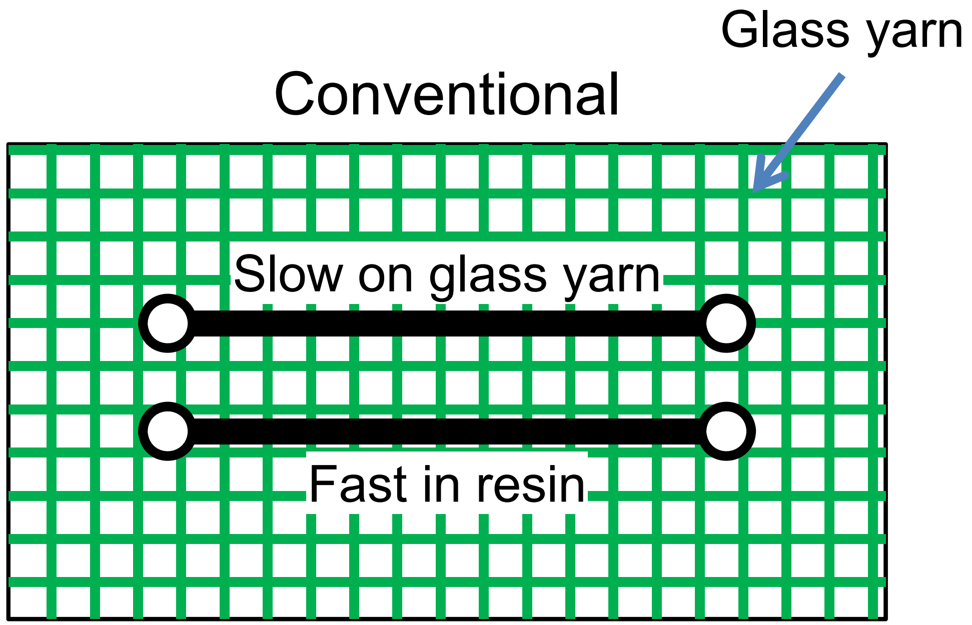
Intra-pair Skew 27ps → Two Peaks → S21dd has a glitch S21cd has a peak

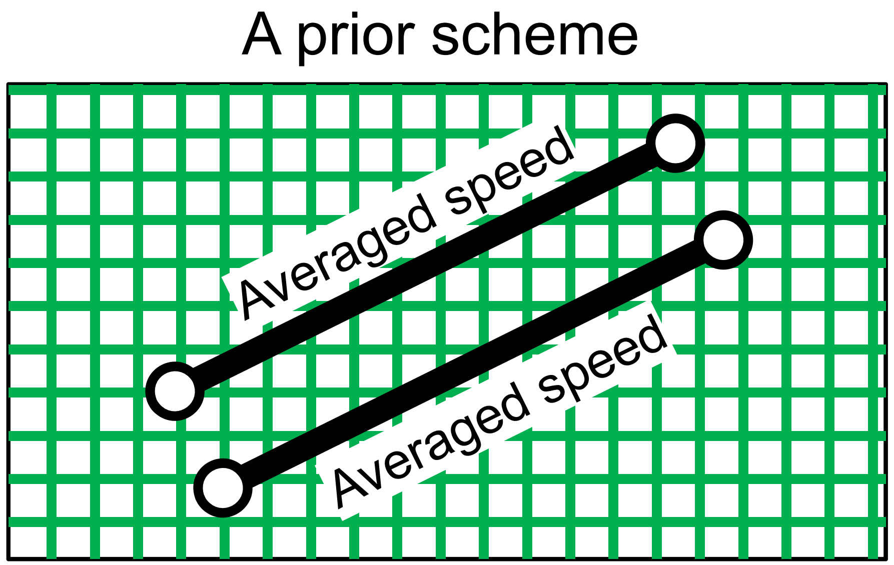
P21dd,P21cc : + +
P21cd : + –

at 1/(2*27ps) = 18.5GHz

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





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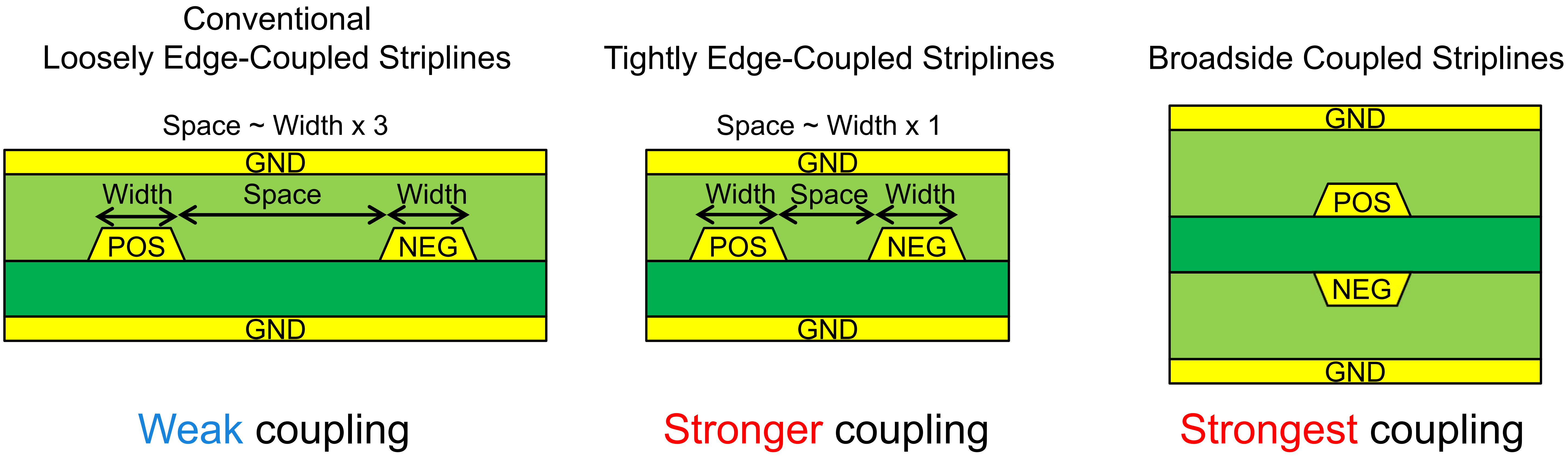
Stronger Coupling: Tight Edge Coupling or Broadside Coupling

- 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.

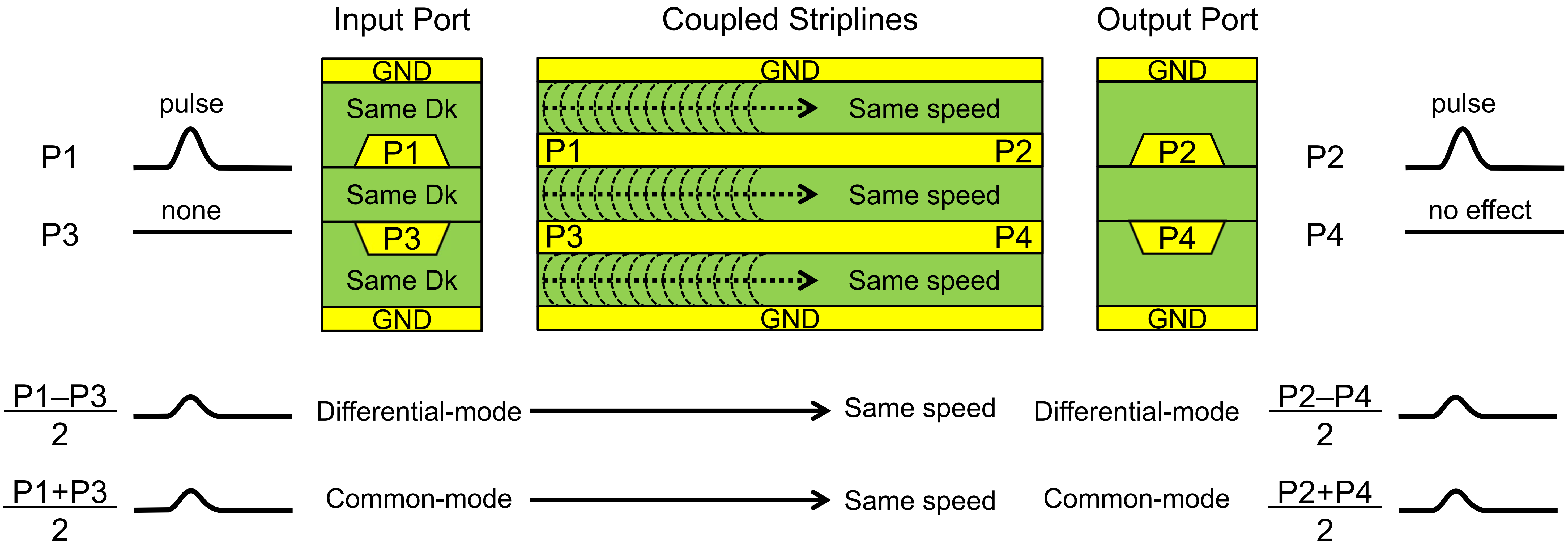


Overview of Capacitive / Inductive / *Neutral* Coupling

Coupling mode	Capacitive	Inductive	*Neutral*
Description	Dominant coupling by electric field	Dominant coupling by magnetic field	Equal capacitive and inductive coupling canceling each other
Homogeneity of dielectric material	Non-homogeneous	Non-homogeneous	Homogeneous
DKdiff vs DKcom	DKdiff > DKcom	DKdiff < DKcom	DKdiff = DKcom
Propagation speed	Diff < Com	Diff > Com	Diff = Com
Reduction of mode conversion	Yes	Yes	No

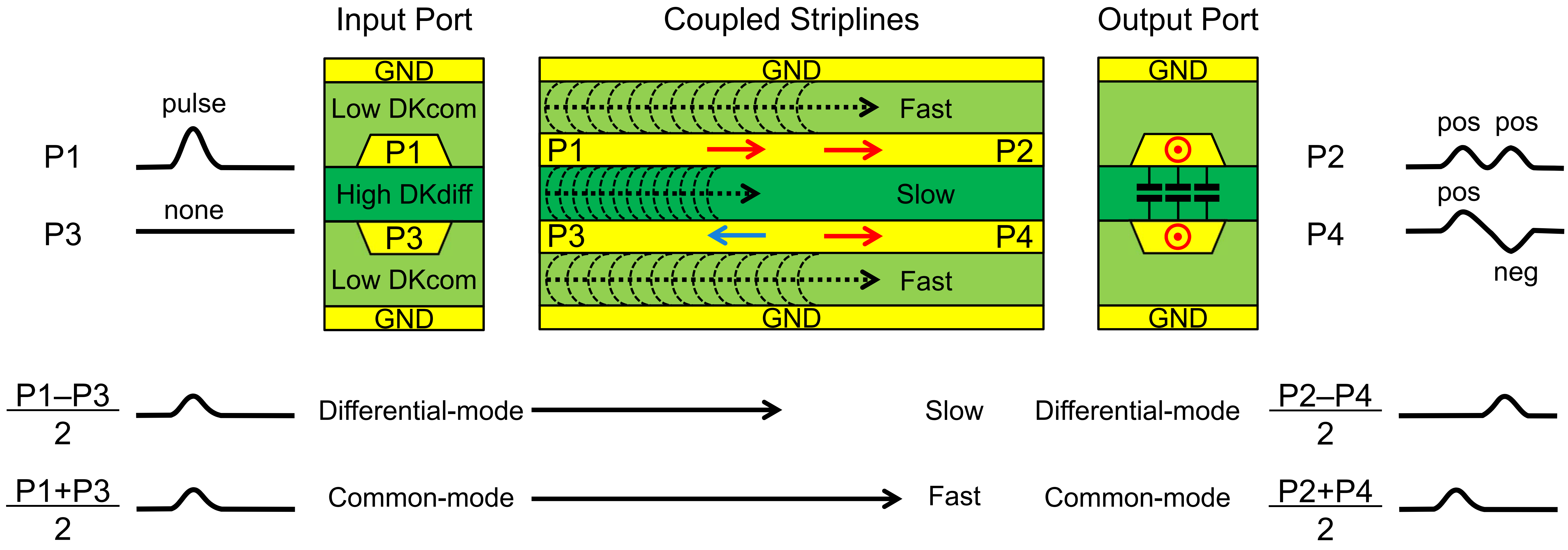
Neutral Coupling in Homogenous Dielectric Material

- 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



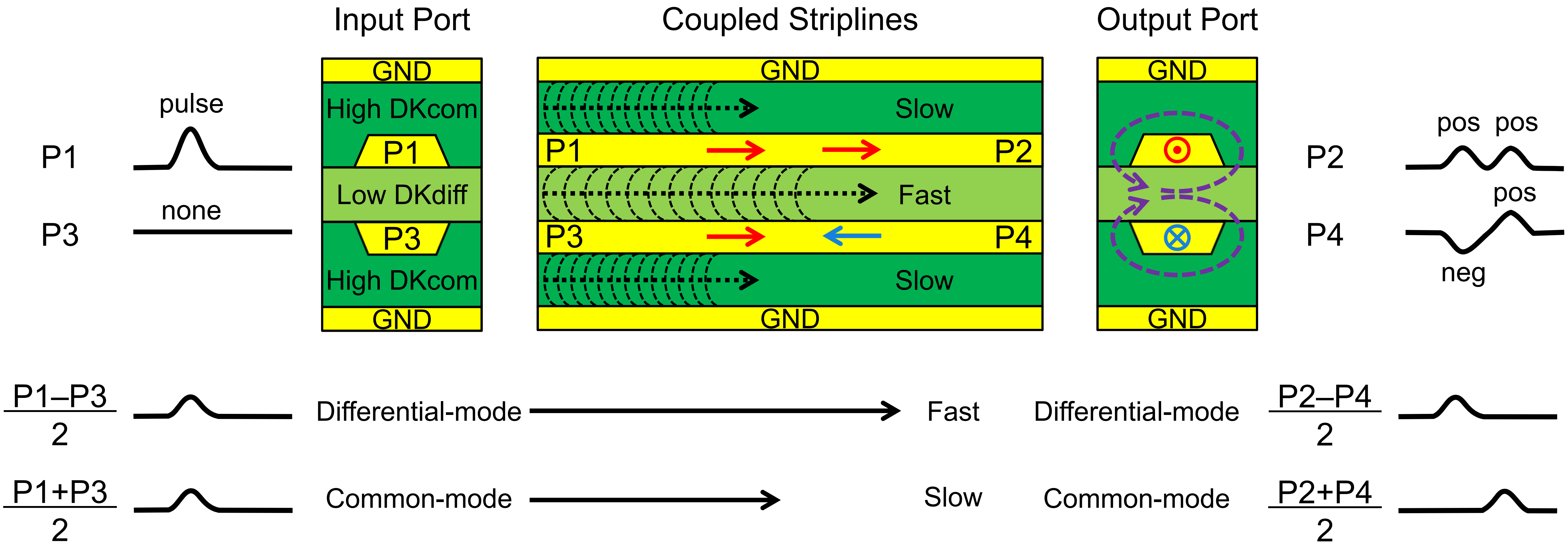
Capacitive Coupling in Non-homogenous Dielectric Material

- Capacitive coupling occurs when DKdiff is higher than DKcom
  - 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



