Practical Notes on Mixed-Mode Transformations in Differential Interconnects

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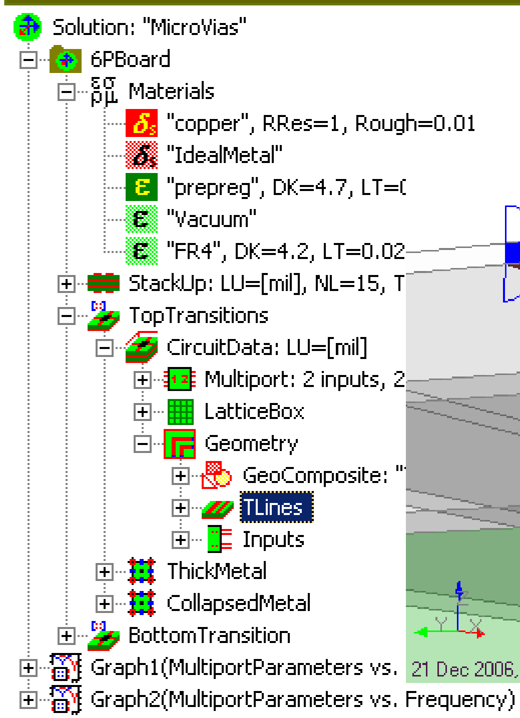

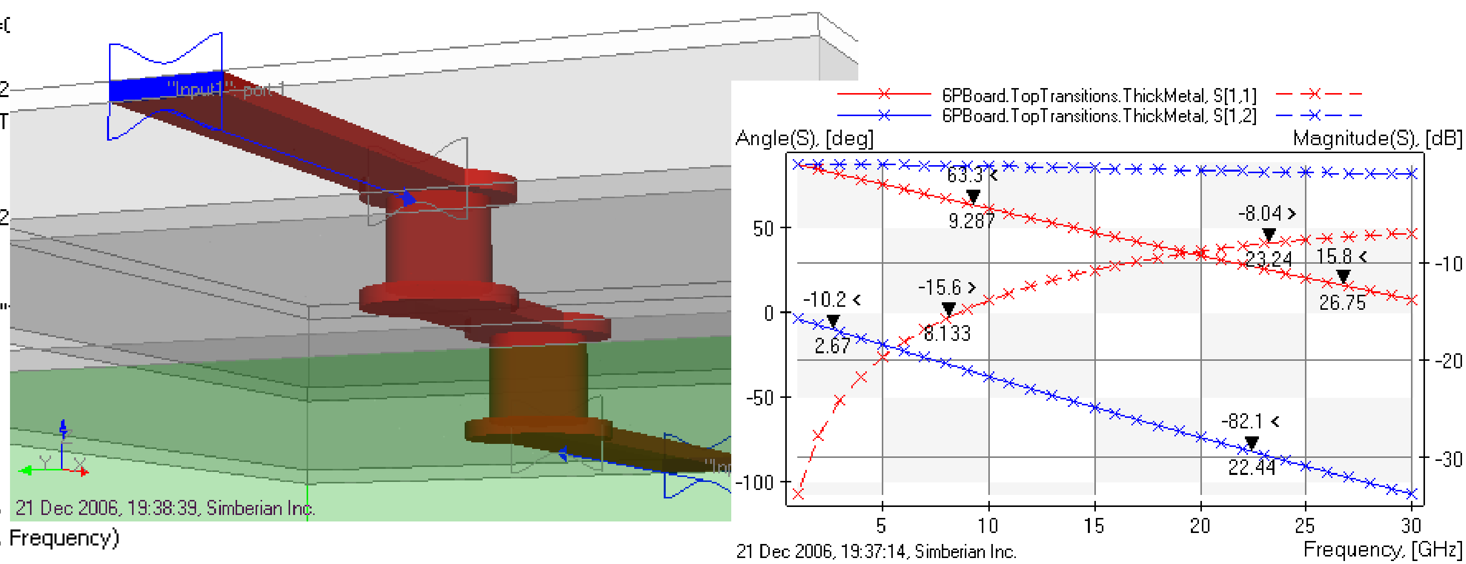

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Overview

- Introduction
- Mixed-mode transformations
- Double micro-strip line bend
- Investigation of micro-strip channel with two reversed bends in frequency and time domain
- Experimental validation
- Investigation of possibilities to minimize the mode transformation
- Conclusion
- Solutions and contacts

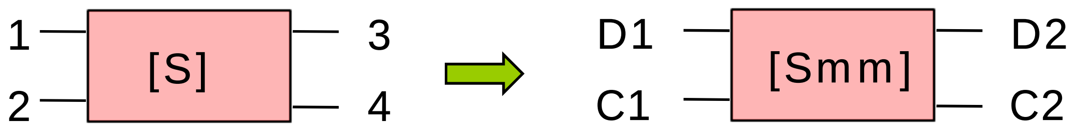
Introduction

- Transformation from differential to common modes is unwanted effect in differential interconnects
  - Common mode may cause signal degradation and electromagnetic emission
- Transformation usually takes place at bends and non-symmetrical routing near via-holes
- In case of bends the effect can be simulated with local electromagnetic analysis (unlike in cases of vias without stitching vias for common mode)
- This app note illustrates how to simulate and minimize the transformation effect – example of what if analysis of different routing scenarios
- Simbeor 2008 built on November 3, 2008 has been used for all computations, except time-domain analysis
- Simbeor 2008.01 Beta is used for time-domain analysis

Mode transformation in reciprocal 4-port

- See details in D.E. Bockelman, W.R. Eisenstadt, Combined differential and common-mode scattering parameters: Theory and simulation, IEEE Trans. on MTT, vol. 43, 1995, N7, p. 1530-1539

Terminal space | Mixed-mode space



$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{bmatrix}$$

$$Smm = \begin{bmatrix} S_{D1,D1} & S_{D1,D2} & S_{D1,C1} & S_{D1,C2} \\ S_{D1,D2} & S_{D2,D2} & S_{D2,C1} & S_{D2,C2} \\ S_{D1,C1} & S_{D2,C1} & S_{C1,C1} & S_{C1,C2} \\ S_{D1,C2} & S_{D2,C2} & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

$$Smm = T \cdot S \cdot T^t$$

$$T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

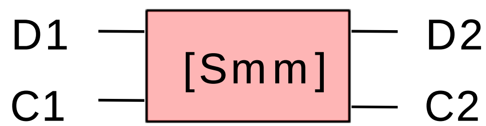
Mode Transformation Terms:

$$S_{D1,C1} = 0.5 \cdot \left(S_{1,1} - S_{2,2} \right)$$
$$S_{D1,C2} = 0.5 \cdot \left(S_{1,3} - S_{2,3} + S_{1,4} - S_{2,4} \right)$$
$$S_{D2,C1} = 0.5 \cdot \left(S_{1,3} - S_{1,4} + S_{2,3} - S_{2,4} \right)$$
$$S_{D2,C2} = 0.5 \cdot \left(S_{3,3} - S_{4,4} \right)$$

All S-matrices are symmetrical (S[i,j]=S[j,i]) due to reciprocity property (if only isotropic materials used to manufacture interconnects)

Mixed-Mode Terminology

- Block DC describes modal transformations or conversion (highlighted blocks of the mixed-mode S-parameters)



Notation used here:

$$Smm = \begin{bmatrix} S_{D1,D1} & S_{D1,D2} & S_{D1,C1} & S_{D1,C2} \\ S_{D1,D2} & S_{D2,D2} & S_{D2,C1} & S_{D2,C2} \\ S_{D1,C1} & S_{D2,C1} & S_{C1,C1} & S_{C1,C2} \\ S_{D1,C2} & S_{D2,C2} & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

Alternative forms:

$$Smm = \begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD12} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{DC11} & S_{DC21} & S_{CC11} & S_{CC12} \\ S_{DC12} & S_{DC22} & S_{CC12} & S_{CC22} \end{bmatrix}$$

$$Smm = \begin{bmatrix} S^{dd}_{1,1} & S^{dd}_{1,2} & S^{dc}_{1,1} & S^{dc}_{1,2} \\ S^{dd}_{1,2} & S^{dd}_{2,2} & S^{dc}_{2,1} & S^{dc}_{2,2} \\ S^{dc}_{1,1} & S^{dc}_{2,1} & S^{cc}_{1,1} & S^{cc}_{1,2} \\ S^{dc}_{1,2} & S^{dc}_{2,2} & S^{cc}_{1,2} & S^{cc}_{2,2} \end{bmatrix}$$

S[D1,C1], S[D2,C2] – **Near end mode transformation** or transformation from differential to common mode at the same side of the multiport

S[D1,C2], S[D2,C1] – **Far end mode transformation** or transformation from differential mode on one side to the common mode on the opposite side of the multiport

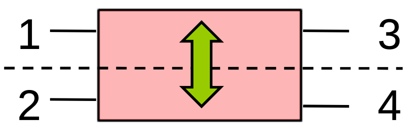
Transformation from common to differential is exactly the same due to reciprocity (symmetrical S-matrix)

Properties of S-parameters of reciprocal and symmetrical 4-ports

- Group theory can be used to investigate properties of S-matrix of symmetrical 4-port – see details in R.H. Dicke - Symmetry of waveguide junctions, in Montgomery, Dicke, Purcell, Principles of Microwave Circuits, 1964

S-matrix of reciprocal 4-port is symmetric as shown below (S[i,j]=S[j,i]):

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{bmatrix}$$



Group generator for mirror symmetry operator for 4-port structure:

$$F = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

S-matrix must commute with F: $F \cdot S = S \cdot F \Rightarrow \begin{bmatrix} S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \end{bmatrix} = \begin{bmatrix} S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{2,2} & S_{1,2} & S_{2,4} & S_{2,3} \\ S_{2,3} & S_{1,3} & S_{3,4} & S_{3,3} \\ S_{2,4} & S_{1,4} & S_{4,4} & S_{3,4} \end{bmatrix}$

It means that: $\begin{matrix} S_{2,2} = S_{1,1}, S_{2,3} = S_{1,4} \\ S_{2,4} = S_{1,3}, \; S_{4,4} = S_{3,3} \end{matrix}$

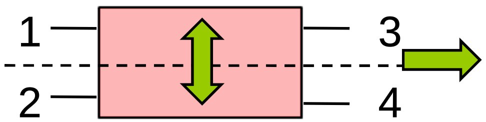
Final S-matrix of reciprocal symmetrical 4-port:
Holds for mirror or axial symmetry with the plane or axis along the propagation direction

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{1,3} & S_{1,4} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{1,3} & S_{3,4} & S_{3,3} \end{bmatrix}$$

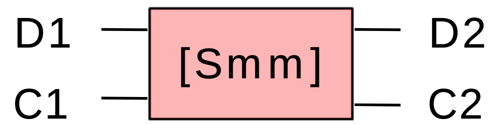
only 6 independent parameters

Mode transformation in reciprocal and symmetrical 4-port

Terminal space



Mixed-mode space



No mode transformation!

$$S=\begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{1,3} & S_{1,4} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{1,3} & S_{3,4} & S_{3,3} \end{bmatrix}$$

$$Smm=\begin{bmatrix} S_{D1,D1} & S_{D1,D2} & 0 & 0 \\ S_{D1,D2} & S_{D2,D2} & 0 & 0 \\ 0 & 0 & S_{C1,C1} & S_{C1,C2} \\ 0 & 0 & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

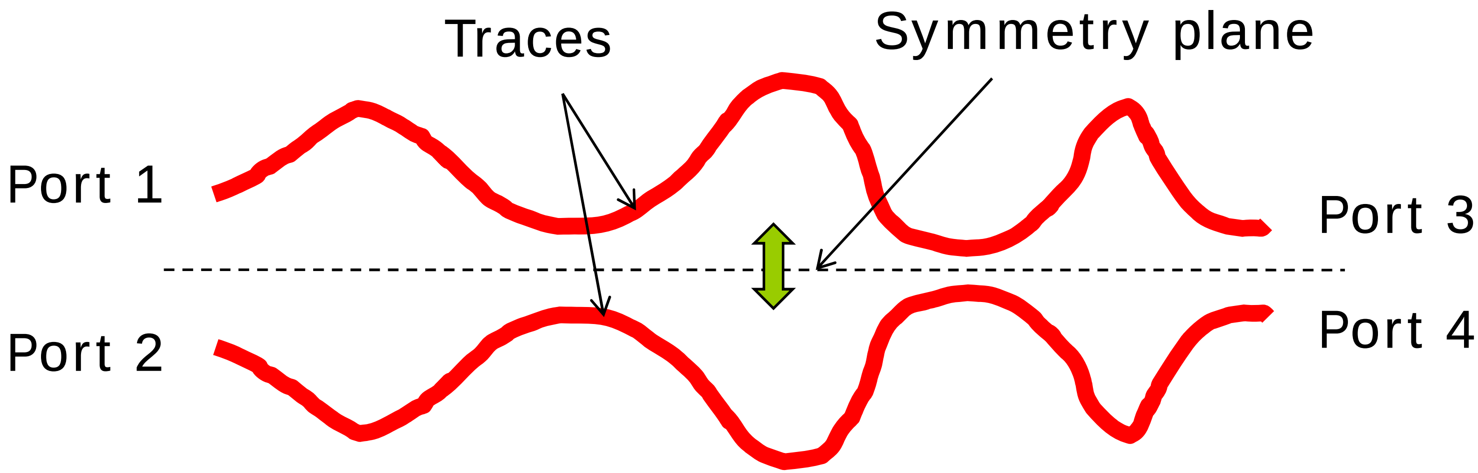
$$S_{2,2}=S_{1,1}, S_{2,3}=S_{1,4}$$
$$S_{2,4}=S_{1,3},\ S_{4,4}=S_{3,3}$$

