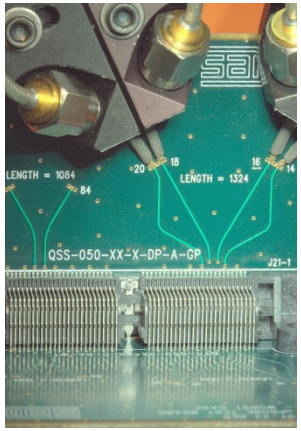
TERASPEED CONSULTING GROUP

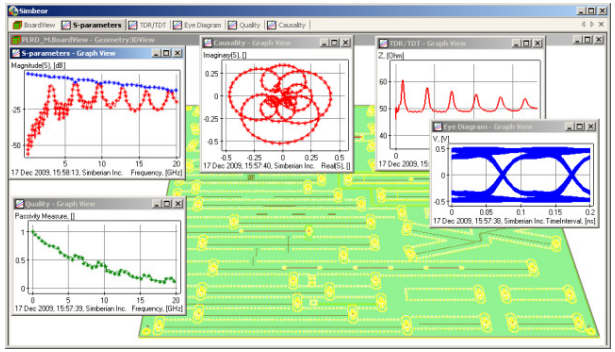
Simberian Electromagnetic Solutions

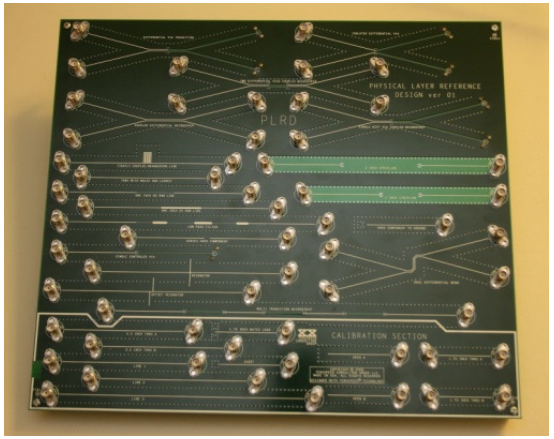
Quality of High Frequency Measurements: Practical Examples, Theoretical Foundations, and Successful Techniques that Work Past the 40GHz Realm

Samtec-Simberian-Teraspeed
Tutorial for DesignCon2010

Tom Dagostino, Teraspeed Consulting Group
Yuriy Shlepnev, Simberian Inc.







Property rights disclosure

"PROPERTY OF TERASPEED CONSULTING GROUP LLC"

Information contained in this document is not to be reproduced in any form without permission of Teraspeed Consulting Group LLC. Any information in this document is proprietary and may not be used or disclosed without the express permission of Teraspeed Consulting Group LLC.

"CONFIDENTIAL PROPERTY OF TERASPEED CONSULTING GROUP LLC"

This document includes valuable trade secrets. Unauthorized disclosure of use of this document may violate the Uniform Trade Secrets Act.

Property rights disclosure

- Copyright © 2009 by Simberian Inc., All rights reserved.
  - THIS DOCUMENT IS CONFIDENTIAL AND PROPRIETARY TO SIMBERIAN INC. AND MAY NOT BE REPRODUCED, PUBLISHED OR DISCLOSED TO OTHERS WITHOUT PERMISSION OF SIMBERIAN INC.
- Simberian® and Simbeor® are registered trademarks of Simberian Inc.
  - Other product and company names mentioned in this presentation may be the trademarks of their respective owners.

What we show

- Even well calibrated VNA measurements have significant quality issues
  - Passivity and reciprocity violations
  - Causality problems due to noise and glitches or anomalies due to multi-line calibration (TRL)
- Building Rational Compact Models (RCM) resolves the key quality issues
  - Passivity/causality improvements
  - Good correspondence in frequency and in time domains

$$S_{i,j}(\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}} \left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r_{ij,n}^*}{i\omega - p_{ij,n}^*} \right) \right] \cdot e^{-i\omega \cdot T_{ij}}$$

If you happen to…

- Build interconnect models for internal use
- Send interconnect models to customers developing consumer products
- Confirm models with measurements or electromagnetic analysis
- Use models for compliance level testing
- …

You need to have …

Pristine S-parameters

- Reciprocal (no non-linear or anisotropic materials)

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

- Passive (interconnects do not generate energy)

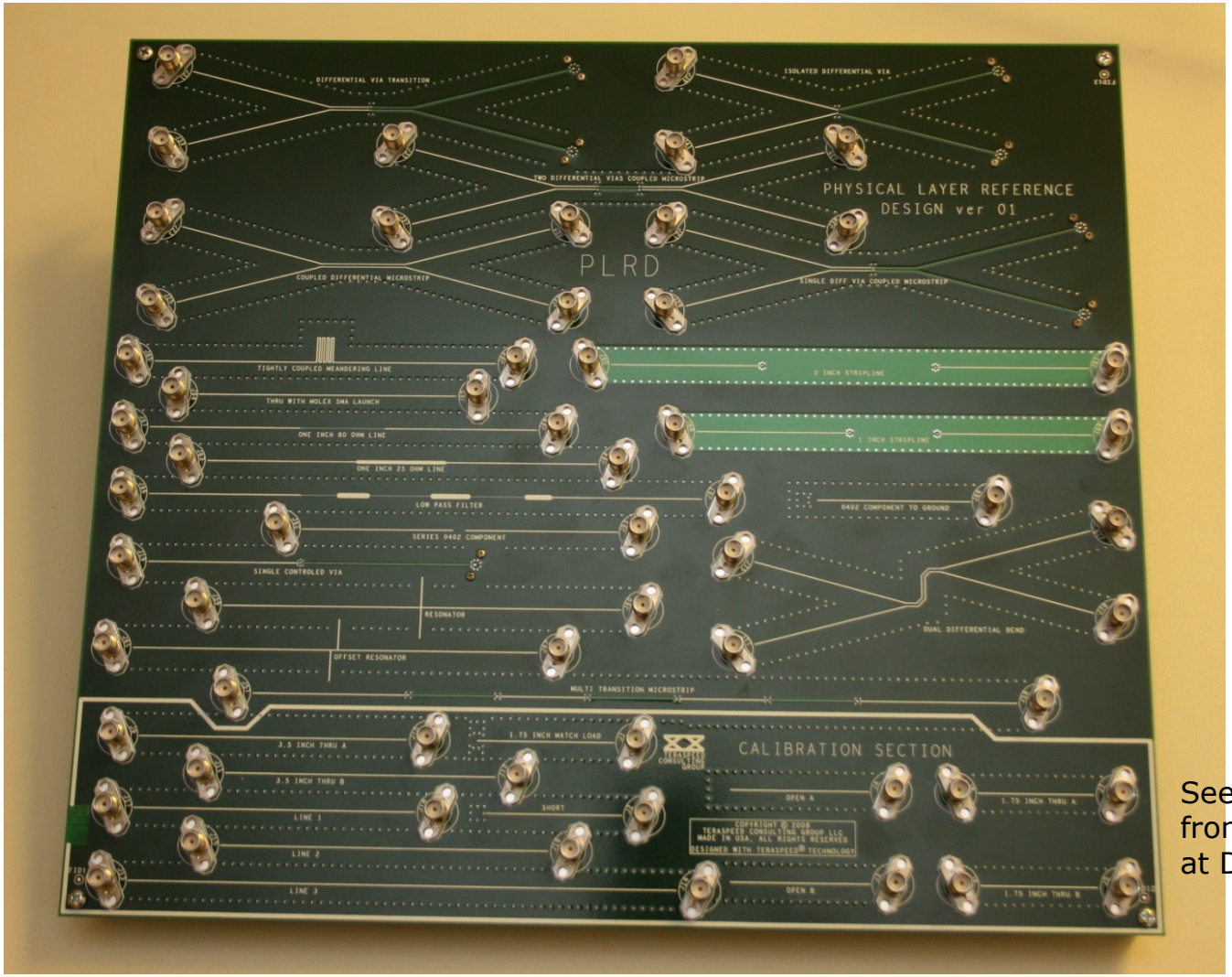
$$P_{in} = \bar{a}^* \cdot \left[U - S^* S \right] \cdot \bar{a} \geq 0 \quad \Rightarrow \quad eigenvals\left[S^* \cdot S \right] \leq 1$$

- Causal – no response before the excitation or

$$S_{i,j}(t) = 0, \quad t < T_{ij}$$

- Otherwise your simulation is not reliable and may be even not possible due to stability issues

Getting Started: PLRD-1 calibration and benchmarking board from Teraspeed Consulting Group



See details in our papers from DesignCon2009 and at DesignCon2010

We noticed some *BAD* problems with even good data!

Report for SOLT calibrated measurements

- Project1.SOLT_1_INCH_STRIPLINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.61%; SymmetryQM=69.96%; CausalityQM=31.3%
- Project1.SOLT_2_INCH_STRIPLINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.85%; SymmetryQM=72.11%; CausalityQM=41.2%
- Project1.SOLT_COUPLED_DIFFERENTIAL_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9967%; ReciprocityQM=99.35%; SymmetryQM=73.76%; CausalityQM=6.9%
- Project1.SOLT_DIFFERENTIAL_VIA_TRANSITION_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9969%; ReciprocityQM=99.35%; SymmetryQM=67.64%; CausalityQM=11.1%
- Project1.SOLT_DUAL_DIFFERENTIAL_BEND_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9966%; ReciprocityQM=99.35%; SymmetryQM=75.68%; CausalityQM=4.4%
- Project1.SOLT_ISOLATED_DIFFERENTIAL_VIA_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9962%; ReciprocityQM=99.34%; SymmetryQM=45.31%; CausalityQM=7.4%
- Project1.SOLT_LOW_PASS_FILTER_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=99.32%; CausalityQM=82.1%
- Project1.SOLT_MULTI_TRANSITION_MICROSTRIP_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=99.24%; SymmetryQM=70.57%; CausalityQM=62.8%
- Project1.SOLT_OFFSET_RESONATOR_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.86%; SymmetryQM=39.01%; CausalityQM=80.5%
- Project1.SOLT_RESONATOR_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.91%; SymmetryQM=31.21%; CausalityQM=75.8%
- Project1.SOLT_ONE_INCH_25_OHM_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.5%; SymmetryQM=57.84%; CausalityQM=54.5%
- Project1.SOLT_ONE_INCH_80_OHM_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.52%; SymmetryQM=69.36%; CausalityQM=40.7%
- Project1.SOLT_SINGLE_CONTROLLED_VIA_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.38%; SymmetryQM=72.05%; CausalityQM=9.5%
- Project1.SOLT_SINGLE_DIFF_VIA_COUPLED_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9967%; ReciprocityQM=99.33%; SymmetryQM=66.84%; CausalityQM=13.1%
- Project1.SOLT_THRU_WITH_MOLOEX_LAUNCH_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.16%; SymmetryQM=80.57%; CausalityQM=26.5%
- Project1.SOLT_TIGHTLY_COUPLED_MEANDERING_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=99.09%; SymmetryQM=53.75%; CausalityQM=64.2%
- Project1.SOLT_TWO_DIFFERENTIAL_VIAS_COUPLED_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9971%; ReciprocityQM=99.4%; SymmetryQM=65.49%; CausalityQM=29.3%