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



Reduction of Mode Conversion by Capacitive Coupling

Neutral
DK1 = DK2

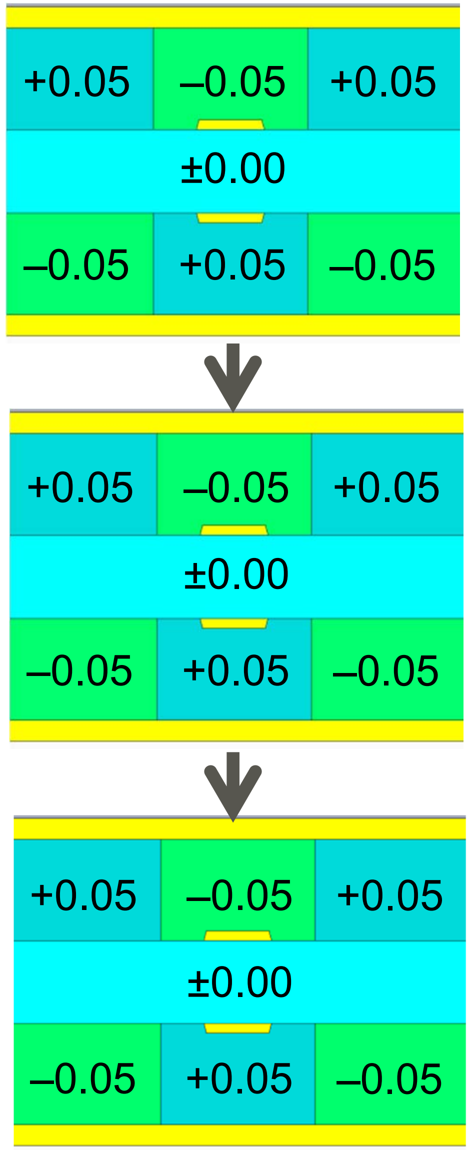
DK2=3.42
DK1=3.42
DK2=3.42

Capacitive
DK1 > DK2

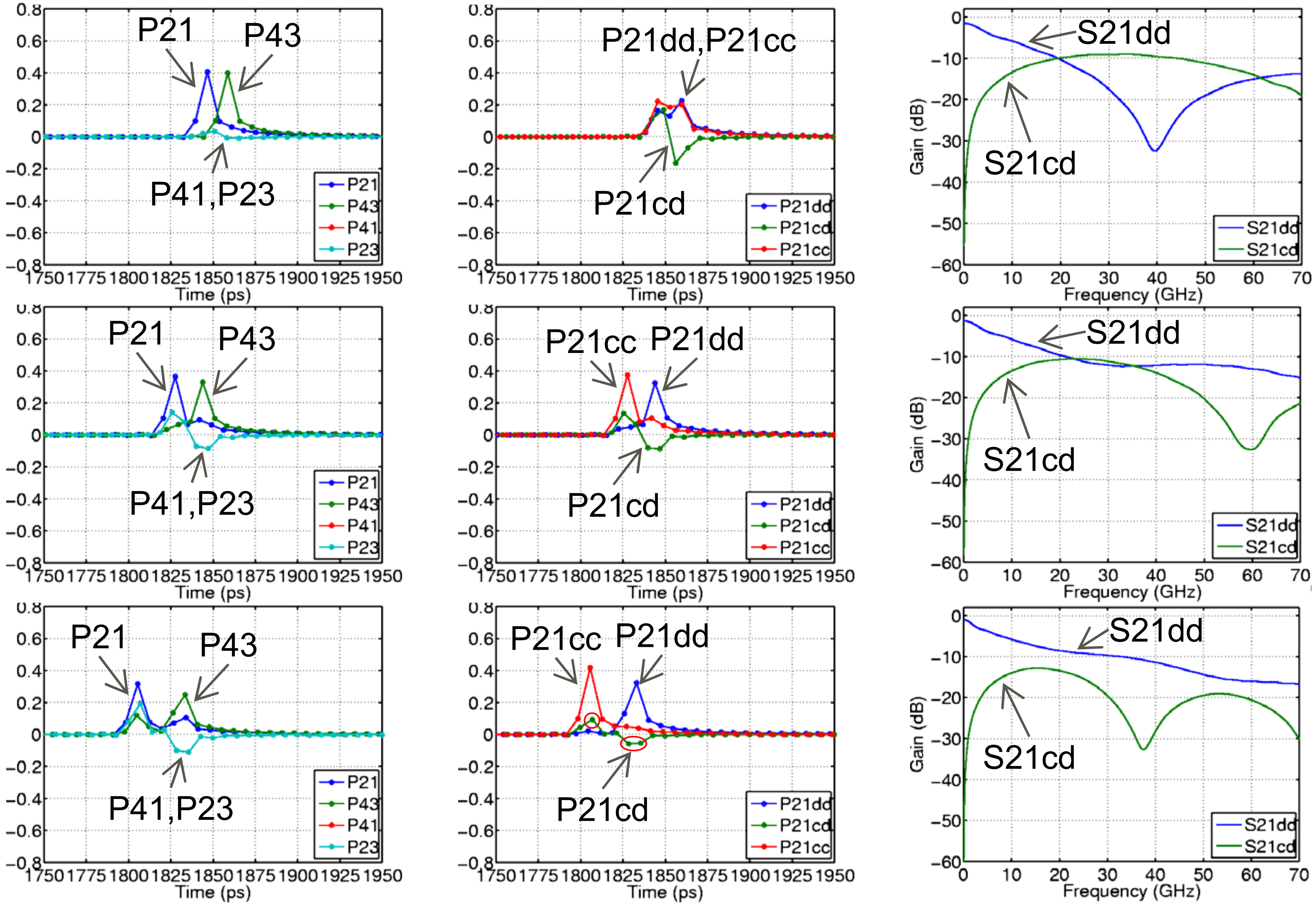
DK2=**3.32**
DK1=3.42
DK2=**3.32**

Strong Capacitive
DK1 >> DK2

DK2=**3.22**
DK1=3.42
DK2=**3.22**



SE Impulse Response | MM Impulse Response | Frequency-Domain Response



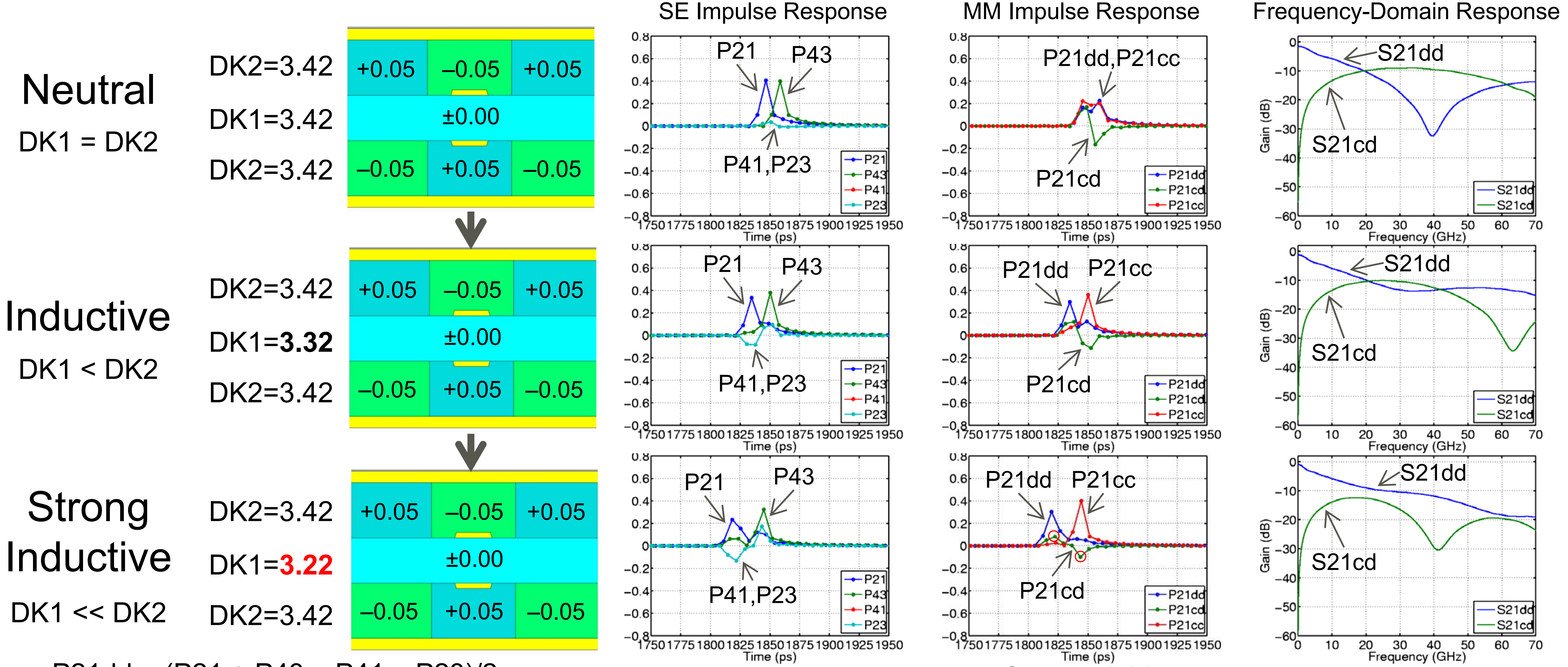
P21dd = (P21 + P43 – P41 – P23)/2
P21cd = (P21 – P43 + P41 – P23)/2
P21cc = (P21 + P43 + P41 + P23)/2

Larger P41, P23
Separated peaks

Smaller P21cd
Separated peaks
Larger inter-mode skew

Reduced S21cd gain
Reduced S21cd freq.

Reduction of Mode Conversion by Inductive Coupling



P21dd = (P21 + P43 – P41 – P23)/2

P21cd = (P21 – P43 + P41 – P23)/2

P21cc = (P21 + P43 + P41 + P23)/2

Larger P41, P23
Separated peaks

Smaller P21cd
Separated peaks
Larger inter-mode skew

Reduced S21cd gain
Reduced S21cd freq.

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

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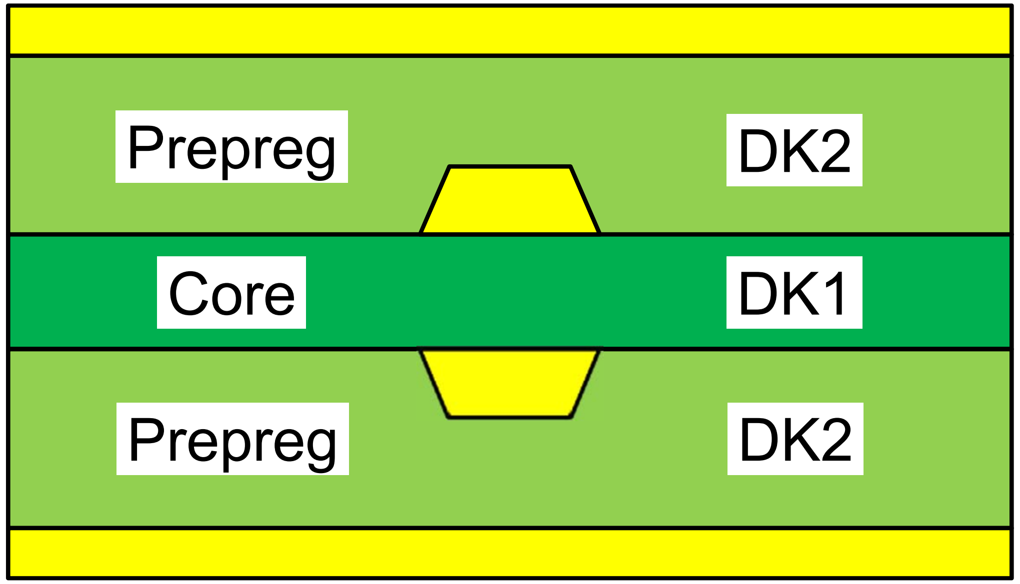
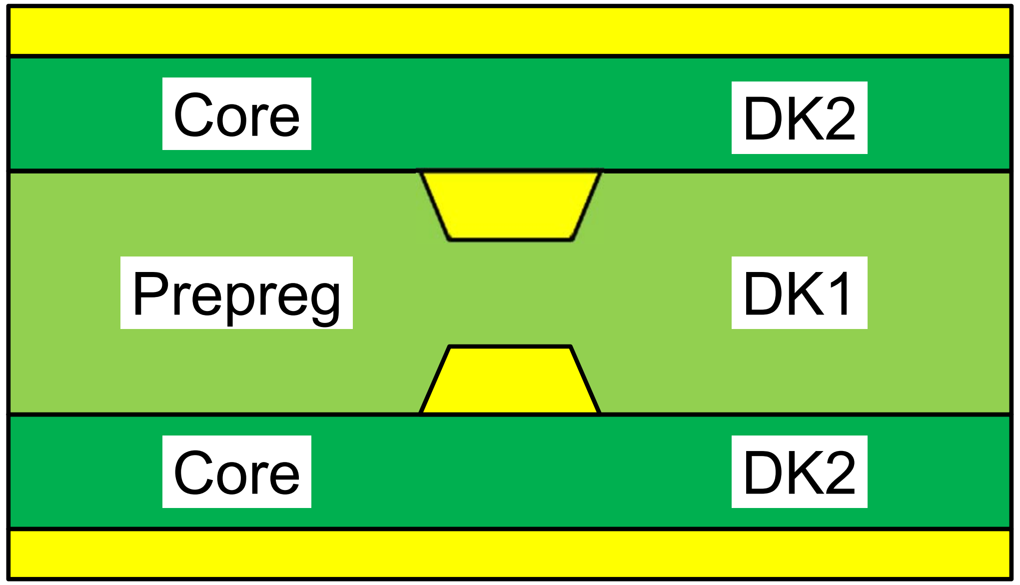
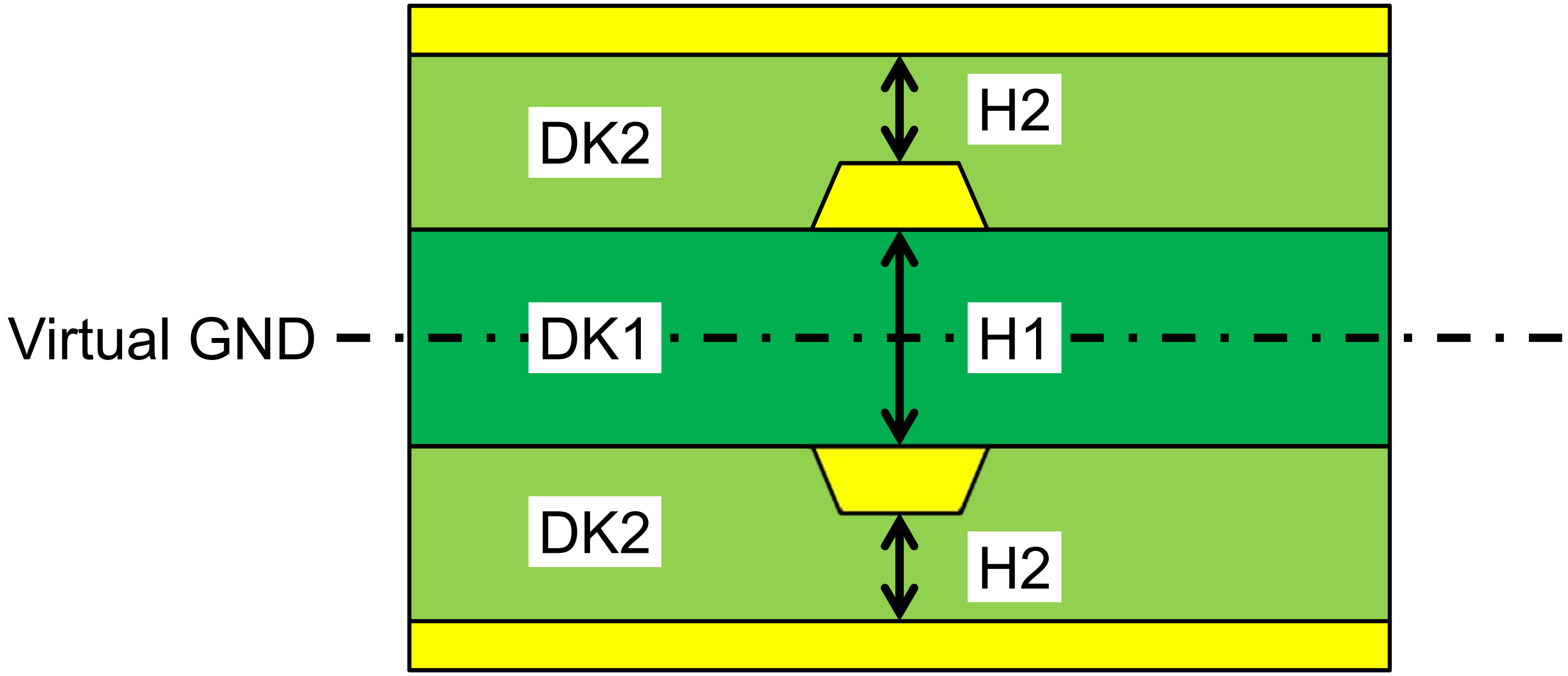
Implementation Issue 1: Location of Core and Prepreg

	PCP stack		CPC stack
			
Pros	Small misalignment error between two sides of a core	Pros	DK1 (prepreg) is likely low → Likely inductive coupling → P21dd always looks causal
Cons	DK1 (core) is likely high → Likely capacitive coupling → P21dd may look non-causal	Cons	Large misalignment error between two laminated cores