Mode Transformation Terms are Zeroes!

$$S_{D1,C1}=0.5\cdot\left(S_{1,1}-S_{2,2}\right)=0$$
$$S_{D1,C2}=0.5\cdot\left(S_{1,3}-S_{2,3}+S_{1,4}-S_{2,4}\right)=0$$
$$S_{D2,C1}=0.5\cdot\left(S_{1,3}-S_{1,4}+S_{2,3}-S_{2,4}\right)=0$$
$$S_{D2,C2}=0.5\cdot\left(S_{3,3}-S_{4,4}\right)=0$$

NO Mode Transformation Condition

- Mirror symmetry about the plane along the interconnects is the necessary and sufficient condition of no mode transformation



NO TRANSFORMATION from Differential to Common mode and back – follows from the symmetry property

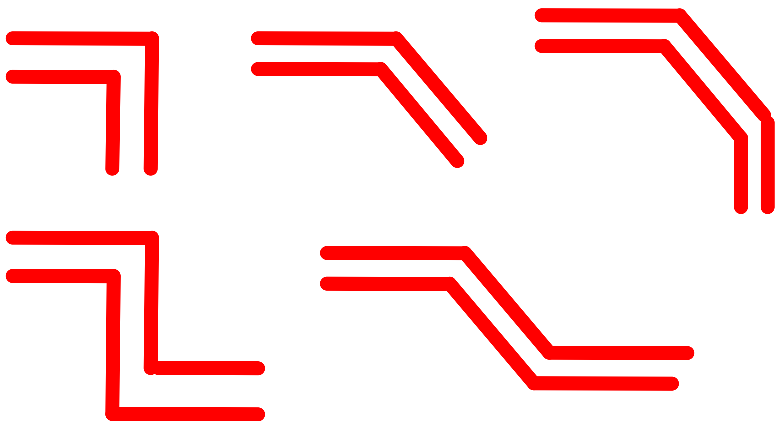
Rotational symmetry about the axis along the interconnect is another case that is less interesting for practical applications

Typical interconnect elements that cause mode transformations

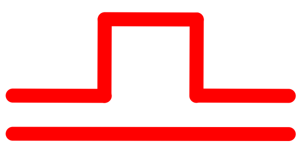
- All share one property – no symmetry of type discussed above

Can be simulated locally:

Bends (single and dual):

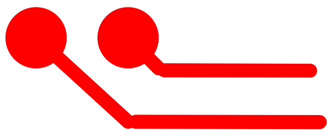


Bypass or “length equalization” elements as shown:



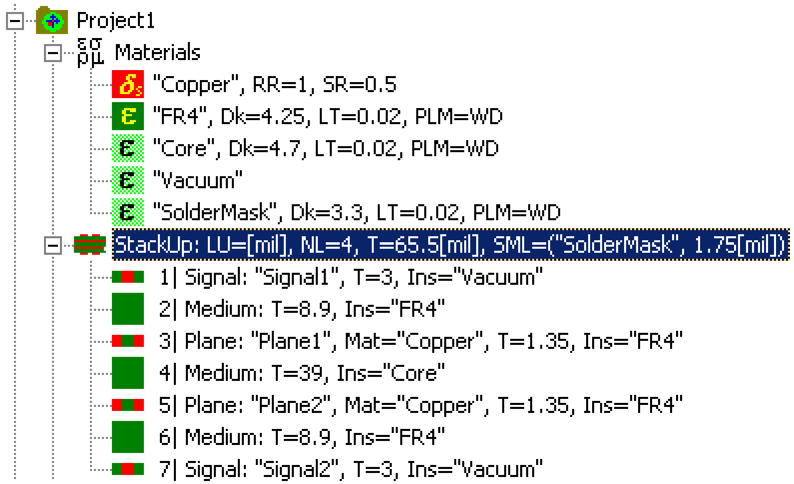
May require board-level simulation to capture common mode behavior (hybrid or full-wave):

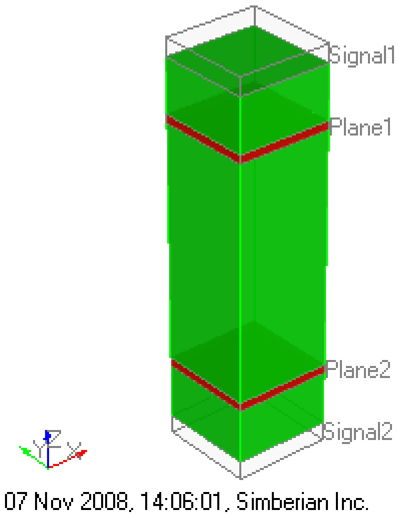
Non-symmetrical break-out from vias:



With stitching vias between all reference planes of the connected lines – can be simulated locally (conditional on the distance between vias)

Double bend in micro-strip line: Materials and Stackup



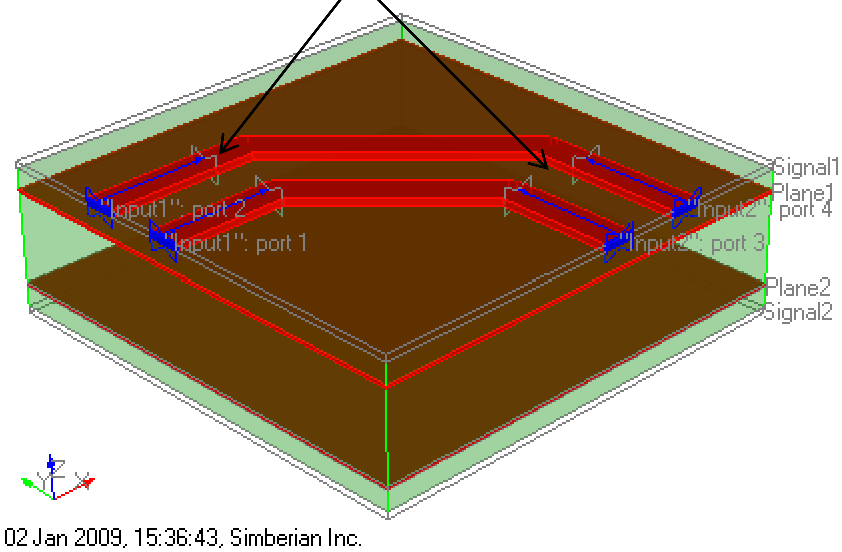


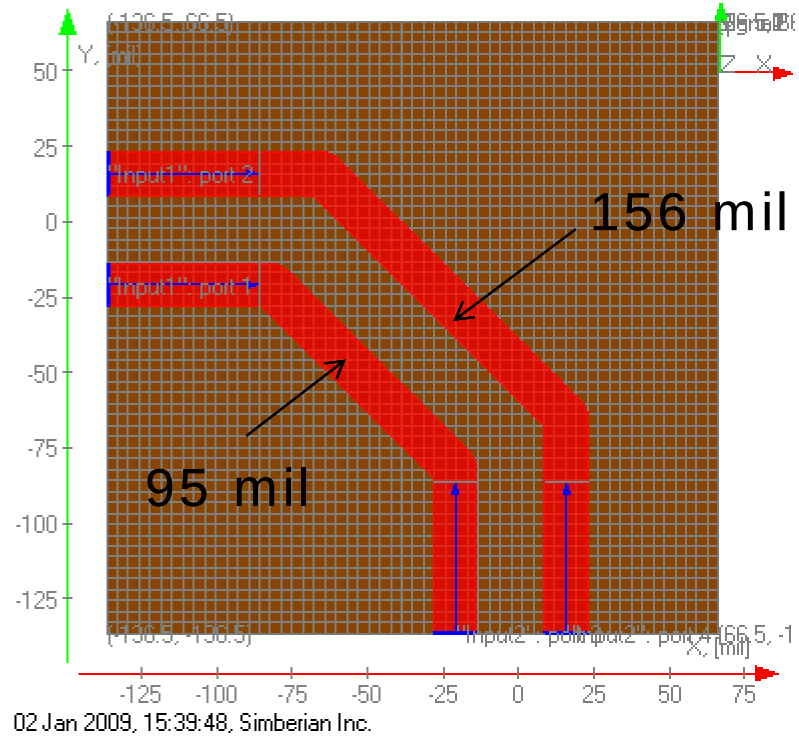
- **Materials**:
  - Copper bulk resistivity 1.724e-8 Ohm meters, roughness 0.5 um (roughness factor 2 is guessed)
  - Solder mask: DK=3.3, LT=0.02
  - FR-4 core dielectric: DK=4.7, LT=0.02 @ 1 GHz
  - FR-4 dielectric between signal and plane layers: DK=4.25, LT=0.02 @ 1 GHz
  - All dielectrics are modeled with the Wideband Debye model

Single micro-strip bend geometry

- Composed of two 45-degree bends
- Strip width 15 mil, separation 22 mil

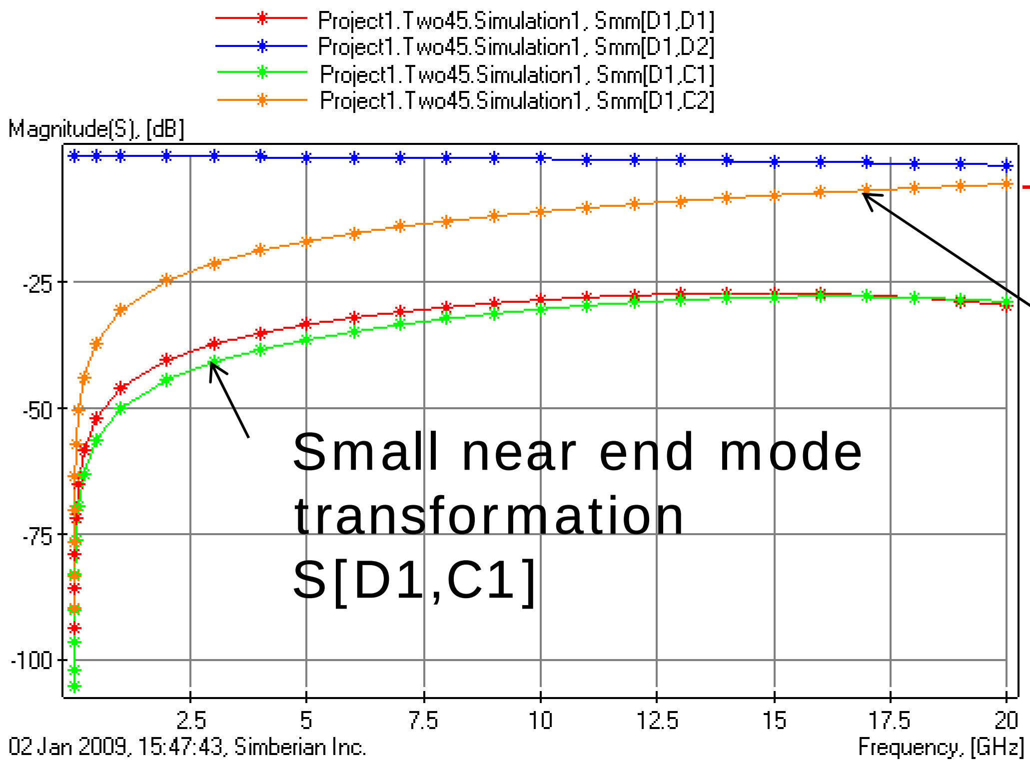
Two-port inputs are de-embedded and S-parameters phase reference planes are shifted to these planes