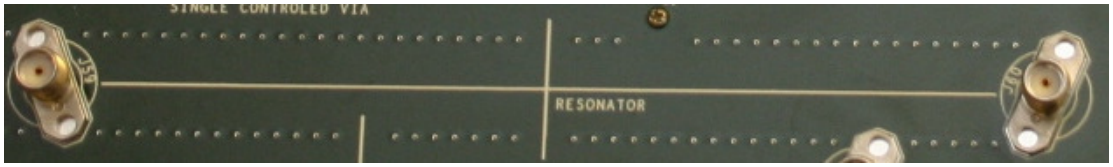
Fixable low causality measure due to noise in small reflection coefficients

Passivity and Reciprocity are OK

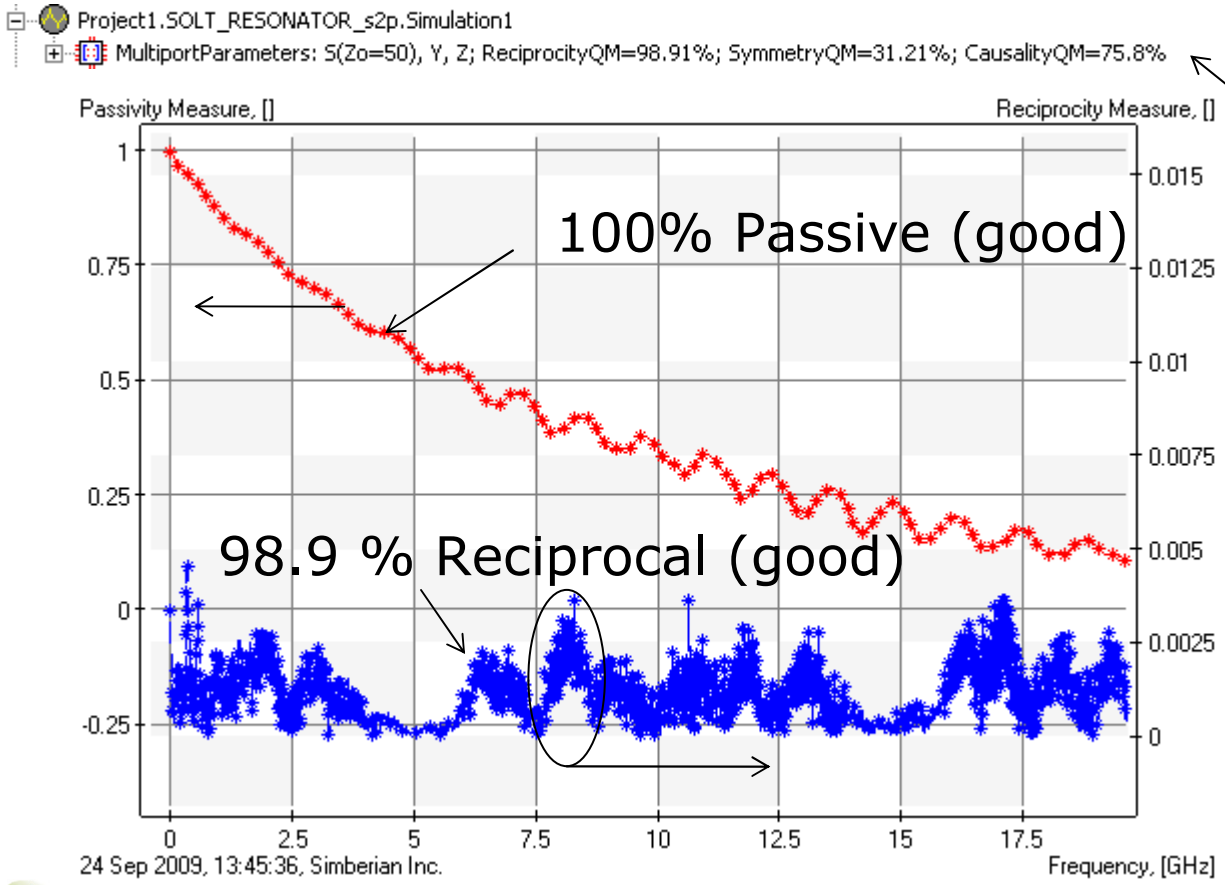
Non-symmetry is due to non-symmetry of the physical structures

S-parameters for a high-reflection structure: Resonator, SOLT calibration (crash test)

Port 1



Port 2



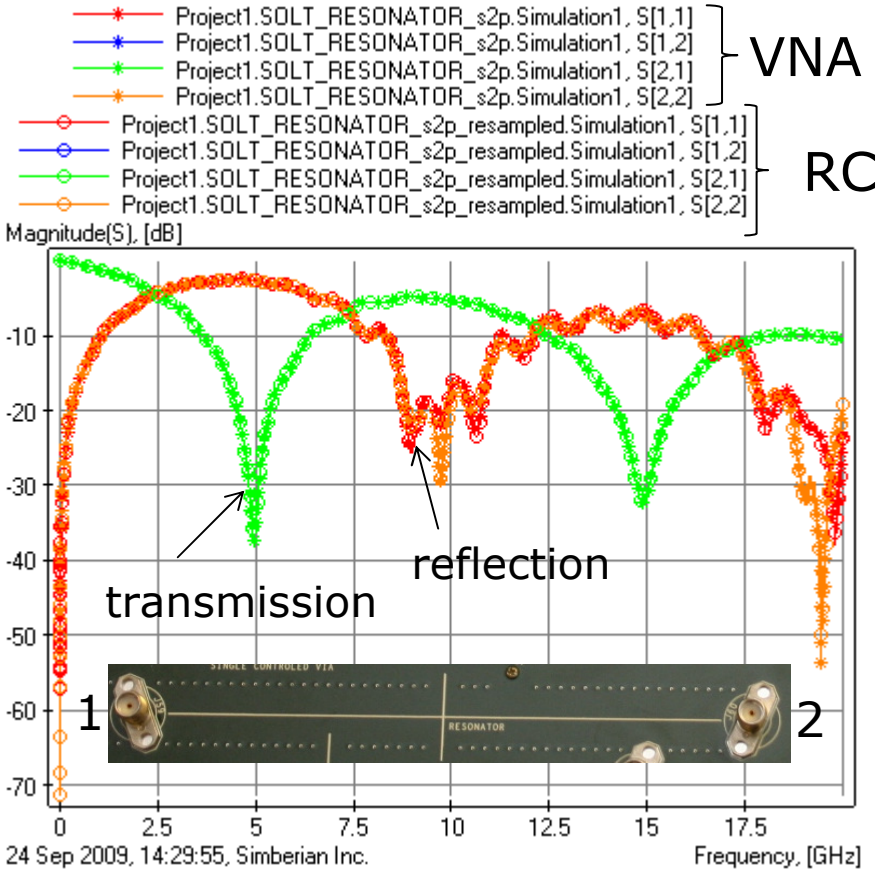
Causality is also OK

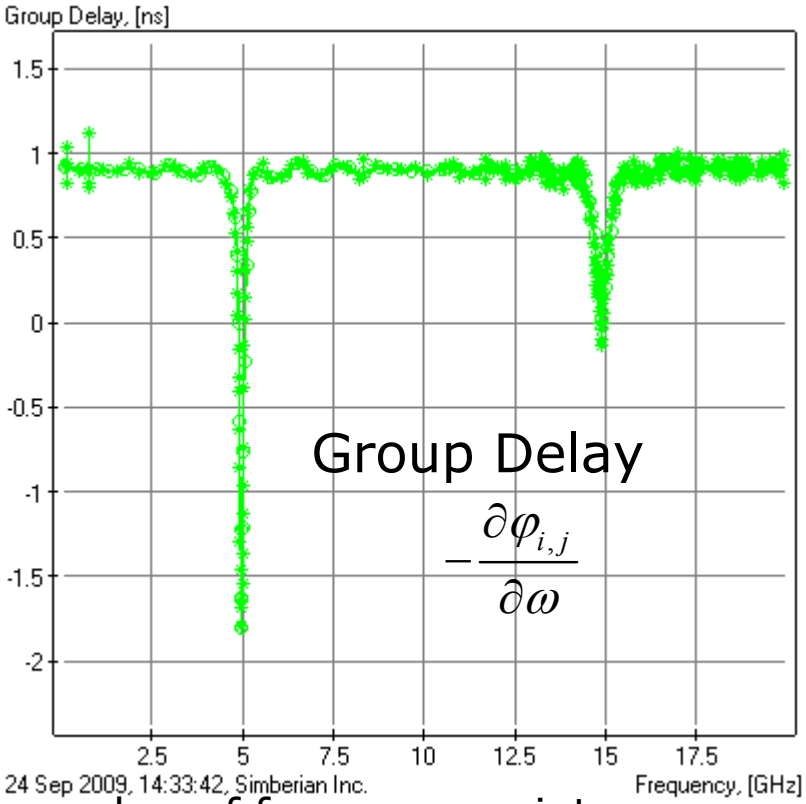
Practically nothing to improve, but what about extrapolation and consistent time-domain analysis

Resonator (SOLT): RCM for S-parameters

$$S_{i,j} = \left|S_{i,j}\right| \cdot \exp\left(i\varphi_{i,j}\right)$$

RCM model RMS Error is 0.003 (very good)
Passive from DC to infinity, causal and reciprocal



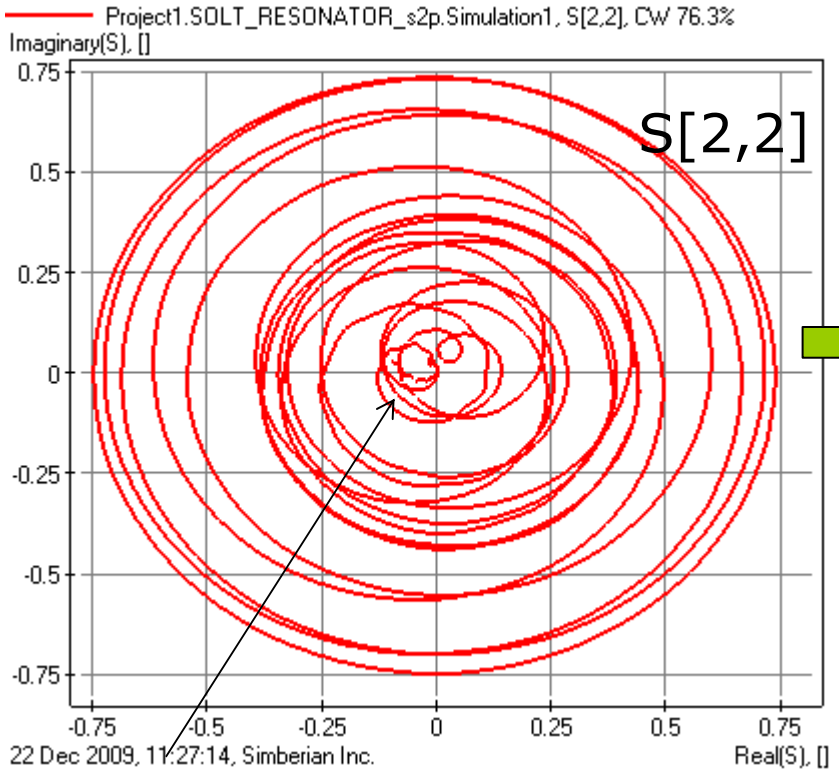


Touchstone model with DC and reduced number of frequency points or BB SPICE model can be produced from RCM

