Simbeor Application Note #2010_04, November 2010

Simberian
Electromagnetic Solutions

Material Identification With GMS-Parameters of Coupled Lines

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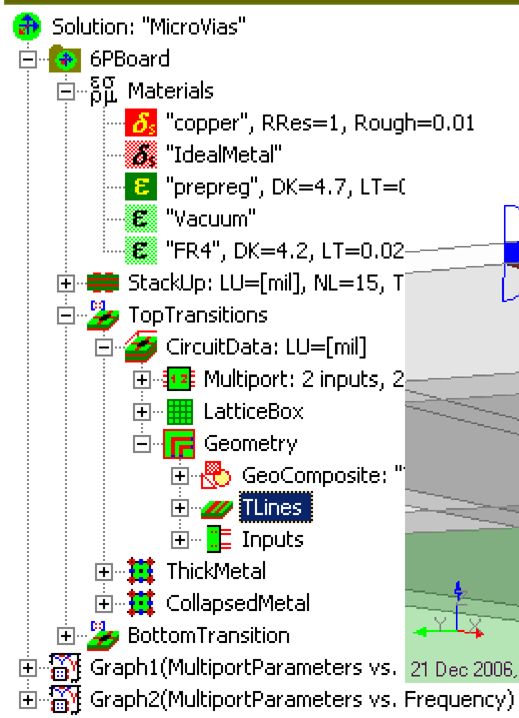

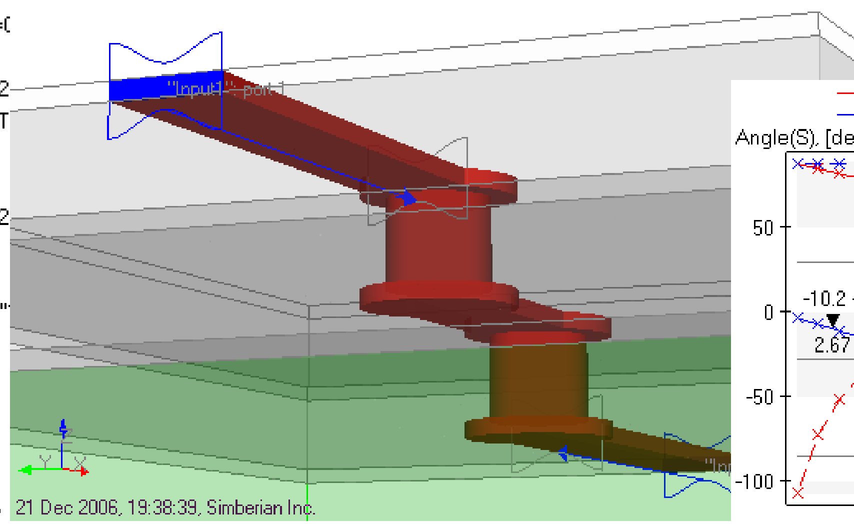

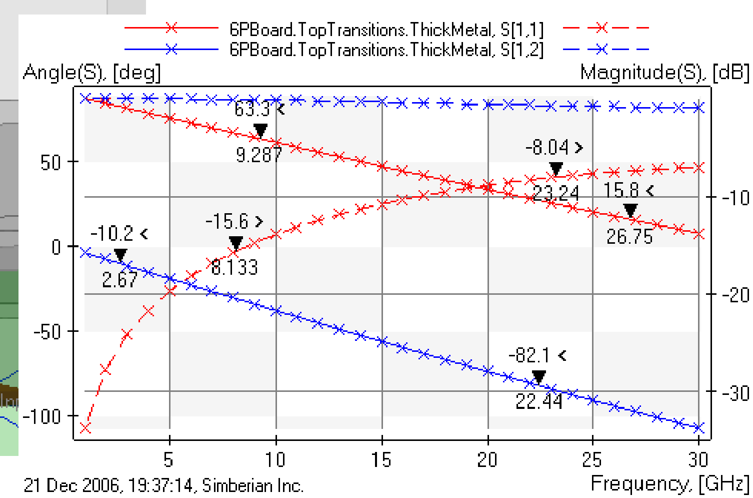

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Overview

- Introduction
- Identification of material parameters with Generalized Modal S-parameters of coupled lines
- Coupled microstrip configuration
- Coupled microstrip configuration with solder mask
- Coupled strip configuration in homogeneous dielectric
- Coupled strip configuration in non-homogeneous dielectric
- Effect of bends in coupled microstrip lines on GMS-parameters
- Effect of bends in coupled strip-lines on GMS-parameters
- Conclusion

Introduction

- Broadband dielectric and conductor models are the requisite foundation for performing meaningful electromagnetic verification of multi-gigabit interconnects
- Such model can be effectively identified with Generalized Modal S-parameters (GMS-parameters)
  - The method is the simplest possible and is based on fitting computed and measured GMS-parameters as outlined in: *Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications – DesignCon 2010 – available at* ***http://www.designcon.com/infovault/***
- PCB dielectrics are inhomogeneous – it is usually a mixture of glass and epoxy
- Space between traces in coupled microstrip lines may be filled with the solder mask dielectrics
- Prepreg and core layers in strip-line configurations may have slightly different dielectric properties
- Space between traces in coupled strip lines may be filled with only epoxy or even with air
- For accurate characterization of such structures we may need to identify and use parameters of at least 2 dielectrics (or one anisotropic dielectric model)
- This app note shows how to use GMS-parameters of coupled lines for identification of material properties
- Sensitivity of the method to bend discontinuities is also investigated
- Simbeor 2011 (64bit) released on Nov. 15th 2010 is used to generate the results

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Material parameters identification with GMS-parameters

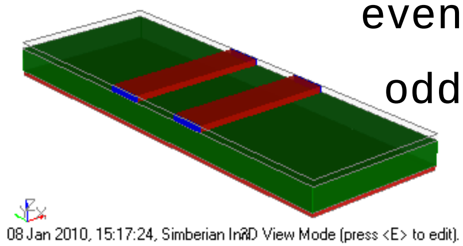
- Measure S-parameters of two test fixtures with different length of line segments S1 and S2
- Transform S1 and S2 to the T-matrices T1 and T2, diagonalize the product of T1 and inversed T2 and compute GMS-parameters of the line difference
- Select material models and guess values of the model parameters
- Compute GMS-parameters of the line difference segment by solving Maxwell's equation for t-line cross-section (only propagation constants are needed)
- Adjust material parameters until computed GMS parameters fit measured GMS-parameters with the computed

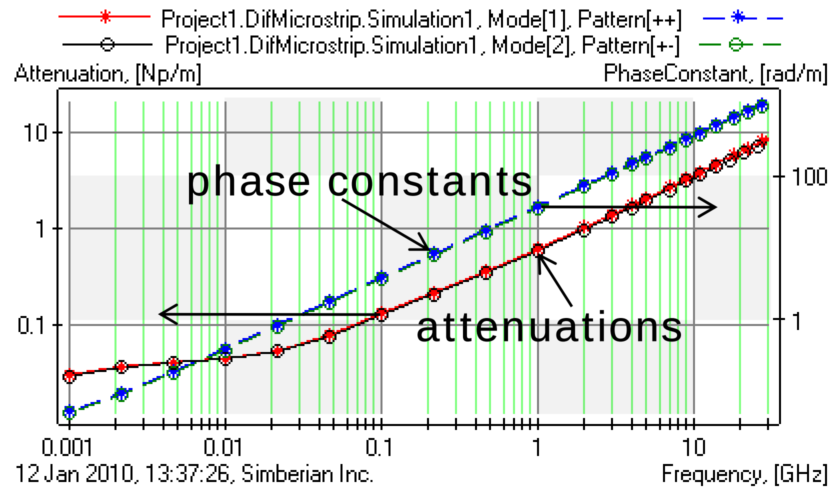
Generalized Modal S-parameters (GMS-parameters) for two-conductor line

1. Compute propagation constants for 2 modes

even $\Gamma_1(f) = \alpha_1(f) + i \cdot \beta_1(f)$

odd $\Gamma_2(f) = \alpha_2(f) + i \cdot \beta_2(f)$

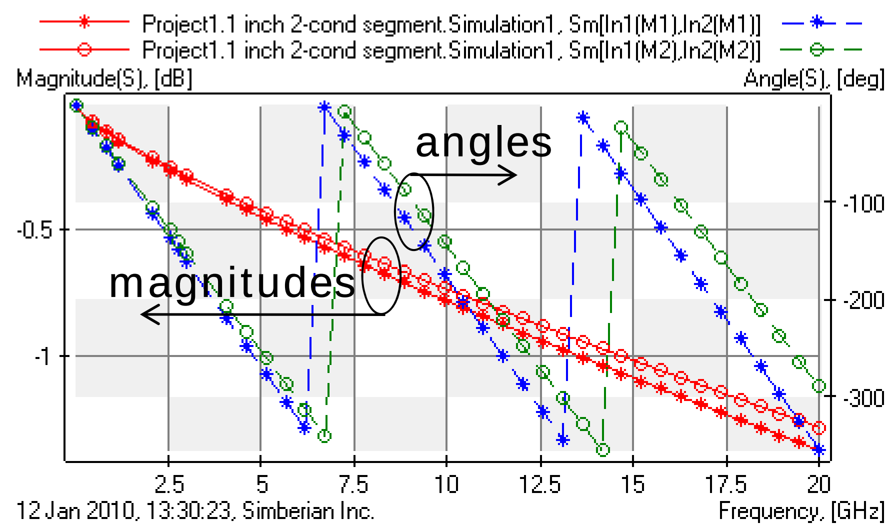




2. Compute 4x4 GMS of line segment with length dL

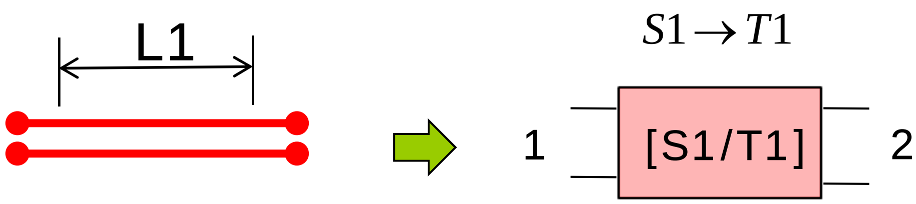
$$GMSc = \begin{bmatrix} 0 & 0 & \exp(-\Gamma_1 \cdot dL) & 0 \\ 0 & 0 & 0 & \exp(-\Gamma_2 \cdot dL) \\ \exp(-\Gamma_1 \cdot dL) & 0 & 0 & 0 \\ 0 & \exp(-\Gamma_2 \cdot dL) & 0 & 0 \end{bmatrix}$$

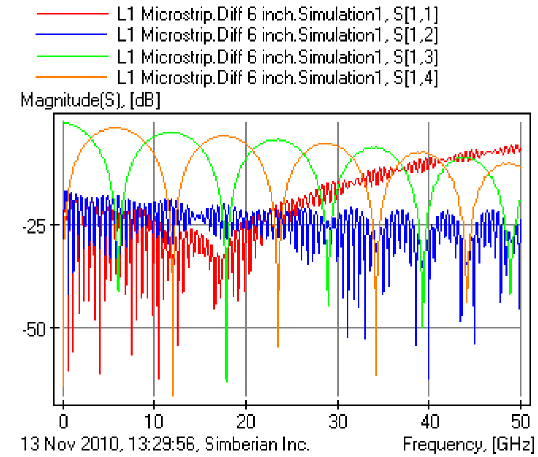
Relatively simple to compute and a lot of zeroes!



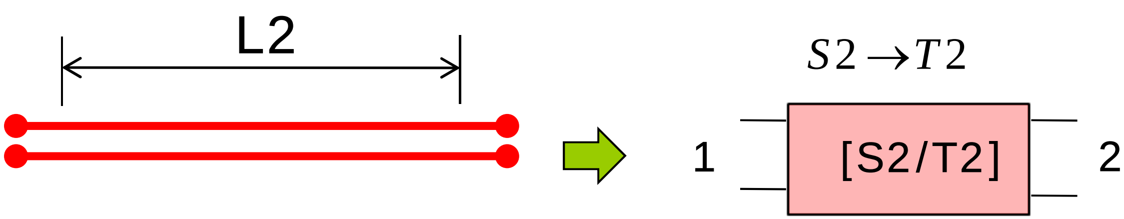
Measure S-parameters of two test fixtures with line segments (no calibration is required)

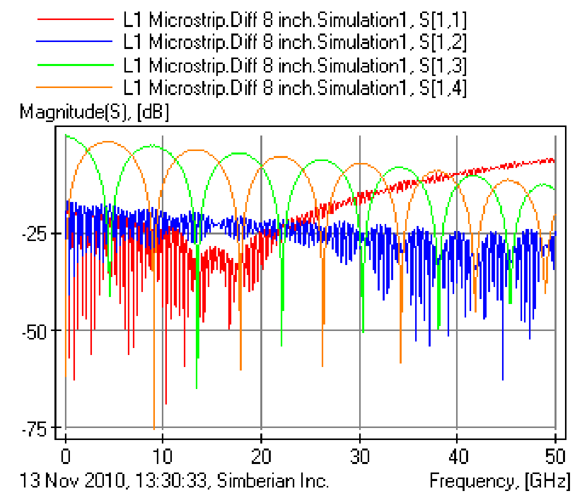
- S1 and T1 for line with length L1





- S2 and T2 for line with length L2



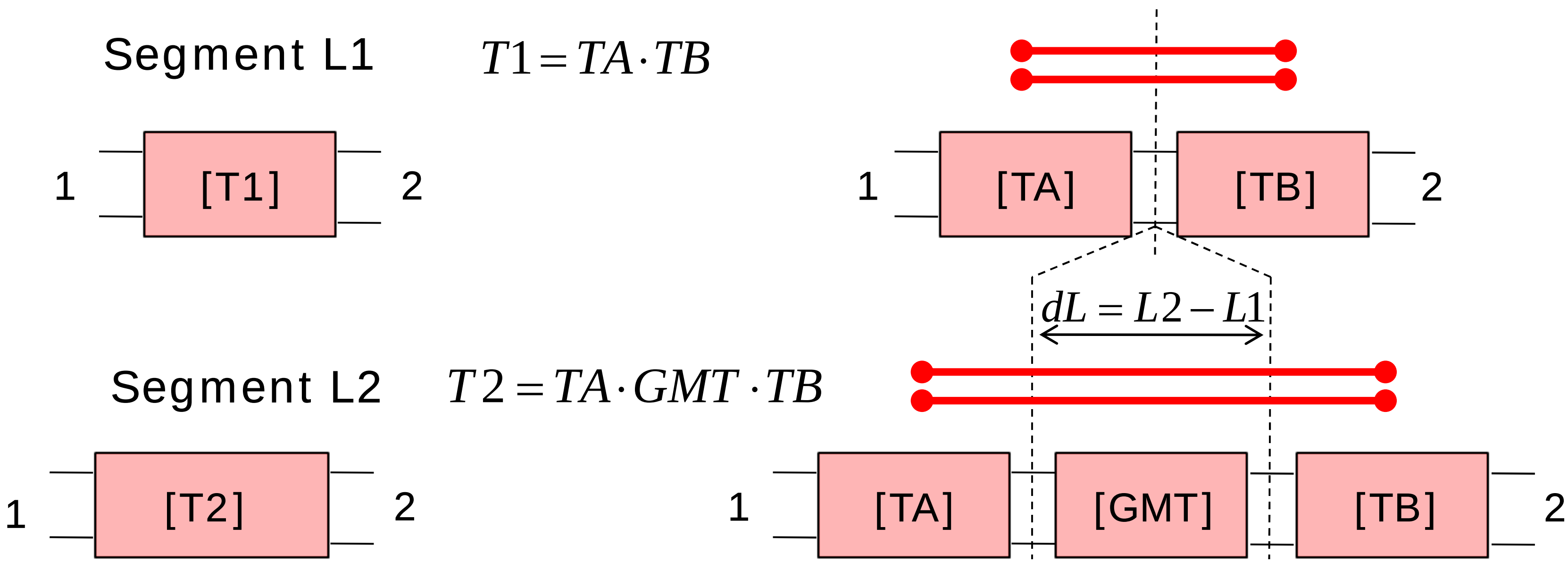


T1 and T2 matrices are scattering T-parameters (computed directly from S-parameters)

Extract Generalized Modal T-parameters (GMT) and then GMS-Parameters

Segment L1 $T1 = TA \cdot TB$

Segment L2 $T2 = TA \cdot GMT \cdot TB$



GMT is non-reflective modal T-matrix (normalized to the unknown characteristic impedances of the modes)

$$T2 \cdot T1^{-1} = TA \cdot GMT \cdot TA^{-1}$$

$$GMT \doteq eigenvals\left(T2 \cdot T1^{-1}\right)$$

For 2-conductor line we get:

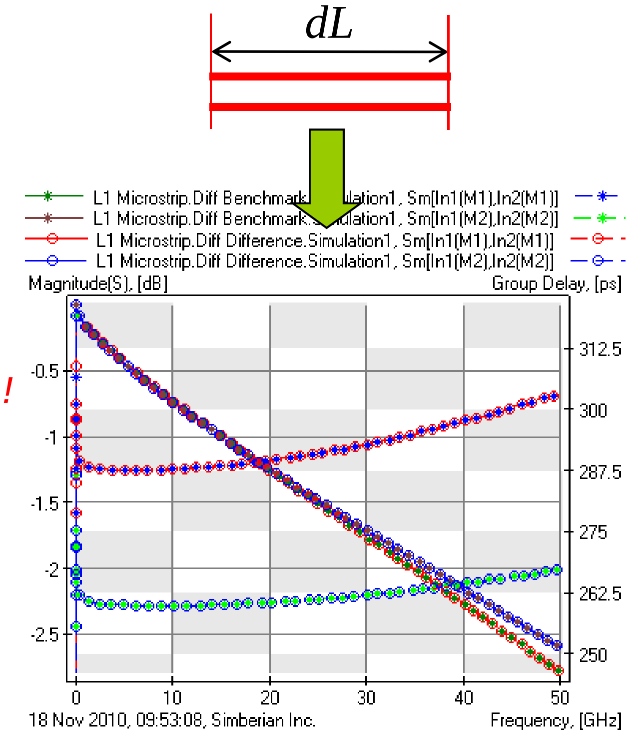
$$GMT = \begin{bmatrix} T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \\ 0 & 0 & T_{11}^{-1} & 0 \\ 0 & 0 & 0 & T_{22}^{-1} \end{bmatrix} \Rightarrow GMSm = \begin{bmatrix} 0 & 0 & T_{11} & 0 \\ 0 & 0 & 0 & T_{22} \\ T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \end{bmatrix}$$

Just 2 complex functions!

Identifying dielectrics by fitting GMS-parameters

- Solve Maxwell's equations for 2-conductor line:

$$GMSc=\begin{bmatrix} 0 & 0 & \exp(-\Gamma_1\cdot dL) & 0 \\ 0 & 0 & 0 & \exp(-\Gamma_2\cdot dL) \\ \exp(-\Gamma_1\cdot dL) & 0 & 0 & 0 \\ 0 & \exp(-\Gamma_2\cdot dL) & 0 & 0 \end{bmatrix}$$



- Fit measured data: *Only 2 complex functions!*

$$GMSm=\begin{bmatrix} 0 & 0 & T_{11} & 0 \\ 0 & 0 & 0 & T_{22} \\ T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \end{bmatrix}$$

- Measured GMS-parameters of the segment can be directly fitted with the calculated GMS-parameters for material parameters identification
- Two functions can be used to identify 2 dielectrics!

The GMS-parameters technique is the simplest possible

- Needs un-calibrated measurements for 2 t-lines with any geometry of cross-section and transitions
  - No extraction of propagation constants (Gamma) from measured data (difficult, error-prone)
  - No de-embedding of connectors and launches (difficult, error-prone)
- Needs the simplest numerical model
  - Requires computation of only propagation constants
  - No 3D electromagnetic models of the transitions
- Minimal number of smooth complex functions to match
  - One parameter for single and two parameters for differential
  - All reflection and modal transformation parameters are exactly zeros

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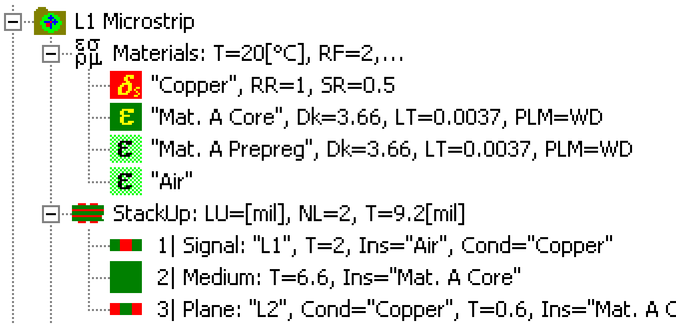
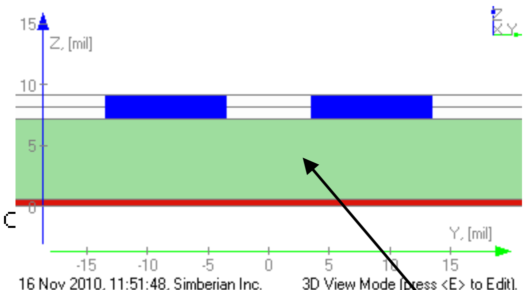
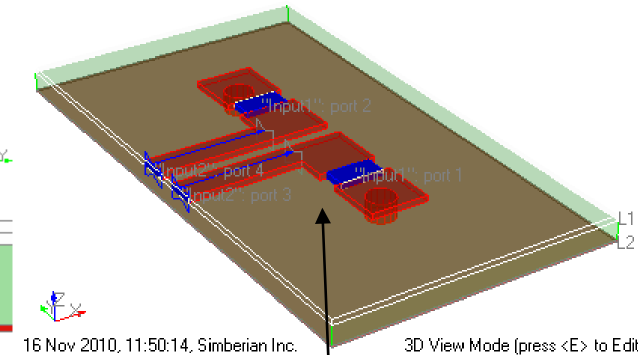
Numerical identification experiment

- Microstrip configuration – no solder mask

Materials & Stackup

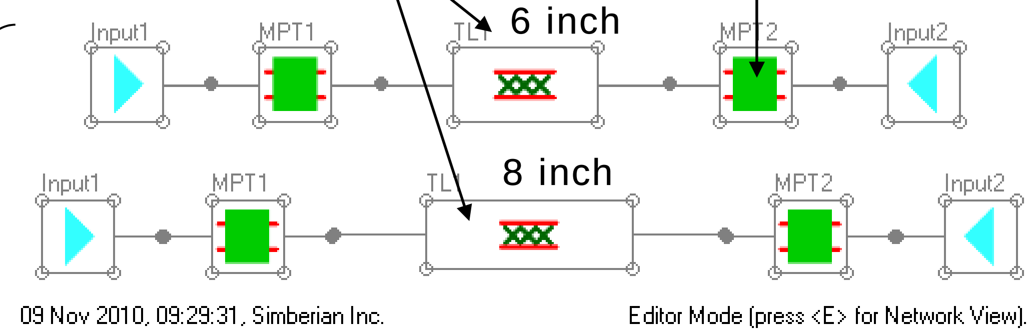






10 mil strips 7 mil apart

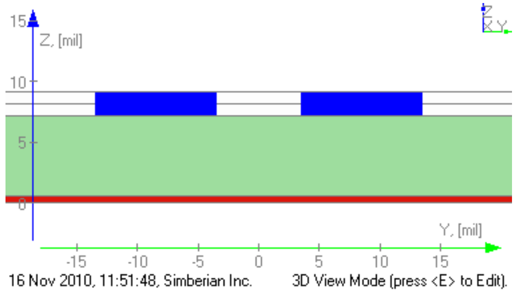
Models of the launches (all identical)

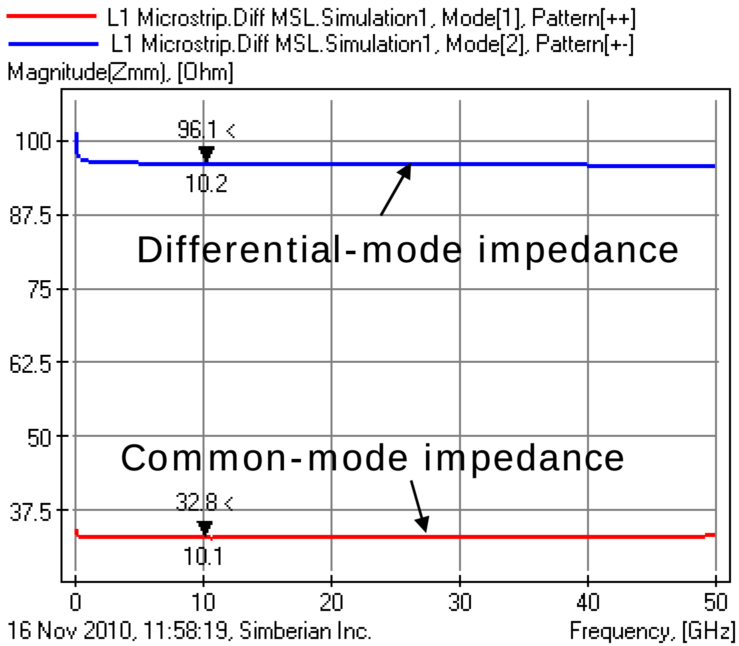


From simulated S-parameters of 2 structures we extract GMS-parameters of 2-inch coupled line segment and compare it with the GMS-parameters of 2-inch segment computed directly