Implementation Issue 2: Common-Mode Impedance

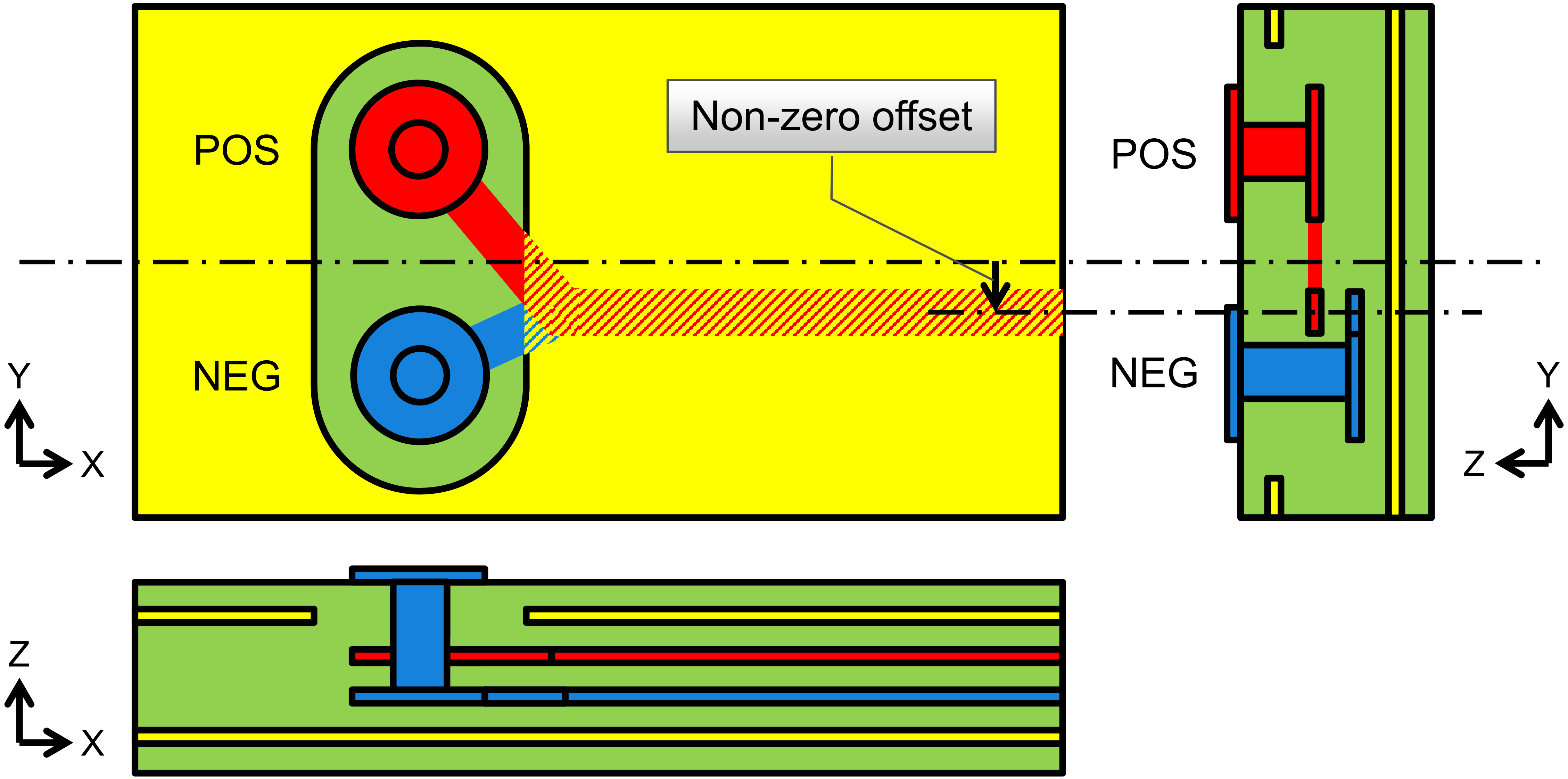
- To make common-mode impedance 25 ohm and differential impedance 100 ohm, H2 must be half of H1
- If we use 1-ply cloth for DK1, available H1 will be limited such as up to 125um
- Then, H2 will be up to 62.5um, and trace width will be too narrow (such as less than 50um)

- 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



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

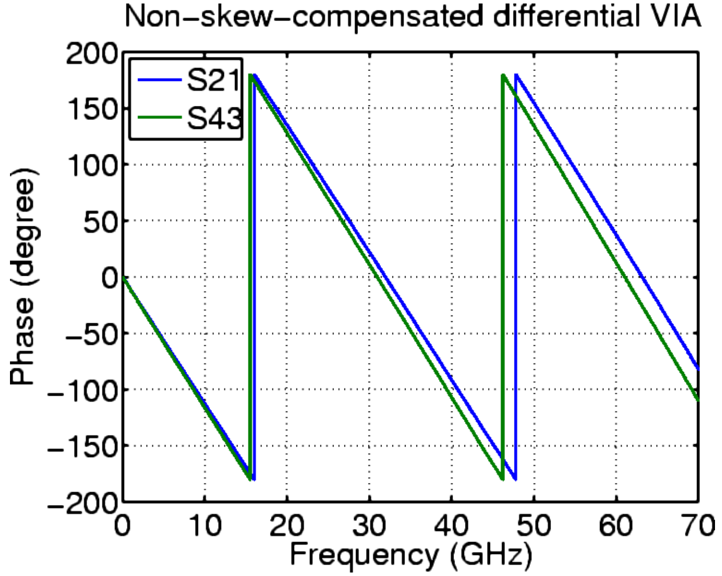


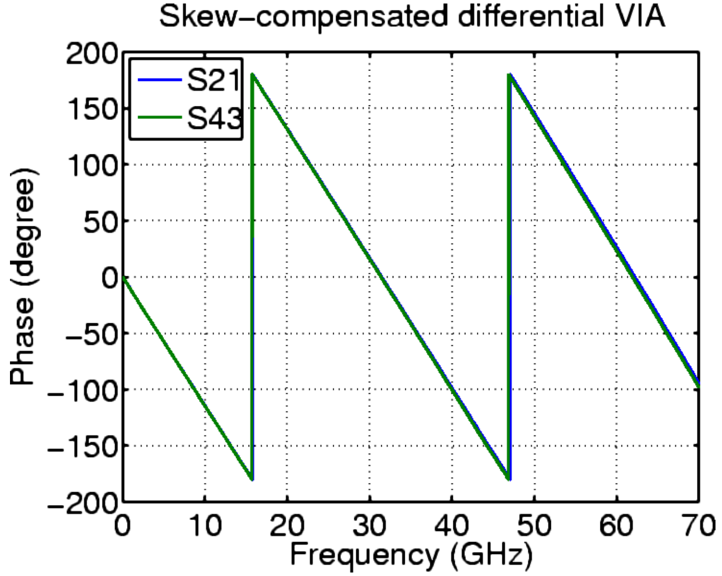
Simulation Results of Skew-Compensated Differential VIA

Without Skew Compensation

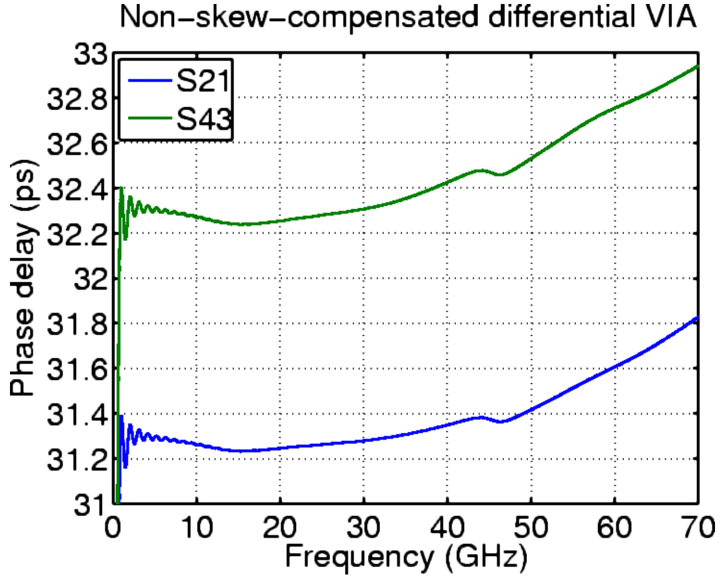
With Skew Compensation

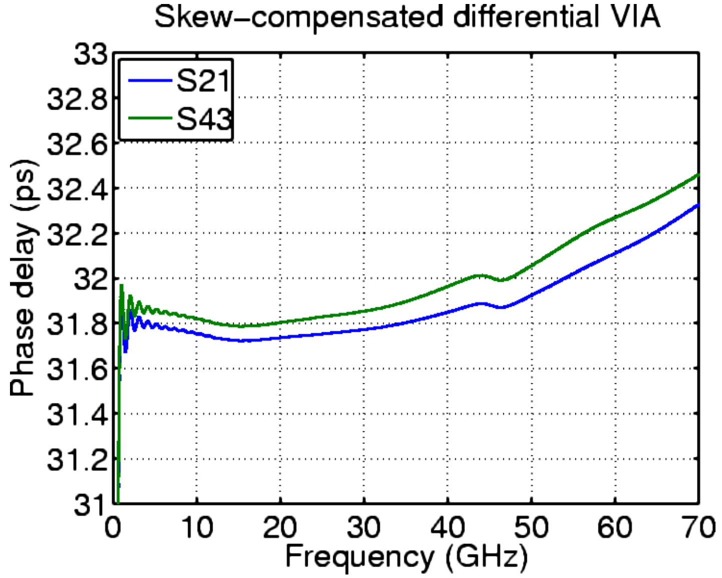
Phase





Phase Delay





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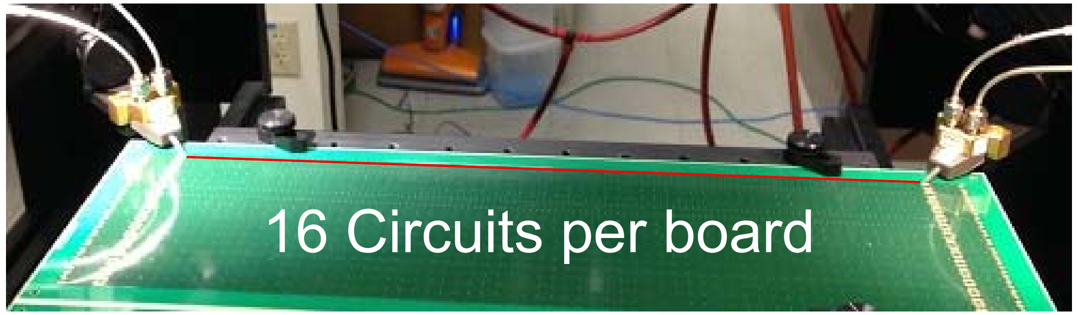
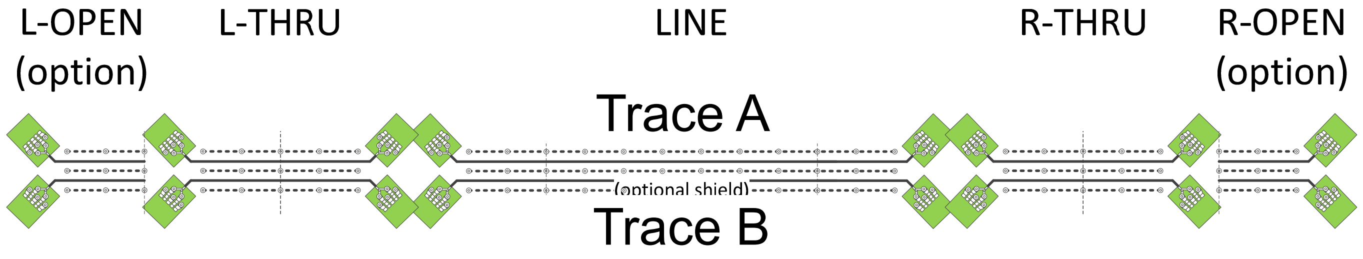
Overview of Test Board

