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Electromagnetic Solutions

Electromagnetic Analysis of AC Coupling Capacitor Mounting Structures

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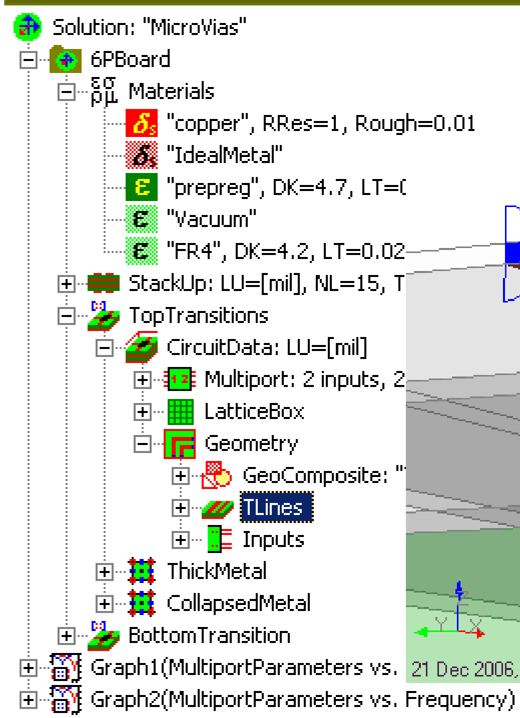

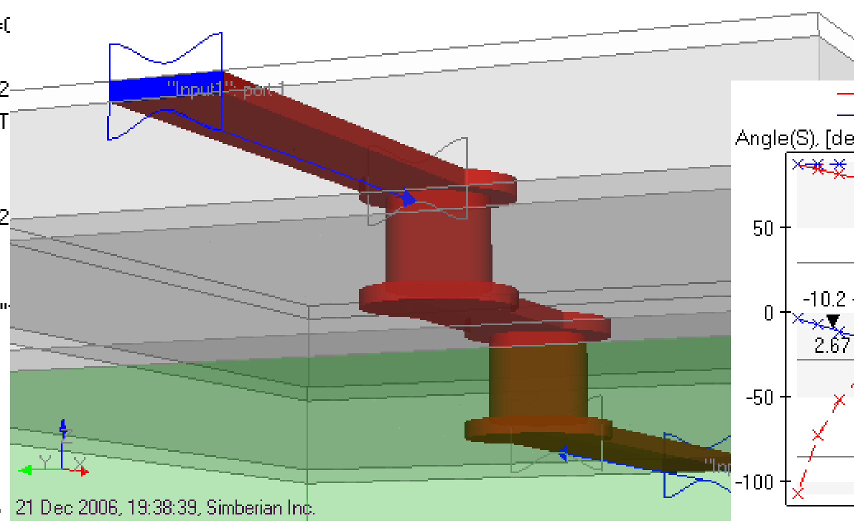

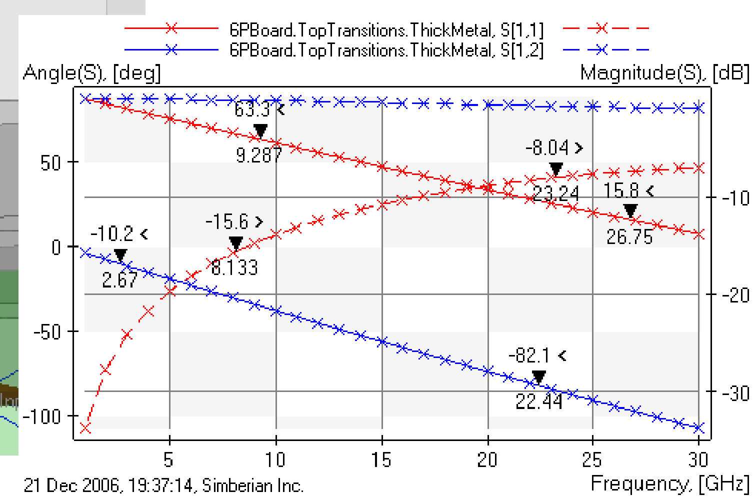

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Overview

- Introduction
- De-compositional analysis of a channel with AC decoupling capacitors
- Constructing internal ports to connect lumped or distributed components
- Validation of internal port model with experimental data
- Building models for AC capacitor mounting structures for a single-ended channel
- Building models for AC capacitor mounting structures for a differential channel
- Conclusion

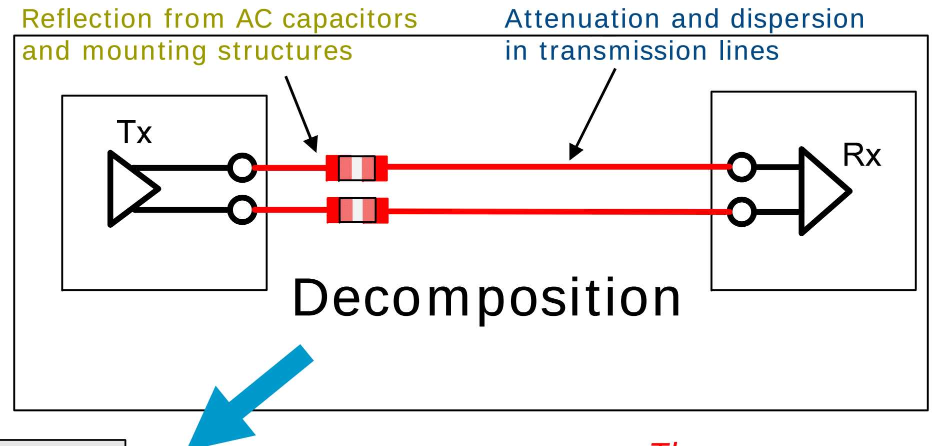
Introduction

- Serial multi-gigabit data channels usually have capacitors connected in series either in single-ended micro-strip or differential micro-strip lines to pass through the high-frequency signals content and to allow different DC supply for a driver and receiver at the same time
  - Such capacitors are often called AC coupling capacitors
  - Mounting structures of such capacitor and capacitors themselves are discontinuities and have to be accounted for in a system-level analysis
  - Accurate models for the AC coupling capacitor mounting structures can be built with a 3-D full-wave electromagnetic solver
- This example demonstrates how to build 3D full-wave models for the AC coupling capacitor mounting structures and how to build a system-level model of a simple channel with AC coupling capacitors
- Simbeor 2007 electromagnetic solver from Simberian Inc. and HyperLynx+Eldo system-level solver from Mentor Graphics are used to generate the results

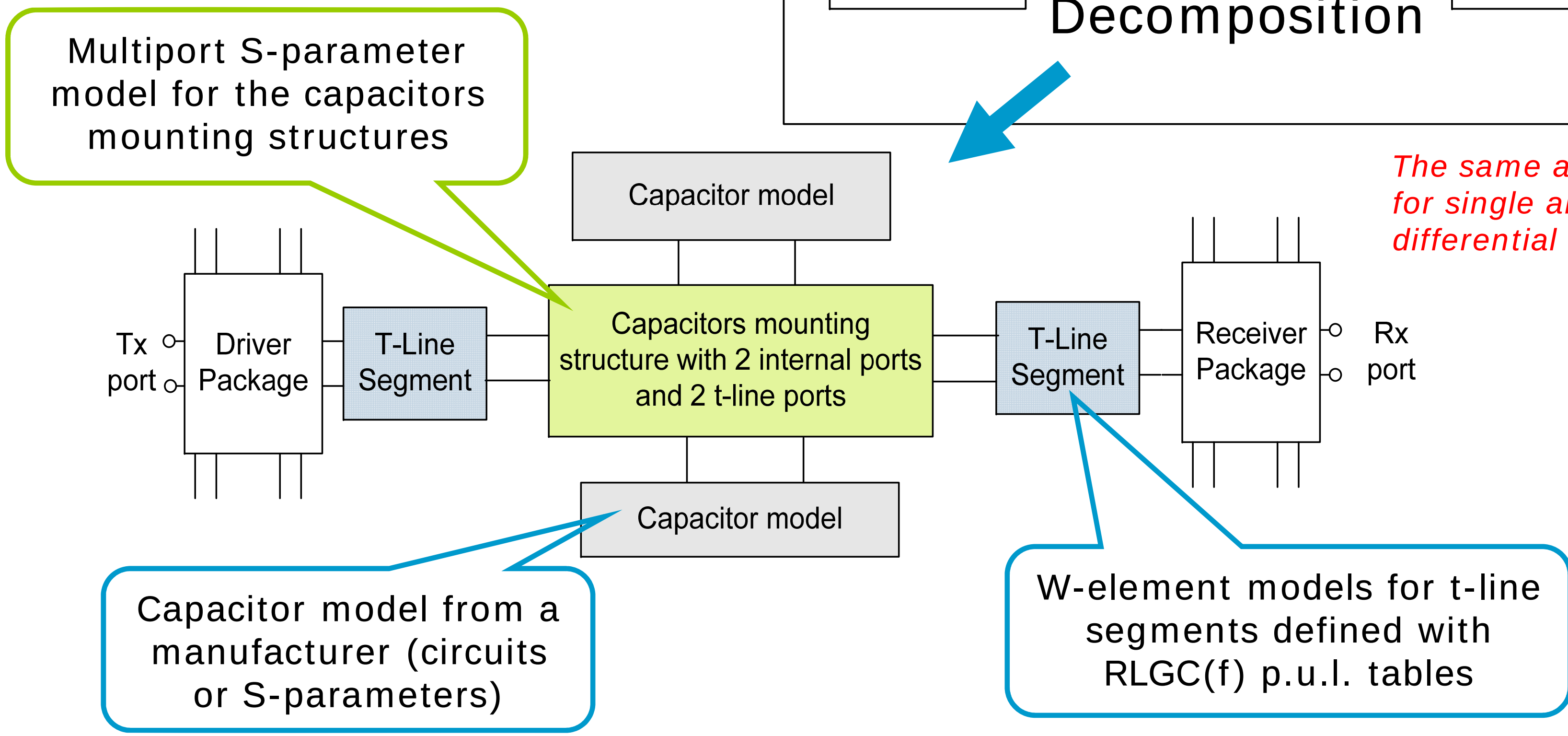
De-compositional analysis of a serial multi-gigabit channel with AC coupling capacitors

3-D full-wave electromagnetic analysis is required to generate models both for the mounting structure and transmission lines!

We will use Simbeor to do it.

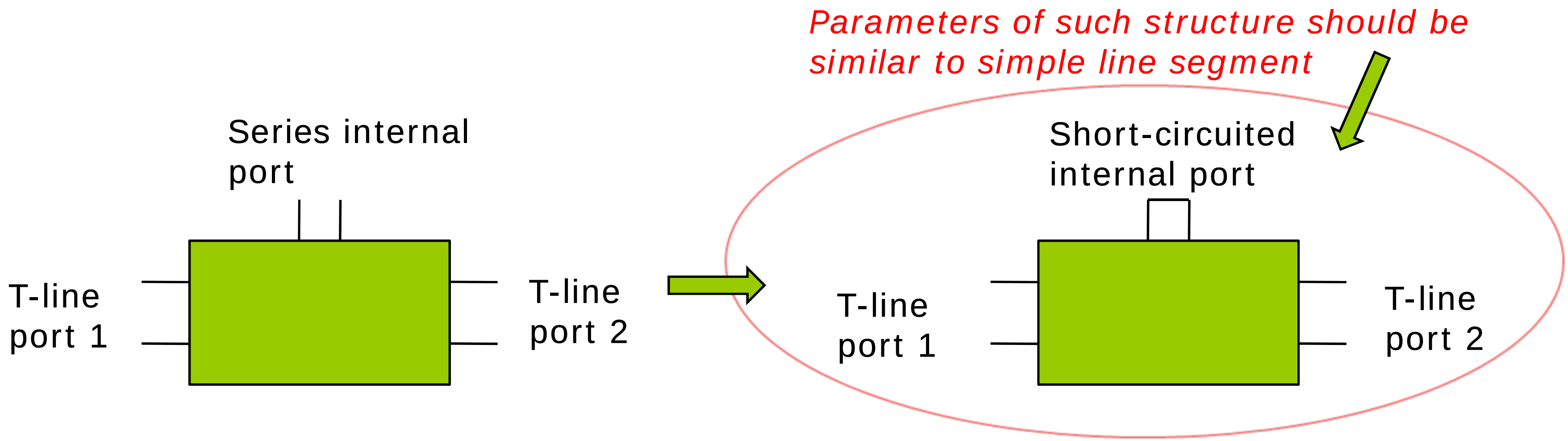


The same approach for single and differential channels



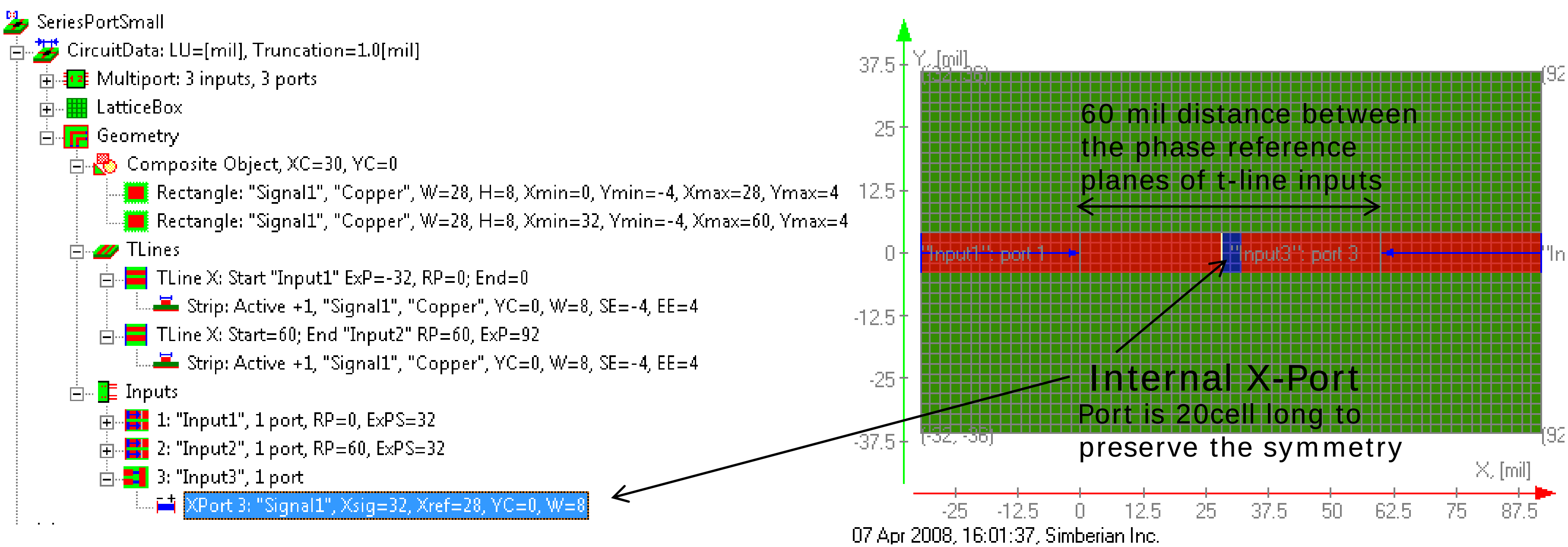
Internal port concept

- Internal or lumped ports can be constructed and used to connect models of the capacitors or other components with external models
- Before investigating the capacitors mounting structures, we construct and investigate behavior of the internal ports
  - Solution LumpedPorts.esx created to do this investigation (link to the file with all zipped solutions is on the last page)
  - Micro-strip line with 8-mil wide strip on 4.5 mil substrate with DK=4.2 and LT=0.02 are used for all experiments with the internal ports
  - We construct a set of structures with different internal ports and perform numerical experiments with predictable results such as shown below:



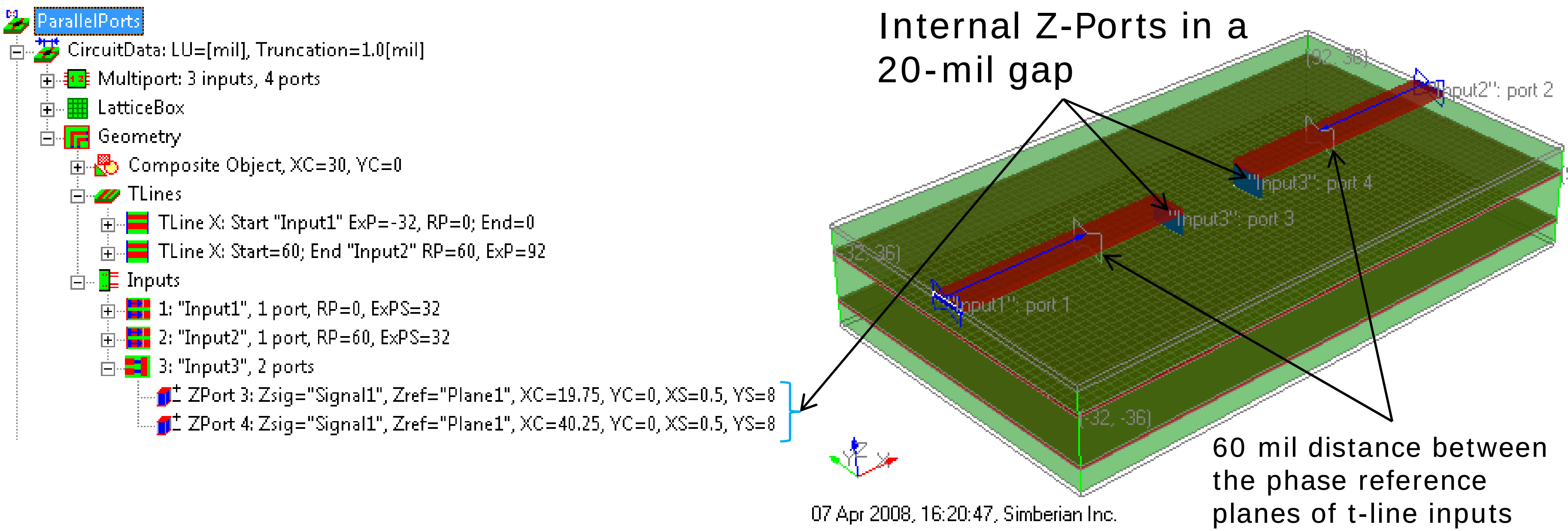
Series internal ports (SeriesPortSmall)

- Connected into a strip-line in series
- Ports can be as small as possible (down to 1 cell along the port) or correspond to a footprint of a lumped component to be connected
- The results of analysis are S-parameters of 3-port multiport



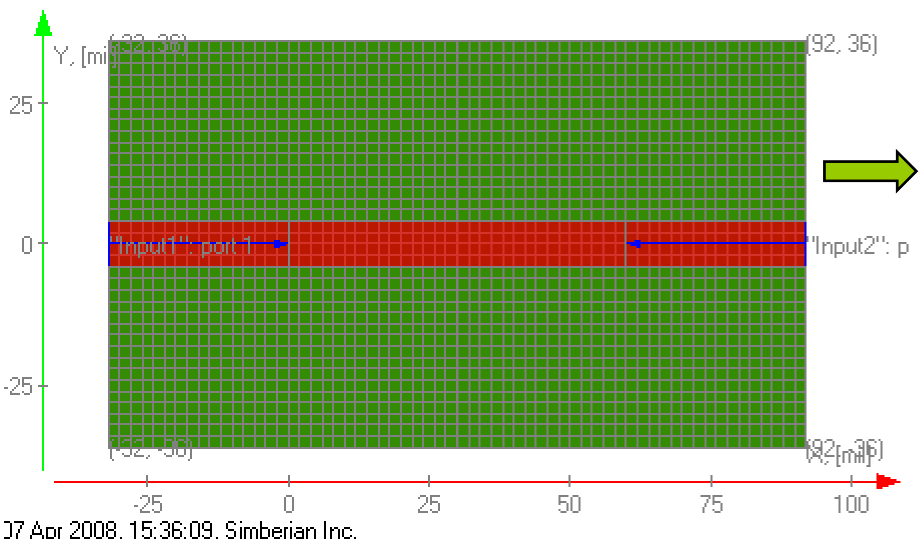
Parallel internal ports (ParallelPorts)

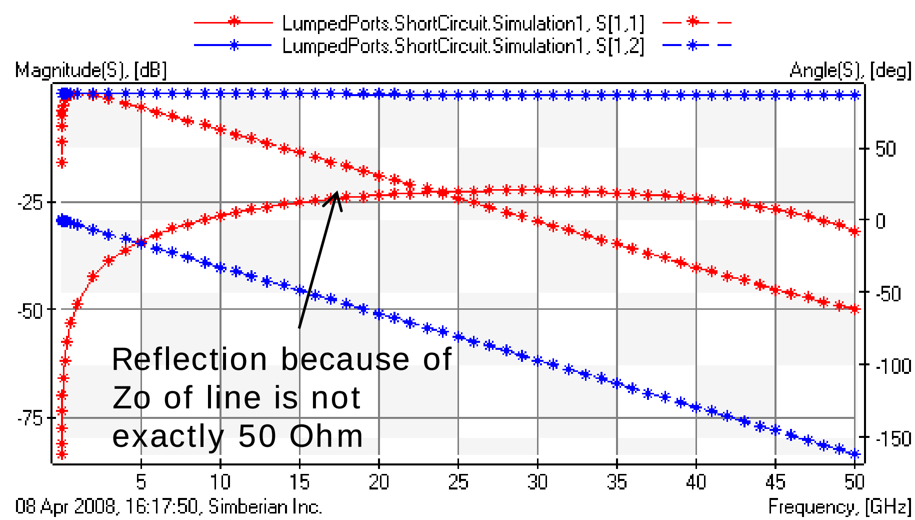
- Connected at the ends of strip-line in parallel
- One of the sizes of the port can correspond to actual lumped device size another is as small as possible on the grid
- Ports span between the strip line and the reference plane or strip
- The results of analysis are S-parameters of 4-port multiport



60-mil micro-strip line segment for comparison (ShortCircuit)

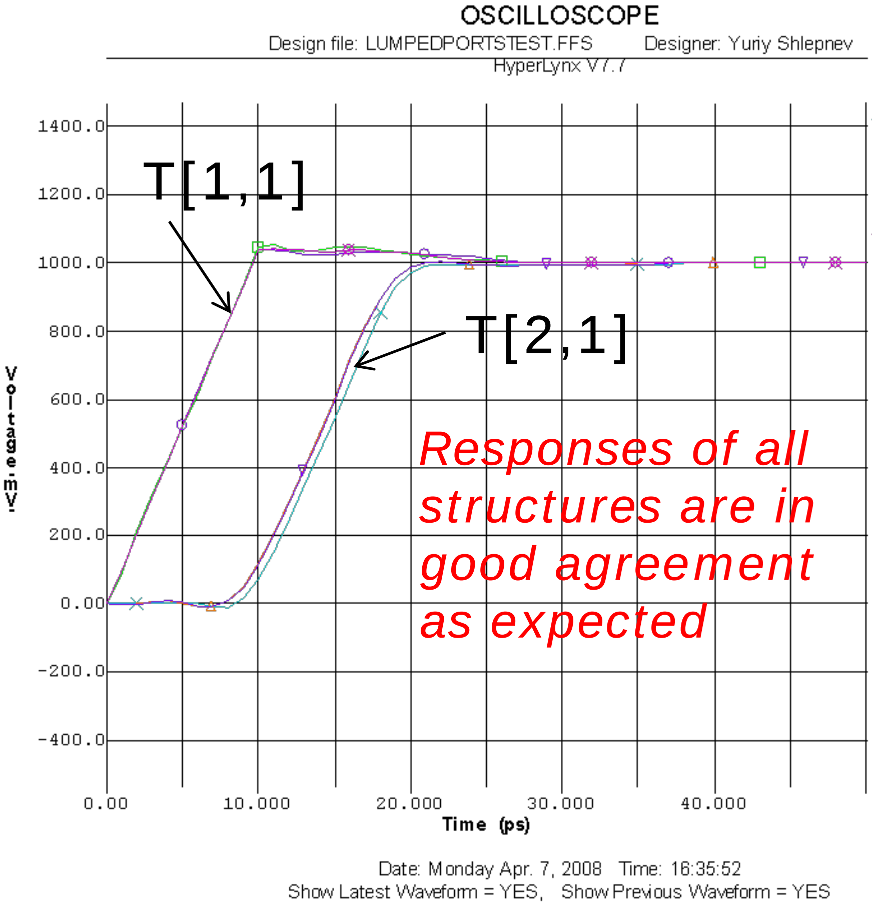
- Micro-strip line with 8-mil wide strip on 4.5 mil substrate with DK=4.2 and LT=0.02 are used for all experiments with the internal ports
- The results of analysis are 2-port S-parameters with automatically de-embedded transmission line inputs with phase reference planes shifted to have 60 mil segment in the middle



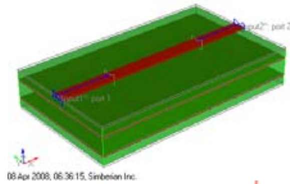


Through calibration of the ports with 10-ps step response

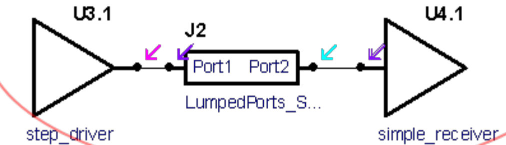
Simbeor models used in HyperLynx 7.7 with Eldo for the analysis

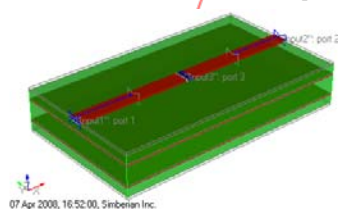


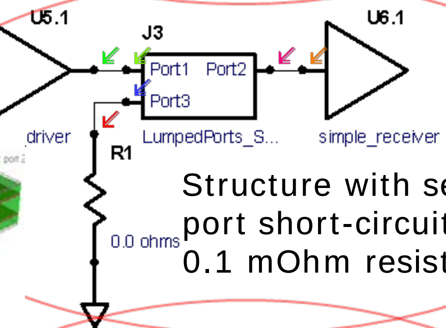
Responses of all structures are in good agreement as expected



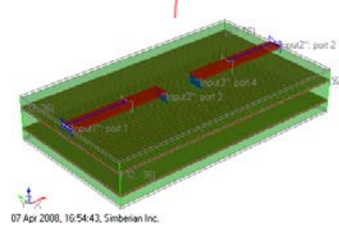
60-mil micro-strip line segment

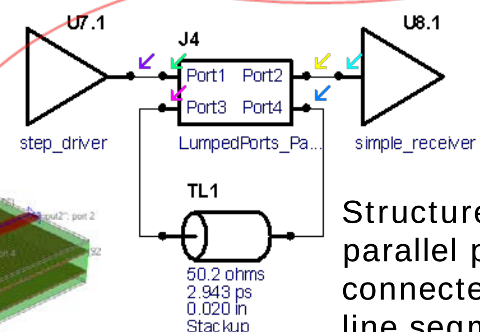






Structure with series port short-circuited by 0.1 mOhm resistor

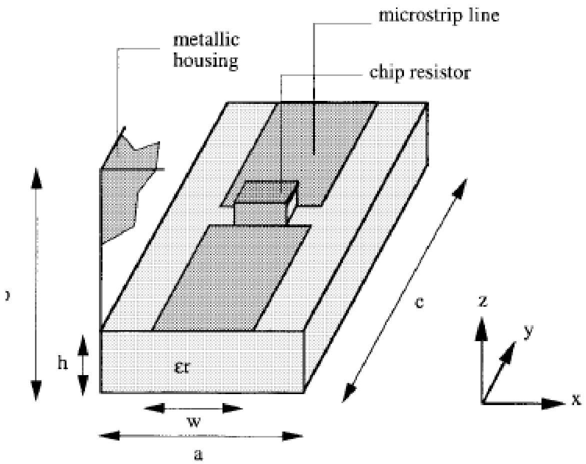




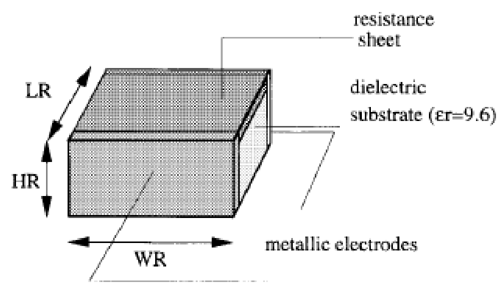
Structure with two parallel ports connected to 20-mil line segment to fill the gap

Validation of the internal port models

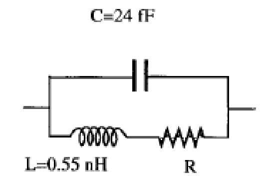
- For validation of the internal port models we can use structure with thick film chip resistor connected in series into micro strip line and investigated numerically and experimentally in
  - Y. C. Lau, M. S. Leong, and P. S. Kooi, “Modeling of chip resistors for high-frequency microwave applications with the use of the FDTD method,” *Microwave Opt. Technol. Lett., vol. 14, no. 5, pp. 259–261,* Apr. 1997.
  - R. Gillard, S. Dauguet, and J. Citerne, “Correction Procedures for the Numerical Parasitic Elements Associated with Lumped Elements in Global Electromagnetic Simulators”, IEEE Trans. on MTT, v. 46, N9, 1998, p. 1298-1306.



Studied structure. (a) The loaded microstrip line (a = 6.578 mm, b = 3.048 mm, c = 55.653 mm, DK= 2.2, h = 0.508 mm, w = 1.518 mm).