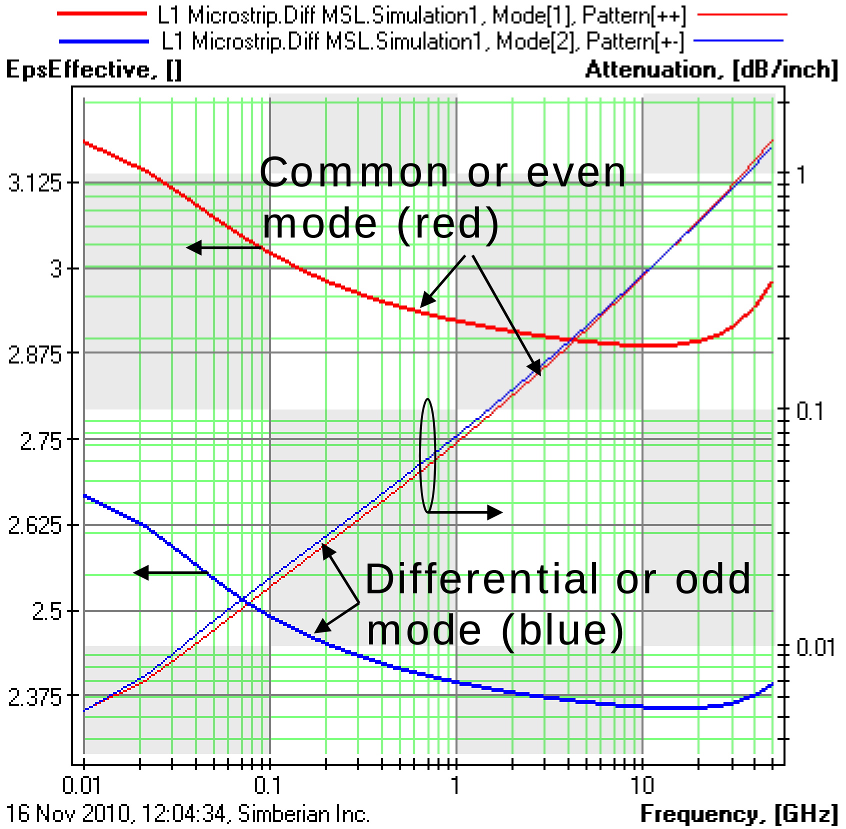
2-conductor microstrip line parameters

10 mil strips 7 mil apart





Modes have different attenuation and propagation constant and high-frequency dispersion



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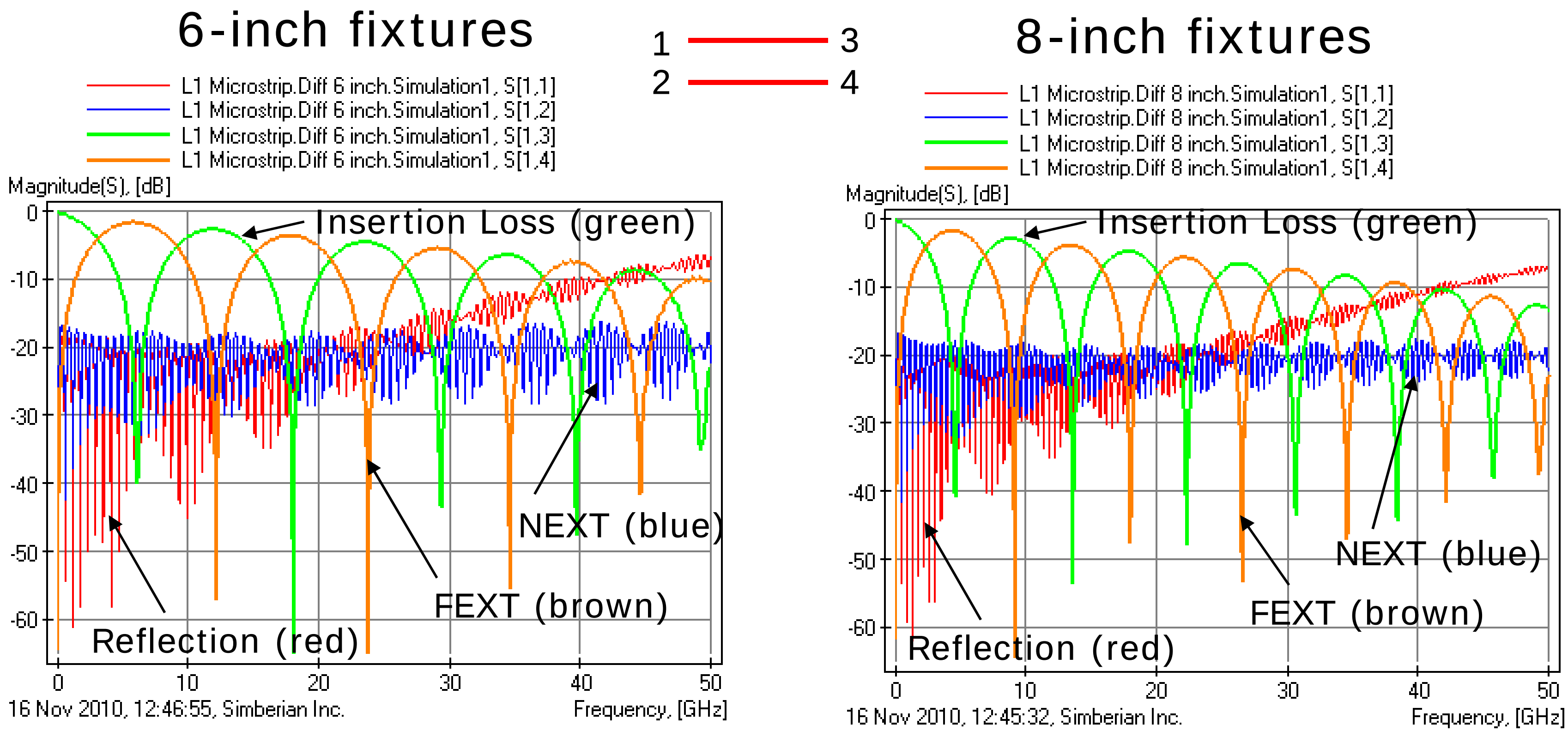
Single-ended parameters of test fixtures



Elements of one row of S-matrix are plotted

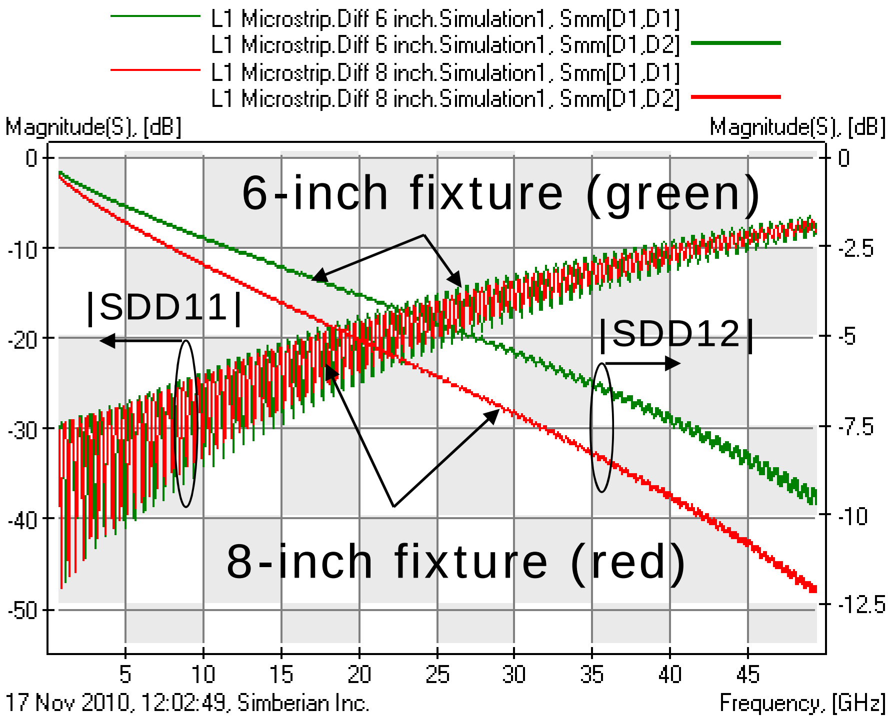
Reflection is mostly due to the reflection at the launches

Not very convenient for the material identification!

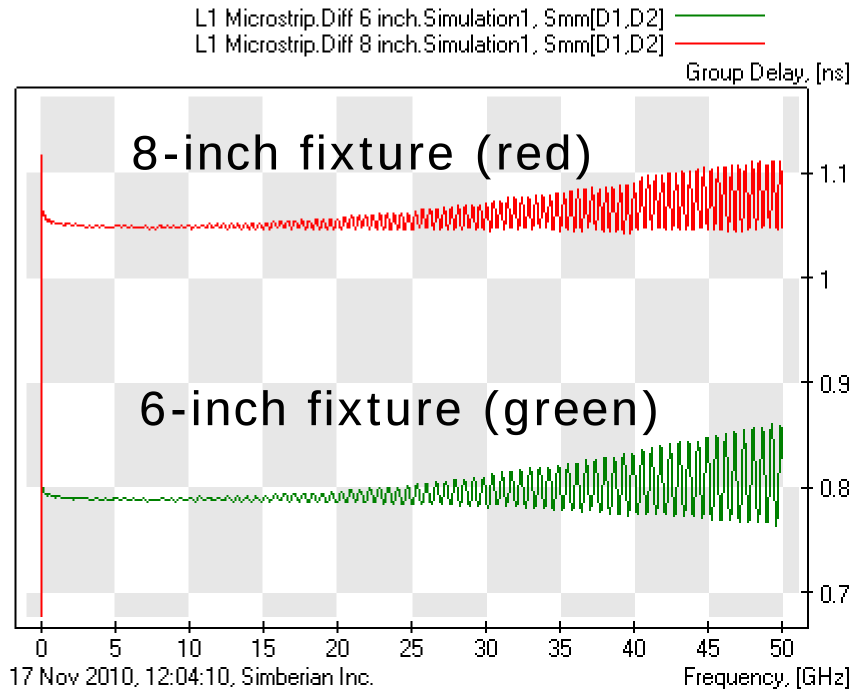
Differential parameters of test fixtures

Magnitudes

D1 D2



Group delays $-\frac{\partial \varphi}{\partial \omega}$

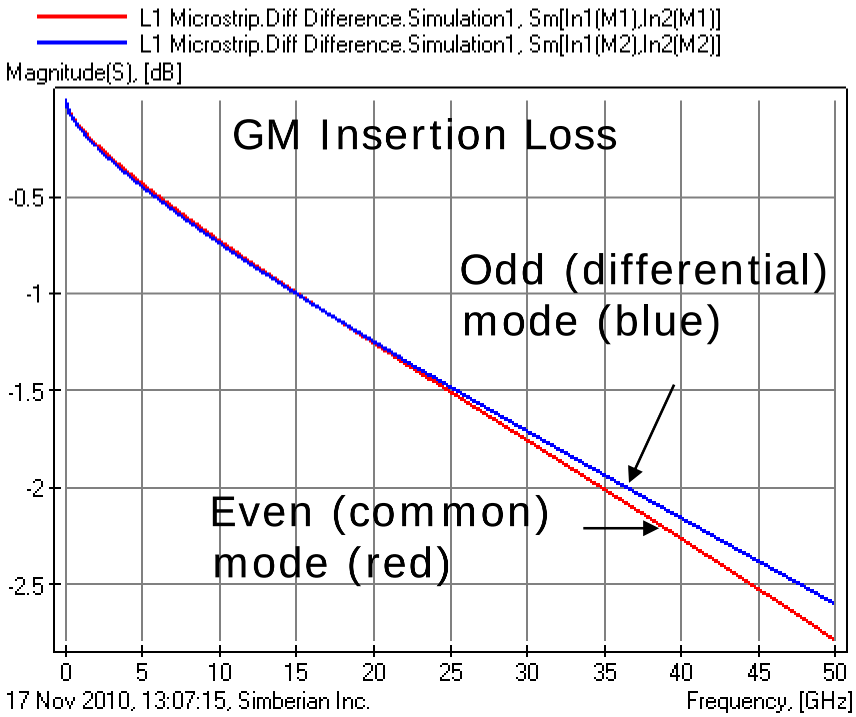


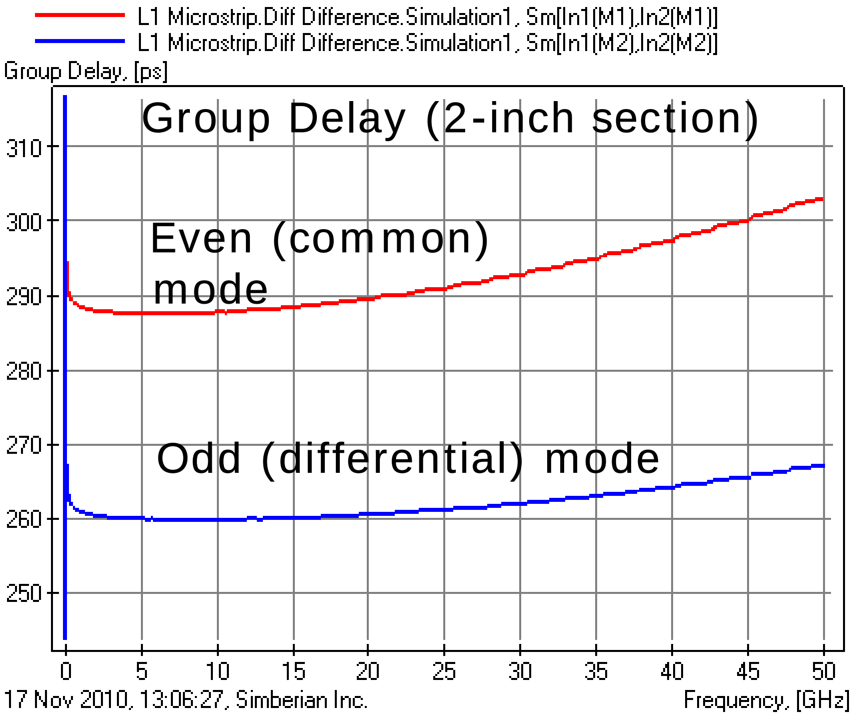
Reflection is mostly due to the reflection at the launches

Still not convenient for the material identification – oscillations and too many parameters to match!

Conversion into GMS-parameters

From S-parameters of 2 fixtures we compute GMS-parameters with just 2 unique non-zero elements: Common and differential GM transmission parameters

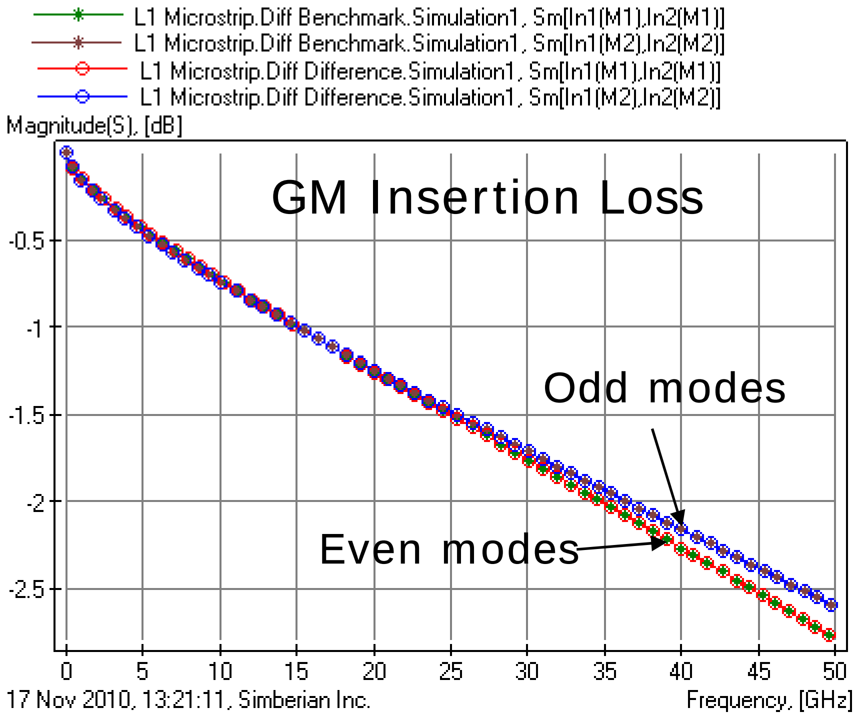


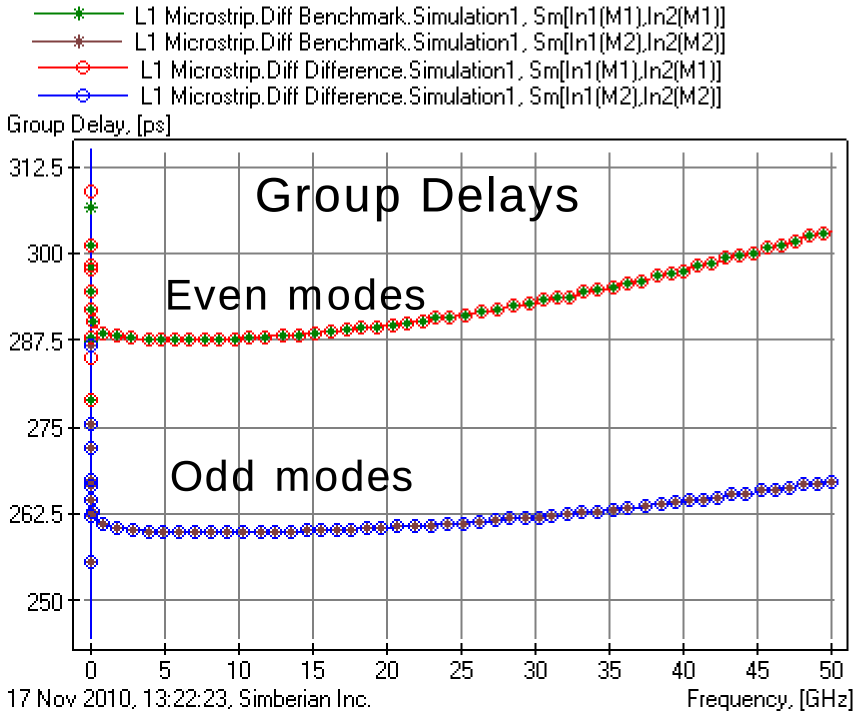


Very convenient for the material parameters identification!

Identification with two modes (IL&GD)

GM transmission of 2-inch segment (brown and green stars) match GM transmission extracted from S-parameters of 2 test fixtures (red and blue circles)



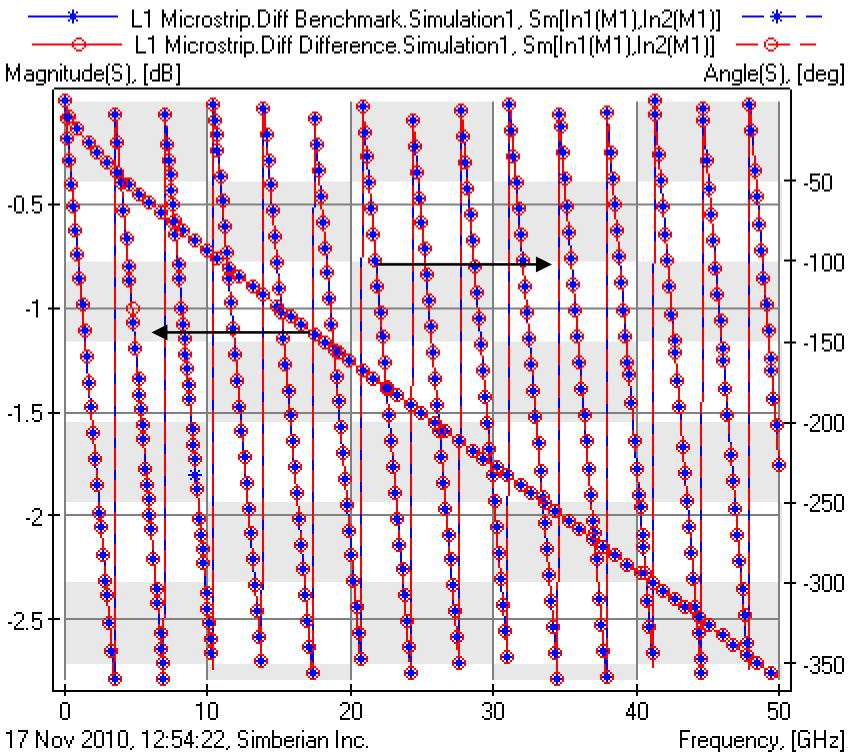


The results are independent of cross-section and launch construction as long as the widths and launches are identical in the test fixtures!

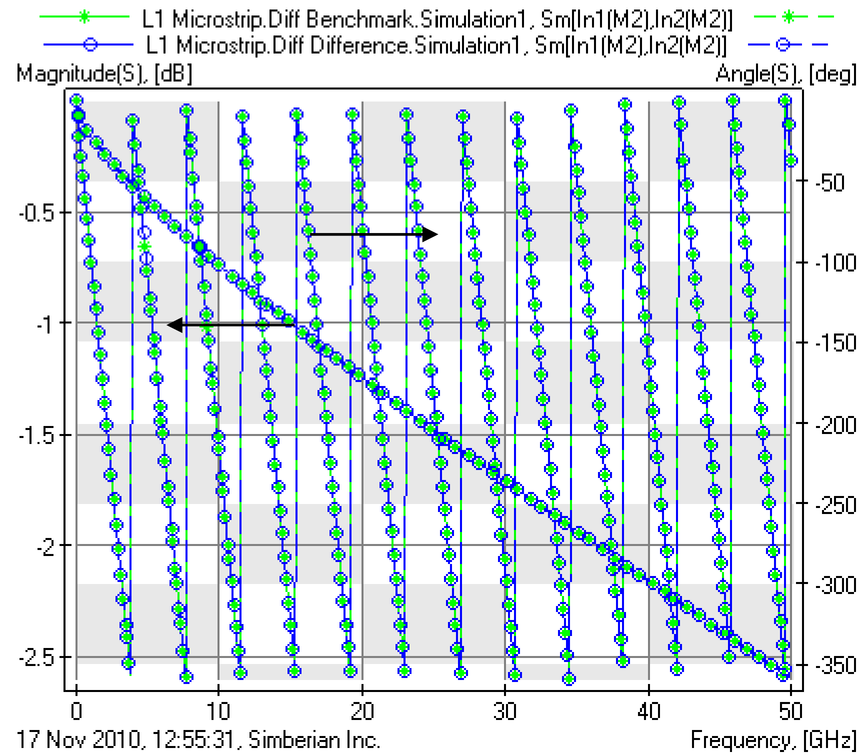
Identification with two modes (IL&PD)

GM transmission of 2-inch segment (blue and green stars) match GM transmission extracted from S-parameters of 2 test fixtures (red and blue circles)

Even (common) Modes:



Odd (differential) Modes:



The results are independent of cross-section and launch construction as long as the widths and launches are identical in the test fixtures!

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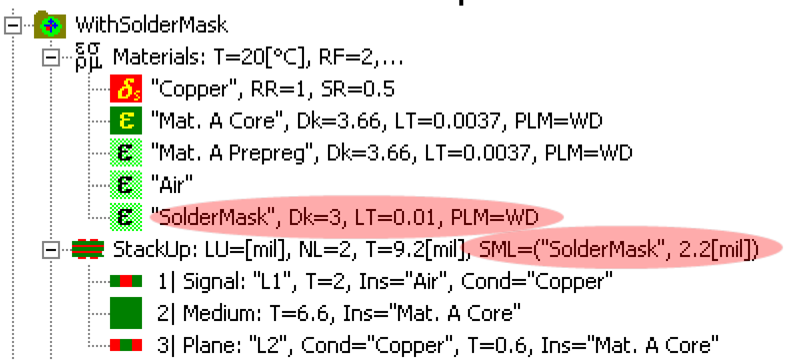
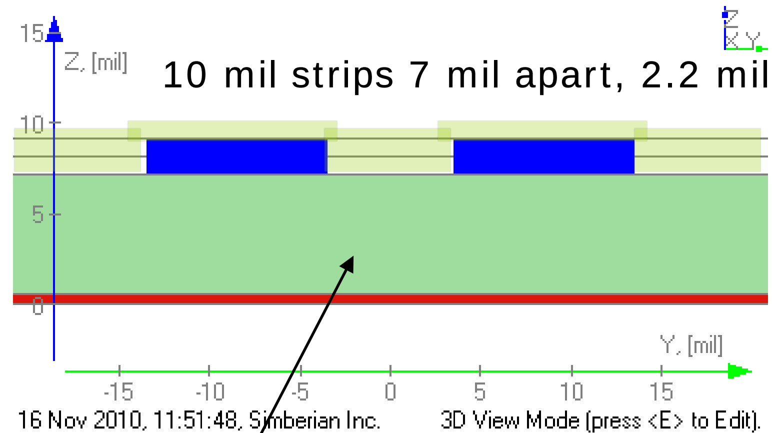
What if real structure has solder mask layer made of dielectric with different properties?