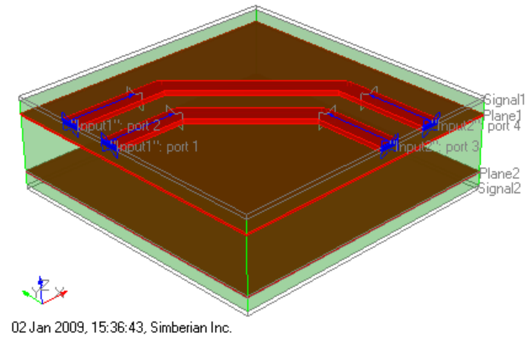
Mode transformation at single micro-strip line bend

Mode transformation due to non-symmetry

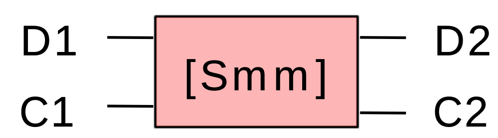


Small near end mode transformation S[D1,C1]

-5.5 dB

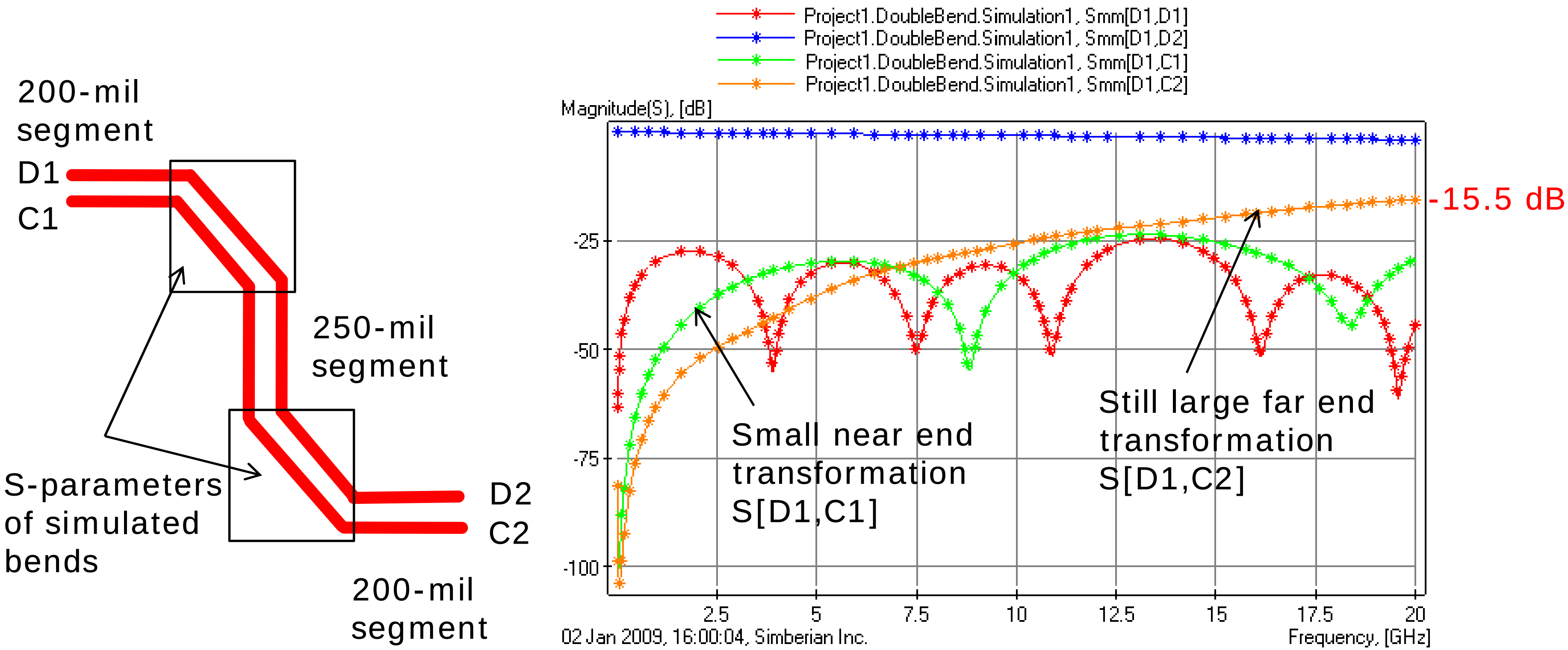


Large far end mode transformation S[D1,C2]



Can we compensate the transformation?

- By using reversed bend to match the length of the traces?

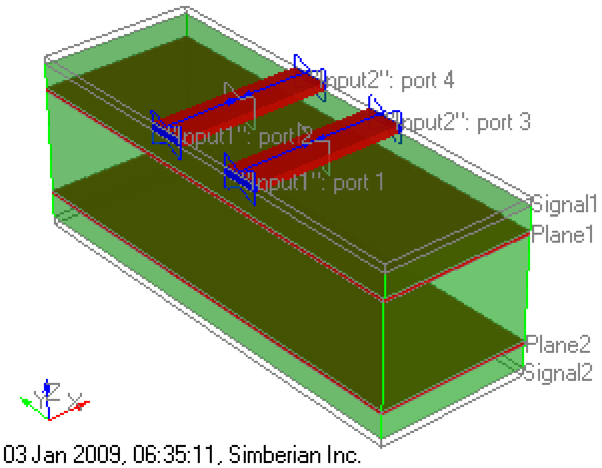


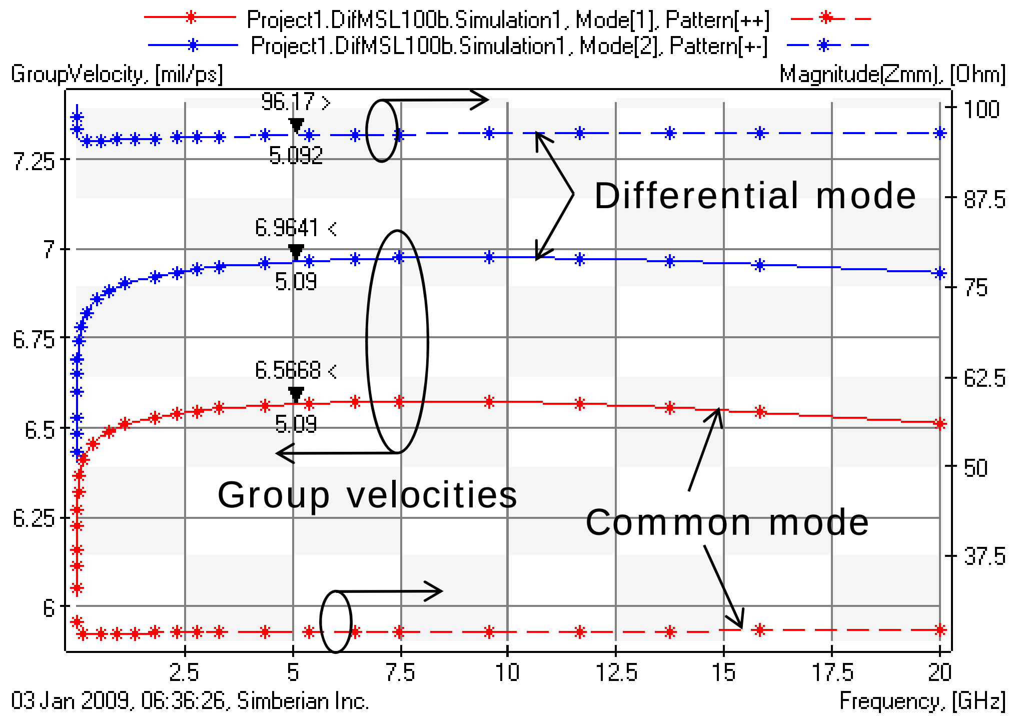
Far end transformation has been reduced by 10 dB, but did not disappear even with ideal match of the trace lengths!

What is the reason of the transformation in case with dual bends?

- Difference in the propagation velocities of differential and common modes in micro-strip line:
  - Difference in the group velocities is about 6% over the frequency band

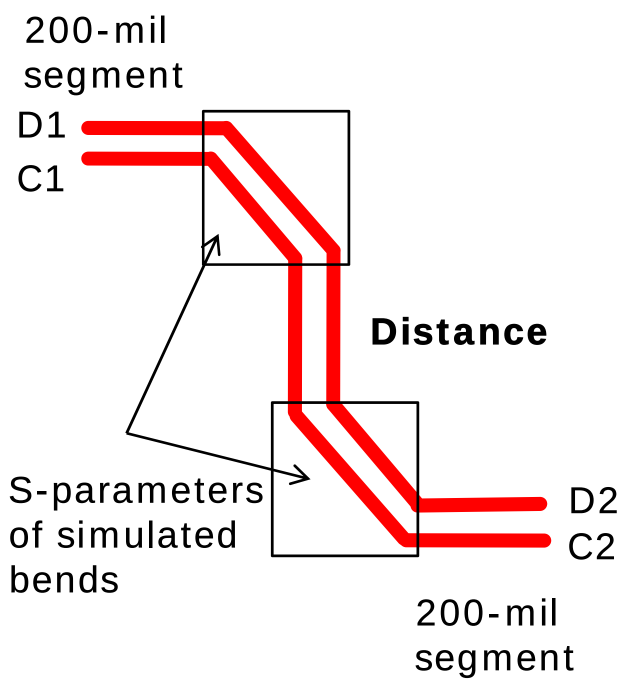
Strip width 15 mil, separation 22 mil

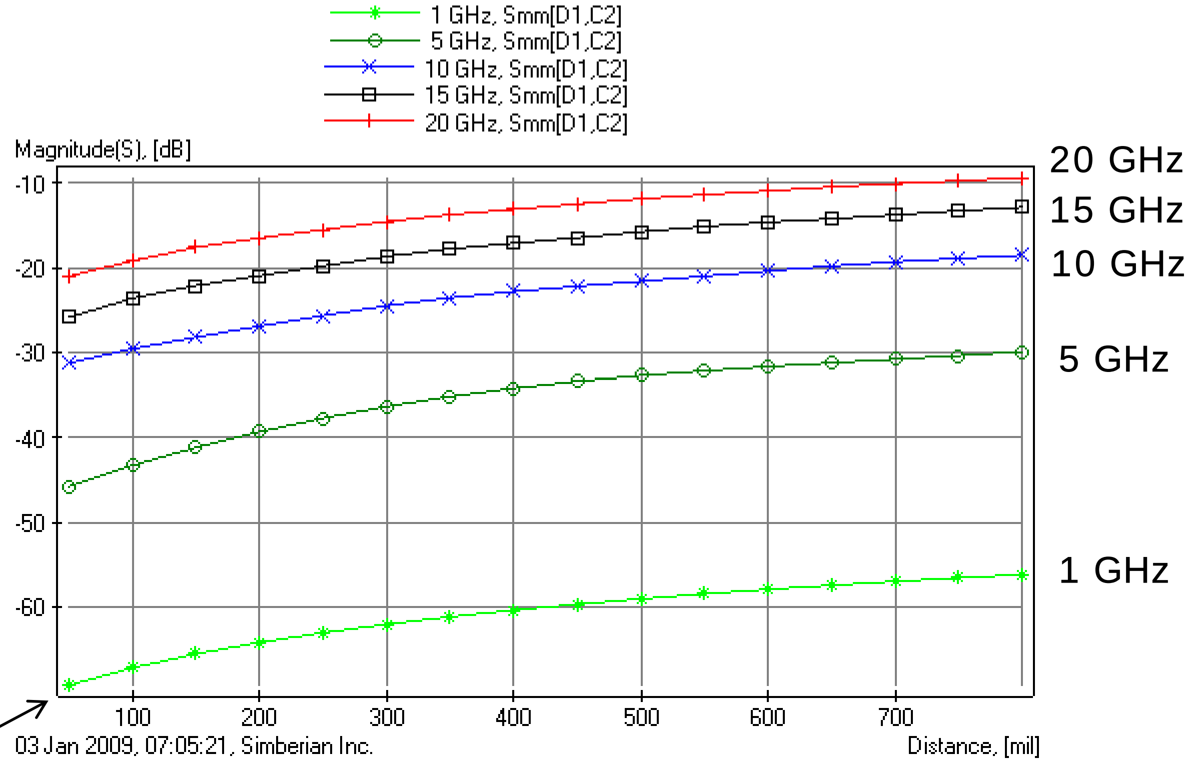




What if we move bends closer?