Resonator (SOLT): Original S[2,2] and RCM

$$S_{i,j} = \mathrm{Re}\left(S_{i,j}\right) + i\,\mathrm{Im}\left(S_{i,j}\right)$$

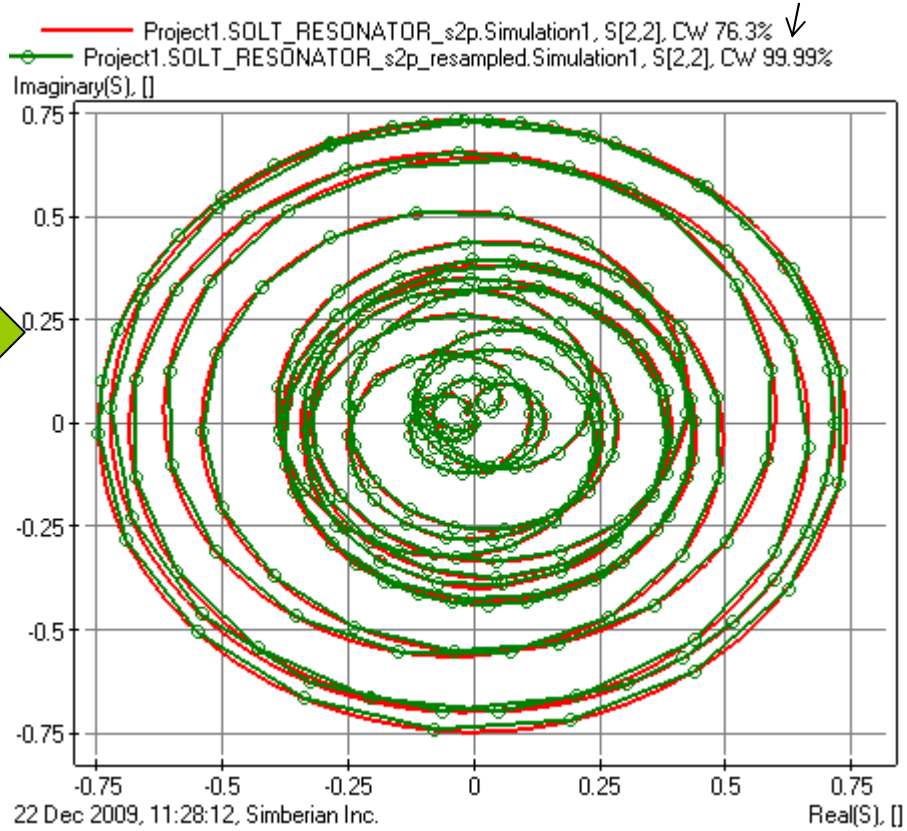
VNA Measurement: 3201 points starting from 300 KHz



Some noise at higher frequencies (minor issue)

Re-sampled RCM: 485 points distributed adaptively starting from 0 Hz

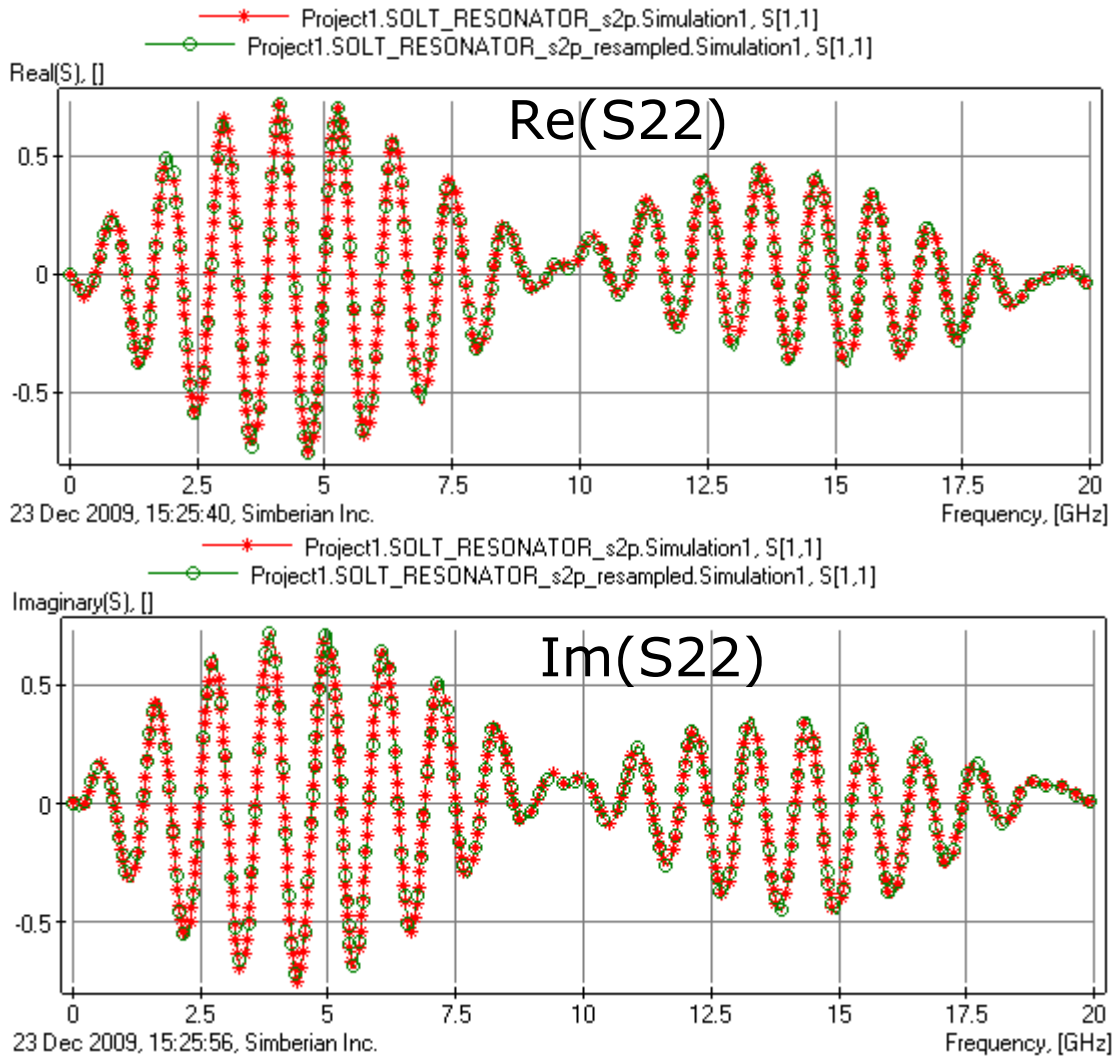
CAUSAL!



Red line – original VNA data
Green line with circles – RCM

Resonator (SOLT): Original S[2,2] and RCM

$$S_{i,j} = \mathrm{Re}\left(S_{i,j}\right) + i\,\mathrm{Im}\left(S_{i,j}\right)$$



Stars – VNA data

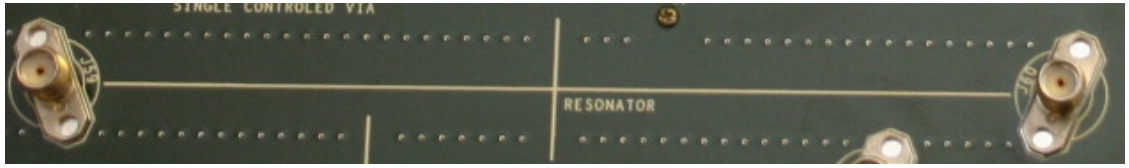
Circles – RCM model

RCM: RMS Error 0.003, 64 poles

RCM is practically indistinguishable and works in frequency as well as in time domain!

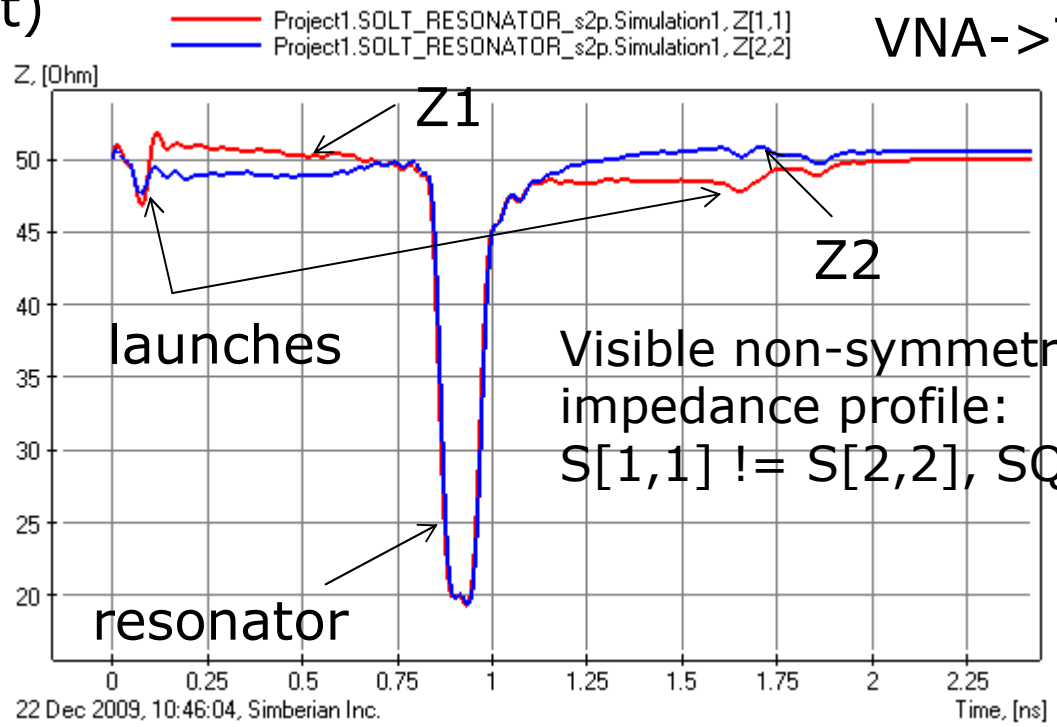
Resonator TDR from RCM (SOLT)

Port 1



Port 2

Z(t)



VNA->TDR

Z1

Z2

launches

resonator

Visible non-symmetry in the impedance profile:
S[1,1] != S[2,2], SQM=31%

Effect of non-symmetry on TRL calibration is also the subject of our research

S-parameters for a medium-reflection structure: Single controlled via, SOLT calibration

