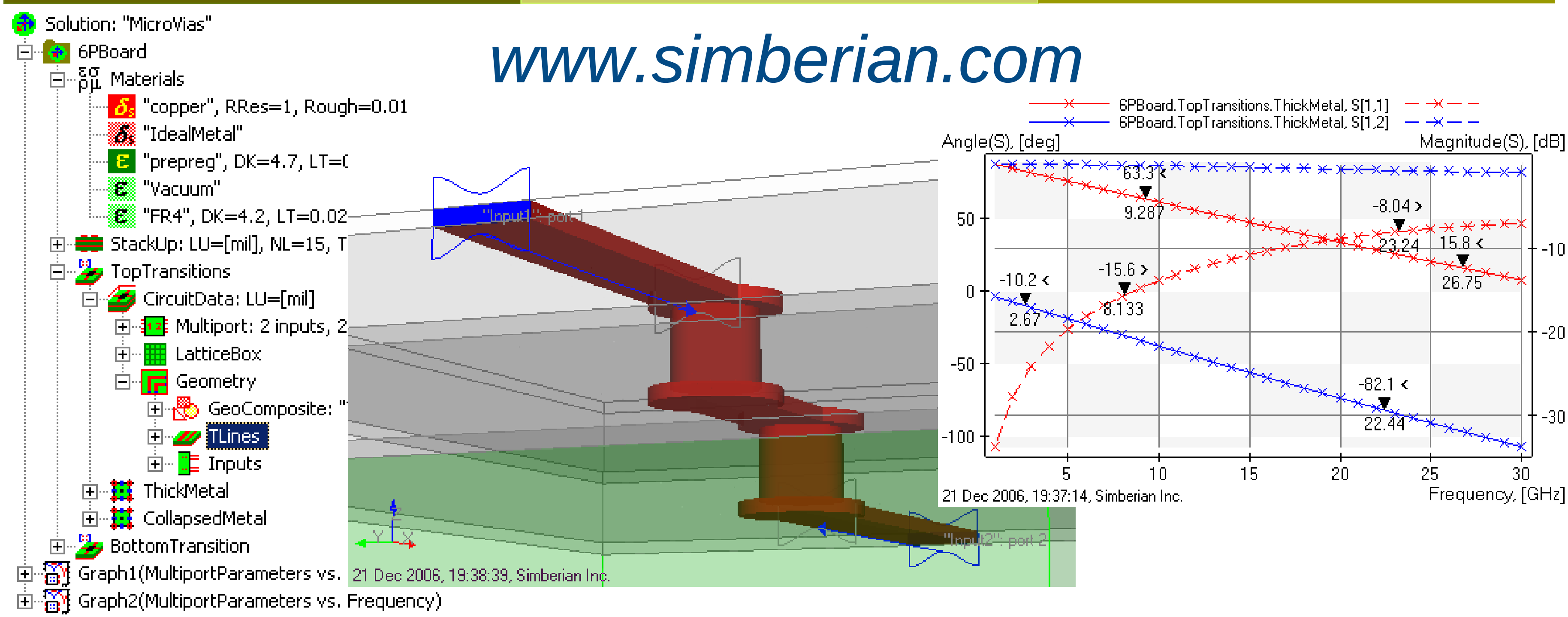
Simberian
Electromagnetic Solutions

Simbeor Application Note #2011_04, April 2011

Material parameters identification with GMS-parameters in Simbeor 2011

www.simberian.com



Simbeor®: Accurate, Fast, Easy, Affordable Electromagnetic Signal Integrity Software…

Outline

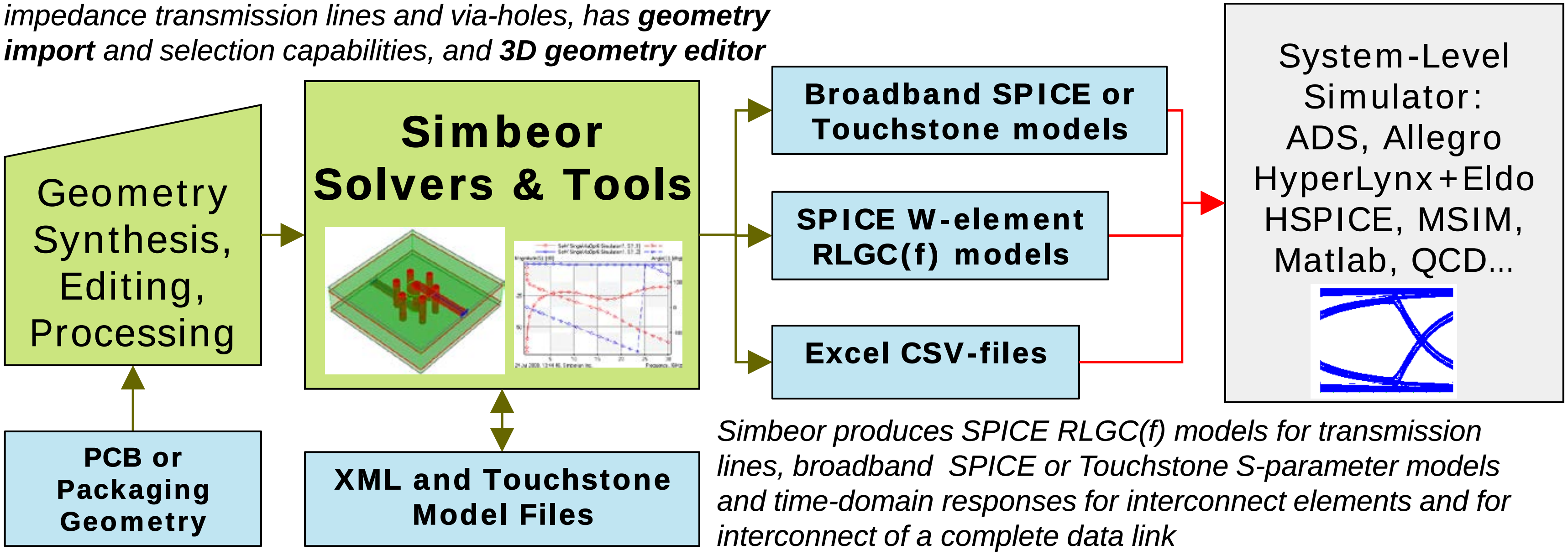
- Simbeor 2011 overview
- Material parameters identification with GMS-parameters
- Example of dielectric identification for PLRD-1 board
- Molex/Teraspeed Consulting Group board
- Wild River Technology CMP-08 board
- Roughness characterization (Isola's board)
- Nickel characterization (Teraspeed's board)
- Conclusion

Simbeor can be used for

- ***PCB and packaging interconnects compliance analysis with advanced 3D full-wave models***
  - ***Stackup planning and interconnect budget exploration***
  - ***Interconnect design verification***
- ***Identification of models for conductive and dielectric materials (patent pending)***
- ***Building broadband SPICE macro-models for consistent analyses in frequency and time domains***
- ***Automation of S-parameters quality assurance and all macro-modeling tasks***

Simbeor is synthesis, full-wave analysis and macro-modeling tool for interconnects

*Simbeor enables **geometry synthesis** for controlled impedance transmission lines and via-holes, has **geometry import** and selection capabilities, and **3D geometry editor***

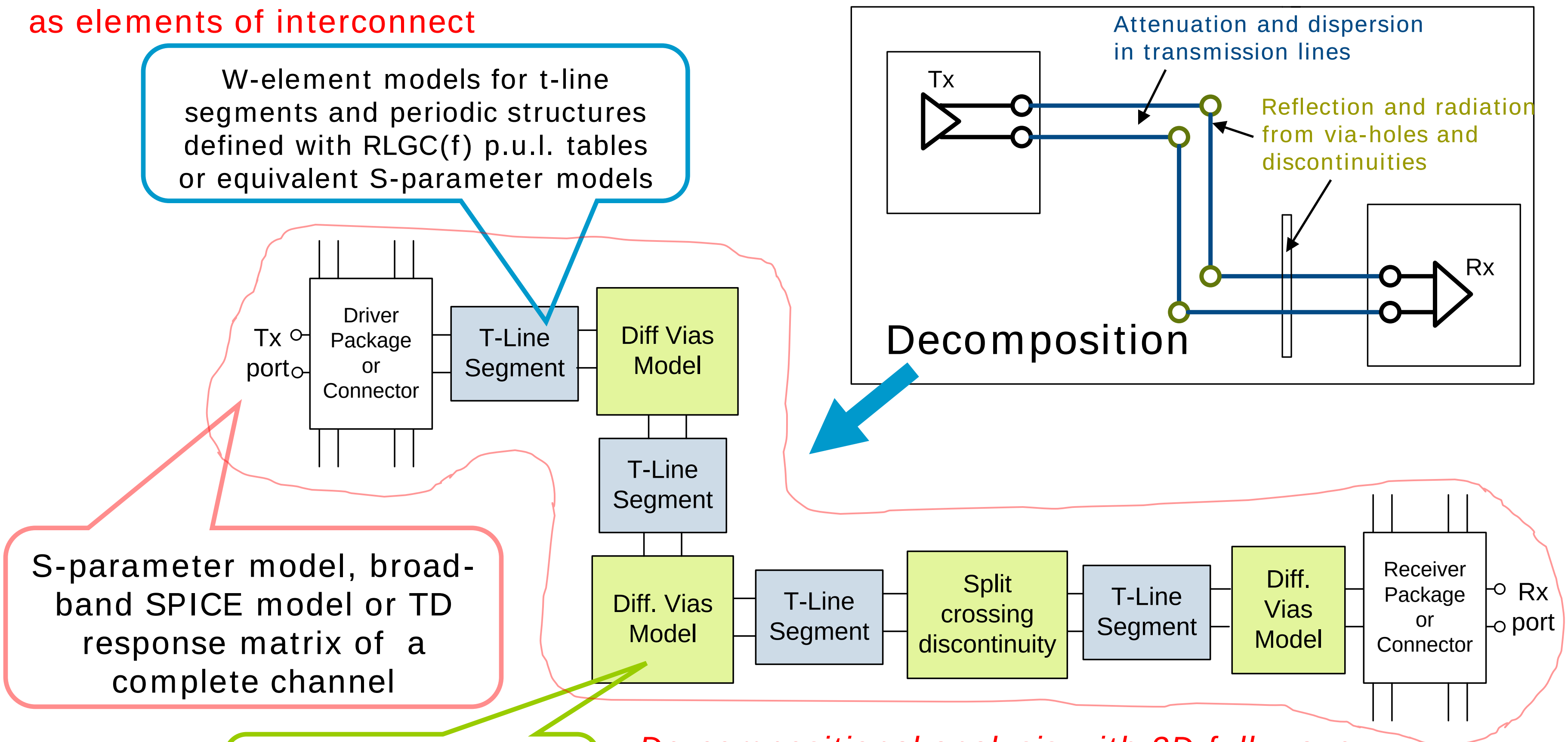


Simbeor produces SPICE RLGC(f) models for transmission lines, broadband SPICE or Touchstone S-parameter models and time-domain responses for interconnect elements and for interconnect of a complete data link

Simbeor is the one-stop solution for interconnect budget exploration, design verification with electromagnetic and linear analyses and macro-modeling tasks

Simbeor is based on de-compositional electromagnetic analysis of interconnects

Connectors and cable models can be included as elements of interconnect



S-parameter models for via-hole transitions and discontinuities

De-compositional analysis with 3D full-wave electromagnetic models is the fastest and the most accurate way to characterize interconnects with 6-100 Gb/s data rates and fast rise and fall time!

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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 model 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

Procedure is implemented in Simbeor 2011

Simberian's patent pending #**13/009,541**

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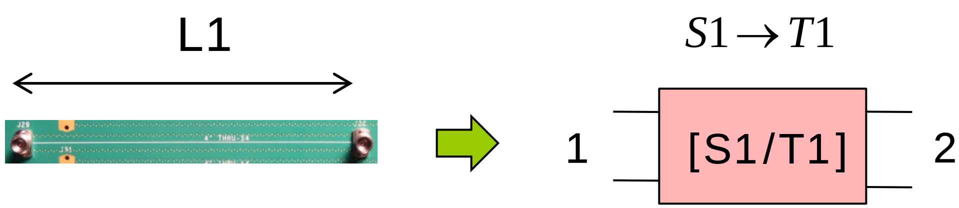
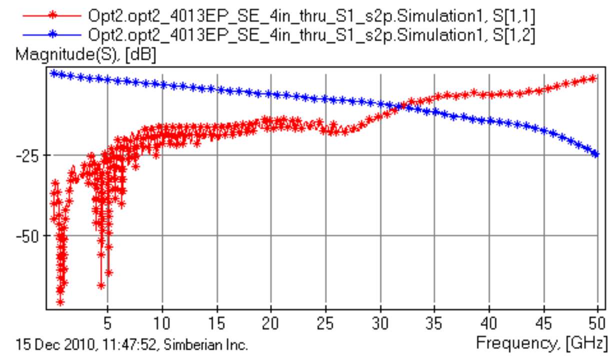
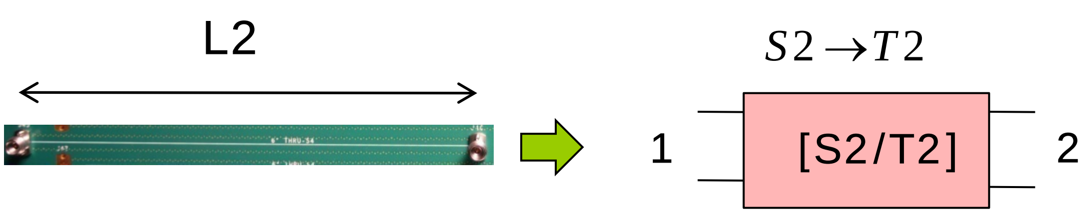
Measure S-parameters of two test fixtures with line segments (no SOLT calibration is required)

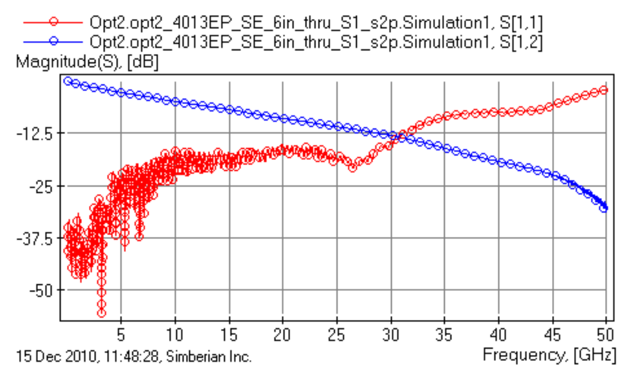
- S1 and T1 for line with length L1





- S2 and T2 for line with length L2

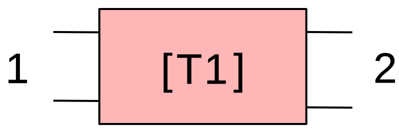


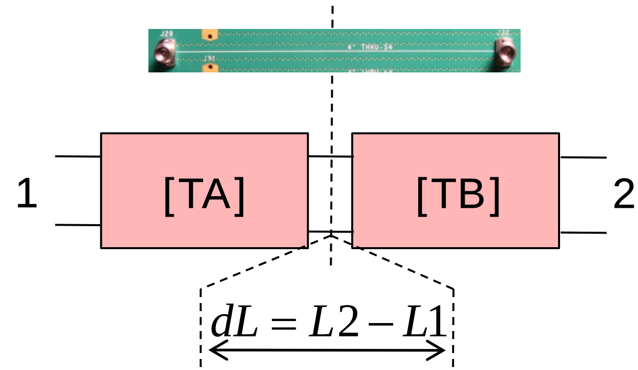


T1 and T2 matrices are scattering T-parameters (computed directly from S-parameters)

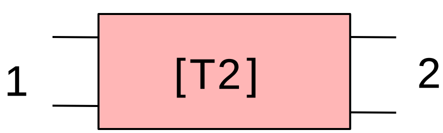
Extract Generalized Modal T-parameters (GMT) and then GMS-Parameters (1-conductor case)

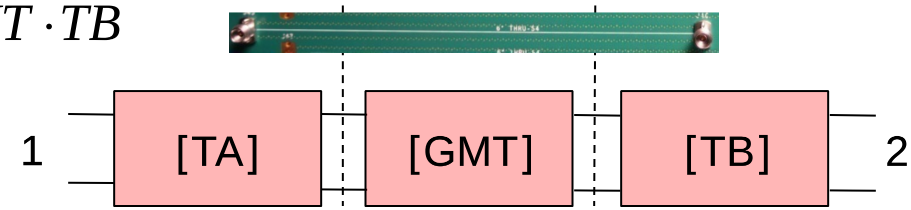
Segment L1 $T1 = TA \cdot TB$





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





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

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

⇩

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

Easy to compute!