- Parametric sweep with the Distance between two bends as a parameter allows us to investigate this scenario

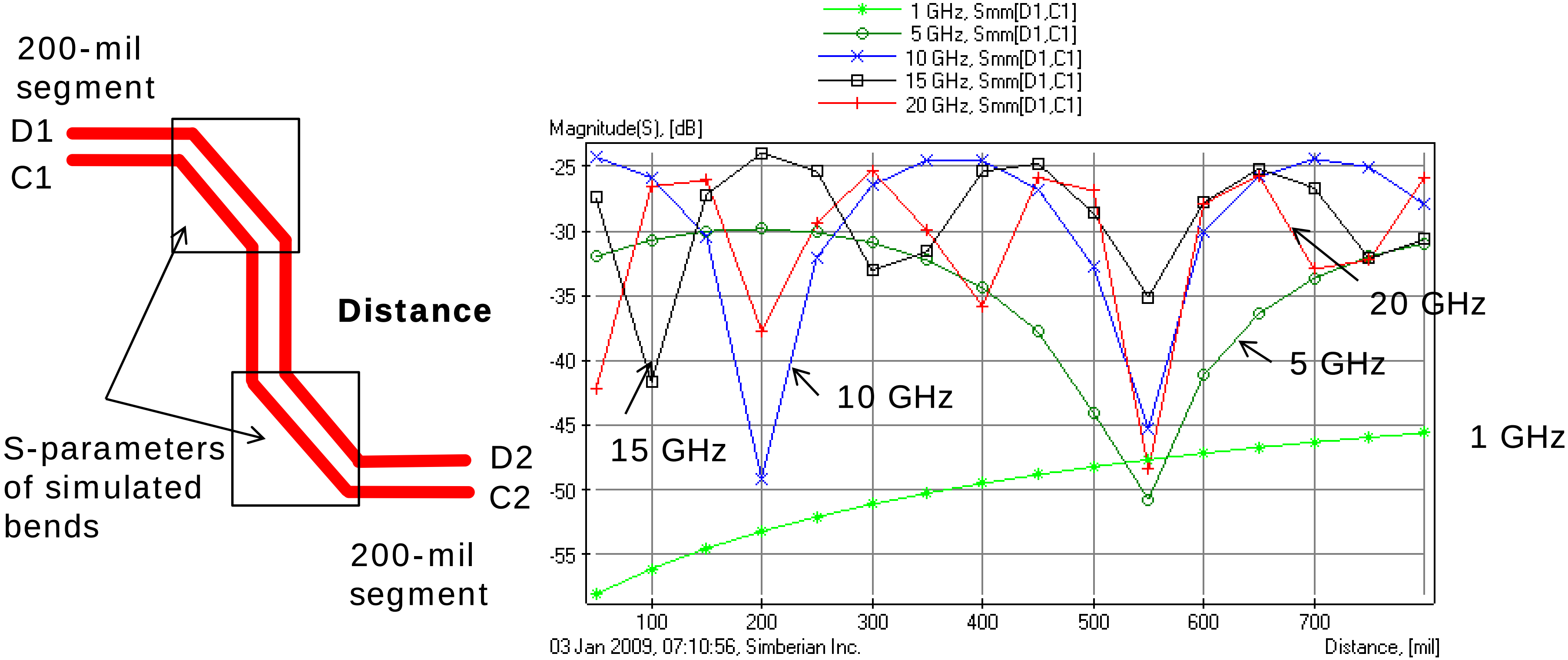




The smaller the Distance between the bends, the smaller the far end mode transformation coefficient S[D1,C2]

What about the near end mode transformation coefficient?

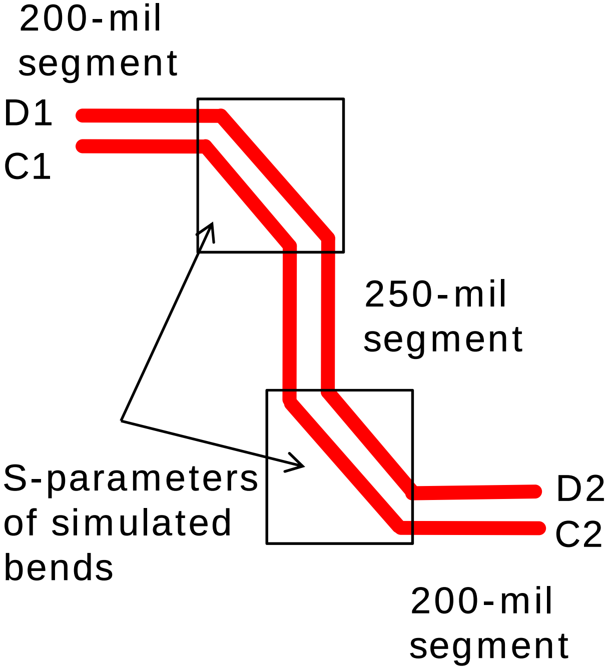
- The Distance between two bends does not have much effect on the maximal value of the near end mode transformation coefficient

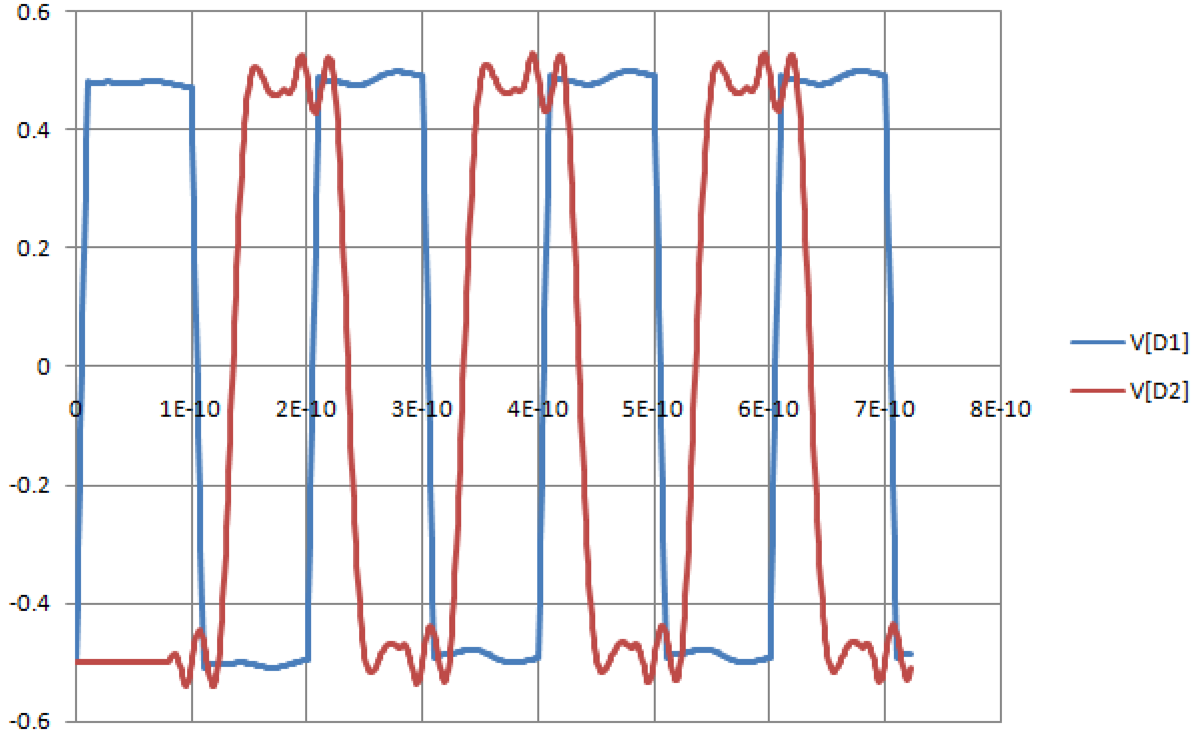


Though, the level of S[D1,C1] is relatively small (below -20 dB) due to 45-degree section used in each bend

Effect of mode transformation on signal degradation in time domain

- 10 Gbps NRZ bipolar pulse train with 10 ps rise and fall time and 1 V magnitude, 100 Ohm termination for differential mode and 25 Ohm for the common mode

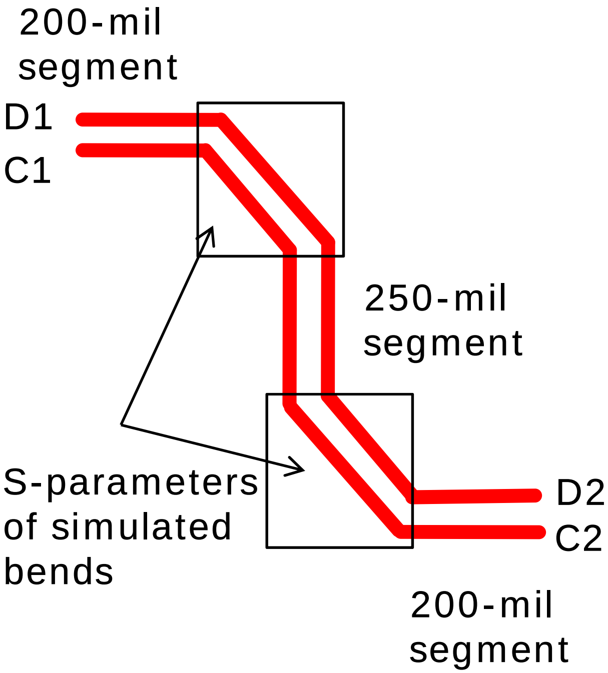


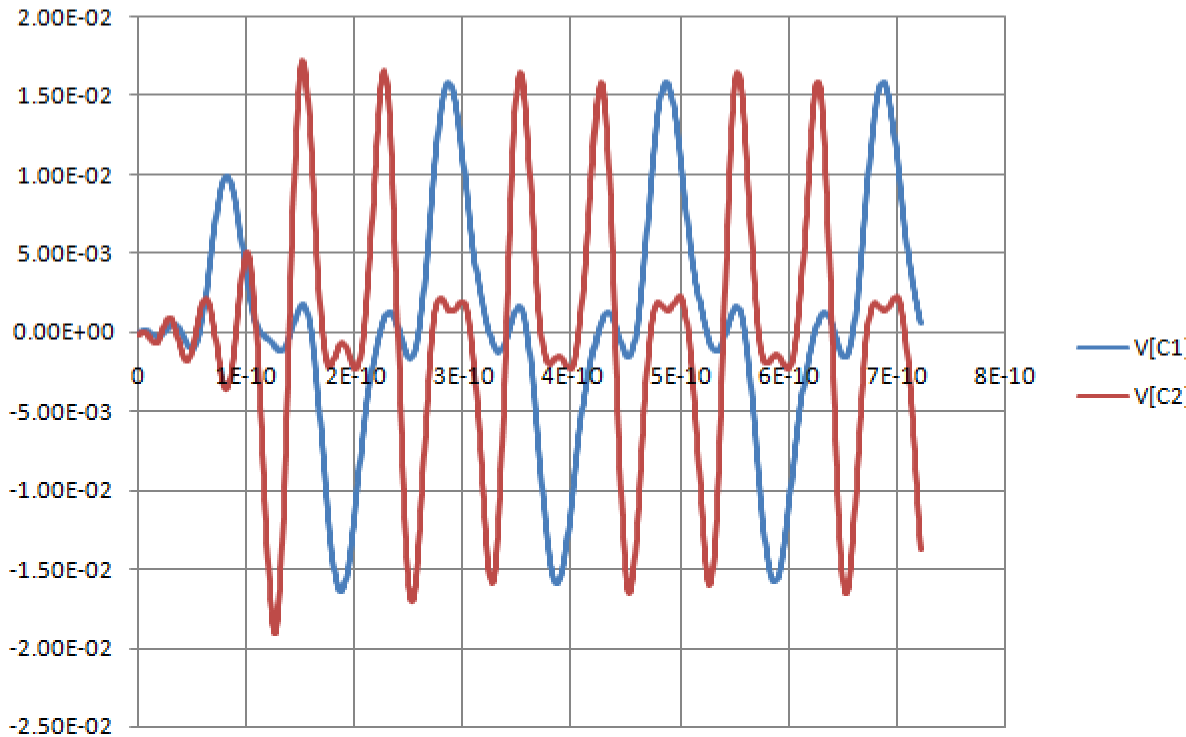


Acceptable signal degradation can be observed - partially due to the mismatch of the source (100 Ohm) and the differential mode (about 96 Ohm) – almost no skew!