- Numerical experiment with microstrip line and 2 dielectrics

Materials & Stackup

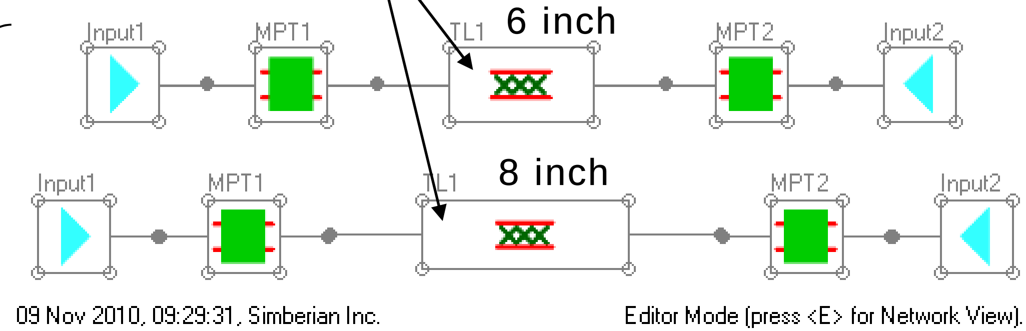




Solder Mask (SM) has smaller DK and larger LT

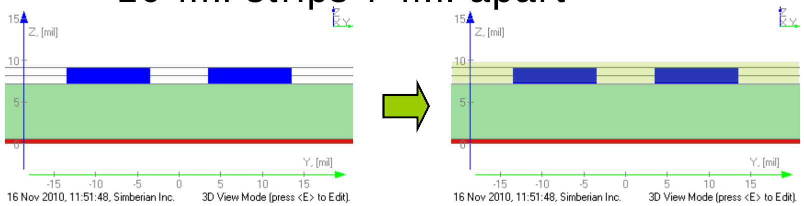
Differential microstrip line segments with solder mask

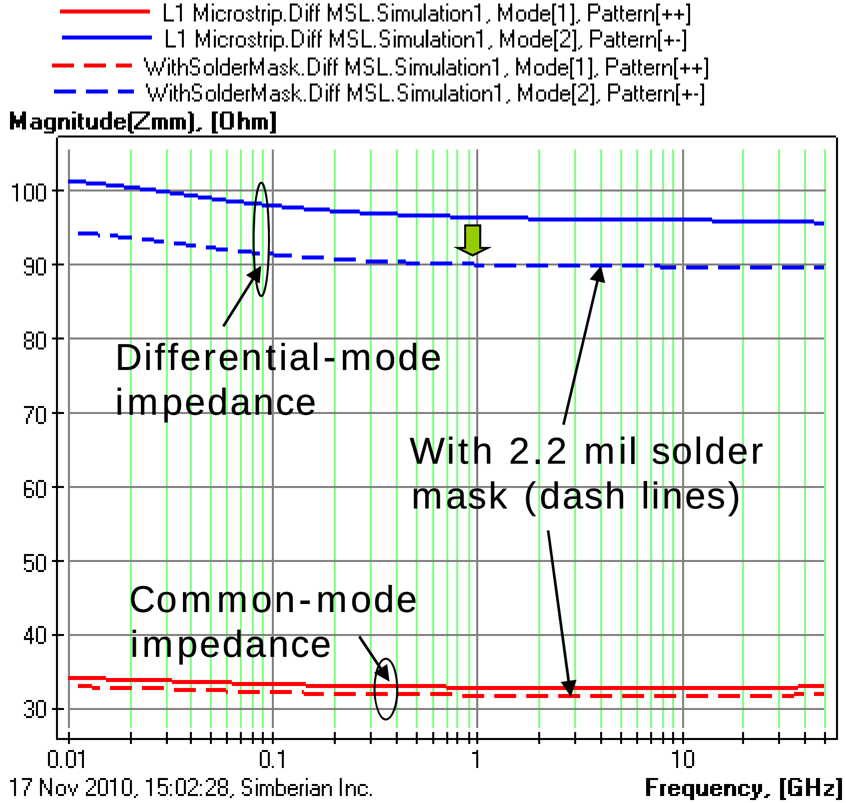
From simulated S-parameters of 2 structures with SM we extract GMS-parameters of 2-inch coupled line segment and compare it with the GMS-parameters of 2-inch segment computed directly without SM



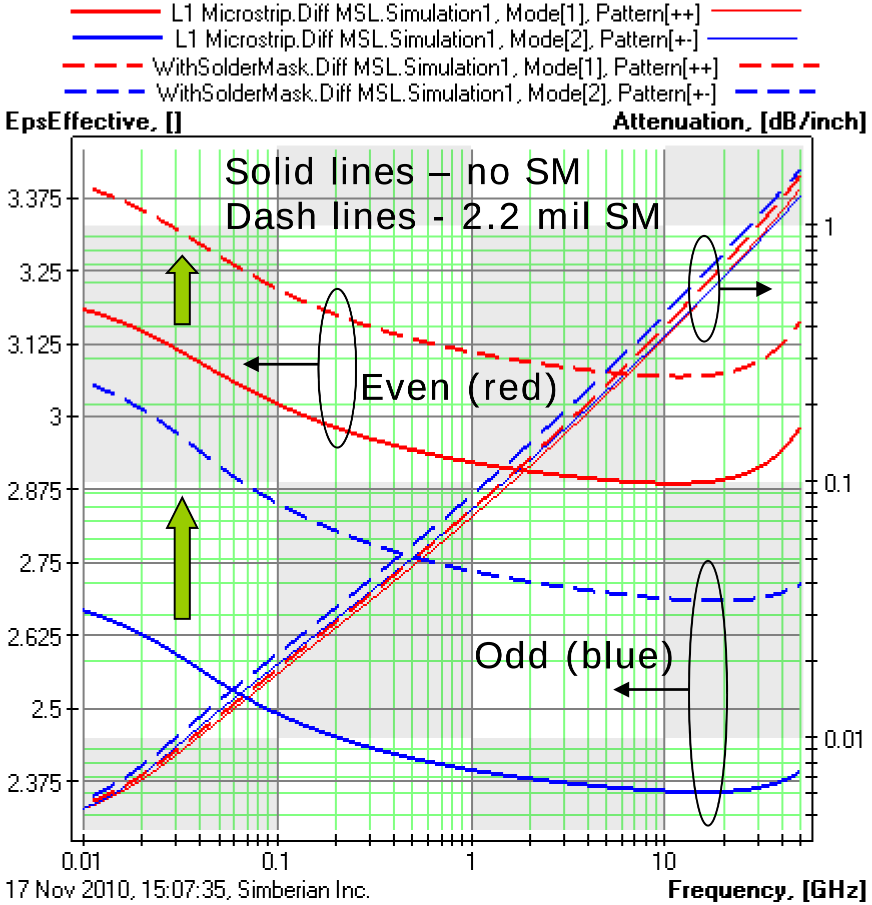
Effect of solder mask on modal parameters of 2-conductor t-line

10 mil strips 7 mil apart

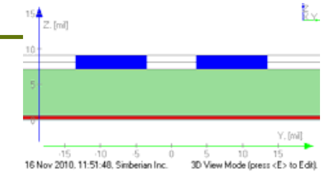




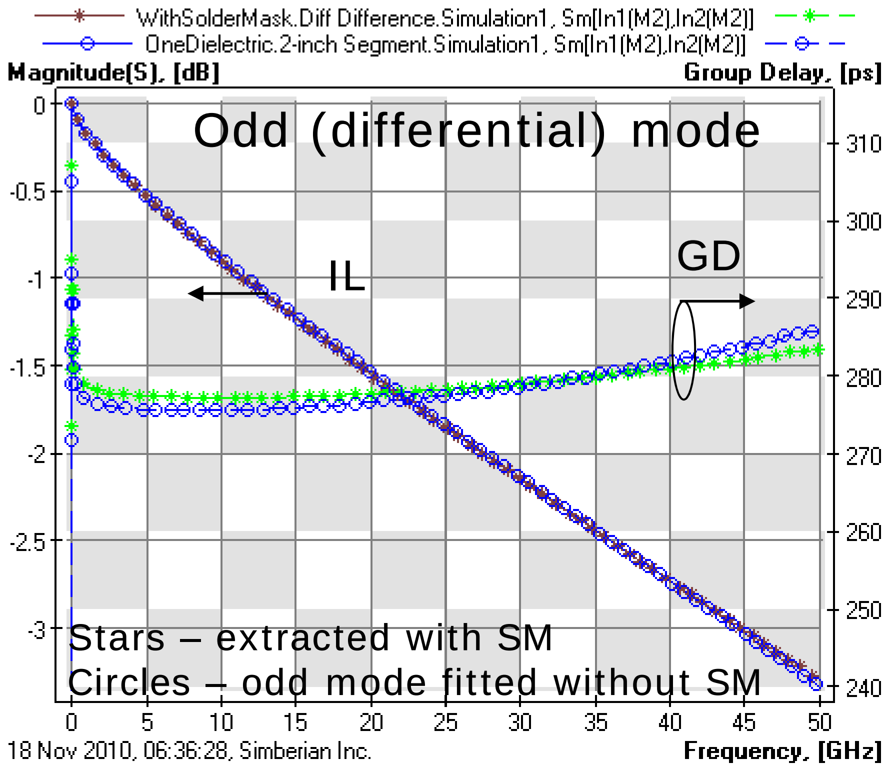
Solder mask in this case increases attenuation and propagation constant and decreases modal impedance

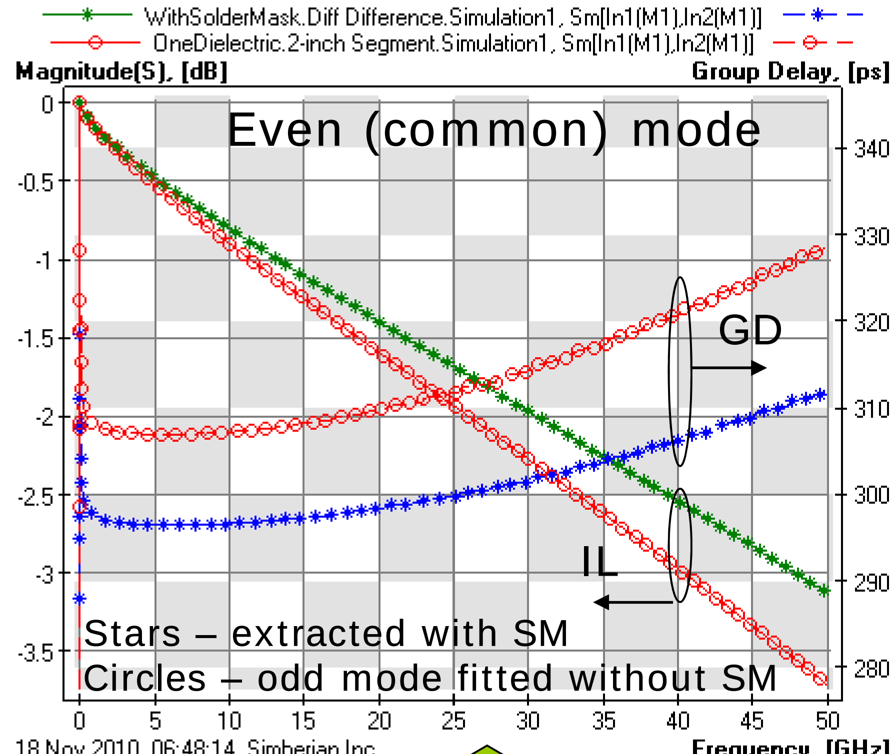


Attempt to fit extracted GMS-parameters with computed without solder mask



DK of substrate is adjusted from actual 3.66 to 4.25 and LT is adjusted from actual 0.0037 to 0.0053 to fit the differential mode IL and group delay (left graph)





GD of odd mode cannot be matched perfectly due to difference in dispersion

The even (common) mode IL and GD cannot be simultaneously matched (right graph)!

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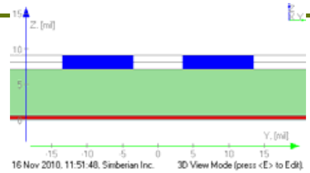
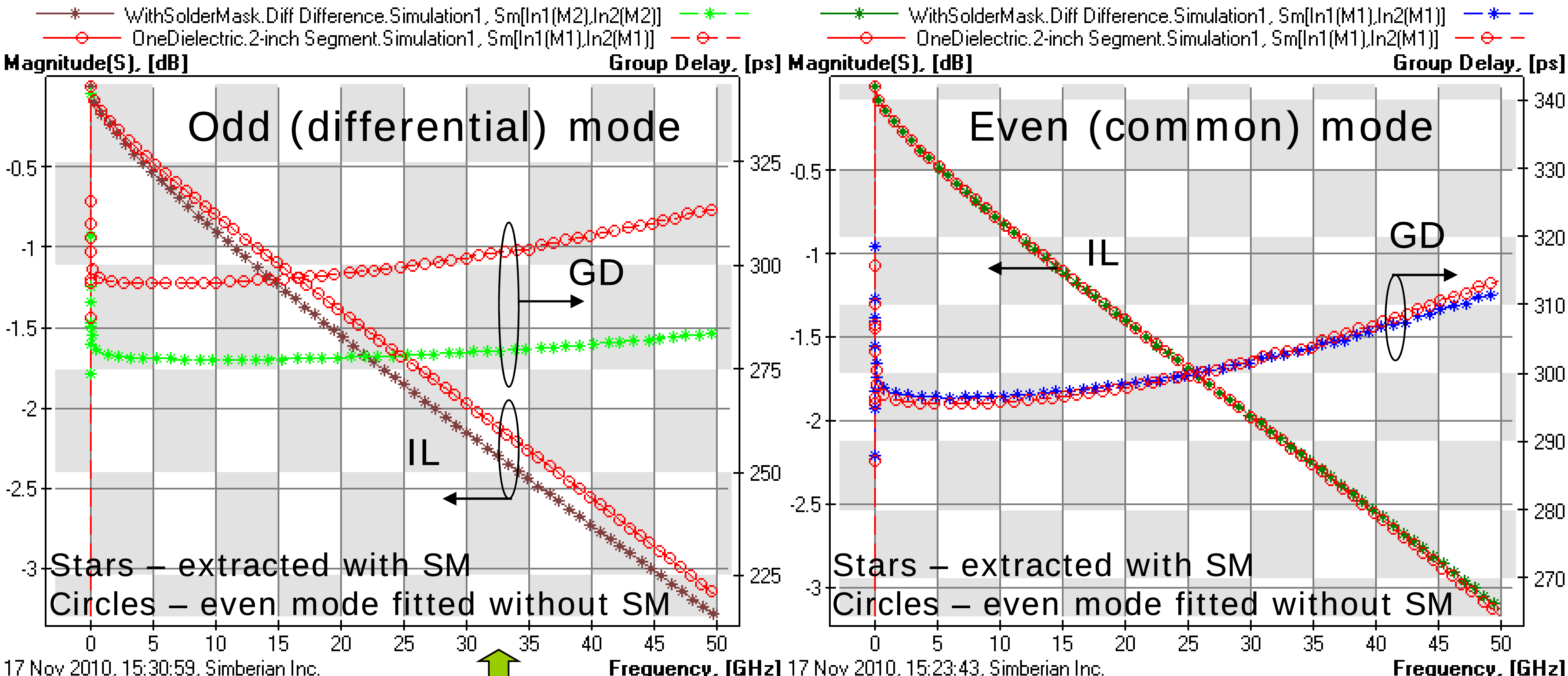
Attempt to fit extracted GMS-parameters with computed without solder mask



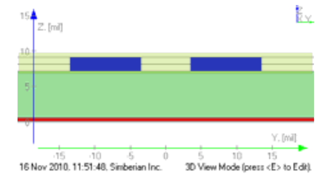
DK of substrate is adjusted from 3.66 to 3.9 and LT is adjusted from 0.0037 to 0.0044 to fit the differential mode IL and group delay (right graph)

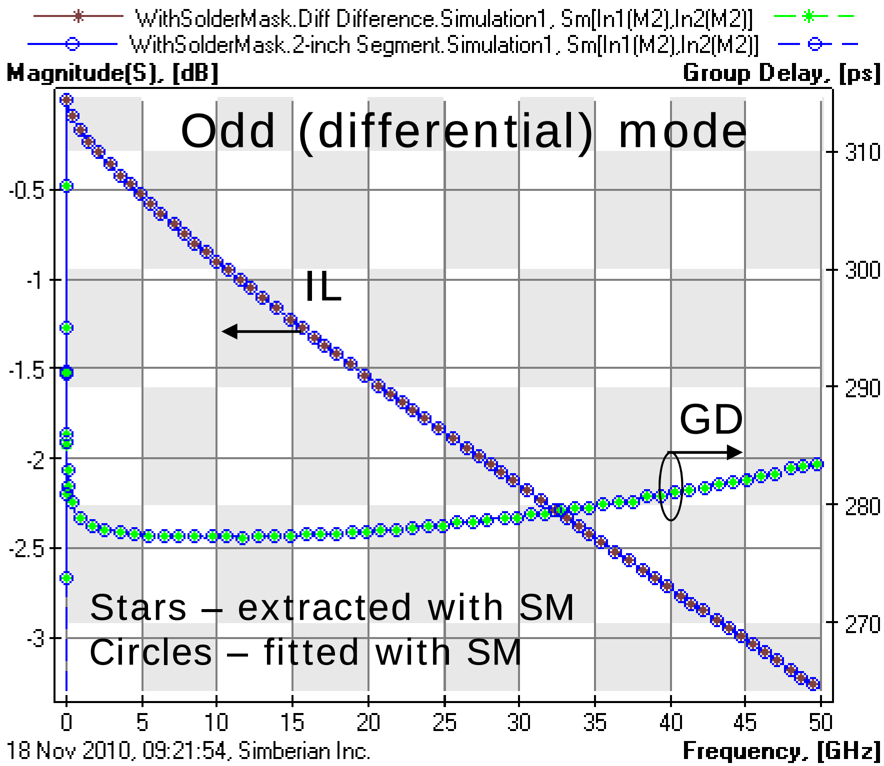


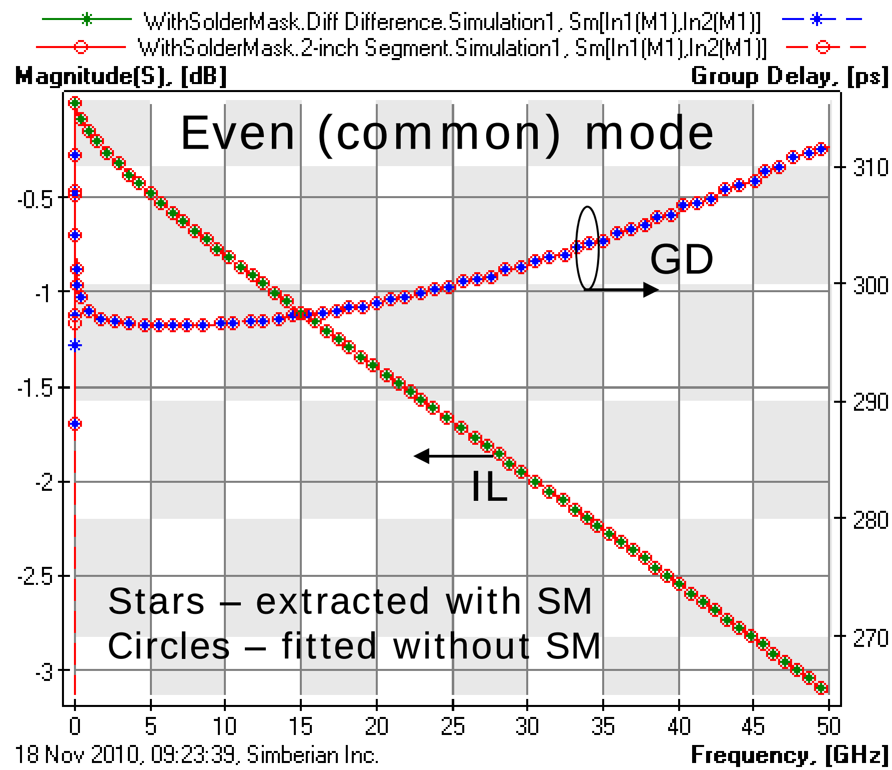
But the odd (differential) mode IL and GD cannot be simultaneously matched (left graph)!

Fitting with solder mask

Only analysis with the solder mask with different DK and LT can produce perfect match of GMS-parameters extracted from 2 fixtures and computed







The identification may be not unique – additional experiment might be needed!

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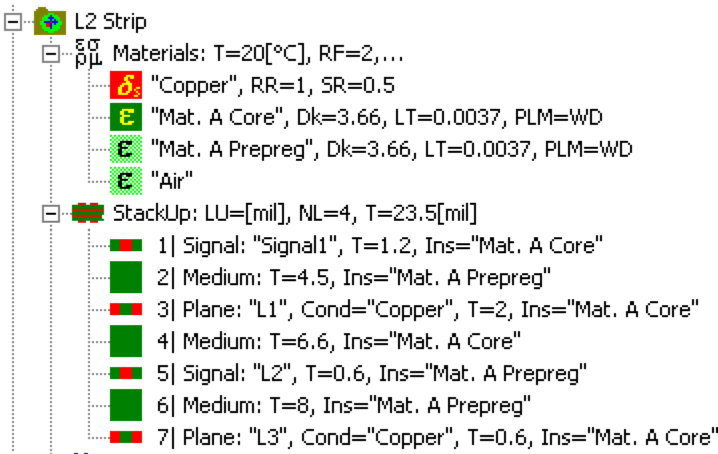
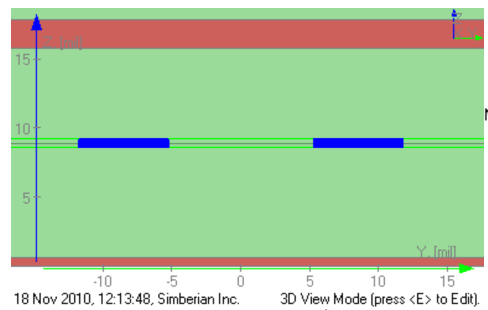
Numerical identification experiment

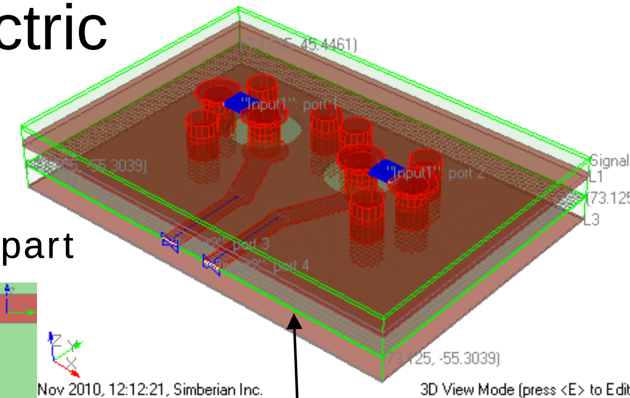
- Strip-line configuration – uniform dielectric

Materials & Stackup



6.5 mil strips 10.5 mil apart

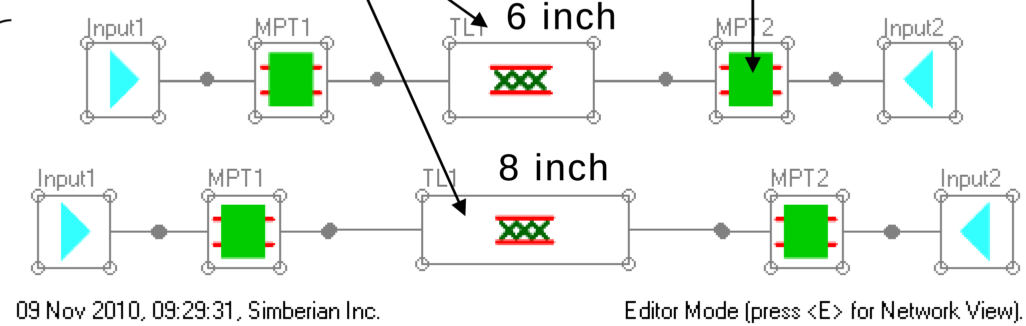




Models of the launches (all are identical)

6 inch

8 inch



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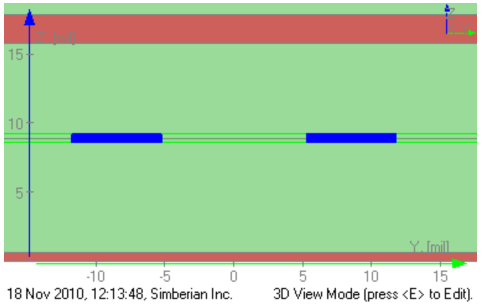
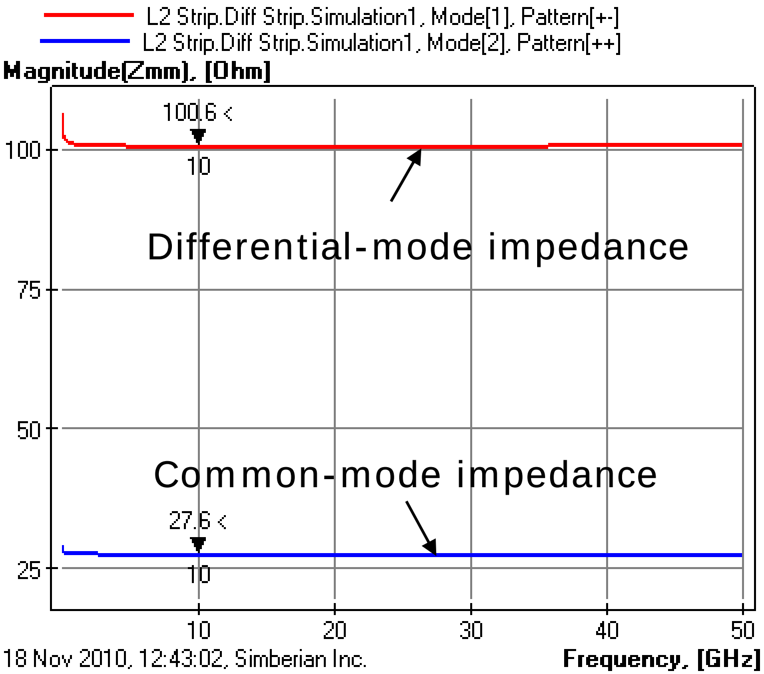
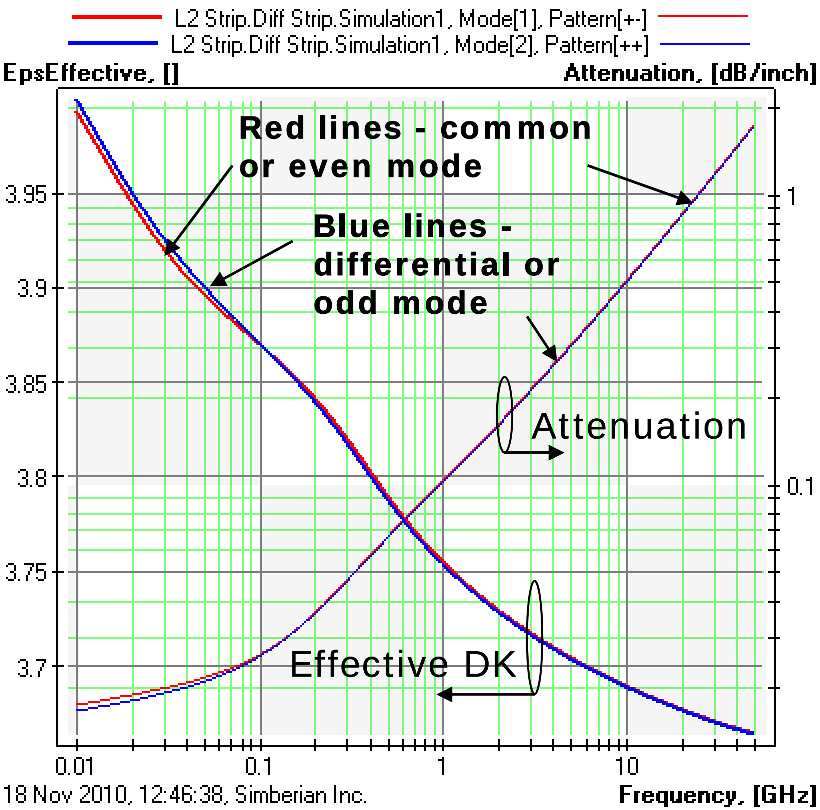
2-conductor strip-line parameters

