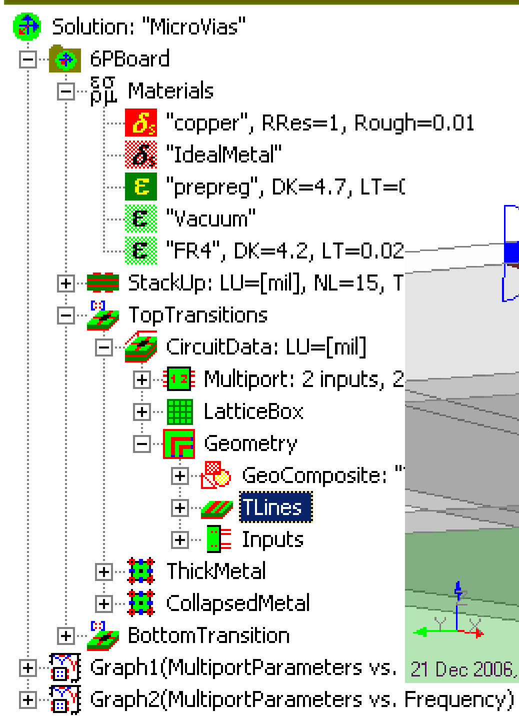
Reciprocity and Symmetry of Interconnects with AC Coupling Capacitors



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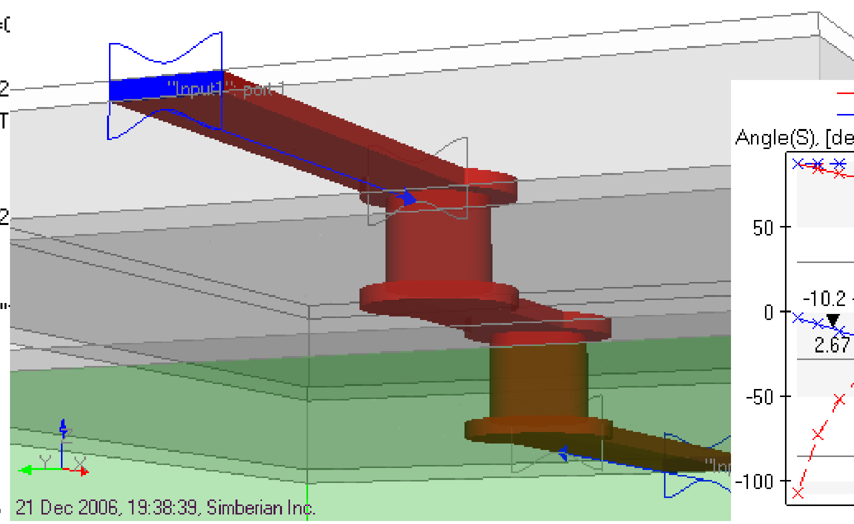

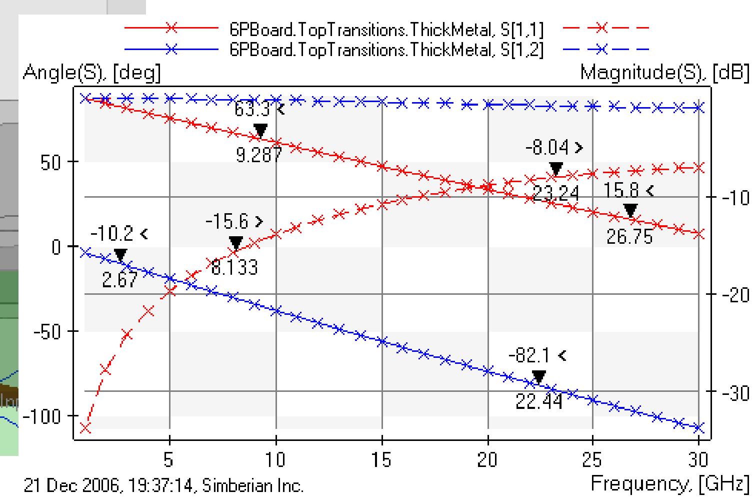

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Overview

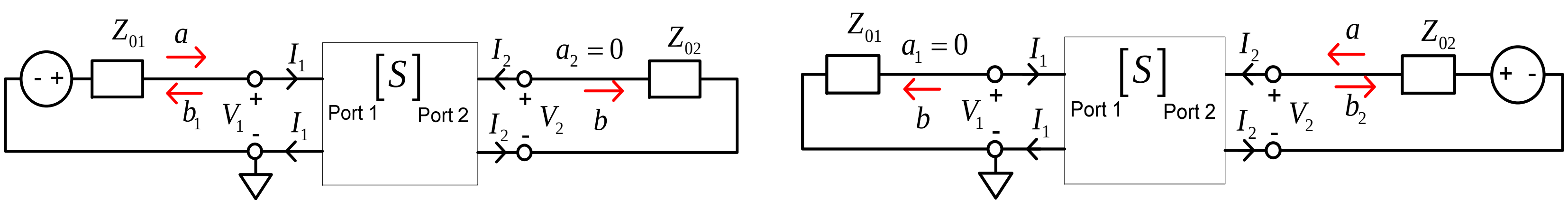
- Introduction
- Reciprocity and symmetry properties
- Simple channel with 0402 AC coupling capacitor
- Simple channel with 0603 AC coupling capacitor
- Conclusion
- Backup slides – “what if” experiments
  - What if driver and receiver have different impedances
  - What if there are resonances in the channel

Introduction

- Serial multi-gigabit data channels have capacitors connected in series (AC coupling capacitors) to allow different DC supply for a driver and receiver
  - Mounting structures of such capacitor and capacitors themselves can be considered as discontinuities for high-frequency harmonics in the channel
  - The observable effect of such discontinuities depends on the capacitor behavior, geometry of capacitors mounting structure as well as on location in the channel
- This example is follow-up to App Notes #2008_02, #2008_04 and:
  - Explains reciprocity and symmetry properties of multiport parameters - important to understand the generality of the numerical results observed for simple cases
  - Demonstrates the effect of AC capacitors mounting structure and position in the channel on the transmission and reflection parameters and TDR/TDR responses
  - Demonstrates how to simulate a simple channel with AC coupling capacitors within Simbeor environment
- Simbeor 2008.01 built on March 30th 2010 is used to generate the results

Reciprocity

- Linear systems with reciprocal materials are reciprocal according to Lorentz's theorem of reciprocity:
  Reflected wave measured at port 2 with incident wave at port 1 is equal to reflected wave measured at port 1 with the same incident wave at port 2



$$b = S_{2,1} \cdot a \qquad\qquad b = S_{1,2} \cdot a$$

$$S_{2,1} = S_{1,2}$$

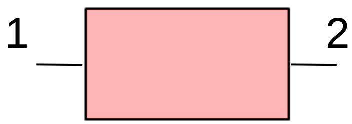
- In general it means that the scattering matrices are symmetric

$$S_{i,j} = S_{j,i} \quad or \quad S = S^t$$ at all frequencies

  and TDT response at port j with source at port i is exactly the same as TDT response at port i with the source at port j

S-parameters of reciprocal systems

- Single-ended channel

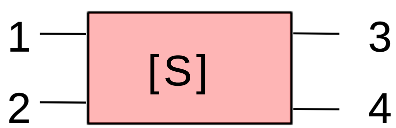


$$S = \begin{bmatrix} S_{1,1} & S_{1,2} \\ S_{1,2} & S_{2,2} \end{bmatrix}$$

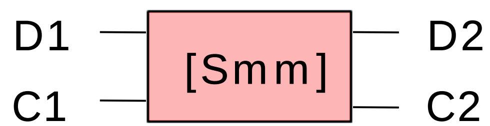
All matrices are symmetrical that also leads to identity of the TDT responses!

- Differential channel

Terminal space



Mixed-mode space



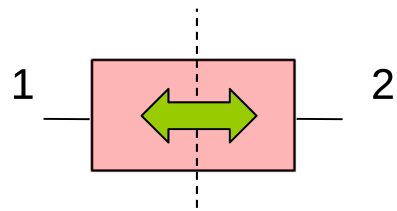
$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{bmatrix}$$

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

Geometric mirror symmetry input to output: Single-ended interconnecs

S-matrix of a reciprocal 2-port:

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



Symmetry group generator:

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

S-matrix must commute with F: $F \cdot S = S \cdot F \Rightarrow$

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

It means that: $S_{2,2} = S_{1,1}$

Final S-matrix of reciprocal symmetrical 2-port: $S = \begin{bmatrix} S_{1,1} & S_{1,2} \\ S_{1,2} & S_{1,1} \end{bmatrix}$

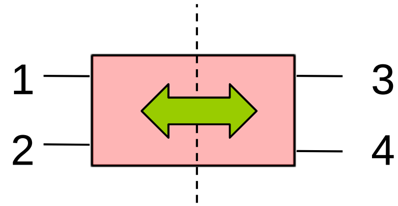
only 2 independent parameters

TDR response of such system will be identical for port 1 and port 2!

Geometric mirror symmetry input to output: Differential interconnects

S-matrix of a reciprocal 4-port:

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



Symmetry group generator:

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

S-matrix must commute with F: $F\cdot S=S\cdot F \Rightarrow$

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

It means that: $S_{3,3}=S_{1,1},\ S_{2,3}=S_{1,4}$
$S_{4,4}=S_{2,2},\ S_{3,4}=S_{1,2}$

Final S-matrix of reciprocal symmetrical 4-port has only 6 independent parameters:

Terminal space

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

Mixed-mode space

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

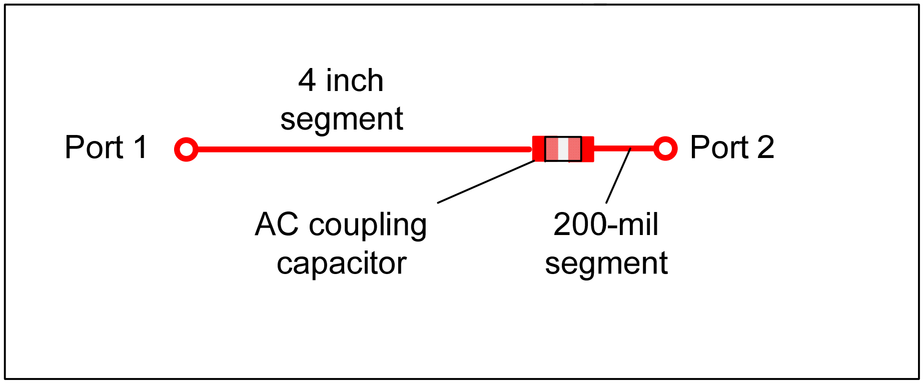
Observations on symmetry and reciprocity

- Real structures on PCBs are rarely symmetrical
  - Even straight line segments with almost identical pads or connectors are not exactly symmetrical due to manufacturing tolerances and weave effect
  - Non-symmetry leads to differences in the reflection from the opposite ends of a channel
- All materials used for PCBs and packages are reciprocal
  - Scattering matrices must be symmetrical and TDT responses are identical for each port pair
  - Violation of reciprocity is the error either in measurements or simulations and measure of actual non-reciprocity can be used to estimate the quality of the model
- See more on multiport parameters quality metrics in presentation #2010_01 at http://www.simberian.com/TechnicalPresentations.php

H. Barnes, Y. Shlepnev, J. Nadolny, T. Dagostino, S. McMorrow, Quality of High Frequency Measurements: Practical Examples, Theoretical Foundations, and Successful Techniques that Work Past the 40GHz Realm, Tutorial materials from DesignCon 2010, Santa Clara, February 1, 2010

De-compositional analysis of a single-ended channel with AC coupling capacitor

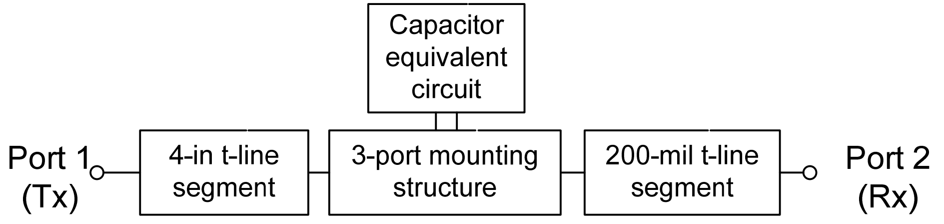
- Capacitor model: C=100 nF, ESR=1 mOhm, ESL= 100 nH
- Capacitor is placed closer to the port 2



Sketch of the channel

We will use broadband RLGC(f) model of 50-Ohm micro-strip line and extracted S-parameters of the capacitor mounting structure

Simbeor de-compositional model of the channel



The channel is simulated as connection of multiports both in frequency and time domains

Materials and stack-up for analysis of simple channel with AC coupling capacitors