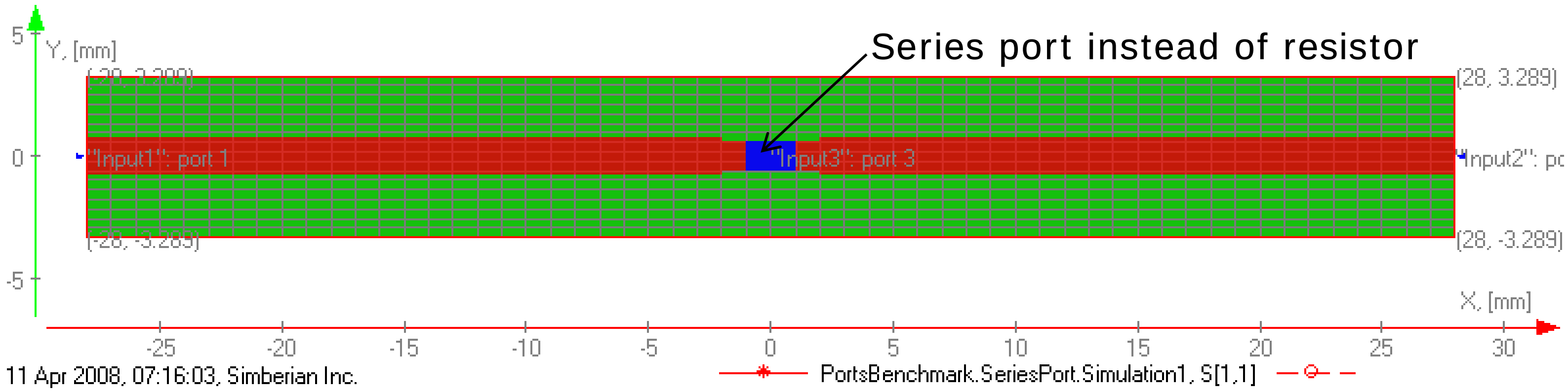
(b) The thick-film chip resistor (WR = 1.214 mm, HR = 0.508 mm, LR = 4.047 mm).



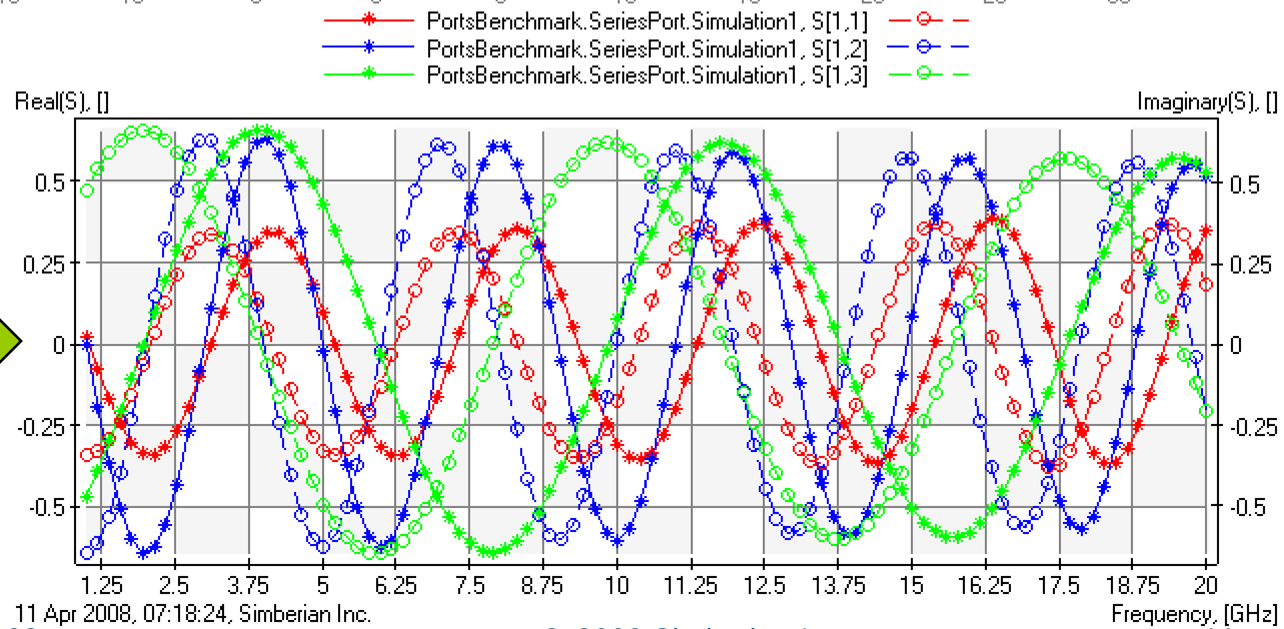
Lumped resistor model

Electromagnetic model with series port

- Simbeor solution PortsBenchmark.esx, circuit SeriesPort



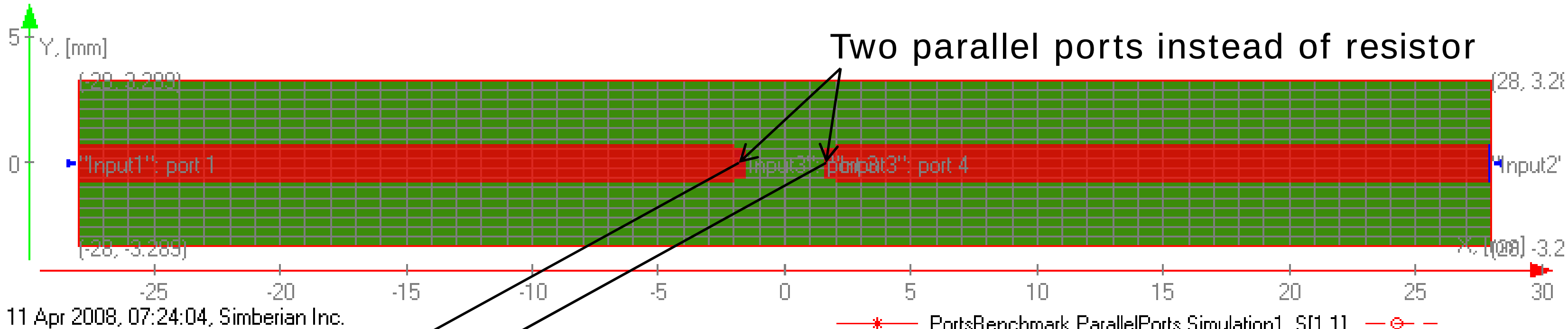
3-port model is created with transmission line ports 1 and 2 and internal port 3

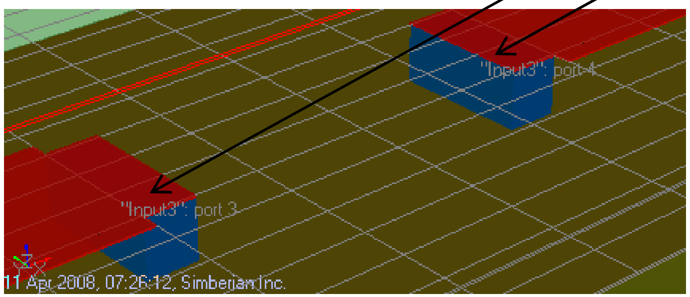


Electromagnetic model with parallel ports

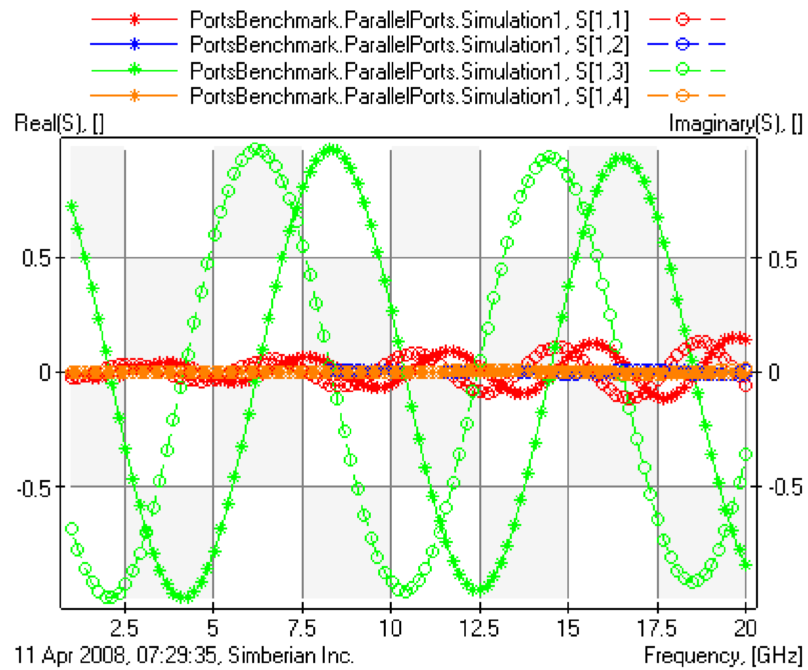
- Simbeor solution PortsBenchmark.esx, circuit ParallelPorts

Two parallel ports instead of resistor





4-port model is created with transmission line ports 1 and 2 and internal ports 3 and 4



10-Ohm resistor in micro-strip line

- Good correspondence of data computed by 3 different methods and experiment from [7] up to 10 GHz (the structure is electrically oversized above 10 GHz and lumped model becomes inaccurate in this case)

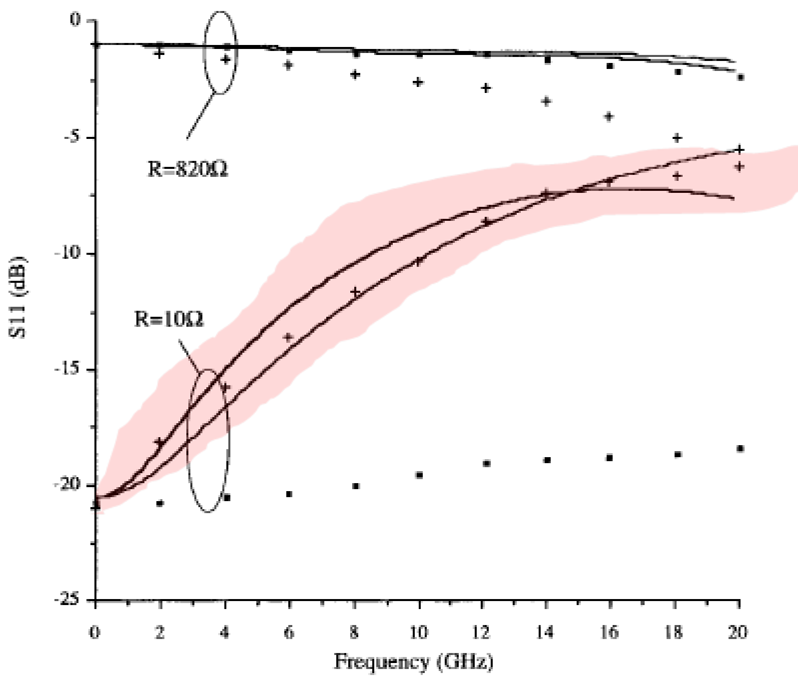
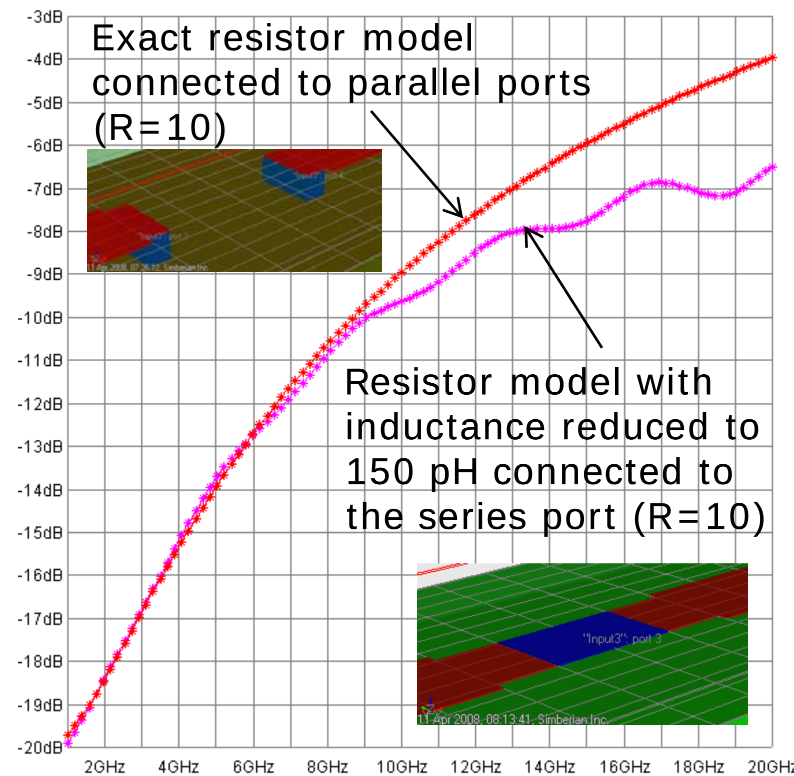


Fig. 7. Return loss versus frequency for different modelings. —: this analysis. ∘∘∘: exact description [7]. +: measurements [7]. ■: [7].

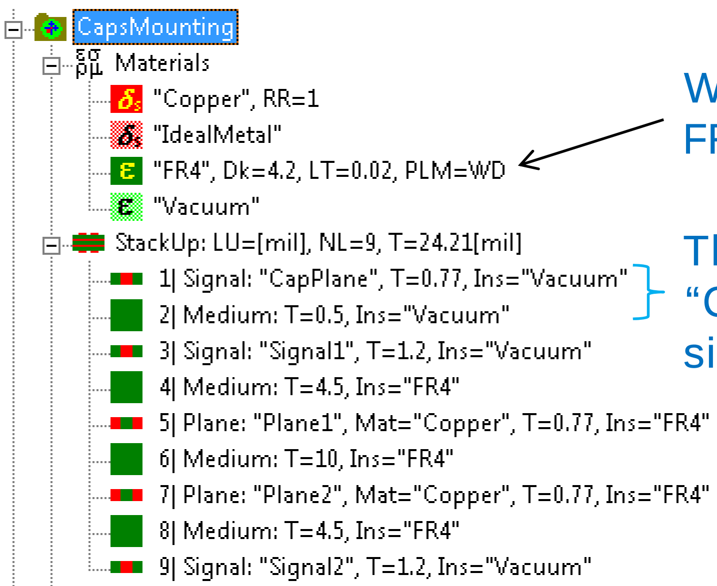
Graph from R. Gillard, S. Dauguet, and J. Citerne, IEEE on MTT, N9, p. 1302

[7] is paper of Y. C. Lau, M. S. Leong, and P. S. Kooi



Materials and stack-up for analysis of the capacitors mounting structures

- Solution CapsMounting.esx created for this investigation (link to the file with all zipped solutions is on the last page)
- Simple 4-layer stackup with two signal layers and two plane layers
- Stackup is extended to simulate connection of the capacitor slightly above the board surface



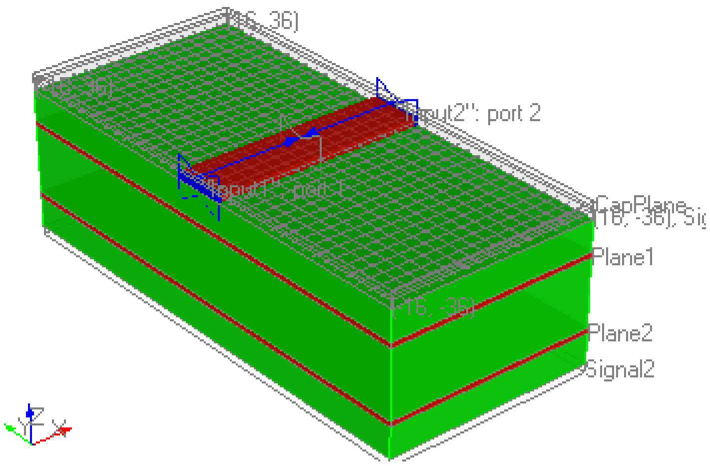
Wideband Debye model for FR-4 type dielectric