6.5 mil strips 10.5 mil apart

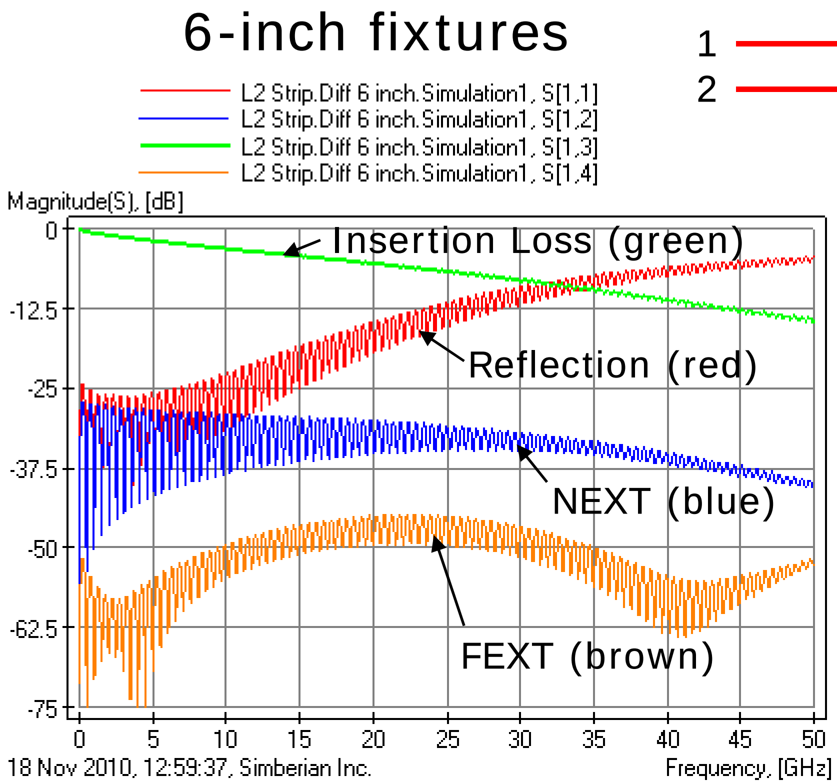




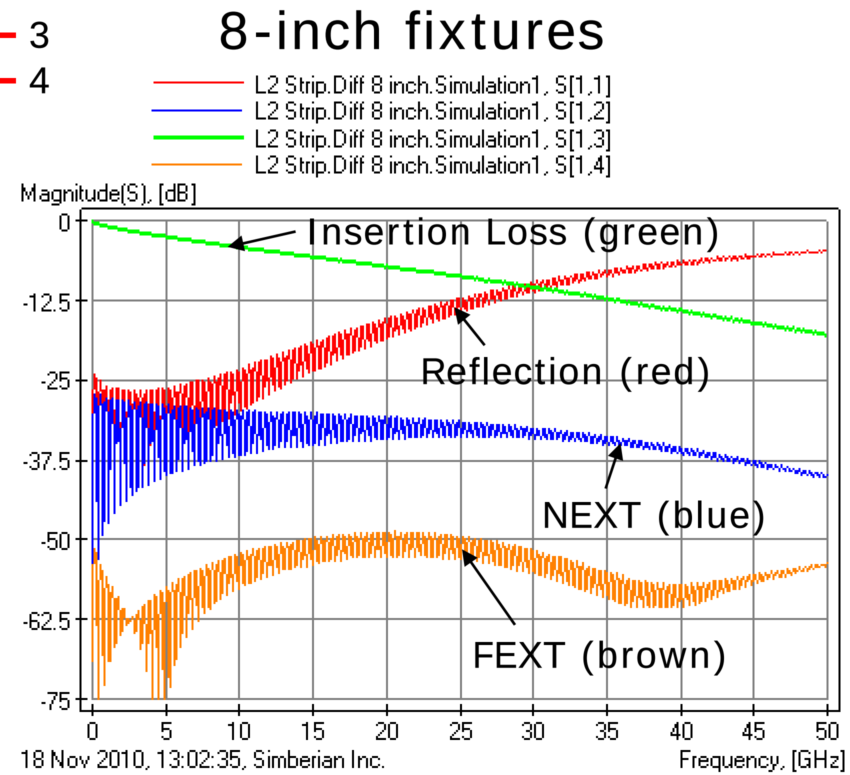
Modes have very close propagation constants and attenuation due to homogeneity of dielectric



Single-ended parameters of test fixtures

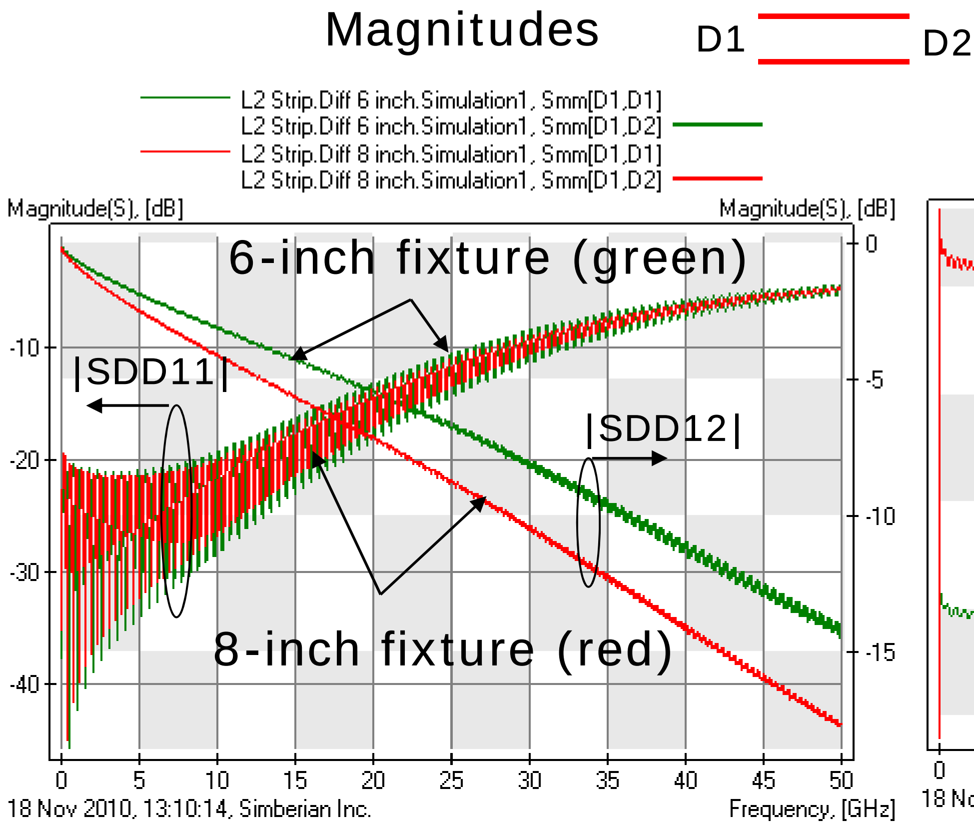


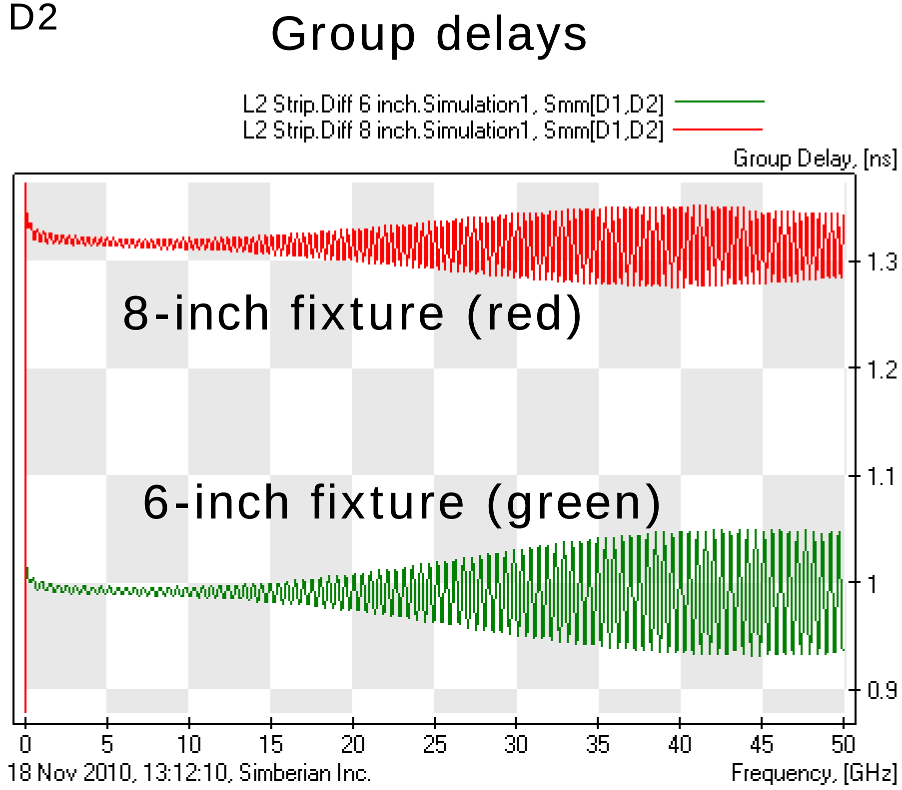
1 — 3
2 — 4



Elements of one row of S-matrix are plotted
Reflection is mostly due to the reflection at the launches
Not very convenient for the material identification!

Differential parameters of test fixtures



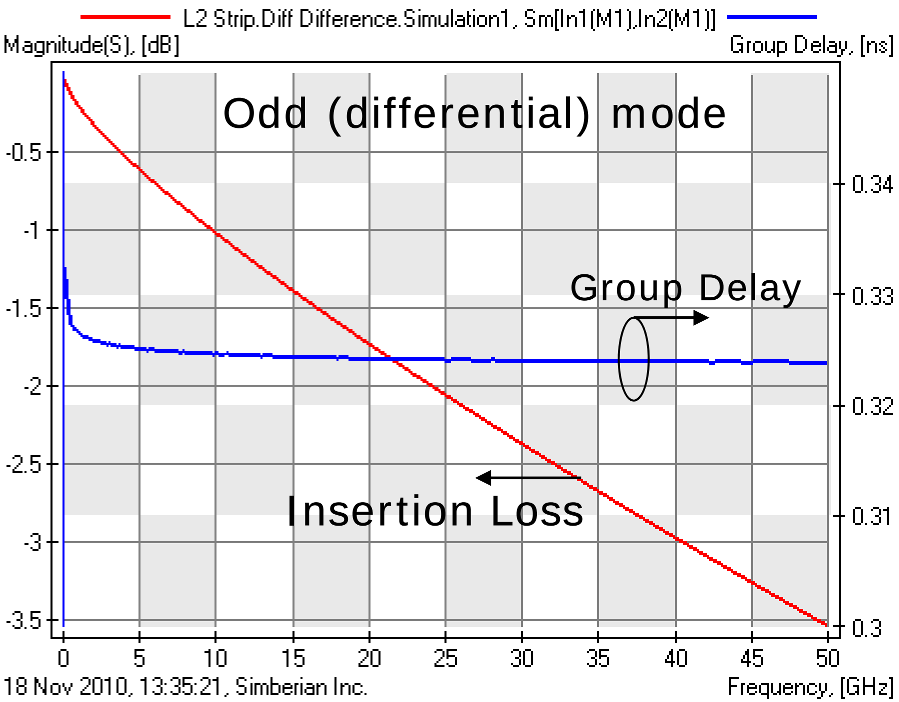


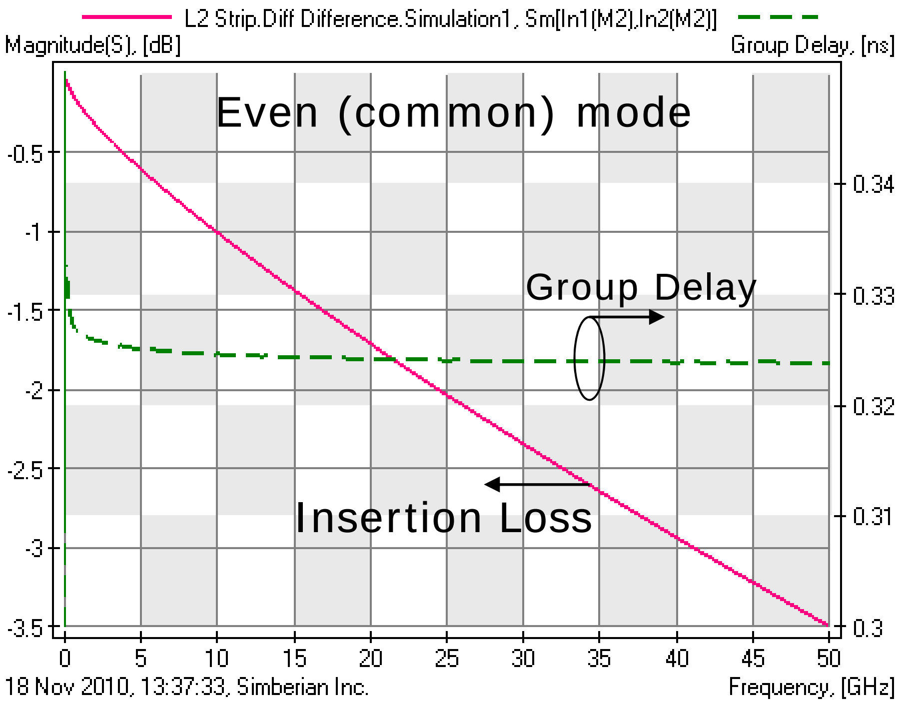
Reflection is mostly due to the reflection at the launches

Still not convenient for the material identification – oscillations and too many parameters to match!

Conversion into GMS-parameters

From S-parameters of 2 fixtures we compute GMS-parameters with just 2 non-zero elements: Common and differential GM transmission parameters



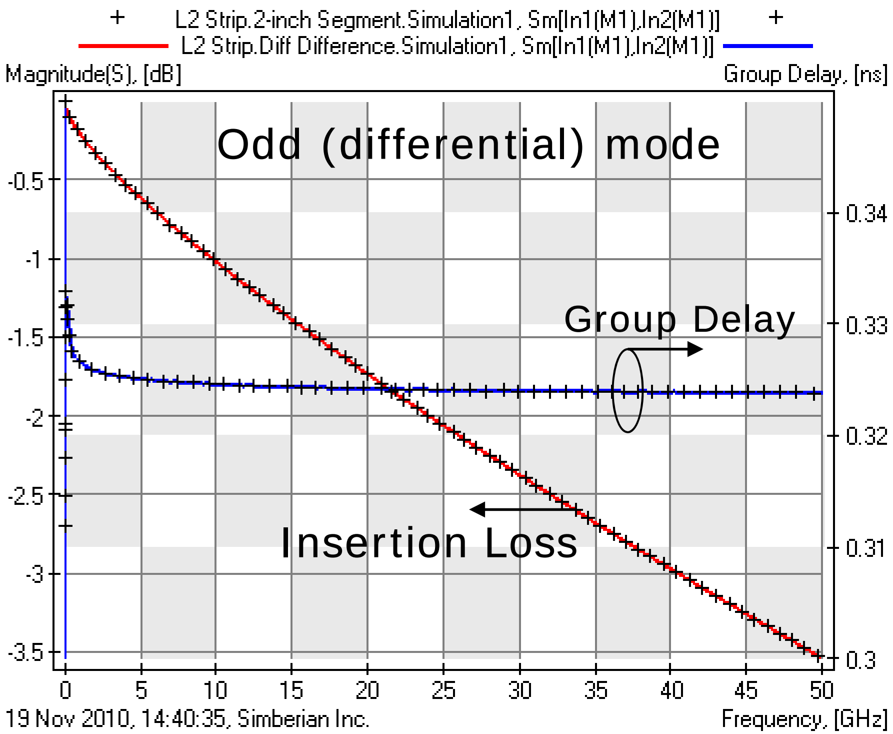


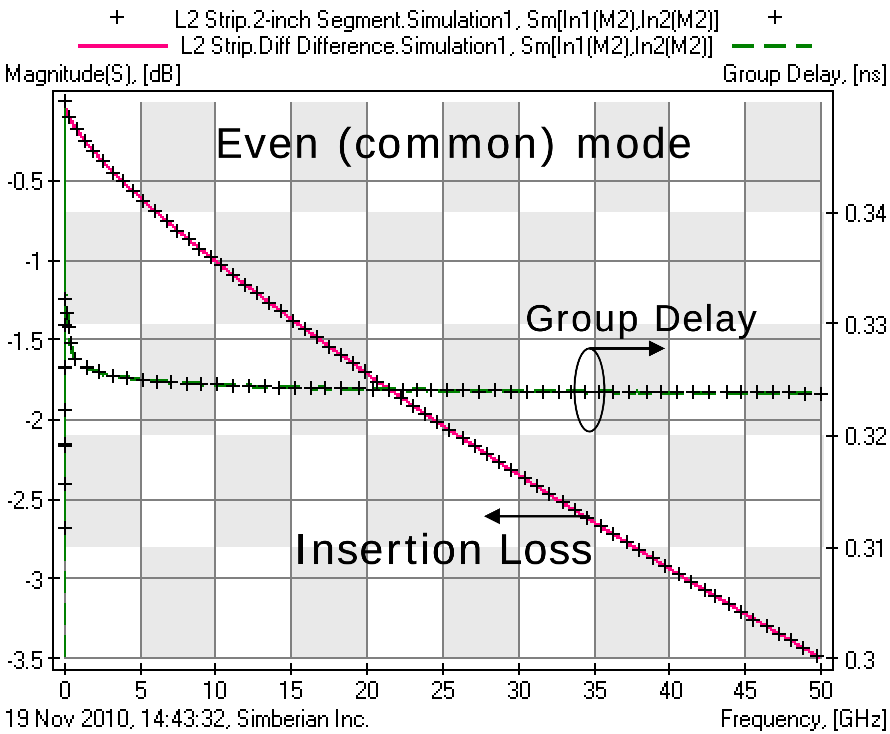
Very convenient for the material parameters identification!

IL and GD are almost identical for both modes – non-identity can be used as the metric of dielectric non-homogeneity

Identification with two modes (IL&GD)

GM transmission of 2-inch segment (black pluses) match GM transmission extracted from S-parameters of 2 test fixtures (lines)



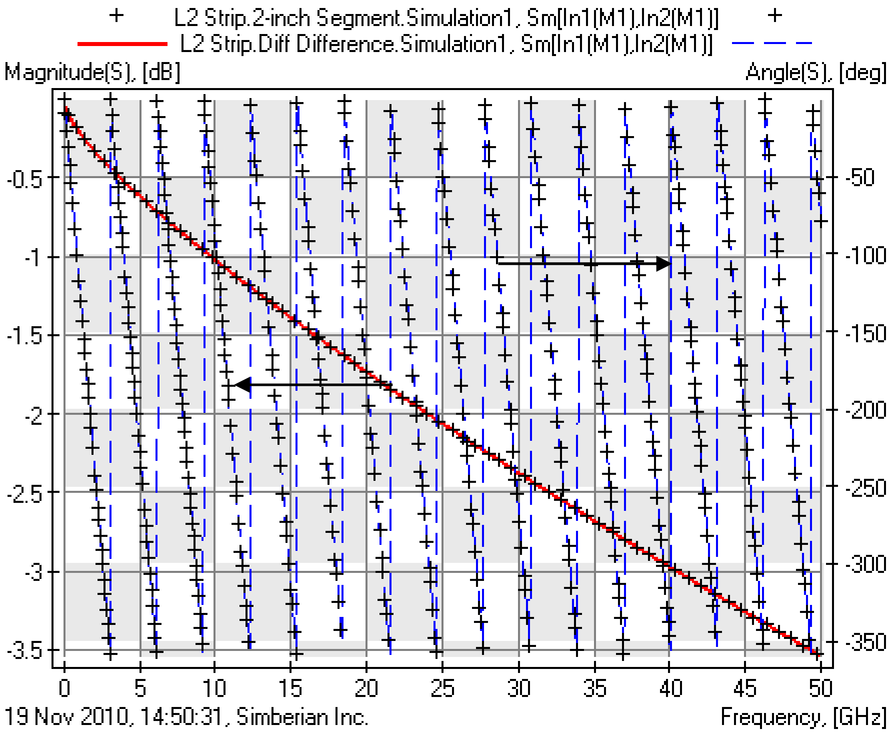


The results are independent of cross-section and launch construction as long as the widths and launches are identical in the test fixtures!

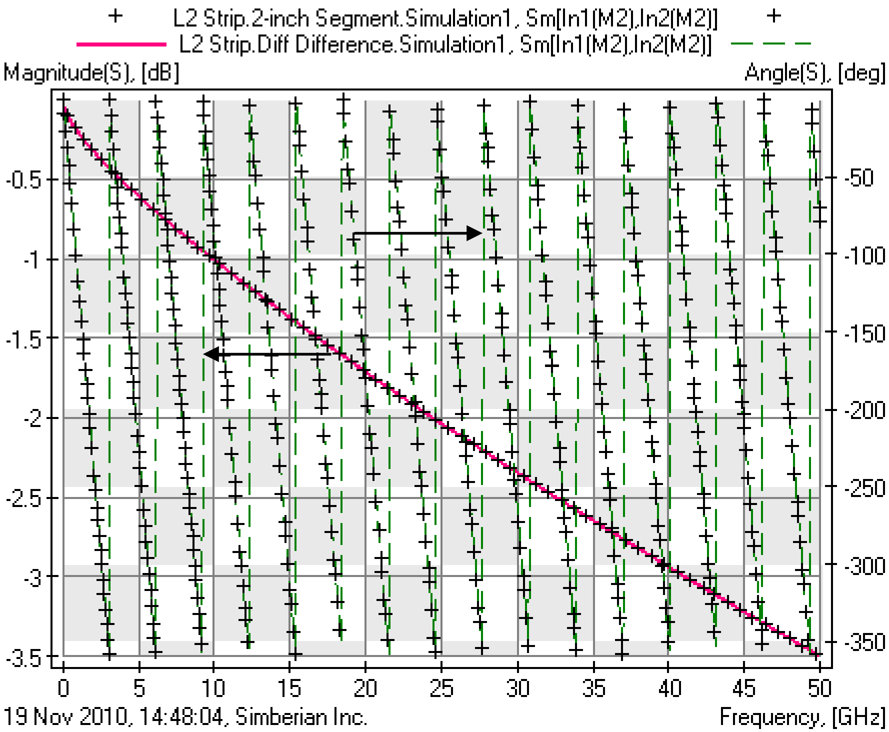
Identification with two modes (IL&PD)

GM transmission of 2-inch segment (black pluses) match GM transmission extracted from S-parameters of 2 test fixtures (lines)

Odd (differential) Modes:



Even (common) Modes:



The results are independent of cross-section and launch construction as long as the widths and launches are identical in the test fixtures!

Overview

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- Effect of bends in coupled strip-lines on GMS-parameters
- Conclusion

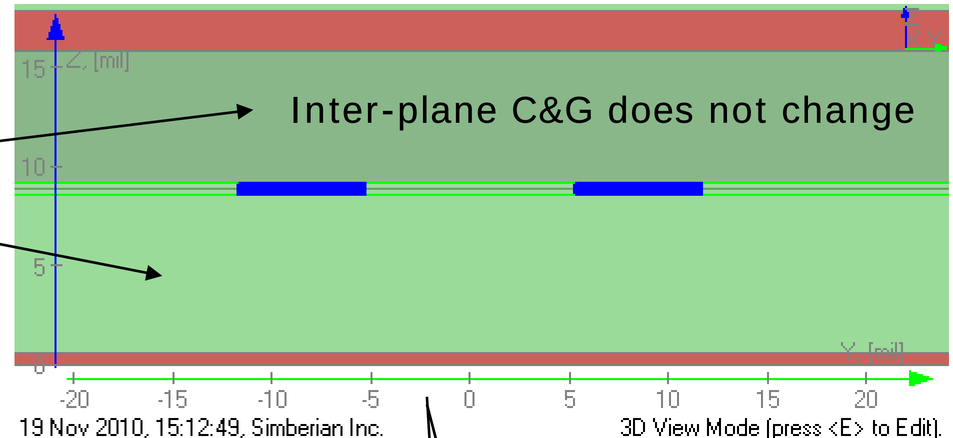
What if one layer has slightly different dielectric properties?