- Solution Simbeor AC_CouplingCaps_2010_02 is created for this investigation (example #101 in the database http://kb.simberian.com)
- 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

```
CapsMounting
  Materials
    "Copper", RR=1
    "IdealMetal"
    "FR4", Dk=4.2, LT=0.02, PLM=WD
    "Vacuum"
  StackUp: LU=[mil], NL=9, T=24.21[mil]
    1| Signal: "CapPlane", T=0.77, Ins="Vacuum"
    2| Medium: T=0.5, Ins="Vacuum"
    3| Signal: "Signal1", T=1.2, Ins="Vacuum"
    4| Medium: T=4.5, Ins="FR4"
    5| Plane: "Plane1", Mat="Copper", T=0.77, Ins="FR4"
    6| Medium: T=10, Ins="FR4"
    7| Plane: "Plane2", Mat="Copper", T=0.77, Ins="FR4"
    8| Medium: T=4.5, Ins="FR4"
    9| Signal: "Signal2", T=1.2, Ins="Vacuum"
```

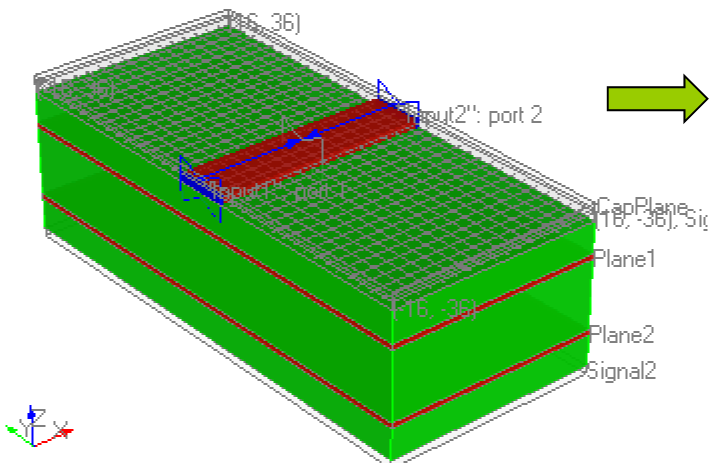
Wideband Debye model for FR-4 type dielectric

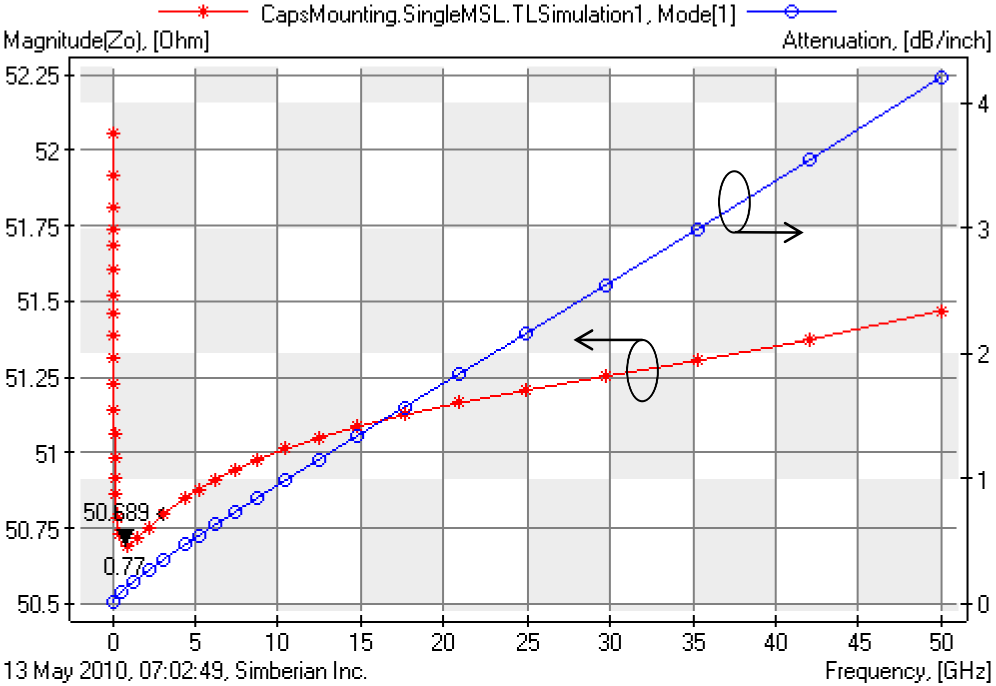
Thin layer of air and additional layer "CapPlane" of signal-type are added to simulate non-flat connection of the capacitors

Use Help > Tutorials > Tutorial 1 or Demo Video #2008_01 to learn how to build models for materials and stackup

Single-ended channel – advanced transmission line model (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



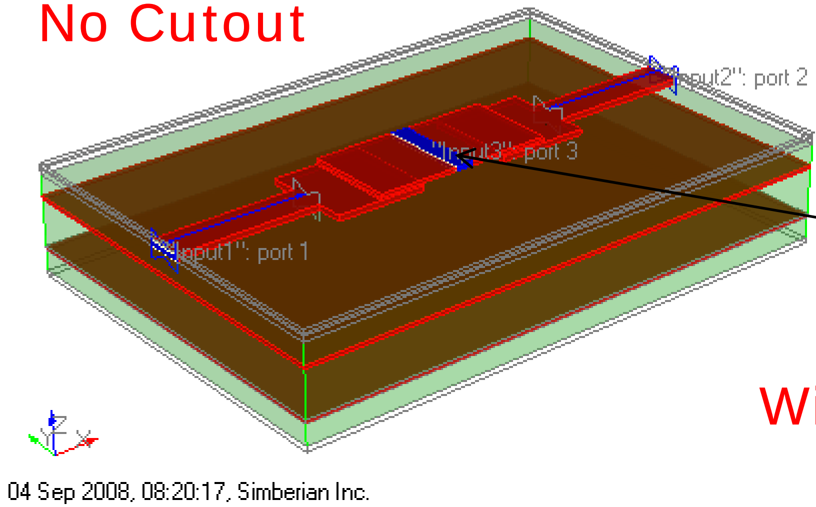


Use Help > Tutorials > Tutorial 2 or Demo Video #2008_02 to learn how to build broadband RLGC(f) models for transmission line

EM analysis of 0402 capacitor mounting structures (circuits SPSingle and SPSingle2)

- Series port is the only option in case of cut-out of the reference plane below the capacitor (no reference below the pads to construct parallel ports)

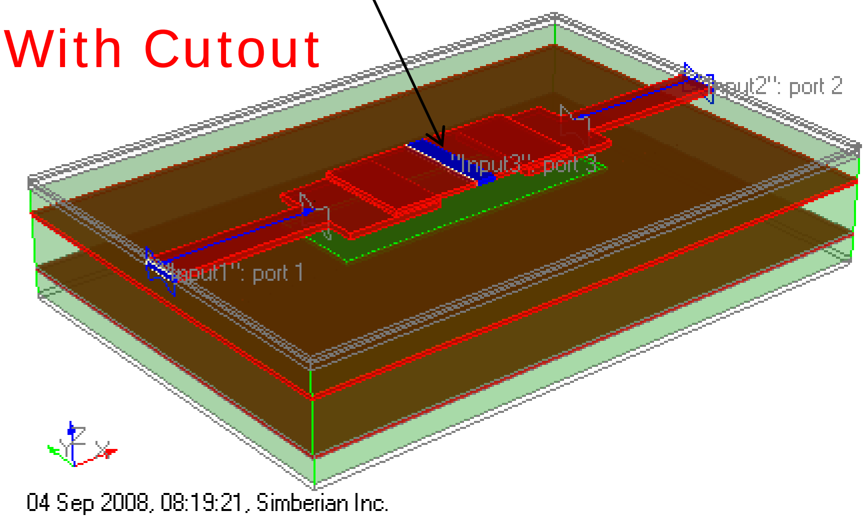
No Cutout



3-port broad-band S-parameter models of the mounting structures are extracted for both configurations

Series X-directed port #3 to connect the capacitor model

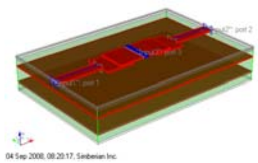
With Cutout



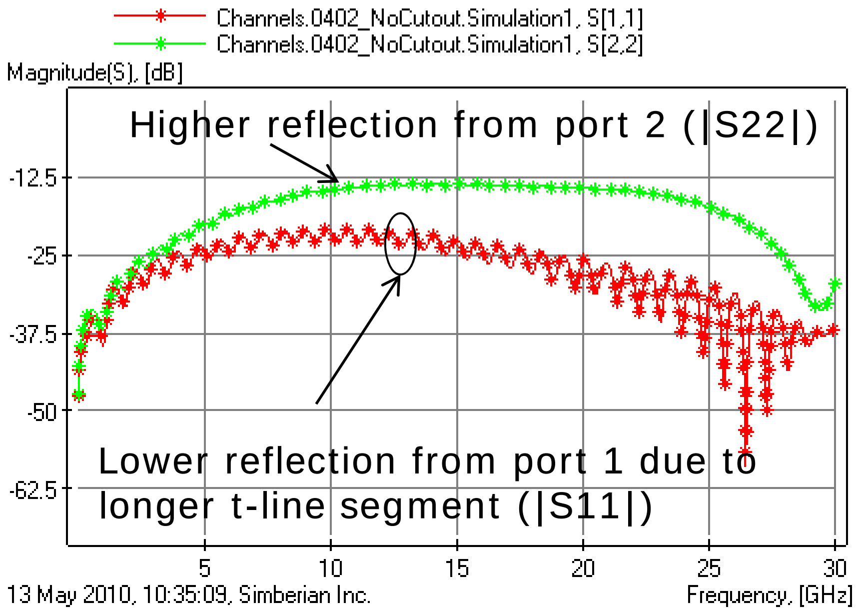
Details on EM analysis setup are in App Notes #2008_02 and #2008_04

Reflection parameters for 0402 case

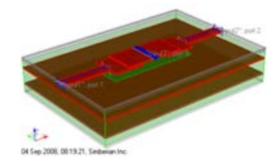
- S[1,1] is different from S[2,2] due to geometrical non-symmetry
- Structure with cut-out has much lower reflections on both ends

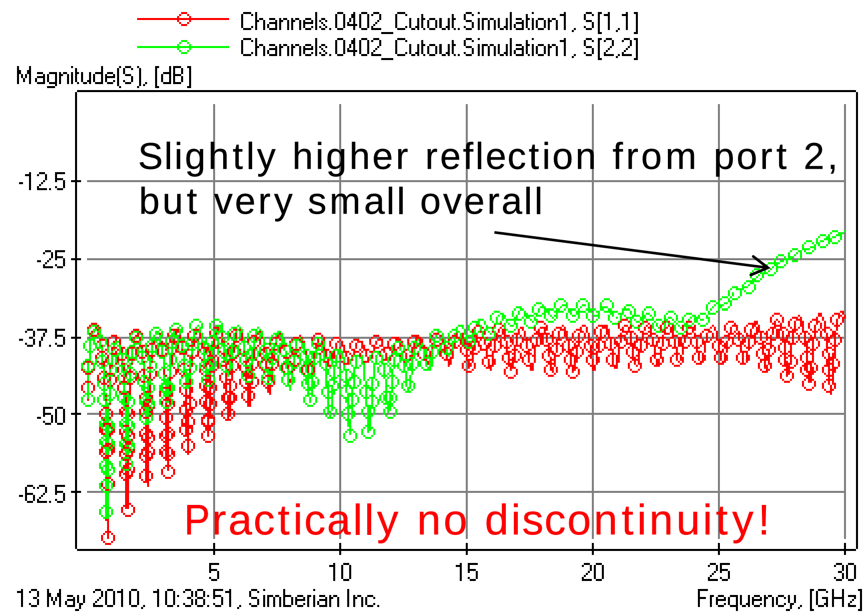


No Cutout



With Cutout

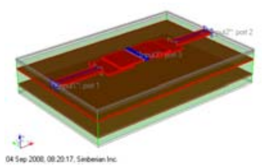




The reflection may be not significant for practical applications

TDR with 40 ps Gaussian step (0.1-0.9) for 0402 case

- TDR at port 1 is different from TDR at port 2 due to the geometrical non-symmetry (similar to S11 and S22 parameters)