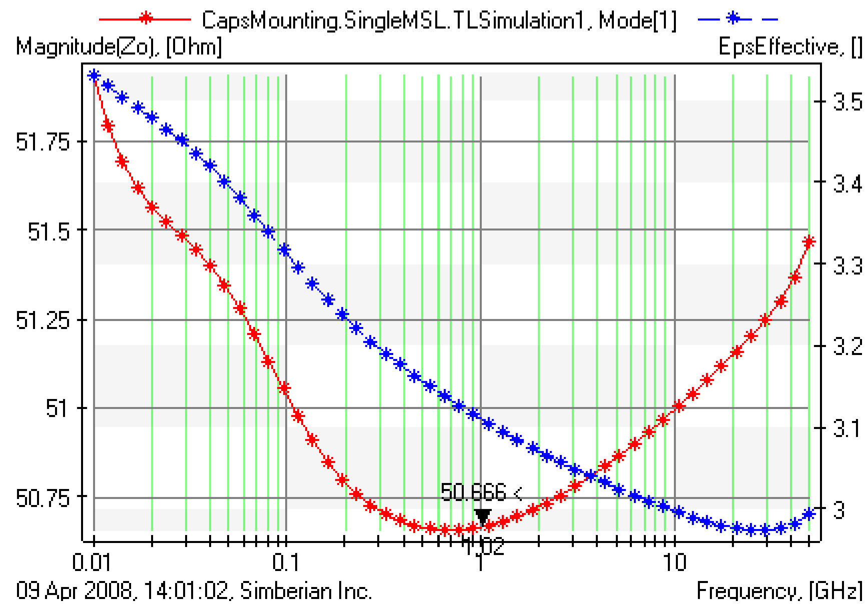
Thin layer of air and additional layer “CapPlane” of signal-type are added to simulate non-flat connection of the capacitors

Use Help > Tutorials > Tutorial 1 to learn how to build models for materials and stackup

Single-ended channel – transmission line (circuit SingleMSL)

- 8 mil wide strip on 4.5 mil substrate with Dk=4.2, LT=0.02 at 1 GHz and wideband Debye dielectric model

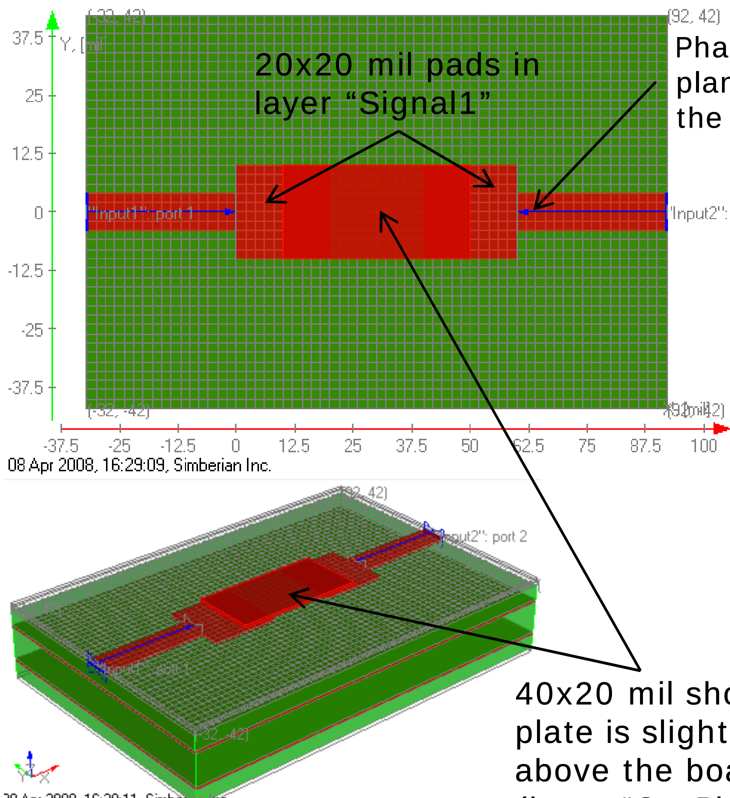




Use Help > Tutorials > Tutorial 2 to learn how to build broadband RLGC(f) models for transmission line

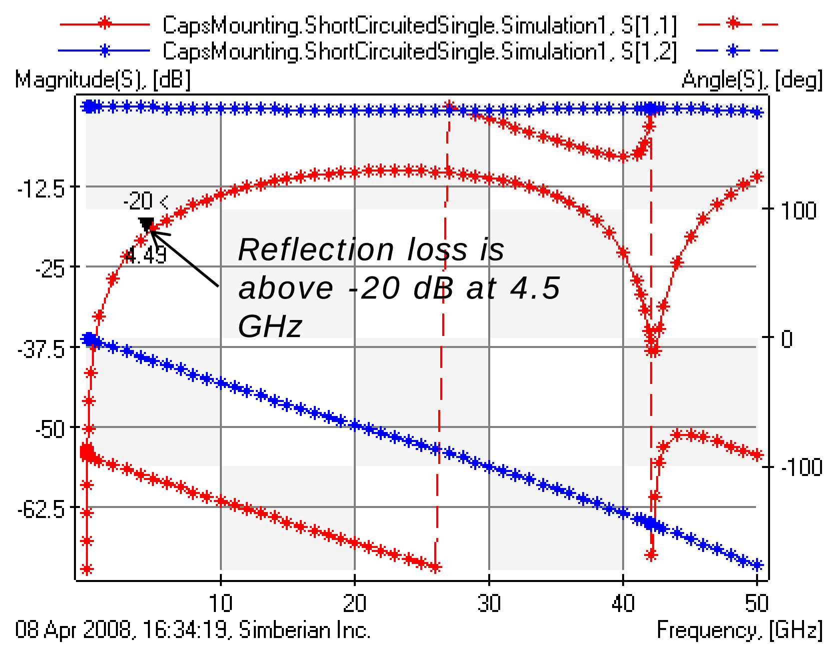
Short-circuit experiment with 0402 capacitor footprint (ShortCircuitedSingle)

- Capacitor in micro-strip line with 8 mil wide trace
- Allows us to estimate of the minimal possible reflection
- May be used to do the through calibration of the internal ports



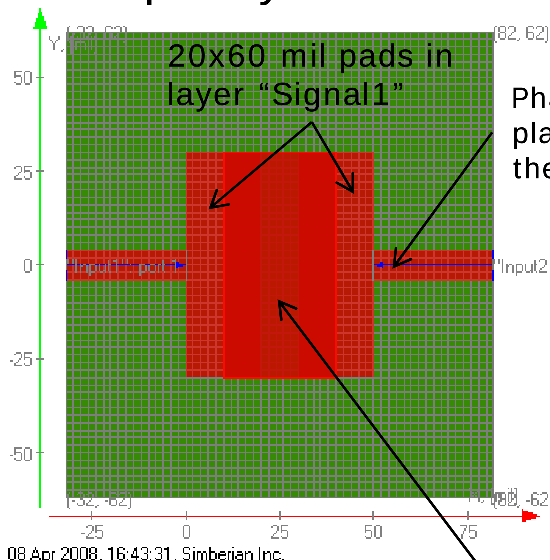
40x20 mil short-circuiting plate is slightly elevated above the board surface (layer “CapPlane”)

Simulation from 10 MHz to 50 GHz

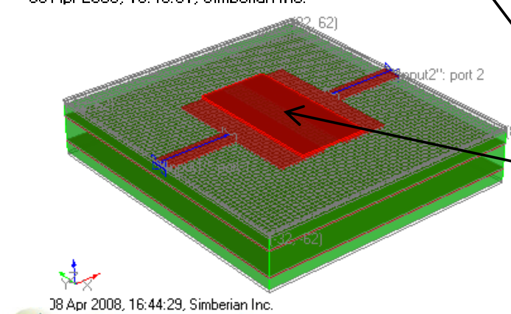


Short-circuit experiment with 0603 capacitor footprint (SCSingle0603)

- The larger the footprint the larger the minimal possible reflection loss
- Impedance of the actual capacitor will make reflection worse at most of the frequency band

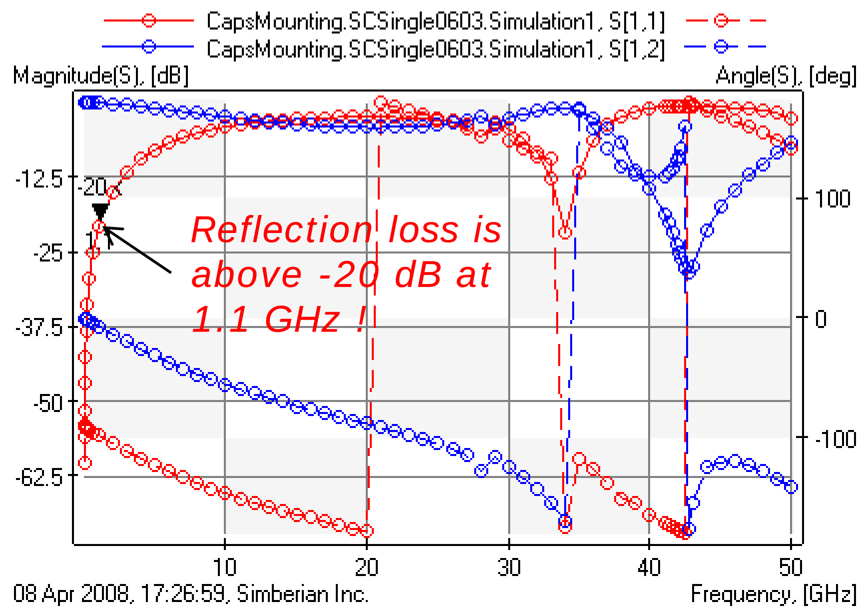


Phase reference planes shifted to the pads



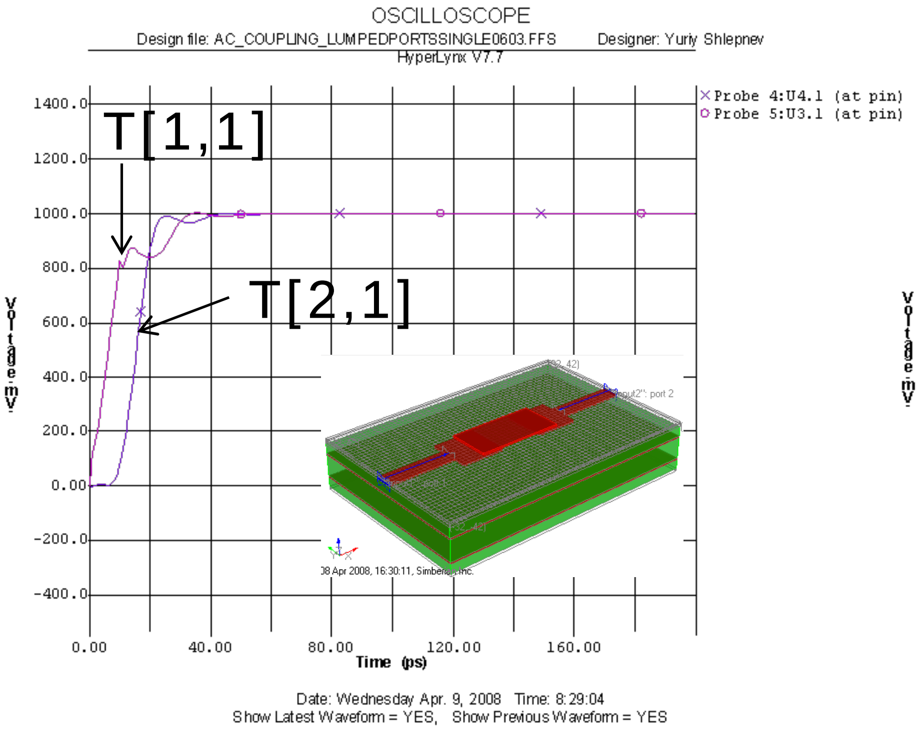
30x60 mil short-circuiting plate is slightly elevated above the board surface (layer "CapPlane")

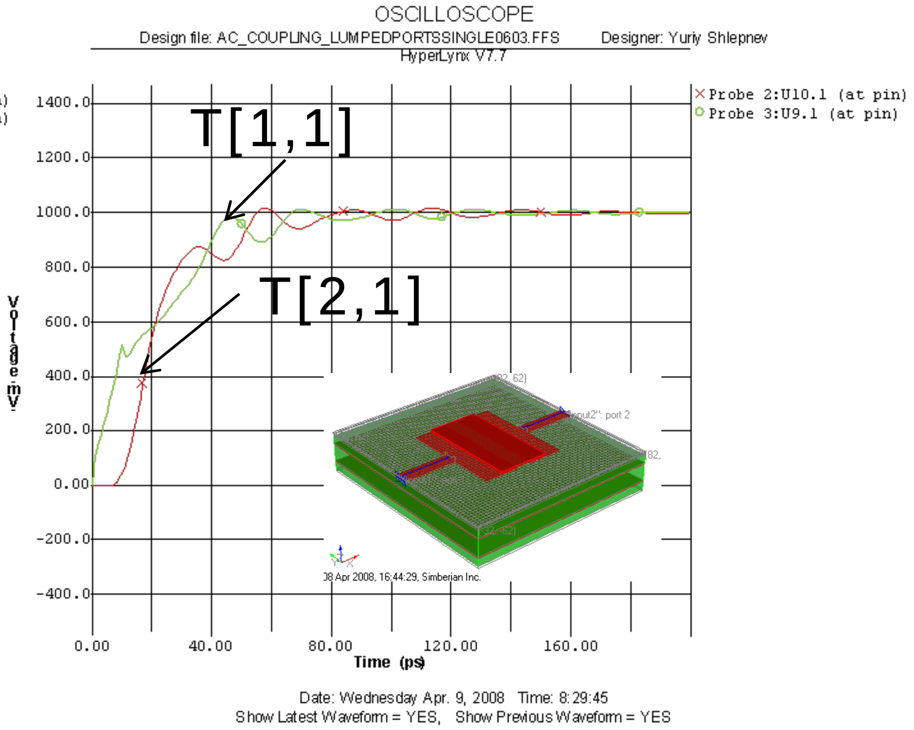
Simulation from 10 MHz to 50 GHz



TDR and TDT of the short-circuited footprints of the capacitors

- Short-circuit is an "ideal" capacitor – the reflection is the minimal possible
- Even in that case the discontinuity in the transmission line is clearly visible in time-domain and may be serious problem in a complicated channel