- Strip-line with inhomogeneous dielectric

Materials & Stackup

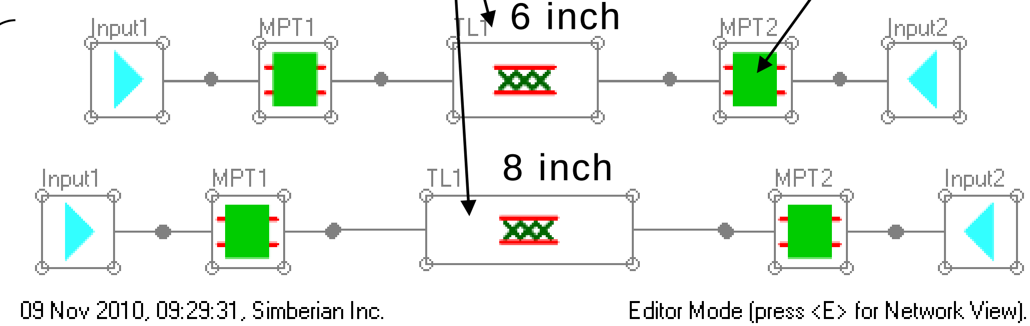
L2 2 Dielectrics
- Materials: T=20[°C], RF=2,…
  - "Copper", RR=1, SR=0.5
  - "Mat. A Core", Dk=4.2, LT=0.0031, PLM=WD
  - "Mat. A Prepreg", Dk=3.33, LT=0.004, PLM=WD
  - "Air"
- StackUp: LU=[mil], NL=4, T=23.5[mil]
  - 1| Signal: "Signal1", T=1.2, Ins="Mat. A Core"
  - 2| Medium: T=4.5, Ins="Mat. A Prepreg"
  - 3| Plane: "L1", Cond="Copper", T=2, Ins="Mat. A Core"
  - 4| Medium: T=6.6, Ins="Mat. A Core"
  - 5| Signal: "L2", T=0.6, Ins="Mat. A Prepreg"
  - 6| Medium: T=8, Ins="Mat. A Prepreg"
  - 7| Plane: "L3", Cond="Copper", T=0.6, Ins="Mat. A Core"

6.5 mil strips 10.5 mil apart



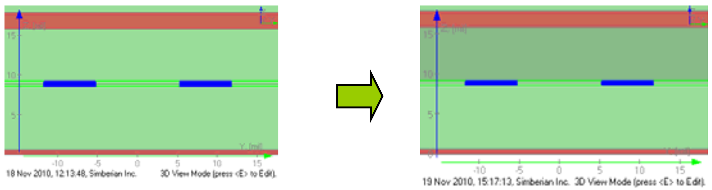
Models of the launches (all are identical)

From simulated S-parameters of 2 structures we extract GMS-parameters of 2-inch coupled line segment and compare it with the GMS-parameters of 2-inch segment computed directly

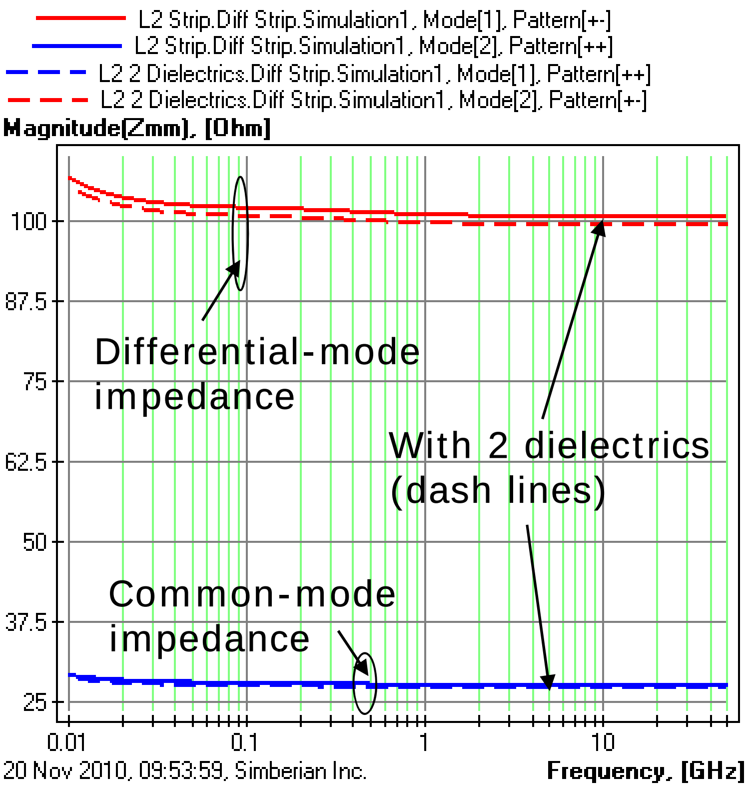


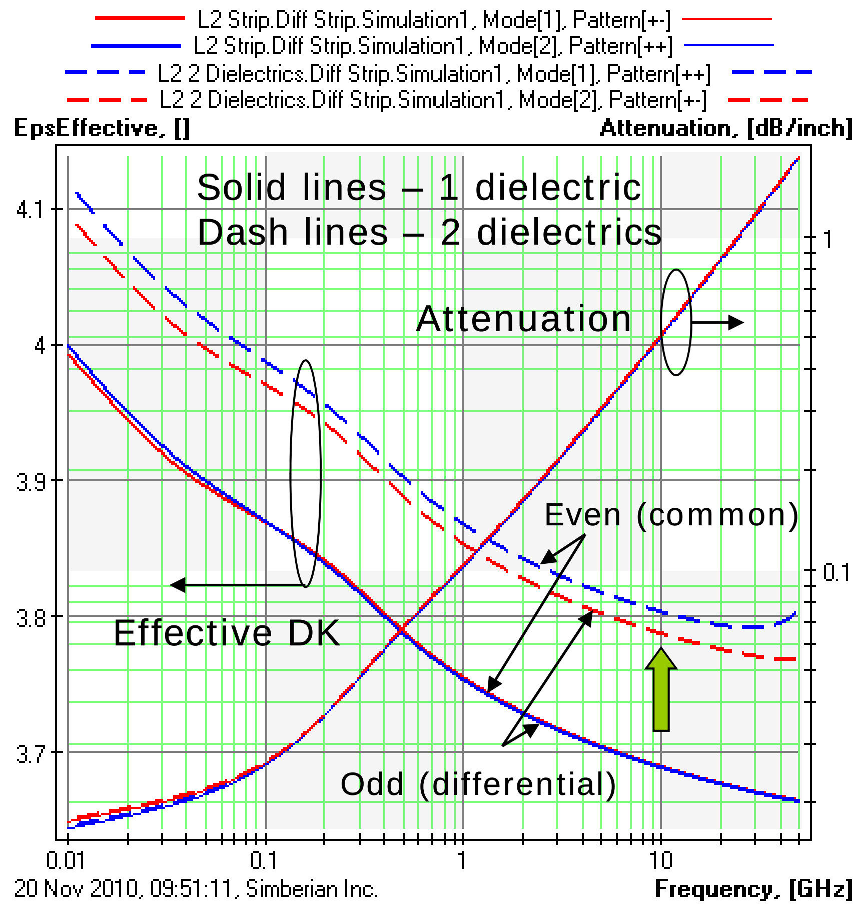
Effect of dielectric difference on modal parameters of 2-conductor t-line

6.5 mil strips 10 mil apart



2 different dielectrics have mostly effect on the propagation constant (Eps Effective)





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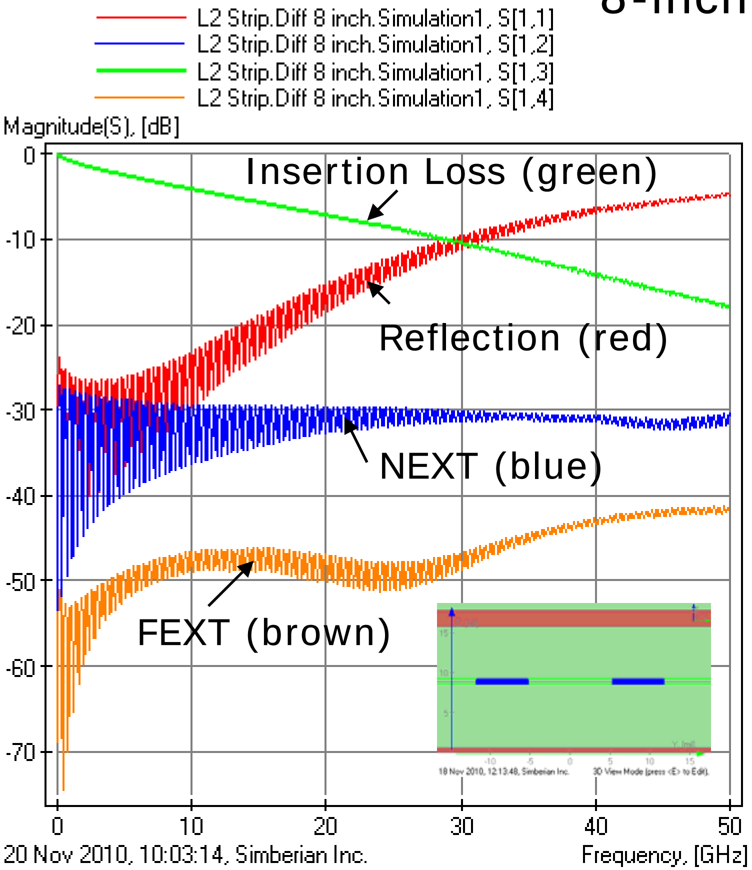
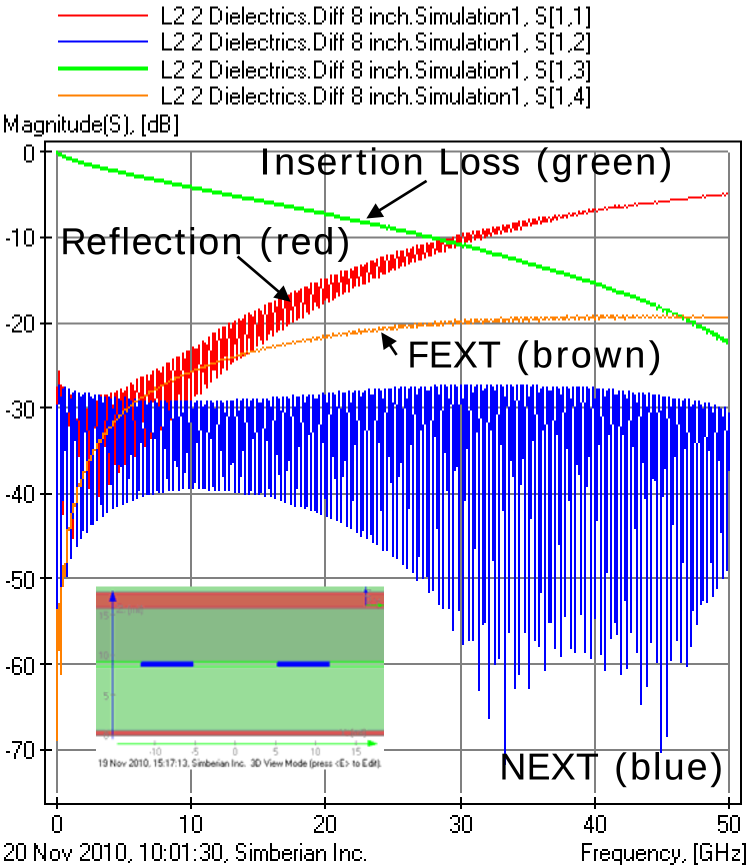
Effect of dielectric difference on SE S-parameters of test fixtures

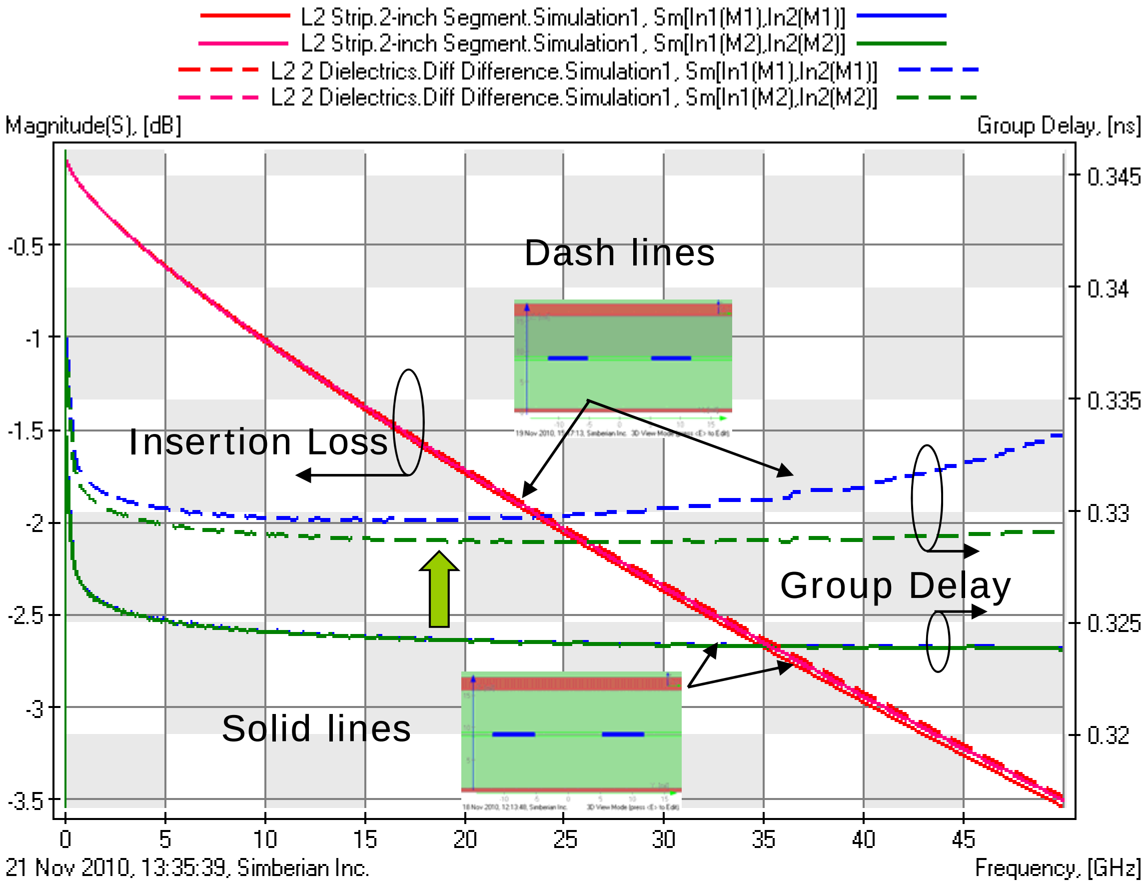
8-inch test fixture





More reflection due to mismatch at the transition and more FEXT due to dielectric non-homogeneity

Effect of dielectric difference on GMS-parameters



Difference is relatively small (about 5 ps at 50 GHz) and may be fitted with 1 dielectric for practical purpose

There is difference in group delay of two modes in structure with in-homogeneous dielectrics that can be interpreted as anisotropy of dielectric

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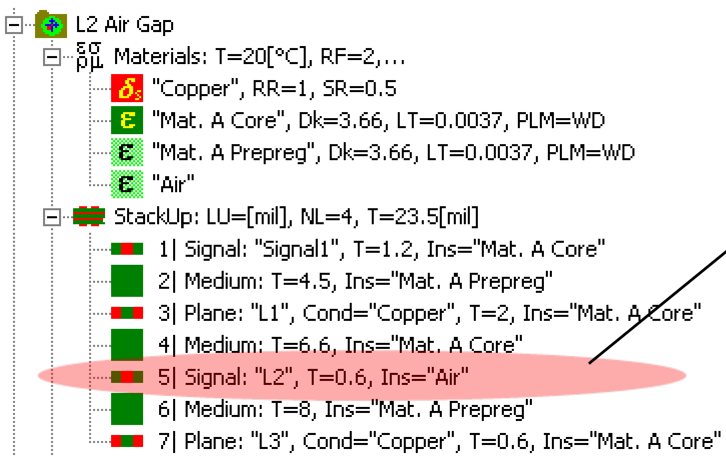
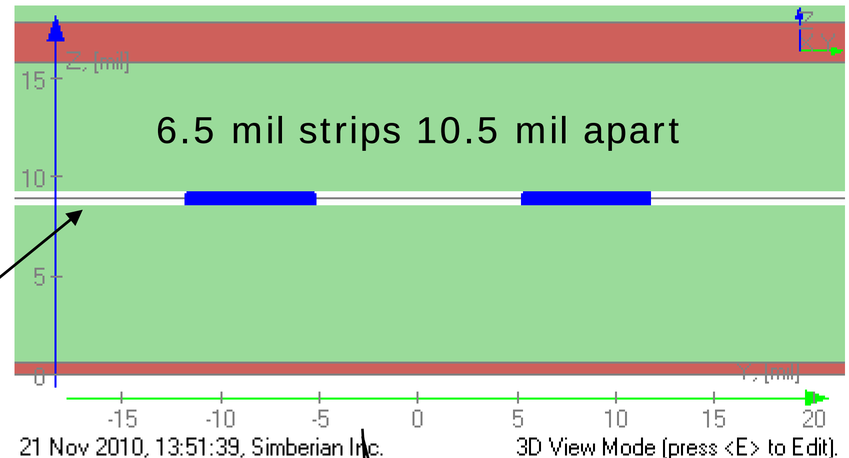
What if there is a gap between dielectric layers filled with air?

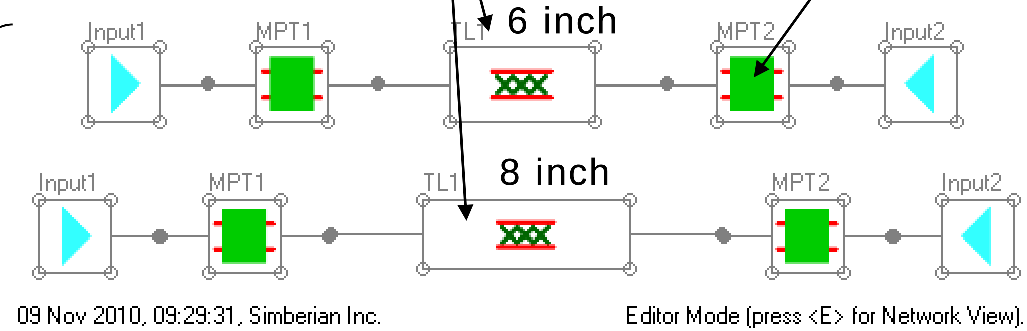
- Strip-line with inhomogeneous dielectric

Materials & Stackup



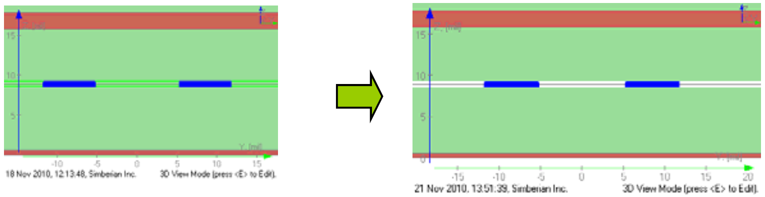


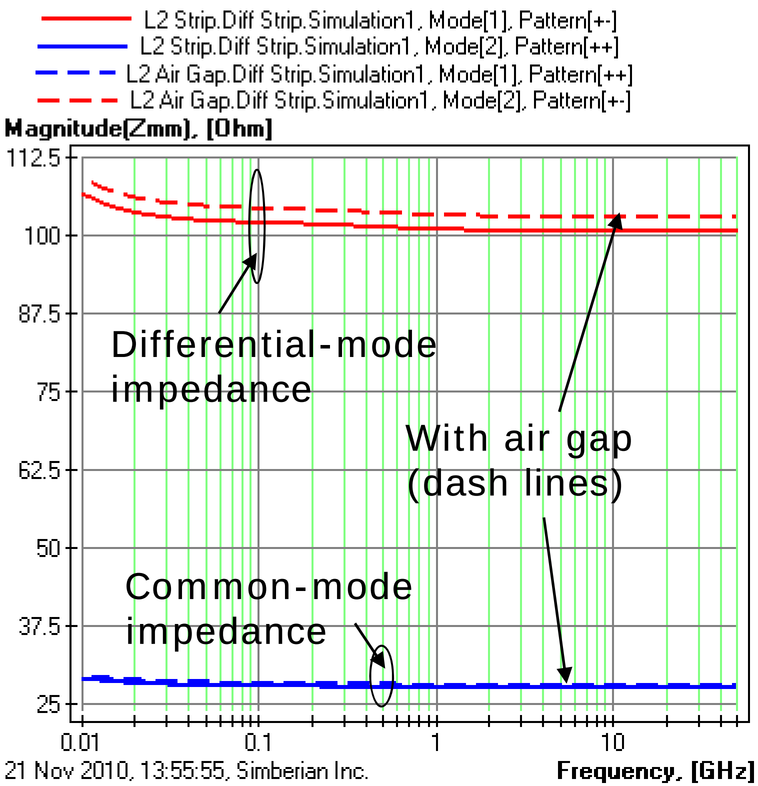
From simulated S-parameters of 2 structures we extract GMS-parameters of 2-inch coupled line segment and compare it with the GMS-parameters of 2-inch segment computed directly



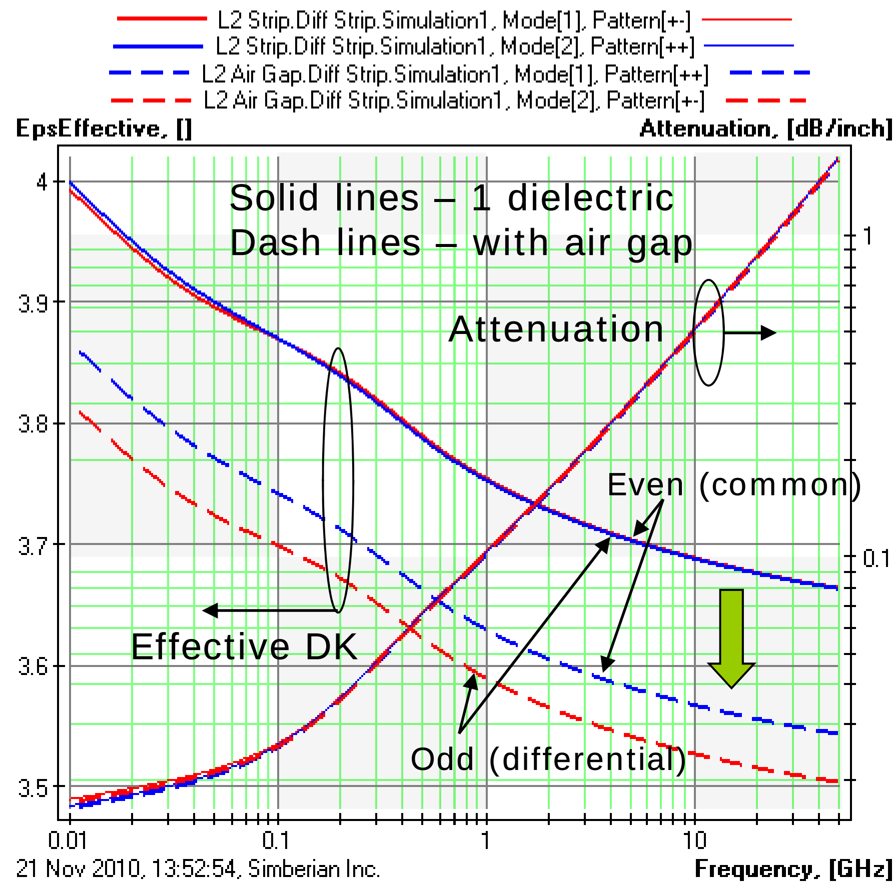
Effect of air gap on modal parameters of 2-conductor t-line

6.5 mil strips 10 mil apart





Air gap has mostly effect on the propagation constant (Eps Effective)



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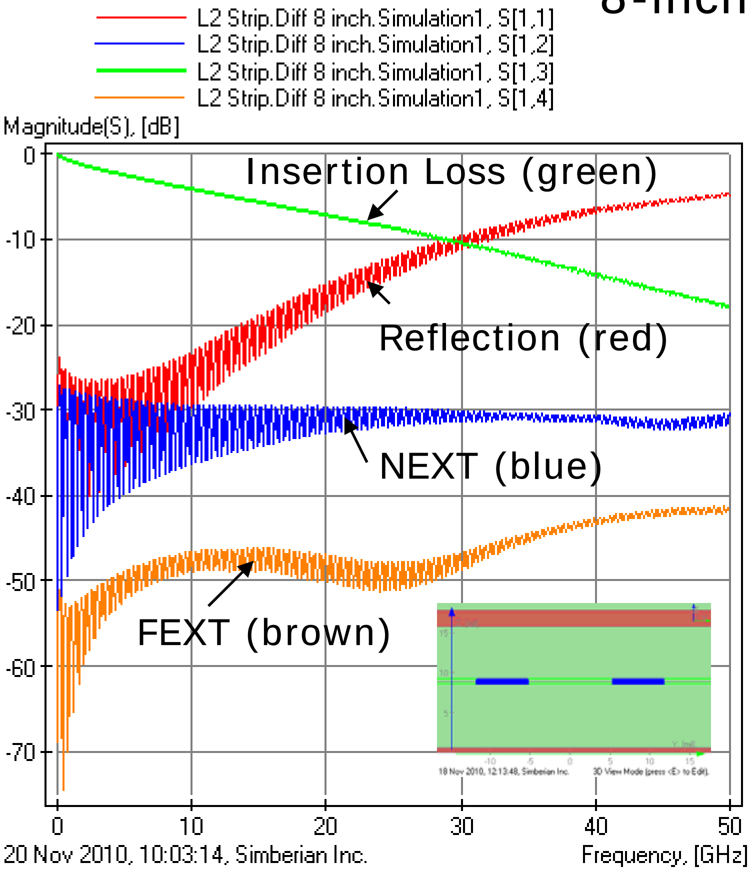
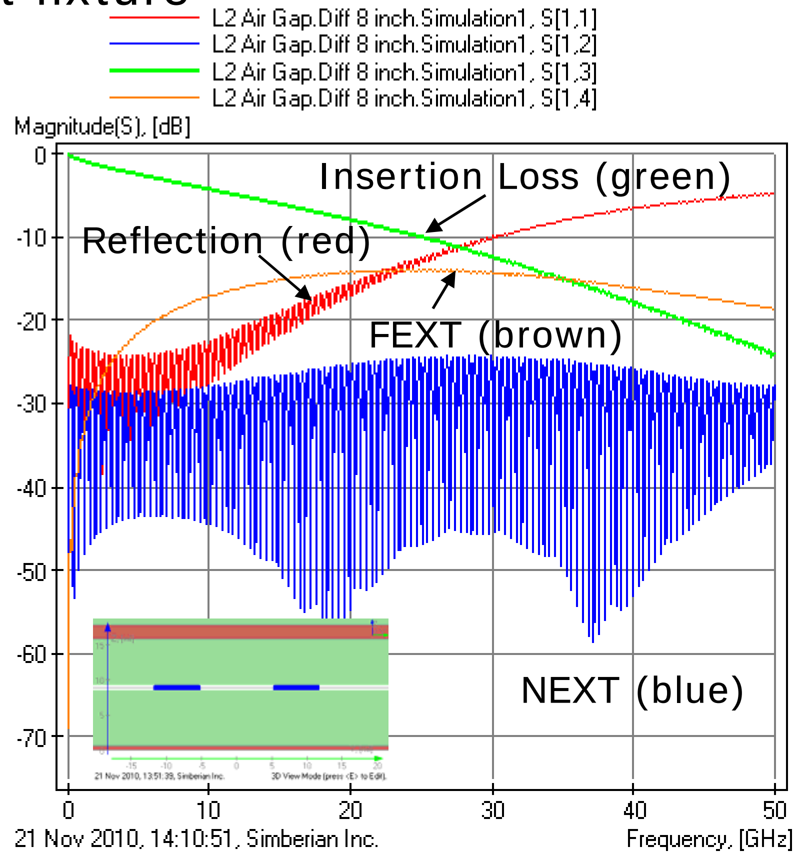
Effect of air gap on SE S-parameters of test fixtures