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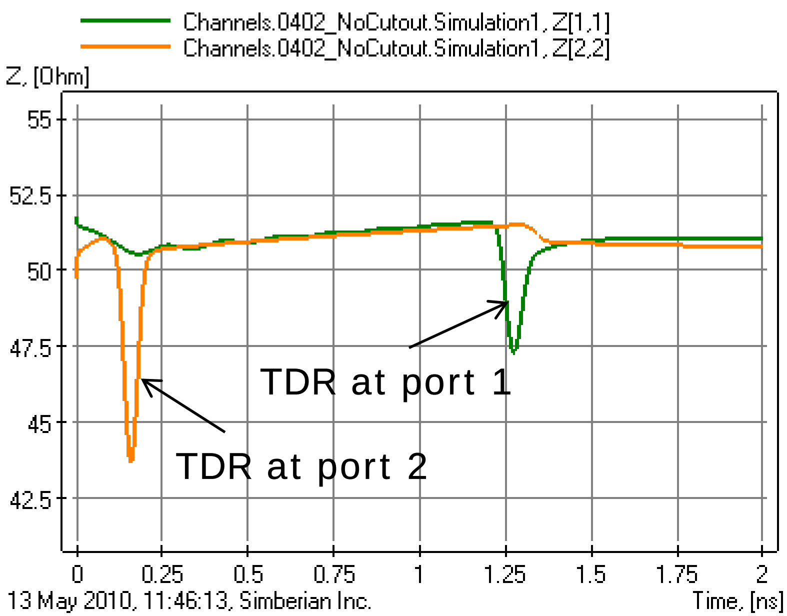
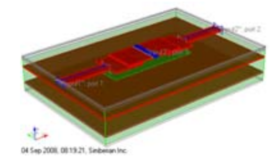
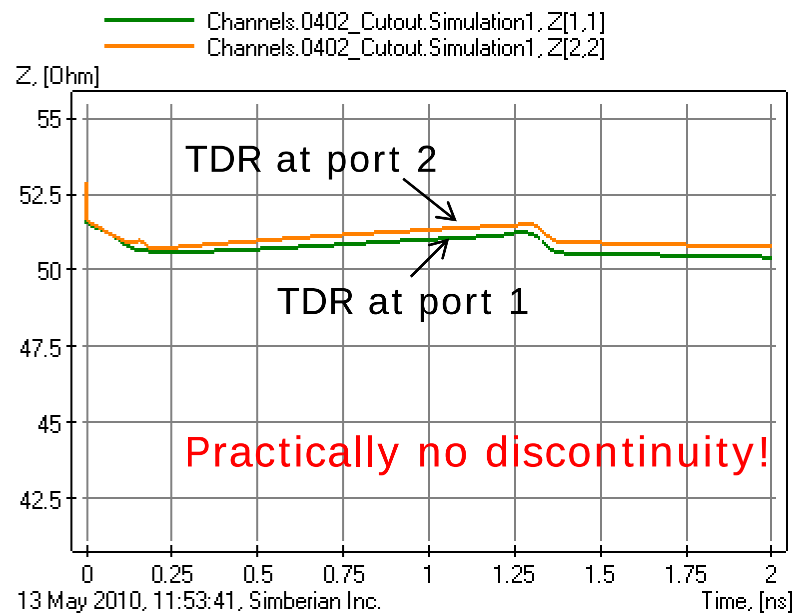


With Cutout

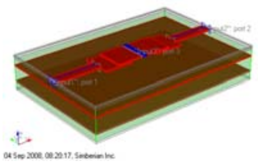




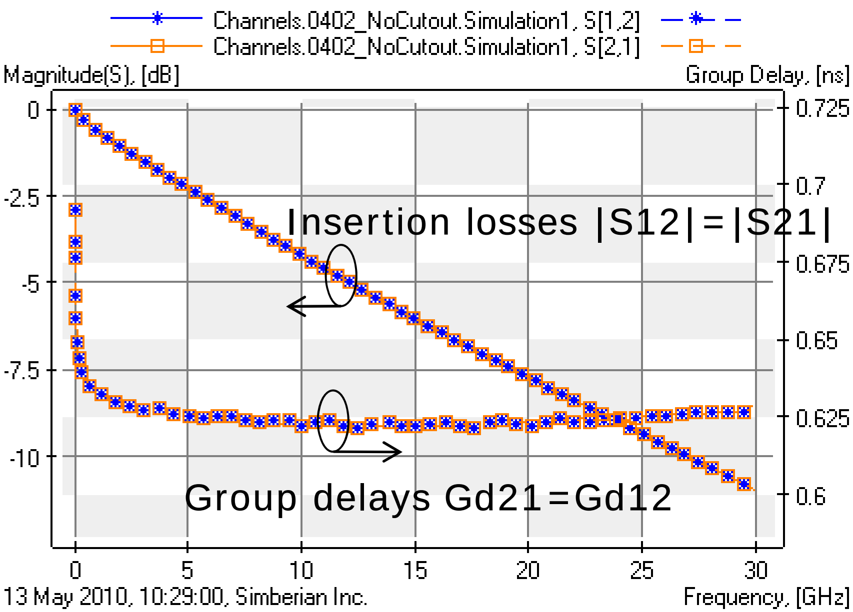
The reflection may be not significant for practical applications

Transmission parameters for 0402 case

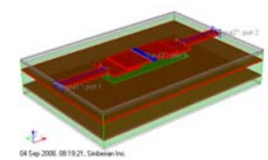
- S[1,2] is identical to S[2,1] as expected due to reciprocity
- Transmissions parameters are practically the same with and without cutout due to very small reflections

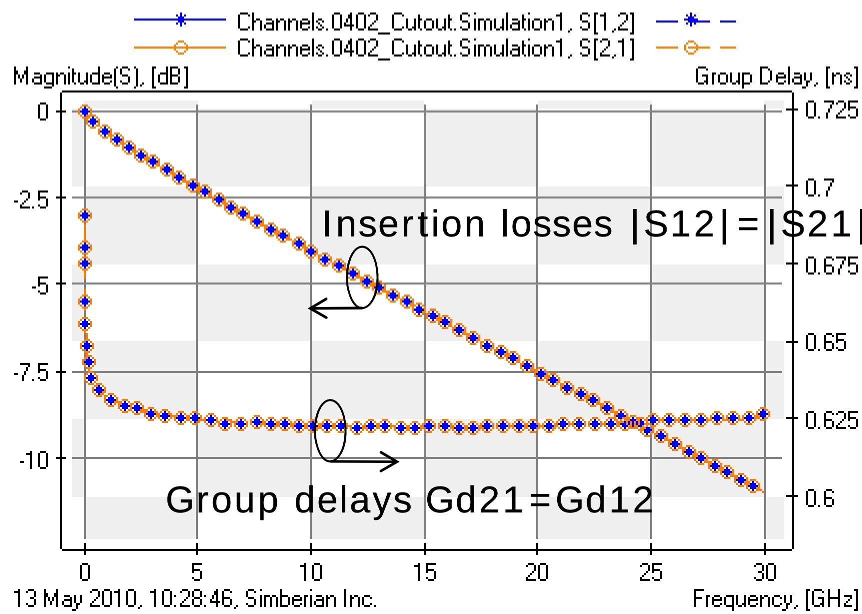


No Cutout



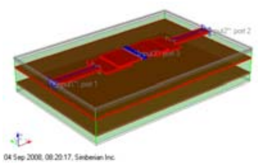
With Cutout





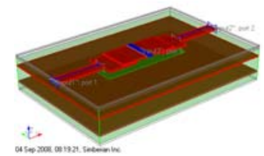
Transmission parameters for 0402 case

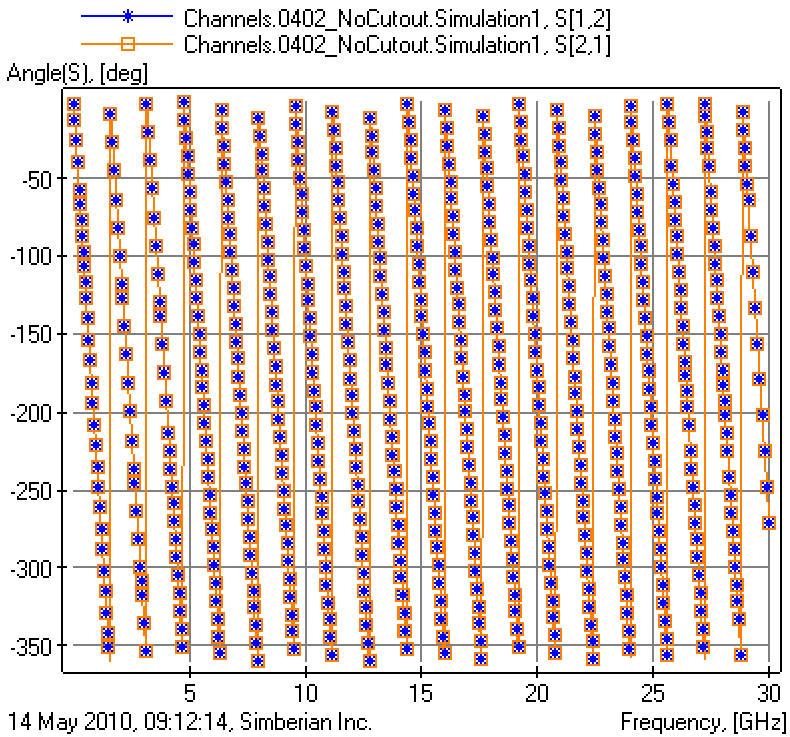
- Phase of S[1,2] is identical to S[2,1] as expected due to reciprocity

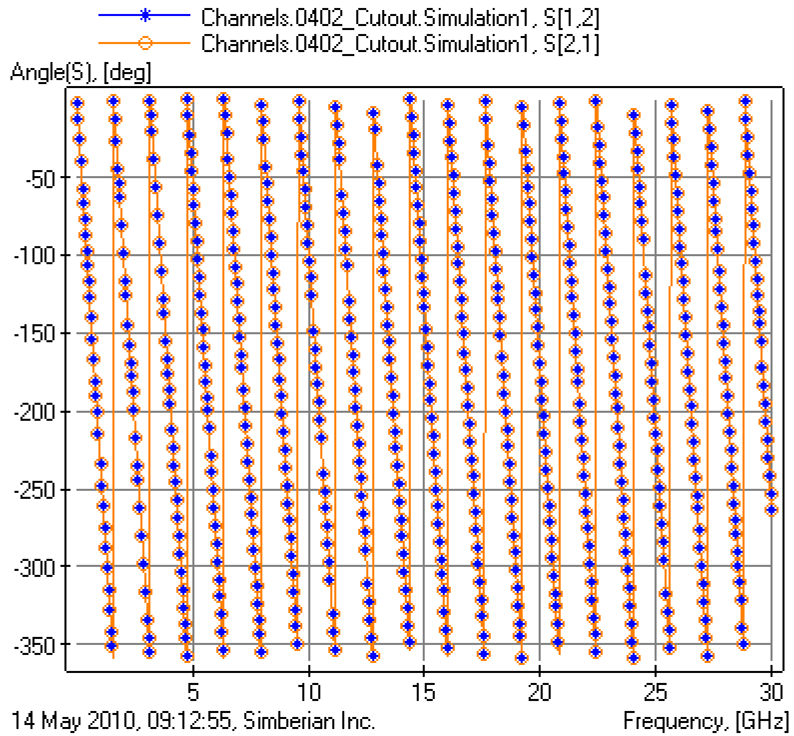


No Cutout

With Cutout

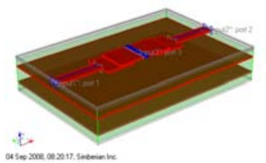






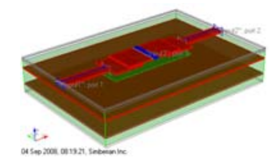
TDT with 40 ps Gaussian step (0.1-0.9) for 0402 case

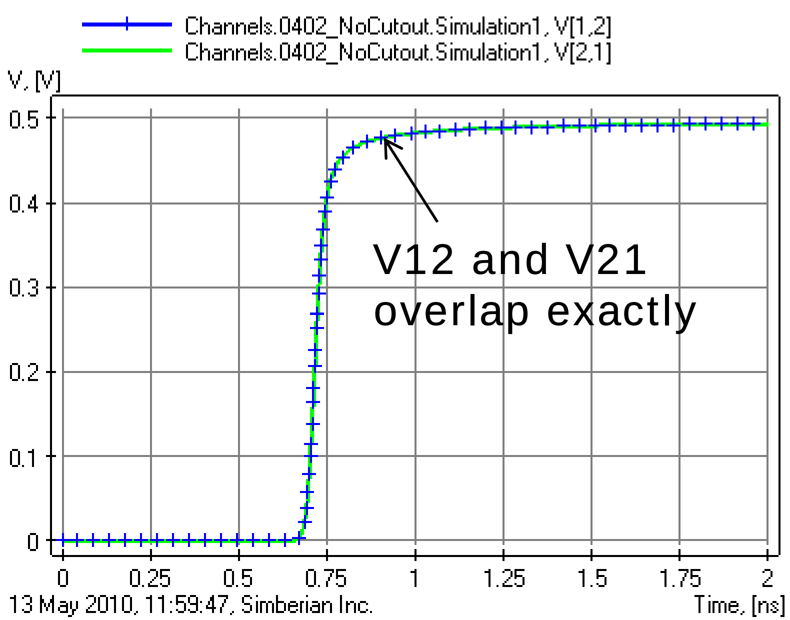
- TDT at port 1 is identical to TDT at port 2 due to reciprocity (similar to S12 and S21 parameters)