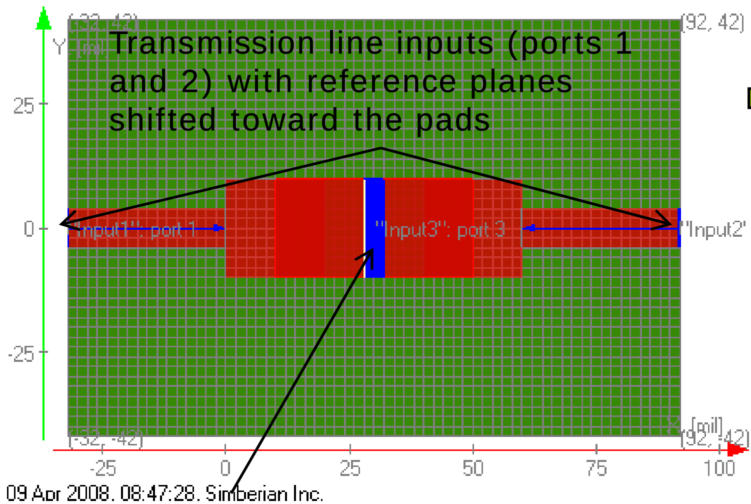




Simbeor models used in HyperLynx 7.7 with Eldo for the analysis

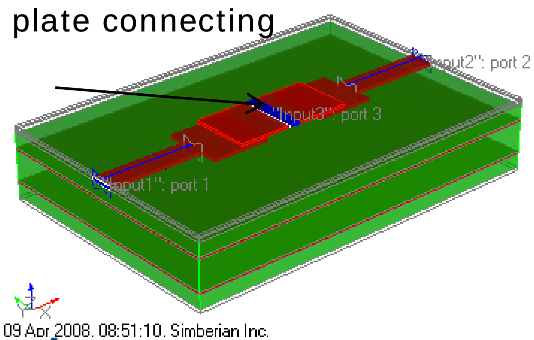
Series internal port to connect 0402 capacitor (SeriesPortSingle)

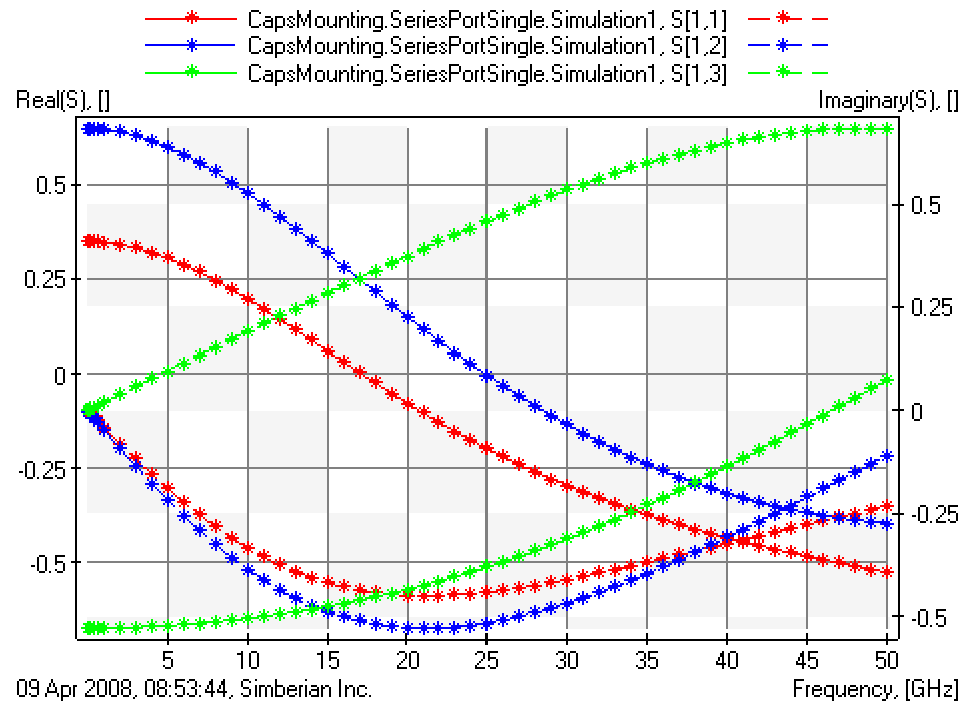
- May be used if capacitor model extracted by comparison with the short-circuited pads (usually leads to lower estimated ESL of the capacitor)



3-port broad-band S-parameter model of the mounting structure exported from Simbeor in Touchstone format

Component input with X-directed port (X-Port port 3) in the middle of the plate connecting two pads



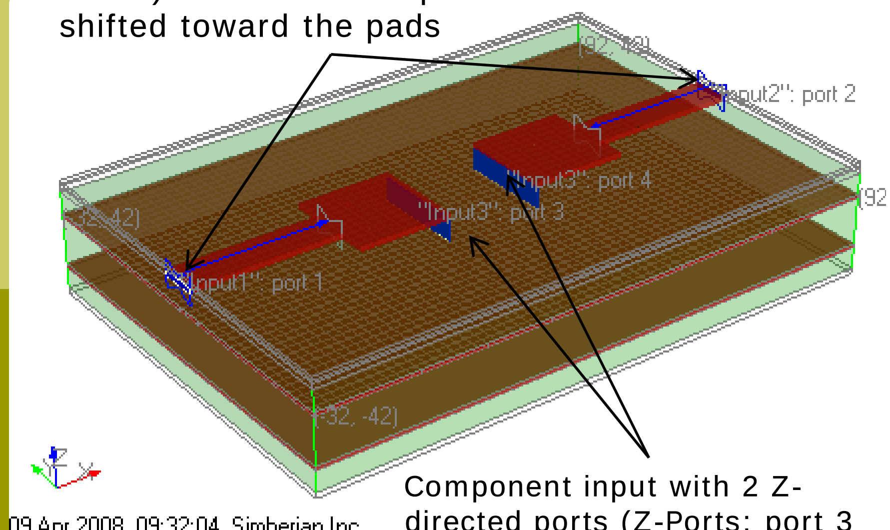


Parallel internal ports to connect 0402 capacitor (ParallelPortsSingle)

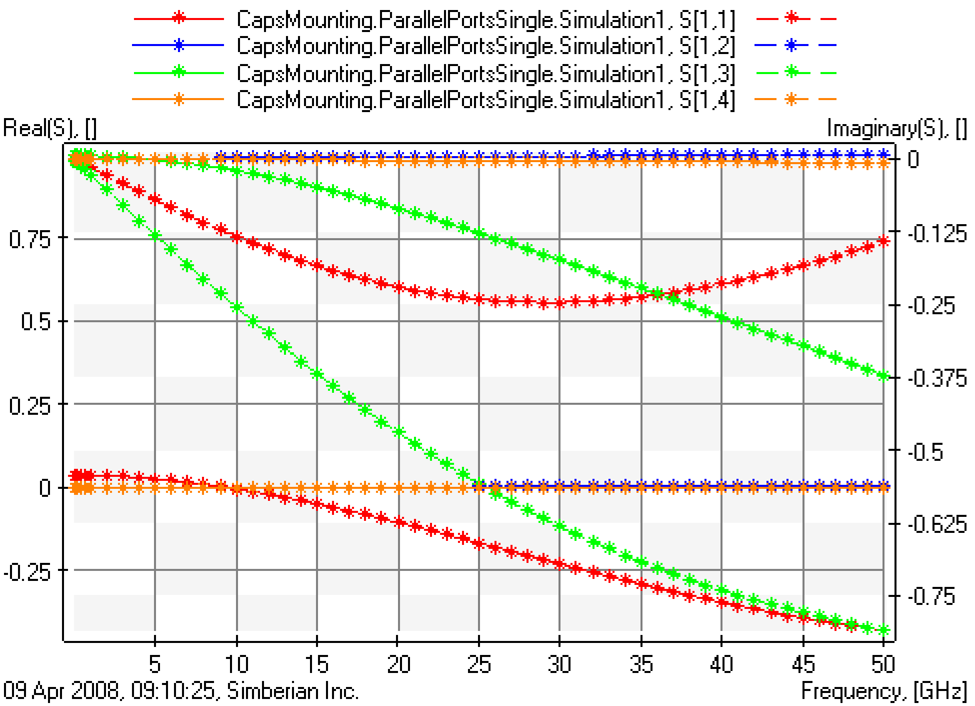
- May be used if capacitor model extracted by comparison with the open-circuited pads (usually leads to complex model with higher ESL and substantial delay in the capacitor model)

4-port broad-band S-parameter model of the mounting structure is exported from Simbeor in Touchstone format

Transmission line inputs (ports 1 and 2) with reference planes shifted toward the pads

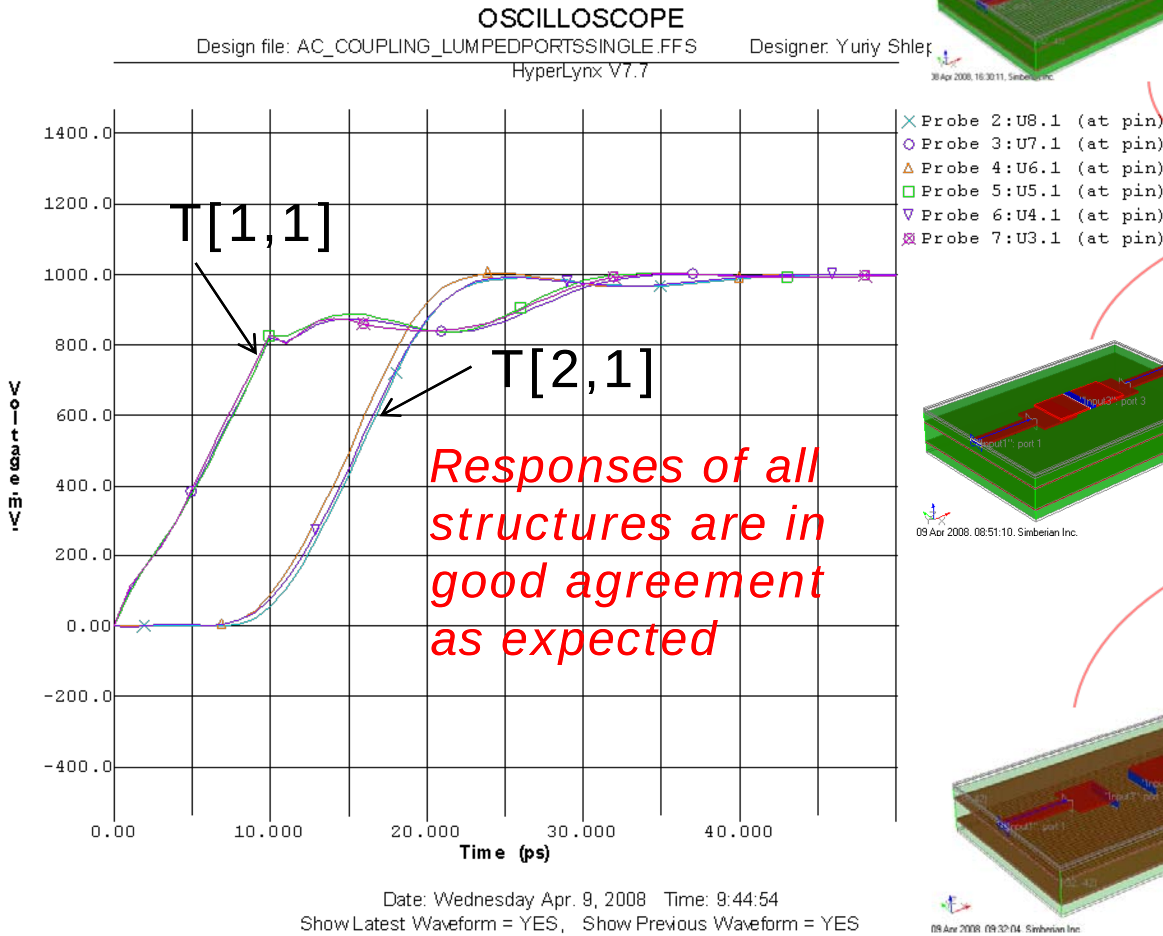


Component input with 2 Z-directed ports (Z-Ports: port 3 and 4) at the edges of the pads