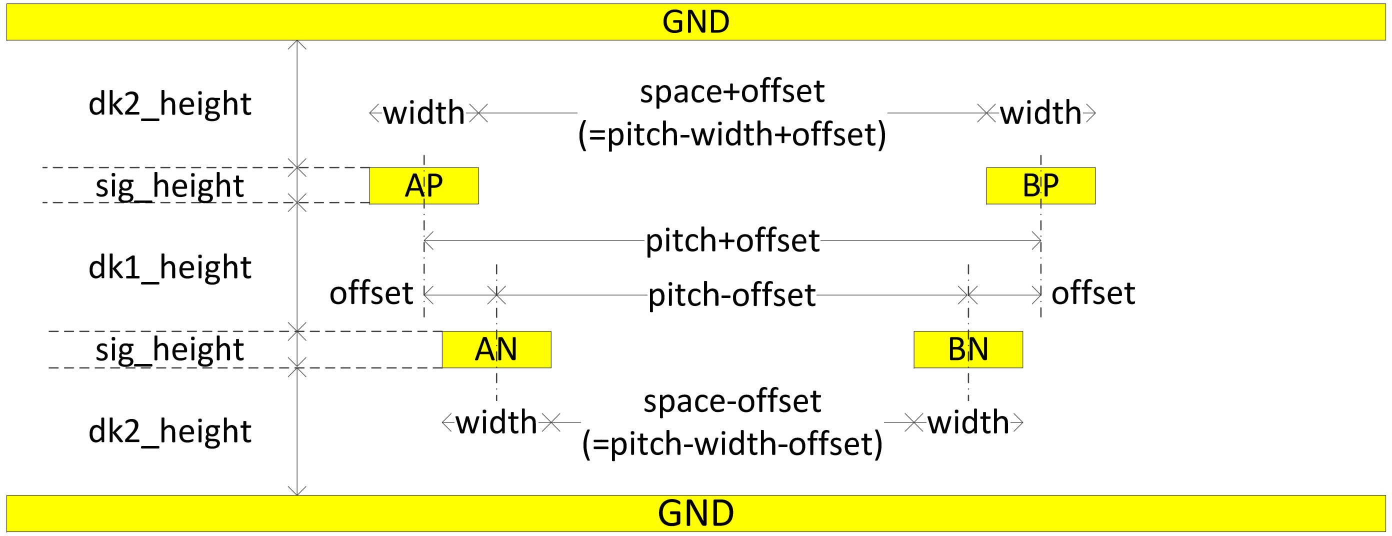
Test Board



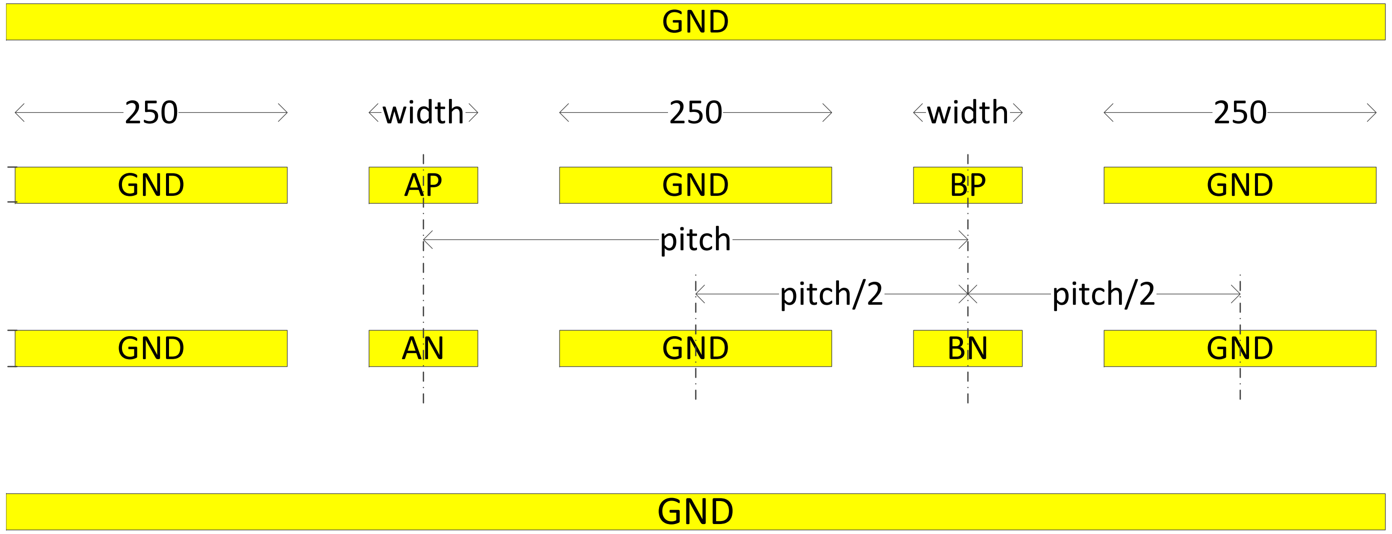
Unit Circuit



Cross Section w/o GND Shield



Cross Section with GND shield

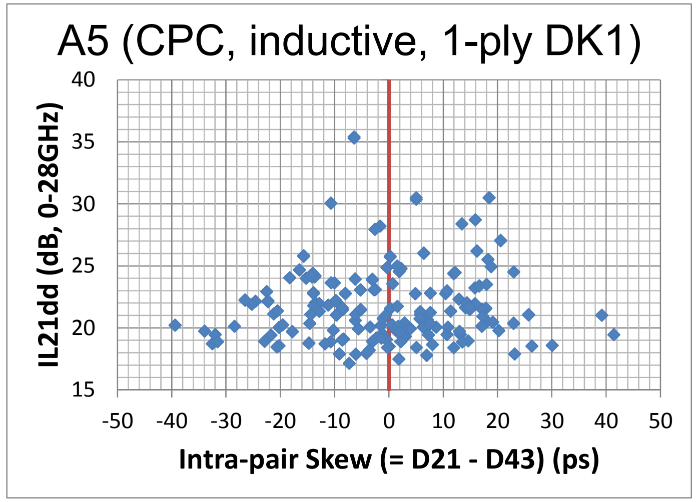


Stack-up Parameters of Test Board

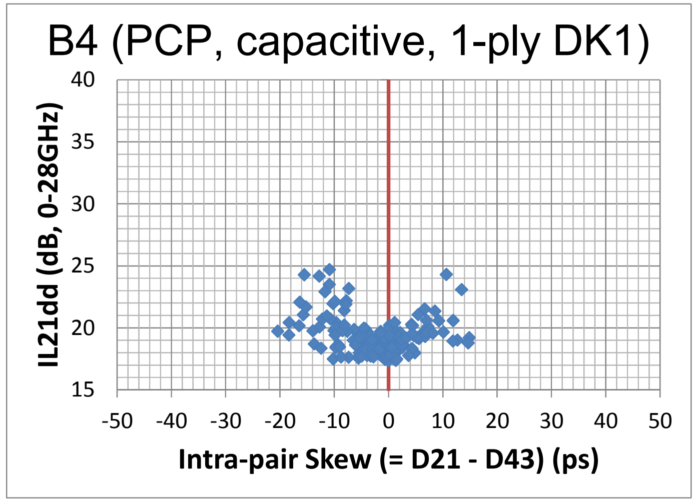
Evaluation Phase		1st Phase			2nd Phase	Previous Project	
Label		A5	B4	C5	B8	M1A (Reference)	
Type		CPC	PCP	CPC	PCP	Edge Coupled	
Coupling Mode		Inductive	Capacitive	Inductive	Strong Capacitive	Neutral	
DK1	Type	Prepreg	Core	Prepreg	Core		
	Resin / Glass	Megtron 6 / NE	Megtron 6 / NE	Megtron 6 / NE	Megtron 6 / E	Core	Megtron6/NE
	Cloth	#1078 * 1 ply	#2116 * 1 ply	#1035 * 2 ply	#2116 * 1 ply		2 ply
	Thickness	118um	125um	148um	125um		100um
	Dk@1GHz	3.13	3.40	3.13	3.71		
DK2	Type	Core	Prepreg	Core	Prepreg		
	Resin / Glass	Megtron 6 / E	Megtron 6 / NE	Megtron 6 / E	Megtron 6 / NE	Prepreg	Megtron6/NE
	Cloth	#1035 * 2 ply	#1035 * 2 ply	#1035 * 2 ply	#1035 * 2 ply		2 ply
	Thickness	120um	148um	120um	148um		120um
	Dk@1GHz	(3.35)	3.13	(3.35)	3.13		
# of measured traces		160	160	96	160	60	
# of measured boards		5	5	3	5	2	

Intra-pair Skew (X) vs Differential Insertion Loss (Y)

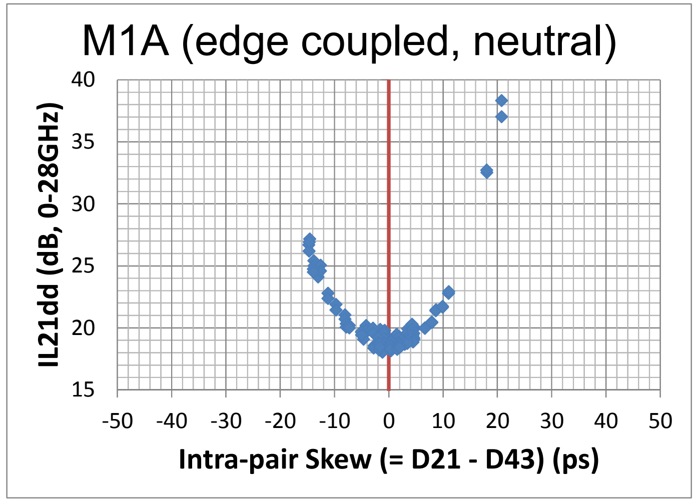
- With BSC SL, differential insertion loss (Y) does not necessarily increase as intra-pair skew (X)



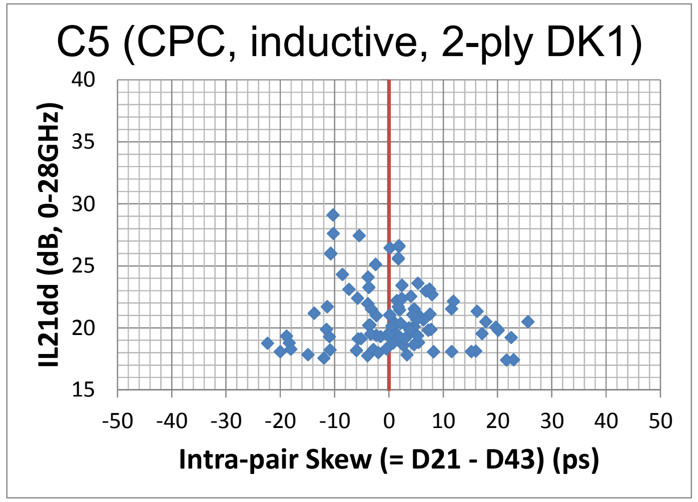
A5: Loss increases randomly



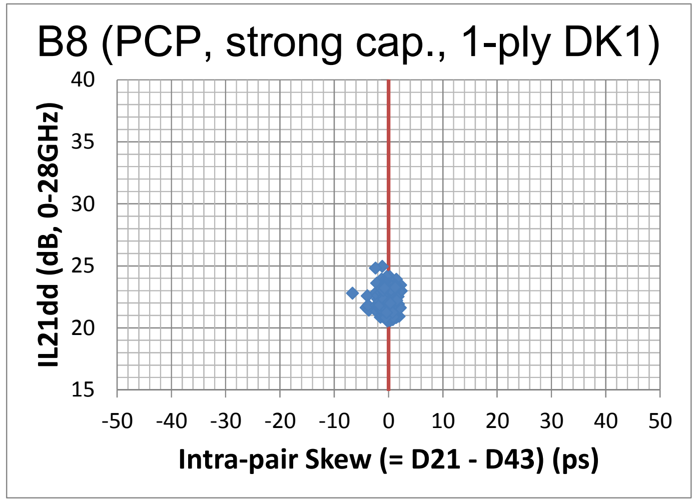
B4: Weak quadratic function



M1A: Strong quadratic function



C5: Loss increases randomly

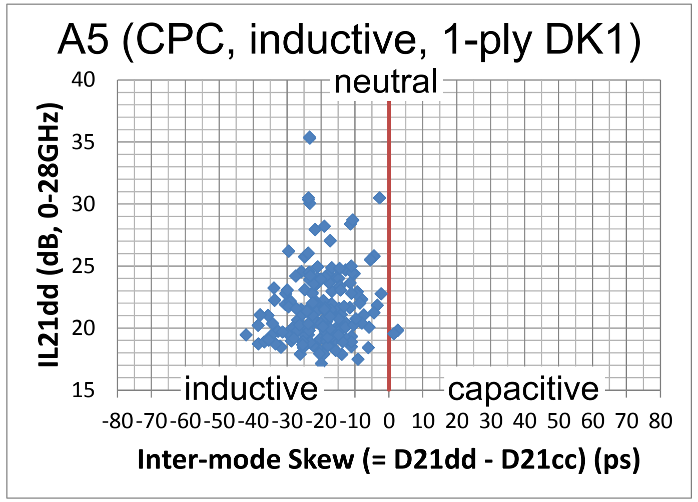


B8: Loss does not increase

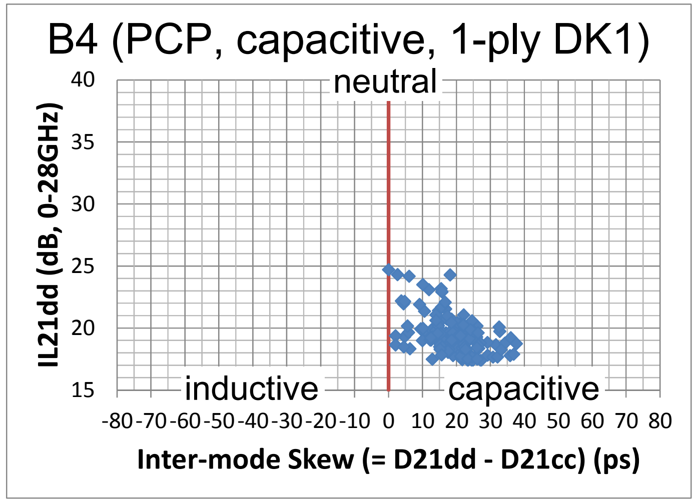
Trace Length
A5/C5/B4: 314.37mm
B8: 343.11mm
M1A: 305.30mm

Inter-mode Skew (X) vs Differential Insertion Loss (Y)

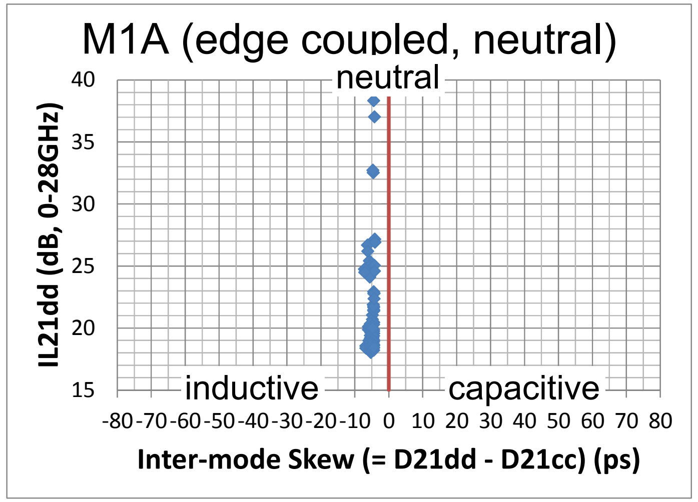
- Differential insertion loss (Y) generally decreases as magnitude of inter-mode skew increases (X)
  - Magnitude of inter-mode skew indicates the coupling strength, and its sign indicates the coupling mode, i.e. inductive or capacitive



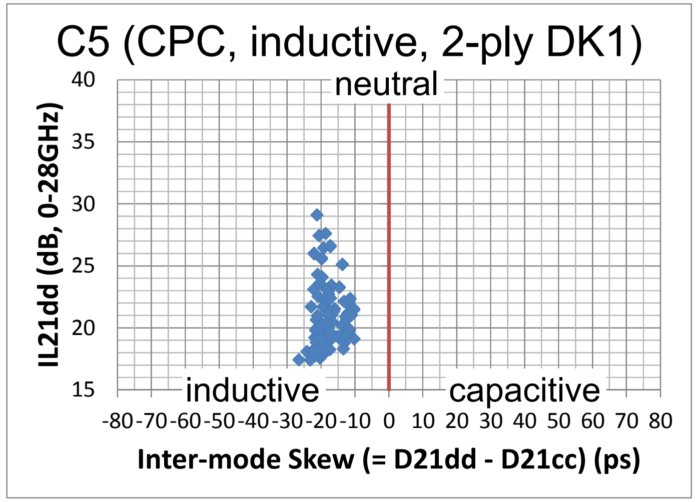
A5: Inter-mode skew < 0



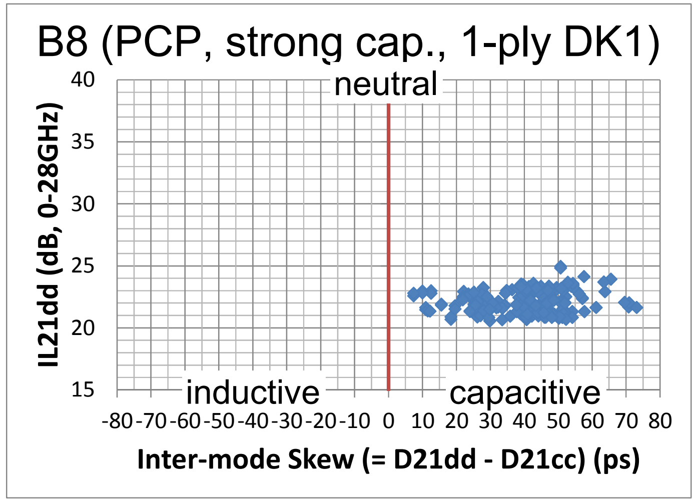
B4: Inter-mode skew > 0



M1A: Inter-mode skew ~ 0



C5: Inter-mode skew < 0

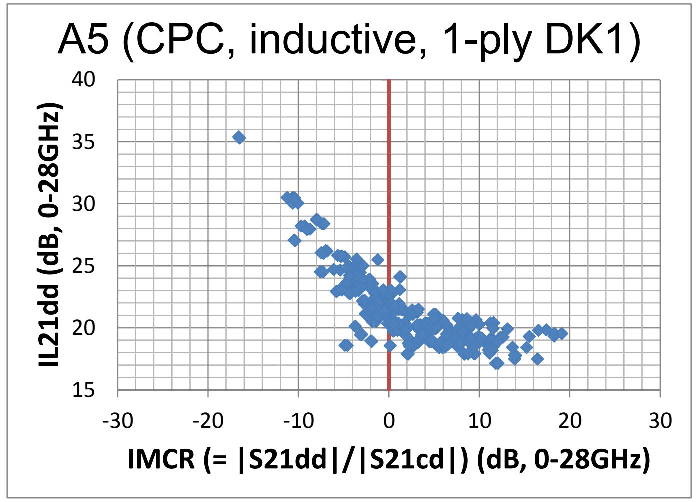


B8: Inter-mode skew > 0

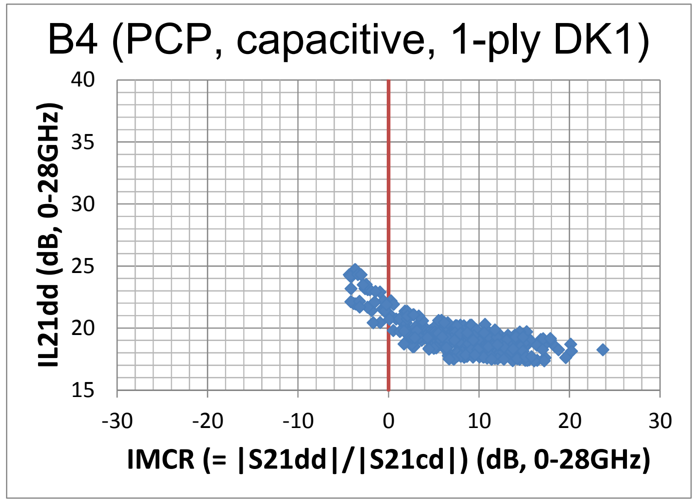
Trace Length
A5/C5/B4: 314.37mm
B8: 343.11mm
M1A: 305.30mm

Insertion Loss to Mode-Conversion Ratio (X) vs Differential IL (Y)

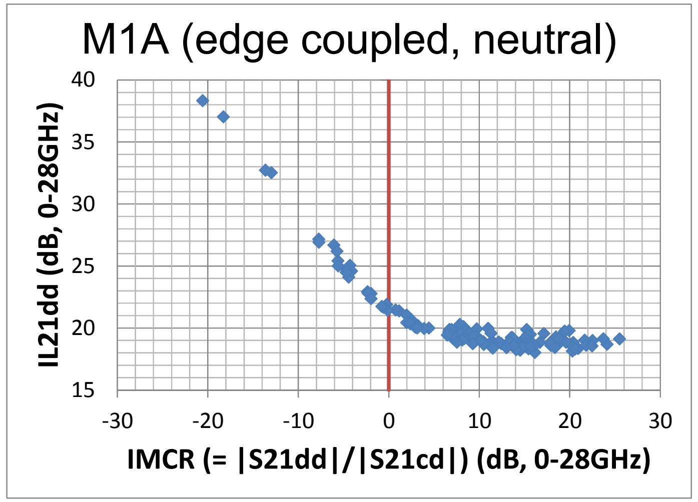
- IMCR (=|S21dd| / |S21cd|, insertion-loss to mode-conversion ratio) shows margin for mode conversion
- Lower side of IMCR looks bounded for B4 (down to – 4dB) and B8 (down to 0dB)