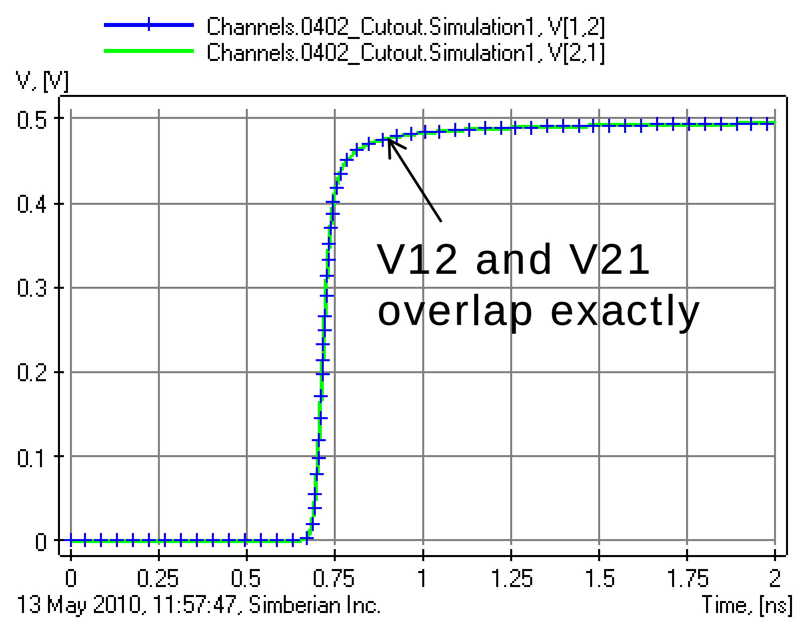


No Cutout

With Cutout





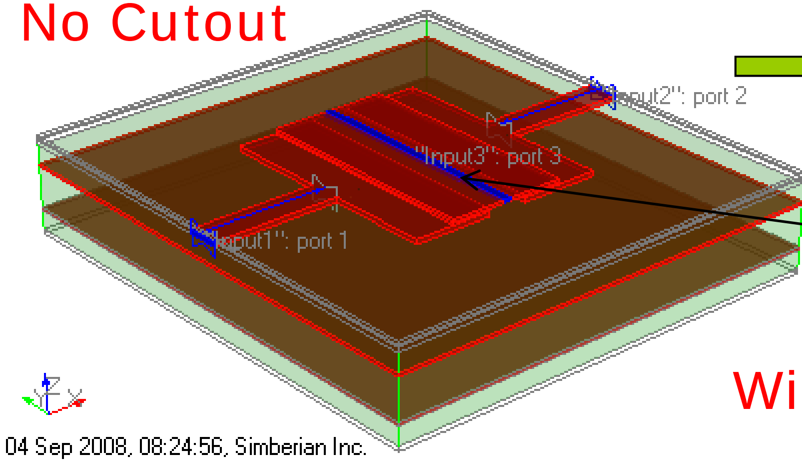


No effect of reflection differences on TDT!

0603 capacitor mounting structures (circuits SPSingle0603 and SPSingle0603_2)

- Series port is the only option in case of cut-out of the reference plane below the capacitor (no reference below the pads to construct parallel ports)

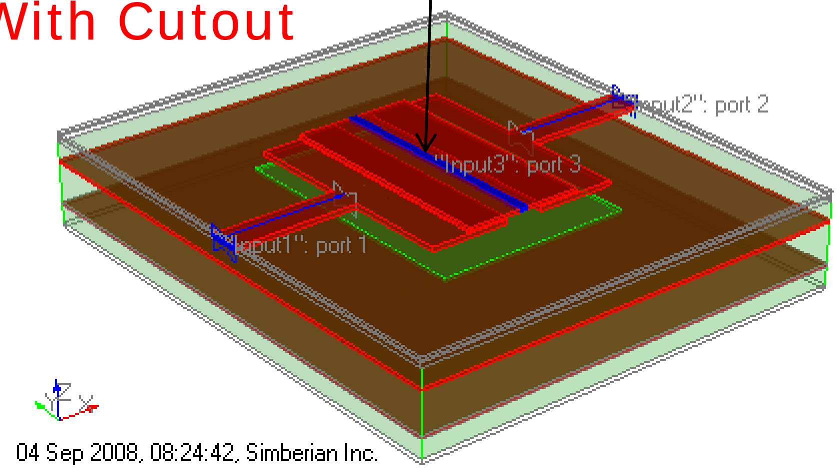
No Cutout



3-port broad-band S-parameter models of the mounting structures are extracted for both configurations

Series X-directed port #3 to connect the capacitor model

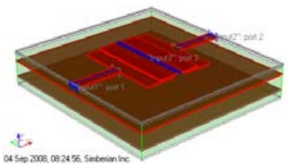
With Cutout



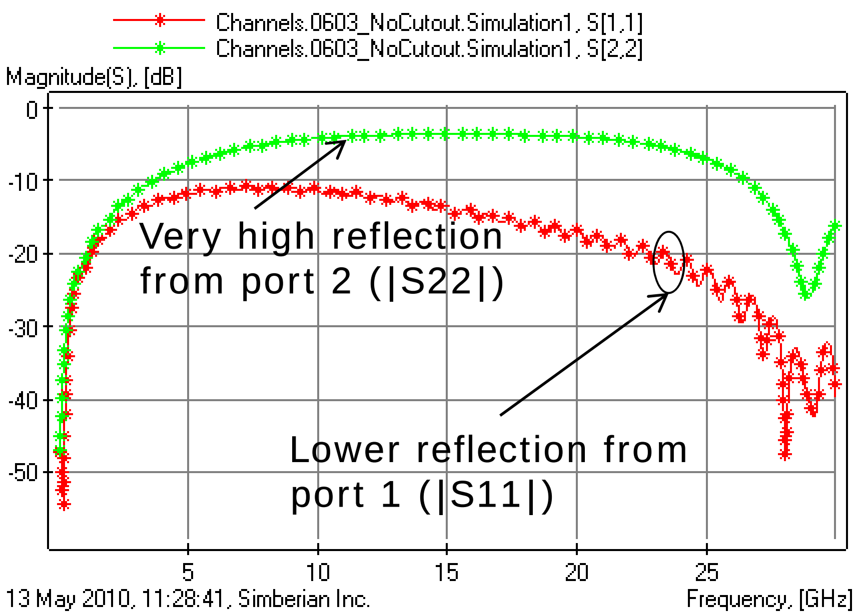
Details on EM analysis setup are in App Notes #2008_02 and #2008_04

Reflection parameters for 0603 case

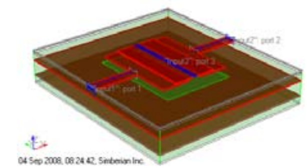
- S[1,1] is different from S[2,2] due to the geometrical non-symmetry
- Structure with cut-out has lower reflections on both ends

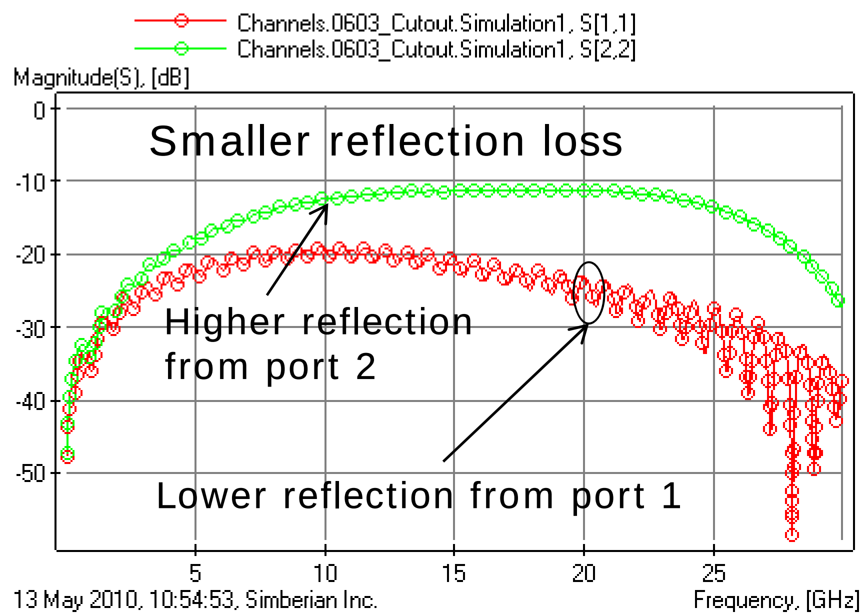


No Cutout



With Cutout

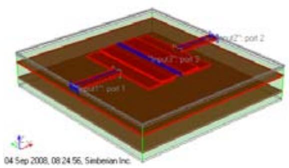




The reflection is not negligible in both cases

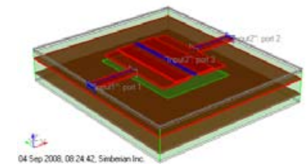
TDR with 40 ps Gaussian step (0.1-0.9) for 0603 case

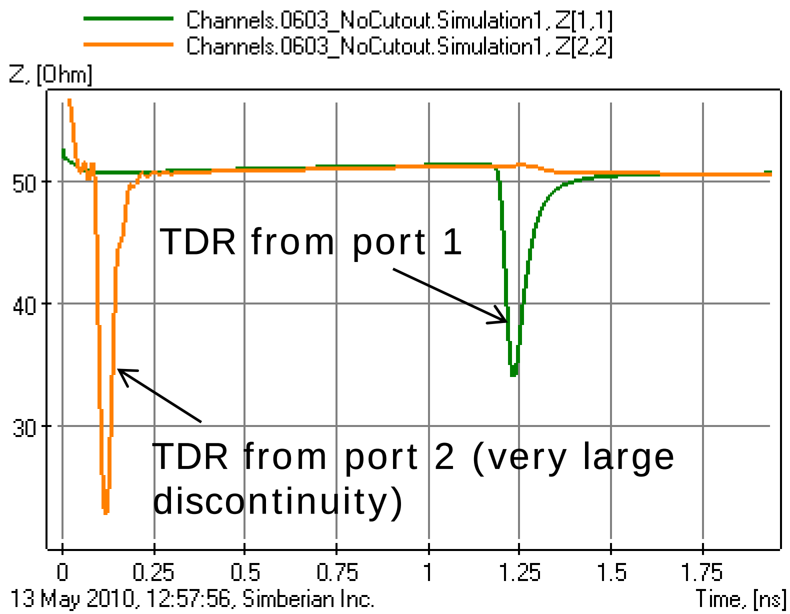
- TDR from port 1 is different from TDR at port 2 due to geometrical non-symmetry (similar to S11 and S22 parameters)