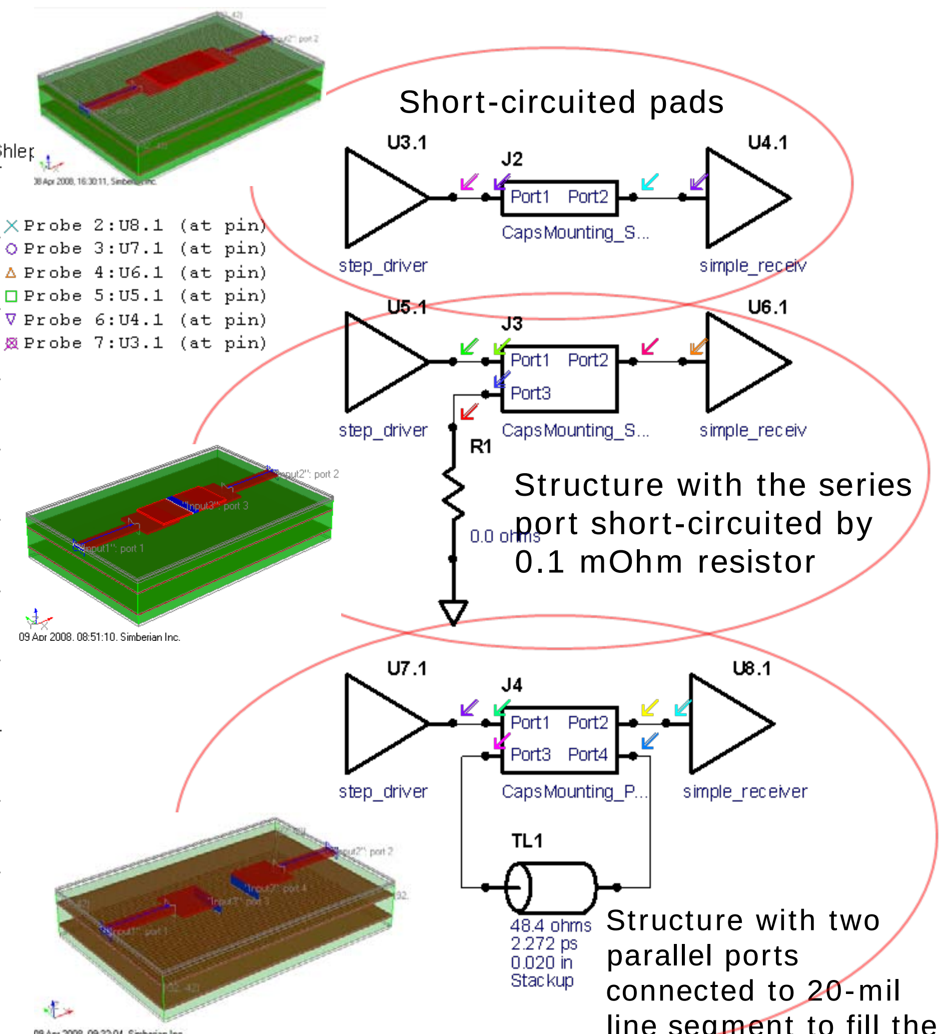


Through calibration of the 0402 capacitor ports with 10-ps step response

Simbeor models are used in HyperLynx+Eldo for the analysis



Responses of all structures are in good agreement as expected



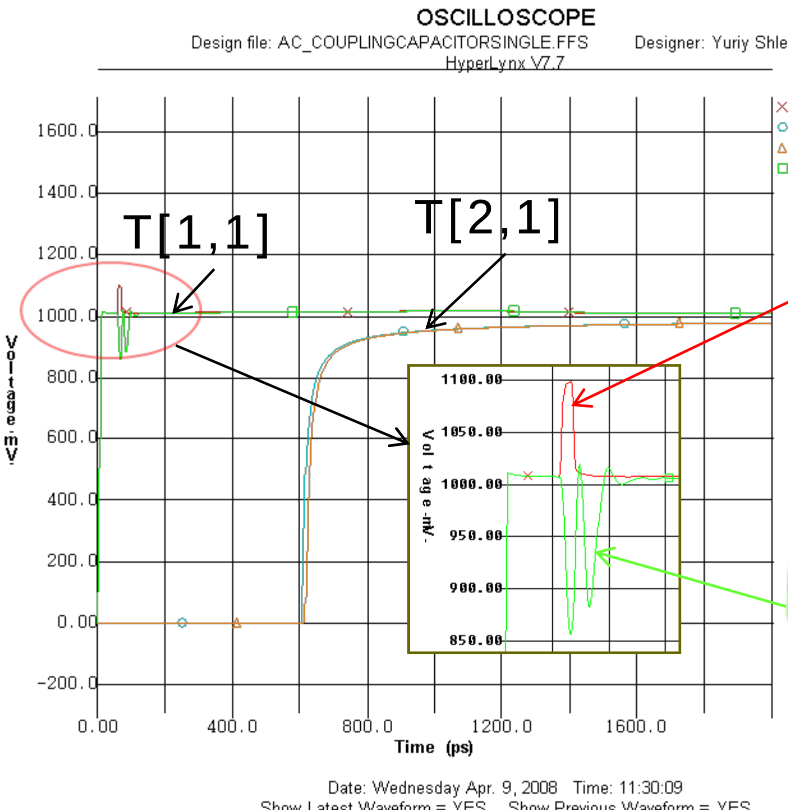
Short-circuited pads

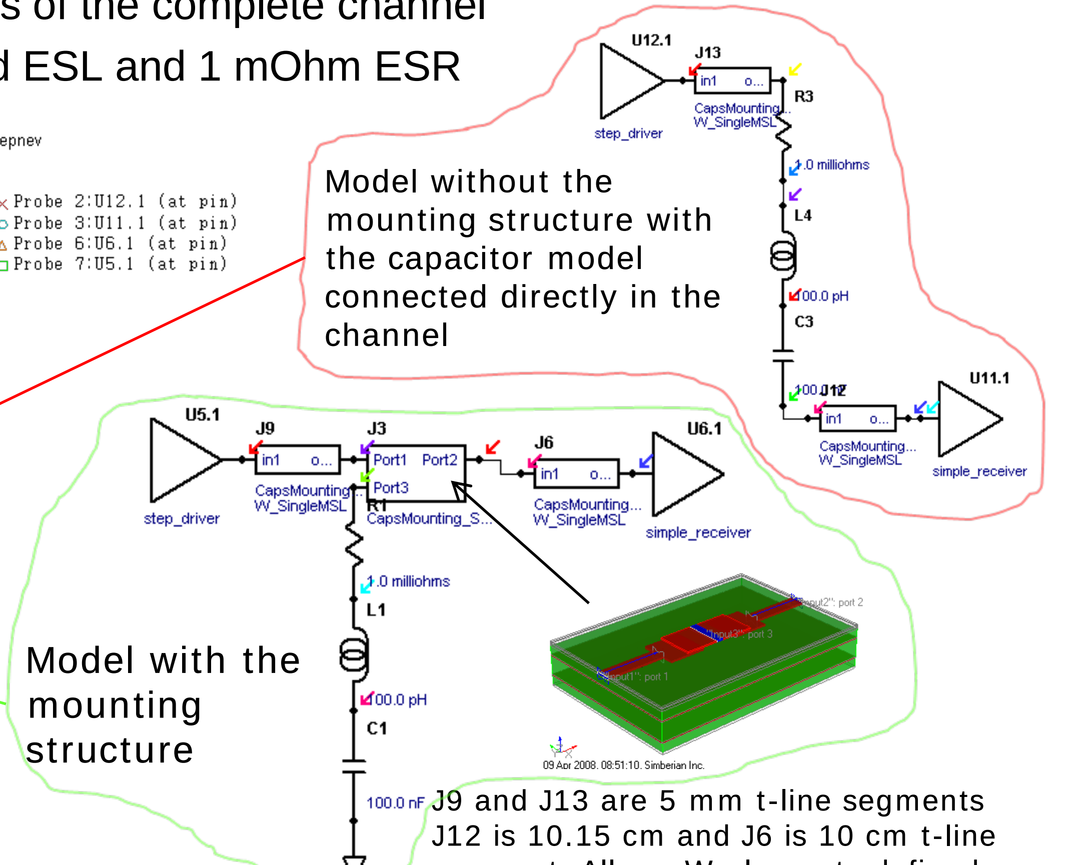
Structure with the series port short-circuited by 0.1 mOhm resistor

Structure with two parallel ports connected to 20-mil line segment to fill the gap

AC coupling capacitor in a simple single-ended channel

- 10.65 cm long channel is simulated with and without the mounting structure
- Simbeor is used to generate models for both t-lines and mounting structure and HyperLynx+Eldo is used for analysis of the complete channel
- 100 nF capacitor has 100 pH added ESL and 1 mOhm ESR

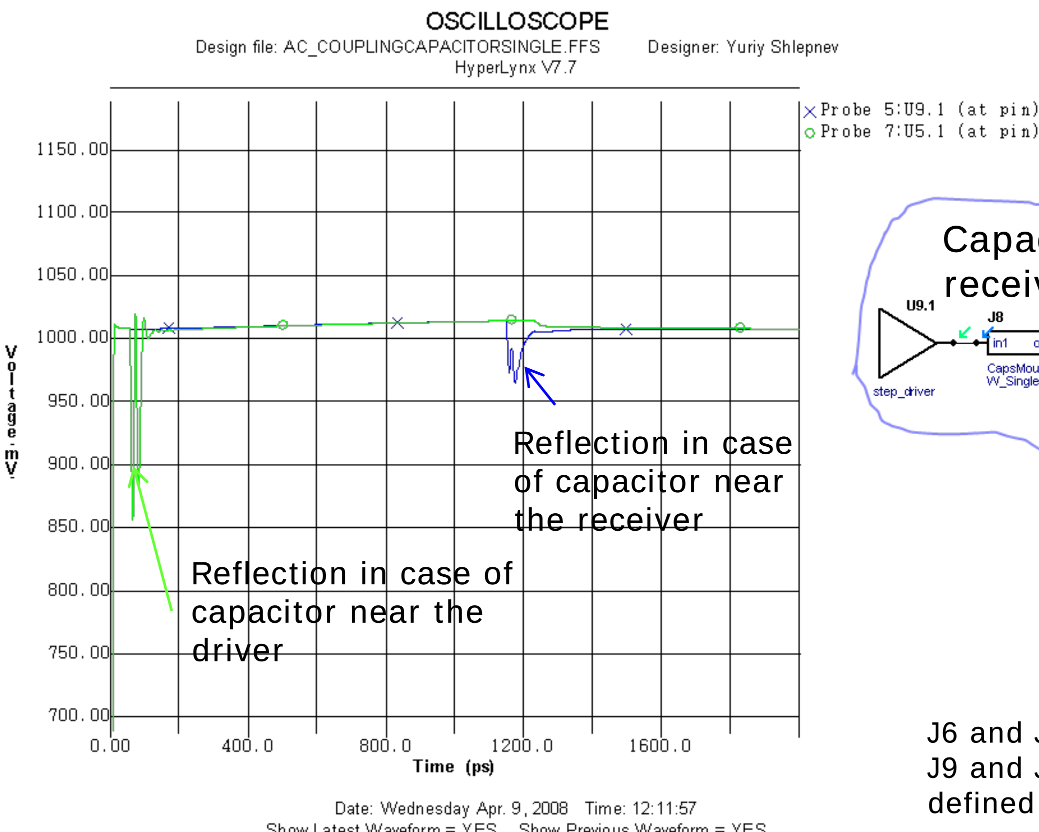


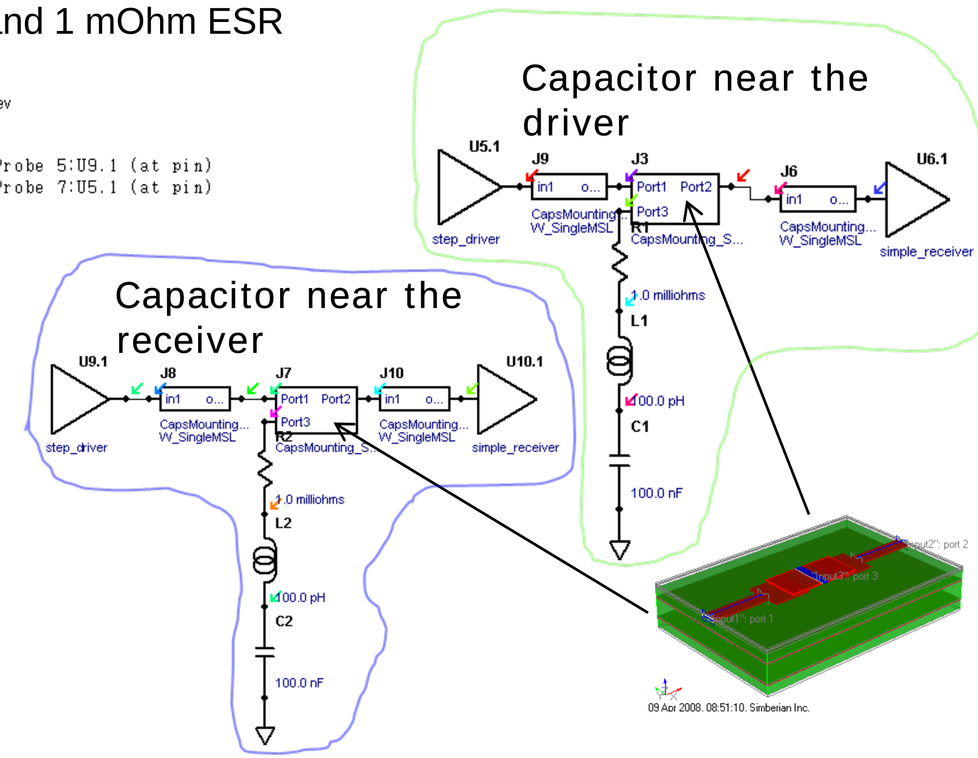


J9 and J13 are 5 mm t-line segments J12 is 10.15 cm and J6 is 10 cm t-line segment. All are W-elements defined with RLGC(f) extracted with Simbeor

AC coupling capacitor in a simple single-ended channel

- 10.65 cm long channel with AC capacitor close either to driver or to receiver is simulated
- Simbeor is used to generate models for both t-lines and mounting structure and HyperLynx+Eldo is used for analysis of the complete channel
- 100 nF capacitor has 100 pH added ESL and 1 mOhm ESR

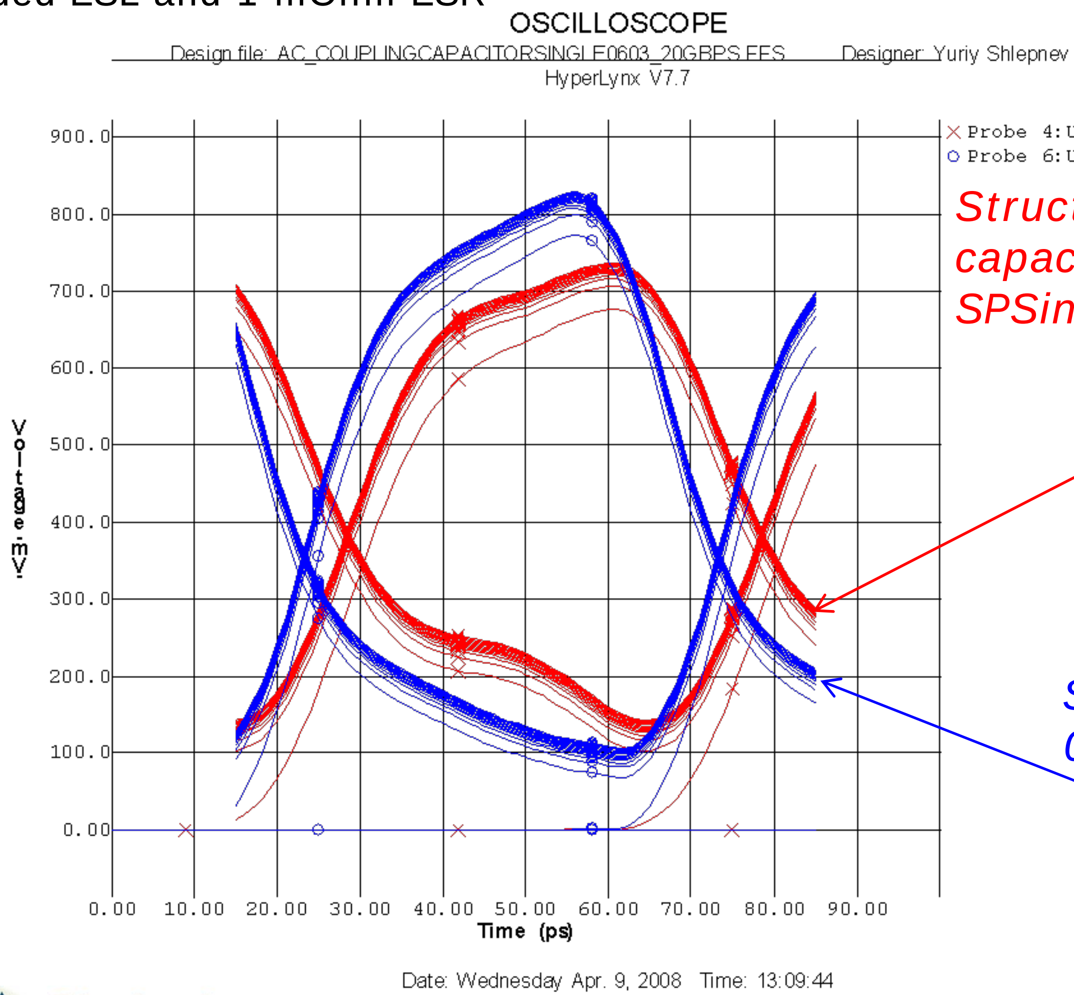




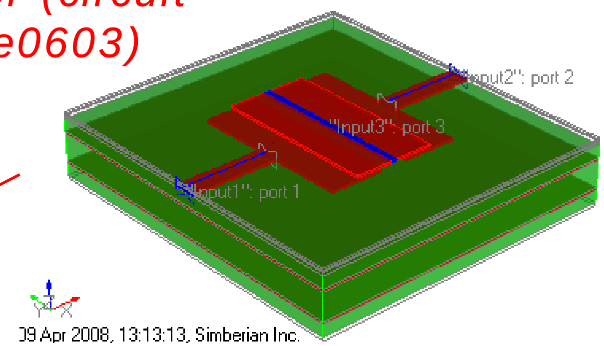
J6 and J8 are 10.15 cm t-line segments
J9 and J10 are 5 mm t-line segment. All are W-elements defined with RLGC(f) extracted with Simbeor