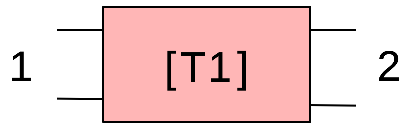
For 1-conductor line we get:

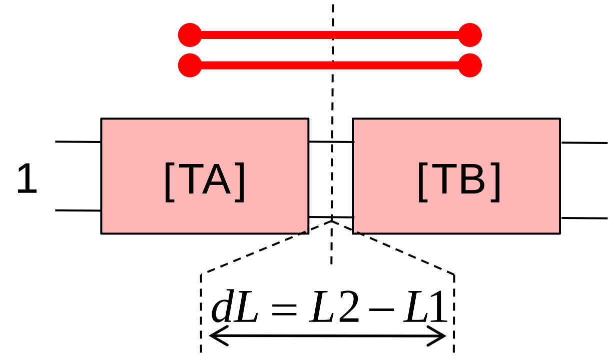
$$GMT = \begin{bmatrix} T_{11} & 0 \\ 0 & T_{11}^{-1} \end{bmatrix} \Rightarrow GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix}$$

Just 1 complex function!

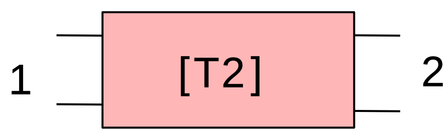
Extract Generalized Modal T-parameters (GMT) and then GMS-Parameters (2-conductor case)

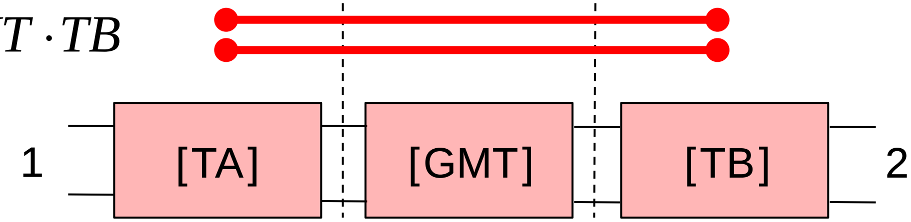
Segment L1 $T1 = TA \cdot TB$





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





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

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

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

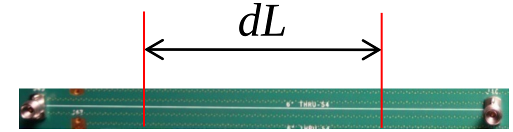
For 2-conductor line we get:

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

Just 2 complex functions!

Identifying dielectrics by fitting GMS-parameters (1-conductor case)

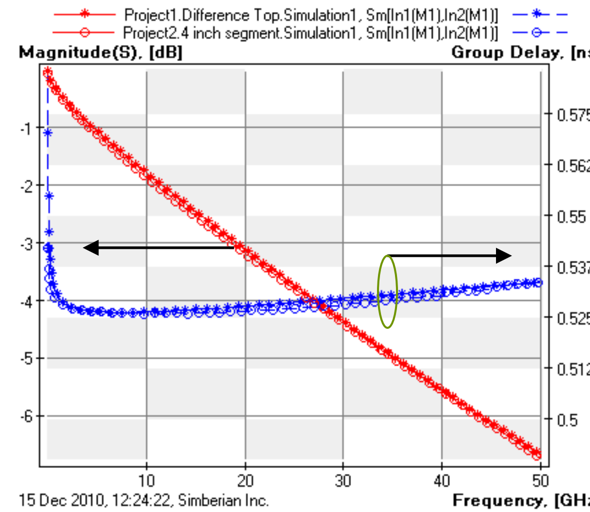
- Solve Maxwell's equations for 1-conductor line:



$$GMSc = \begin{bmatrix} 0 & \exp\left(-\Gamma \cdot dL\right) \\ \exp\left(-\Gamma \cdot dL\right) & 0 \end{bmatrix}$$

- Fit measured data: *Only 1 complex function!*

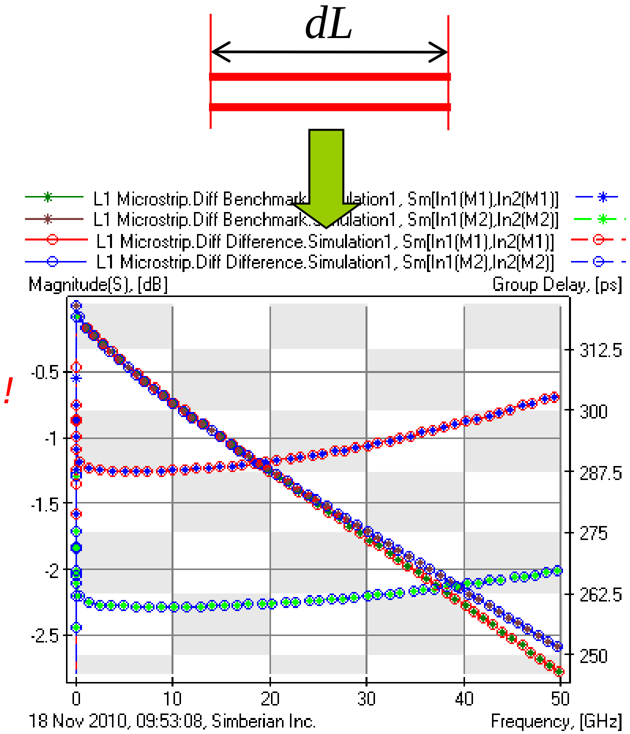
$$GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix}$$



- Measured GMS-parameters of the segment can be directly fitted with the calculated GMS-parameters for material parameters identification
- Phase or group delay can be used to identify DK and insertion loss to identify LT or conductor roughness!

Identifying dielectrics by fitting GMS-parameters (2-conductor case)

- 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!

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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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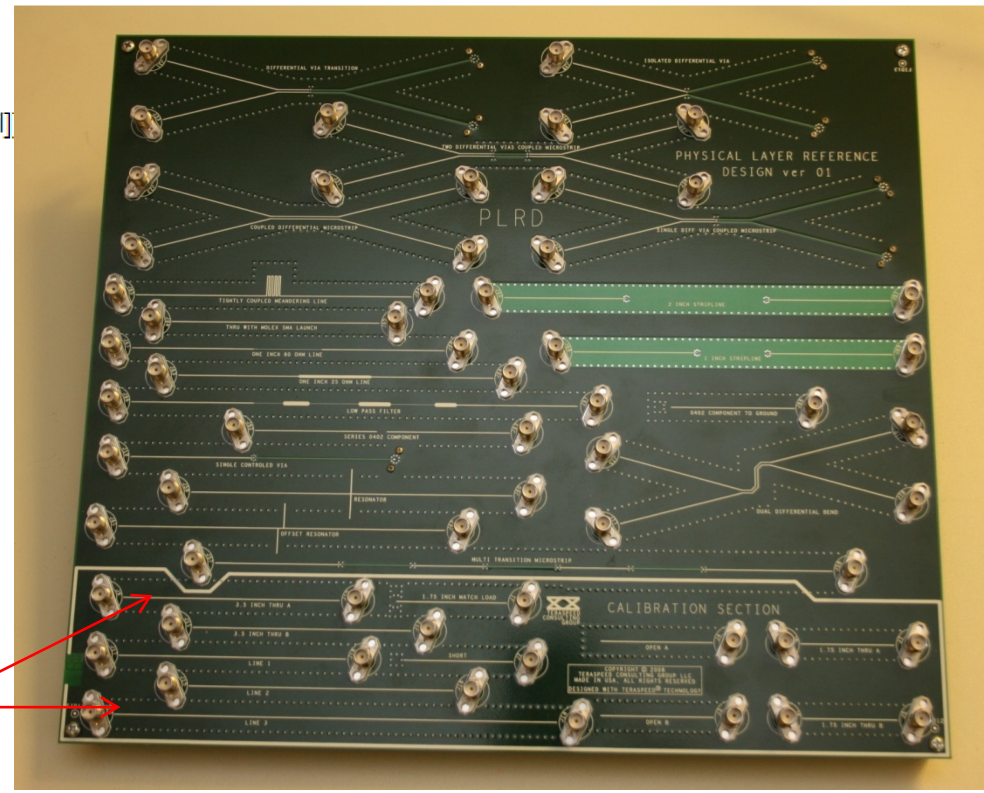
Dielectric identification on PLRD-1

- Solution: "Dielectric Identification"
  - Project1
    - Materials: T=20[°C], RF=2,...
      - "Copper", RR=1, SR=0.5
      - "FR4", Dk=4.2, LT=0.02, PLM=WD
      - "Vacuum"
      - "SolderMask", Dk=3.3, LT=0.02, PLM=WD
    - StackUp: LU=[mil], NL=4, T=62.2[mil], SML=("SolderMask", 1.75[mil]
      - 1| Signal: "Signal1", T=1.35, Ins="Vacuum"
      - 2| Medium: T=8.9, Ins="FR4"
      - 3| Plane: "Plane1", Cond="Copper", T=1.35, Ins="FR4"
      - 4| Medium: T=39, Ins="FR4"
      - 5| Plane: "Plane2", Cond="Copper", T=1.35, Ins="FR4"
      - 6| Medium: T=8.9, Ins="FR4"
      - 7| Signal: "Signal2", T=1.35, Ins="Vacuum"

PLRD-1 validation board designed and investigated by Teraspeed Consulting Group



17 mil wide microstrip line, S-parameters for 2 segments (1.75 in and 3.5 in)

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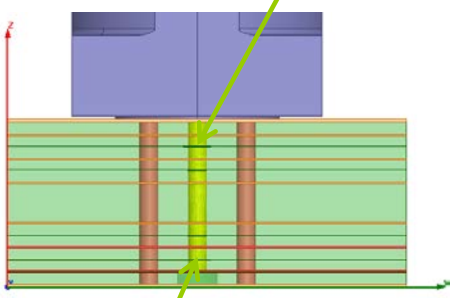
Material identification board from Molex/Teraspeed Consulting Group

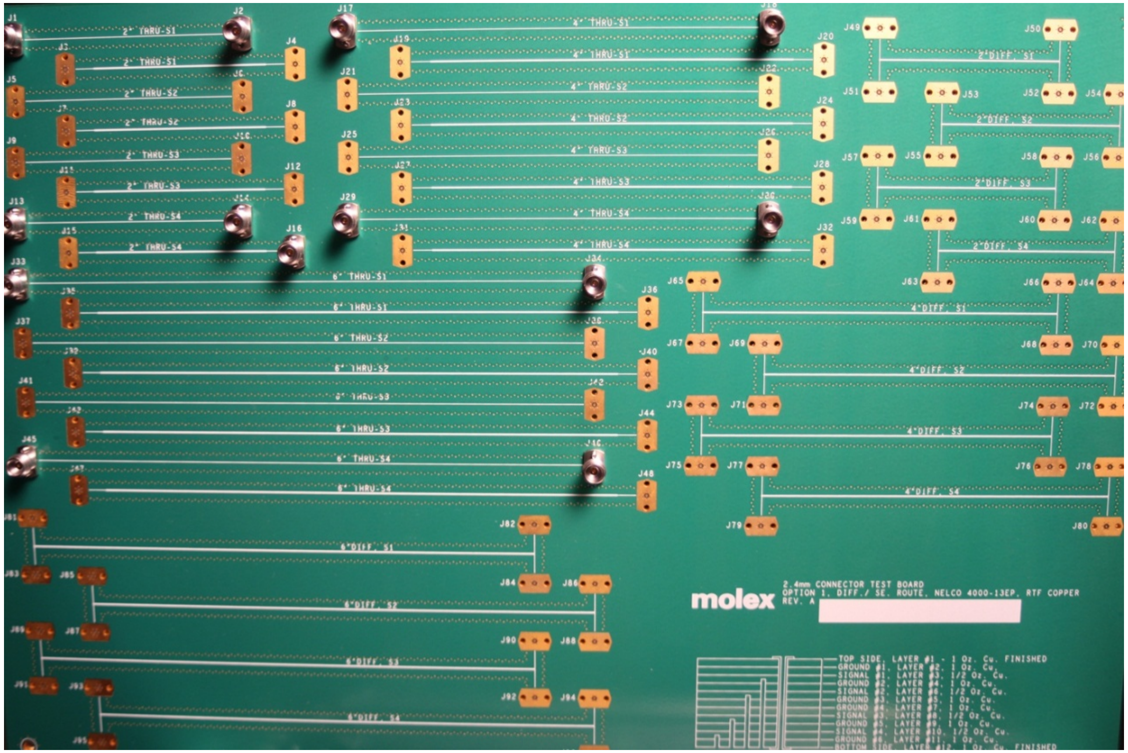
- D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011 (also App Note #2011_01 at www.simberian.com)
- 4000-13EP dielectric

6 test fixtures with 2, 4 and 6 inch strip line segments in Layer 1 and Layer 4

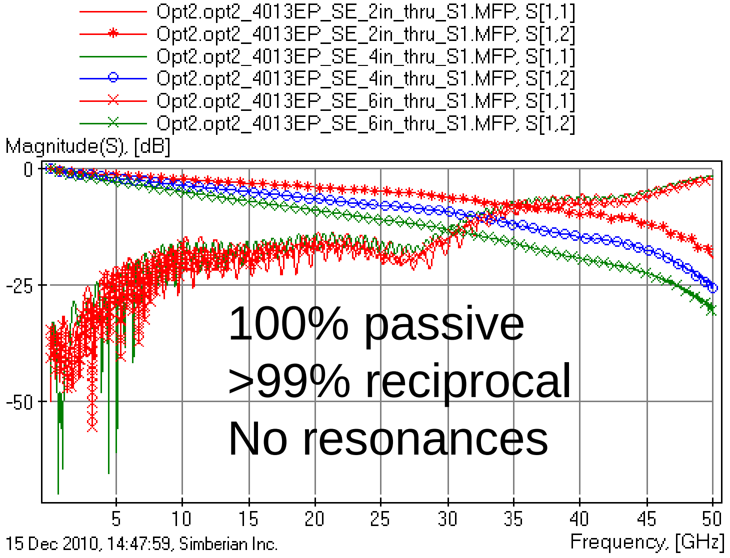
Signal Layer 1



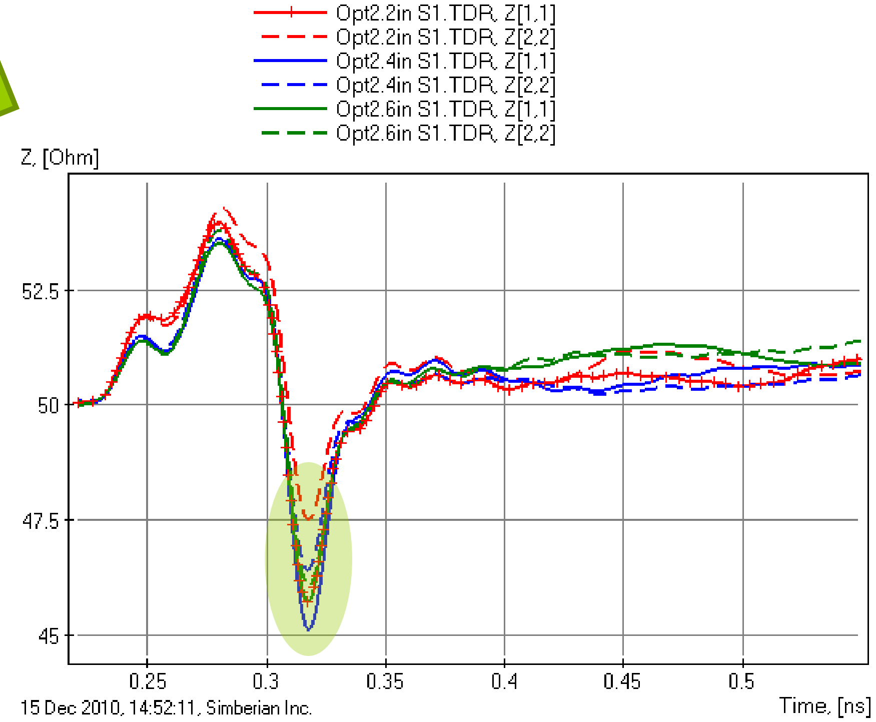
Signal Layer 4



Pre-qualification of launches: Launch 2, layer S1



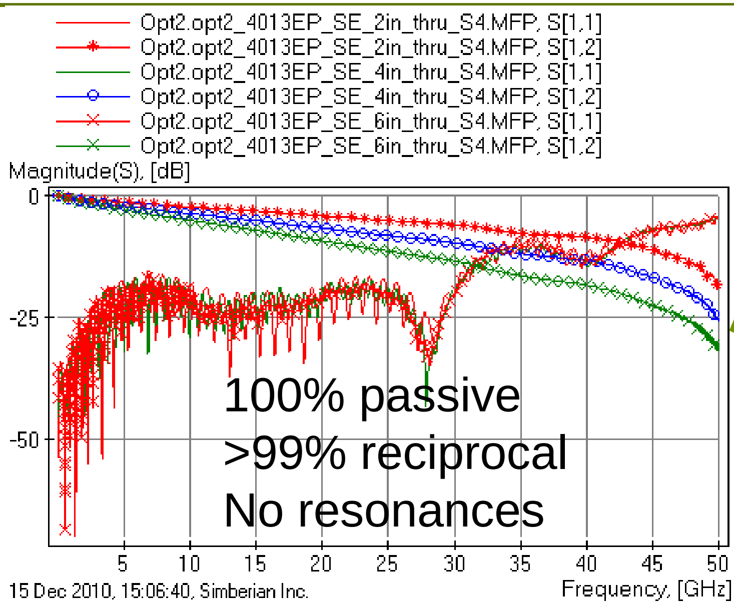
TDR computed with rational macro-models (RMSE<0.005) and Gaussian step with 20 ps rise time