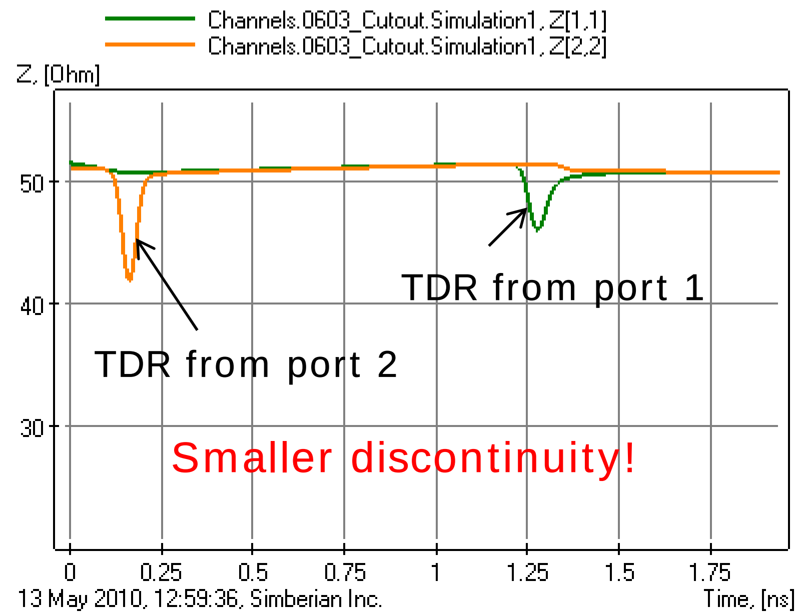


No Cutout

With Cutout



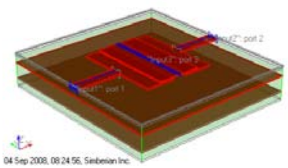


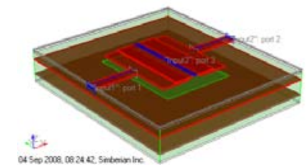


The reflection is significant and must be accounted in analysis

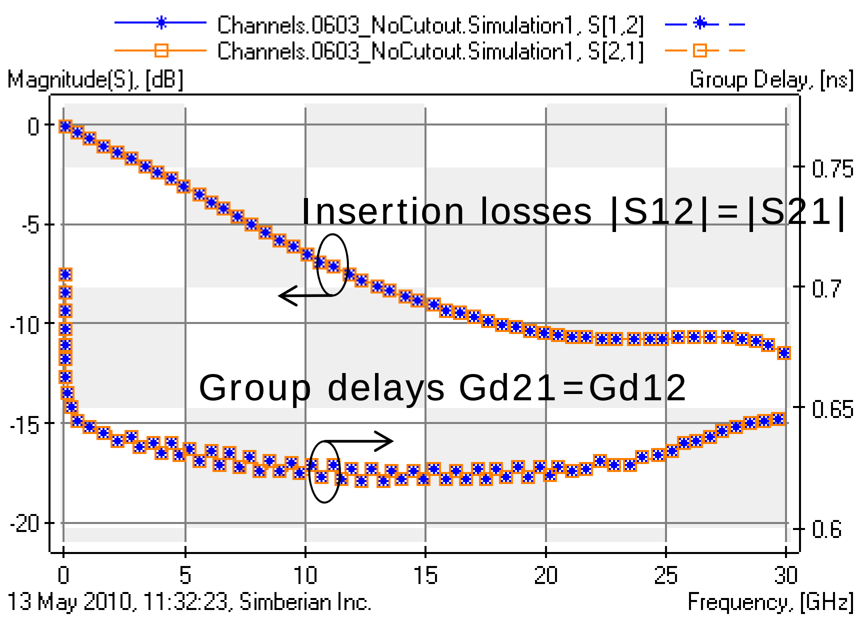
Transmission parameters for 0603 case

- S[1,2] is identical to S[2,1] as expected due to reciprocity
- Insertion loss is smaller in case with cutout due to smaller reflections

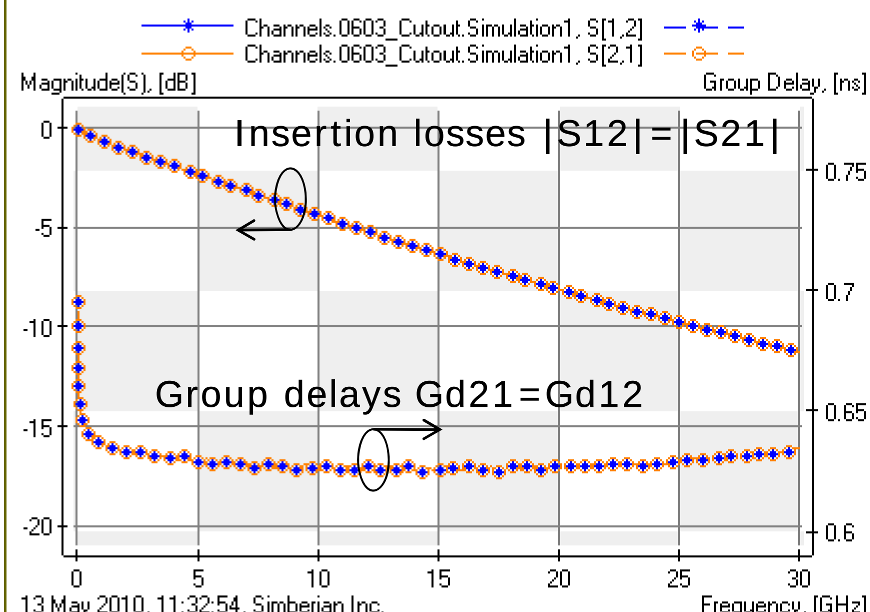




No Cutout

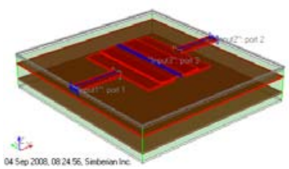


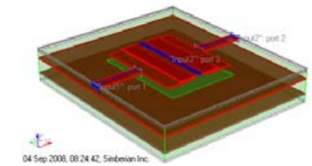
With Cutout



Transmission parameters for 0603 case

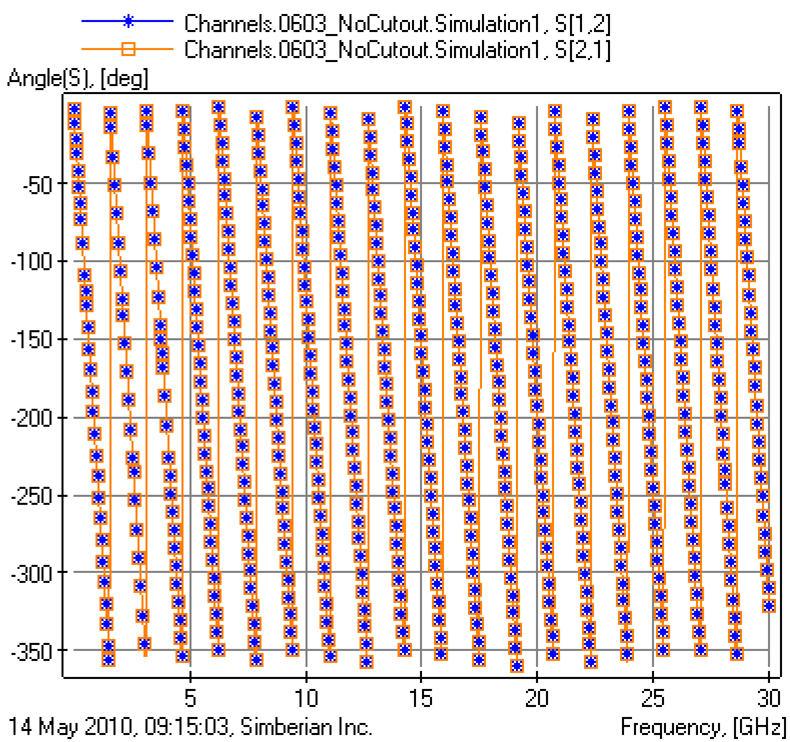
- Phase of S[1,2] is identical to S[2,1] as expected due to reciprocity

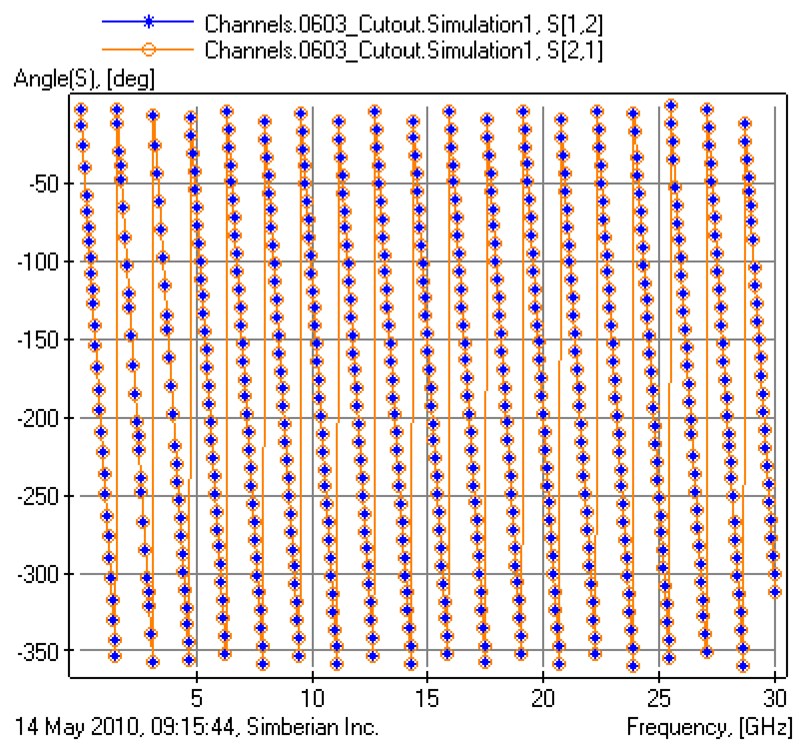




No Cutout

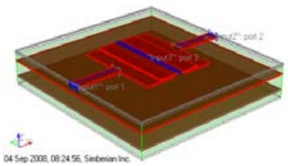
With Cutout





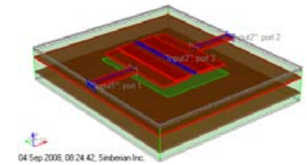
TDT with 40 ps Gaussian step (0.1-0.9) for 0603 case

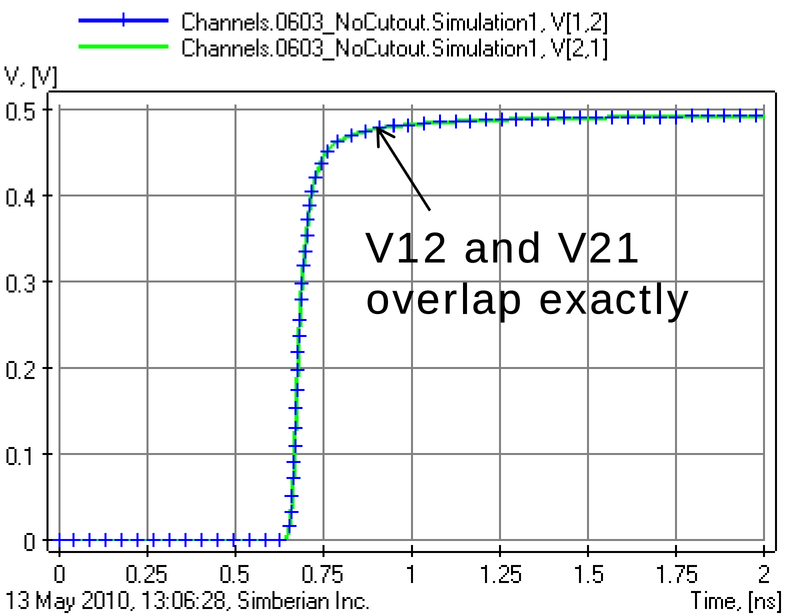
- TDT at port 1 is exactly the same as TDT at port 2 due to reciprocity (similar to S12 and S21 parameters)