Eye-diagram for the simple channel with AC coupling capacitor and 20 Gb/s signal

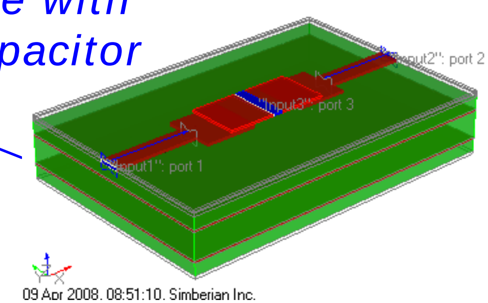
10.65 cm long channel with AC capacitor close to driver, 100 nF capacitor has 100 pH added ESL and 1 mOhm ESR



Structure with 0603 capacitor (circuit SPSingle0603)

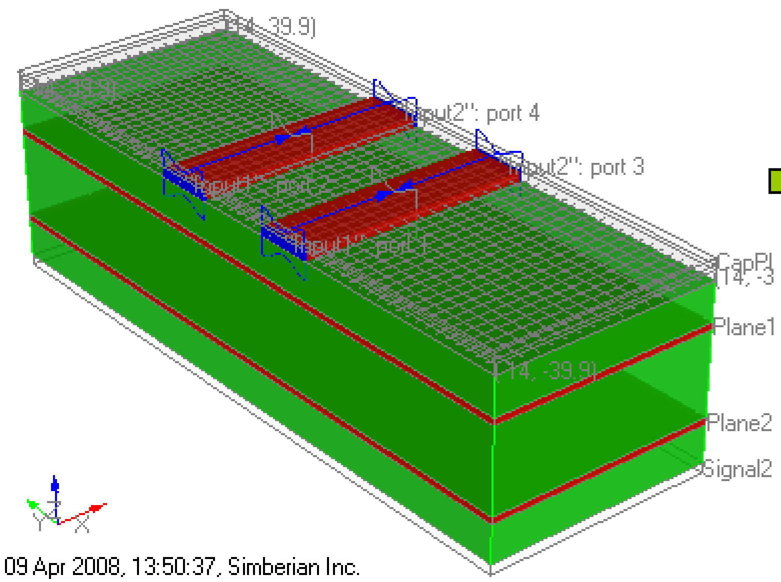


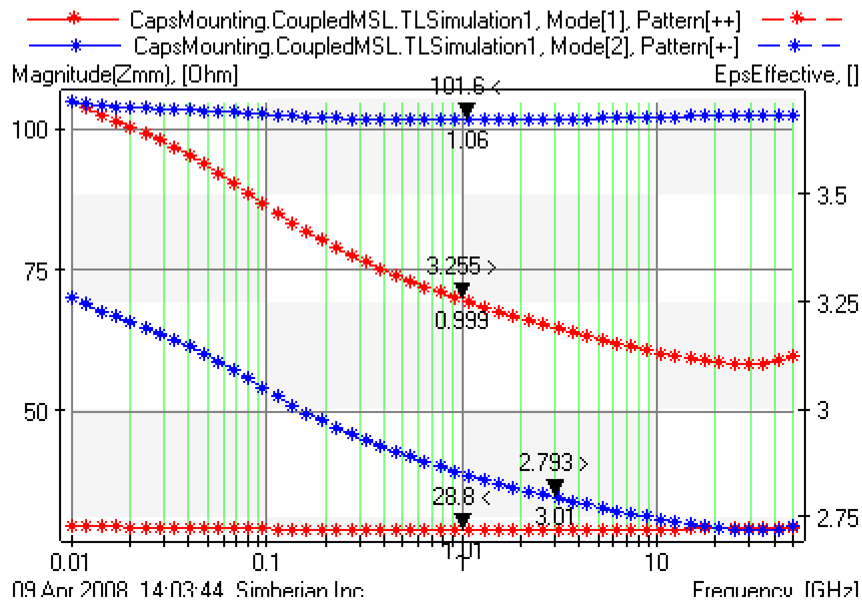
Structure with 0402 capacitor



Differential channel – transmission line (circuit CoupledMSL)

- Two 7 mil wide strips with 17 mil distance between centers on 4.5 mil substrate with Dk=4.2 and LT=0.02





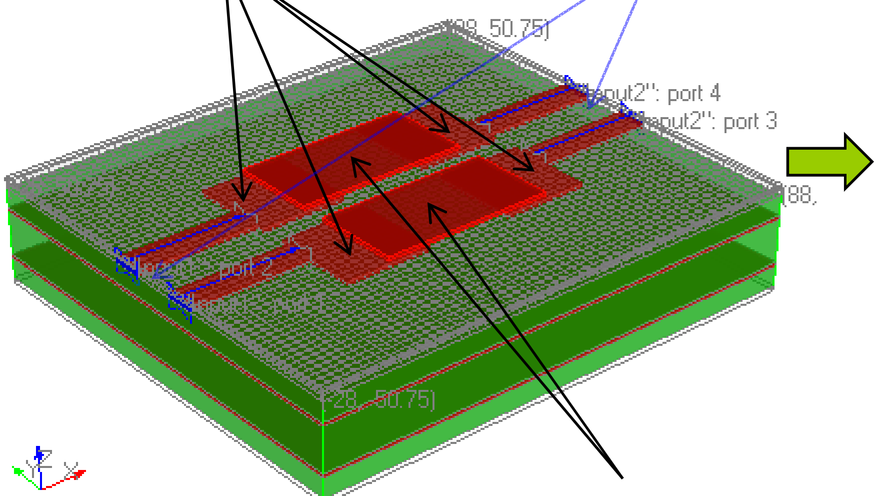
Use Help > Tutorials > Tutorial 2 to learn how to build broadband RLGC(f) models for differential transmission lines

Short-circuit experiment at 0603 capacitor footprint (SCSingle0603)

- Investigation of the minimal possible reflection of the differential mode
- Mixed-mode S-parameters plotted to investigate the reflection (see more on S-parameters conversion and plotting in Help > Manual > Mixed-mode scattering parameters)

20x60 mil pads in layer “Signal1”

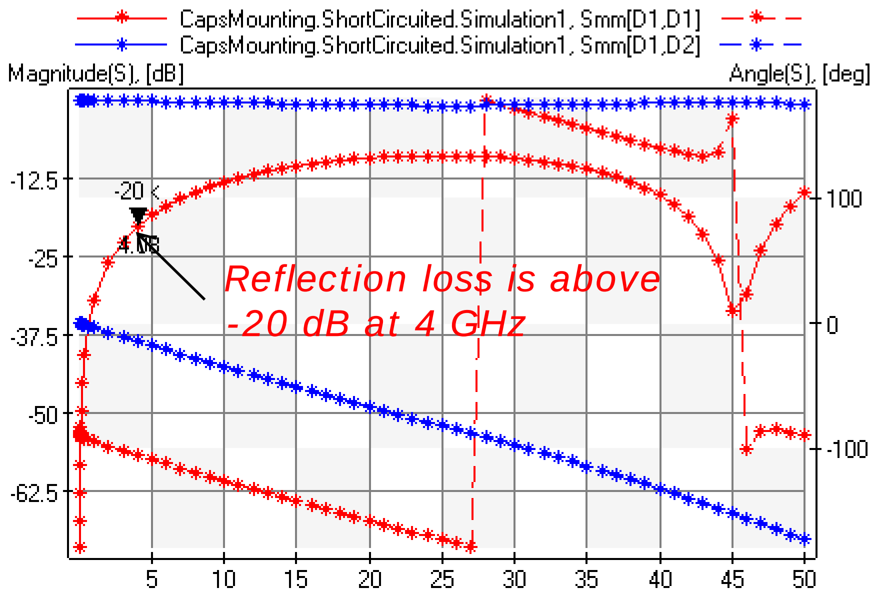
Phase reference planes of t-line inputs shifted toward the pads



09 Apr 2008, 14:05:20, Simberian Inc.

30x60 mil short-circuiting plates are slightly elevated above the board surface (layer “CapPlane”)

Simulation from 10 MHz to 50 GHz



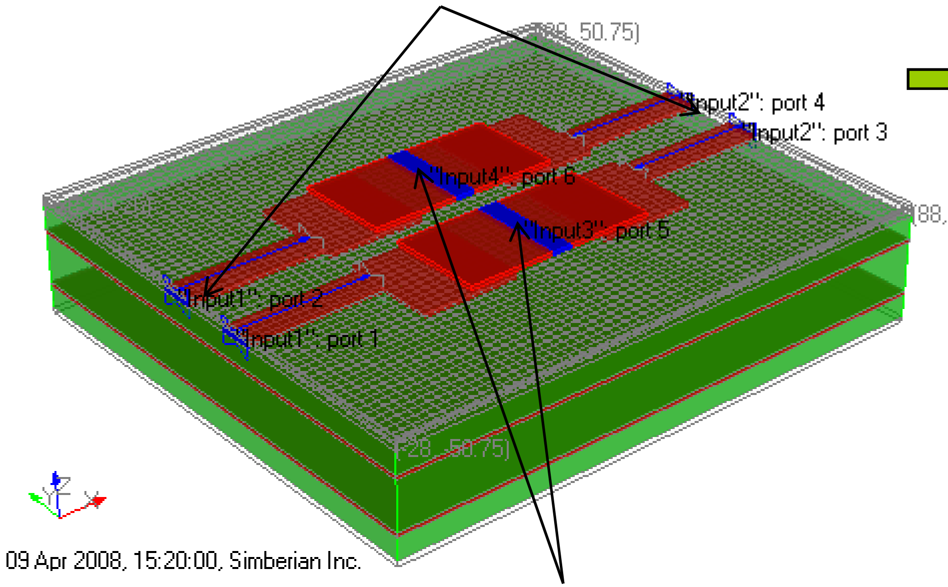
09 Apr 2008, 14:12:38, Simberian Inc.

Multiport parameters profile has to be adjusted to see the mixed-mode S-parameters on the graph (Simulation > Results > Multiport Parameters > Set New Profile > Input Space > Mixed Mode)

Series internal ports to connect two 0402 capacitors (circuit SeriesPorts)

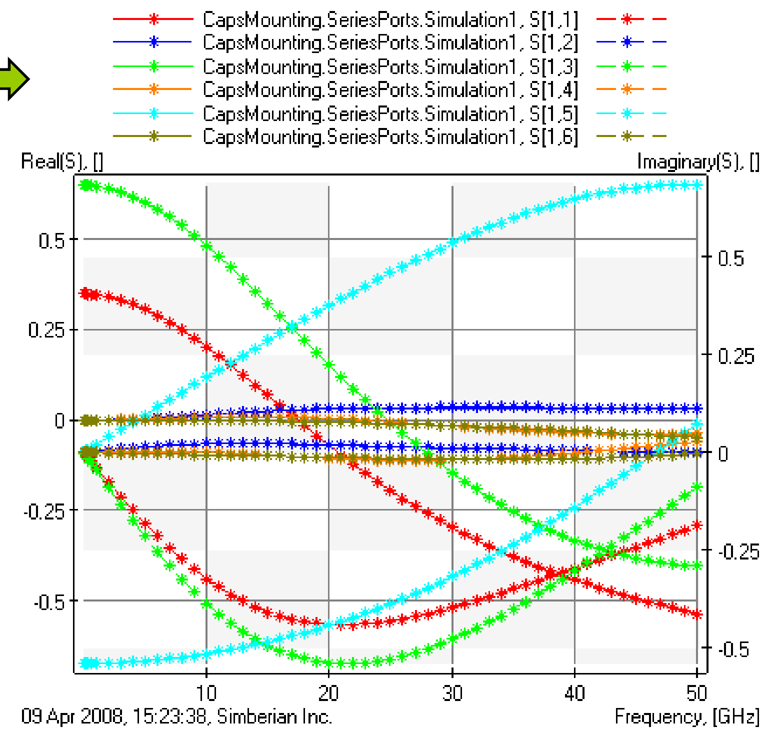
- May be used if capacitor model extracted by comparison with the short-circuited pads (usually leads to lower estimated ESL of the capacitor)

Coupled transmission line inputs (ports 1, 2 on one side and 3,4 on the other) with reference planes shifted toward the pads



Two component inputs with X-directed port (X-Port, ports 5 and 6) in the middle of the plate connecting two pads

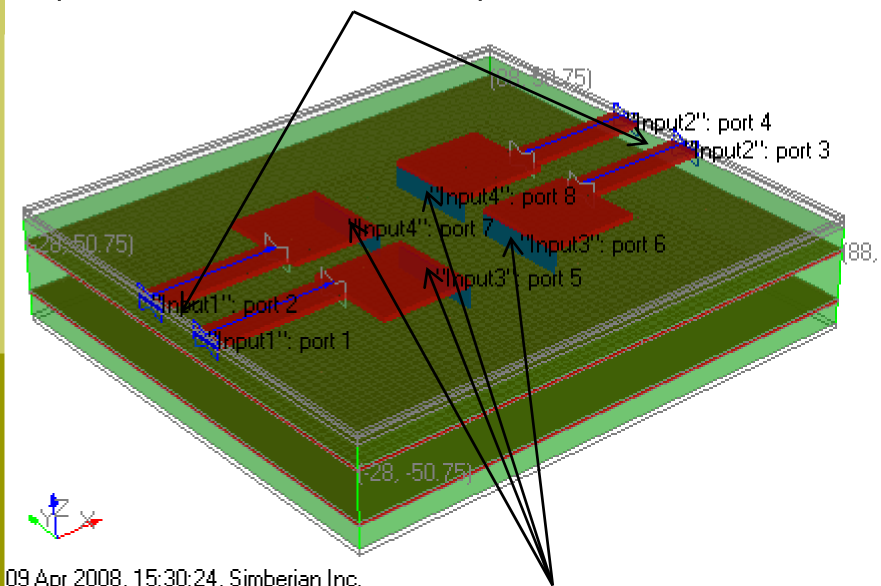
6-port broad-band S-parameter model of the mounting structure exported from Simbeor in Touchstone format



Parallel internal ports to connect two 0402 capacitors (circuit ParallelPorts)

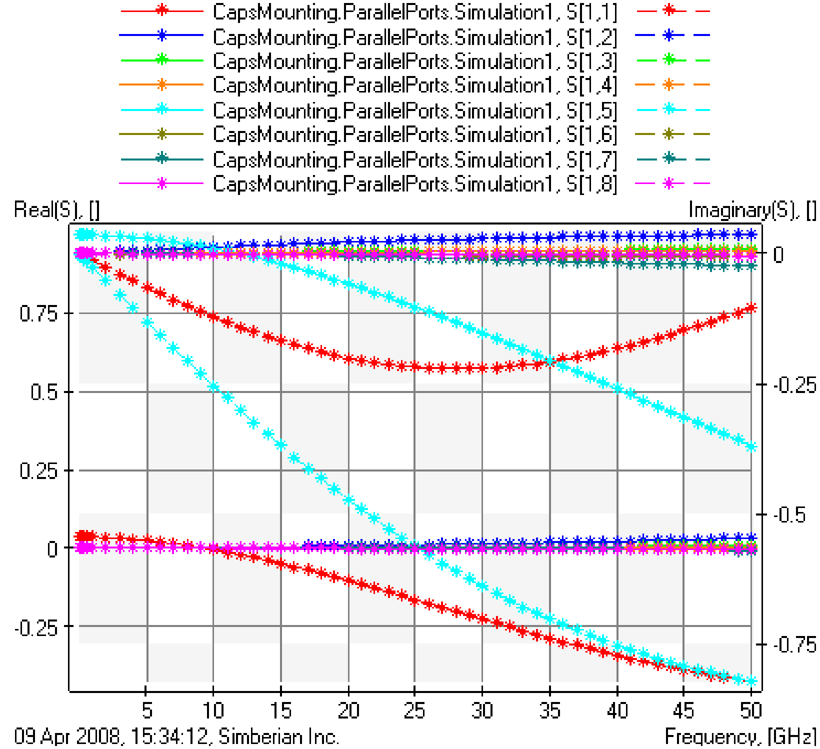
- May be used if capacitor model extracted by comparison with the open-circuited pads (usually leads to complex model with higher ESL and substantial delay in the capacitor model)