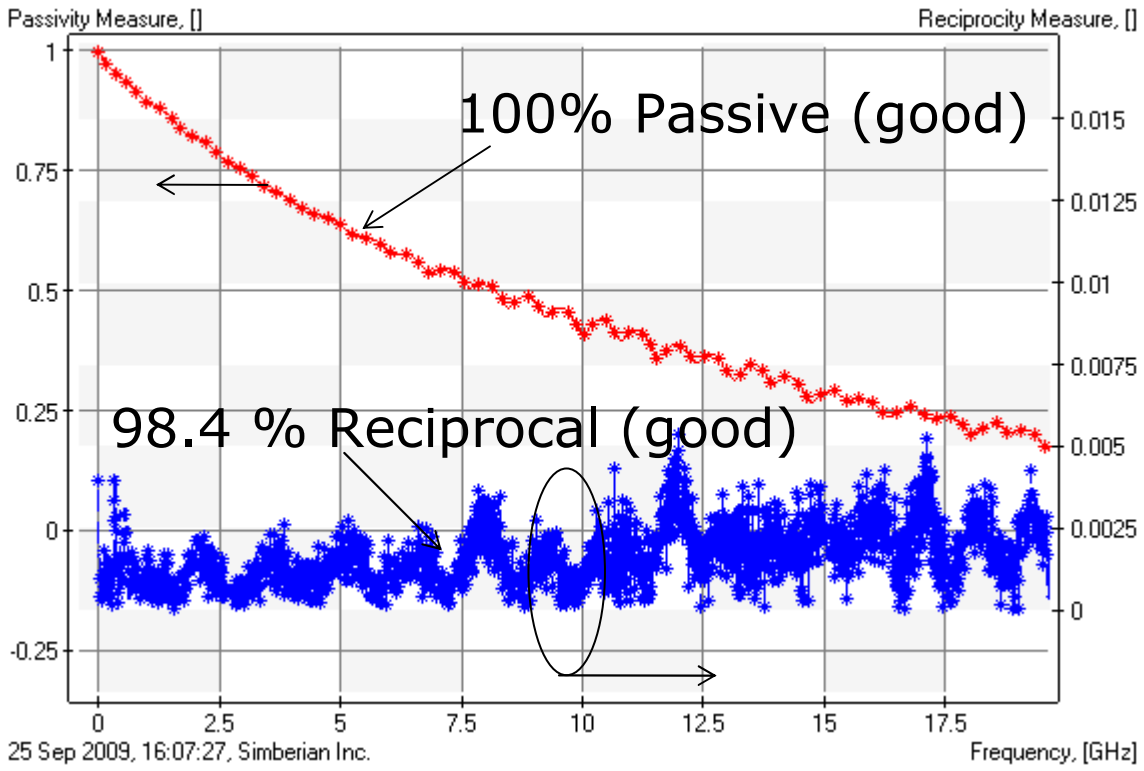
Port 1

Port 2

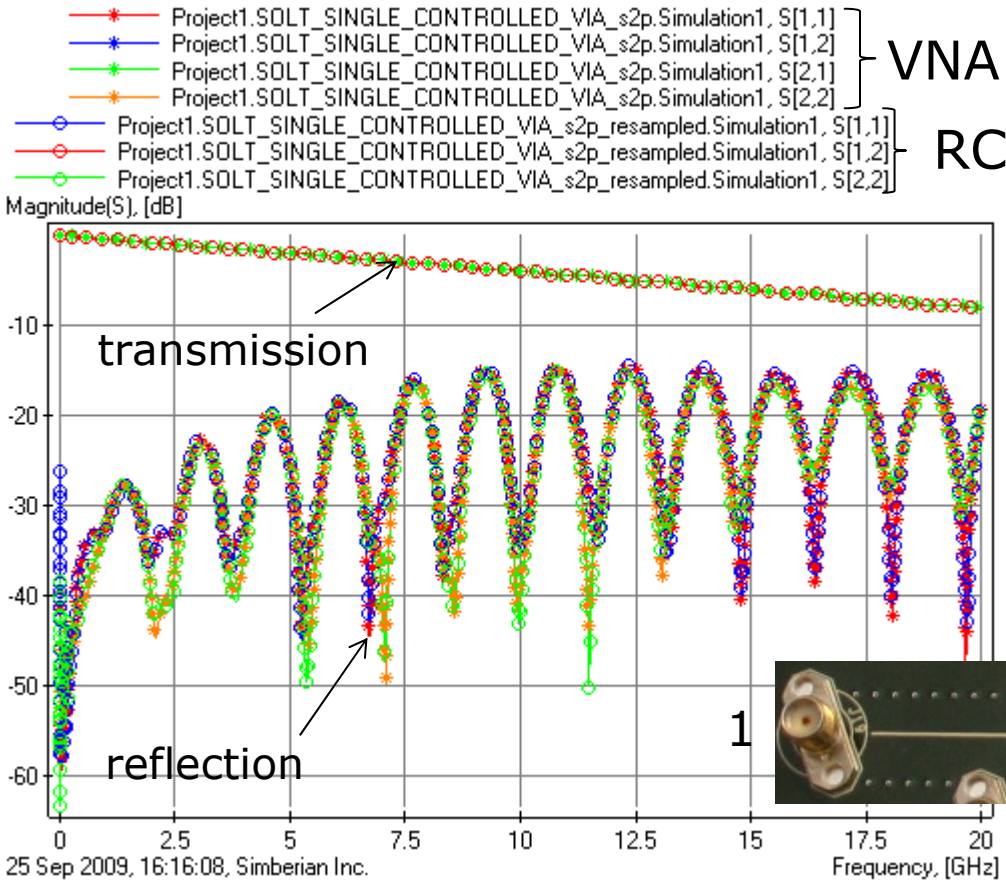
Project1.SOLT_SINGLE_CONTROLLED_VIA_s2p.Simulation1

MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.38%; SymmetryQM=72.05%; CausalityQM=9.5%

Causality problem, but it can be restored with RCM



Single controlled via (SOLT): Improving S-parameters with RCM

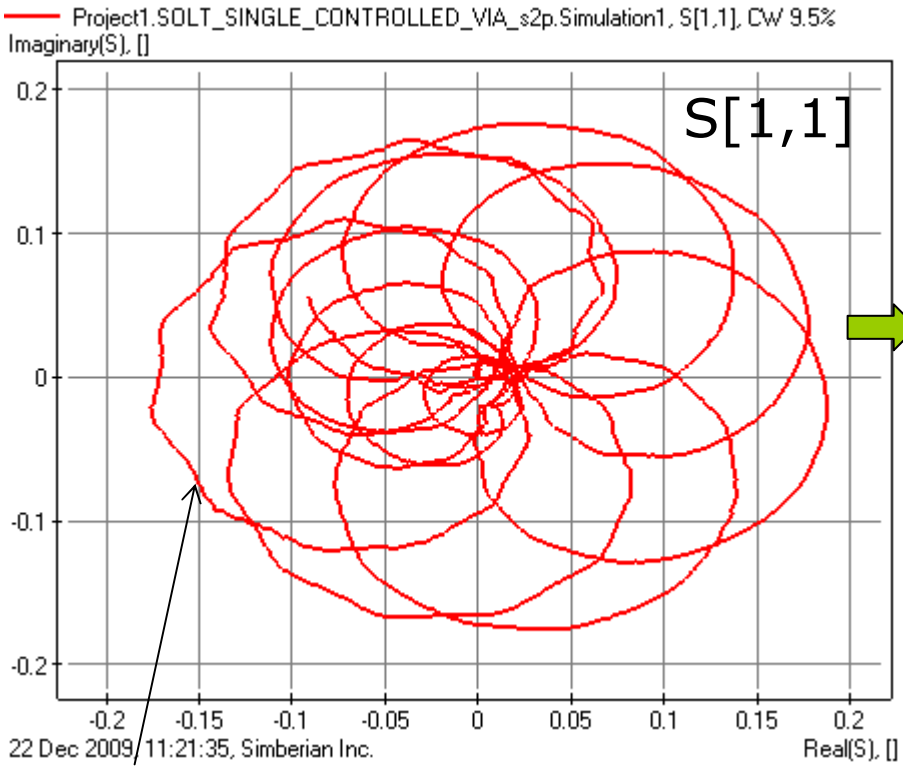


RCM model has RMS Error is 0.0034 (very good), is passive from DC to infinity and 100% causal and reciprocal

Touchstone model with DC and reduced number of frequency points or BB SPICE model can be produced from RCM

Single controlled via (SOLT): Original S[1,1] and RCM

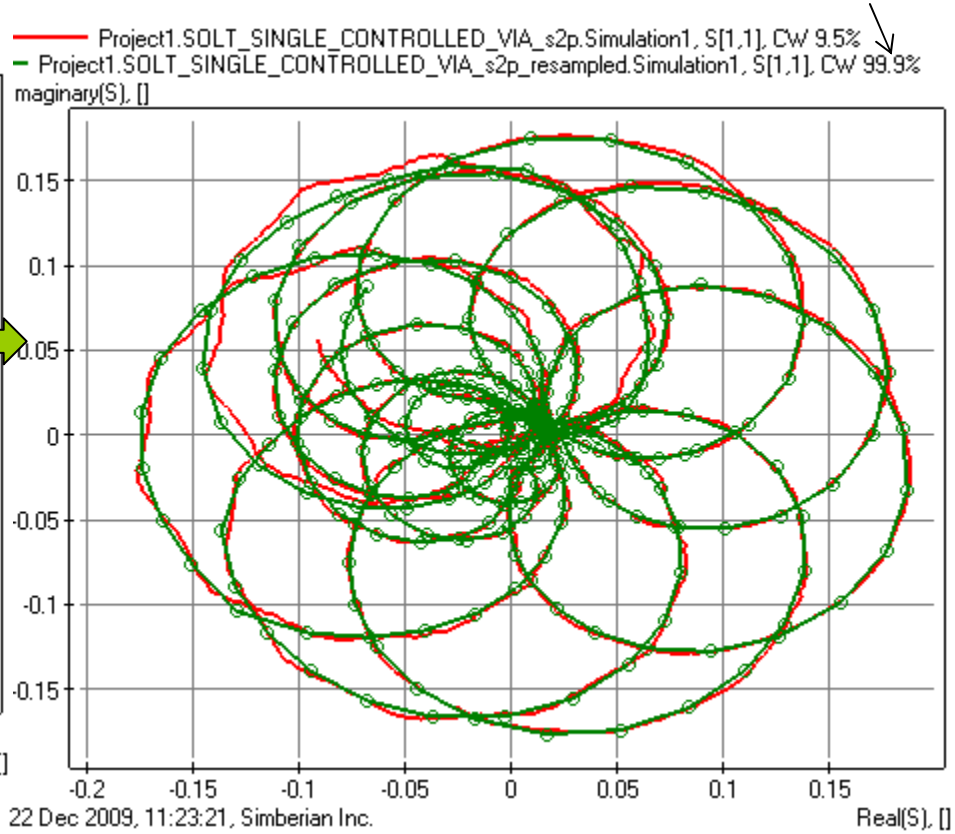
VNA Measurement: 3201 points starting from 300 KHz