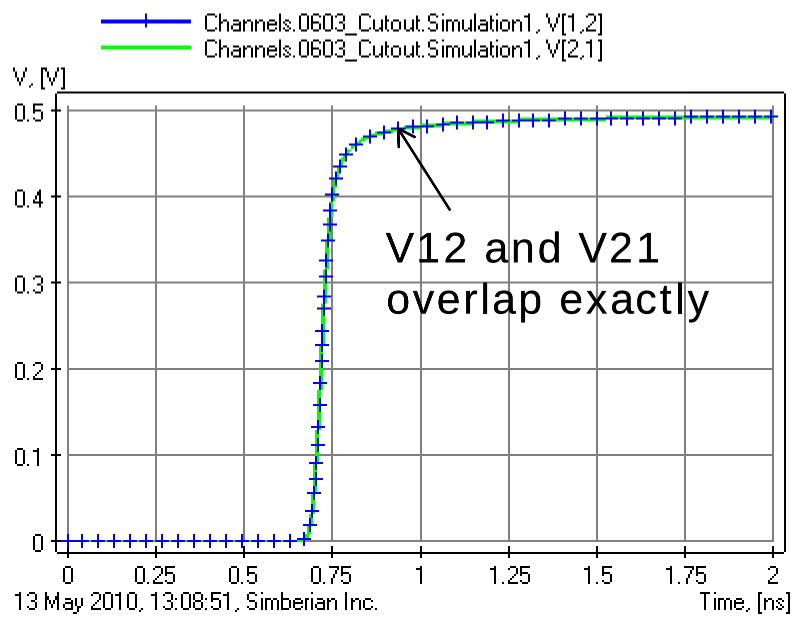


No Cutout

With Cutout



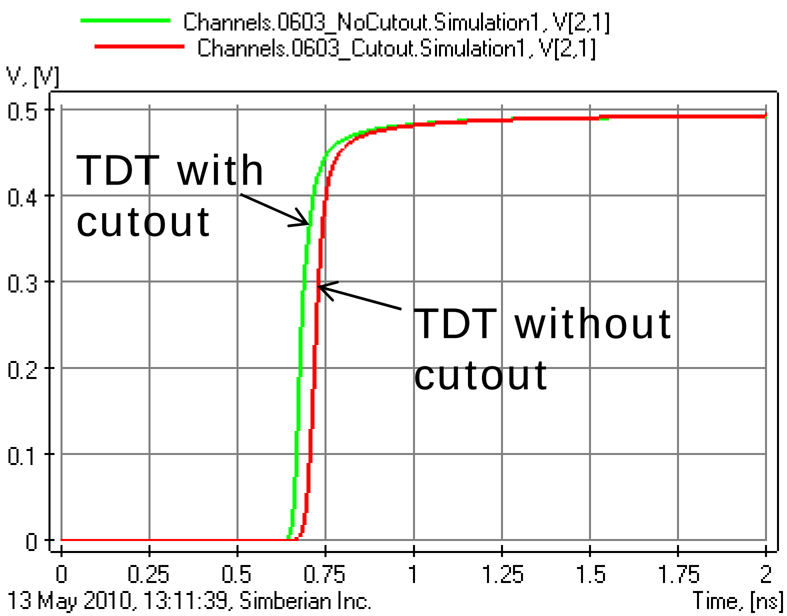


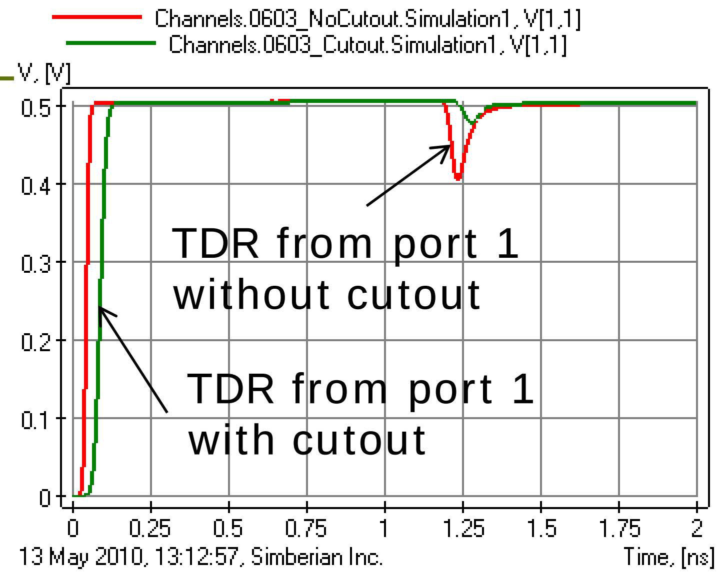


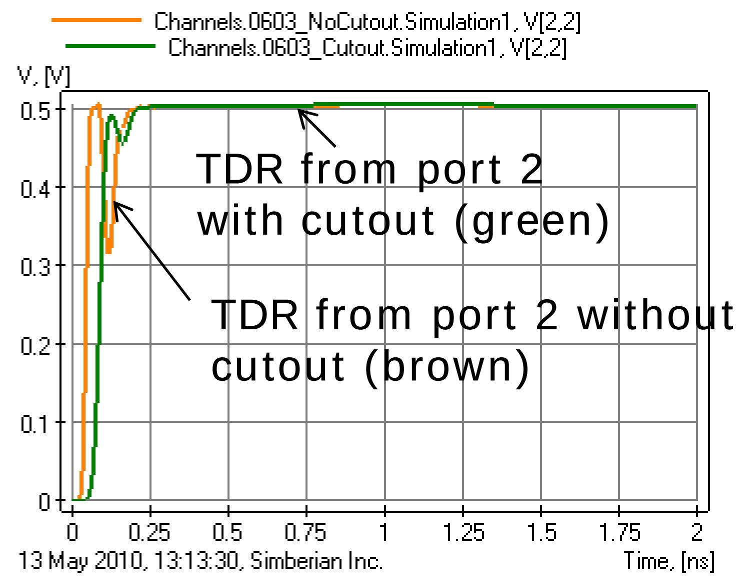
No effect of reflection differences on TDT!

TDT/TDT with 40 ps Gaussian step for 0603 case

- Optimized AC cap mounting structure reduces the reflection loss and the effect of cap placement

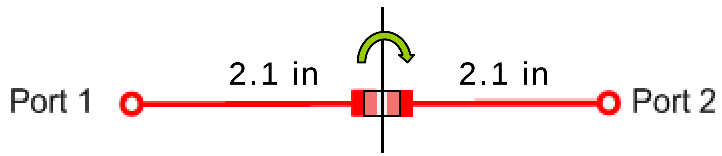


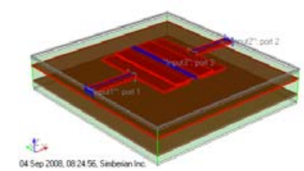




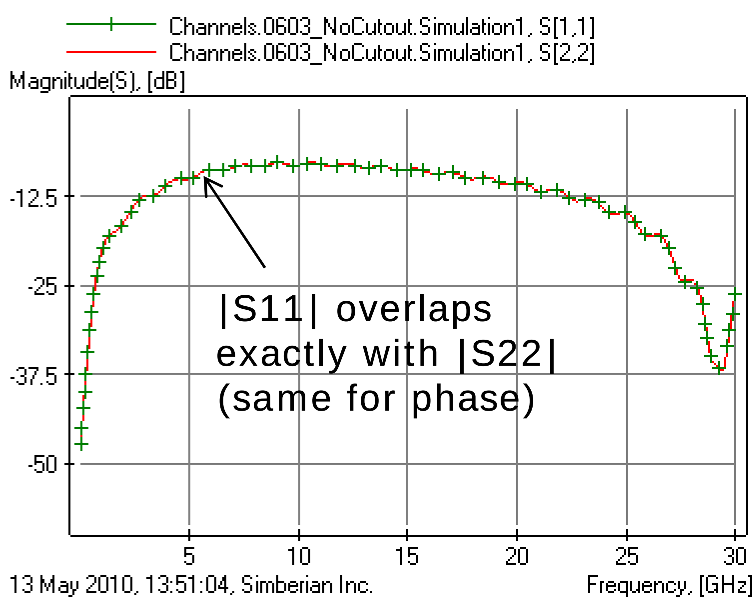
0603 case with geometrical symmetry

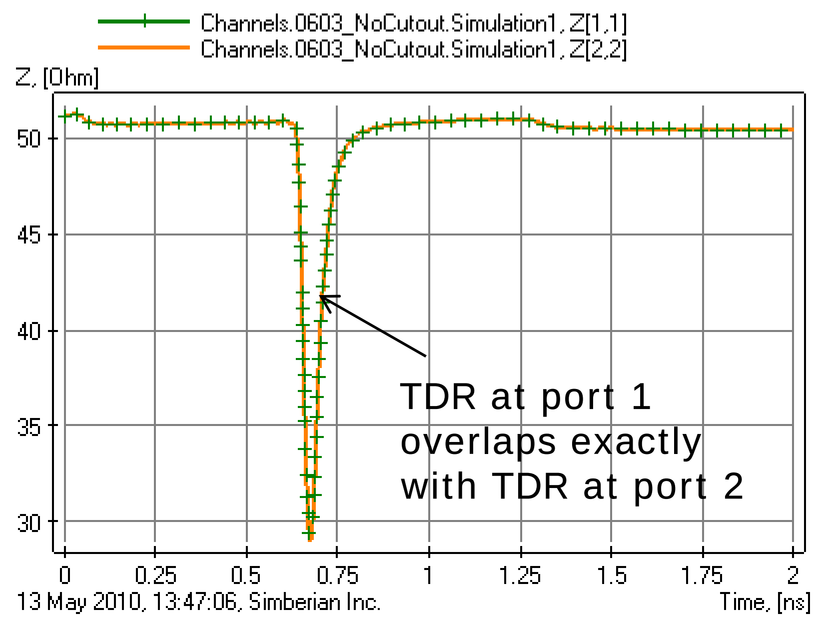
- Reflection parameters from both ports are identical and TDR at port 1 is identical to TDR at port 2 due to the geometrical symmetry





No Cutout





Conclusion

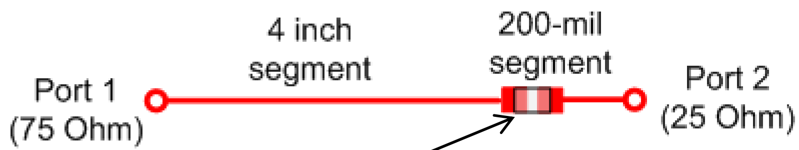
- Effect of reciprocity and geometrical symmetry on scattering parameters and TDR/TDT responses of a system is explained
- The effect of reciprocity and symmetry is illustrated with de-compositional electromagnetic analysis of simple channels with AC coupling capacitors
- It is observed that:
  - Transmission parameters and TDT responses depend on geometry of the capacitor mounting structure and do not depend on the position of the capacitors
  - Reflection parameters and TDR responses depend on the geometry of the mounting structure as well as on the position of the capacitor in the channel
  - The reflections can be minimized by optimization of the mounting structure geometry (use of cut-outs in the reference planes) and by positioning the capacitors farther from the signal source
- Effect of the reflections must be always investigated with all elements of channel such as connectors, packages, vias, non-linear and reflective driver and receiver included
- Analysis and loss minimization for differential channels is similar
- Setting up all simulations and model building with Simbeor took less than 1 hour

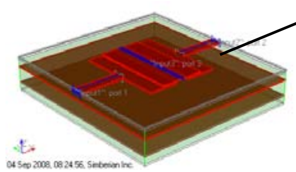
Solutions and contact

- Simbeor solution file is #101 in the database
  http://kb.simberian.com/SimbeorExample.php?example=101
  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

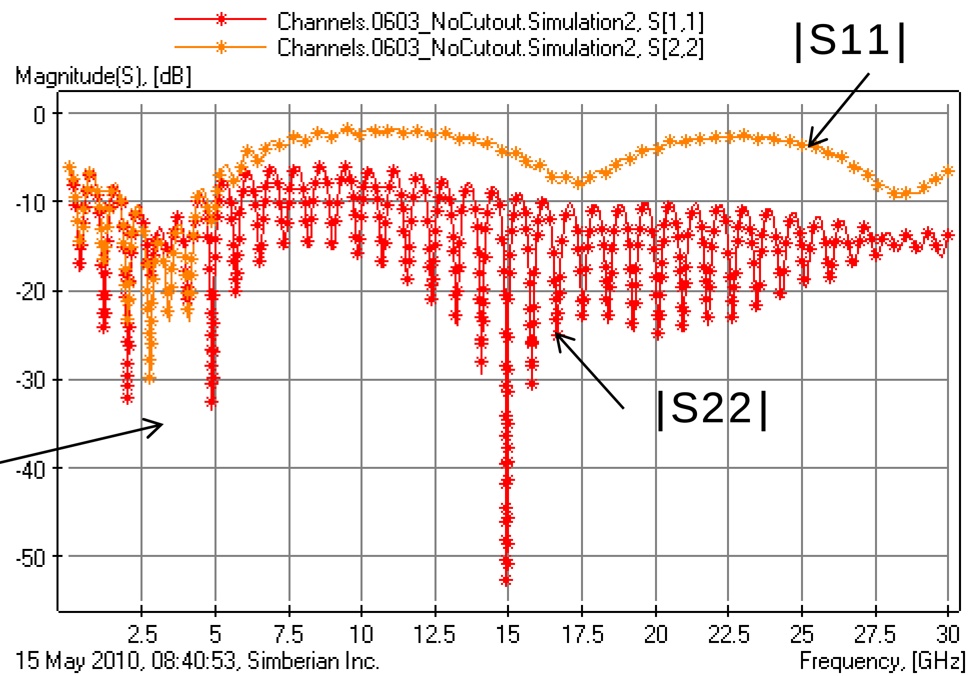
What if driver and receiver are mismatched?

- In all previous examples signal sources had 50 Ohm resistance in series – corresponds to ideally matched driver and receiver
- What if we have 75 Ohm resistance on one side and 25 Ohm on the other?