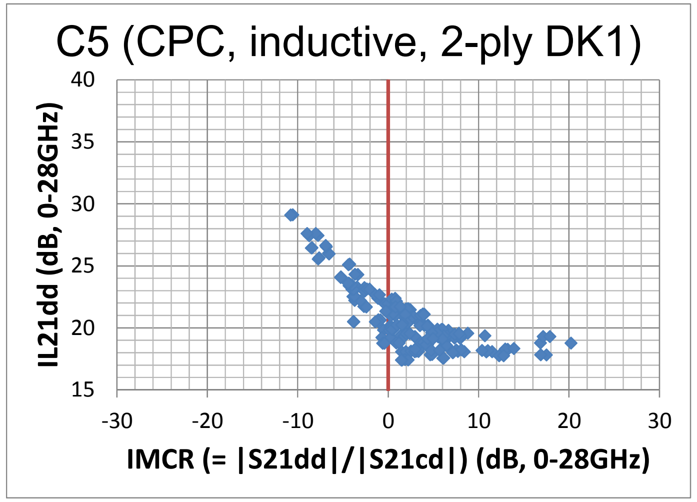
A5: IMCR lower bound – no clear limit



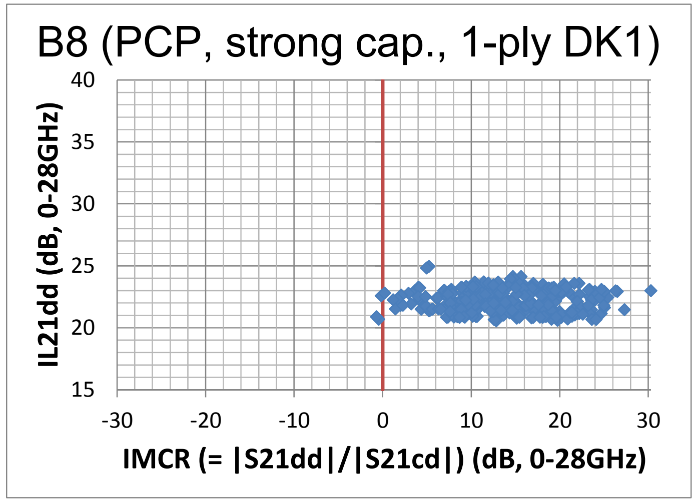
B4: IMCR lower bound ~ – 4dB



M1A: IMCR lower bound – no clear limit



C5: IMCR lower bound – no clear limit

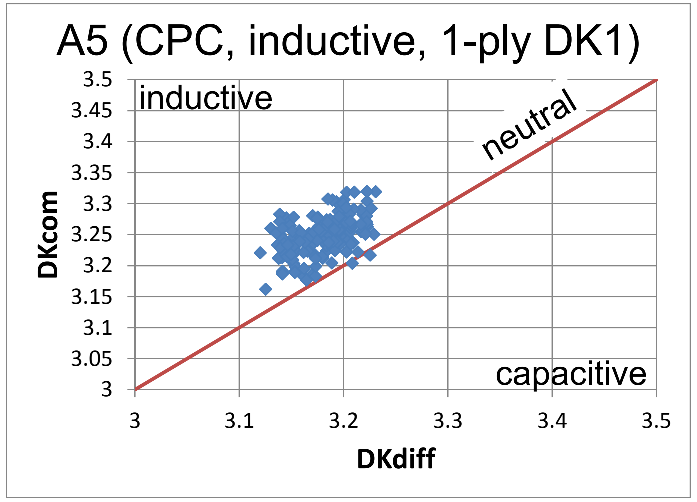


B8: IMCR lower bound ~ 0dB

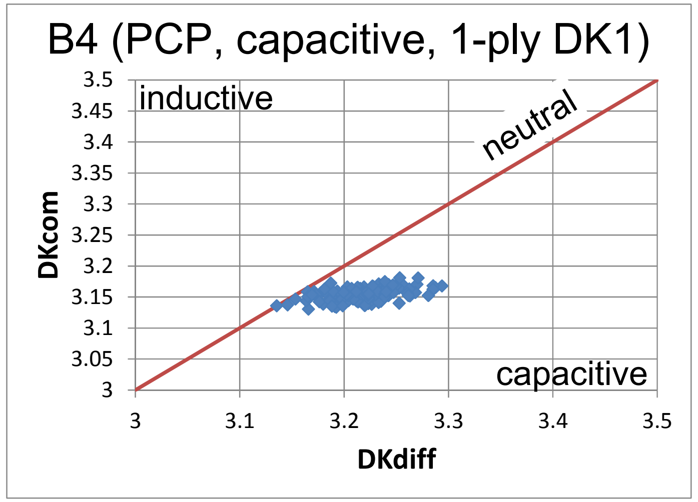
Trace Length
A5/C5/B4: 314.37mm
B8: 343.11mm
M1A: 305.30mm

Effective DKdiff (X) vs Effective DKcom (Y)

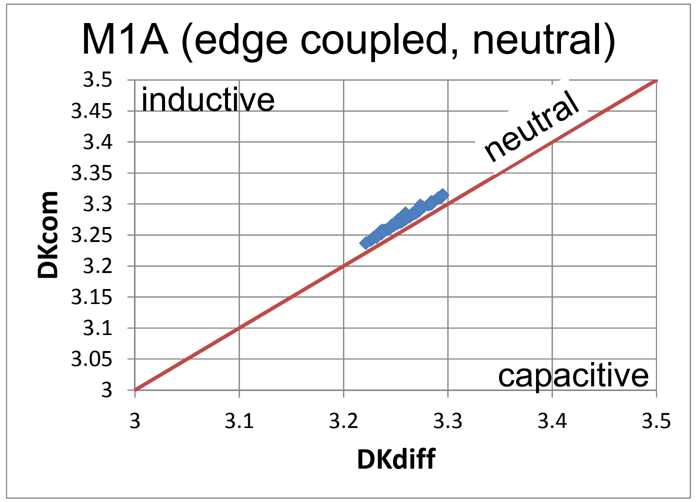
- Confirmed that A5 and C5 are inductive, B4 and B8 are capacitive, and M1A is weak inductive.



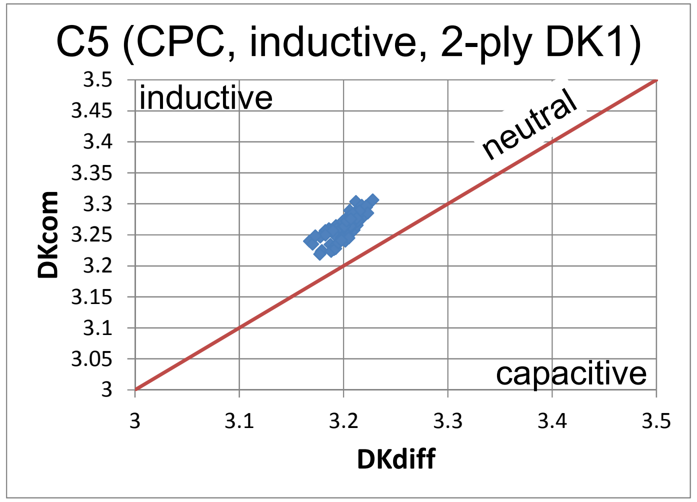
A5: Mostly inductive



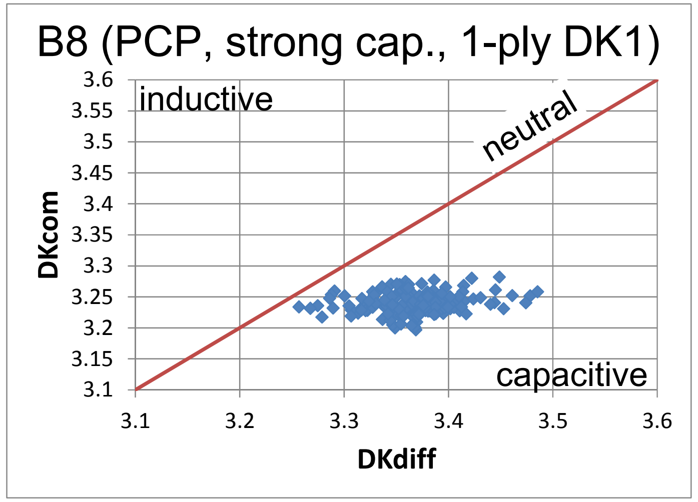
B4: Mostly capacitive



M1A: All weak inductive



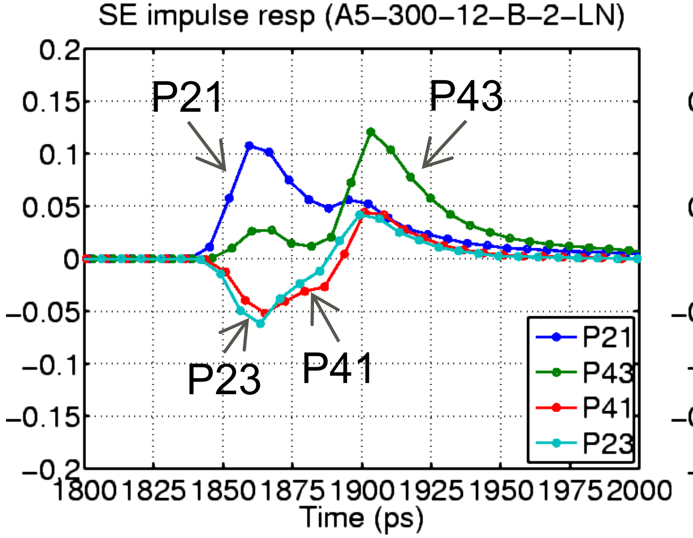
C5: All inductive

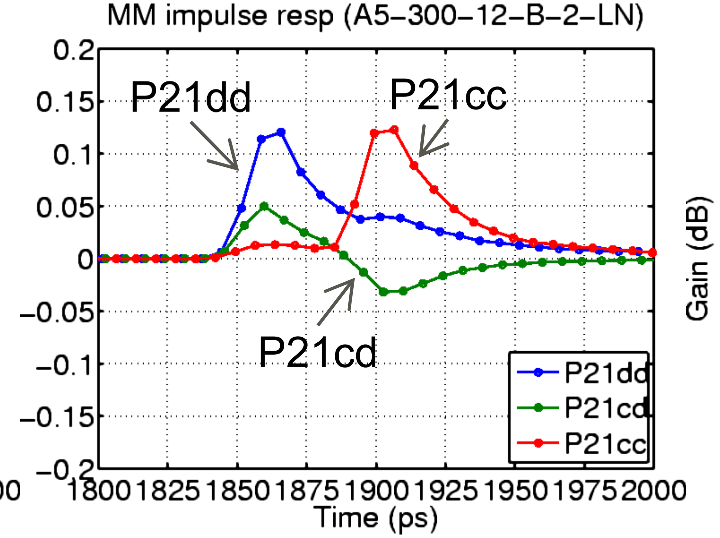


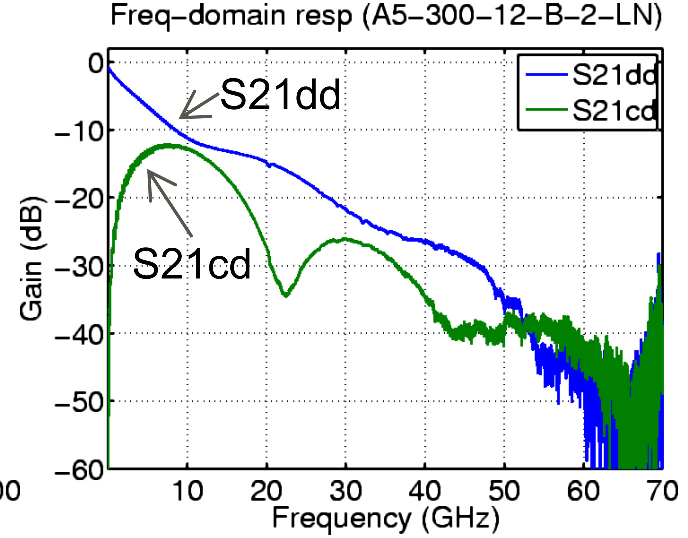
B8: All capacitive

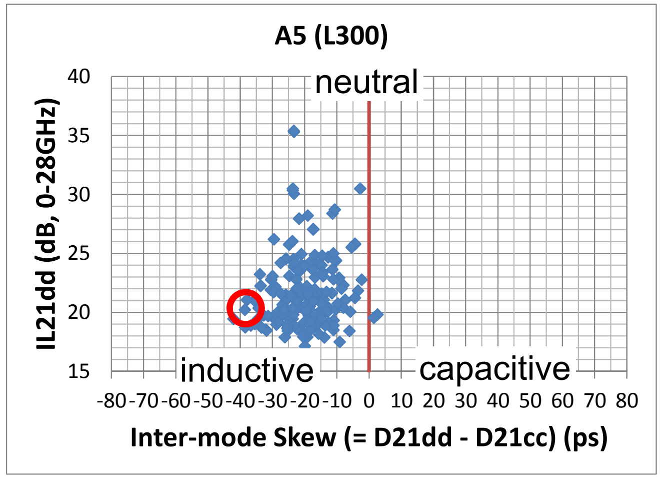
A Successful Case of Inductive Coupling (A5)

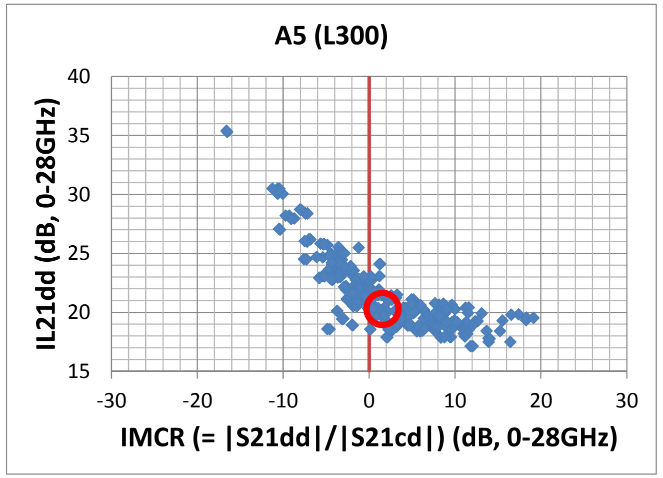
- While intra-pair skew is large, inductive coupling successfully suppressed mode conversion.