2-inch fixture (red lines) has large variation in the impedance

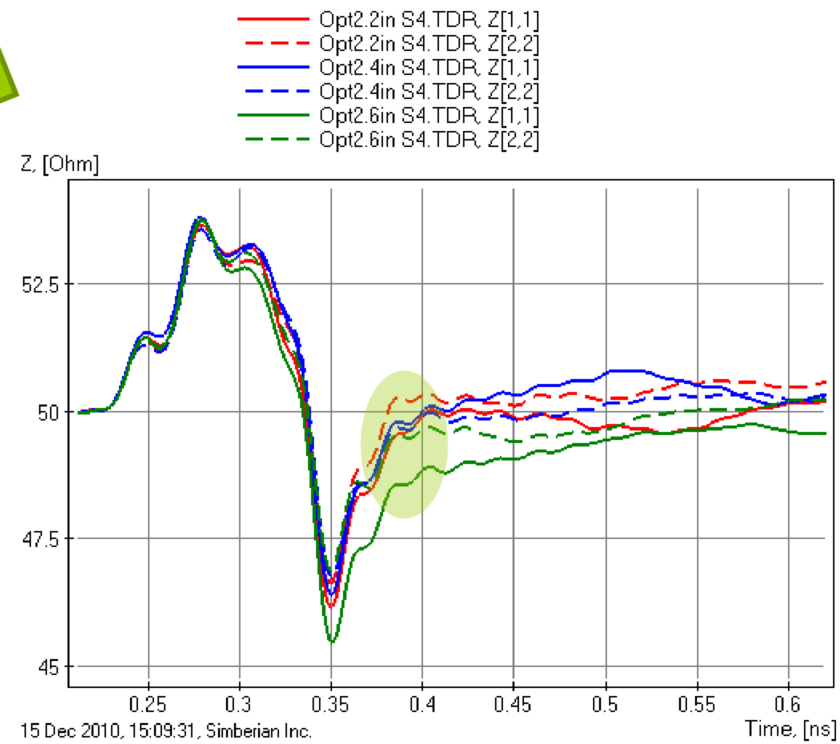
4 and 6 inch structures are within 1 Ohm - suitable for the identification

Pre-qualification of launches: Launch 2, layer S4



100% passive
>99% reciprocal
No resonances

TDR computed with rational macro-models (RMSE<0.005) and Gaussian step with 20 ps rise time



6-inch fixture (green lines) is questionable (near launch)
2 and 4 inch structures are within 1 Ohm - suitable for the identification

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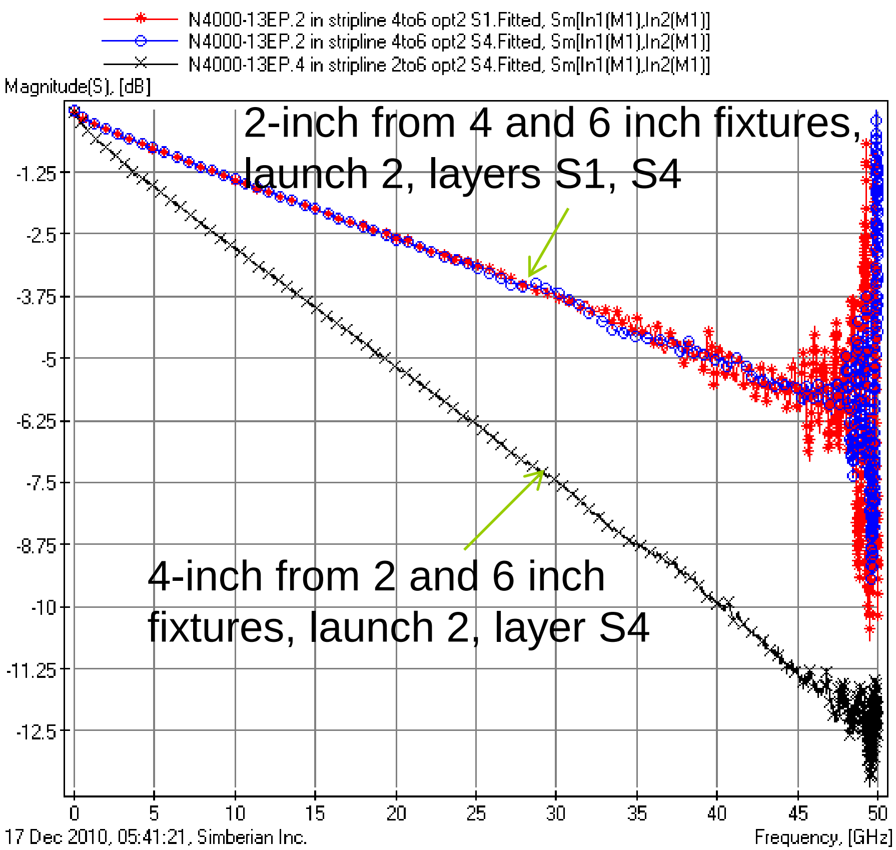
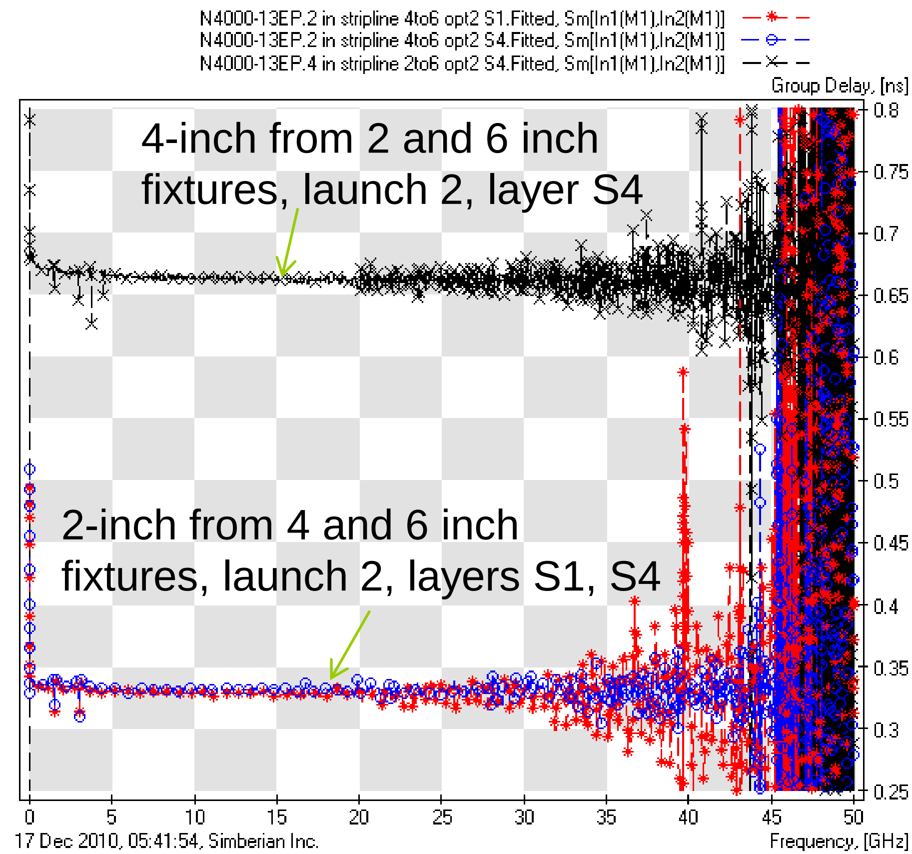
GMS-parameters from 3 best pairs

Generalized Insertion Loss



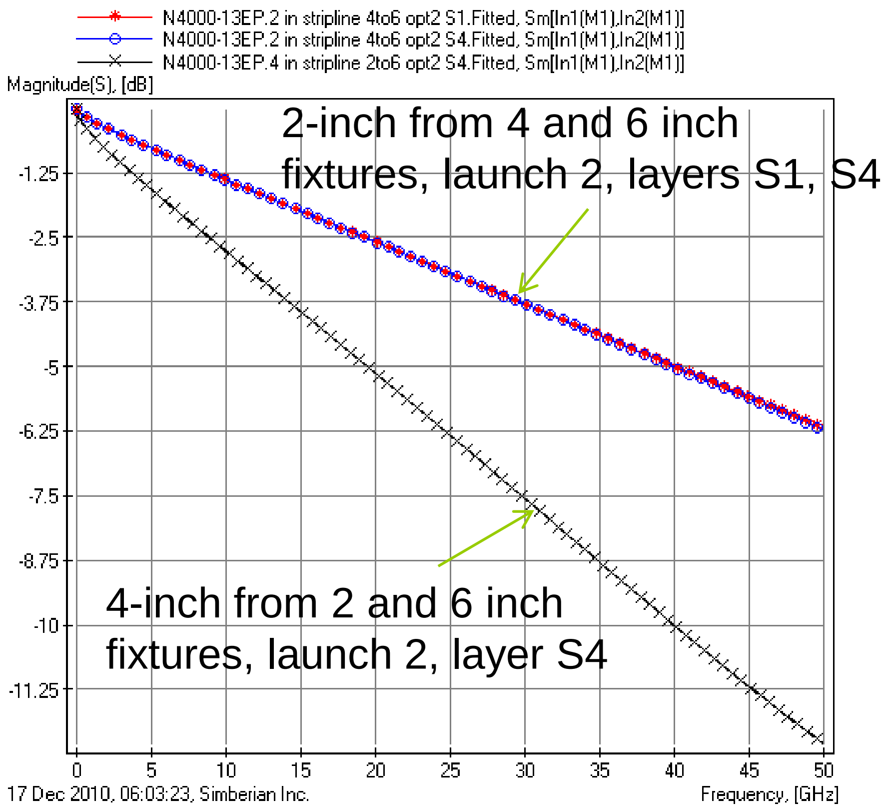
Generalized Group Delay



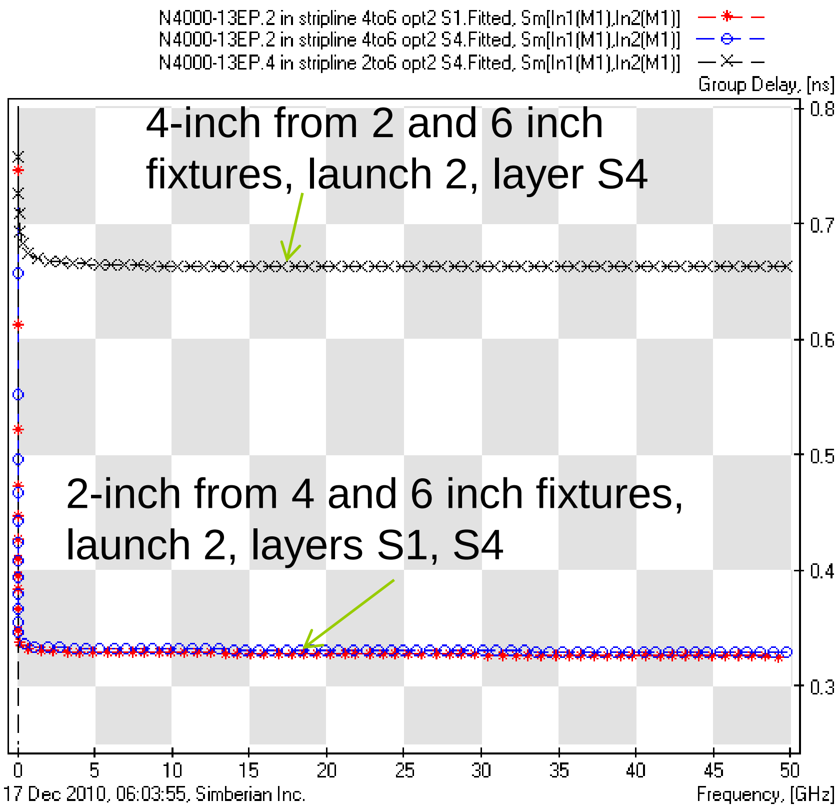
Already suitable for the identification, but can be further improved with post-processing

Fitted GMS-parameters from 3 best pairs

Generalized Insertion Loss

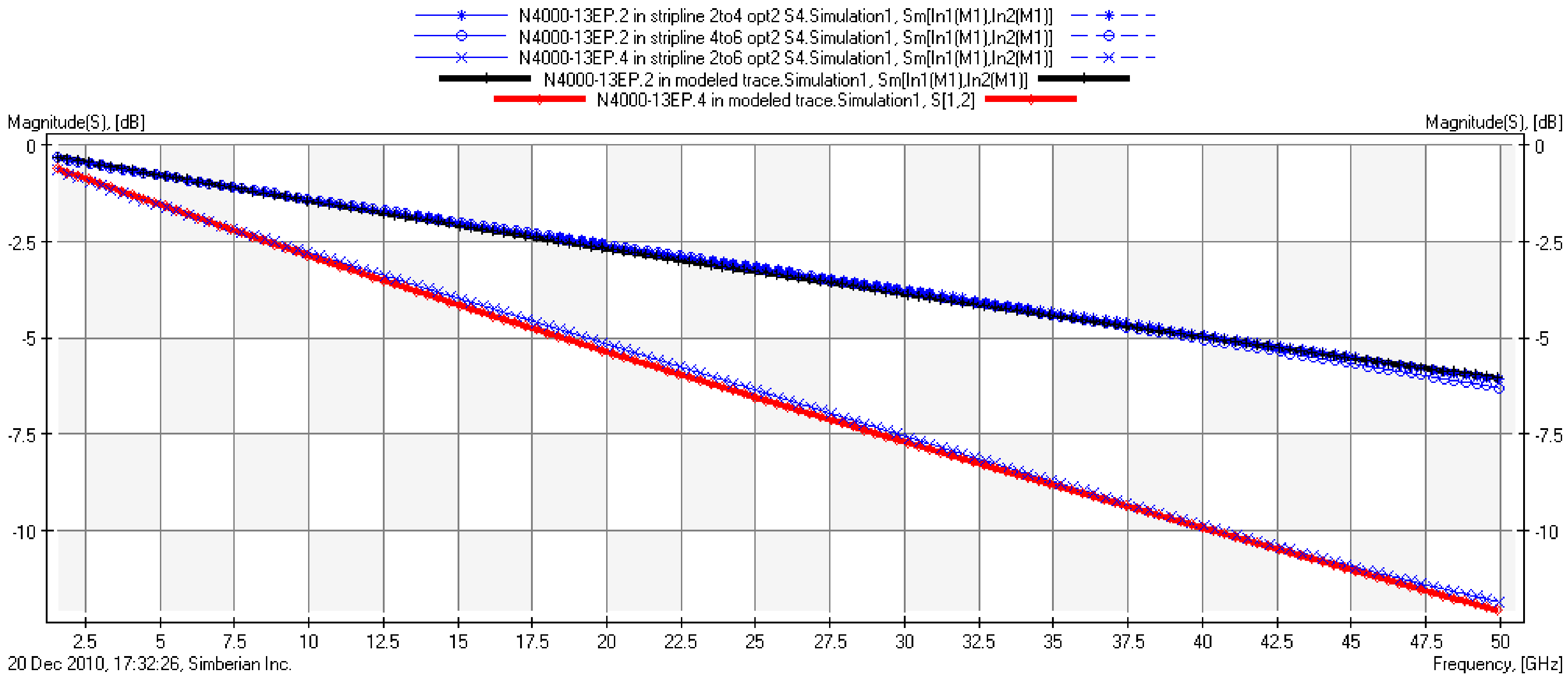


Generalized Group Delay



Now data are suitable for precise characterization of materials!