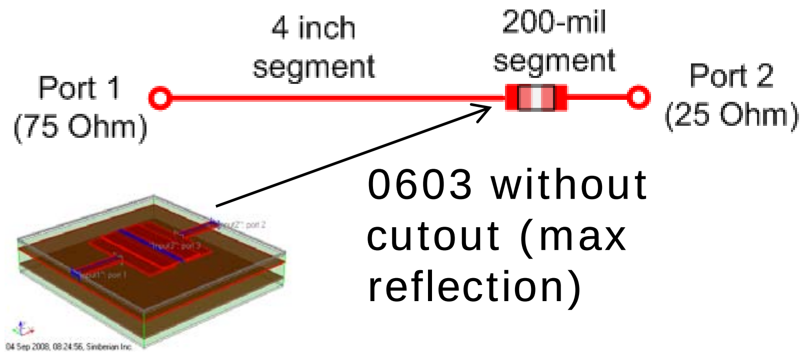
0603 without cutout (max reflection)

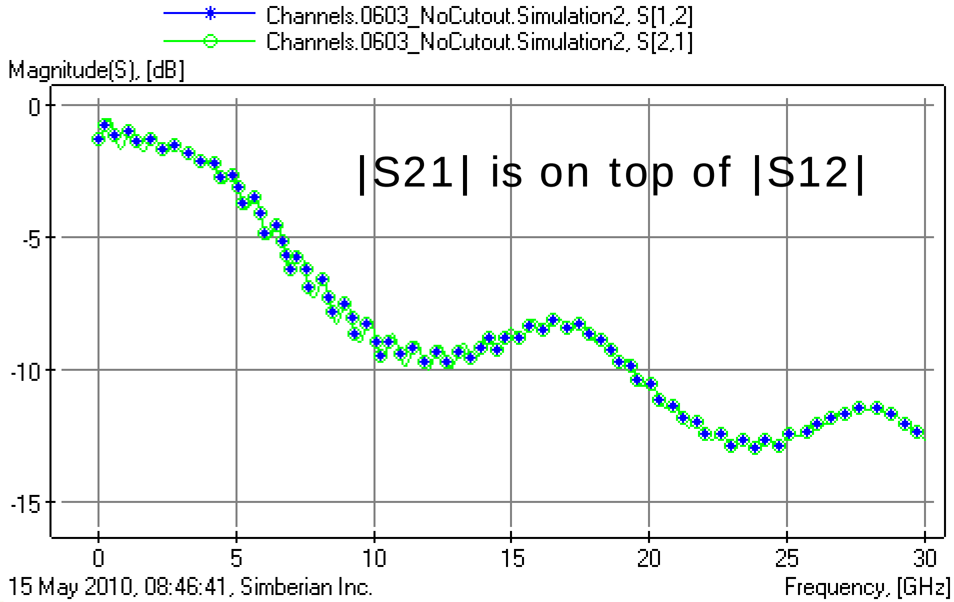


Superposition of resonances in the reflection parameters due to mismatches of the longer and shorter segments on each side of the capacitor

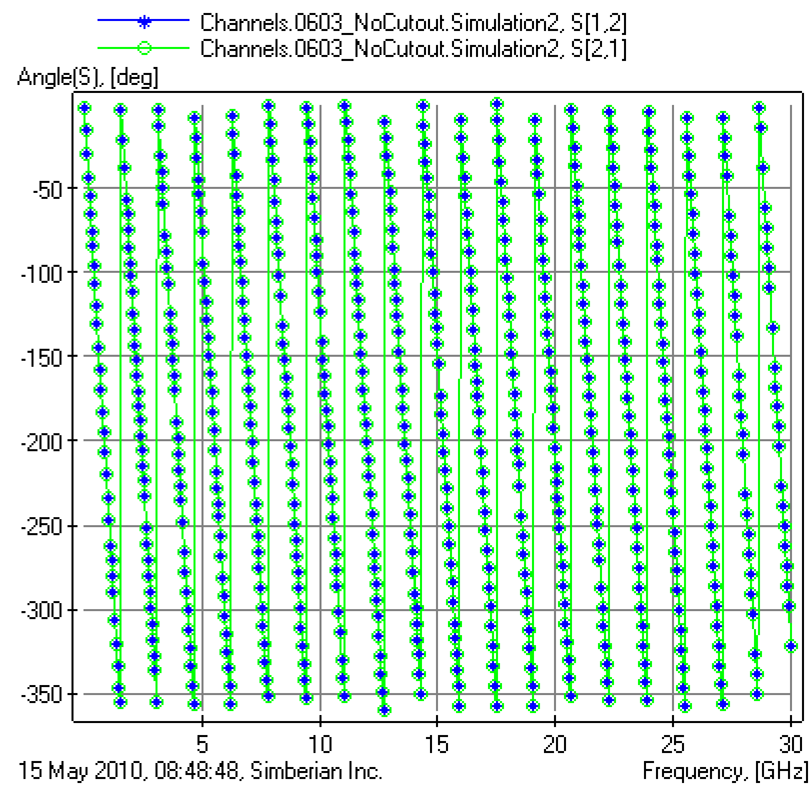
What about the transmission parameters?

- S12 is still identical to S21 due to the reciprocity theorem!



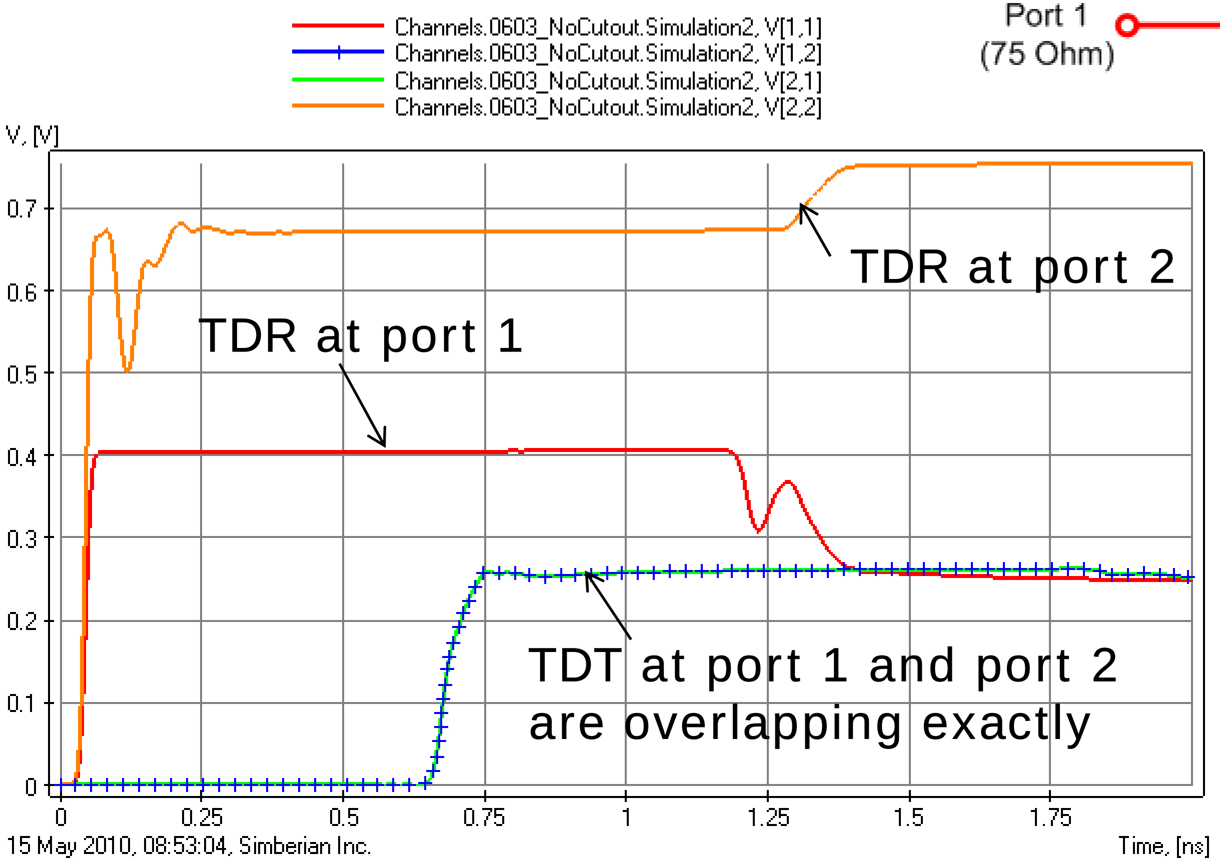


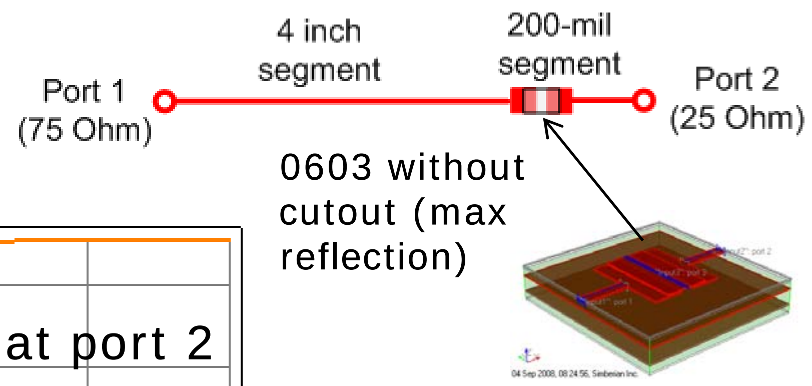
Phase of S21 is on top of S12



TDR/TDT outcome is the same as in the 50-Ohm case

- TDR responses are different, but TDT at port 1 is still identical to TDT at port 2

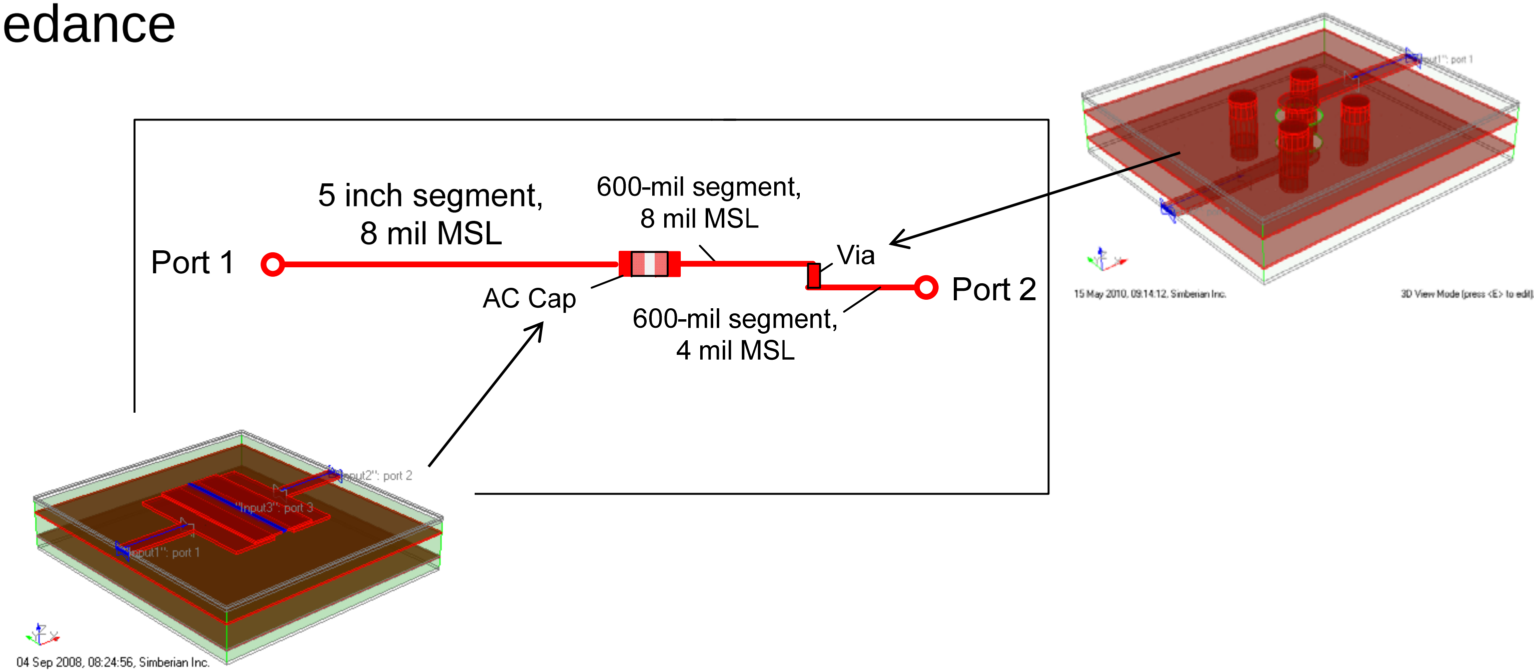




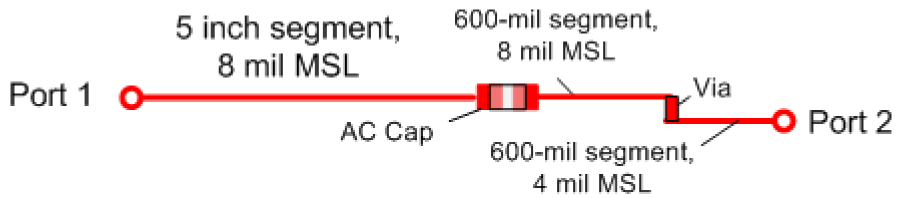
H. A. Lorentz's theorem holds!