Coupled transmission line inputs (ports 1,2 and 3,4) with reference planes shifted toward the pads



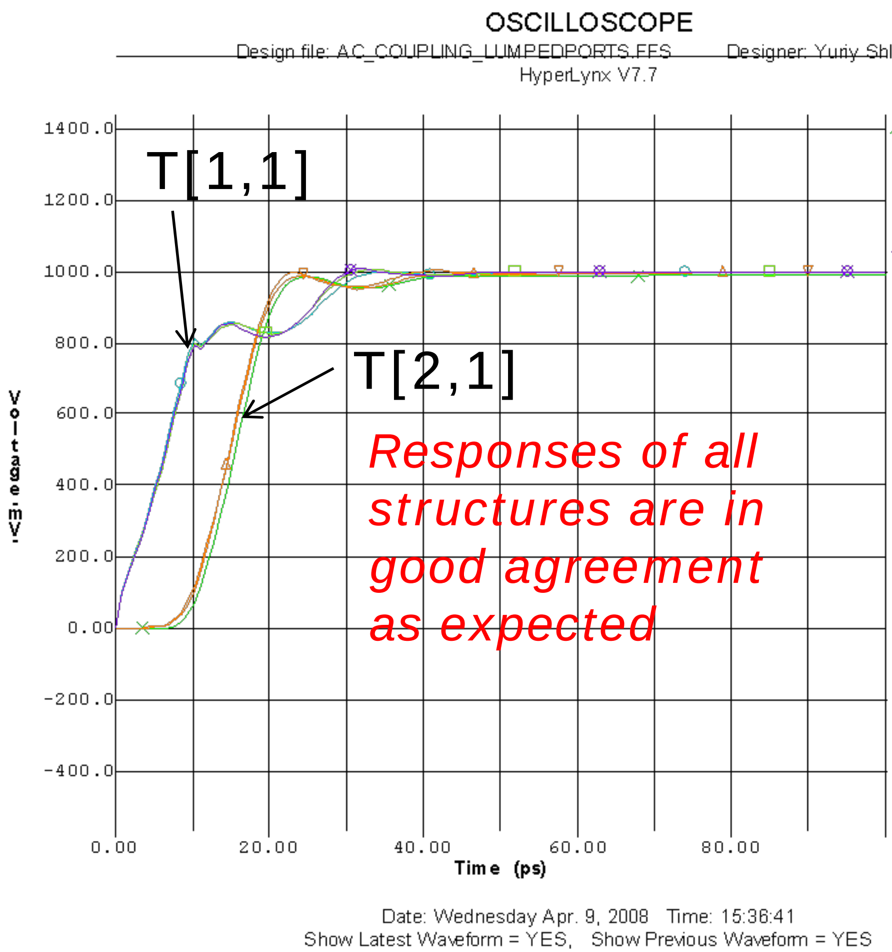
Component inputs with 2 Z-directed ports each (Input 3 - ports 5 and 6, Input 4 – ports 7 and 8) at the edges of the pads

8-port broad-band S-parameter model of the mounting structure exported from Simbeor in Touchstone format

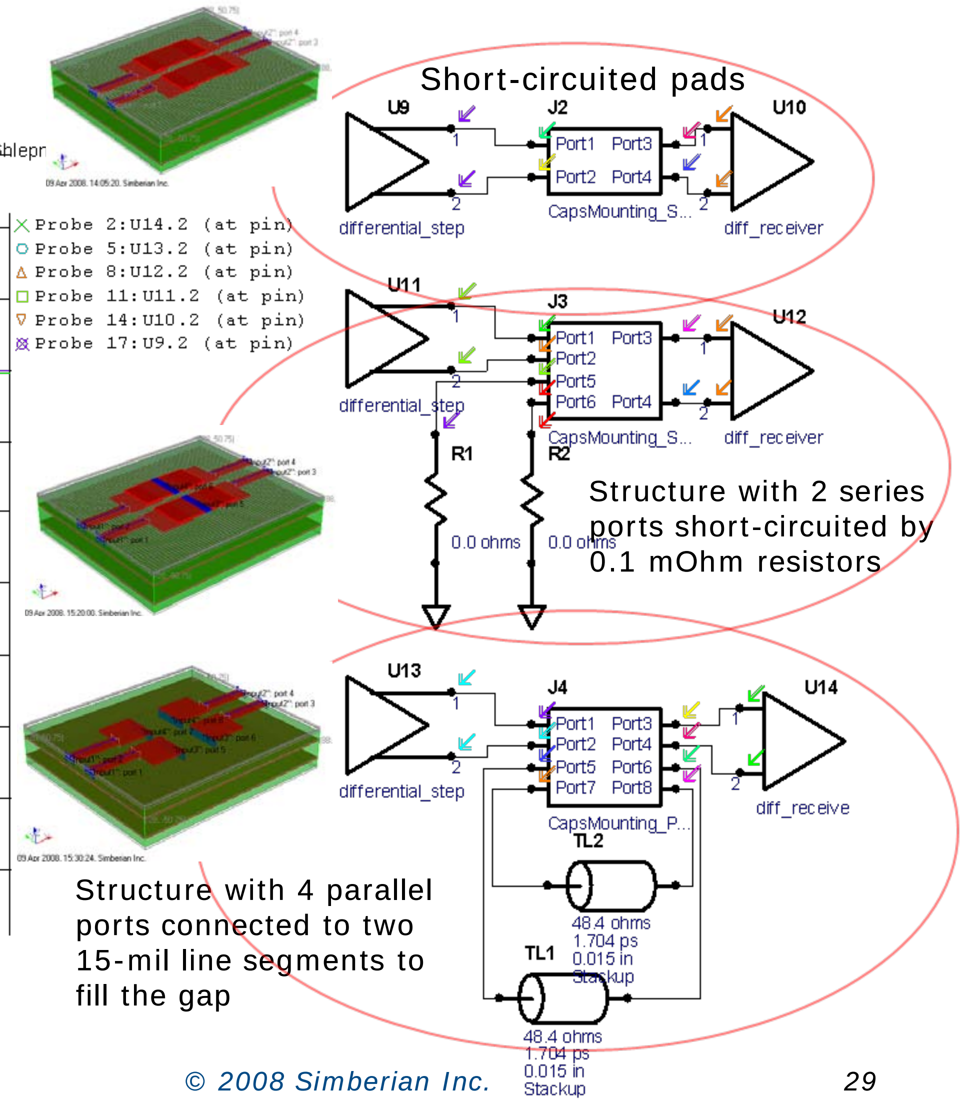


Through calibration of the 0402 capacitor ports with 10-ps step response

Simbeor models are used in HyperLynx+Eldo for the analysis



Responses of all structures are in good agreement as expected

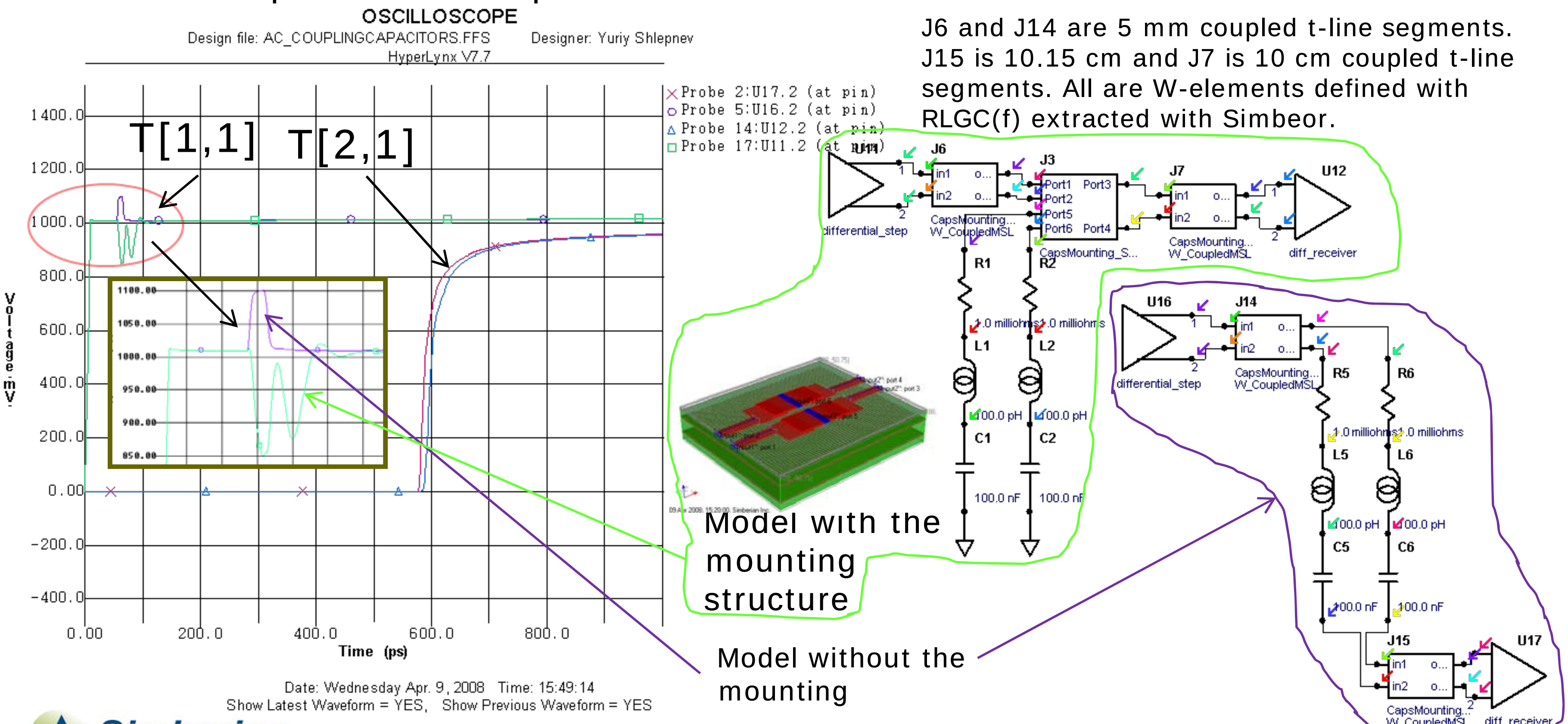


Structure with 2 series ports short-circuited by 0.1 mOhm resistors

Structure with 4 parallel ports connected to two 15-mil line segments to fill the gap

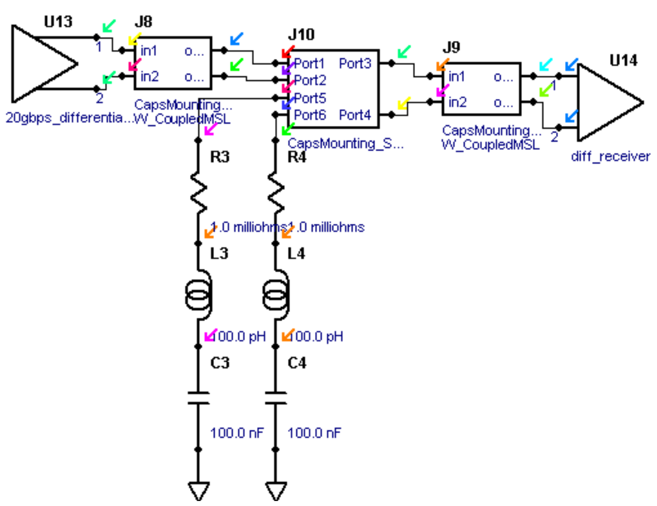
AC coupling capacitor in a simple differential channel

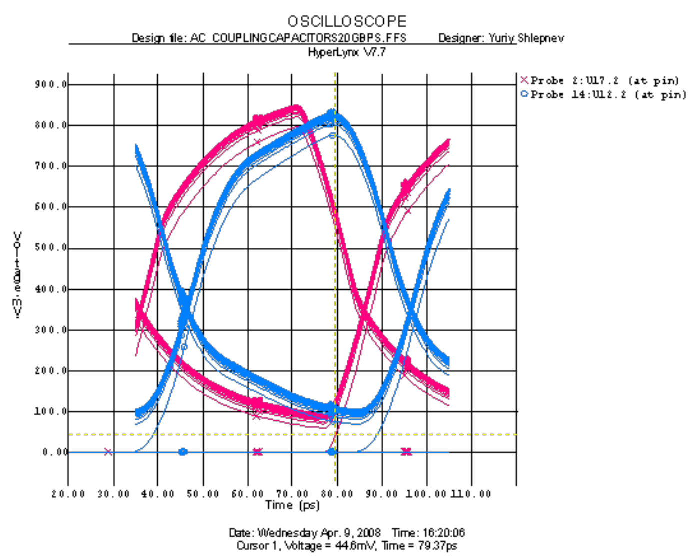
- 10.65 cm long channel is simulated with and without the mounting structure
- Simbeor is used to generate models both for t-lines and mounting structure and HyperLynx+Eldo is used for analysis of the complete channel
- 100 nF capacitor has 100 pH added ESL and 1 mOhm ESR



More numerical experiments…

- HyperLynx file AC_CouplingCapacitors.ffs set up to investigate TDR and TDT of differential channel with capacitor connected closer to driver and receiver
- HyperLynx file AC_CouplingCapacitors20Gbps.ffs set up to investigate propagation of 20 Gb/s signal in a differential channel with the AC coupling capacitors





Conclusion

- Simple examples of Simbeor application for extraction of electromagnetic models of capacitor mounting structure are provided
- The effect of the mounting structures for 0402 capacitors is minor, though larger footprints like 0603 cause visible degradation of multi-gigabit signal even in a simple channel without other discontinuities
  - The problem may be more visible in case if there are some via-holes in the channel and interactions between multiple discontinuities produce resonances at some critical frequencies
- Electromagnetic models of the mounting structures can be used
  - For accurate modeling of multi-gigabit serial data channels
  - For identification of the models for the capacitors by comparison of simulation and measurement results
- Setting up all simulations and model building with Simbeor took approximately 2 hours

Solutions and contact

- Simbeor solution files and HyperLynx schematic files are available for download from the simberian web site
  - http://www.simberian.com/AppNotes/Solutions/AC_CouplingCapacitors_2008_02.zip
- Send questions and comments to
  - General: info@simberian.com
  - Sales: sales@simberian.com
  - Support: support@simberian.com
- Web site www.simberian.com