Final match after adjustment of Dk/LT and roughness parameters



Enquire Teraspeed for dielectric parameters or do it yourself!

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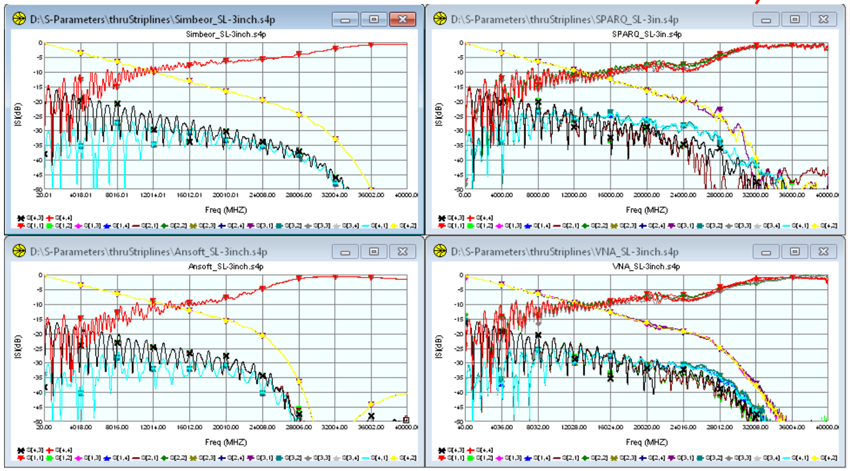
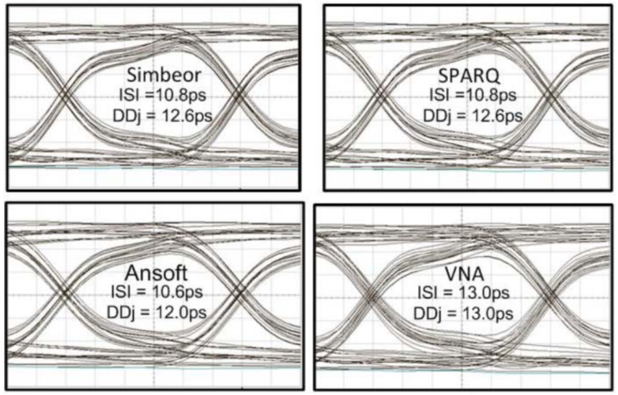
CMP-08 (designed with Simbeor)

- **Validation board with coupled microstrip and strip structures** available from Wild River Technology LLC
- J. Bell, S. McMorrow, M. Miller, A. P. Neves, Y. Shlepnev, Unified Methodology of 3D-EM/Channel Simulation/Robust Jitter Decomposition, DesignCon2011 (also App Note #2011_02 at www.simberian.com)

Good correspondence up to 30 GHz for almost all 38 test structures!



3 inch Differential Stripline Comparison of Noiseless Eye Diagrams, ISI and DDj jitter figures.

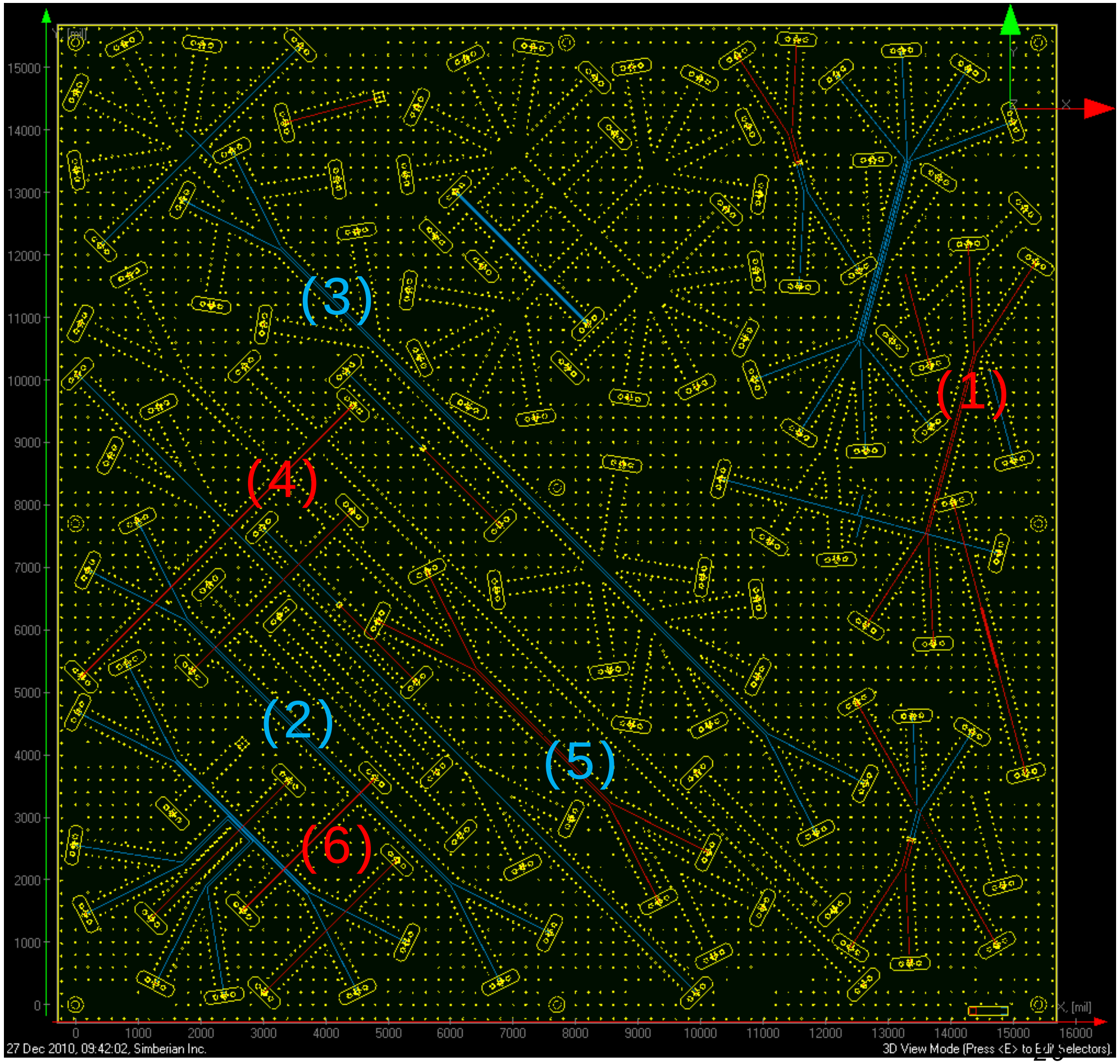


Microstrip line structures

(1) – 3 in coupled line
(2) – 6 in coupled line
(3) – 11 in coupled line
(4)-(6) SE microstrip lines

Top – red
Bottom - blue
GND - yellow

Identify solder mask & prepreg



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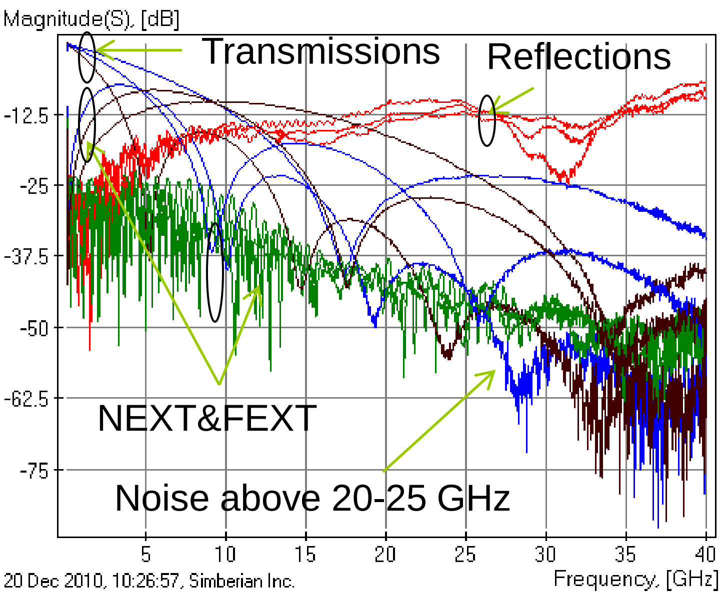
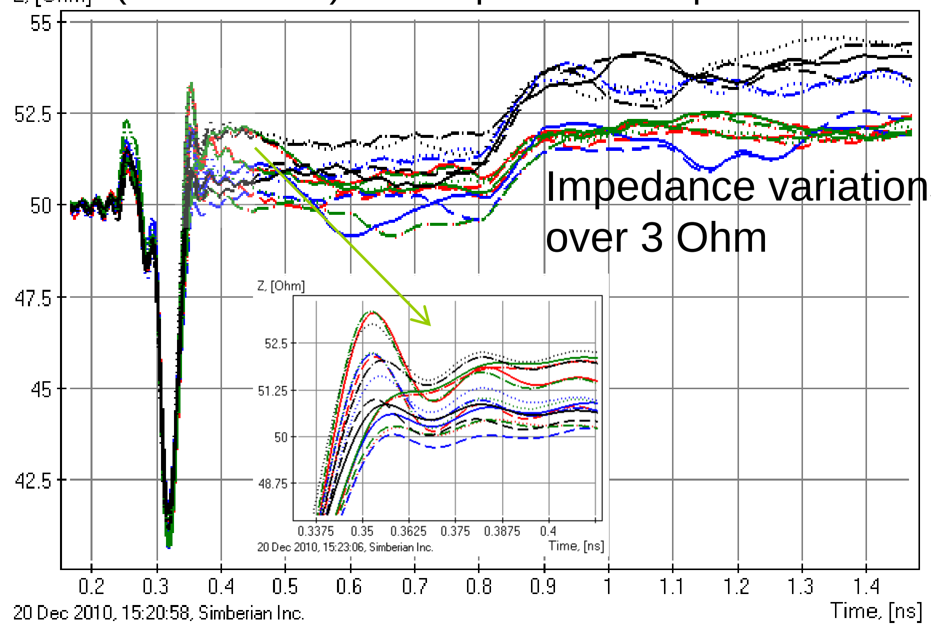
Coupled microstrip line structures

- 3, 6 and 11 in fixtures with coupled microstrip line sections – 3 pairs for identification:

Measured S-parameters
(1-st row of S-matrix for all 3 fixtures)



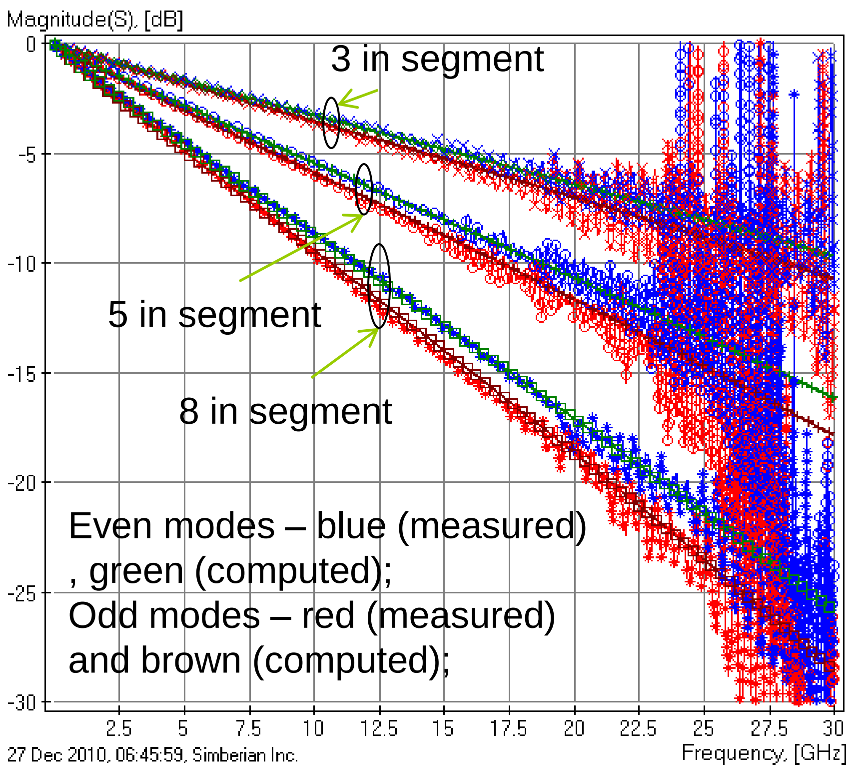
TDR of all 3 fixtures and all ports computed from measured S-parameters with rational macro-model (RMSE<0.03) and 20 ps Gaussian pulse



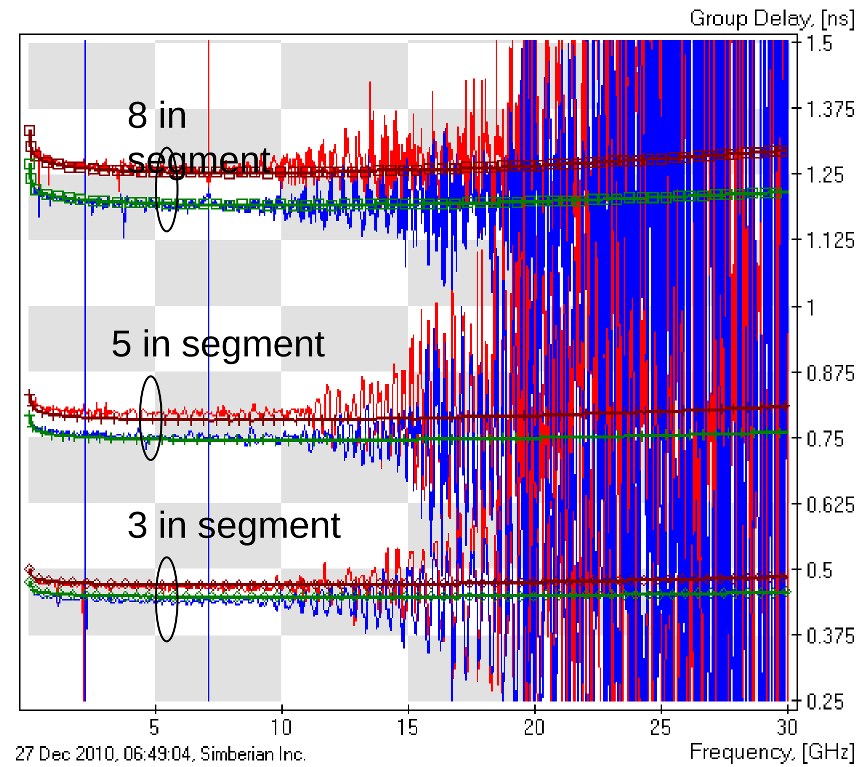
Large variations of impedance profile may distort the GMS-parameters and degrade the material identification accuracy over the whole frequency band