Possible effect of mode transformation on EMI

- 10 Gbps NRZ bipolar pulse train with 10 ps rise and fall time and 1 V magnitude, 100 Ohm termination for differential mode and 25 Ohm for the common mode



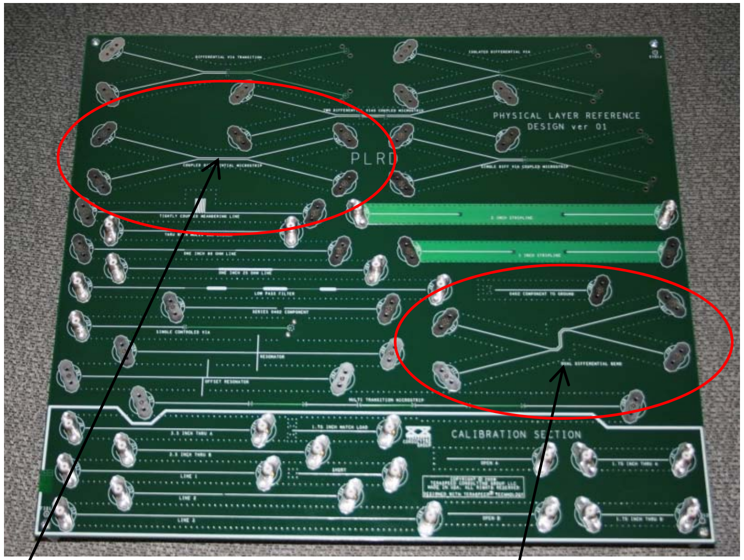


Without termination and with some other favorable conditions 15 mV injected into common mode may cause radiation (EMI problem)

Experimental validation

- PLRD-1 low cost FR4 board created and independently investigated by Teraspeed Consulting Group www.teraspeed.com
- Precise measurement, de-embedding and material properties identification methodologies with the board are available from Teraspeed
  - For more information contact to Alfred Neves at al@teraspeed.com or Yuriy Shlepnev at shlepnev@simberian.com

Stackup of PLRD-1 board is shown on page 10



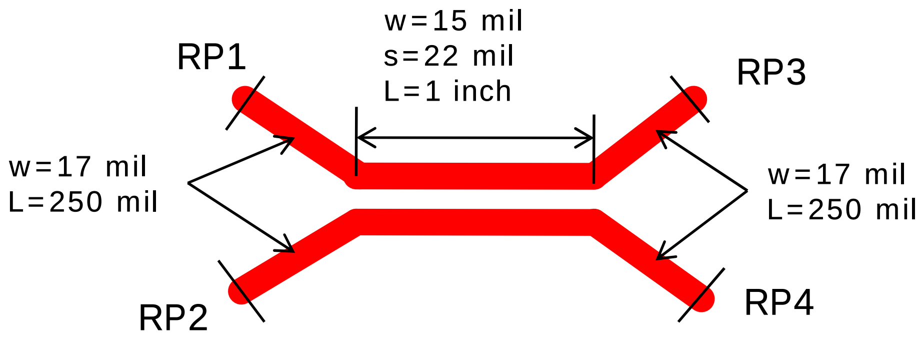
Differential dual bend

Segment of differential line

All measurements and corresponding Simbeor solutions for PLRD-1 are available on request

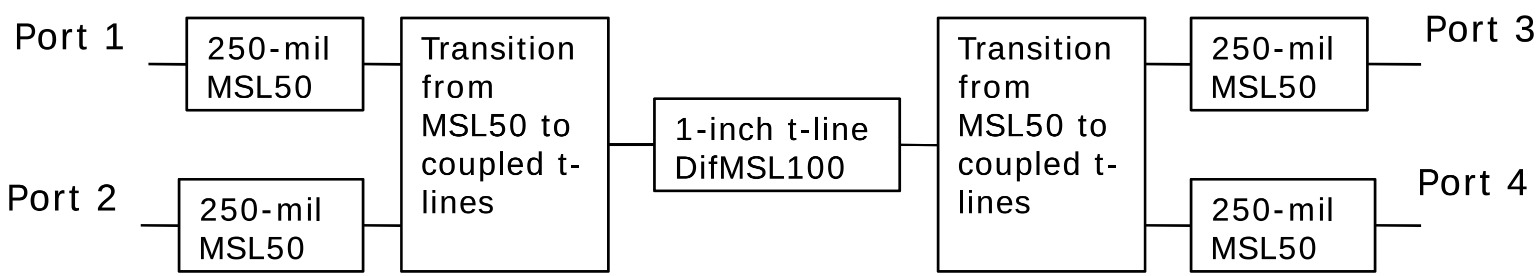
All de-embedding and investigated structures are equipped with SMA connectors

Differential micro-strip line segment – To check the symmetry rule



Stackup is shown on page 10

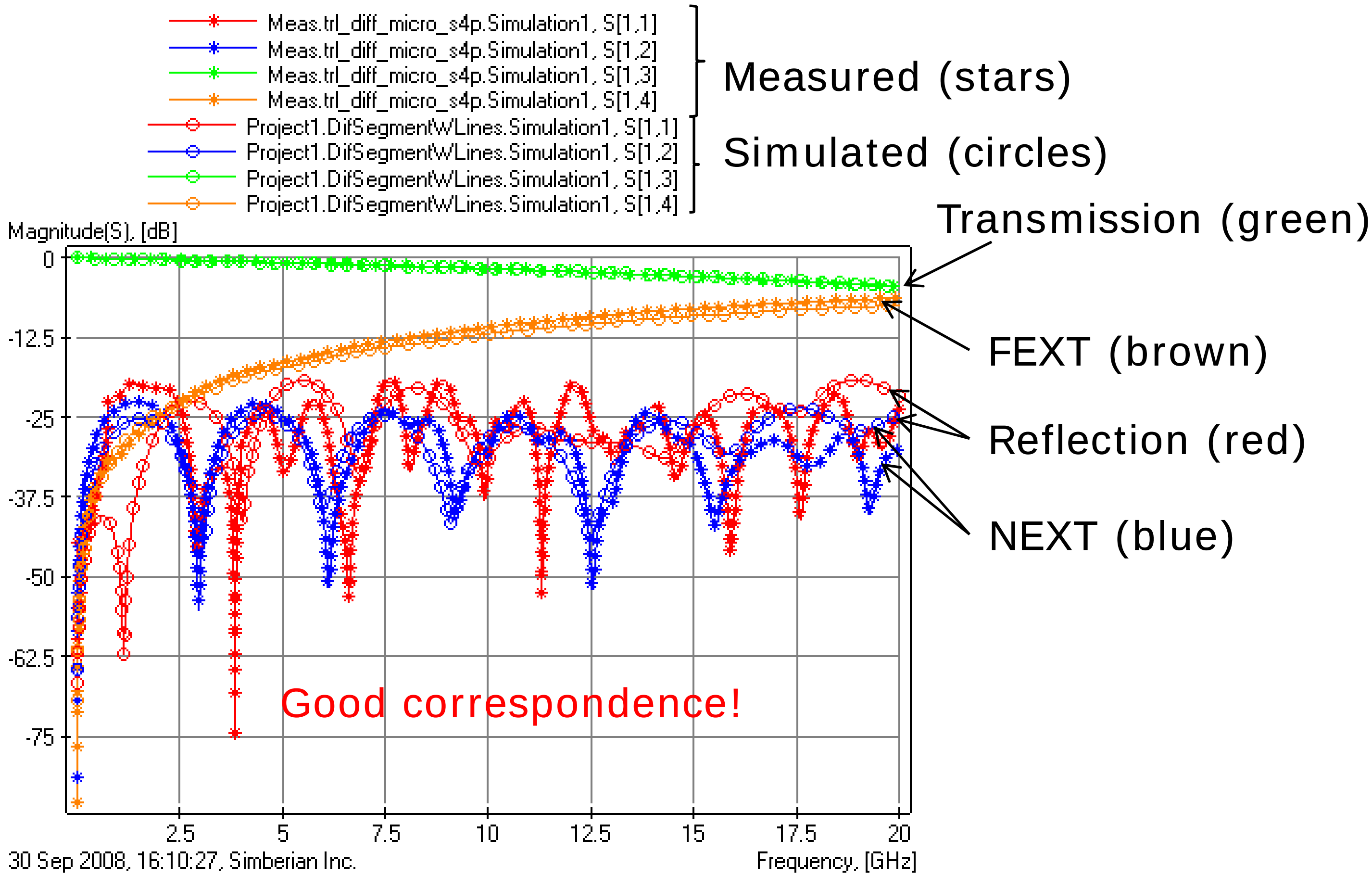
- 1-inch long coupled micro-strip line with 250-mil segment of 17-mil micro-strip lines
- Electromagnetic analysis of single and coupled micro-strip lines and transition between lines is required for comparison with de-embedded measurement results
- Simbeor de-compositional model for linear analysis:



Differential line segment: Correspondence of measured and simulated results

- Magnitudes of single-ended S-parameters (1 row)

1—3
2—4



Differential line segment: Correspondence of measured and simulated results

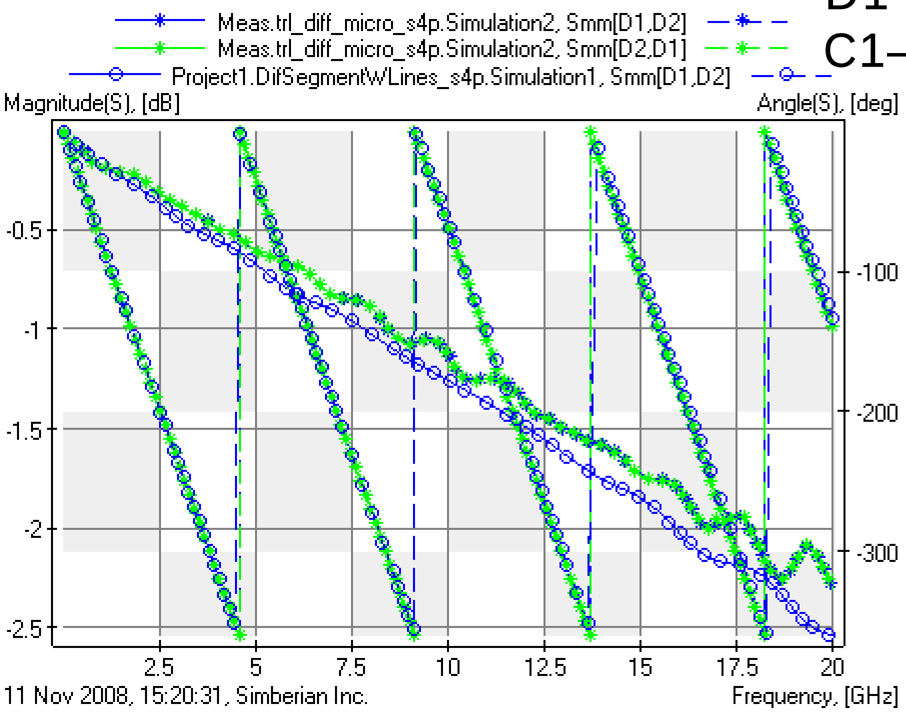
- Transmission coefficients of mixed-mode S-parameters

Good correspondence!