Visible noise and large segments with counter-clockwise rotation

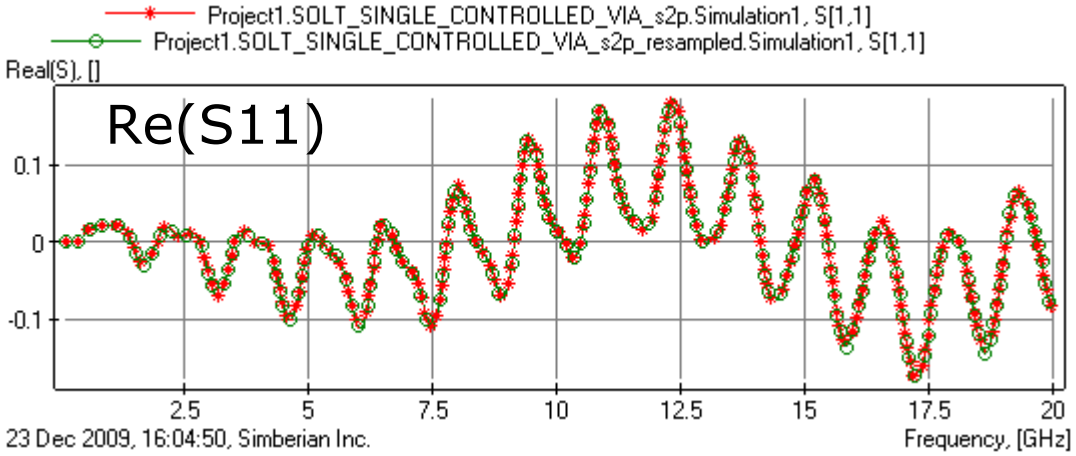
Re-sampled RCM: 769 points distributed adaptively starting from 0 Hz

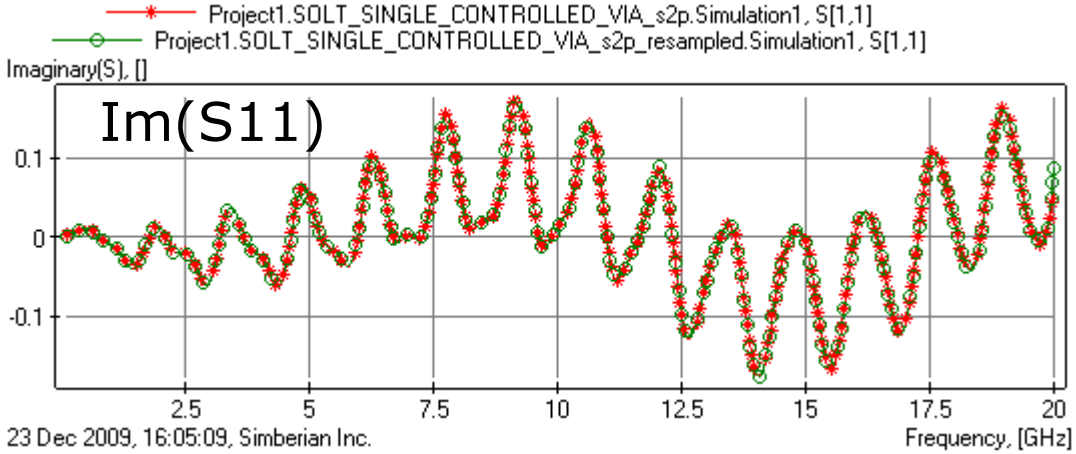
CAUSAL!



Red line – original VNA
Green line with circles - RCM

Single controlled via (SOLT): Original S[1,1] and RCM





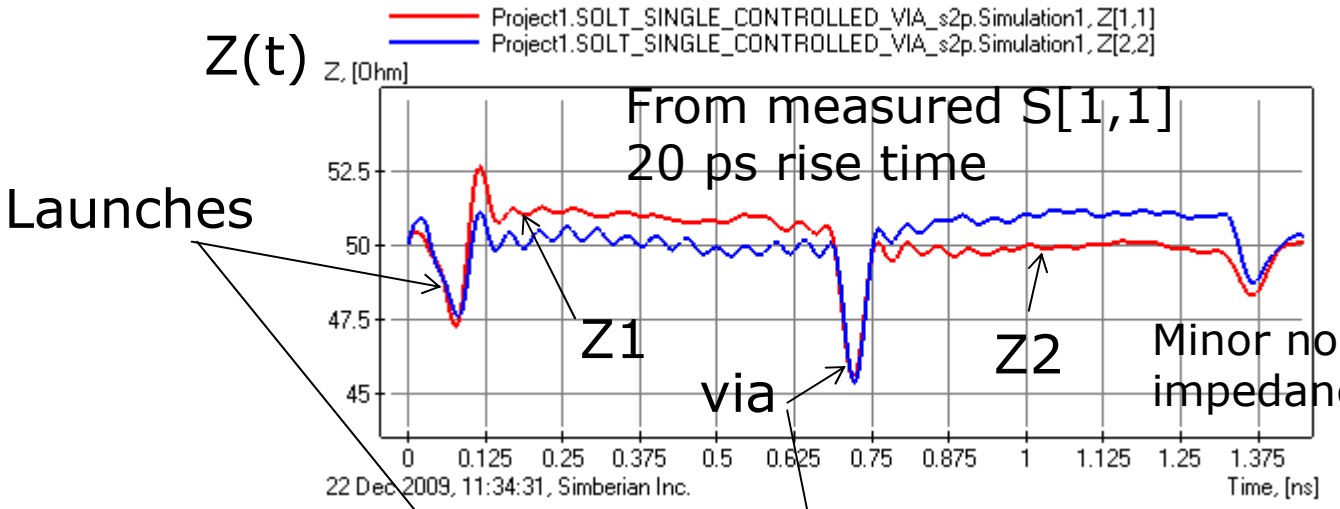
Stars – VNA data

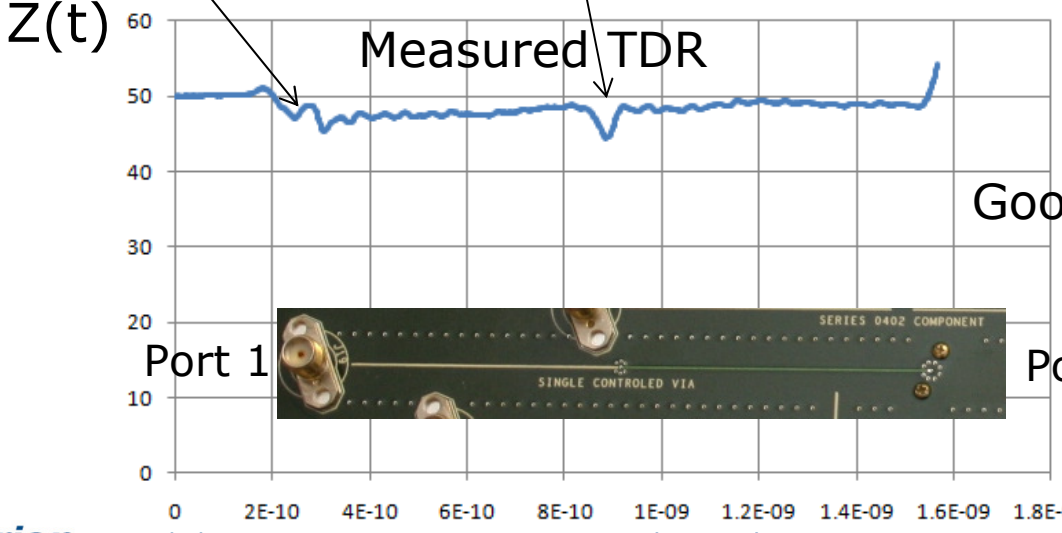
Circles – RCM (corrected)

RCM: 46 poles,
RMS Error 0.0034

Practically indistinguishable!

Single controlled via TDR from RCM (SOLT)





S-parameters from VNA: TRL-calibration data quality report

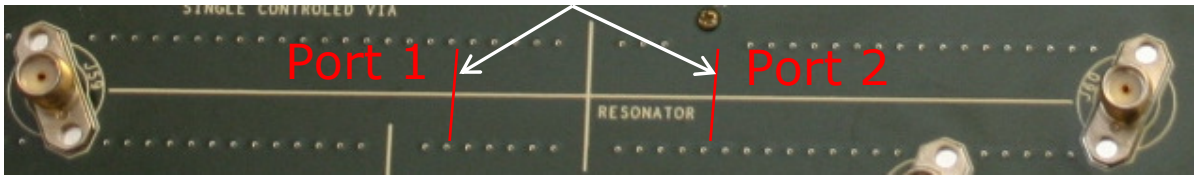
- Project1.TRL_1_INCH_STRIPLINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9953%; ReciprocityQM=98.08%; SymmetryQM=51.48%; CausalityQM=15.8%
- Project1.TRL_2_INCH_STRIPLINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9985%; ReciprocityQM=98.29%; SymmetryQM=57.93%; CausalityQM=20.3%
- Project1.TRL_COUPLED_DIFFERENTIAL_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9987%; ReciprocityQM=99.8%; SymmetryQM=64.5%; CausalityQM=0%
- Project1.TRL_DIFFERENTIAL_VIA_TRANSITION_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9993%; ReciprocityQM=99.76%; SymmetryQM=44.31%; CausalityQM=0%
- Project1.TRL_DUAL_DIFFERENTIAL_BEND_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9971%; ReciprocityQM=99.78%; SymmetryQM=41.22%; CausalityQM=0%
- Project1.TRL_ISOLATED_DIFFERENTIAL_VIA_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9983%; ReciprocityQM=99.74%; SymmetryQM=7.4%; CausalityQM=0%
- Project1.TRL_LOW_PASS_FILTER_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9987%; ReciprocityQM=98.83%; CausalityQM=39%
- Project1.TRL_MULTI_TRANSITION_MICROSTRIP_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9986%; ReciprocityQM=98.82%; SymmetryQM=52.16%; CausalityQM=29.7%
- Project1.TRL_OFFSET_RESONATOR_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9926%; ReciprocityQM=98.5%; SymmetryQM=7.3%; CausalityQM=26.1%
- Project1.TRL_RESONATOR_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9916%; ReciprocityQM=98.51%; SymmetryQM=0%; CausalityQM=9.4%
- Project1.TRL_ONE_INCH_25_OHM_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9588%; ReciprocityQM=97.88%; SymmetryQM=31.92%; CausalityQM=14.2%
- Project1.TRL_ONE_INCH_80_OHM_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9946%; ReciprocityQM=97.98%; SymmetryQM=52.86%; CausalityQM=13.2%
- Project1.TRL_SINGLE_CONTROLLED_VIA_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9524%; ReciprocityQM=97.48%; SymmetryQM=54.05%; CausalityQM=17.7%
- Project1.TRL_SINGLE_DIFF_VIA_COUPLED_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9981%; ReciprocityQM=99.71%; SymmetryQM=32.22%; CausalityQM=0%
- Project1.TRL_THRU_WITH_MOLOEX_LAUNCH_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=0%; ReciprocityQM=97.14%; SymmetryQM=68.1%; CausalityQM=0%
- Project1.TRL_TIGHTLY_COUPLED_MEANDERING_LINE_s2p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9974%; ReciprocityQM=98.62%; SymmetryQM=27.18%; CausalityQM=10%
- Project1.TRL_TWO_DIFFERENTIAL_VIAS_COUPLED_MICROSTRIP_s4p.Simulation1
  - MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9992%; ReciprocityQM=99.72%; SymmetryQM=42.07%; CausalityQM=77.6%