8-inch test fixture





More reflection due to impedance mismatch
A lot more FEXT due to dielectric non-homogeneity

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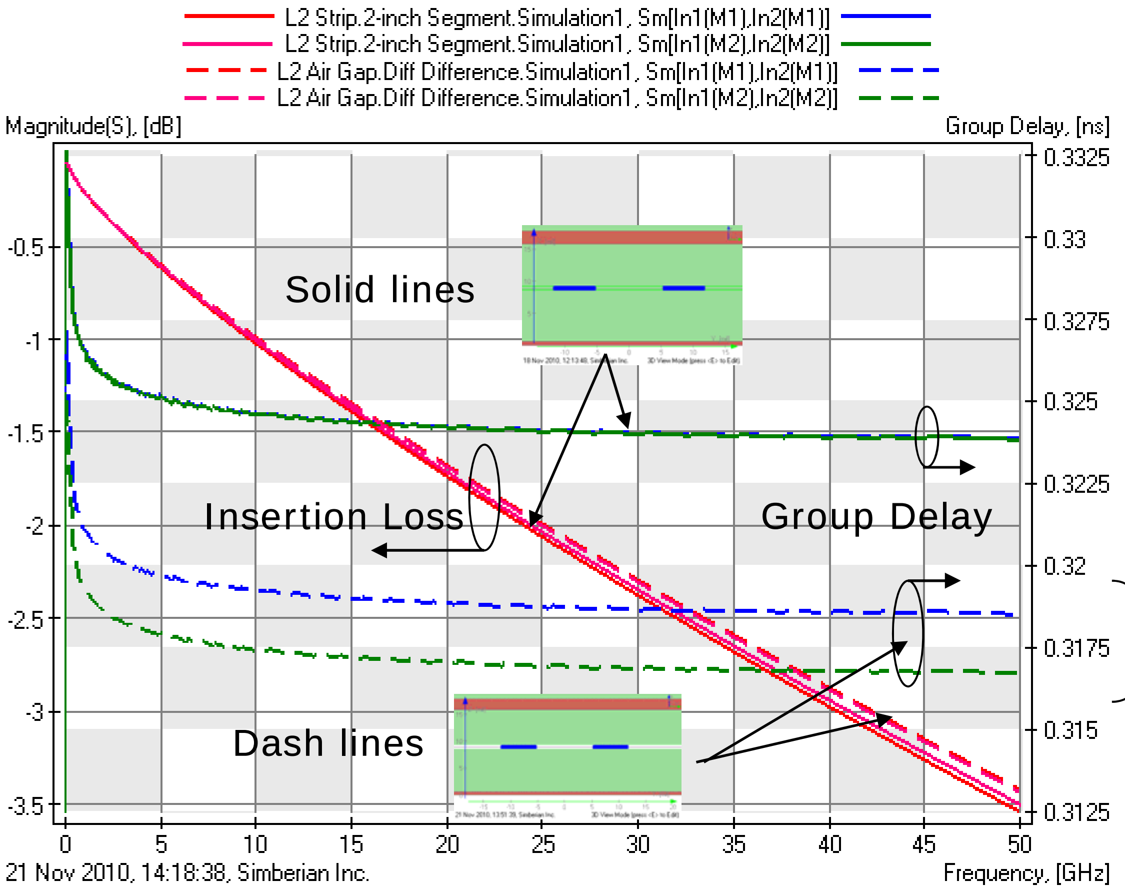
Effect of dielectric difference on GMS-parameters



Difference is small (about 2 ps) and may be fitted with 1 dielectric for practical purpose

There is difference in group delay of two modes in structure with the air gap that can be interpreted as anisotropy of dielectric

Overview

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- Effect of bends in coupled strip-lines on GMS-parameters
- Conclusion

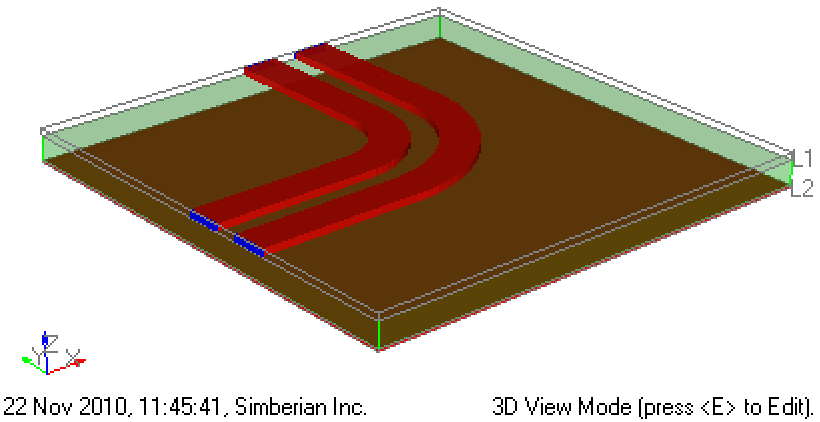
What if microstrip lines in test fixtures are not straight?

- Numerical experiment to investigate effect of bends

Materials & Stackup

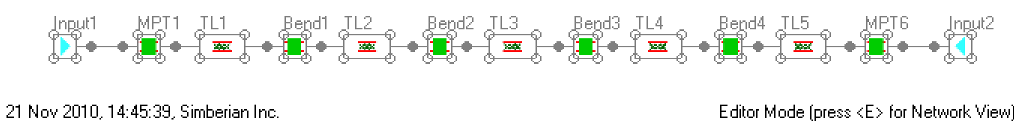
- L1 Microstrip
  - Materials: T=20[°C], RF=2,...
    - "Copper", RR=1, SR=0.5
    - "Mat. A Core", Dk=3.66, LT=0.0037, PLM=WD
    - "Mat. A Prepreg", Dk=3.66, LT=0.0037, PLM=WD
    - "Air"
  - StackUp: LU=[mil], NL=2, T=9.2[mil]
    - 1| Signal: "L1", T=2, Ins="Air", Cond="Copper"
    - 2| Medium: T=6.6, Ins="Mat. A Core"
    - 3| Plane: "L2", Cond="Copper", T=0.6, Ins="Mat. A Core"

Instead of straight line let's try to use lines with multiple arched bends

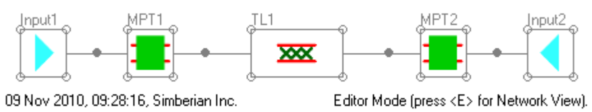


From simulated S-parameters of 2 structures with or without bends we extract GMS-parameters of 2-inch segment and compare it with the GMS-parameters of 2-inch segment computed directly

6 and 8 inch fixtures with 4 bends



6 and 8 inch fixtures without bends



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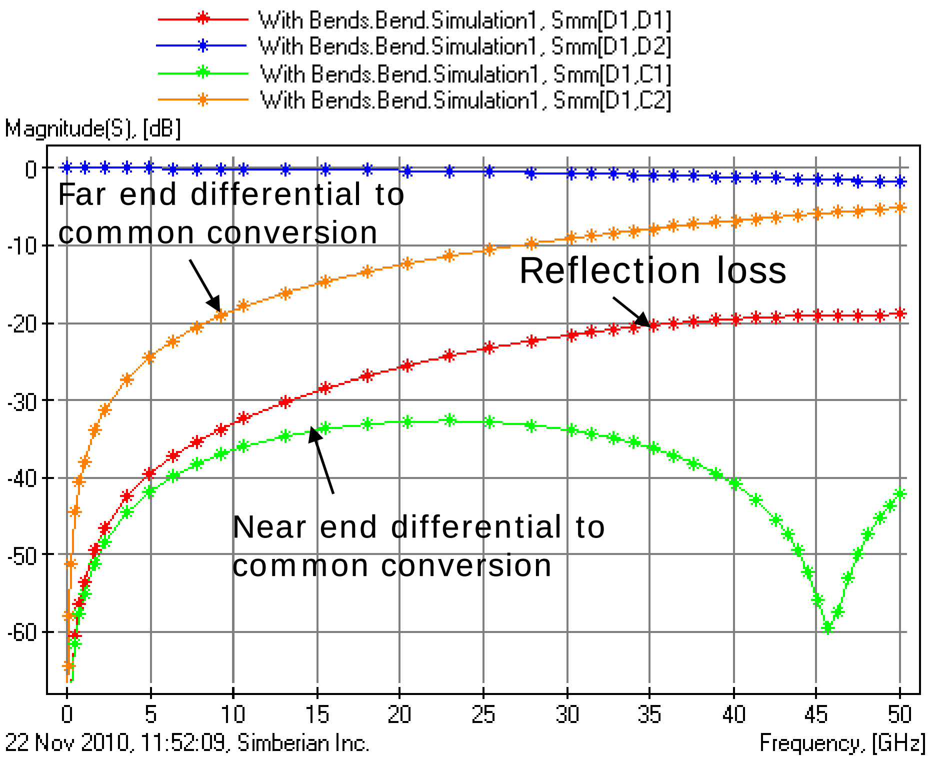
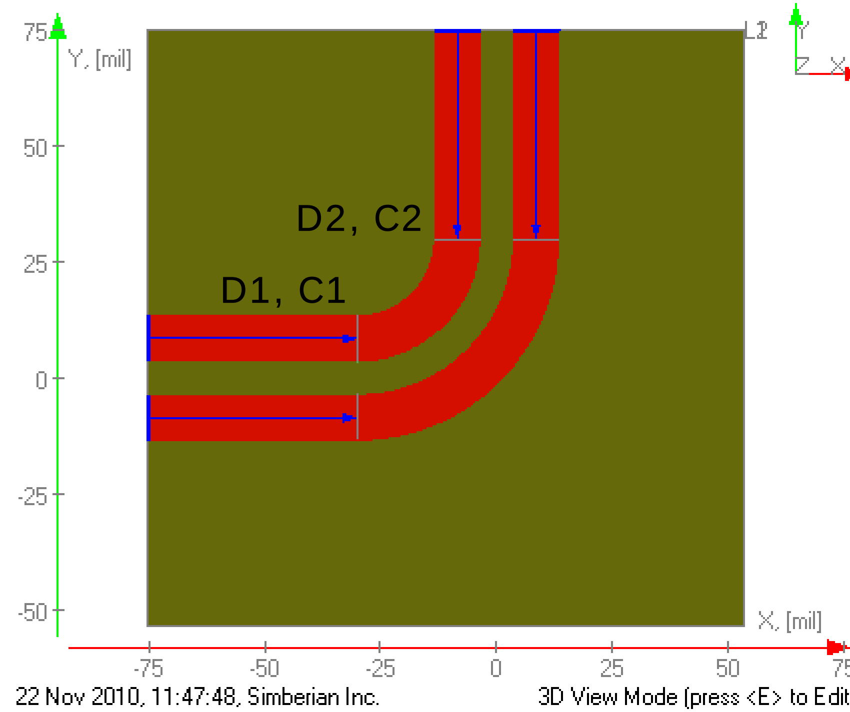
S-parameters of microstrip bend

- Relatively small differential reflection – below -20 dB up to 30 GHz
- Large differential to common mode conversion



Bends in 10-mil microstrip lines 7 mil apart, 30 mil radius along the center (47.12 mil of additional length)

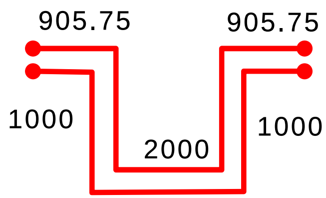


The mode conversion in microstrip line cannot be compensated by matching number of left and right turns – see App Notes 2009_01 and 2009_02

Test fixtures for the extraction

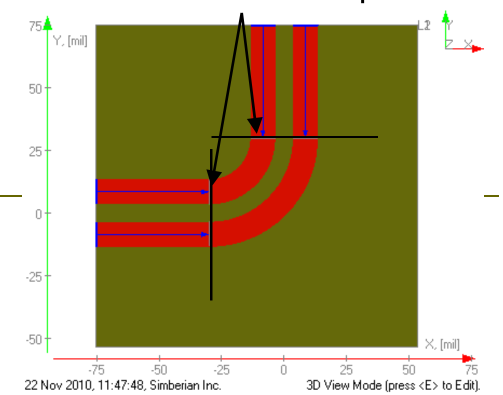
6 inch straight

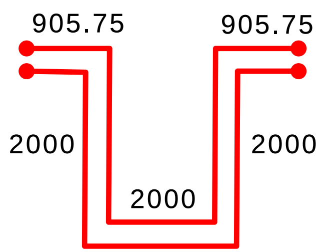
8 inch straight



6 inch with 4 bends (2 left and 2 right)

Bend reference planes



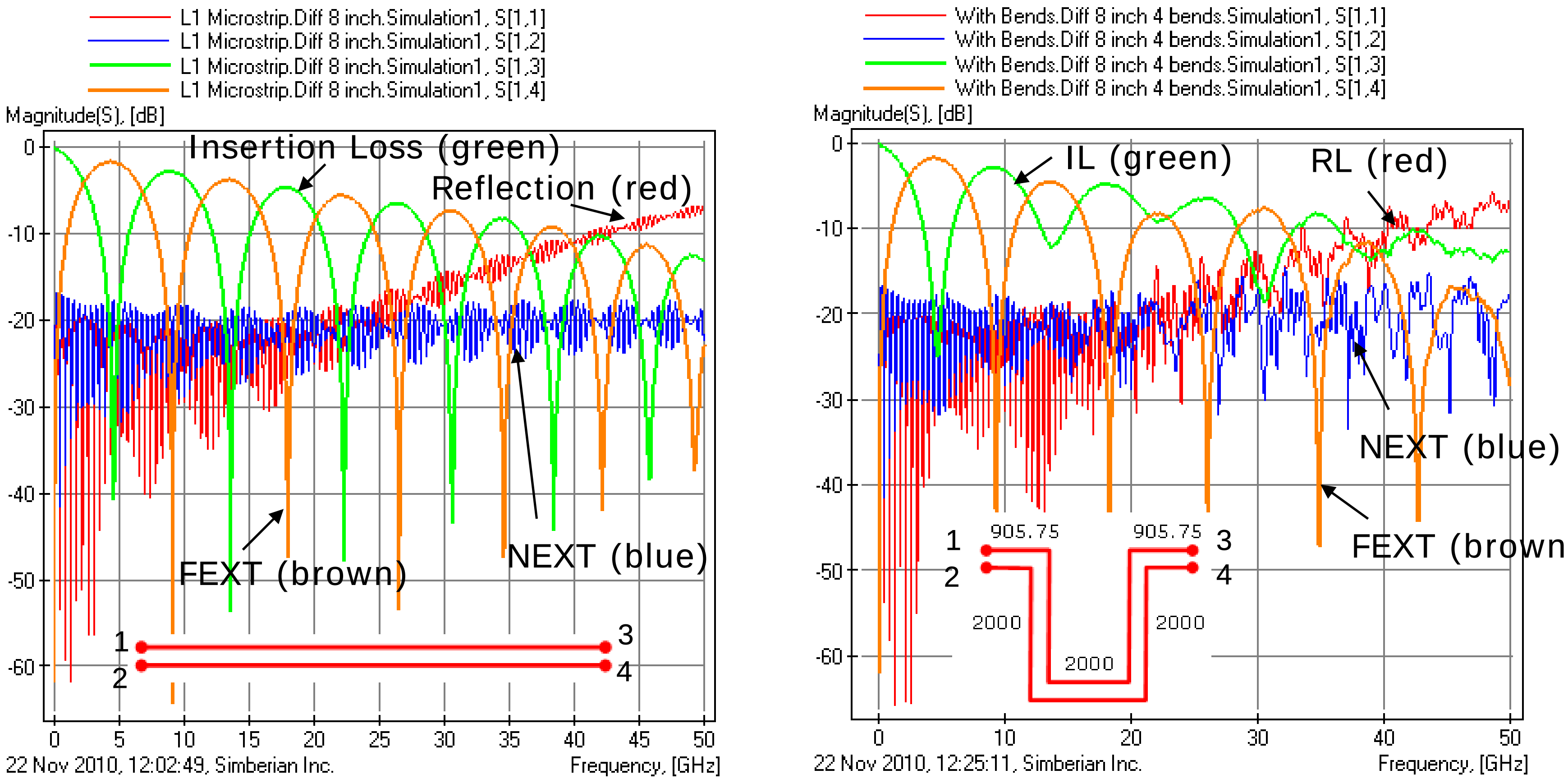


8 inch with 4 bends (2 left and 2 right)

Lengths of structures with bends are adjusted to have 6 and 8 inches along the central lines

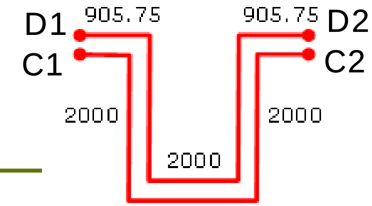
Effect of bends on SE S-parameters of test fixtures

8-inch test fixture

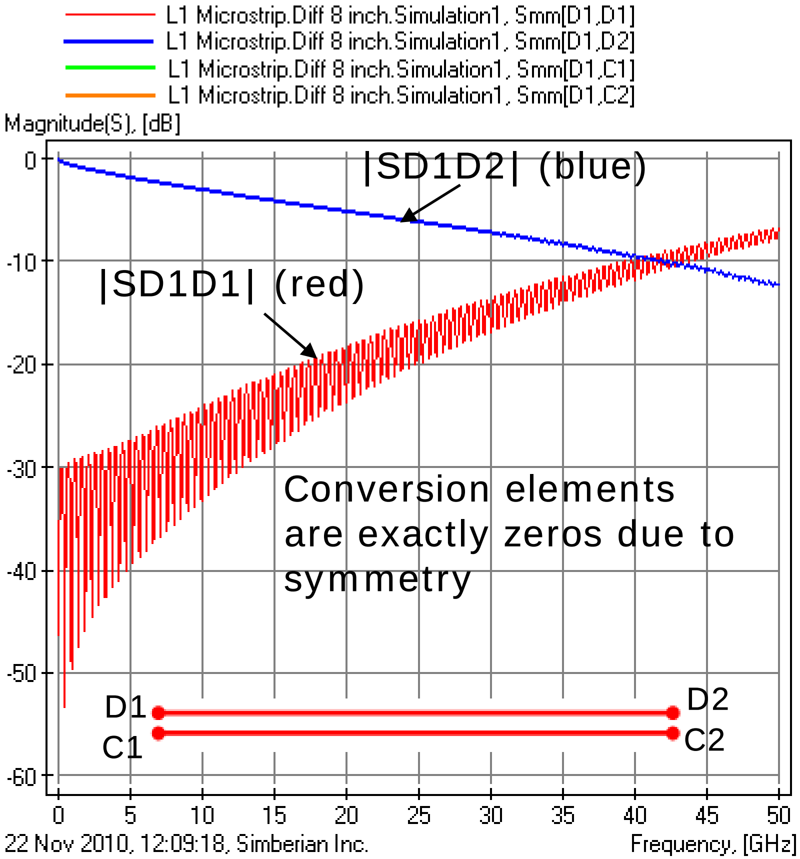


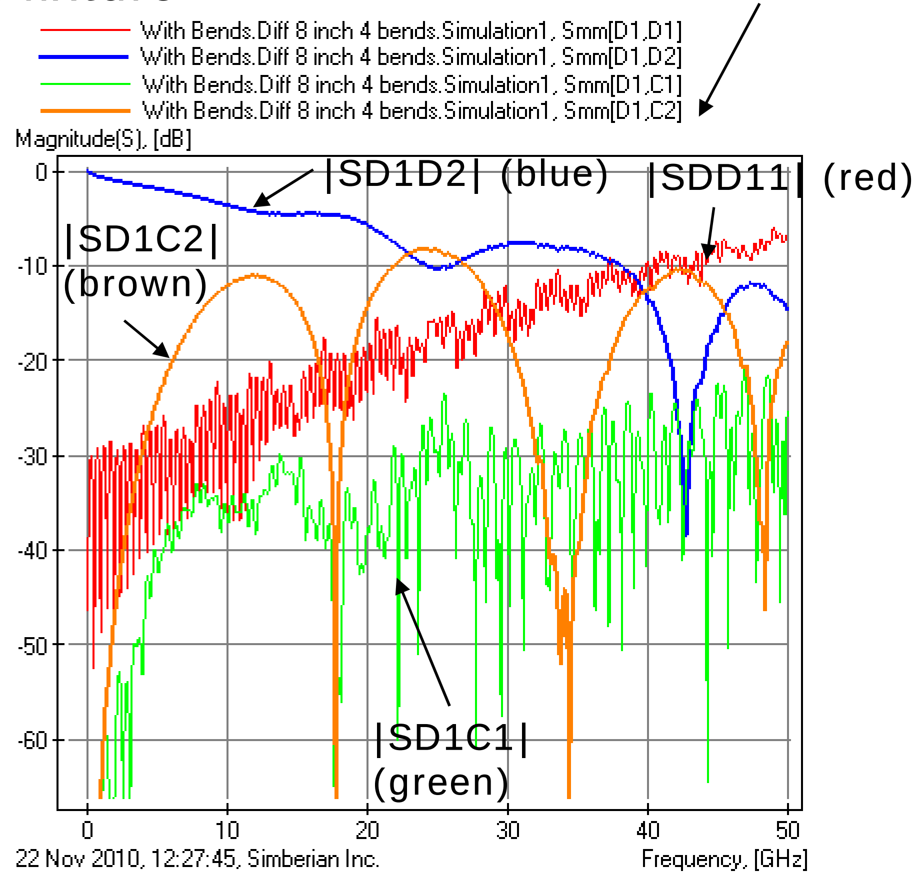
Visible distortion all SE parameters (similar for 6-inch fixture)

Effect of bends on mixed-mode S-parameters of test fixtures



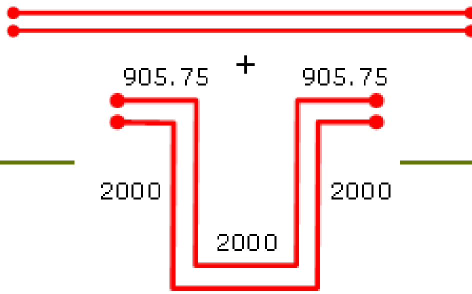
8-inch test fixture



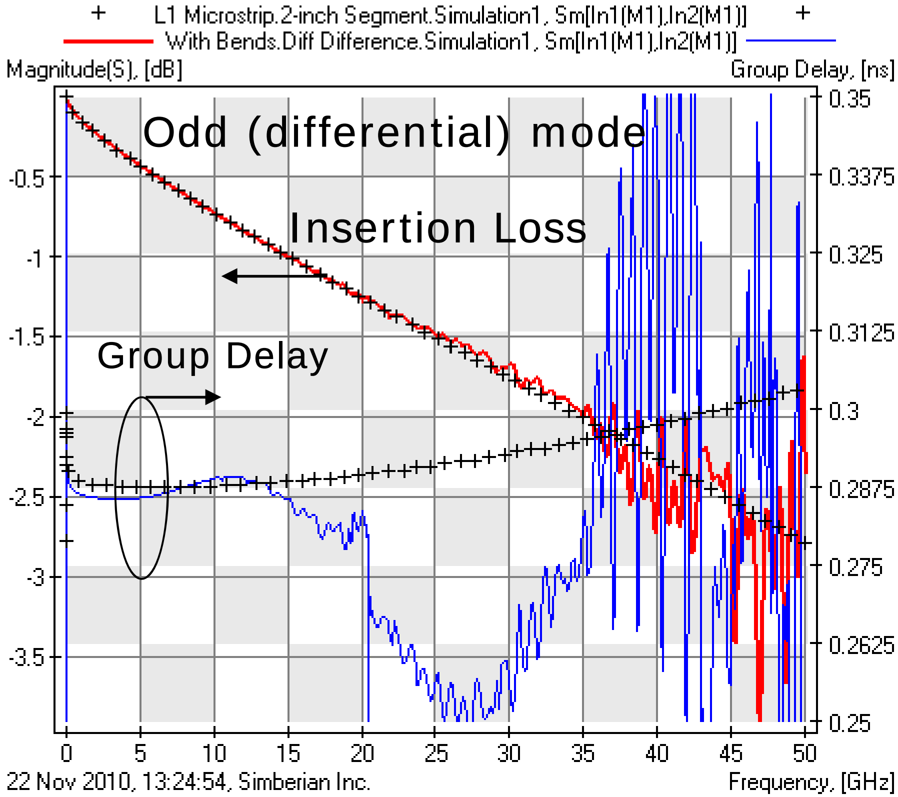


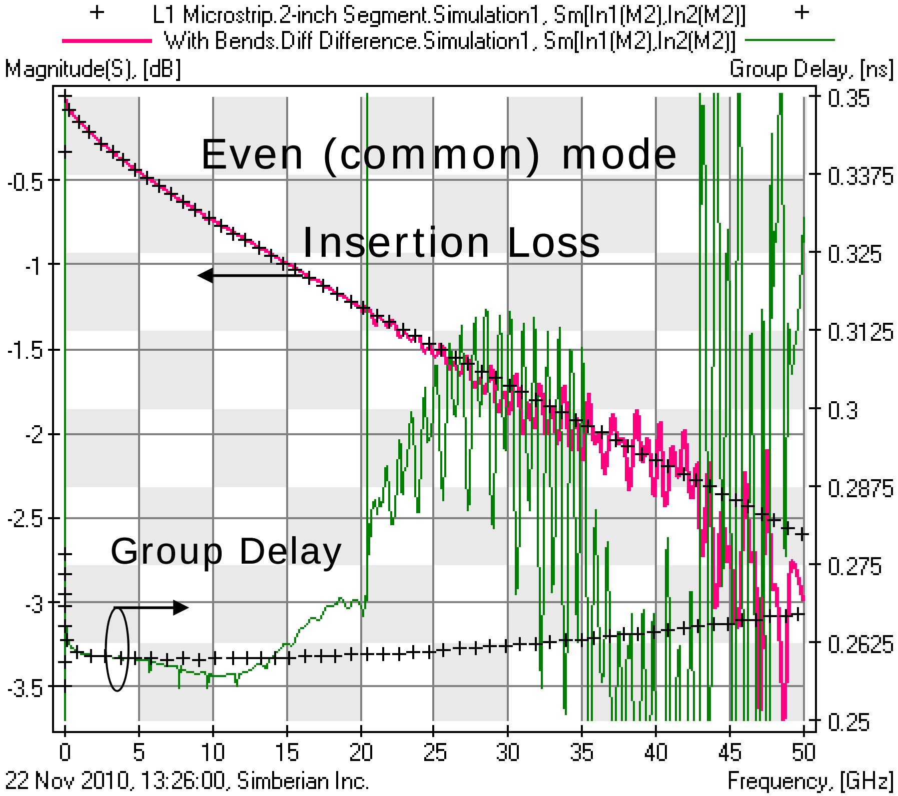
More ripples in reflection, small near-end and very large far-end differential to common mode conversion due to bends