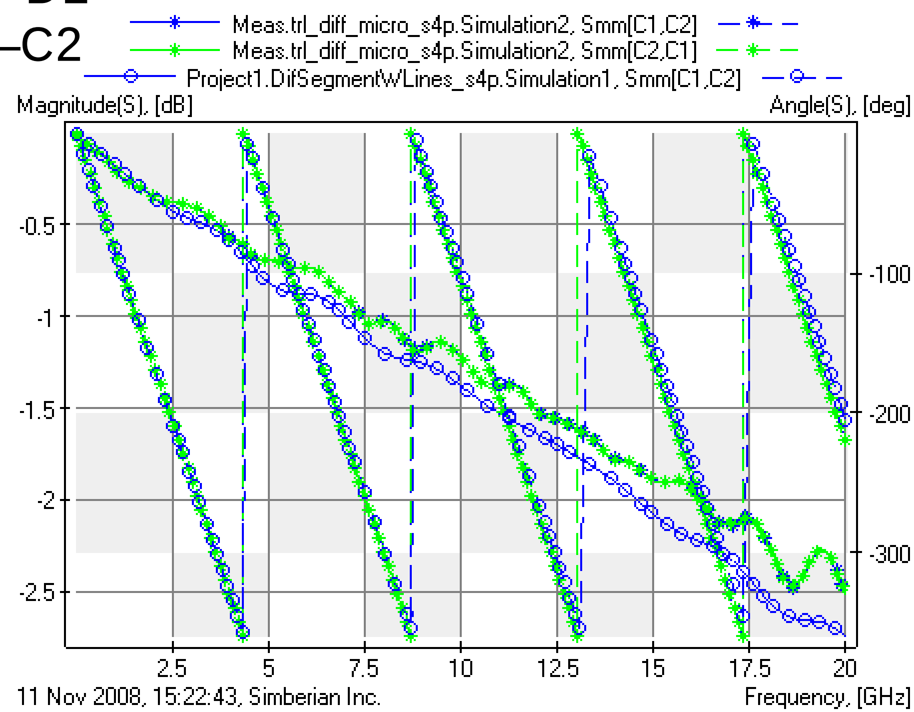
Differential mode transmission magnitude and phase:

D1—D2

C1—C2



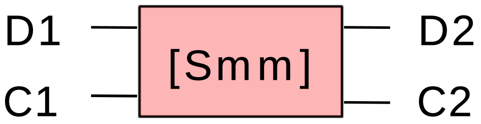
Common mode transmission magnitude and phase:

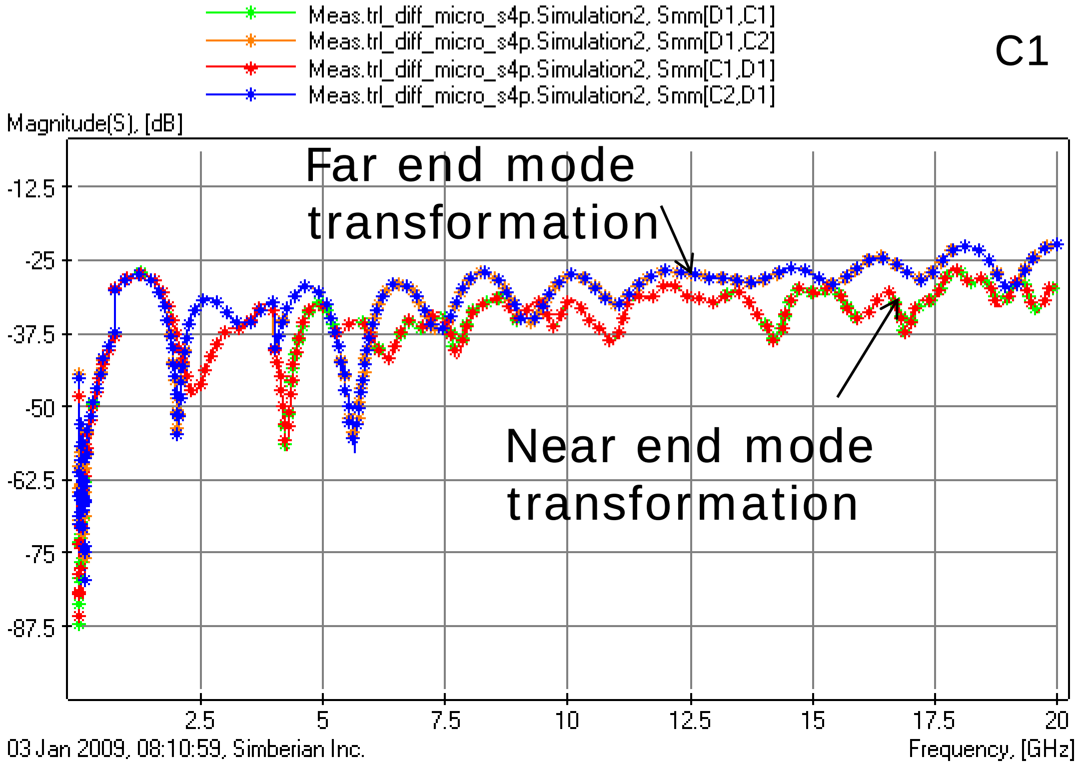


Measured – stars; Simulated - circles

Mode transformation in the differential line segment

- Numerical model predicts zero mode transformation due to the mirror symmetry about the plane along the wave propagation direction

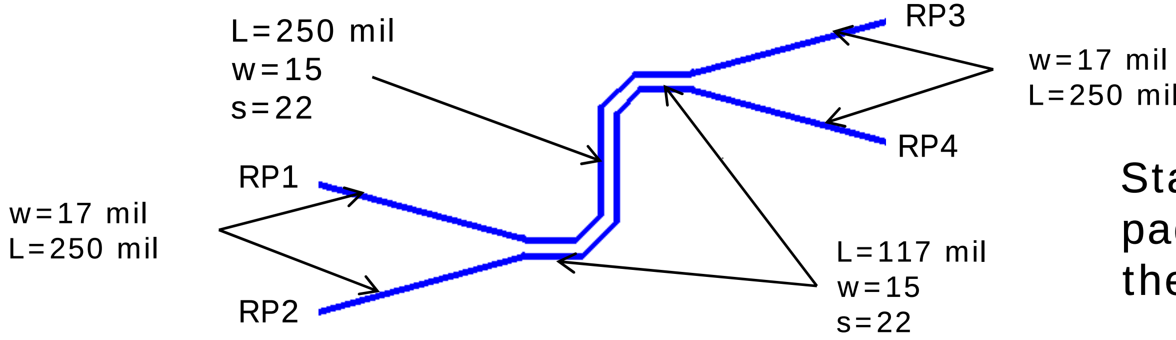




In reality, non-symmetry of connectors, glass fiber in dielectric and trace manufacturing tolerances cause small mode transformations!

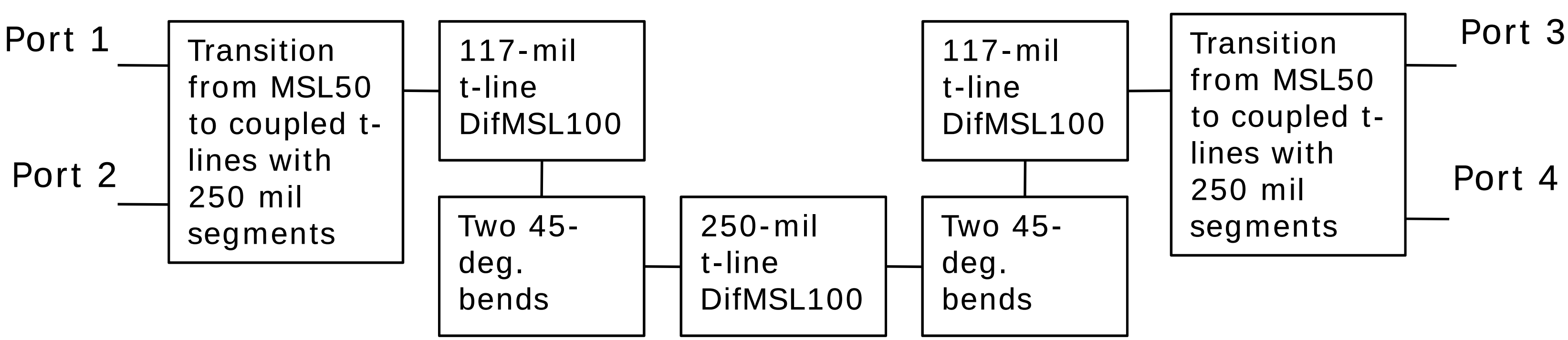
Any optimization of mode transformation below this floor level (-25 dB in that case) does not make sense.

Differential micro-strip line segment with two 45-degree bends



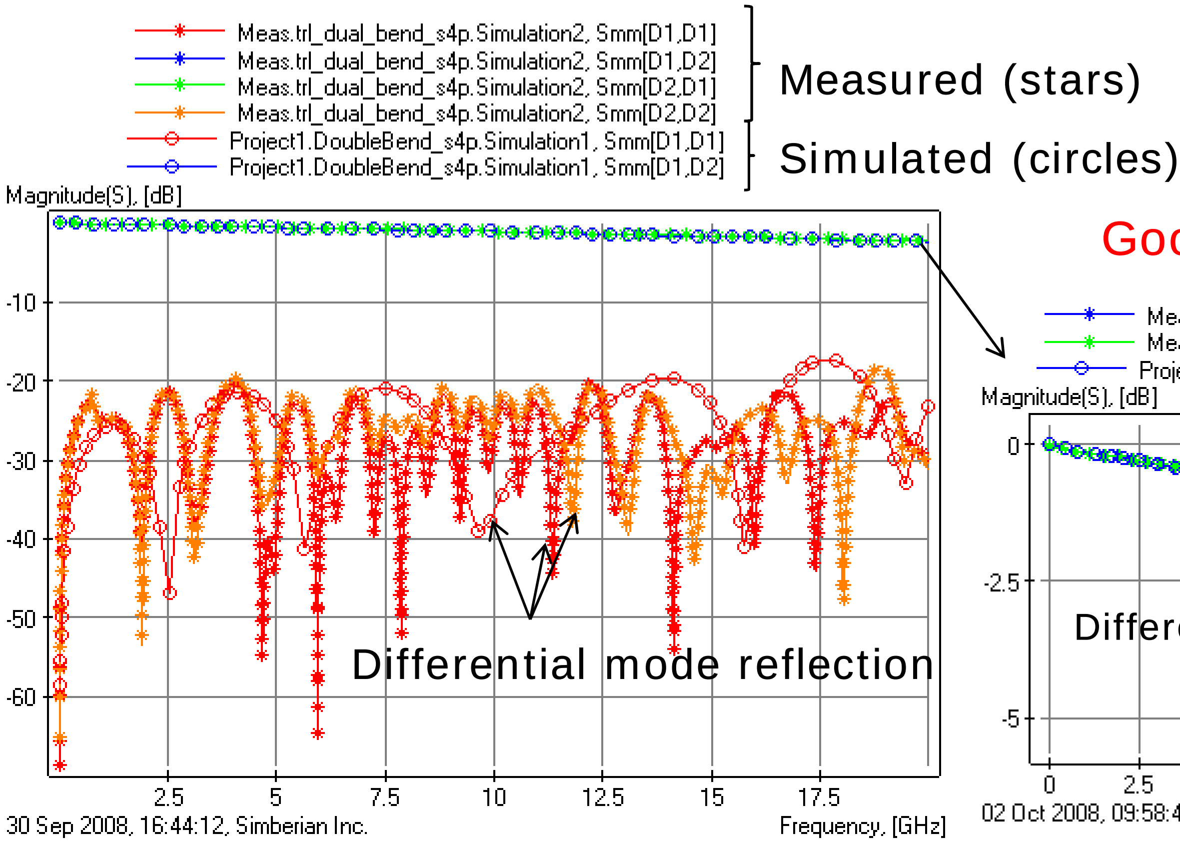
Stackup is shown on page 10, geometry of the bends on page 11

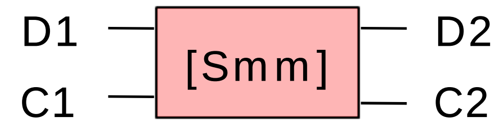
- Two turns in differential micro-strip line with 250 mil 17-mil micro-strip segments
- Single and coupled micro-strip lines transition between lines are exactly as in the case of differential line segment
- Analysis of two 45-deg. bends is required for comparison with de-embedded measurement results
- Simbeor de-compositional model for linear analysis:



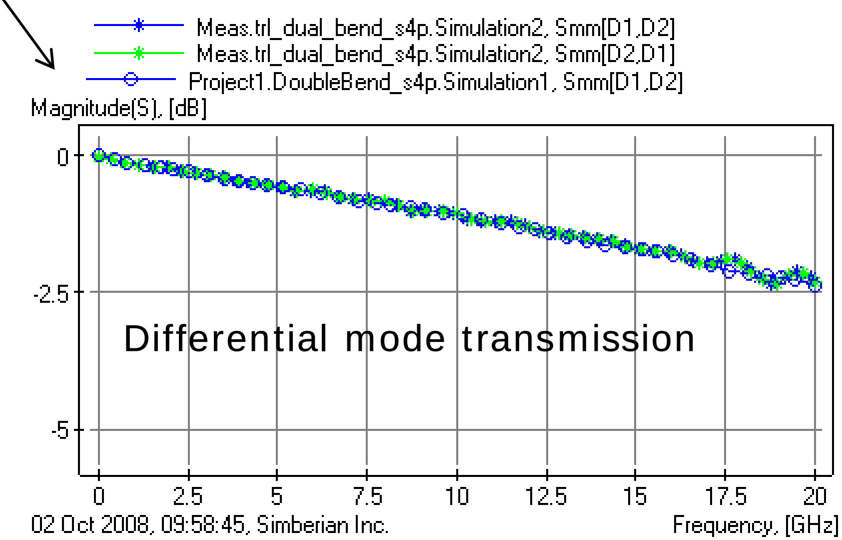
Differential bends: Comparison with de-embedded measurement results (TRL)

- Magnitudes of mixed-mode S-parameters (DD block)