Matching generalized modal IL and GD for coupled microstrip segments

Generalized modal insertion loss



Generalized modal group delay



Computed GMS-parameters match measured with solder mask DK=4.5, LT=0.02 and prepreg DK=4.3, LT=0.025 at 1 GHz, WD model

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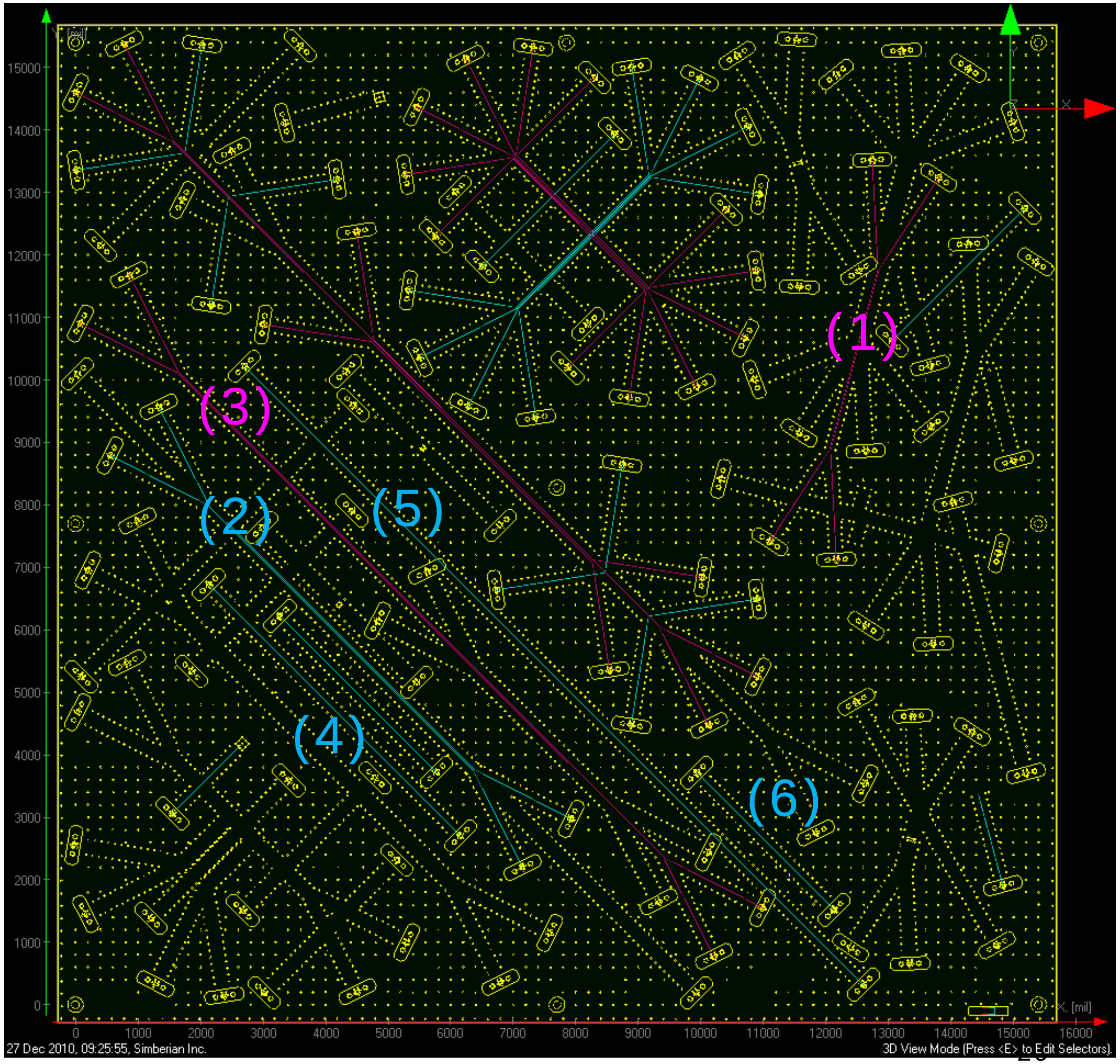
Strip-line structures

(1) – 3 in coupled line
(2) – 6 in coupled line
(3) – 11 in coupled line
(4)-(6) – SE strip lines

S3 – pink
S4 - cyan
GND - yellow

Identify core using prepreg data identified with MSL



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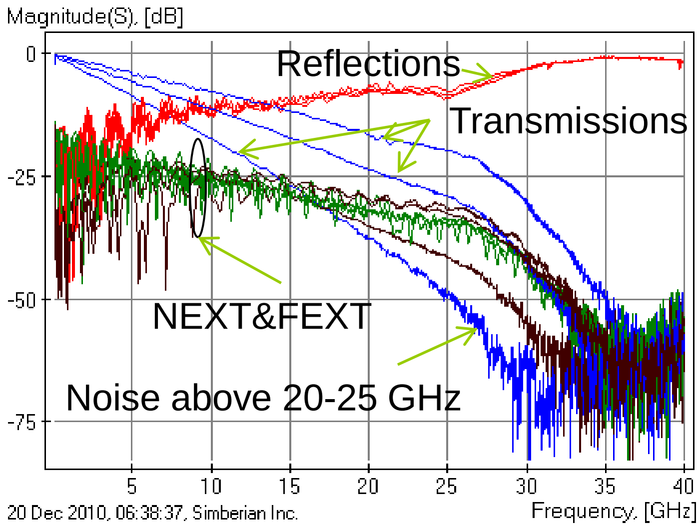
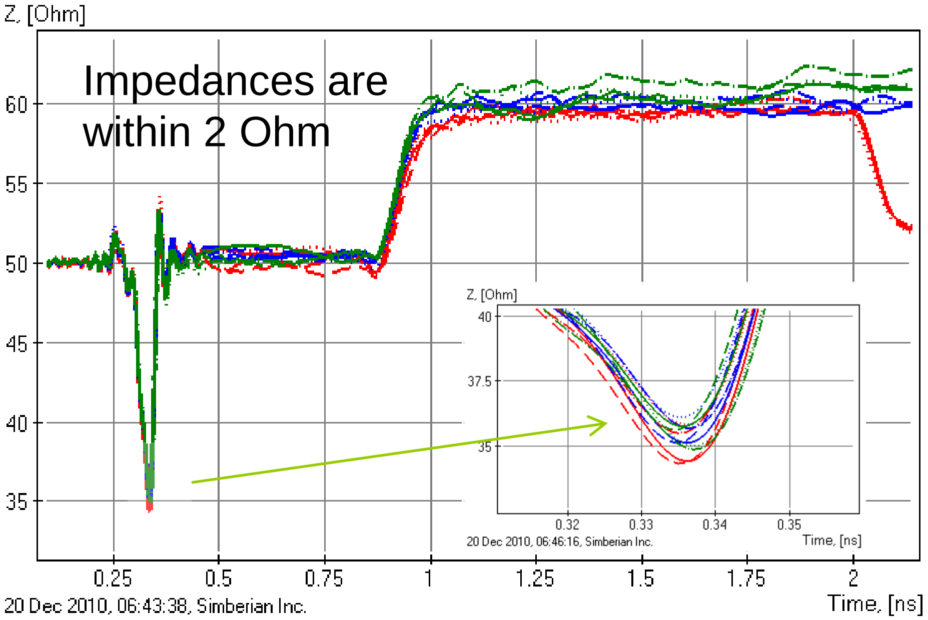
Coupled strip-line structures

- 3, 6 and 11 in fixtures with coupled strip line sections – 3 pairs for identification:

Measured S-parameters
(1-st row of S-matrix for all 3 fixtures)



TDR of all 3 fixtures and all ports computed from measured S-parameters with rational macro-model (RMSE<0.03) and 20 ps Gaussian pulse



Due to relatively large variations of impedance profile and the noise, the GMS-parameters may be distorted and accuracy of the model degraded at all frequencies

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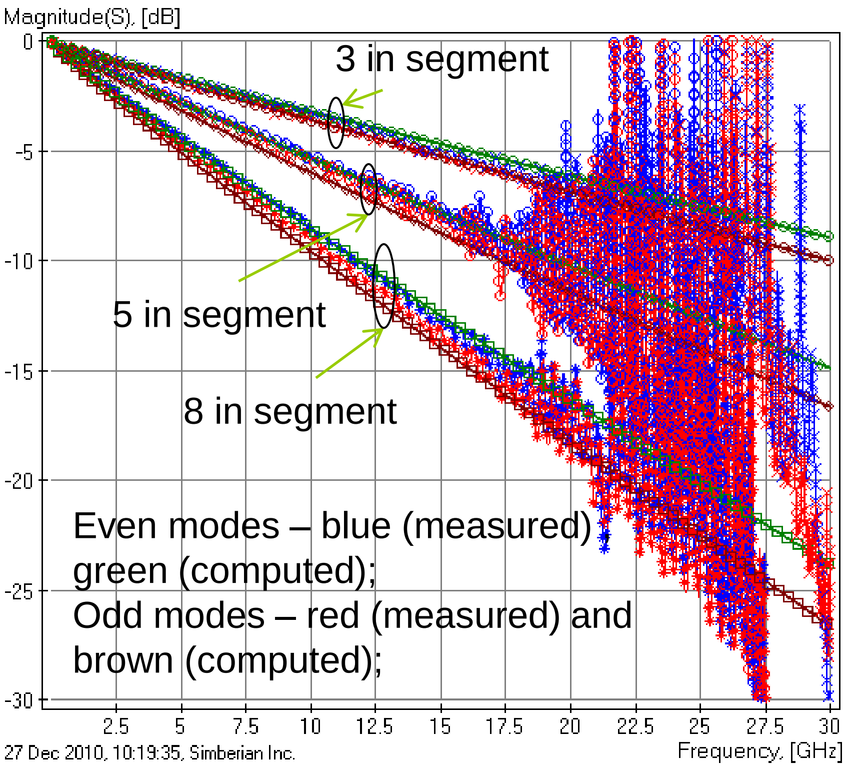
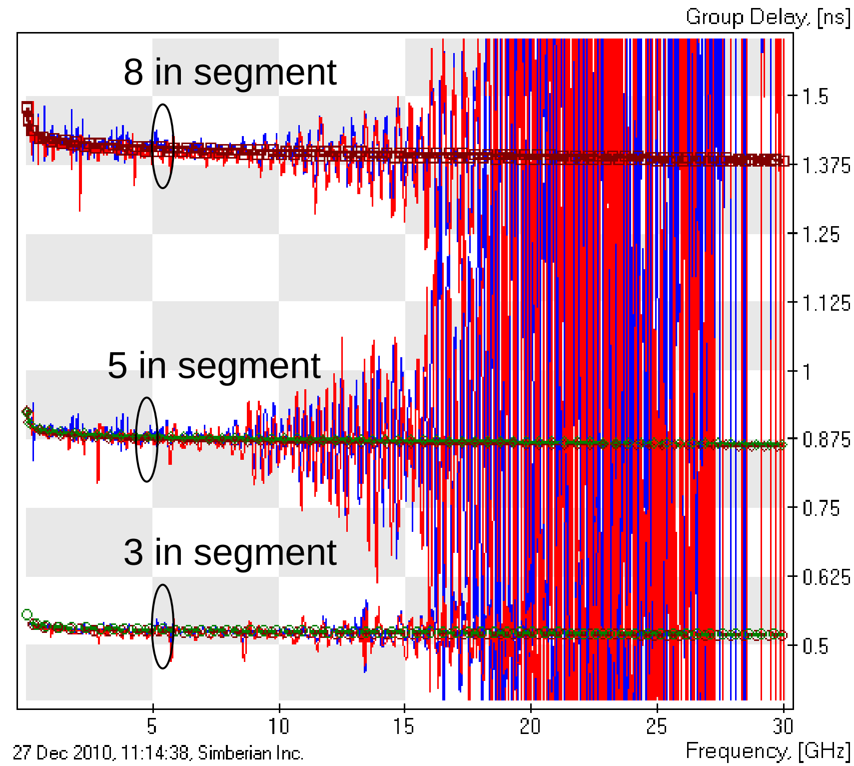
Matching generalized modal IL and GD for coupled strip line segments

Generalized modal insertion loss



Generalized modal group delay



Computed GMS-parameters match measured with core DK=4.45, LT=0.015 and prepreg DK=4.3, LT=0.025 at 1 GHz, WD model

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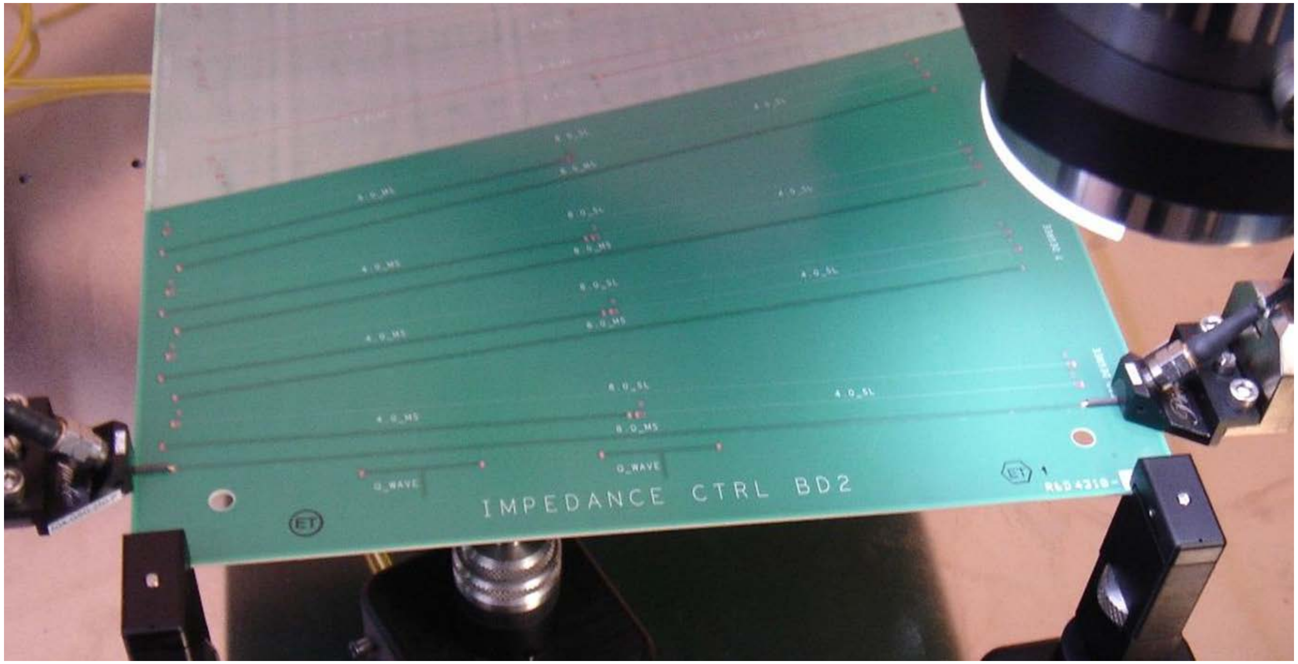
Isola's test board (designed with Simbeor)

- 8 layer stackup with two microstrip layers (Top and Bottom) and 2 strip-line layers (L3, and L6)
- Microstrip Top - TWS copper foil, 1080 prepreg, no solder mask
- Strip L3 - TWS copper foil, laminate 1080 core and prepreg
- Strip L6 – LP3 copper foil, laminate 2116 core and prepreg
- Microstrip Bottom – LP3 copper foil, laminate 2116 prepreg

Test structures – 4 and 8 inch line segment with transitions to probe pads



Initial data from specifications

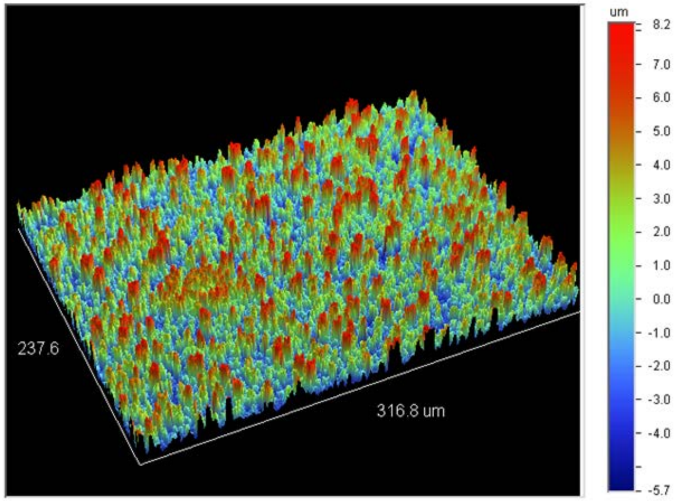
- Dk and LT or Df measured by Berezkin stripline method:

IS680 STANDARD PREPREG OFFERING					
Prepreg Designation	Resin Content (%)	Thickness (in.)	Thickness (mm)	Dk @ 2, 5 and 10 GHz	Df @ 2, 5 and 10 GHz
106	80	0.0030	0.075	2.80	0.0028
1067	80	0.0038	0.095	2.80	0.0028
1080	72	0.0040	0.100	3.00	0.0030
1086	72	0.0047	0.118	3.00	0.0030
3313	60	0.0047	0.118	3.25	0.0032
2116	58	0.0058	0.145	3.30	0.0034

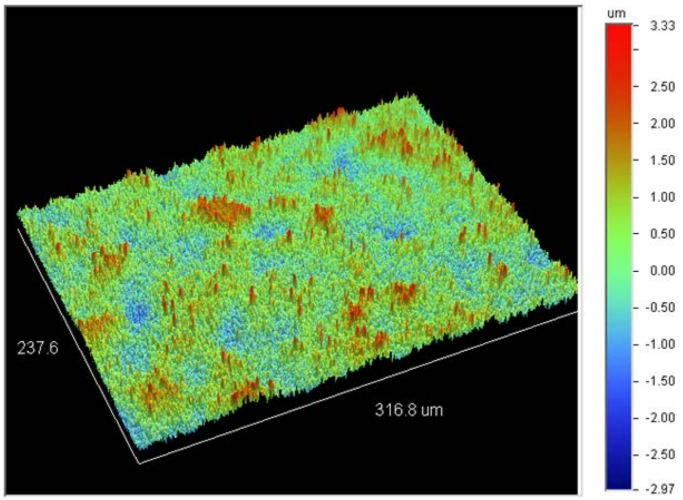
Dk +-0.05
Df +-0.0005

- Roughness parameters are measured with profilometer

TWS: Rq=2.6 um, RF=1.85

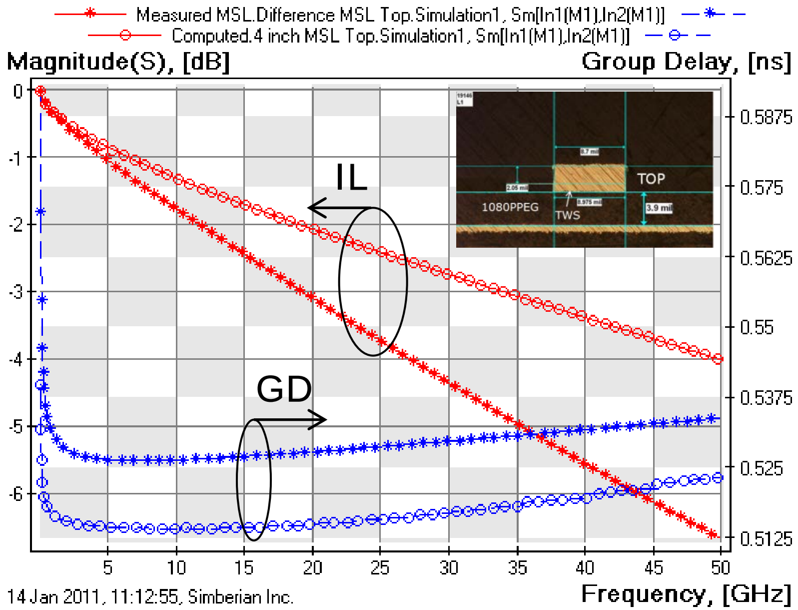


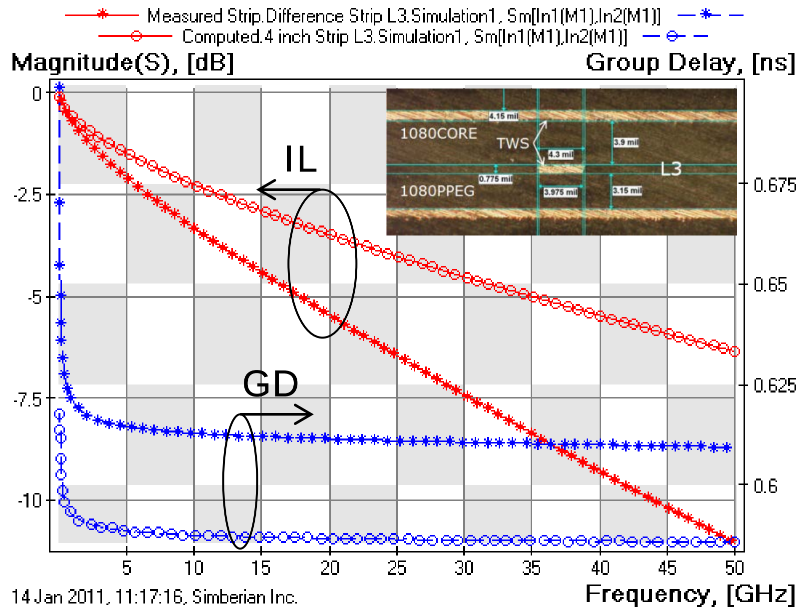
LP3: Rq=0.68 um, RF=1.3



TWS & IS680-1080 – No Roughness

- Huge difference in insertion loss (IL) and in Group Delay both in microstrip and strip-line configurations (GMS, 4-inch)

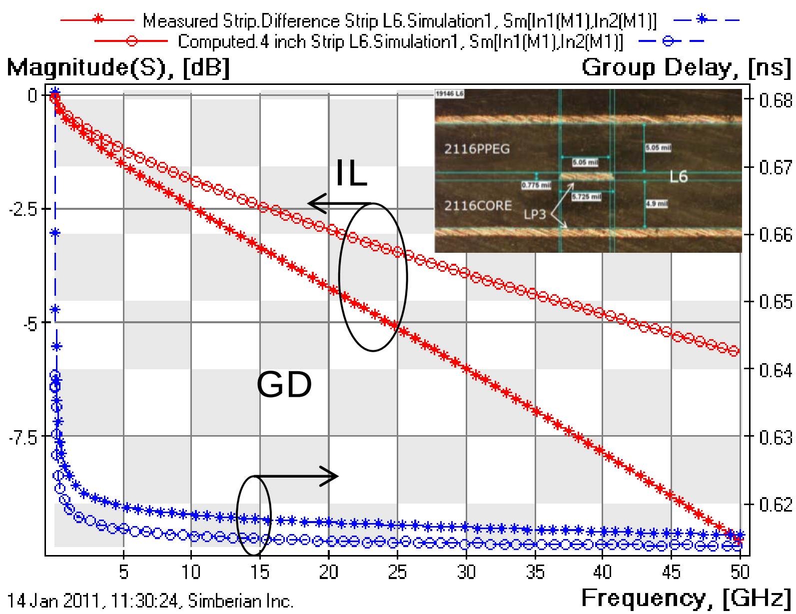


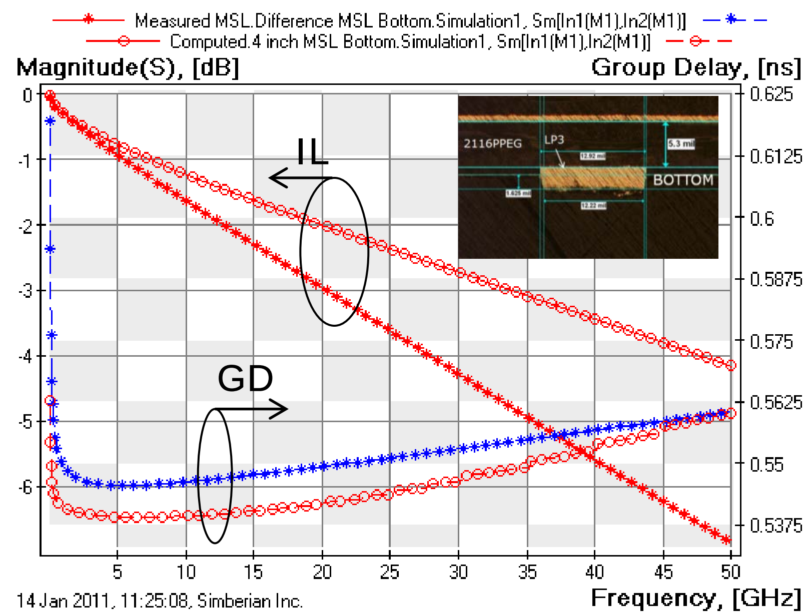


Stars – measured and fitted, Circles - modeled

LP3 & IS680-2116 – No Roughness

- Huge difference in insertion loss (IL) and relatively small in Group Delay both in microstrip and strip-line configurations (GMS, 4-inch)

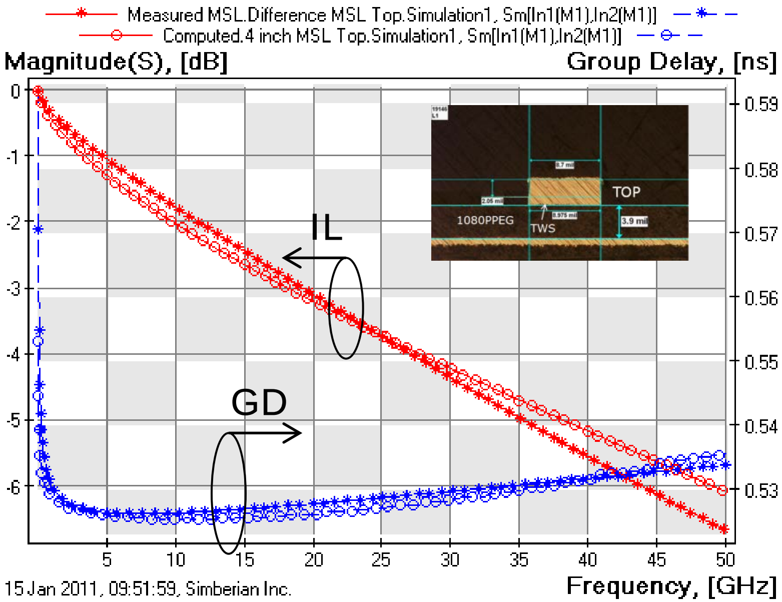


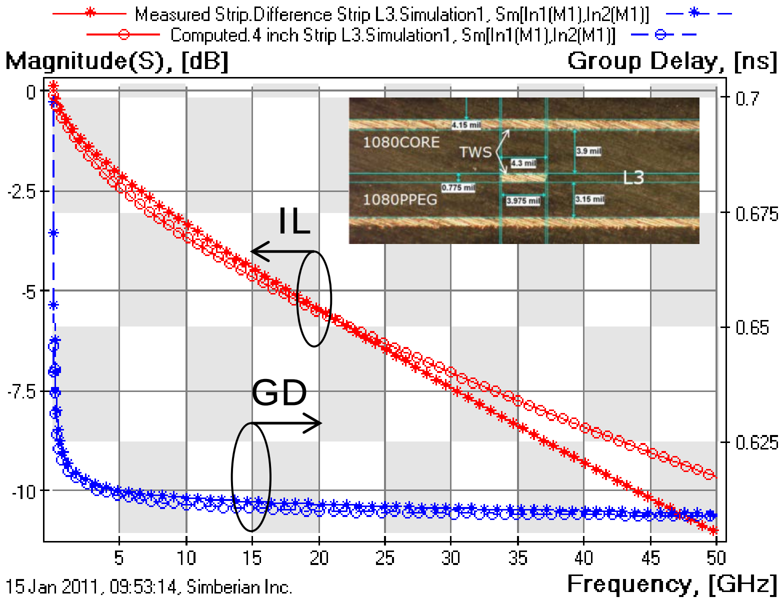


Stars – measured and fitted, Circles - modeled

TWS & IS680-1080 – Roughness from profilometer measurements

- Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core
- Roughness parameters from **profilometer**: Rq=2.6 um, RF=1.85 (25% for shiny)
- Insertion loss still does not match the measurements!

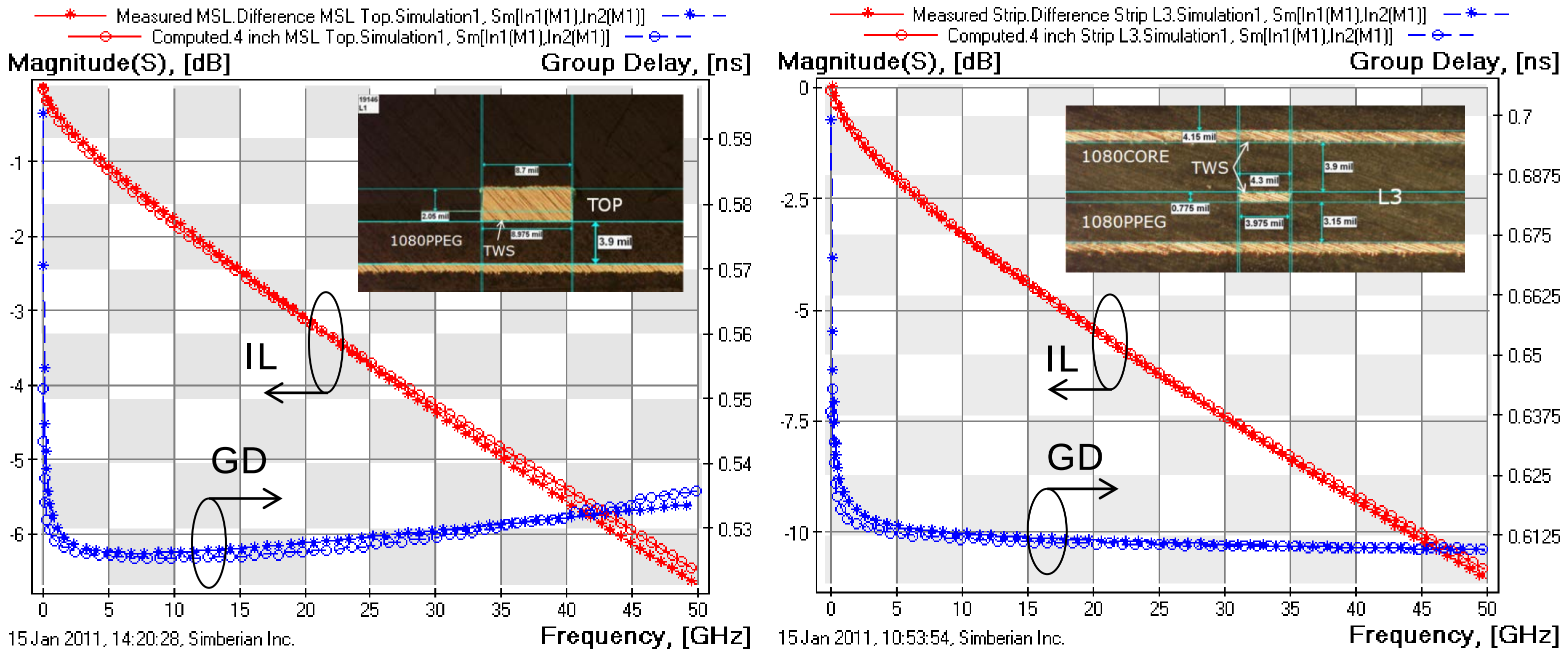




Stars – measured and fitted, Circles - modeled

TWS & IS680-1080 – Adjusted roughness parameters to fit the measurements (Simbeor)

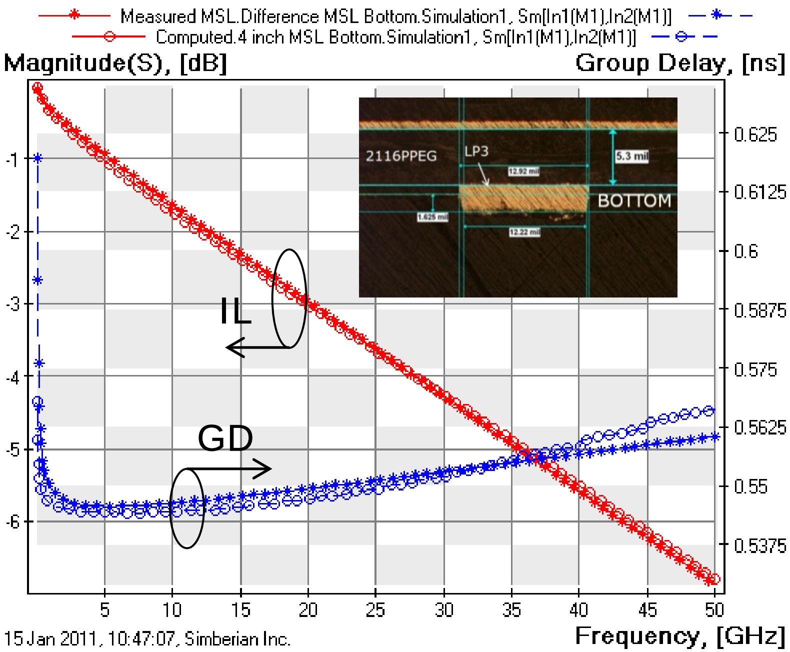
- **Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core**
- Roughness parameters: Rq=0.35 um, RF=2.8 for all surfaces
- Both insertion loss and group delay now match well!