Effect of bends on extracted GMS-parameters



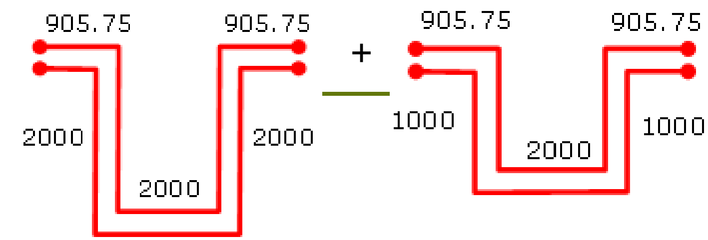
2-inch segment - black pluses;
Extracted from 2 test fixtures – solid lines



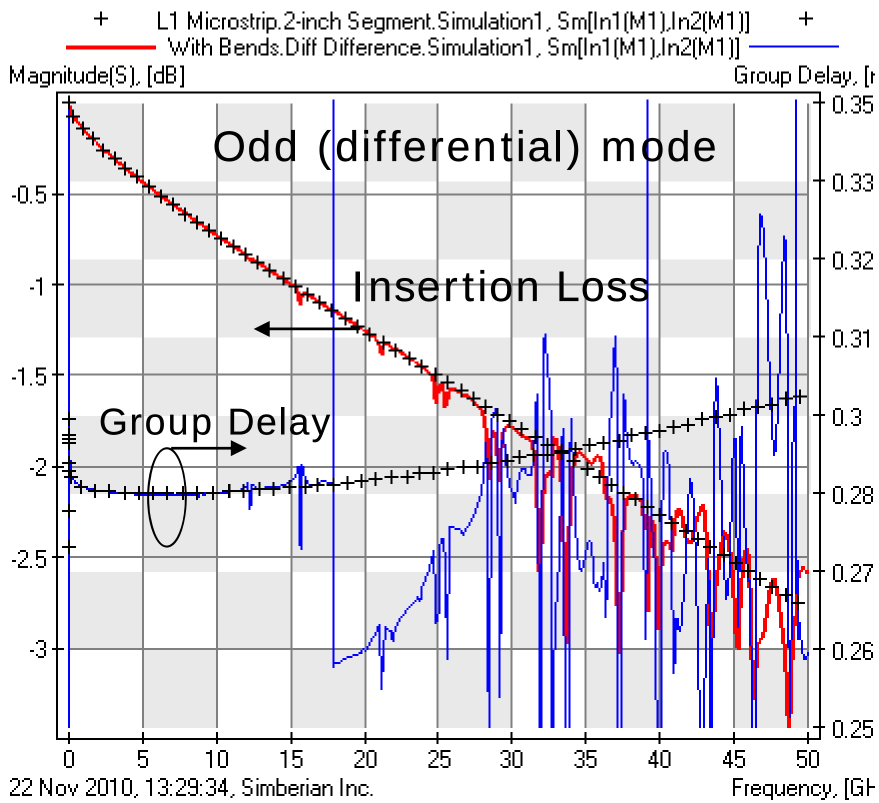


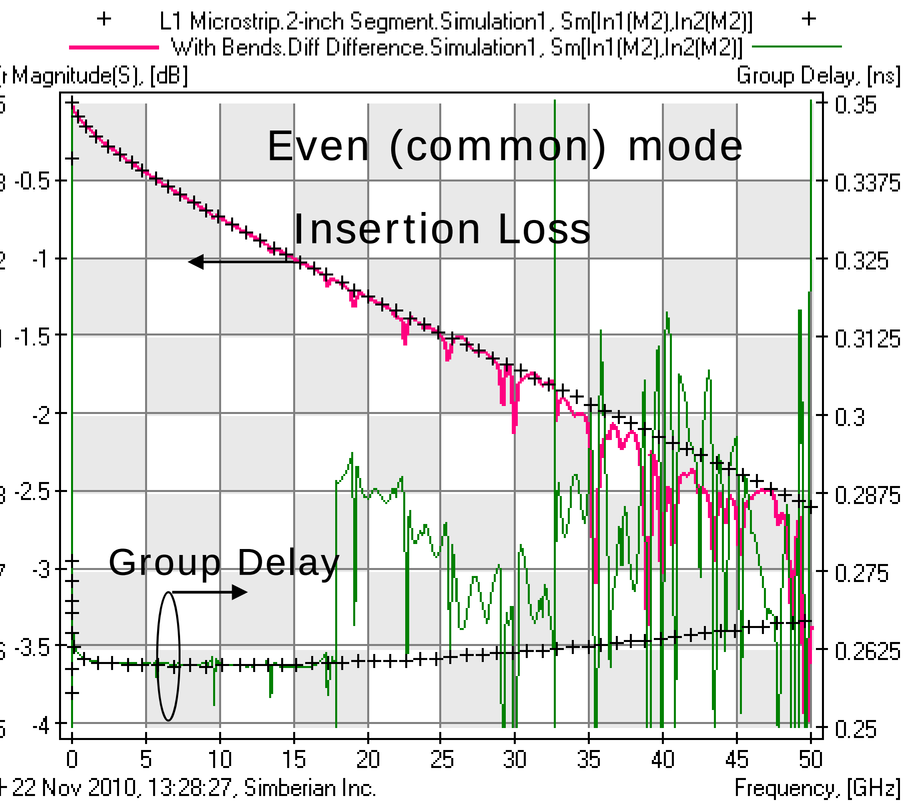
Larger noise in GM insertion loss above 20 GHz and practically not usable group delay

Effect of bends on extracted GMS-parameters



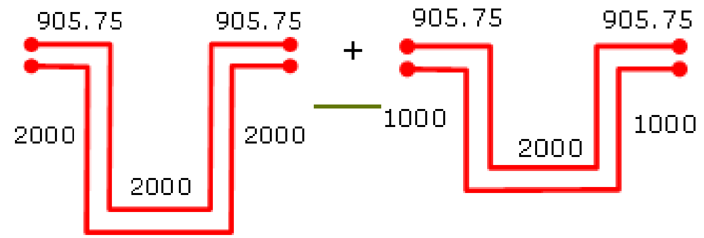
2-inch segment - black pluses;
Extracted from 2 test fixtures – solid and dash lines





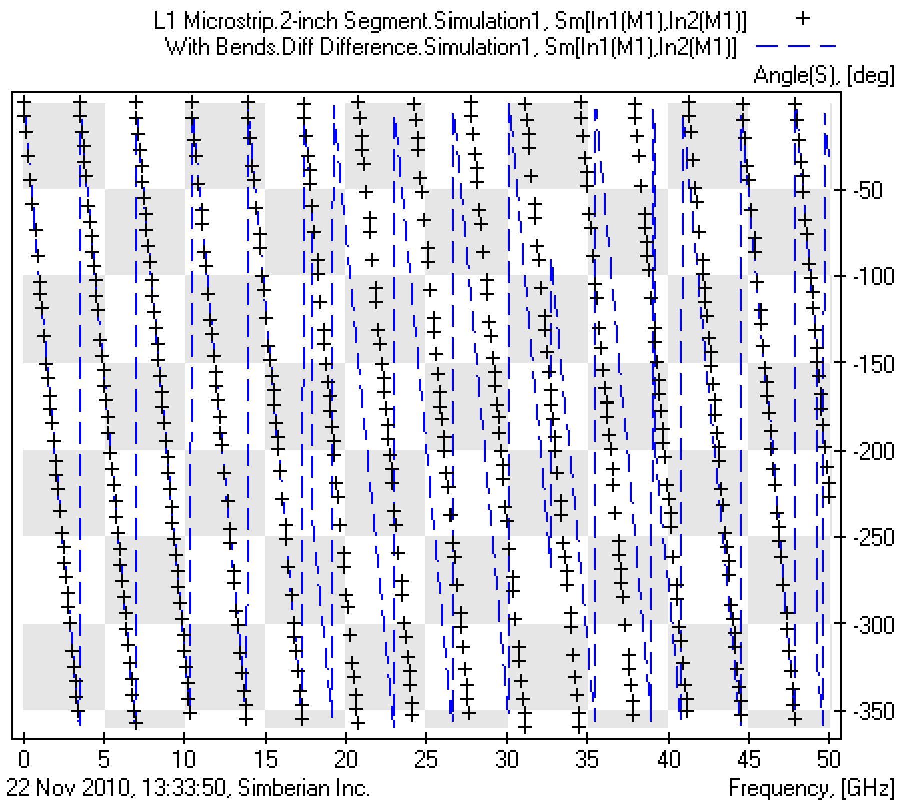
Still large noise in GM insertion loss and practically not usable group delay above 18 GHz

Effect of bends on phases of extracted GMS-parameters

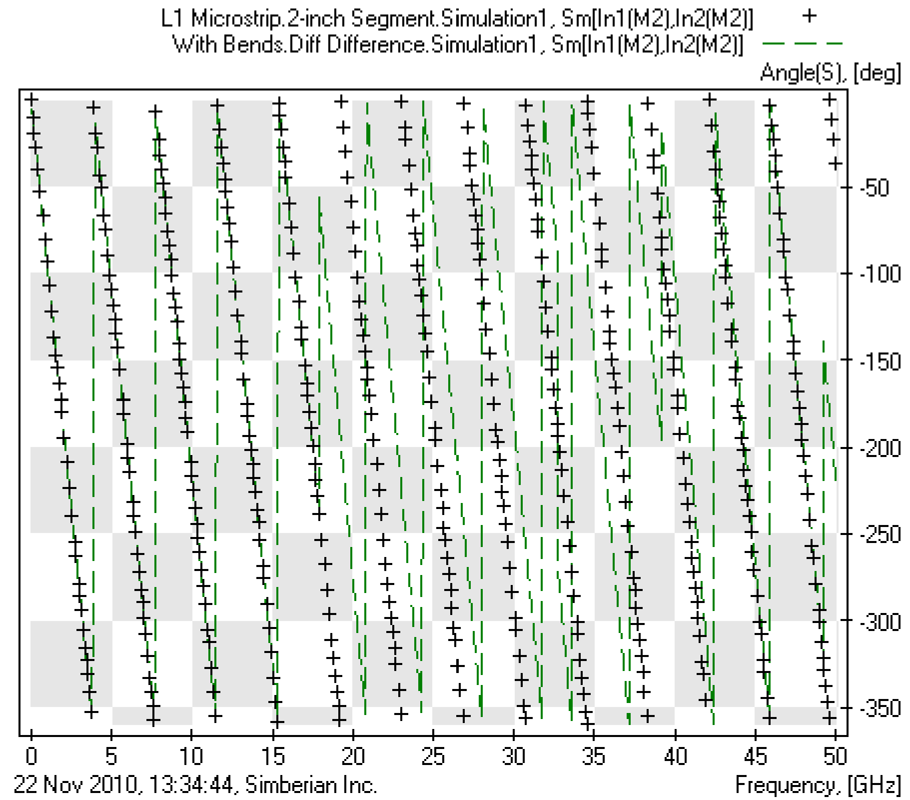


2-inch segment - black pluses;
Extracted from 2 test fixtures – dash lines

Odd (differential) mode



Even (common) mode



Phase is less sensitive but still not usable above about 18 GHz!

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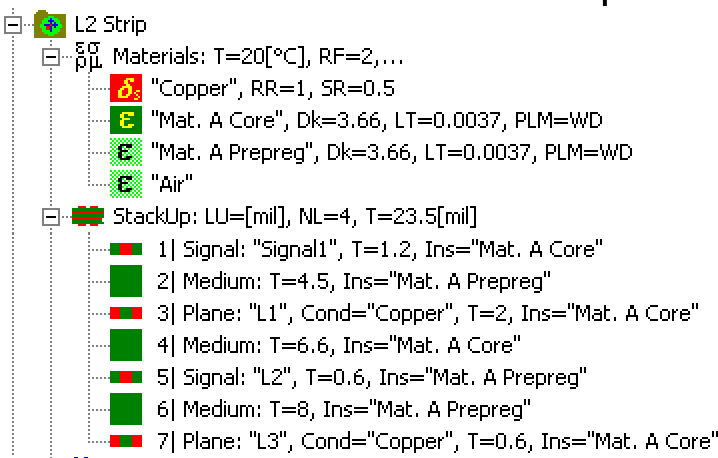
- Effect of bends in coupled strip-lines on GMS-parameters
- Conclusion

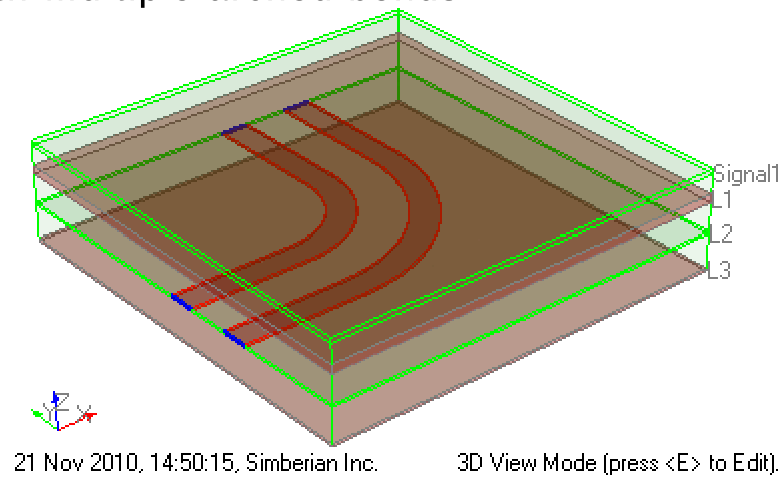
What if strip lines in test fixtures are not straight?

- Numerical experiment to investigate effect of bends

Materials & Stackup

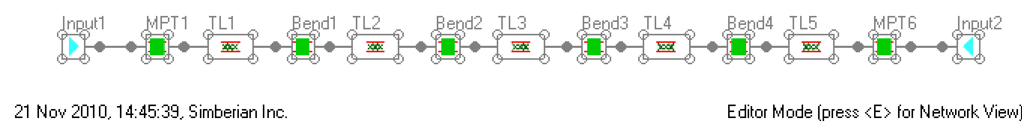


Instead of straight line let's try to use lines with multiple arched bends

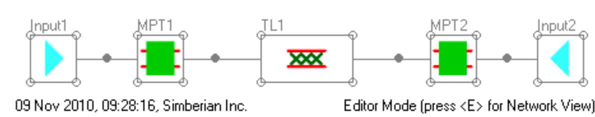


From simulated S-parameters of 2 structures with or without bends we extract GMS-parameters of 2-inch segment and compare it with the GMS-parameters of 2-inch segment computed directly

6 and 8 inch fixtures with 4 bends



6 and 8 inch fixtures without bends



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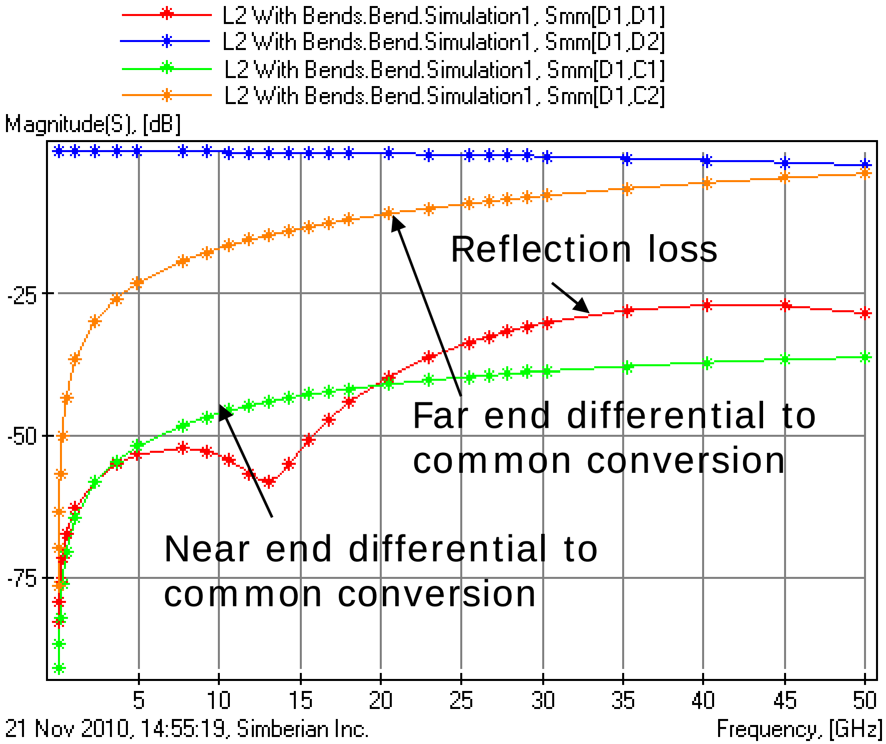
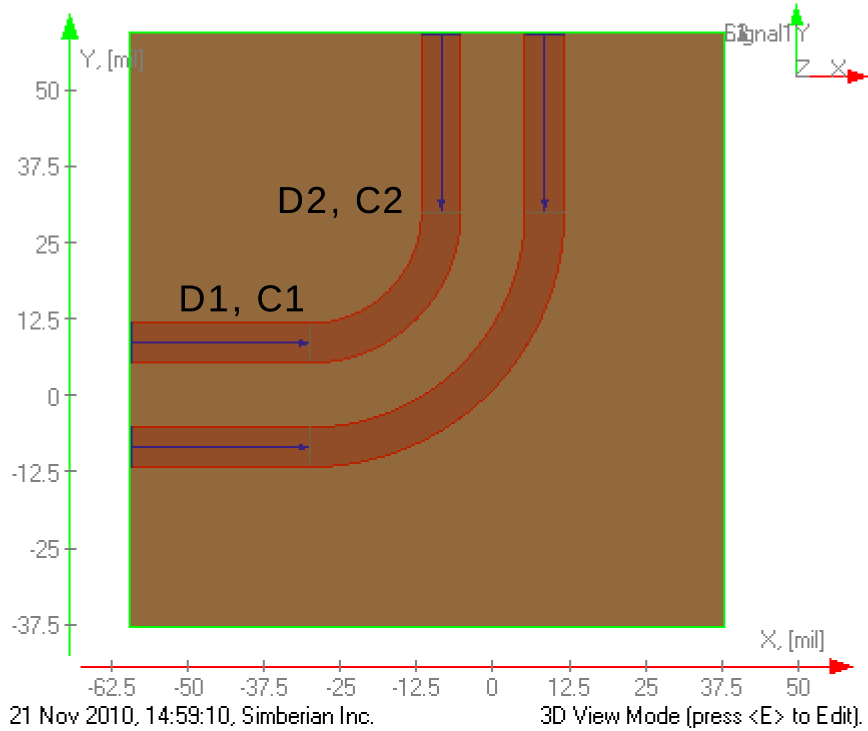
S-parameters of strip-line bend

- Very small differential reflection – below -25 dB up to 40 GHz
- Large differential to common mode conversion

Bend in 6.5-mil strip lines 10.5 mil apart, 30 mil radius along the center (47.12 mil of additional length)



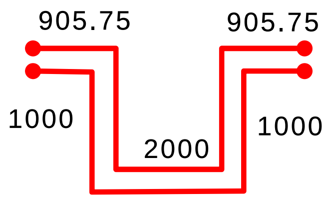


The mode conversion in strip line can be effectively compensated by matching number of left and right turns – see App Notes 2009_01 and 2009_02

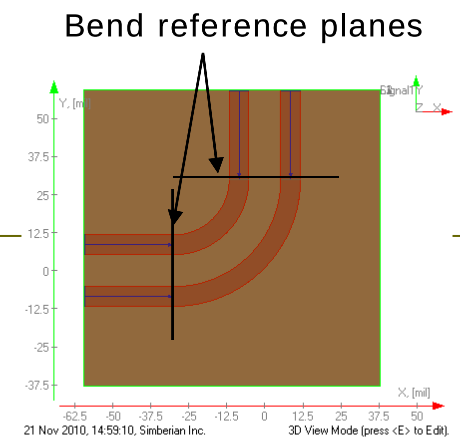
Test fixtures for the extraction

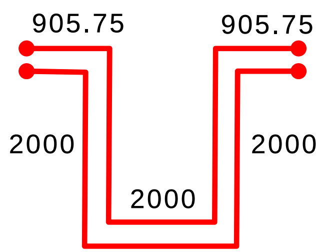
6 inch straight

8 inch straight



6 inch with 4 bends (2 left and 2 right)



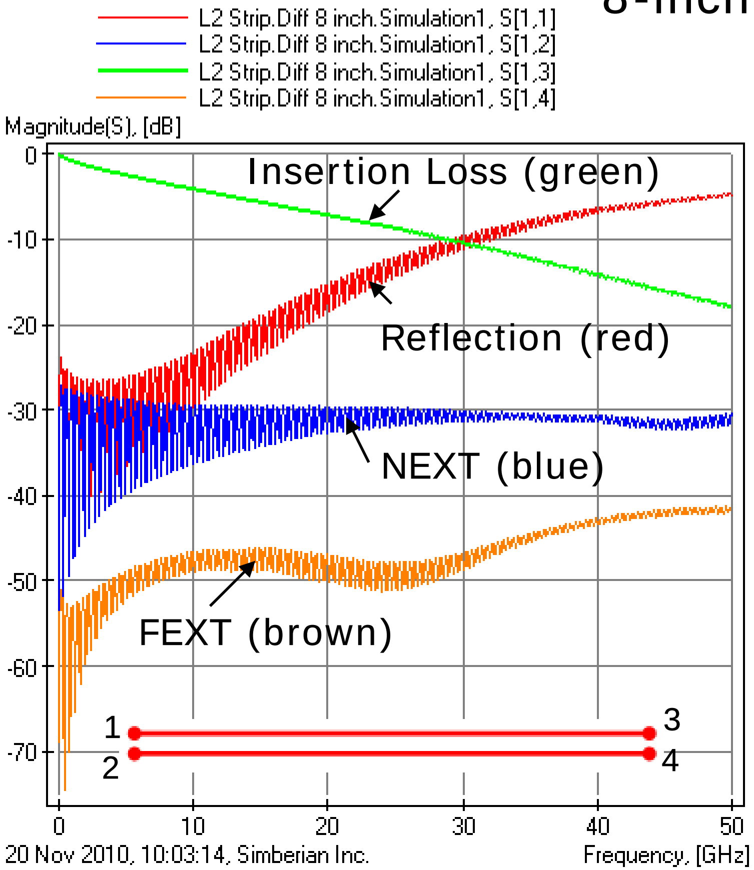


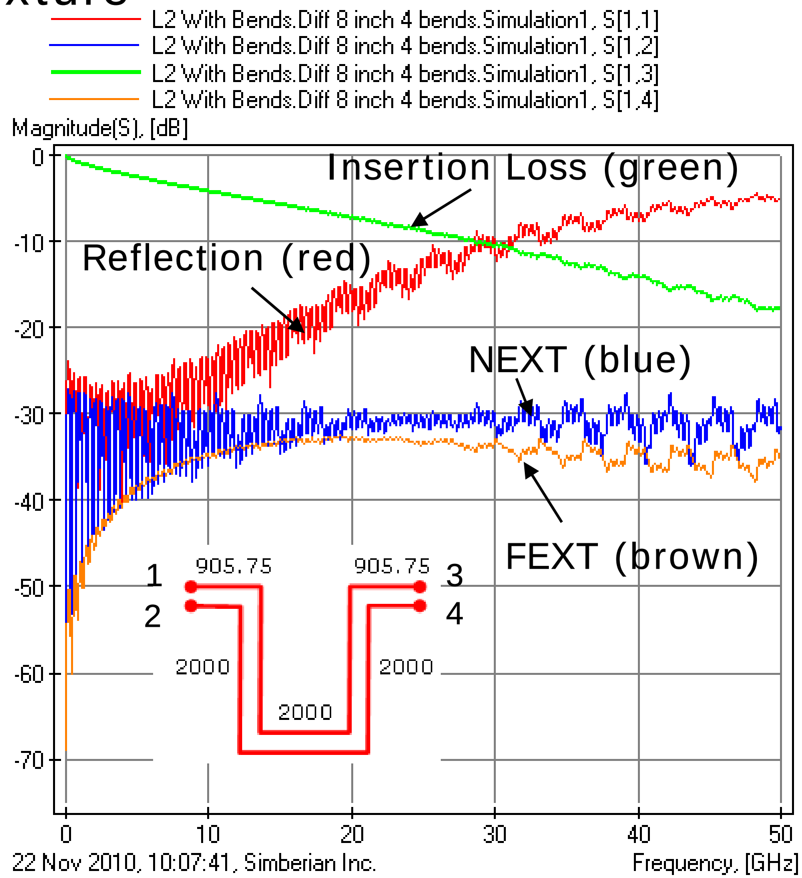
8 inch with 4 bends (2 left and 2 right)