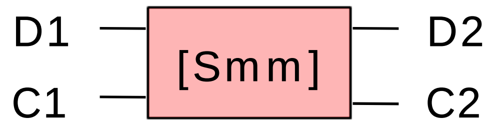


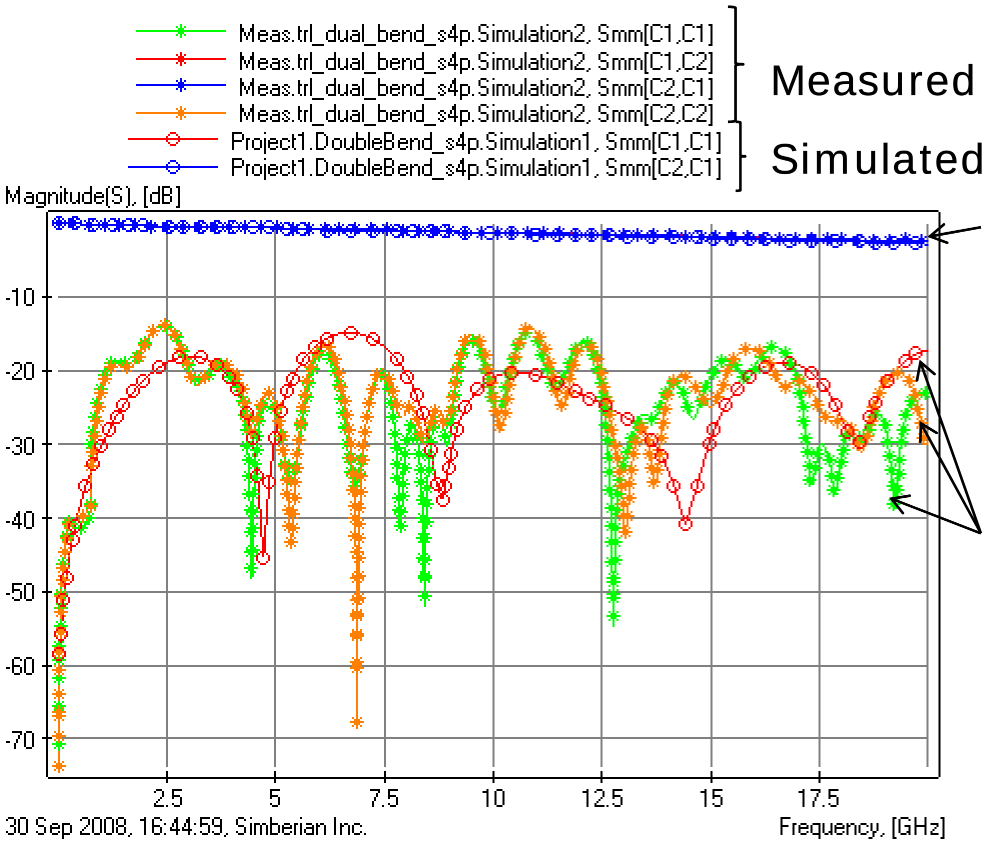
Good correspondence!



Differential bends: Comparison with de-embedded measurement results (TRL)

- Magnitudes of mixed-mode S-parameters (CC block)





Measured (stars)

Simulated (circles)

Common mode transmission

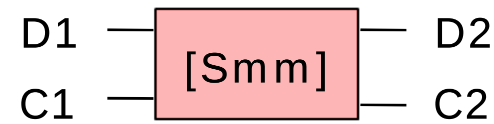
Good correspondence!

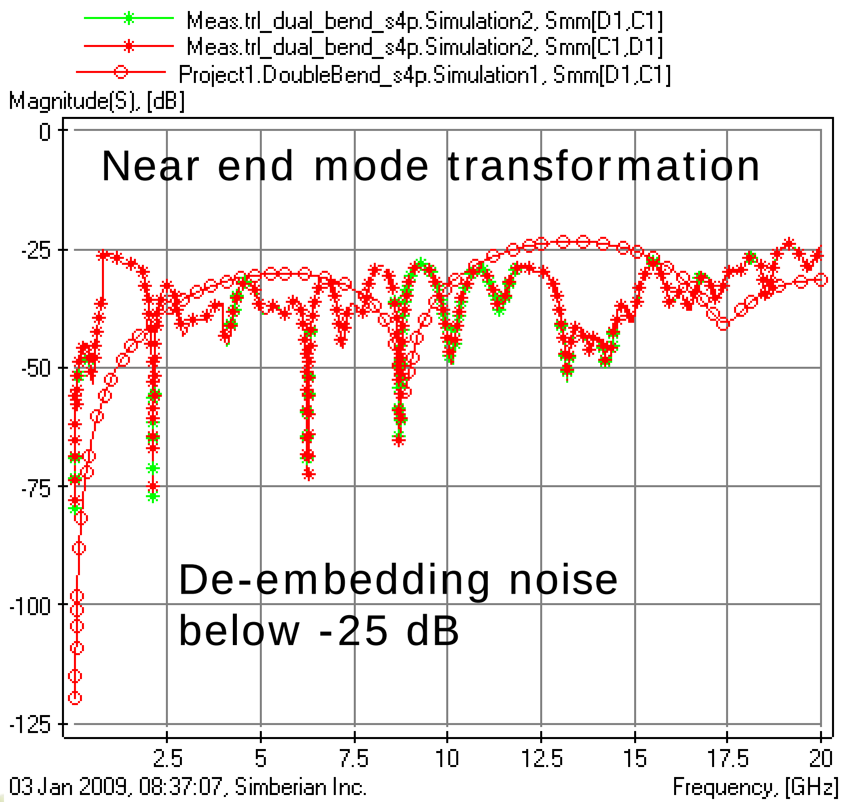
Common mode reflection

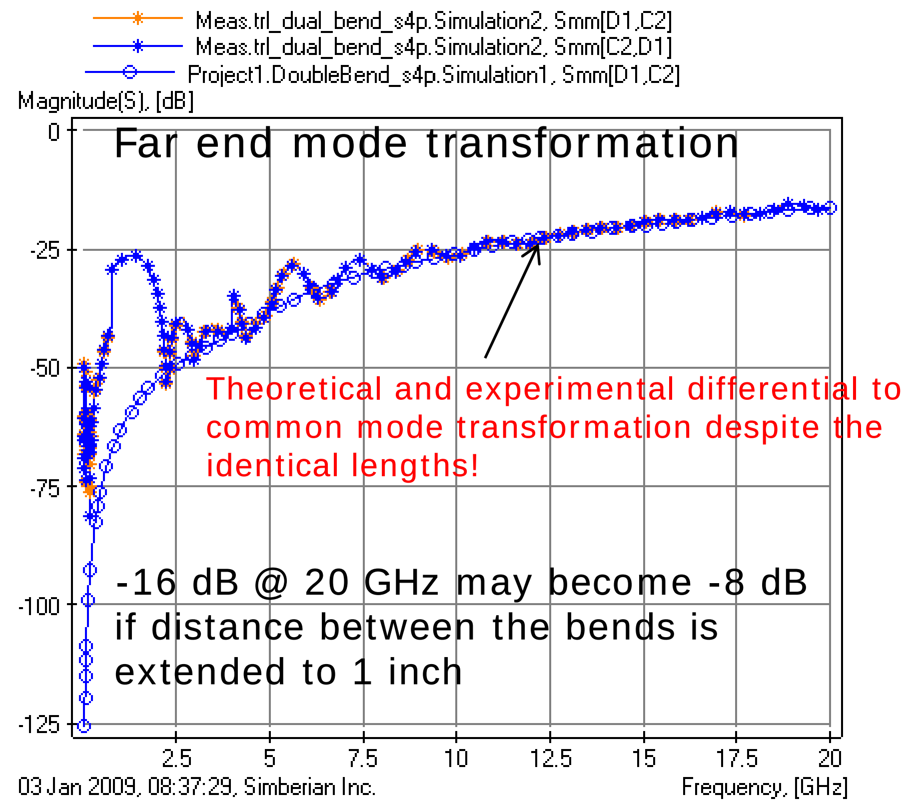
Differential bends: Mode transformation

- Acceptable correspondence between the measurements and simulation

Measured – stars
Simulated – circles







How to minimize the mode transformation?

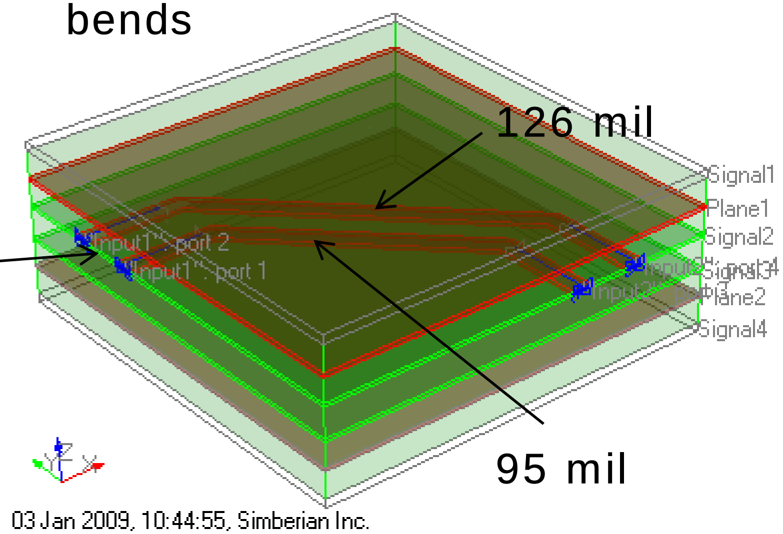
- Reduce size of the bends to minimize both far and near end mode transformation
- Use dual discontinuities with forward and reversed mode transformation as close to each other as possible to minimize far end mode transformation in micro-strip channels
- Use strip line structure with equal common and differential mode propagation velocity to reduce far end mode transformation
  - Disadvantages of such configuration are via-hole transitions to get to the strip layer and stitching vias for both reference planes for possibility to predict the common mode behavior

Let’s investigate smaller strip line configuration

- Strips are in layer Signal2, width 7 mil, 14 mil separation (about 100 Ohm) – leads to smaller length mismatch between two strips at the bend

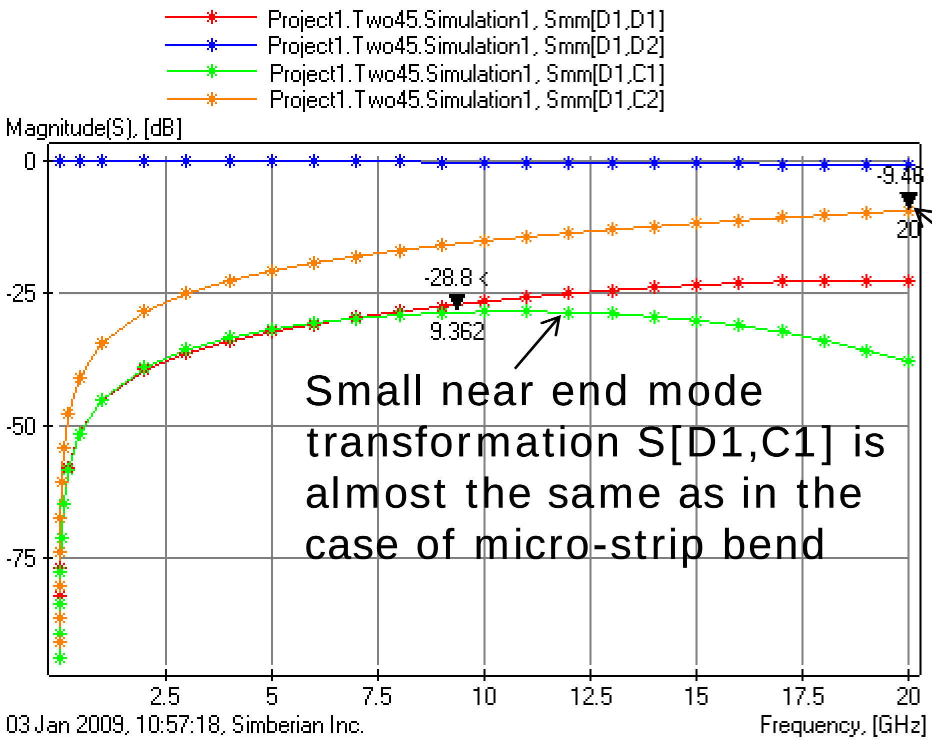
```
Project1
  Materials
    "Copper", RR=1, SR=0.5
    "FR4", Dk=4.25, LT=0.02, PLM=WD
    "Core", Dk=4.7, LT=0.02, PLM=WD
    "Vacuum"
    "SolderMask", Dk=3.3, LT=0.02, PLM=WD
  StackUp: LU=[mil], NL=6, T=54.9[mil], SML=("SolderMask", 1.75[mil])
    1| Signal: "Signal1", T=3, Ins="Vacuum"
    2| Medium: T=8.9, Ins="FR4"
    3| Plane: "Plane1", Mat="Copper", T=1.35, Ins="FR4"
    4| Medium: T=8, Ins="FR4"
    5| Signal: "Signal2", T=1.2, Ins="FR4"
    6| Medium: T=10, Ins="Core"
    7| Signal: "Signal3", T=1.2, Ins="FR4"
    8| Medium: T=8, Ins="FR4"
    9| Plane: "Plane2", Mat="Copper", T=1.35, Ins="FR4"
    10| Medium: T=8.9, Ins="FR4"
    11| Signal: "Signal4", T=3, Ins="Vacuum"
```