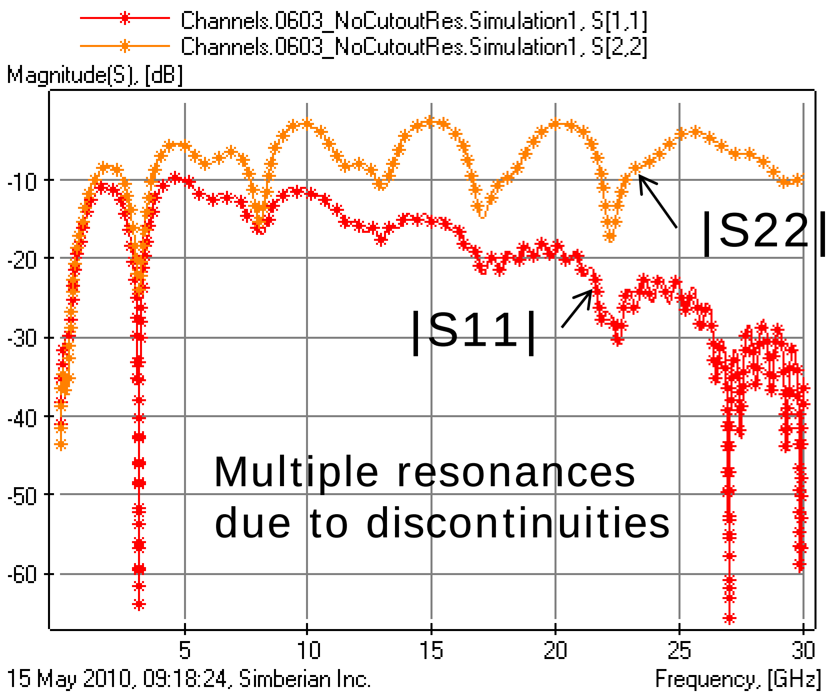
What if there are other discontinuities in the channel?

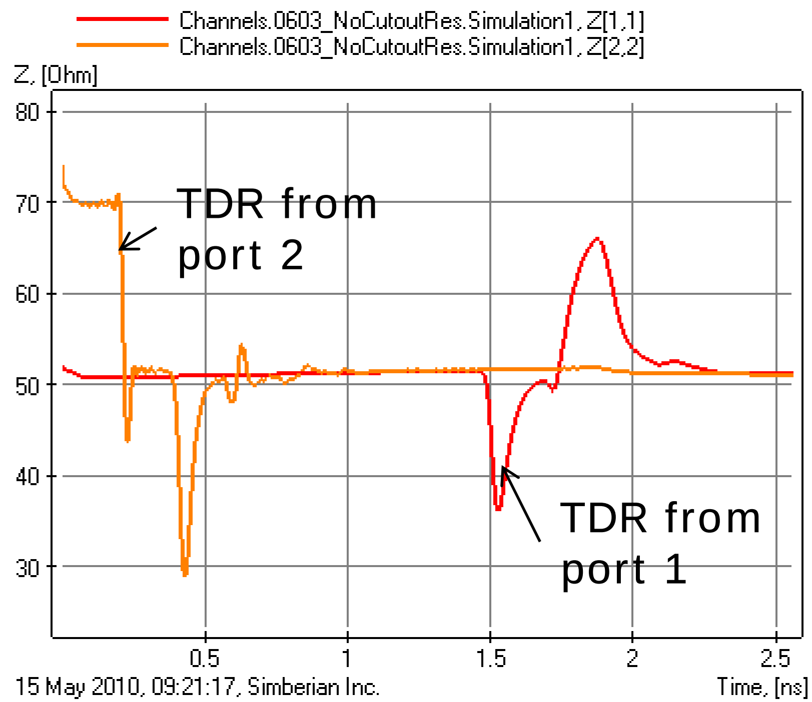
- The reciprocity property is general and does not depend on a particular configuration of a channel
- Let’s investigate a hypothetical channel with AC coupling capacitor, mismatched via and segment of trace with high characteristic impedance



Reflections in frequency and time domains – different at both ports

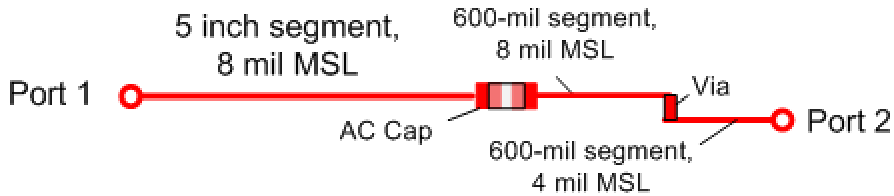


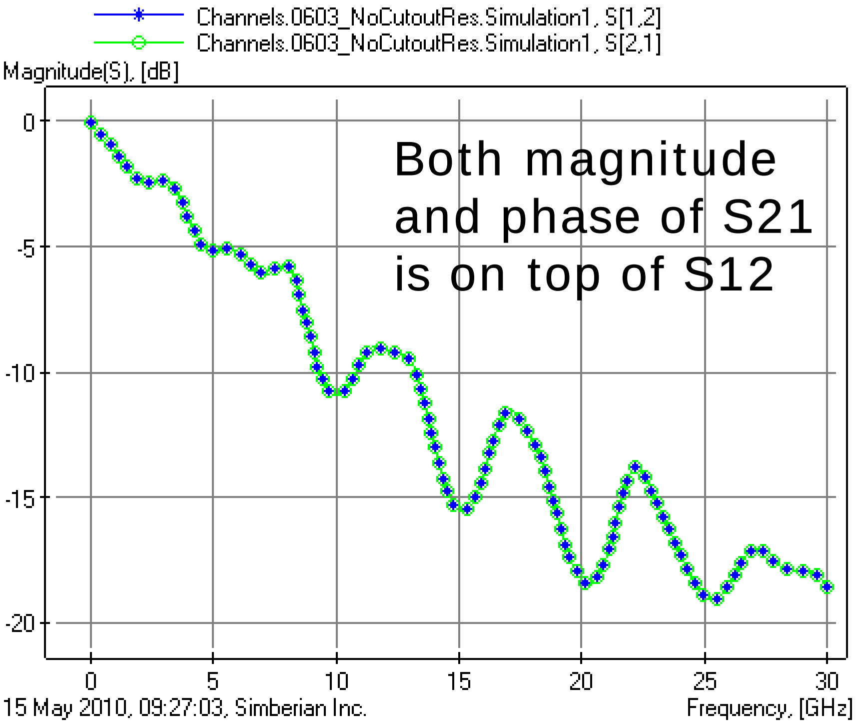


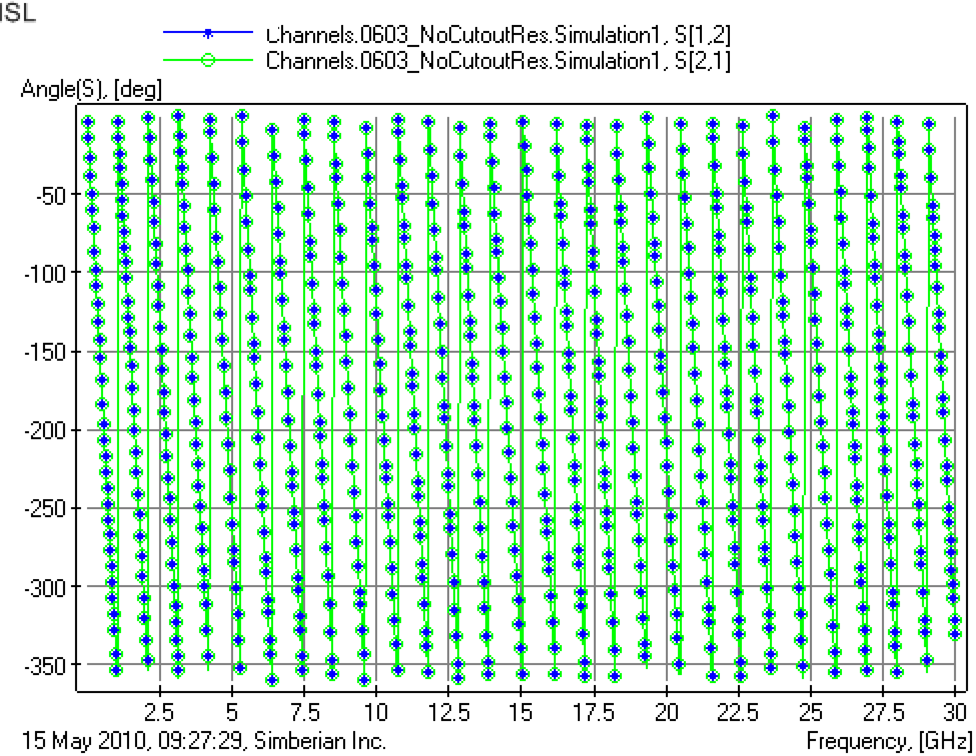


But transmission is still the same

- No violation of reciprocity as expected!

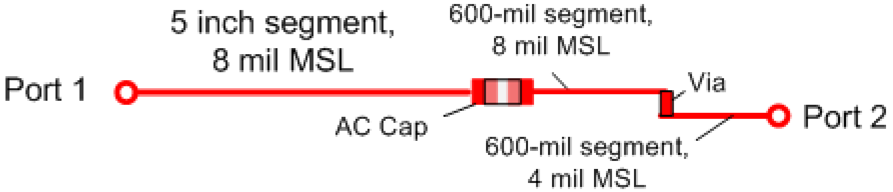


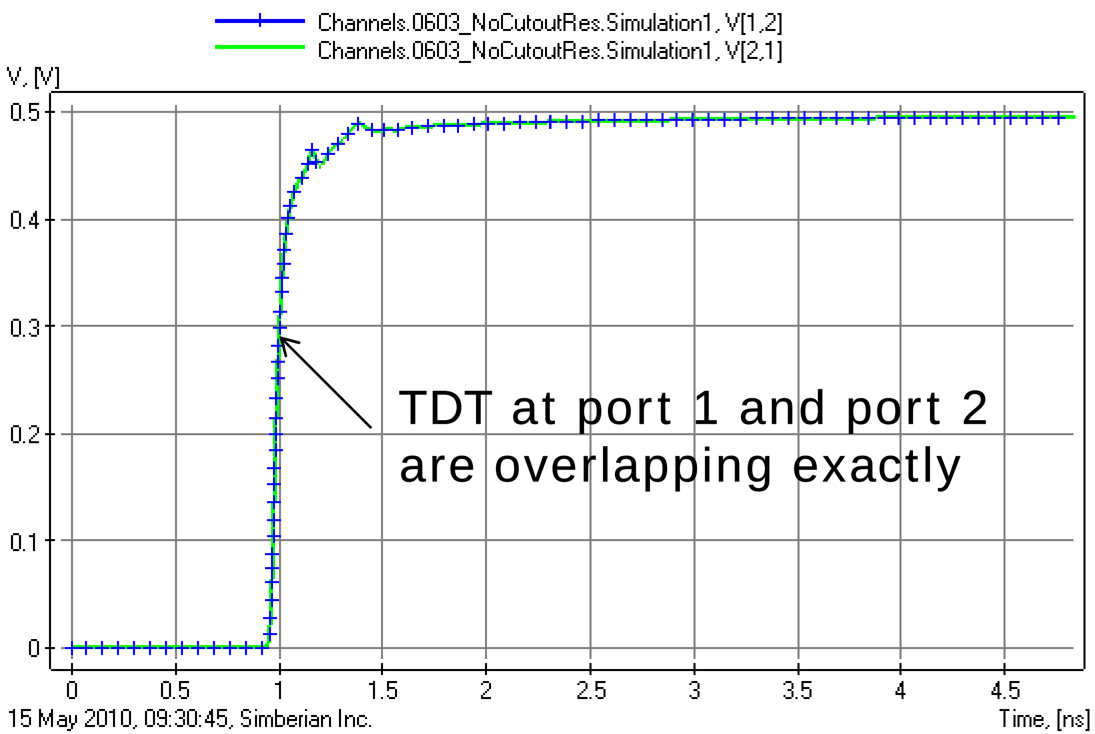




TDTs in channel with resonances

- TDT at port 1 is identical to TDT at port 2





H. A. Lorentz's theorem holds!

May be eye would be different if we swap driver and receiver?

- It may happen only in case of non-linearity of the driver and receiver
- In case of linear driver and receiver the eye diagram will be exactly the same

10 Gbps, 20 ps rise and fall time, PRBS 32, 50 Ohm driver & receiver