Lengths of structures with bends are adjusted to have 6 and 8 inches along the central lines

Effect of bends on SE S-parameters of test fixtures

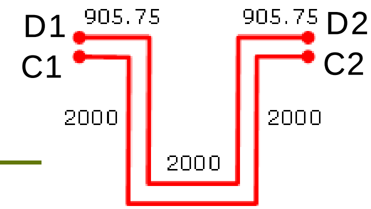
8-inch test fixture



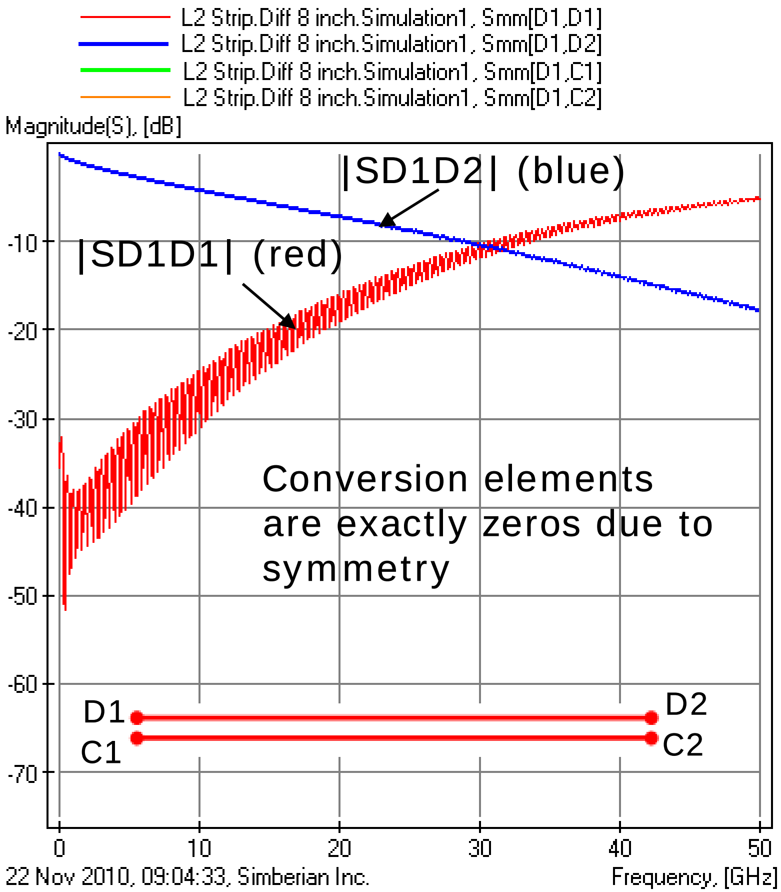


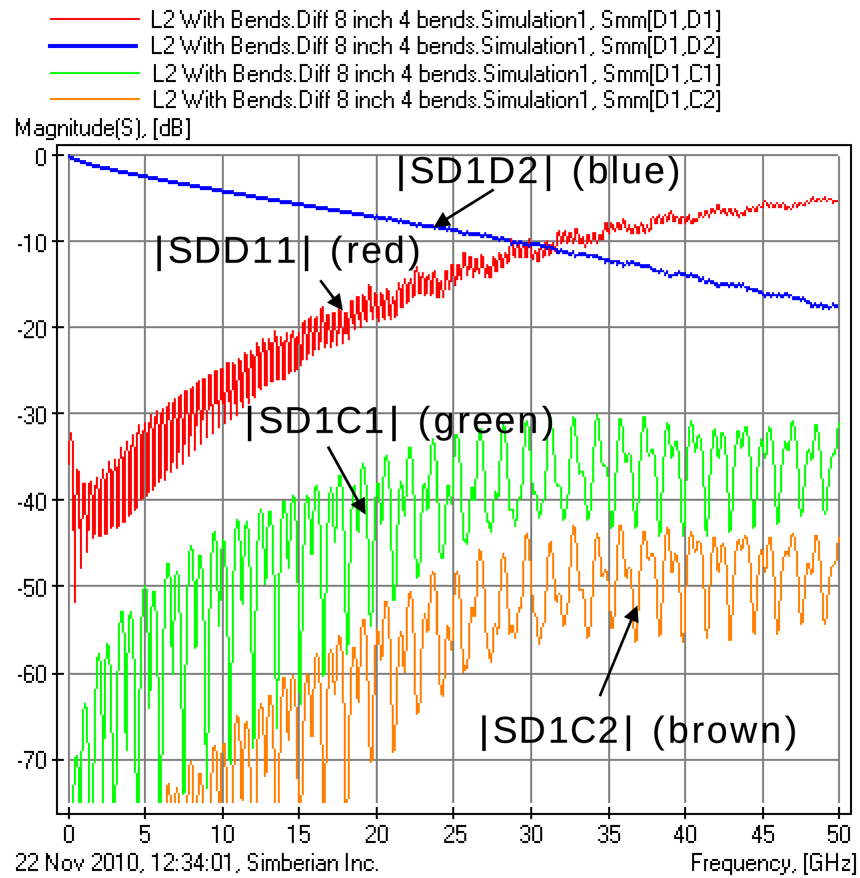
A little more reflection and FEXT (similar for 6-inch fixture)

Effect of bends on mixed-mode S-parameters of test fixtures



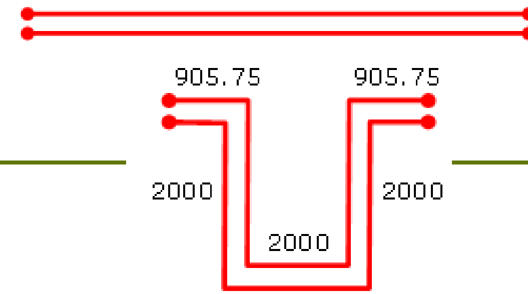
8-inch test fixture



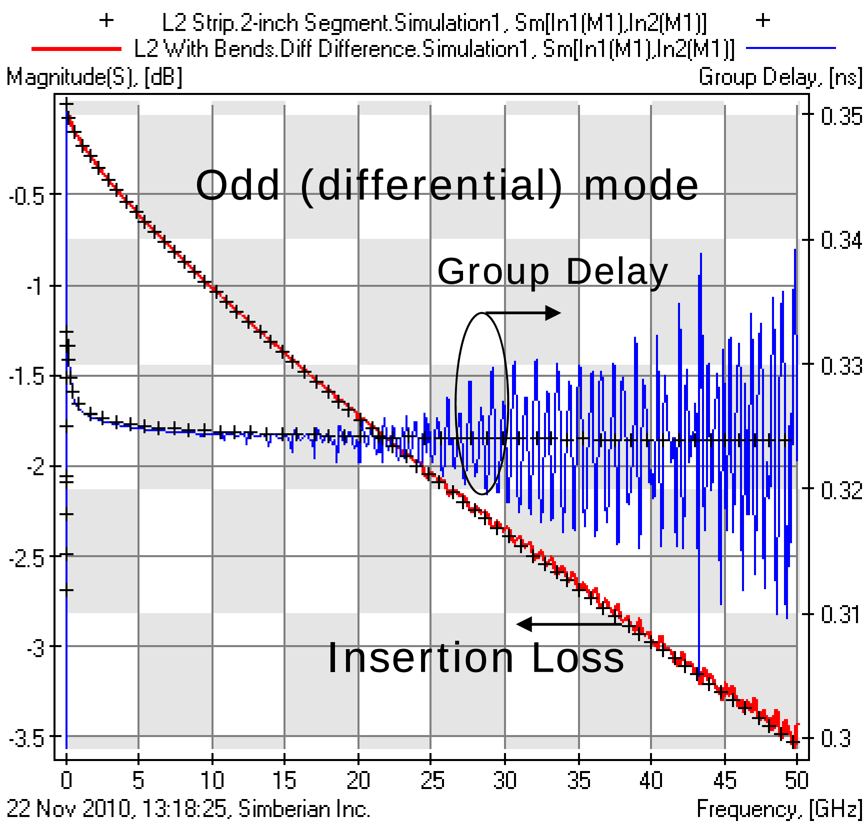


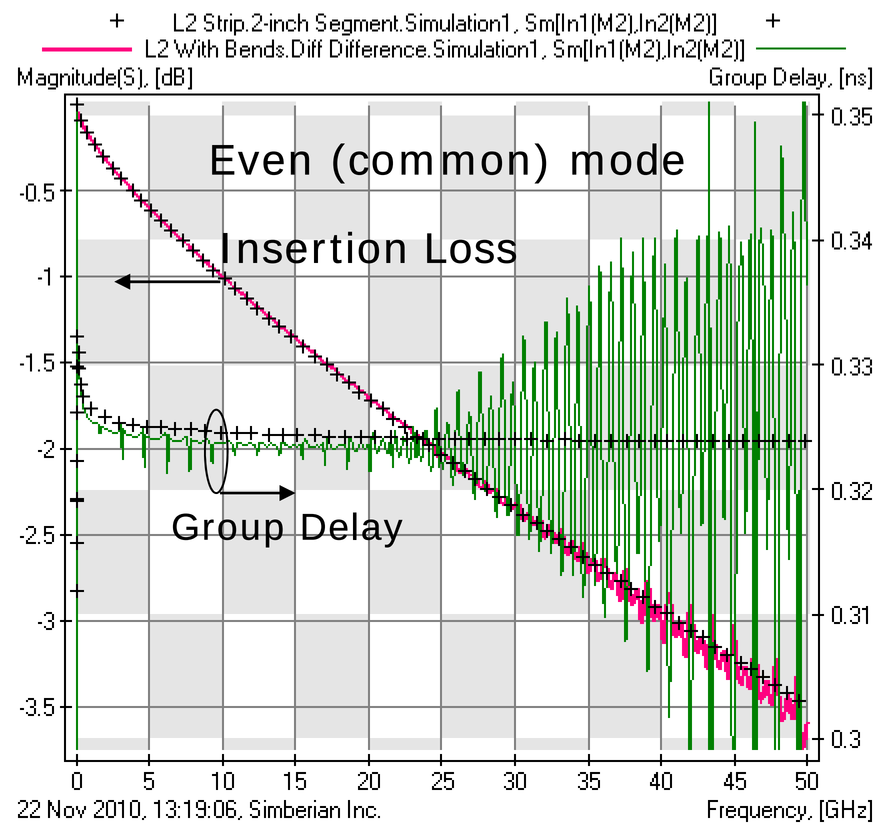
A little more ripples in reflection and almost negligible differential to common mode conversion due to bends

Effect of bends on extracted GMS-parameters



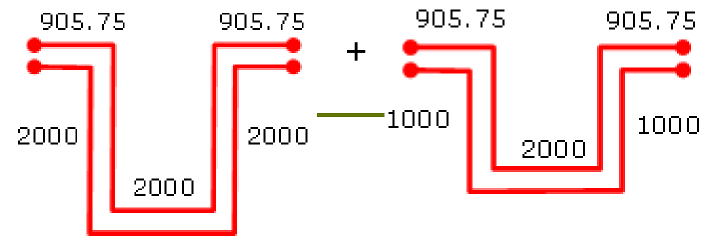
2-inch segment - black pluses;
Extracted from 2 test fixtures – solid and dash lines



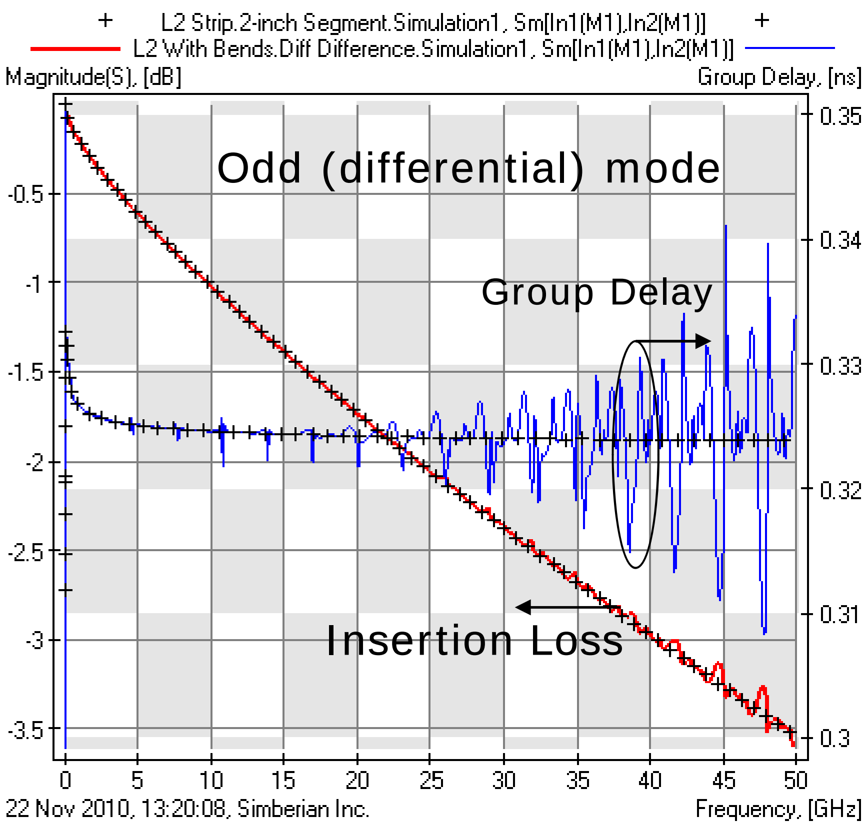


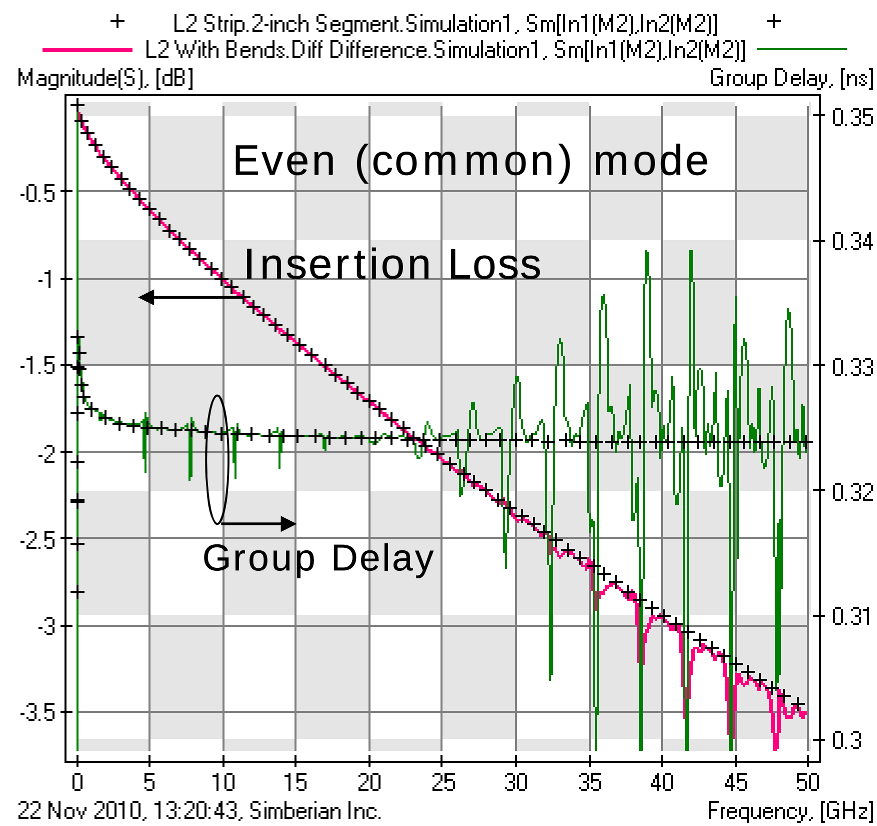
Some noise in GM insertion loss and a lot of noise in modal group delay above 20 GHz

Effect of bends on extracted GMS-parameters



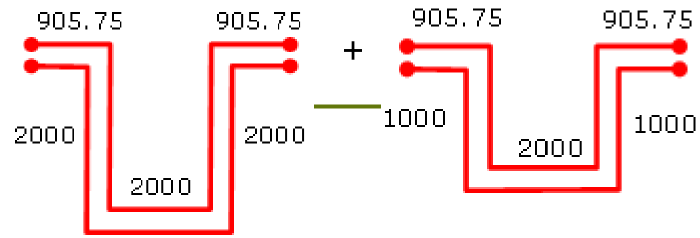
2-inch segment - black pluses;
Extracted from 2 test fixtures – solid and dash lines





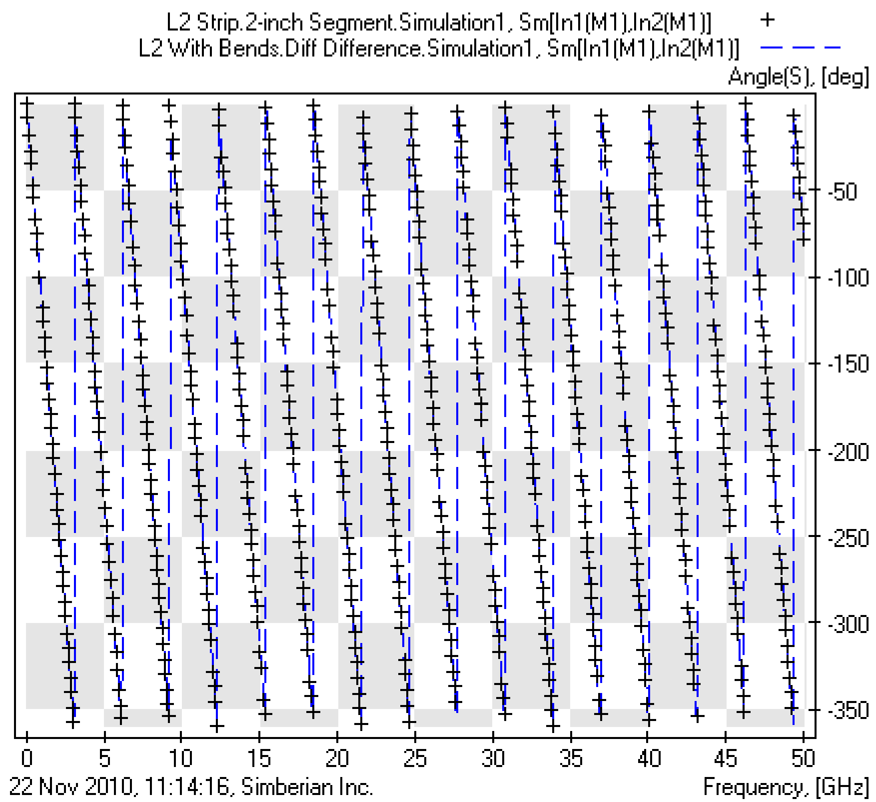
Small noise in GM insertion loss and a lot of noise in modal group delay

Effect of bends on phases of extracted GMS-parameters

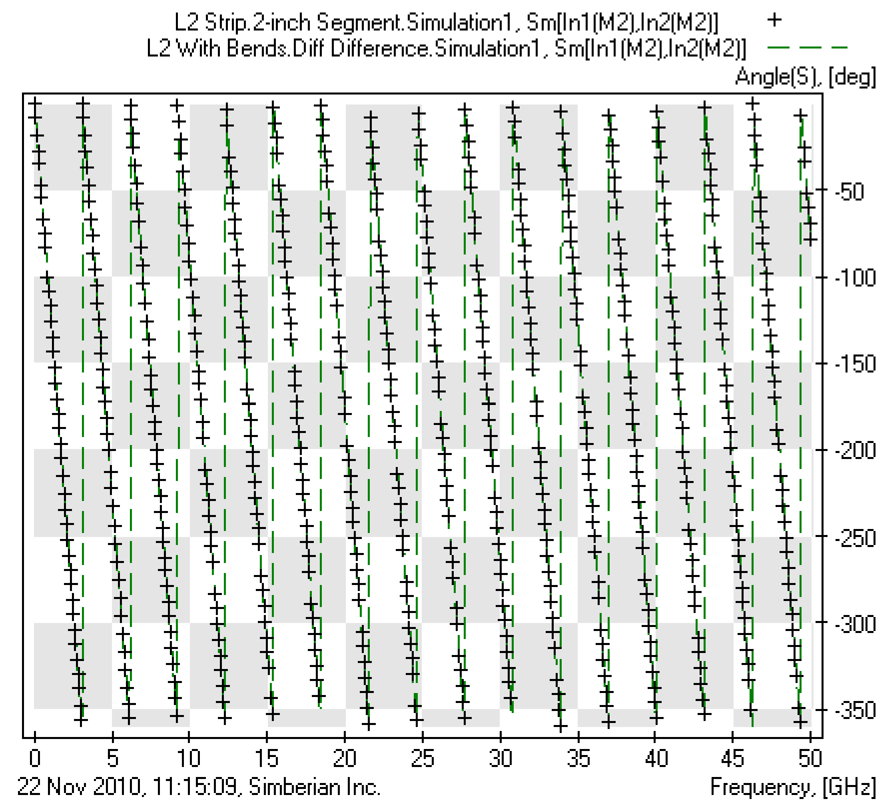


2-inch segment - black pluses;
Extracted from 2 test fixtures – dash lines

Odd (differential) mode



Even (common) mode



Phase is less sensitive and may be preferable for the identification with bends!

Conclusion

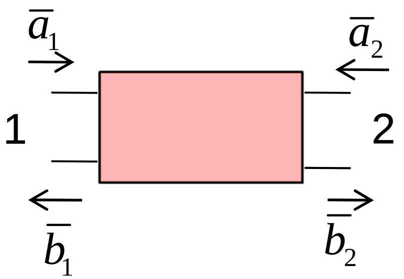
- Overview of material parameters identification by fitting measured and computed GMS-parameters for coupled lines is provided
- GMS-parameters of coupled lines have 2 unique parameters – may be used to identify or confirm the identification for 2 materials
- Two dielectric in micro-strip configuration cannot be identified as one – analysis of common mode is not accurate if differential mode is used and vise versa
- Simultaneous identification of 2 dielectrics may be not unique – fixing properties of one dielectric with additional experiment may be necessary (microstrip without solder mask for instance)
- In case of weakly coupled strip-lines non-homogeneous dielectric can be identified as homogeneous for practical purpose
- Layout of test fixtures with bends may produce noisy results especially in microstrip configurations due to irreversible conversion of modes
- Differences in connectors, launches and cross-sections of differential lines may also produce identification errors, extraction fixtures must be pre-qualified – see App Note #2010_03
- Setting up all simulations and model building with Simbeor took about 4 hours

Solutions and contact

- Simbeor solution files are in the database
  http://kb.simberian.com/SimbeorExamples.php (keyword 2010_04)
  It contains all electromagnetic models and linear circuit analysis both in frequency and time domains
- Send questions and comments to
  - General: info@simberian.com
  - Sales: sales@simberian.com
  - Support: support@simberian.com
- Web site www.simberian.com

S-matrices and T-matrices

Same number of ports on the left and right side of multiport



$$\begin{vmatrix}\overline{b}_1\\ \overline{b}_2\end{vmatrix}=\begin{bmatrix}S_{1,1} & S_{1,2}\\ S_{2,1} & S_{2,2}\end{bmatrix}\cdot\begin{vmatrix}\overline{a}_1\\ \overline{a}_2\end{vmatrix}$$

Cascading of 2 multiports described with S-parameters require solving a linear system

$$\begin{vmatrix}\overline{b}_1\\ \overline{a}_1\end{vmatrix}=\begin{bmatrix}T_{1,1} & T_{1,2}\\ T_{2,1} & T_{2,2}\end{bmatrix}\cdot\begin{vmatrix}\overline{a}_2\\ \overline{b}_2\end{vmatrix}$$

Cascading of 2 multiports described with T-parameters is simple product of two T-matrices

$$\begin{aligned}T_{1,1} &= S_{2,1} - S_{1,1}\cdot S_{2,1}^{-1}\cdot S_{2,2}\\ T_{1,2} &= S_{1,1}\cdot S_{2,1}^{-1}\\ T_{2,1} &= -S_{2,1}^{-1}\cdot S_{2,2}\\ T_{2,2} &= S_{2,1}^{-1}\end{aligned}$$

$$\begin{aligned}S_{1,1} &= T_{1,2}\cdot T_{2,2}^{-1}\\ S_{1,2} &= T_{1,1} - T_{1,2}\cdot T_{2,2}^{-1}\cdot T_{2,1}\\ S_{2,1} &= T_{2,2}^{-1}\\ S_{2,2} &= -T_{2,2}^{-1}\cdot T_{2,1}\end{aligned}$$

All elements are scalars in case of 2-ports (single-ended lines) or matrices in case of multi-conductor lines (differential)

See more in Carlin, Giordano, Network Theory, An Introduction to Reciprocal and Non-Reciprocal Circuits, 1964
Conversion can be generalized for arbitrary number of ports on the left and right