S-parameters phase reference planes shifted toward the bends

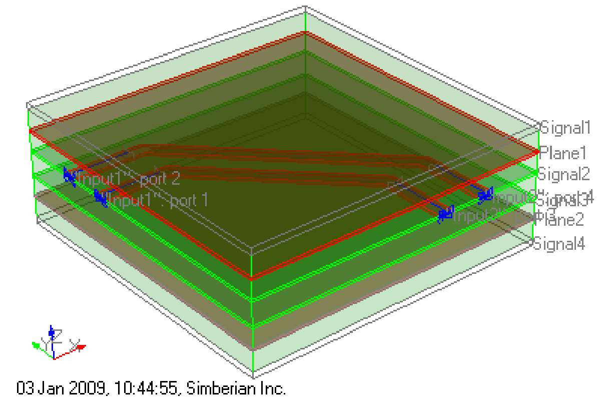


Single strip line bend performance

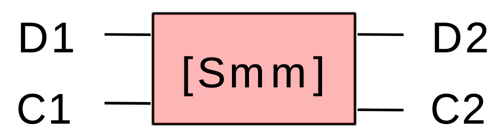
Mode transformation due to the non-symmetry of the bend



Small near end mode transformation S[D1,C1] is almost the same as in the case of micro-strip bend

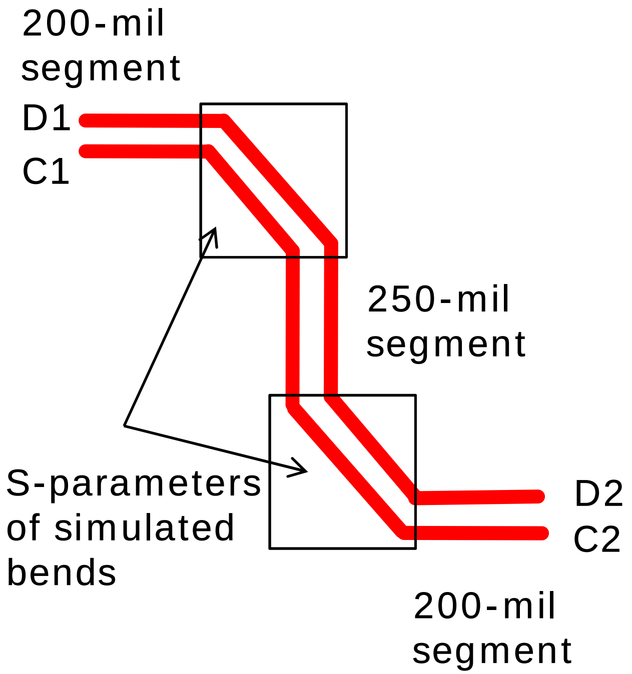


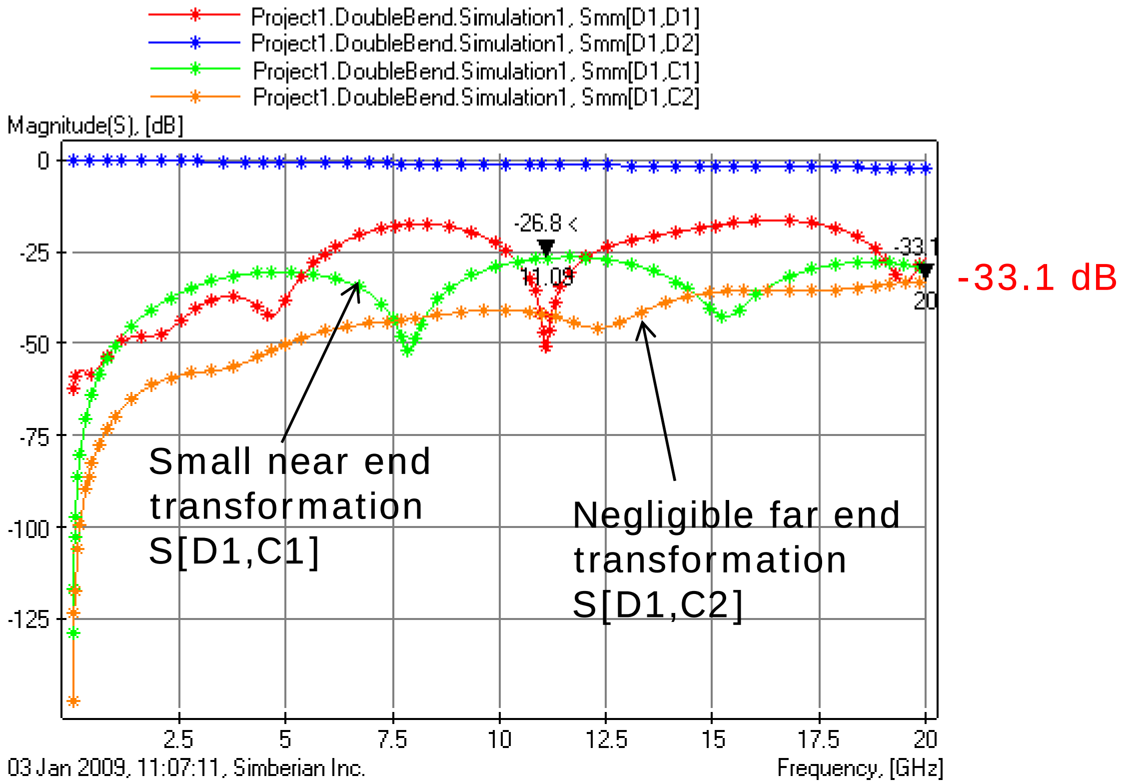
Far end mode transformation S[D1,C2] is smaller by 5 dB than in the case of micro-strip bend



Reduction in the far end mode transformation has been achieved.
Near end transformation is practically the same, though it is very small.

We can reduce the mode transformation further by using the reversed bend

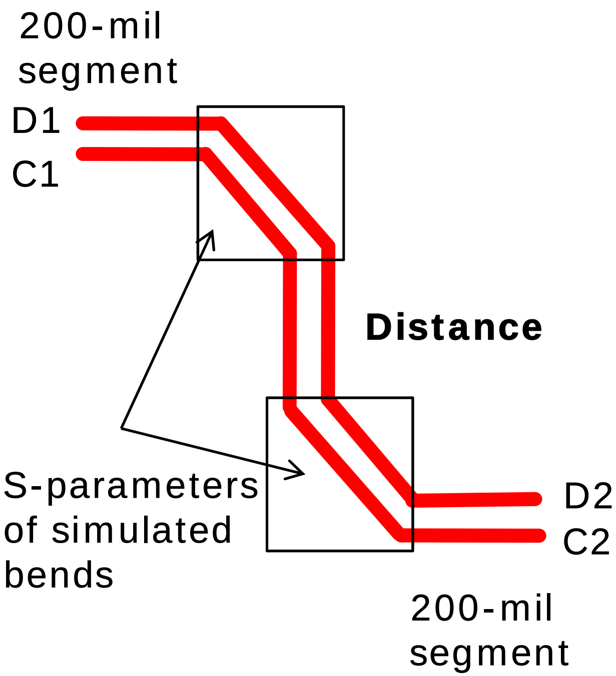


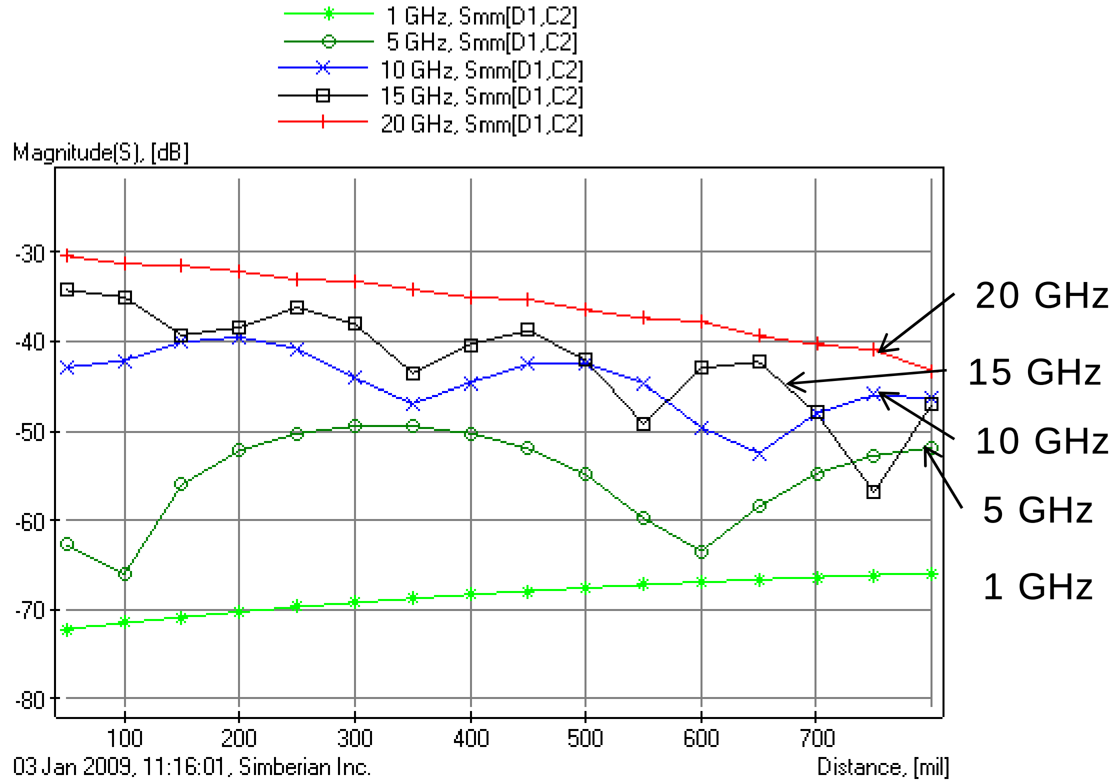


Far end transformation is practically negligible!
Near end transformation stays very small.

Distance between strip line bends does not make it worse – it makes it better!

- Increase of the distance reduces the transformation due to the natural losses in the common mode





The larger the Distance between the bends, the smaller the far end mode transformation coefficient S[D1,C2]!

Conclusion

- Transformation of differential mode to common mode in interconnects is unavoidable if non-symmetrical structures such as bends are used
- Amount of energy transformed into common modes at the bends can be effectively estimated with localized full-wave electromagnetic analysis
- Configurations and patterns that minimize the transformation can be derived on the base of the numerical investigation of interconnects
- Even structures symmetrical by design may have mode transformation due to non-symmetries introduced by dielectric structure and manufacturing tolerances – the transformation value can be used as the floor for the mode transformation optimization
- Transformation may have minor effect on signal quality (signal integrity), but may have more serious consequences on EMI if common mode is not appropriately terminated

Solutions and contact

- Setting up all simulations and analysis took about 2 hours
- Simbeor solution files used to illustrate these notes are available for download from Simberian web site
  - http://www.simberian.com/AppNotes/Solutions/ModeTransformations_2009_01.zip
  - Solution TwoBendsParametric/ TwoBendsParametric.esx - investigation of micro-strip line bends and channels with dual 45-degree bends
  - Solution TwoStripBendsParametric/ TwoStripBendsParametric.esx - investigation of strip line bends and channels with dual 45-degree bends
  - Solution DiffDualBendVerification/ DiffDualBendVerification.esx - verification of micro-strip line configuration by comparison with measured data
  - Solution TwoBends90Parametric/ TwoBends90Parametric.esx - investigation of micro-strip line bends and channels with dual 90-degree bends
  - Solution TransformationMinimization/TransformationMinimization.esx – attempt to minimize the mode transformation by equalizing trance length at the 90-degree bend
- Send questions and comments to
  - General: info@simberian.com
  - Sales: sales@simberian.com
  - Support: support@simberian.com
- Web site www.simberian.com