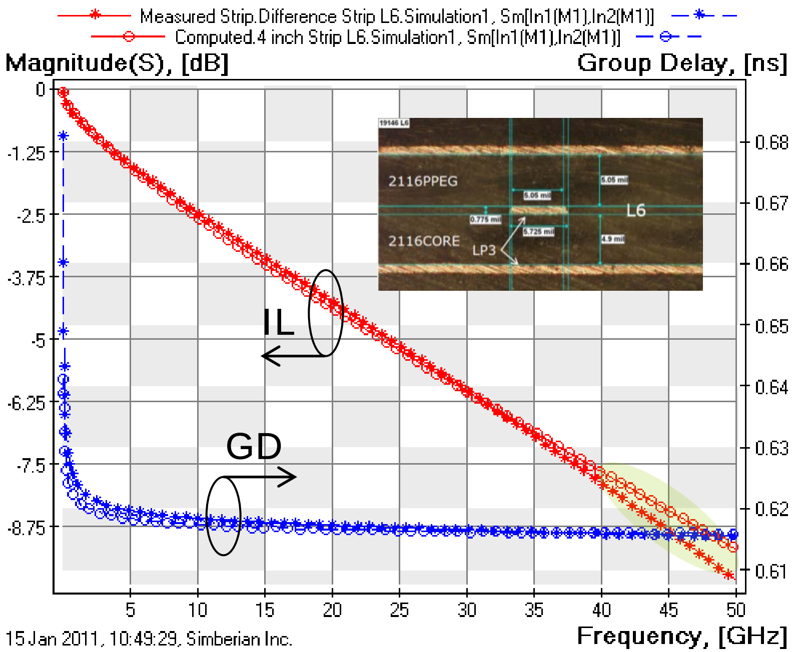


Stars – measured and fitted, Circles - modeled

LP3 & IS680-2116 – Adjusted roughness parameters to fit the measurements

- Dielectric constants are adjusted 3.3 -> 3.36 for 2116 prepreg, 3.3 -> 3.25 for 2116 core
- Roughness parameters: Rq=0.11 um, RF=7 for all surfaces
- Acceptable match for insertion loss and group delay (not perfect for strip)

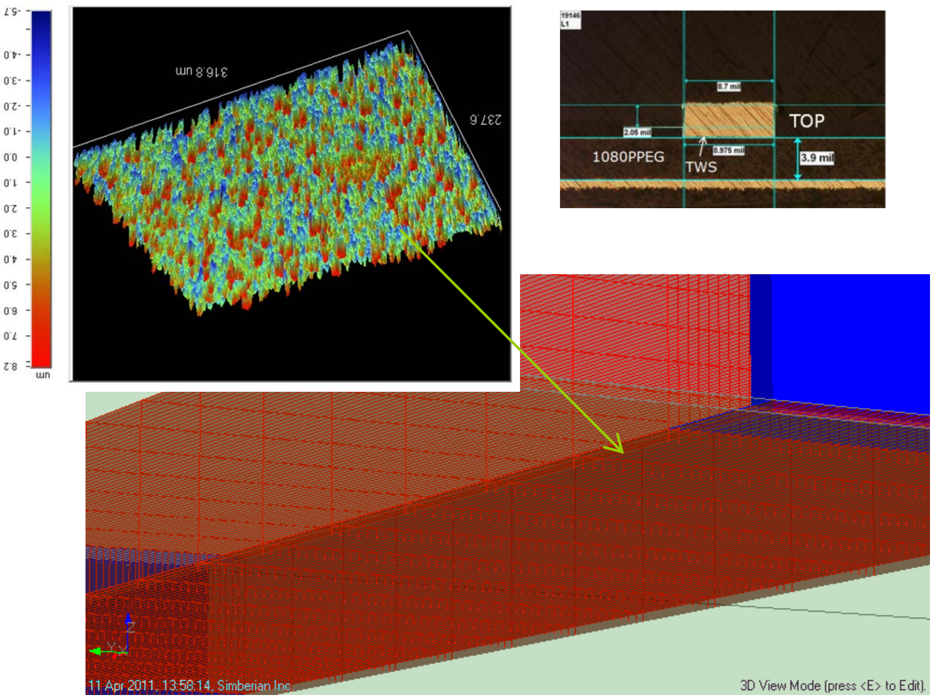


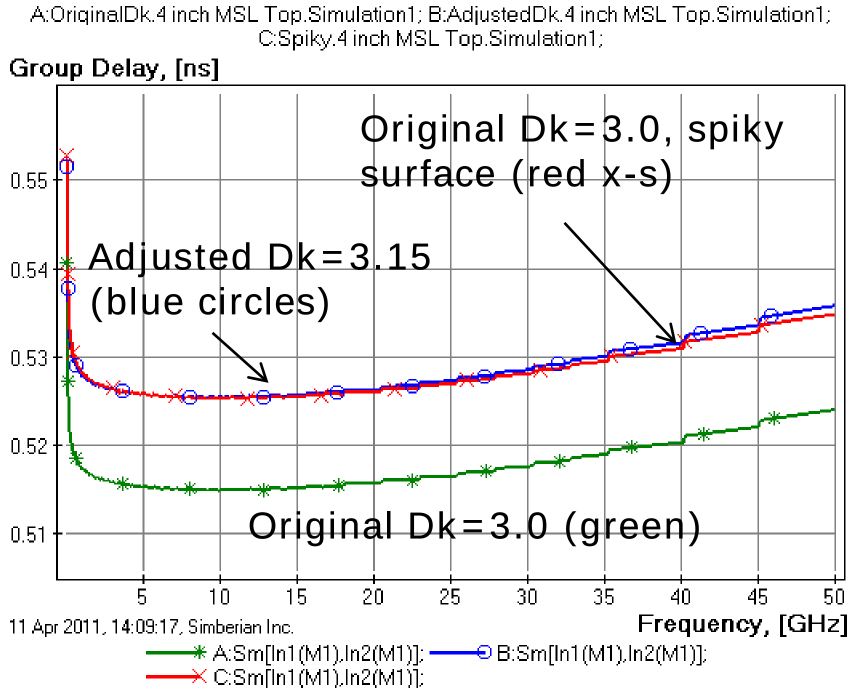


Stars – measured and fitted, Circles - modeled

Singular surface roughness model

- Multiple spikes on the surface of conductor are up to 10 um for TWS copper
- Spikes increase capacitance of the surface due to singularity of electric field
- We are dealing with **singular surfaces**





With appropriate spike size and distribution should work for any strip size without Dk adjustment

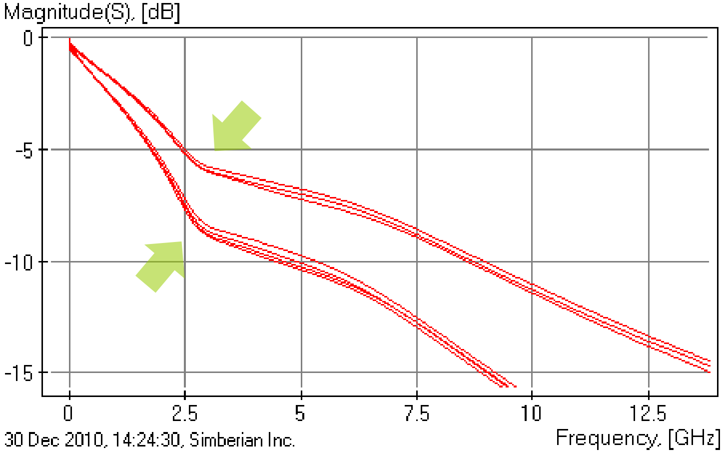
Outline

- Simbeor 2011 overview
- Material parameters identification with GMS-parameters
- Example of dielectric identification for PLRD-1 board
- Molex/Teraspeed Consulting Group board
- Wild River Technology CMP-08 board
- Roughness characterization (Isola's board)
- Nickel characterization (Teraspeed's board)
- Conclusion

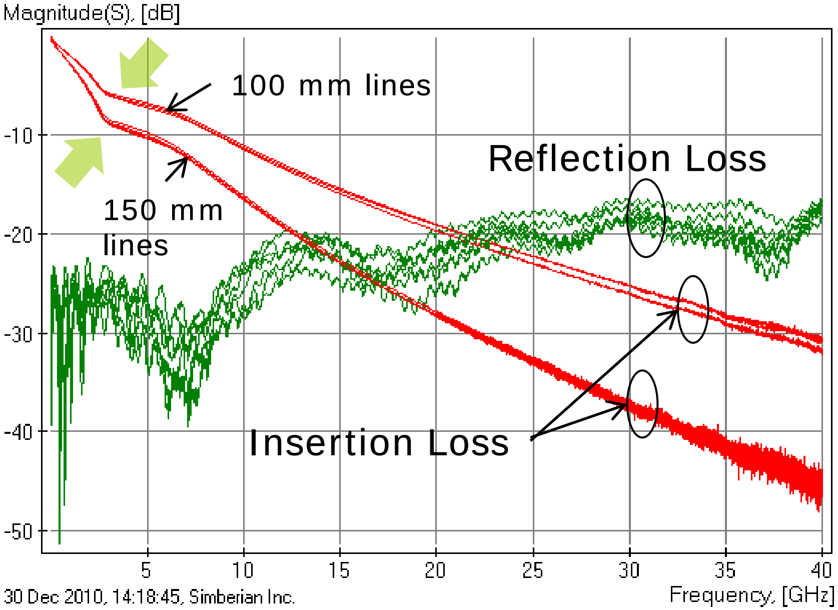
Plated nickel trace anomaly

- S-parameters of single-ended microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper

Anomaly in attenuation around 2.7 GHz – cannot be reproduced with regular metal models



S-parameters for three structures with 100 mm microstrip line segments and for four structures with 150 mm segments are plotted

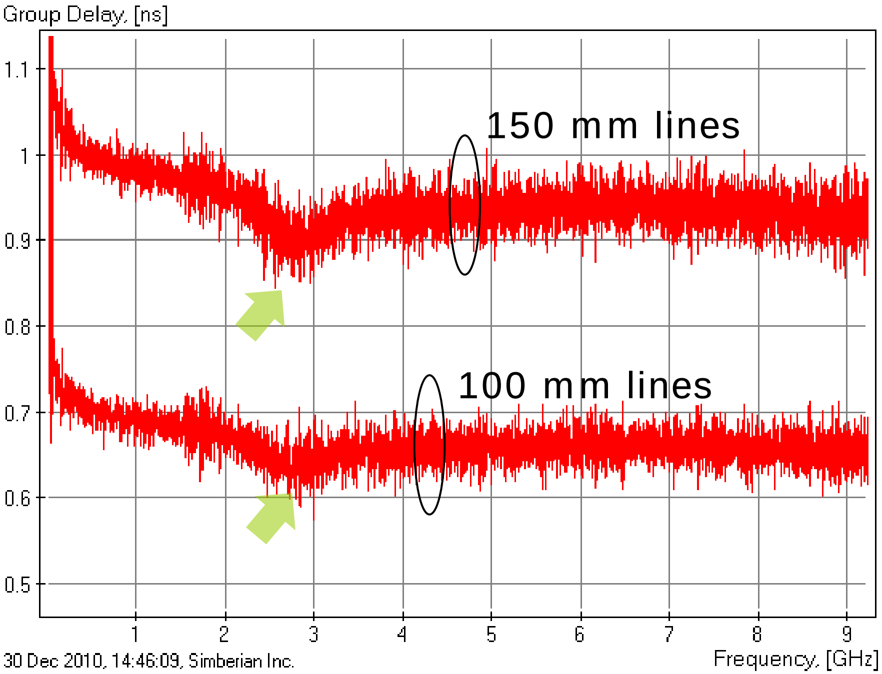


All measurements are from Teraspeed Consulting Group

Plated nickel trace anomaly

- S-parameters of single-ended microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper

Group delays for three structures with 100 mm microstrip line segments and for four structures with 150 mm segments are plotted



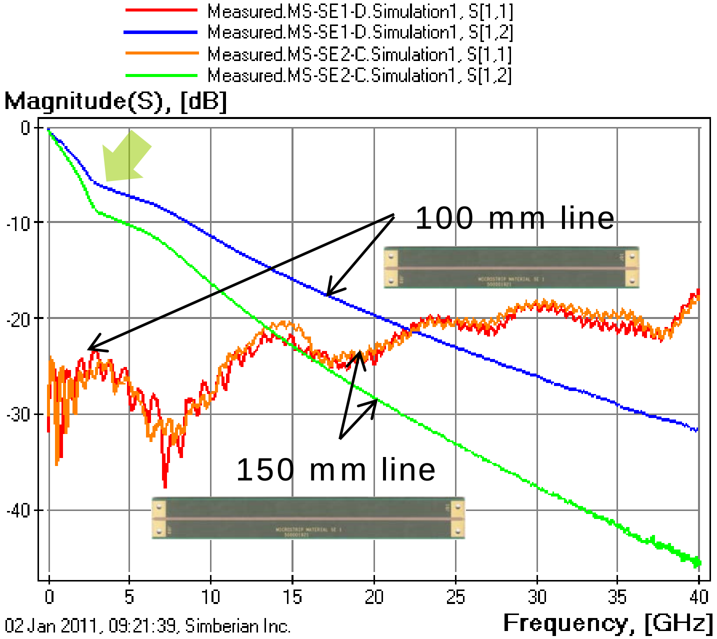
Anomaly in group delay around 2.7 GHz - not previously reported!