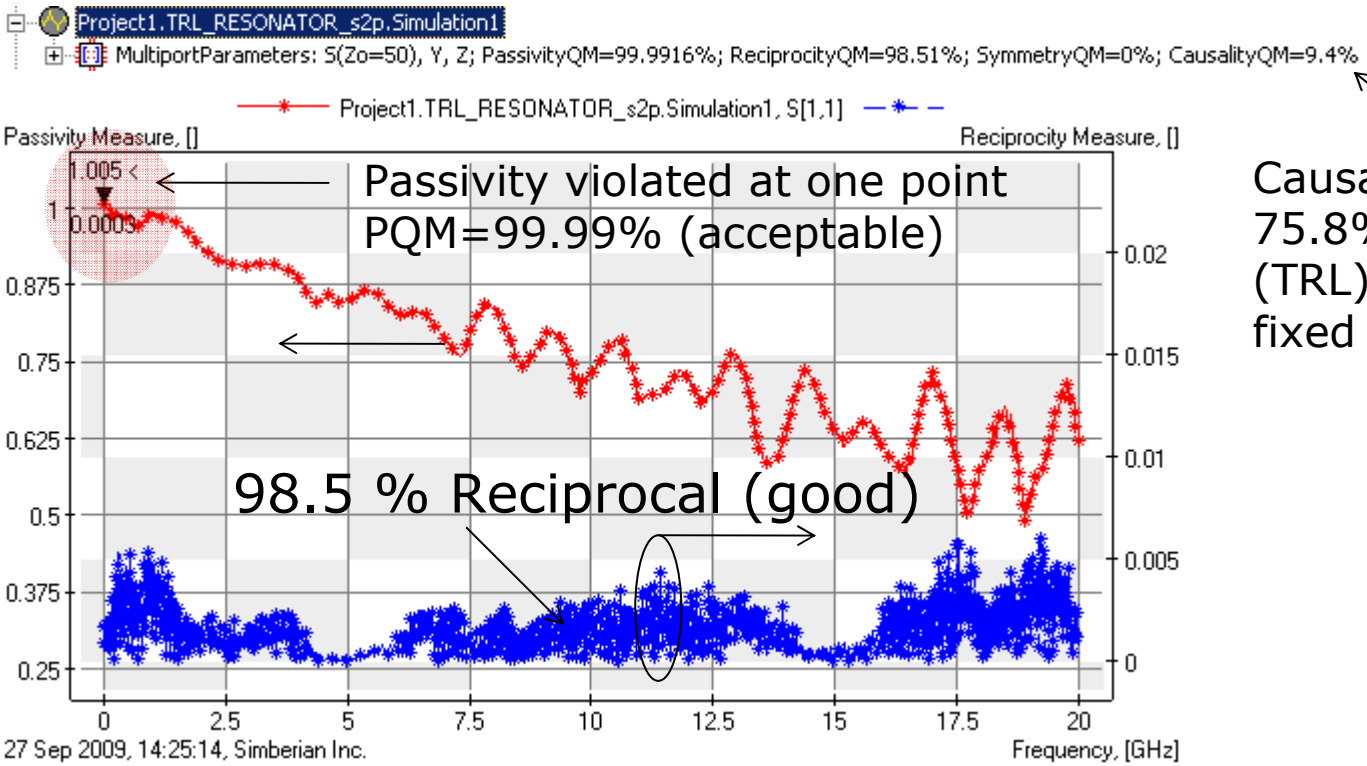
Low causality measure due to noise in small reflection coefficients of SOLT calibrated data

Passivity and Reciprocity are OK
Non-symmetry is due to non-symmetry of the physical structures as in SOLT data

S-parameters for a high-reflection structure: Resonator, TRL-calibration

TRL Reference Planes (750 mil from stubs)



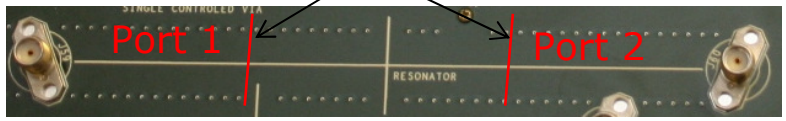


Causality dropped from 75.8% (SOLT) to 9.4% (TRL), but it can still be fixed with RCM

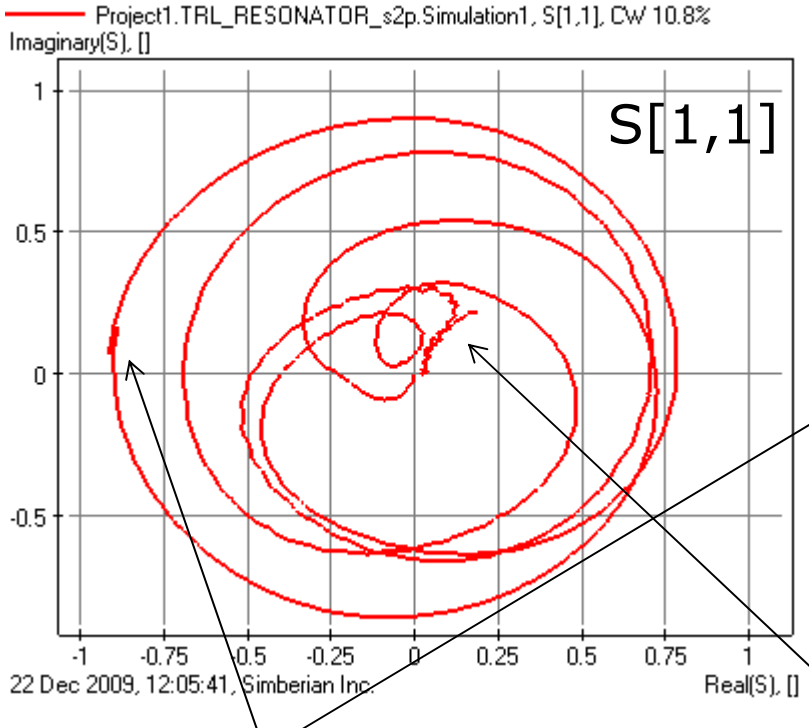
Resonator (TRL): Causality problems

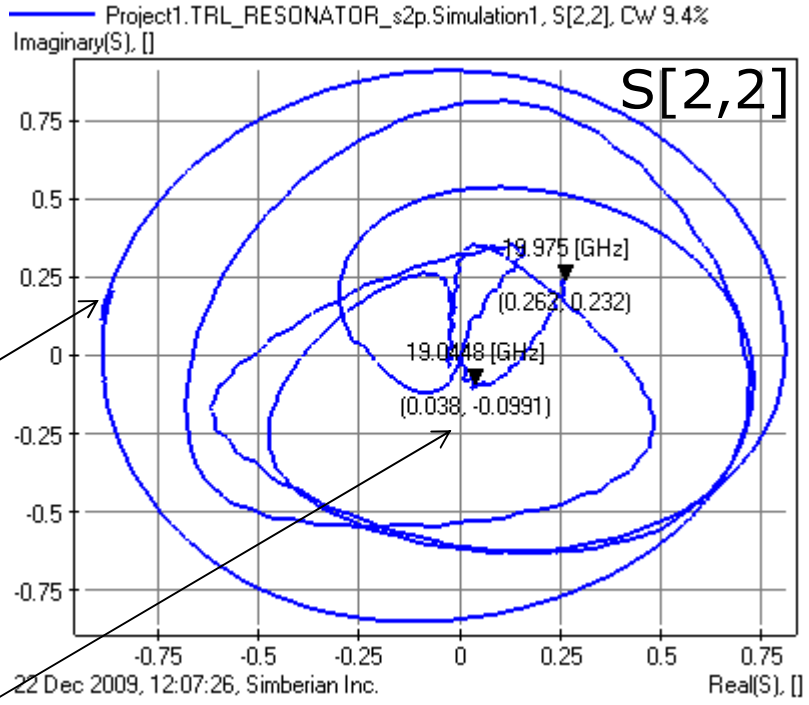
TRL Reference Planes (750 mil from stubs)

S[1,2] is OK



Worst causality





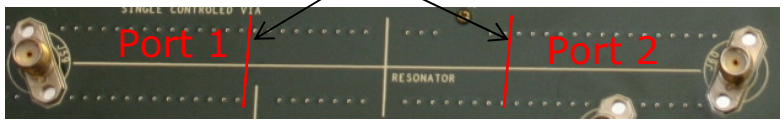
Glitches at 4.6 GHz

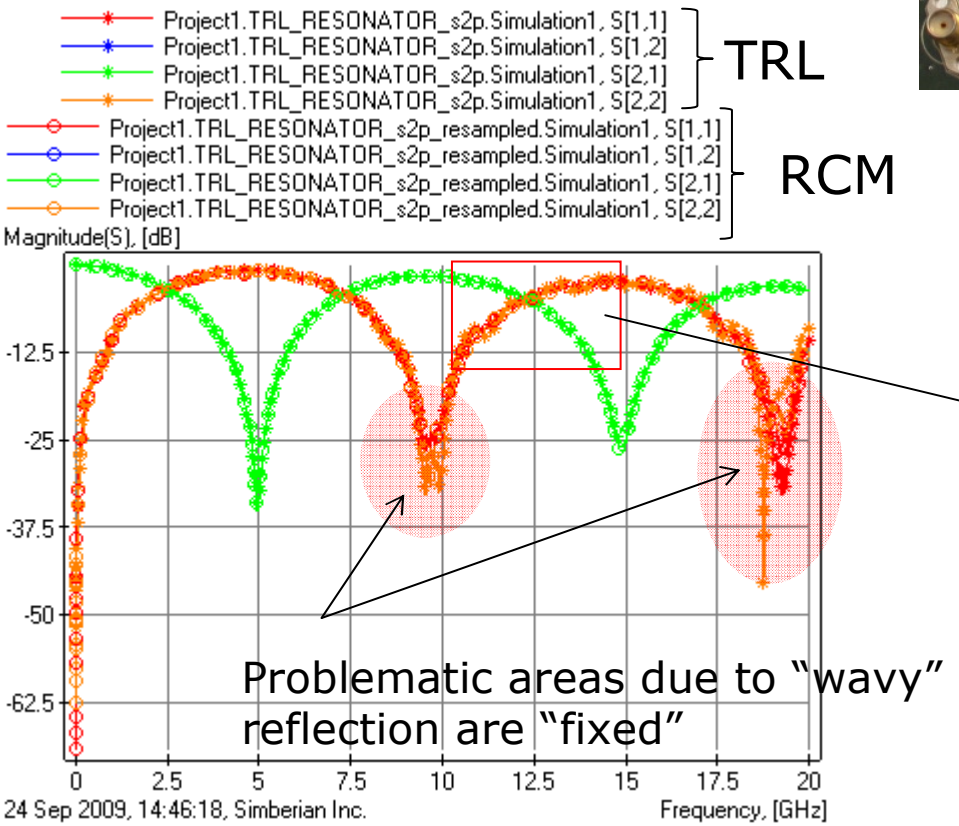
Noise and CCW rotation at low reflection