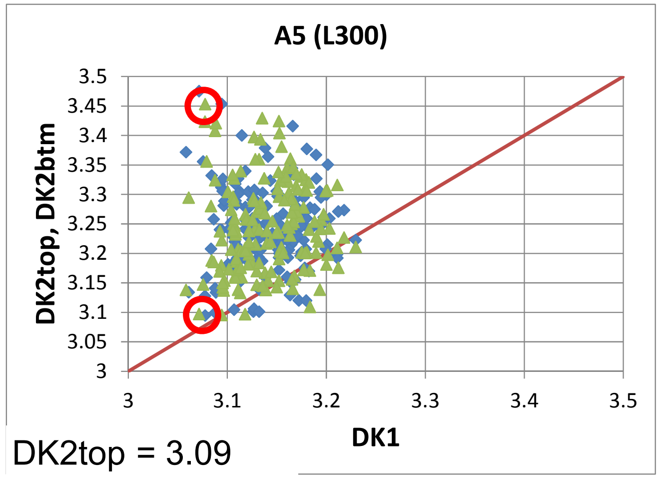






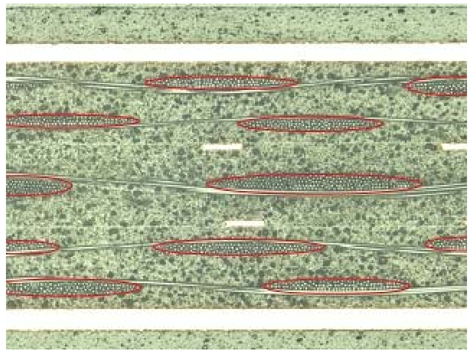






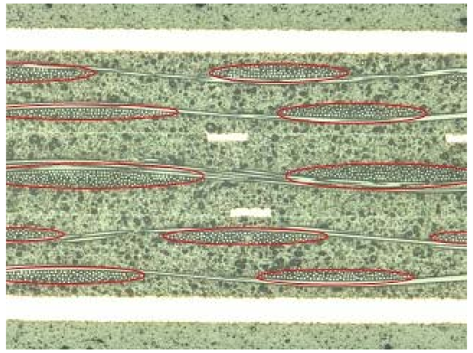
DK2top = 3.09
DK1 = 3.08 (AVG)
DK2btm = 3.45

LEFT (P1/P3 side)



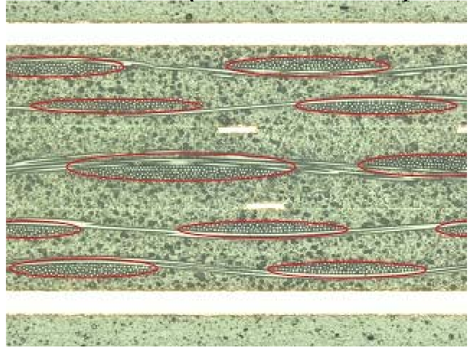
Cloth #1 vs POS: yarn
Cloth #2 vs POS: gap
Cloth #3 vs POS: edge
Cloth #3 vs NEG: yarn
Cloth #4 vs NEG: yarn
Cloth #5 vs NEG: gap

CENTER



Cloth #1 vs POS: edge
Cloth #2 vs POS: gap
Cloth #3 vs POS: gap
Cloth #3 vs NEG: gap
Cloth #4 vs NEG: yarn
Cloth #5 vs NEG: edge

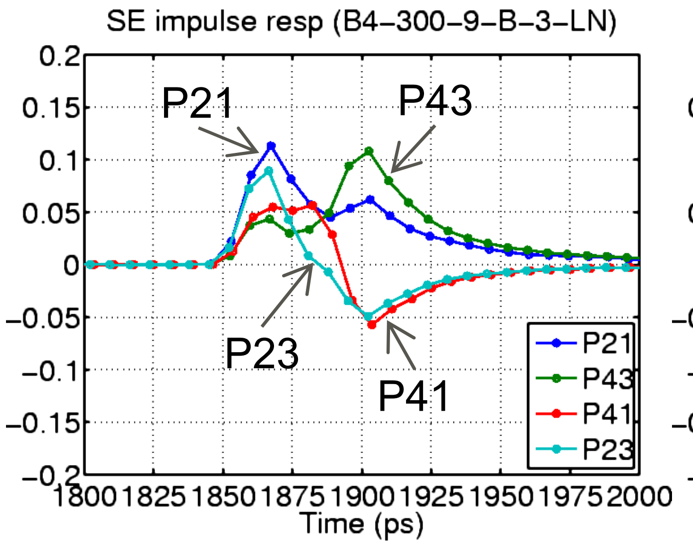
RIGHT (P2/P4 side)

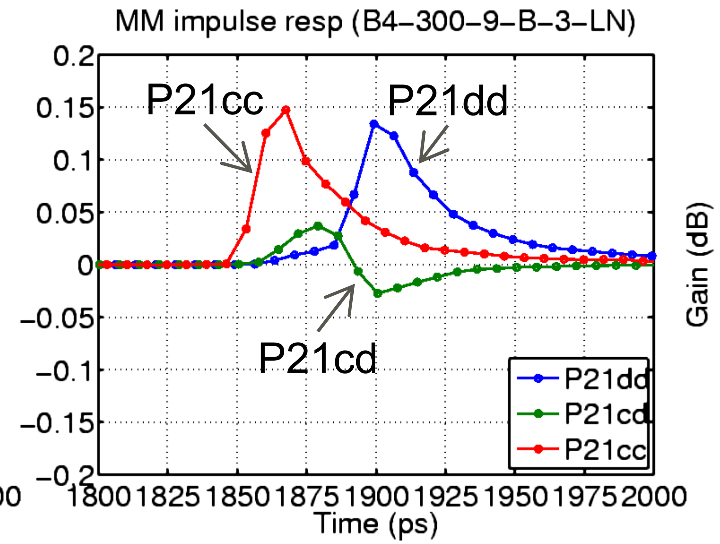


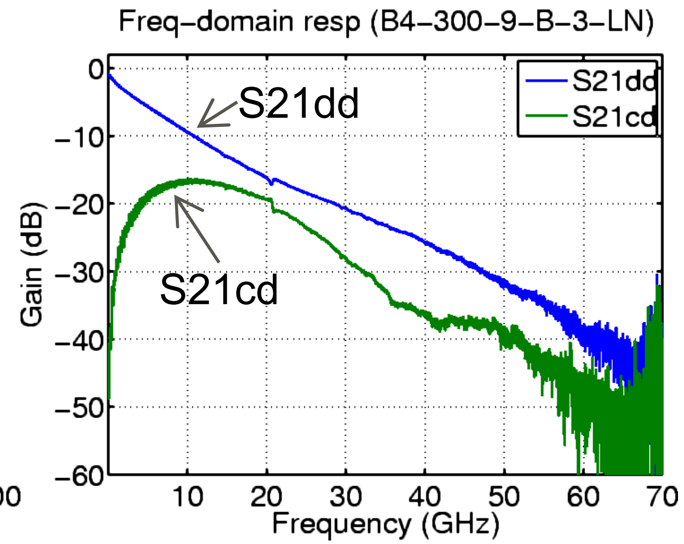
Cloth #1 vs POS: edge
Cloth #2 vs POS: gap
Cloth #3 vs POS: yarn
Cloth #3 vs NEG: yarn
Cloth #4 vs NEG: yarn
Cloth #5 vs NEG: edge

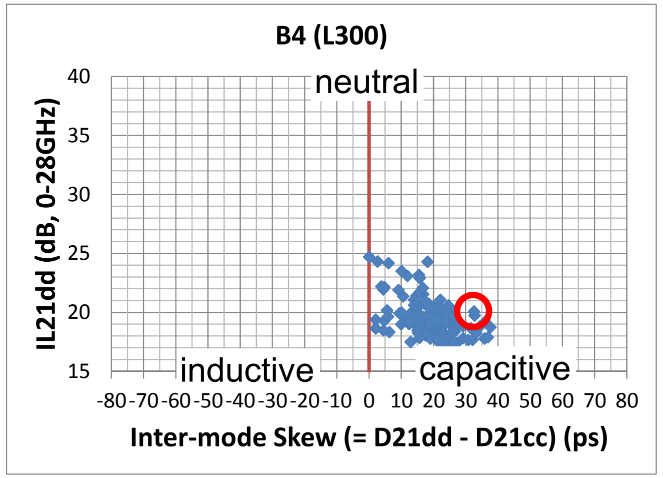
A Successful Case of Capacitive Coupling (B4)

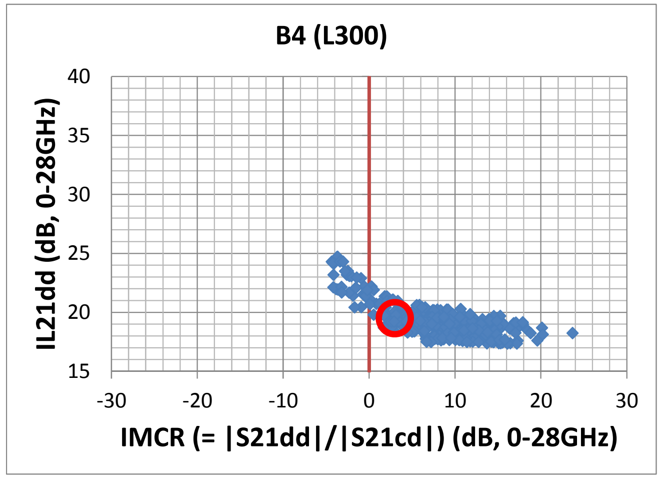
- While intra-pair skew is large, capacitive coupling successfully suppressed mode conversion.

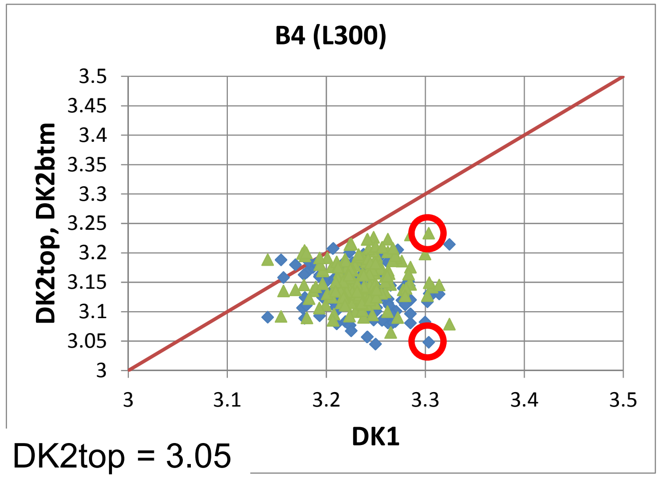






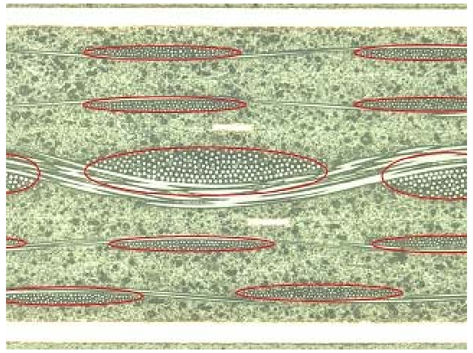






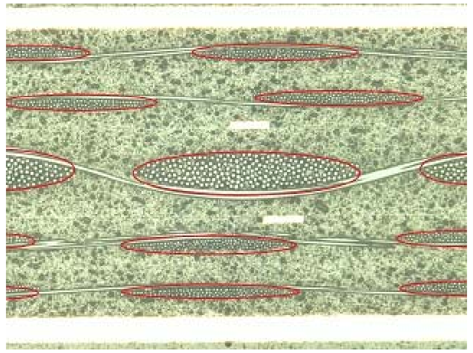
DK2top = 3.05
DK1 = 3.30
DK2btm = 3.23

LEFT (P1/P3 side)



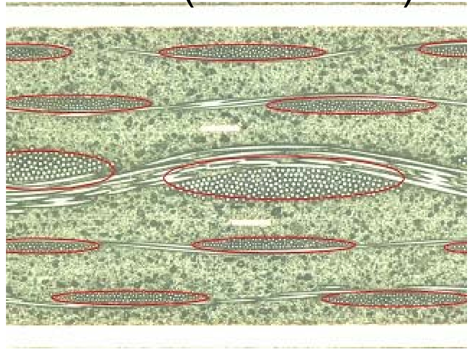
Cloth #1 vs POS: edge
Cloth #2 vs POS: edge
Cloth #3 vs POS: yarn
Cloth #3 vs NEG: yarn
Cloth #4 vs NEG: edge
Cloth #5 vs NEG: edge

CENTER



Cloth #1 vs POS: yarn
Cloth #2 vs POS: edge
Cloth #3 vs POS: yarn
Cloth #3 vs NEG: yarn
Cloth #4 vs NEG: edge
Cloth #5 vs NEG: edge

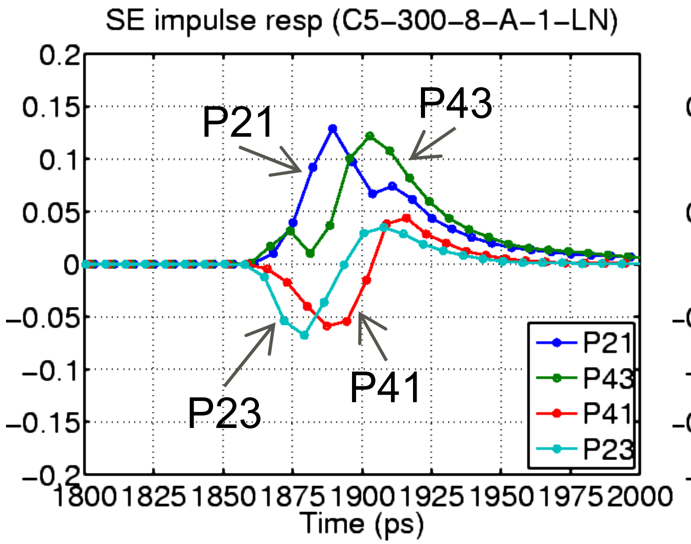
RIGHT (P2/P4 side)

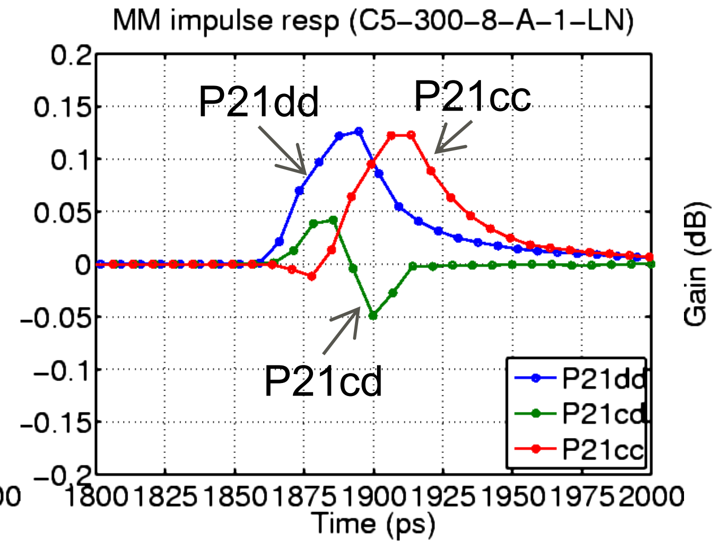


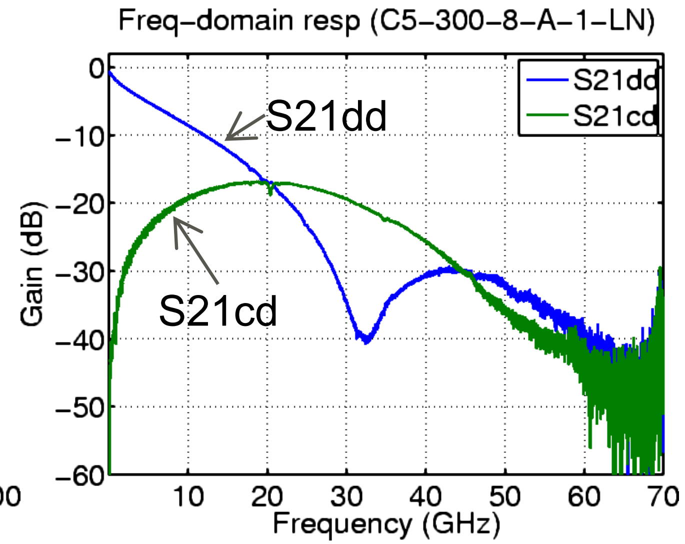
Cloth #1 vs POS: yarn
Cloth #2 vs POS: gap
Cloth #3 vs POS: yarn
Cloth #3 vs NEG: yarn
Cloth #4 vs NEG: yarn
Cloth #5 vs NEG: gap

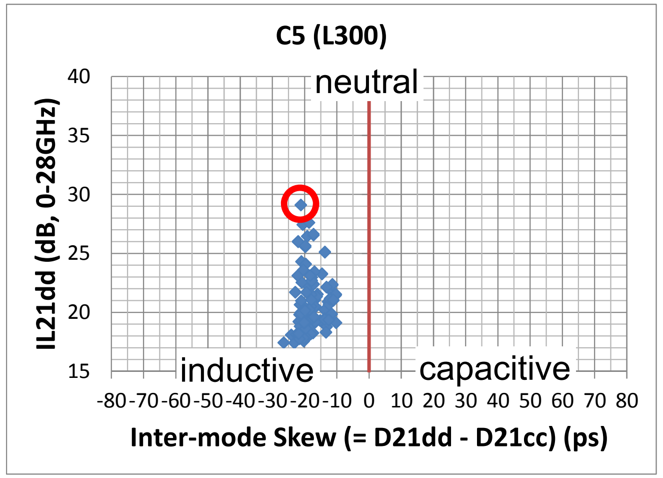
A Failure Case of 2-ply Glass Cloth for DK1 (C5)

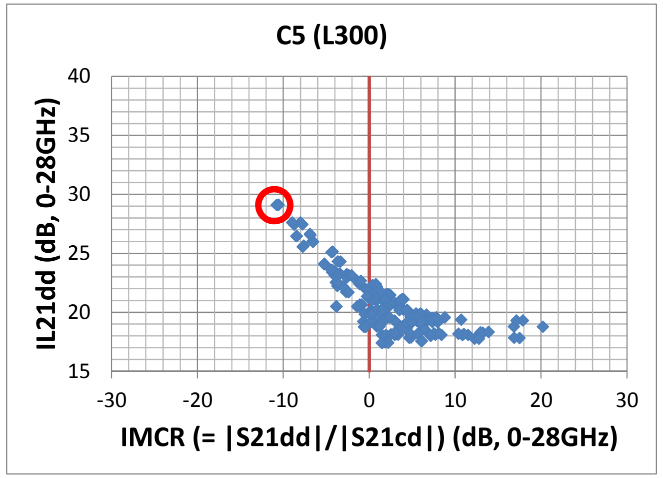
- Mode conversion was not suppressed well, because DK1 was inconsistent between POS and NEG traces