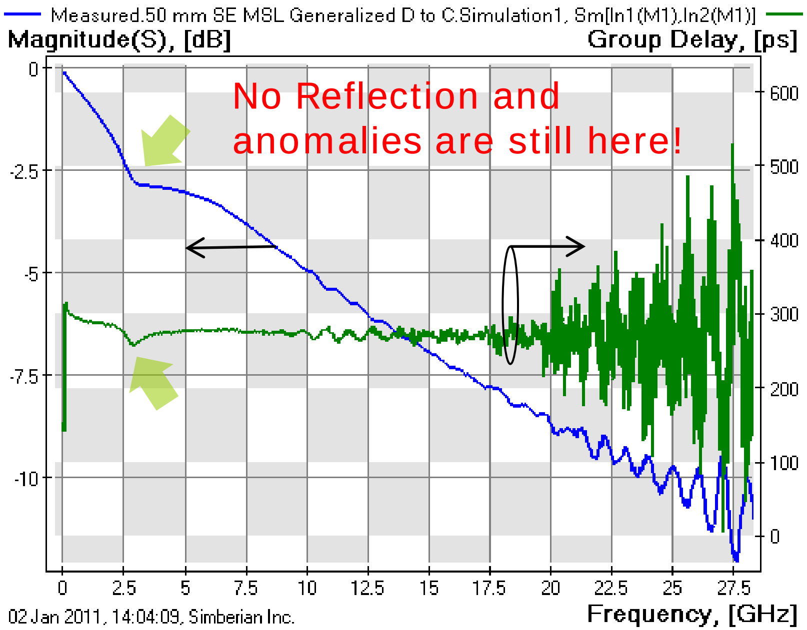
Cannot be reproduced with regular metal model

All measurements are from Teraspeed Consulting Group

GMS-parameters for nickel-plated trace

- S-parameters of reflective structures with 100 mm and 150 mm segments of microstrip line can be converted into GMS-parameters of 50 mm segment



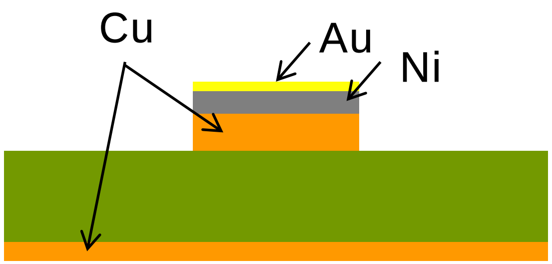


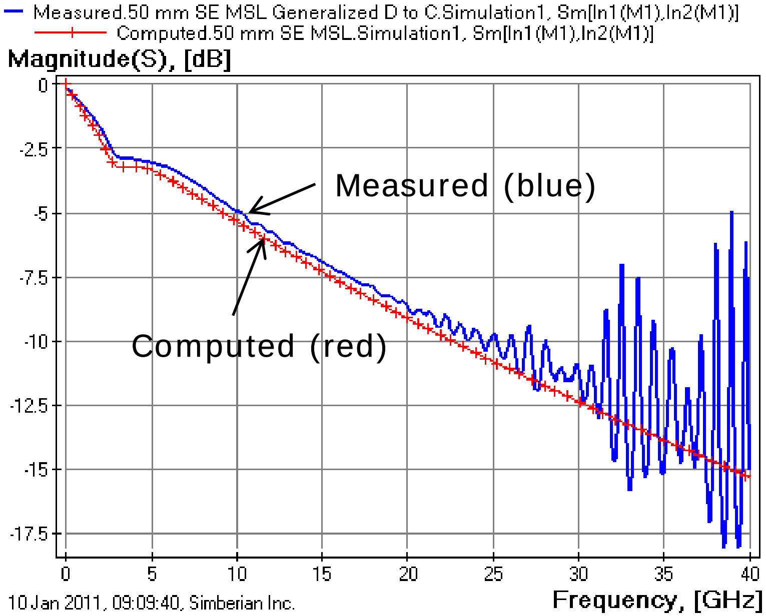
GMS-parameters are noisy at high frequencies due to non-identities of probes/launches and cross-sections of two test structures (see more on sensitivity in app note #2010_03, www.simberian.com)

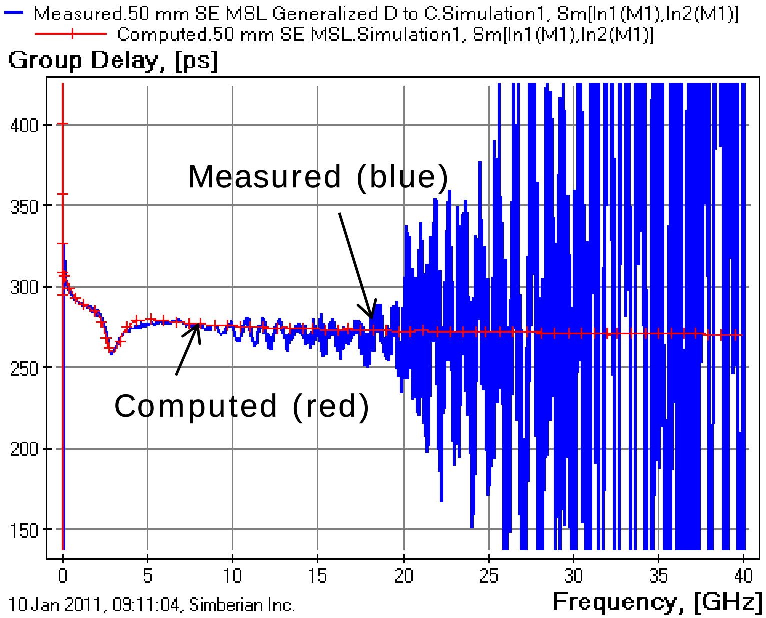
Plated nickel model identification

- Adjust Ni model parameters to match measured and computed GMS-parameters for 50 mm segment of microstrip line, strip width 69 um, thickness 12 um

ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper
Substrate dielectric DK=3.x and LT=0.01x at 1 GHz, wideband Debye model
Landau-Lifshits model for Nickel: Mul=5.7, Muh=1.4, f0=2.5, dc/f0=0.22, relative resistivity 3.75

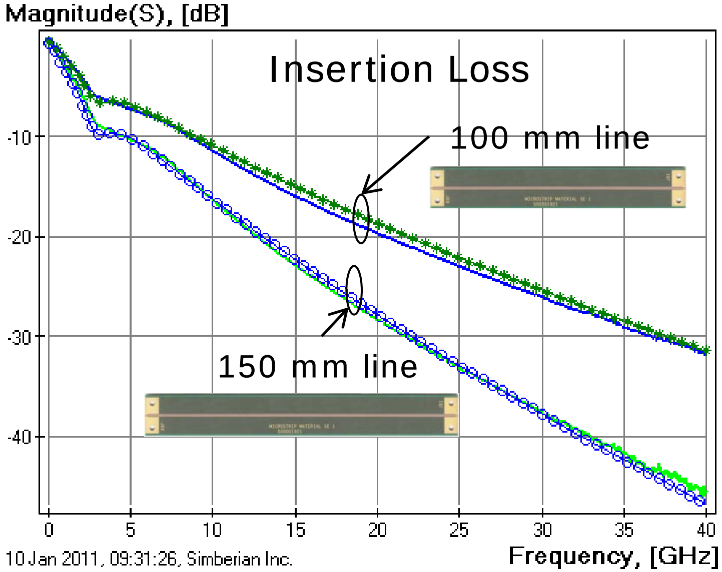


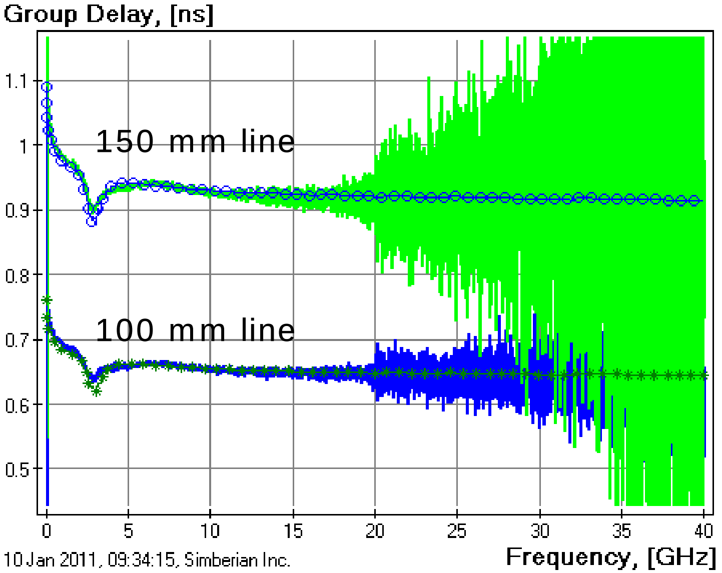




S-parameters of test structures

- Nickel: resistivity 6.46e-8 Ohm*meter, Landau-Lifshits Permeability Model: Mul=5.7, Muh=1.4, f0=2.5, dc/f0=0.22

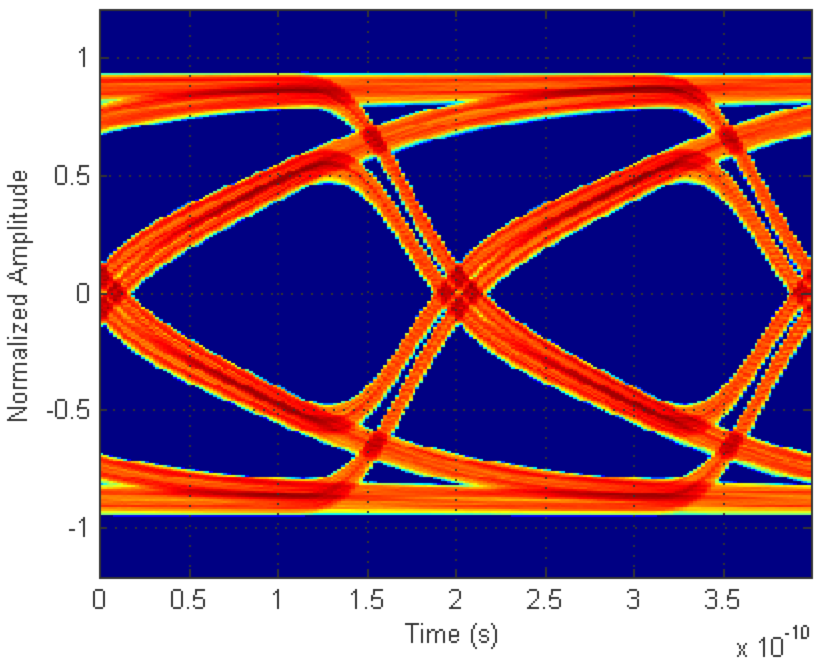




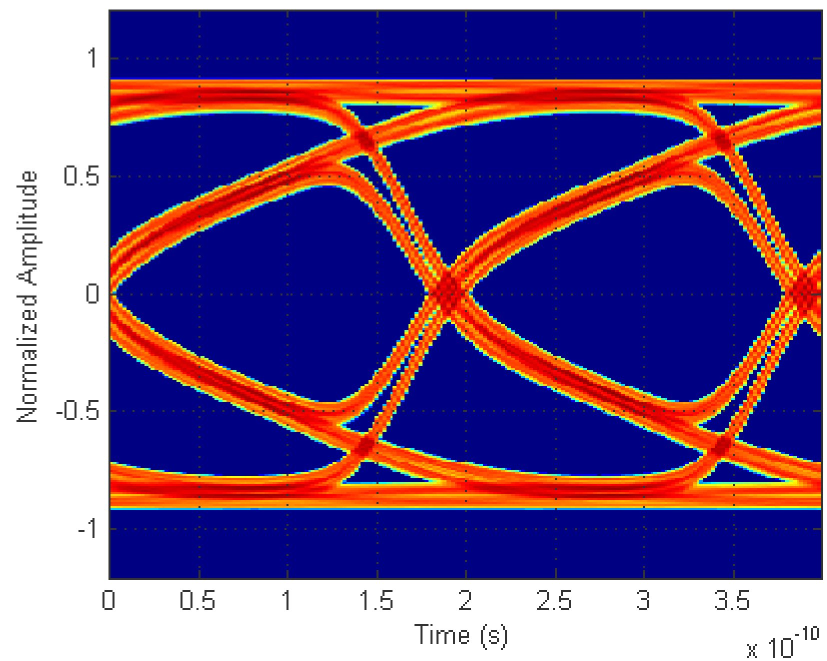
Measured – solid lines
Modeled – stars and circles

5 Gbps signal in structure with 150 mm line

Measured

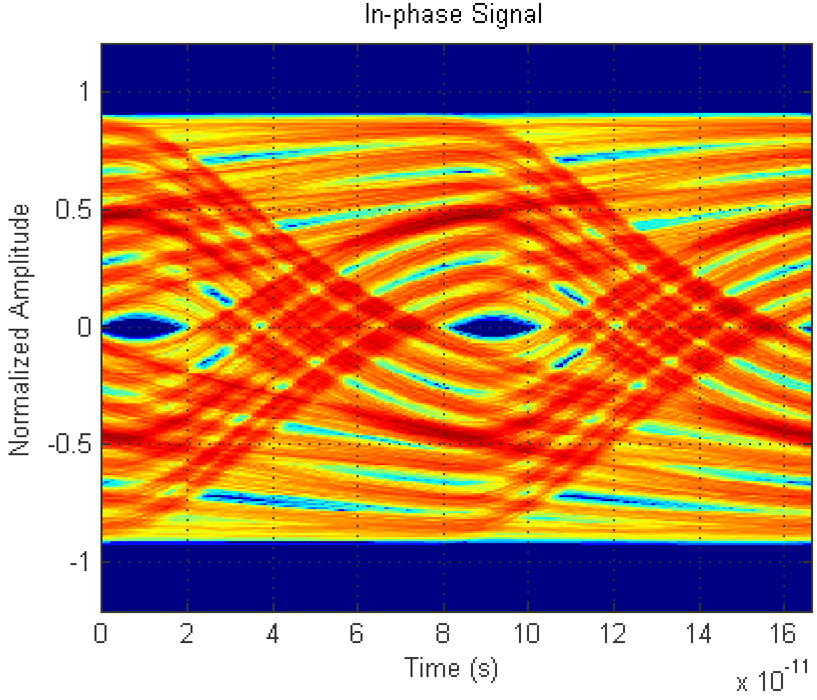


Modeled

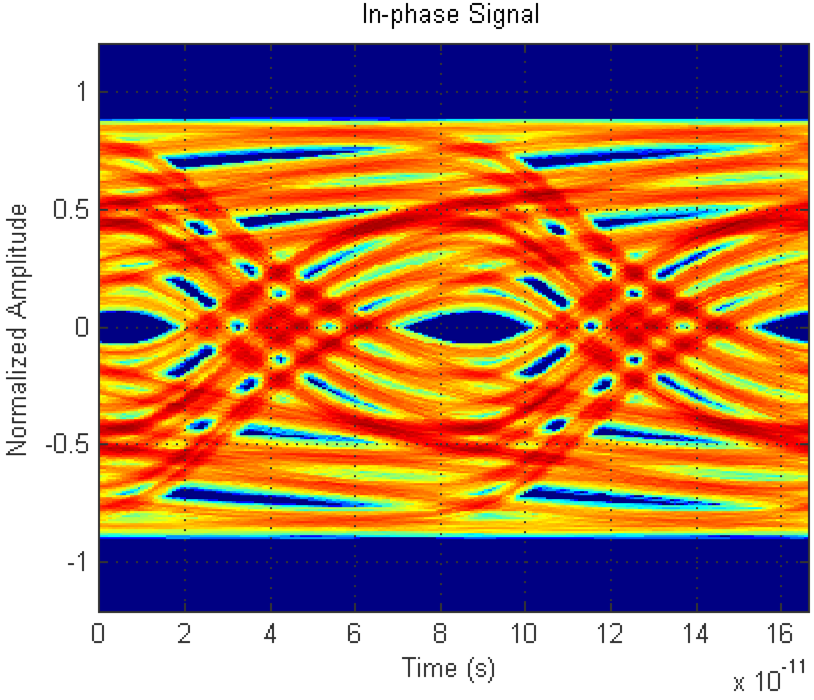


12 Gbps signal in structure with 150 mm line

Measured



Modeled



Conclusion

- Material parameters identification with GMS-parameters is simple and accurate
- Any project must start from the dielectric and roughness parameters identification
- The identification procedure is automated with optimization in Simbeor 2012
- Measured S-parameters have to be pre-qualified
  - Pass the quality metrics in Simbeor TA
  - Have consistent impedance on TDR plots

References

- All are available at http://www.simberian.com/AppNotes.php
- 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 (App Note #2010_01)
- Sensitivity of PCB Material Identification with GMS-Parameters to Variations in Test Fixtures, Simberian App Note #2010_03
- Material Identification With GMS-Parameters of Coupled Lines, Simberian App Note #2010_04
- J. Bell, S. McMorrow, M. Miller, A. P. Neves, Y. Shlepnev, Unified Methodology of 3D-EM/Channel Simulation/Robust Jitter Decomposition, DesignCon2011, (App Note #2011_02)
- D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011 (App Note #2011_03)

About Simberian Inc.

- Mission
  - Build easy-to-use, efficient and cost-effective electromagnetic software for high-speed electronic design automation
- Incorporated in USA on February 28, 2006
  - Founder and President Yuriy Shlepnev
    - PhD in in computational electromagnetics
    - Over 25-years experience in building electromagnetic software
- Development in Las Vegas, USA, Novosibirsk, St. Petersburg and Voronezh Russia
- Location and contacts
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  - Web: www.simberian.com
  - Support knowledge base www.kb.simberian.com