Resonator (TRL): Improving S-parameters with RCM

RCM RMS Error is 0.07 (still OK)
Passive from DC to infinity,
causal and reciprocal

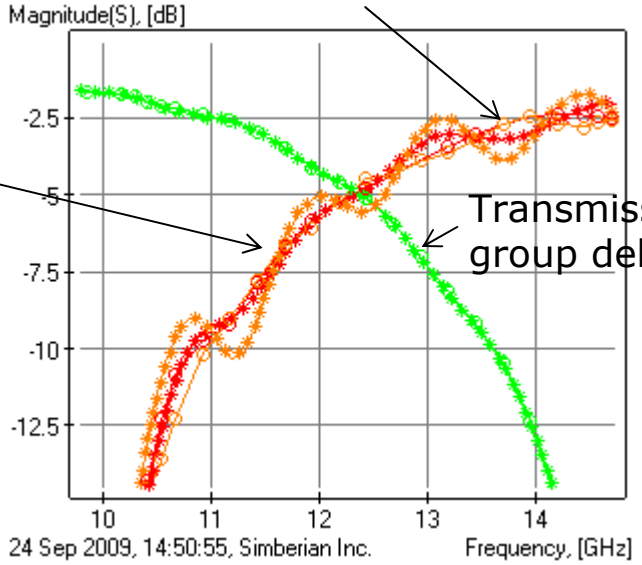
TRL Reference Planes
(750 mil from stubs)





Problematic areas due to "wavy" reflection are "fixed"

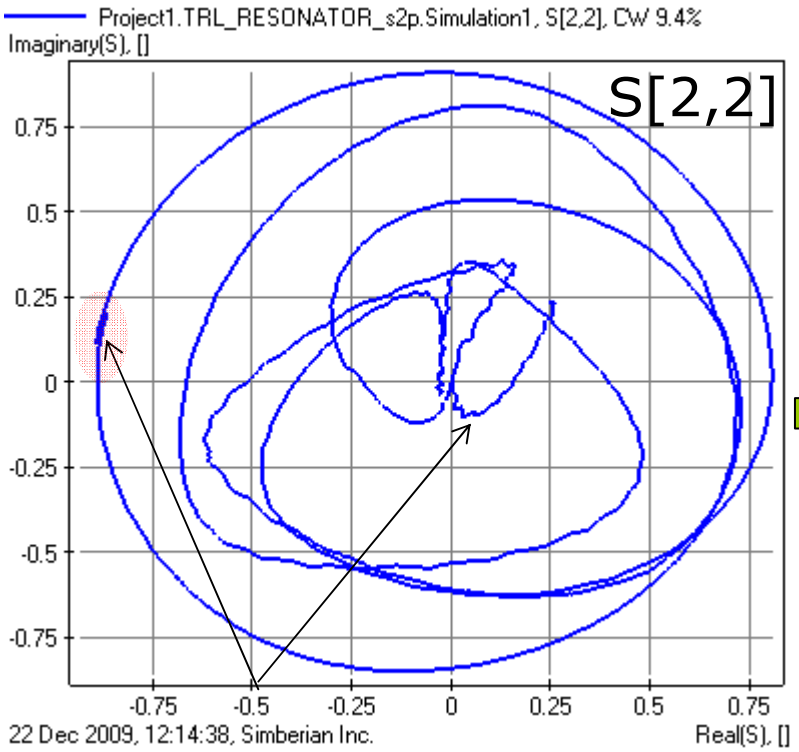
Problem is in the reflection parameters and RCM "fixes" it



Transmission and group delay is OK

Resonator (TRL): Original S[2,2] and RCM

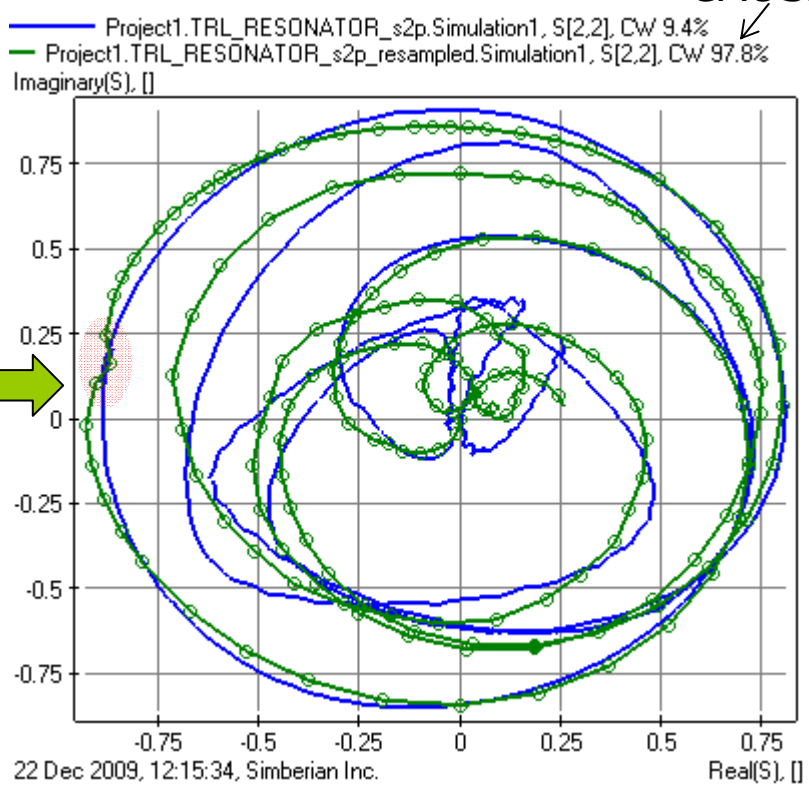
VNA Measurement: 3201 points starting from 300 KHz



Glitch and noisy behavior at high frequencies

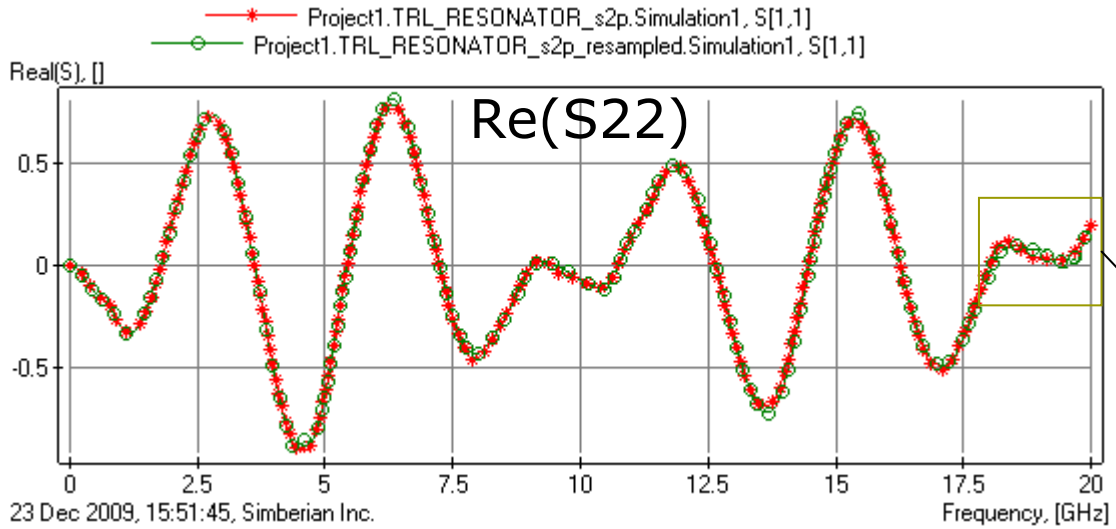
Re-sampled RCM: 310 points distributed adaptively starting from 0 Hz

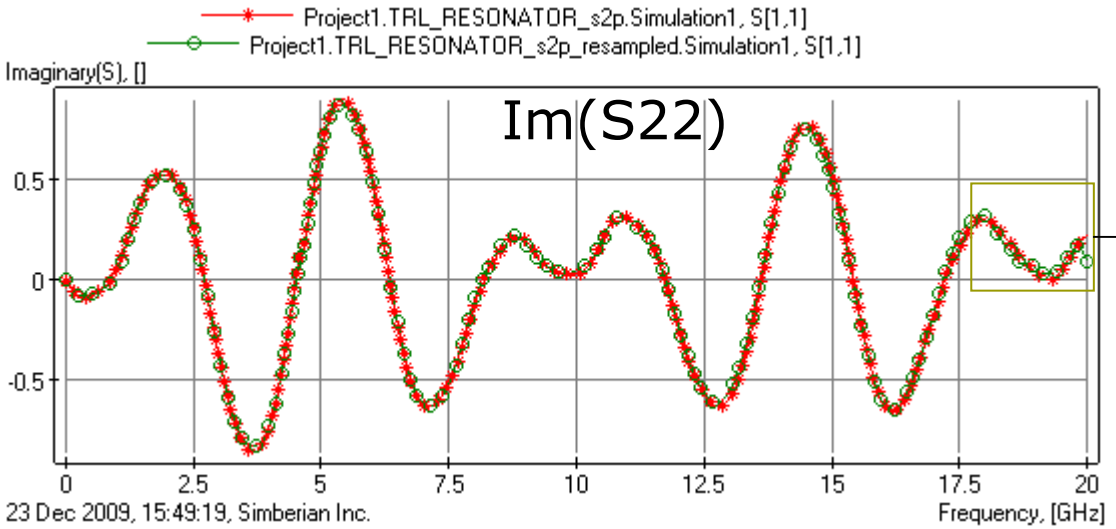
CAUSAL!