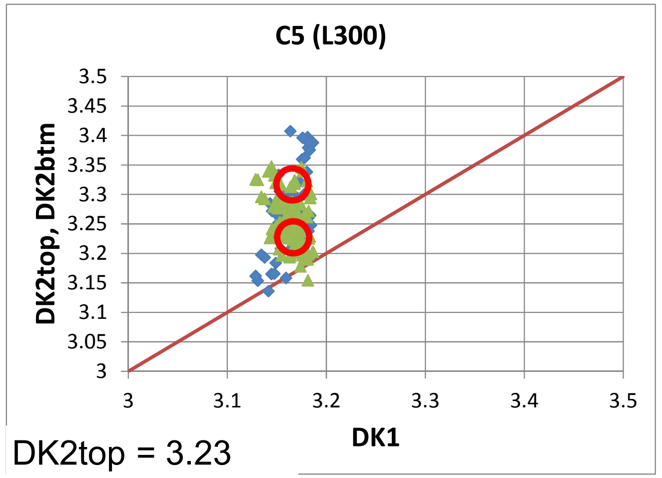






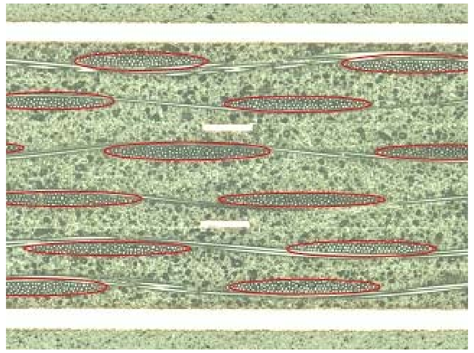






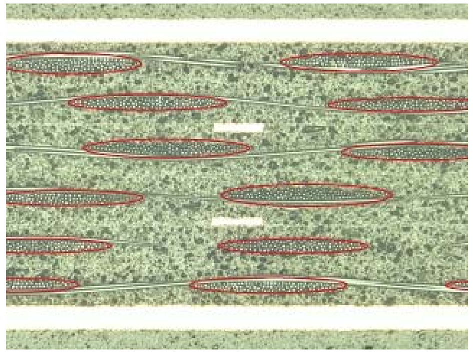
DK2top = 3.23
DK1 = 3.17 (AVG)
DK2btm = 3.32

LEFT (P1/P3 side)



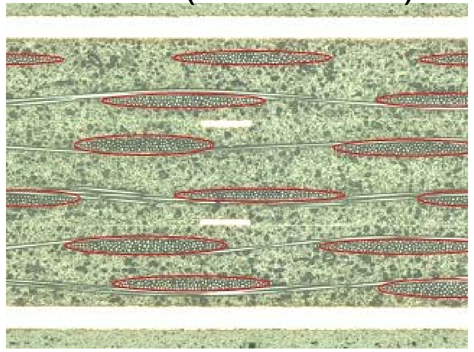
Cloth #1 vs POS: gap
Cloth #2 vs POS: edge
Cloth #3 vs POS: edge
Cloth #4 vs NEG: edge
Cloth #5 vs NEG: gap
Cloth #6 vs NEG: edge

CENTER



Cloth #1 vs POS: gap
Cloth #2 vs POS: gap
Cloth #3 vs POS: edge
Cloth #4 vs NEG: edge
Cloth #5 vs NEG: edge
Cloth #6 vs NEG: yarn

RIGHT (P2/P4 side)



Cloth #1 vs POS: yarn
Cloth #2 vs POS: edge
Cloth #3 vs POS: gap
Cloth #4 vs NEG: yarn
Cloth #5 vs NEG: edge
Cloth #6 vs NEG: yarn

Differential Impedance

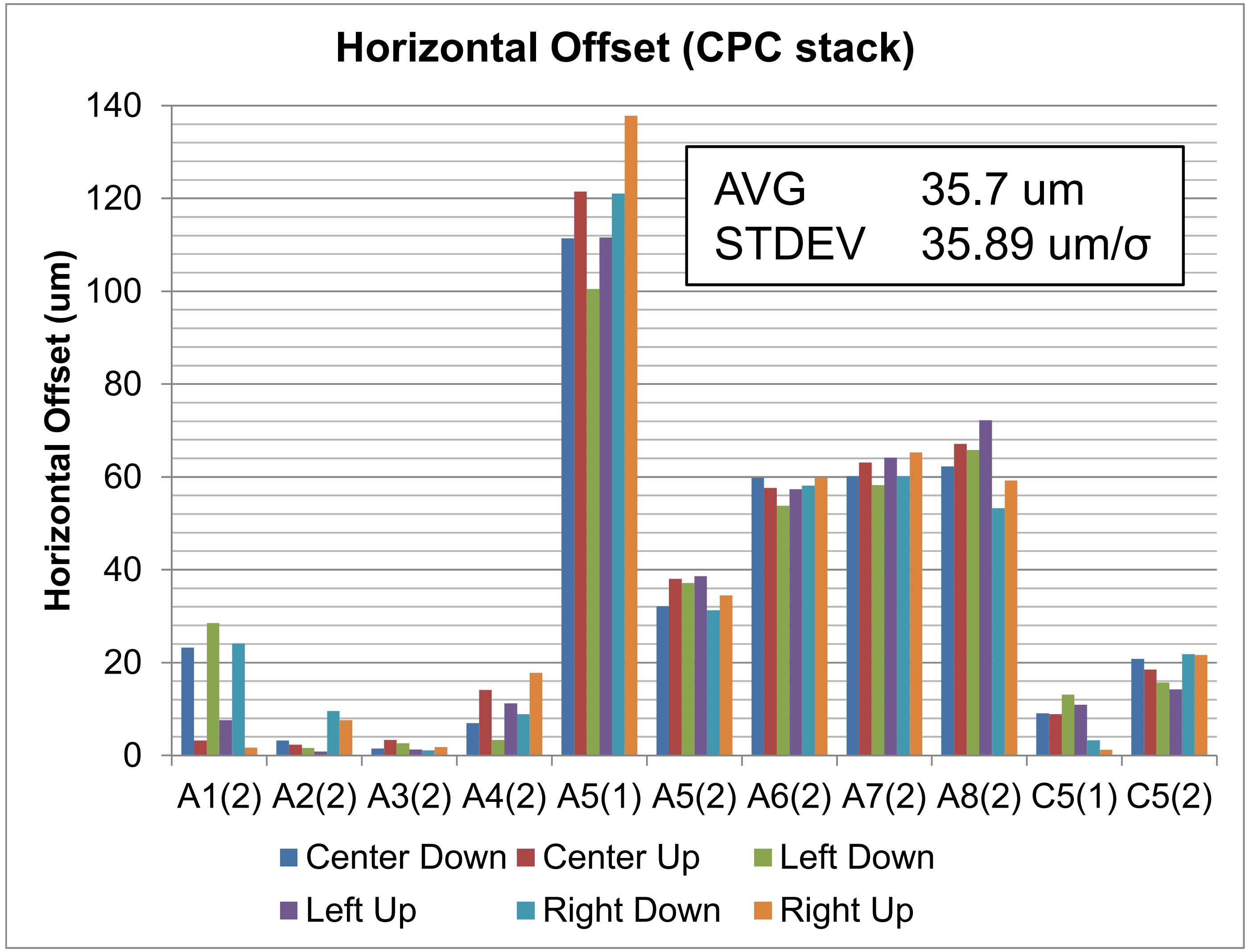
- A5 (CPC stack) has large impedance variation due to large horizontal offset of CPC stack
- B4 and B8 (PCP stack) has small impedance variation comparable to conventional edge coupling

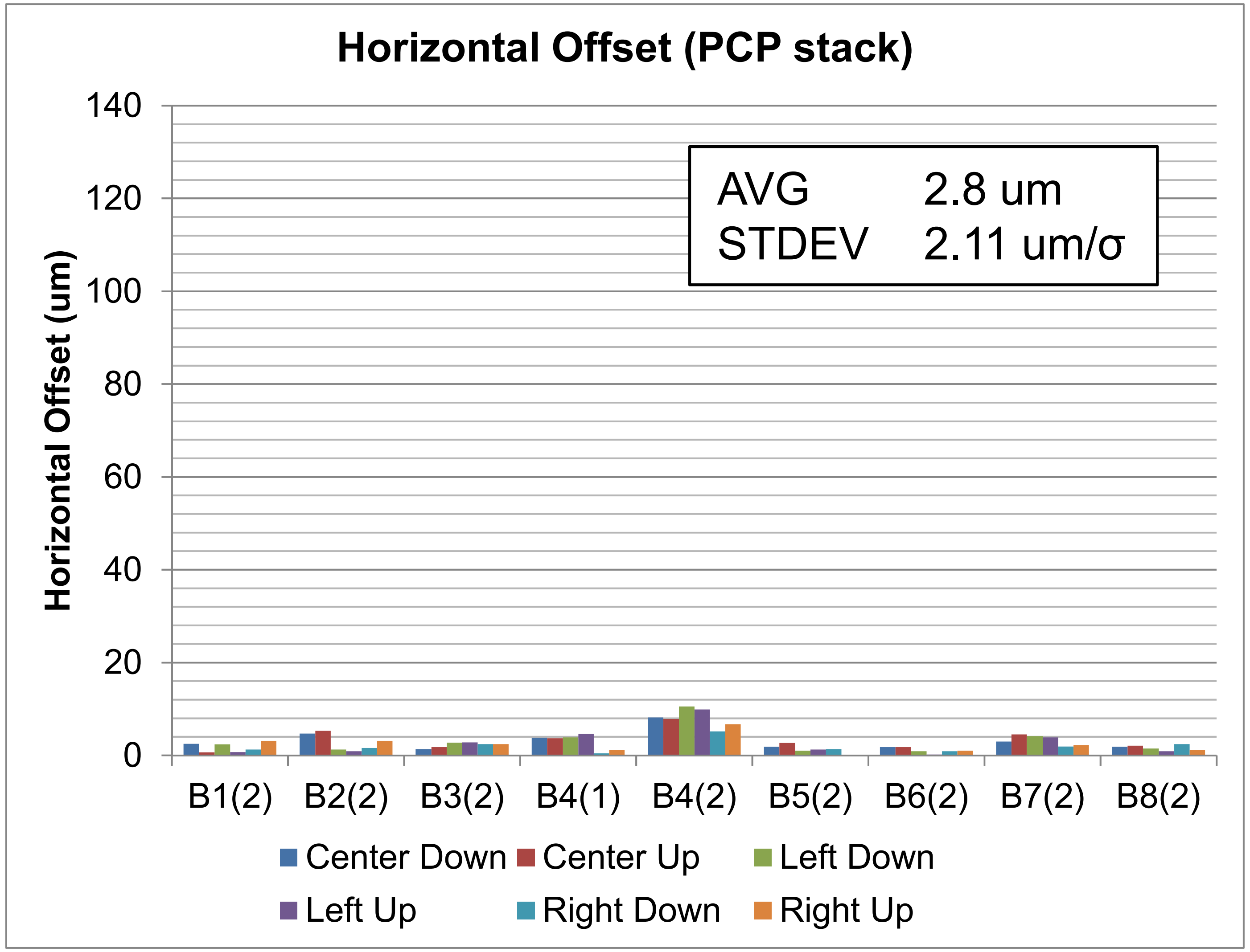
	Stack up type	CPC				PCP				Edge Coupled	
	Label	A5		C5		B4		B8		M1A	
	Cloth Style	#1078x1 (DK1) #1035x2 (DK2)		#1035x2 (DK1) #1035x2 (DK2)		#2116x1 (DK1) #1035x2 (DK2)		#2116x1 (DK1) #1035x2 (DK2)		2 ply (Core) 2 ply (PP)	
	Trace Width		DF		DF		DF		DF		DF
Random Variation	60~100um	6.74Ω/σ	313	1.07Ω/σ	185	1.40Ω/σ	630	1.45Ω/σ	314		
	84um	6.82Ω/σ	76	0.95Ω/σ	44	1.30Ω/σ	156	1.43Ω/σ	76		
	100um	6.09Ω/σ	77	0.88Ω/σ	44	1.11Ω/σ	156	1.31Ω/σ	76		
	120~140um									0.97Ω/σ	116
Average	60~100um	106.92Ω		111.32Ω		113.07Ω		109.95Ω			
	84um	102.22Ω		106.90Ω		108.50Ω		105.51Ω			
	100um	92.74Ω		97.26Ω		98.55Ω		95.61Ω			
	120~140um									88.55Ω	

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.



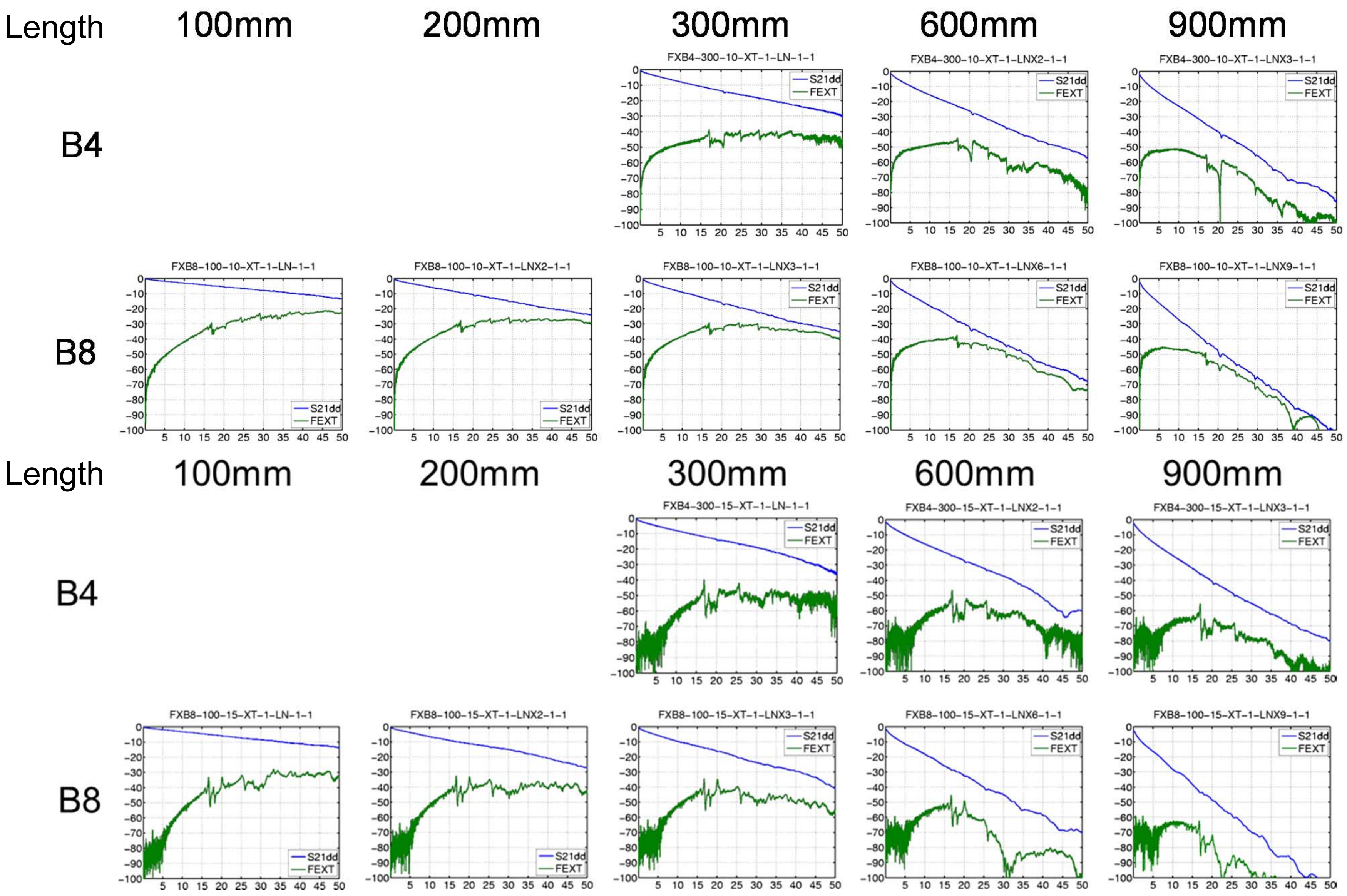


Far End Crosstalk vs S21dd without Shield

- With trace pitch 500um, B8 has less margin than B4
- With trace pitch 1000um, B4 and B8 have similar margin

Trace Pitch 500um

Trace Pitch 1000um

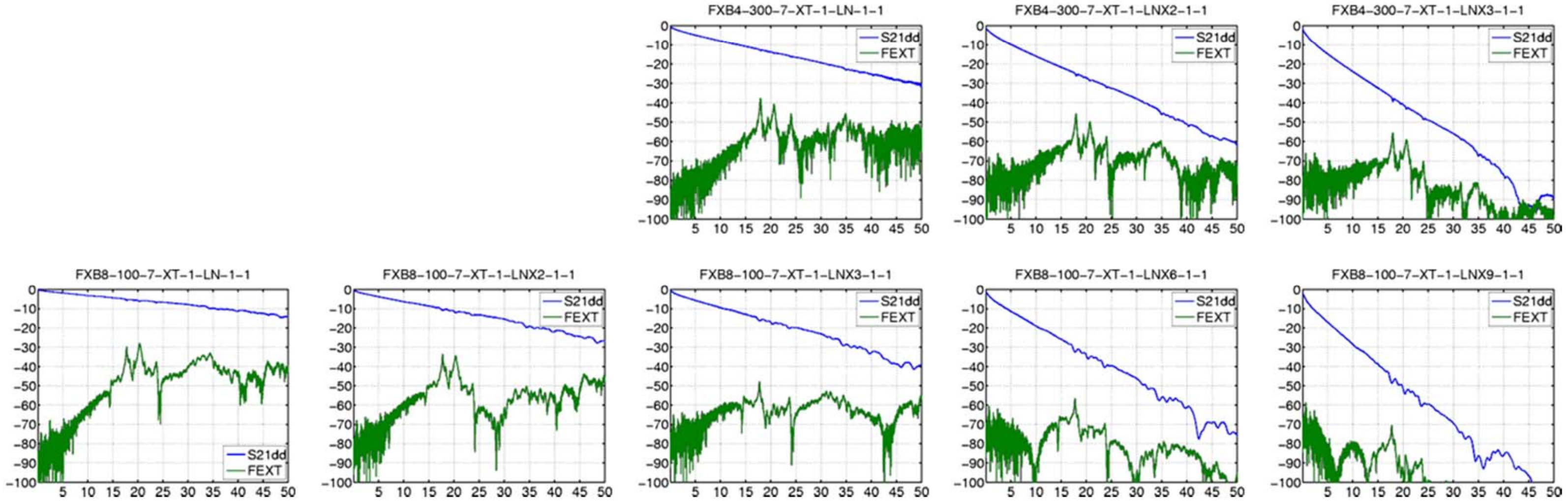


Far End Crosstalk vs S21dd with Shield

- 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

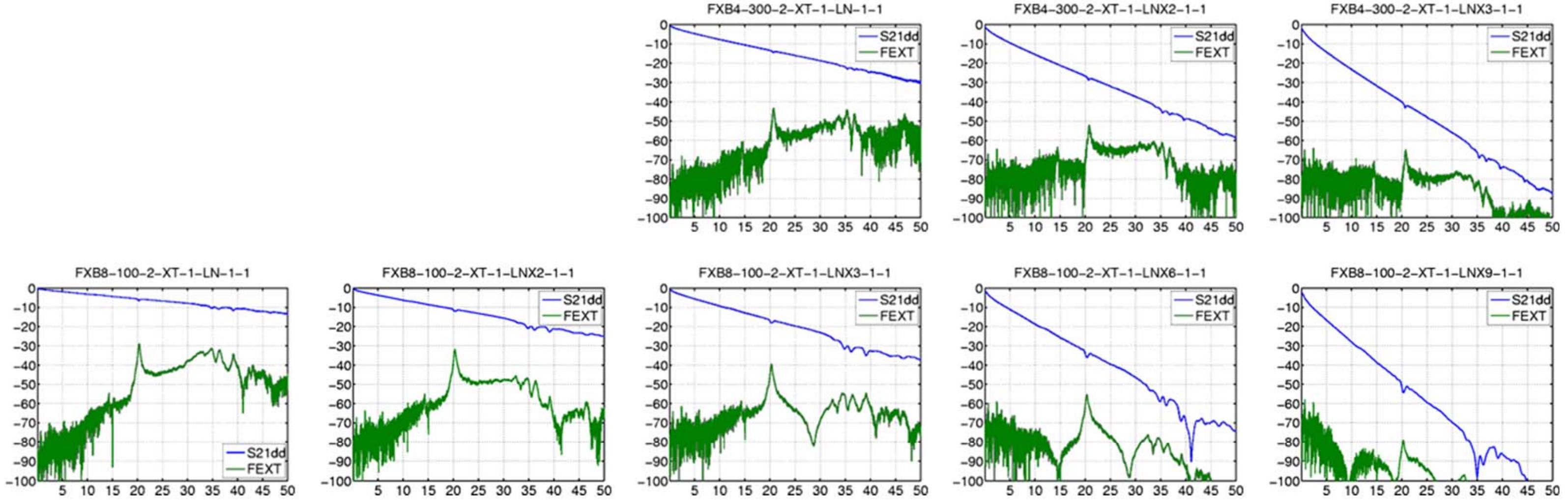
Shield VIA pitch 5.0mm
Trace Pitch 1000um

Length	100mm	200mm	300mm	600mm	900mm
B4					
B8					



Shield VIA pitch 2.5mm
Trace Pitch 1000um

Length	100mm	200mm	300mm	600mm	900mm
B4					
B8					



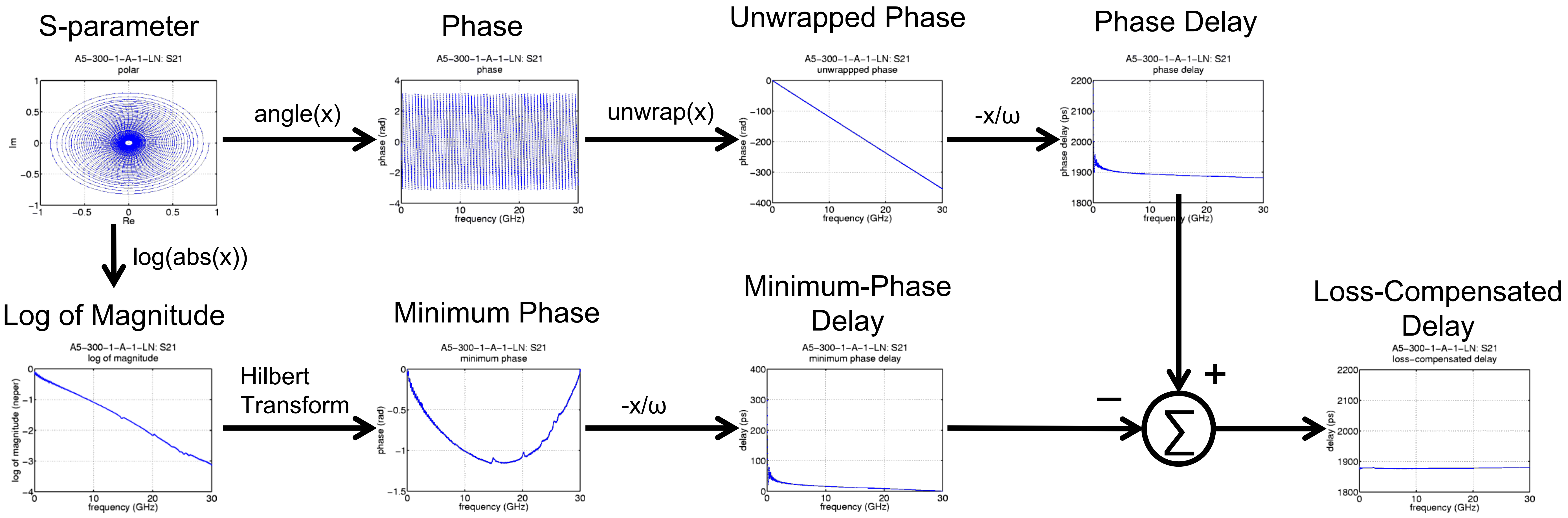
Summary

- 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 DKdiff is higher (lower) than DKcom
  - 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 results in large impedance variation
  - Use 1-ply glass cloth for DK1 (center dielectric)
    - 2-ply cloth for DK1 introduces inconsistent DK1 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 (=|S21dd|/|S21cd|, 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 DK1 and DK2
    - Will reduce variation of coupling strength as glass-weave effects of DK1
    - May realize inductive coupling with PCP stack

Appendix 1: Calculation of Loss-Compensated Delay

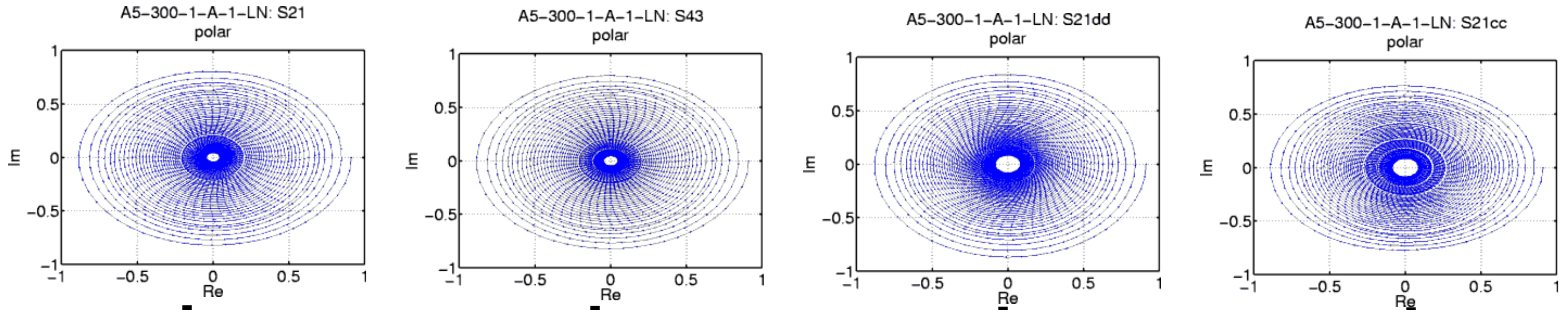


Hilbert Transform was implemented by DFT as follows:

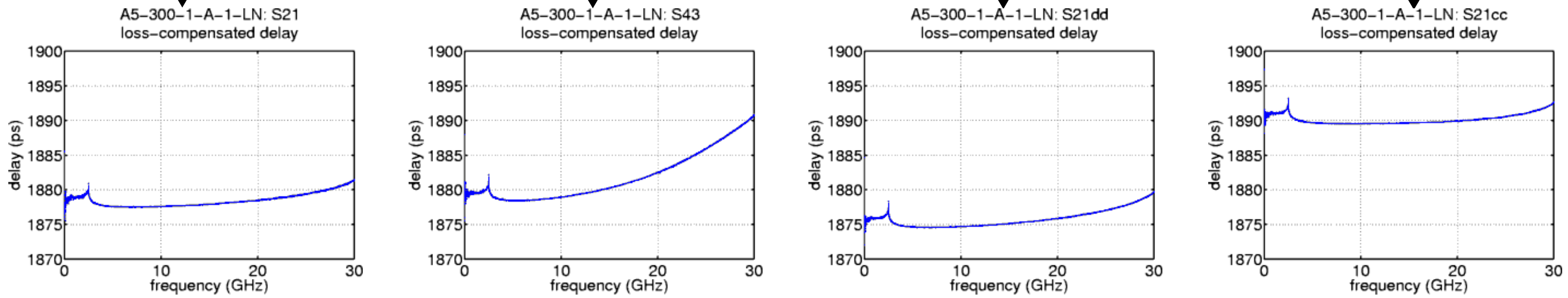
1. R(-f) = R(f) ; get the R value for negative frequency by mirroring the positive frequency value
2. CR(t) = ifft(R(f)) ; get cepstrum of R by inverse DFT
3. CX(t) = CR(t) * sign(t) ; get cepstrum of X by multiplying CR with sign of time
4. X(f) = fft(CX(t)) ; get the X value that is the Hilbert Transform of R by DFT

Appendix 2: Calculation of Effective Dk for each mode

	S21	S43	S21dd	S21cc
S-parameter				

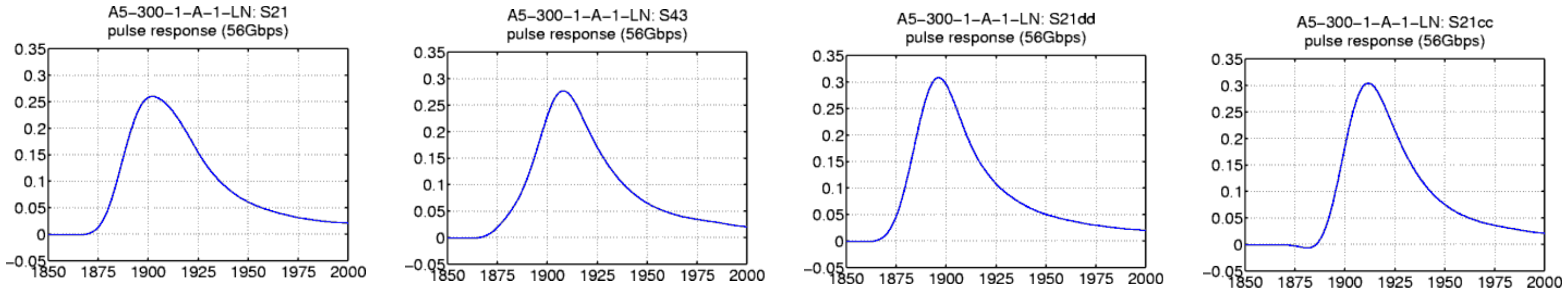


Loss-Compensated Delay



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

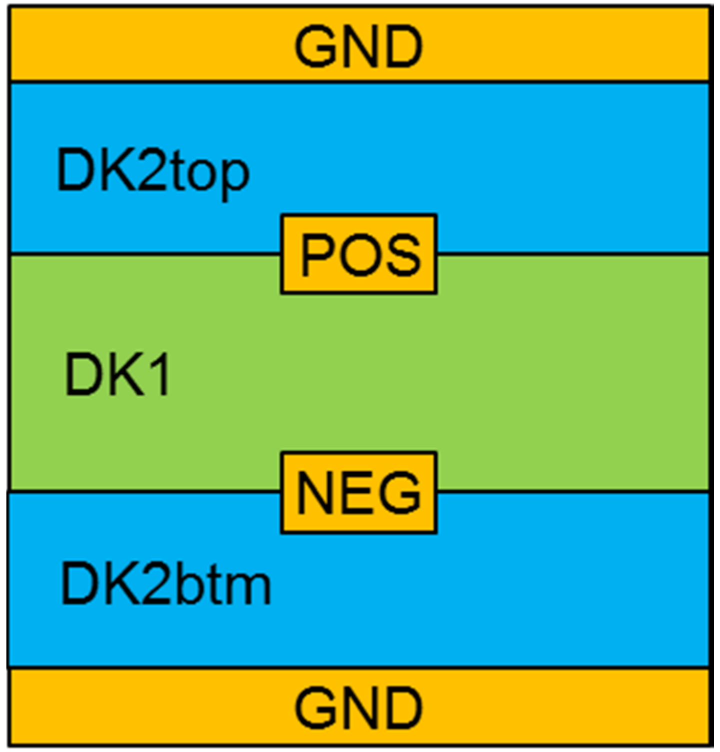
Single-Bit Pulse Response (56Gbps)



Appendix 3: Calculation of Effective Dk for each layer

- Approximation of effective Dk for each mode from effective Dk for each layer

$$\begin{bmatrix} DKpos \\ DKneg \\ DKdiff \\ DKcom \end{bmatrix} \approx X \begin{bmatrix} DK1 \\ DK2top \\ DK2btm \end{bmatrix} \qquad X = \begin{bmatrix} 3/8 & 4/8 & 1/8 \\ 3/8 & 1/8 & 4/8 \\ 4/6 & 1/6 & 1/6 \\ 0 & 1/2 & 1/2 \end{bmatrix}$$



- Approximation of effective Dk for each layer from effective Dk for each mode

$$\begin{bmatrix} DK1 \\ DK2top \\ DK2btm \end{bmatrix} \approx Y \begin{bmatrix} DKpos \\ DKneg \\ DKdiff \\ DKcom \end{bmatrix} \qquad Y = (X^t X)^{-1} X^t = \begin{bmatrix} 0.3101 & 0.3101 & 1.1512 & -0.7713 \\ 1.5504 & -1.1163 & -0.2442 & 0.8101 \\ -1.1163 & 1.5504 & -0.2442 & 0.8101 \end{bmatrix}$$

FUJITSU

shaping tomorrow with you