Blue line – original TRL
Green line with circles - RCM

Resonator (TRL): Original S[2,2] and RCM



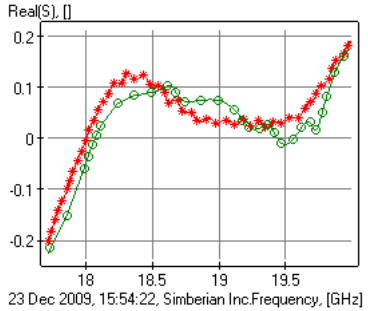


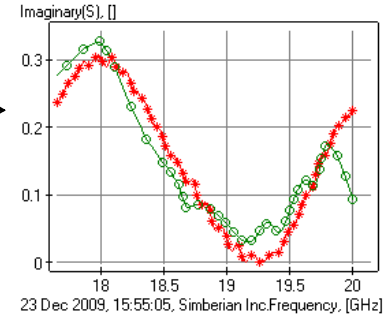
Stars – TRL data

Circles – RCM model

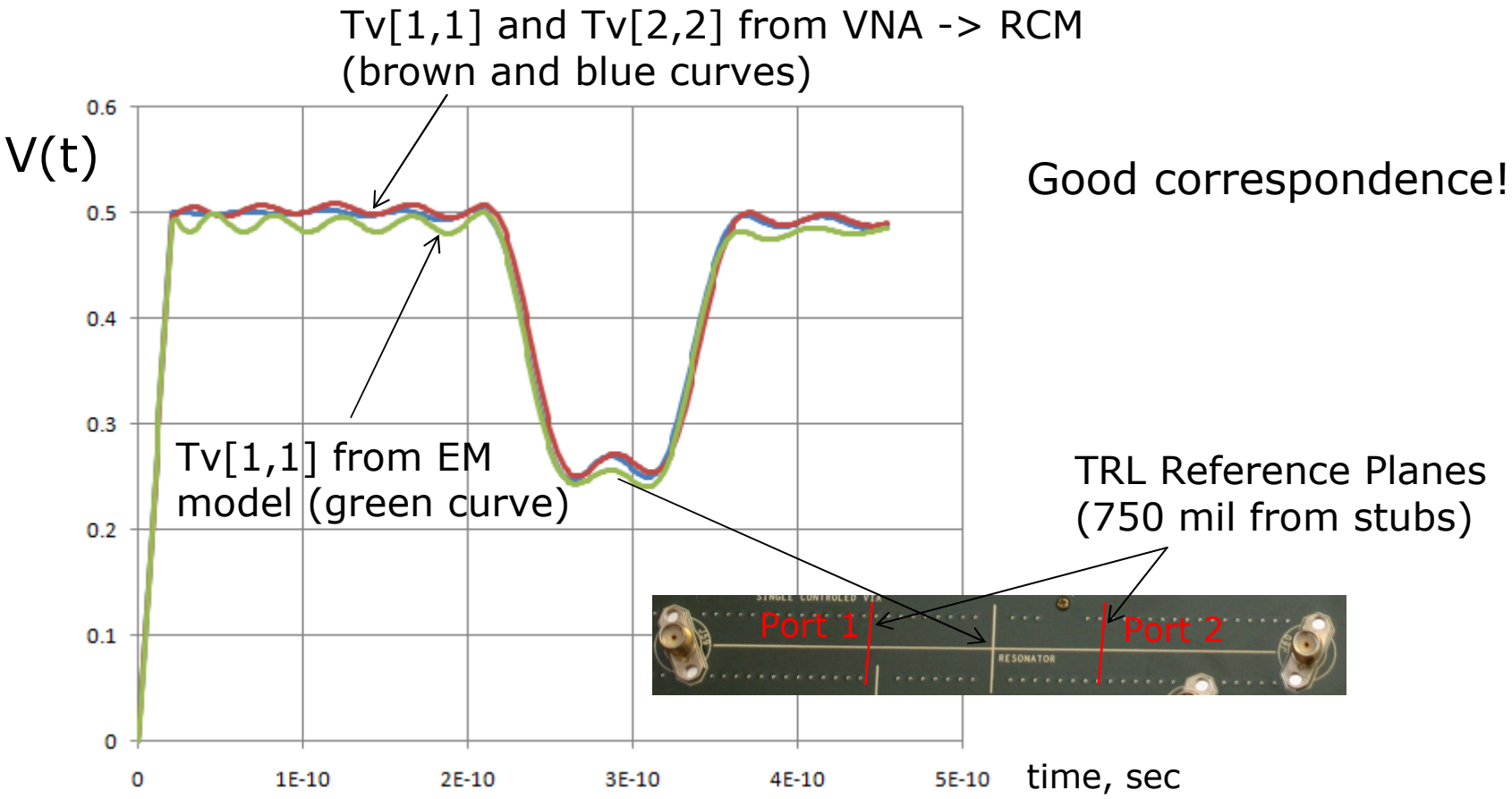
RMS Error 0.07, 50 poles

Problematic non-causal area is fitted as close as possible





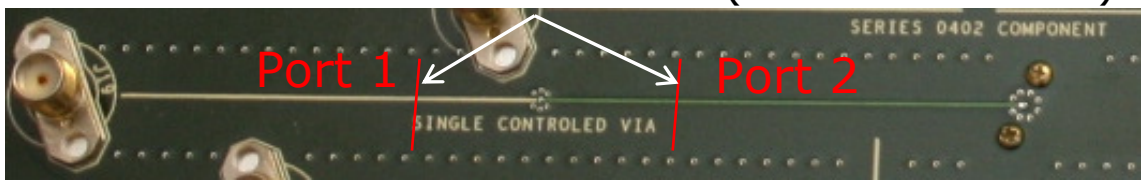
Resonator VNA vs. EM model (TRL)

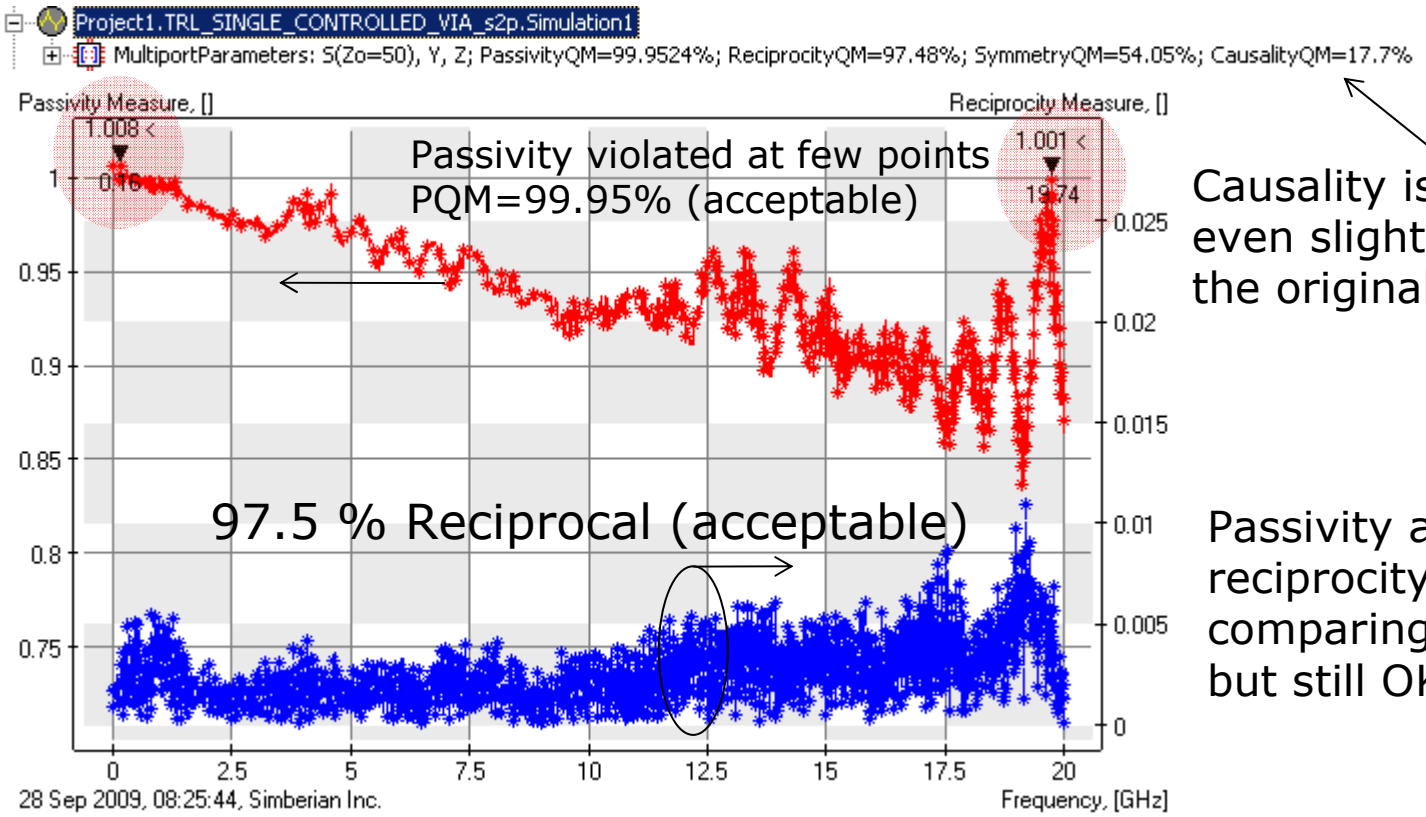


See more on modeling and measurements at *Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR–4 boards for 6–20 Gbps Applications, DesignCon2009* – available at http://www.simberian.com/AppNotes.php

S-parameters for a low-reflection structure: Single controlled via, TRL-calibration

TRL Reference Planes (250 mil from via)



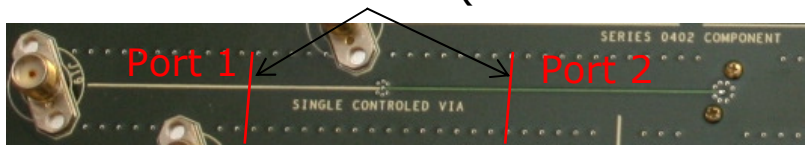


Causality is 17.7%, that is even slightly better than the original SOLT 9.5%

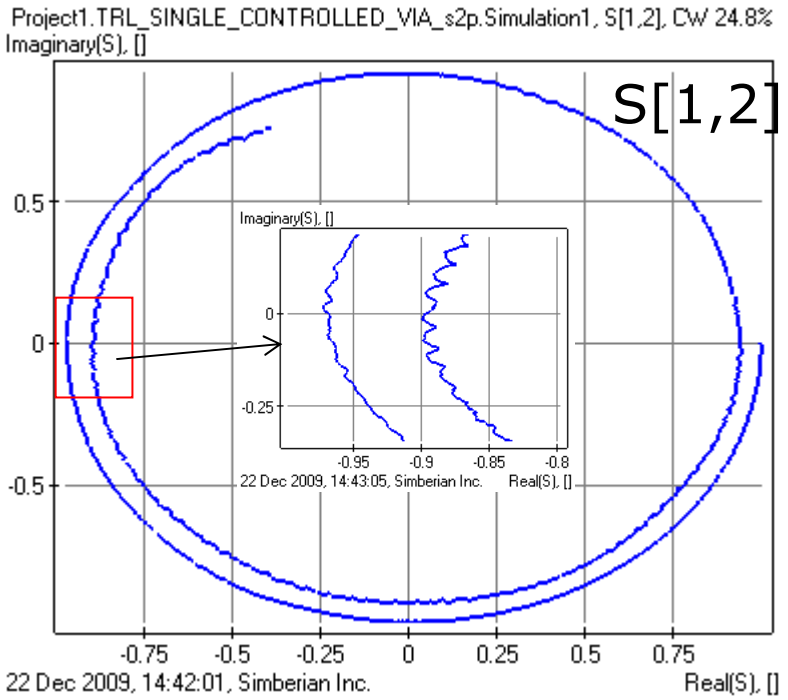
Passivity and reciprocity worsened comparing to SOLT, but still OK

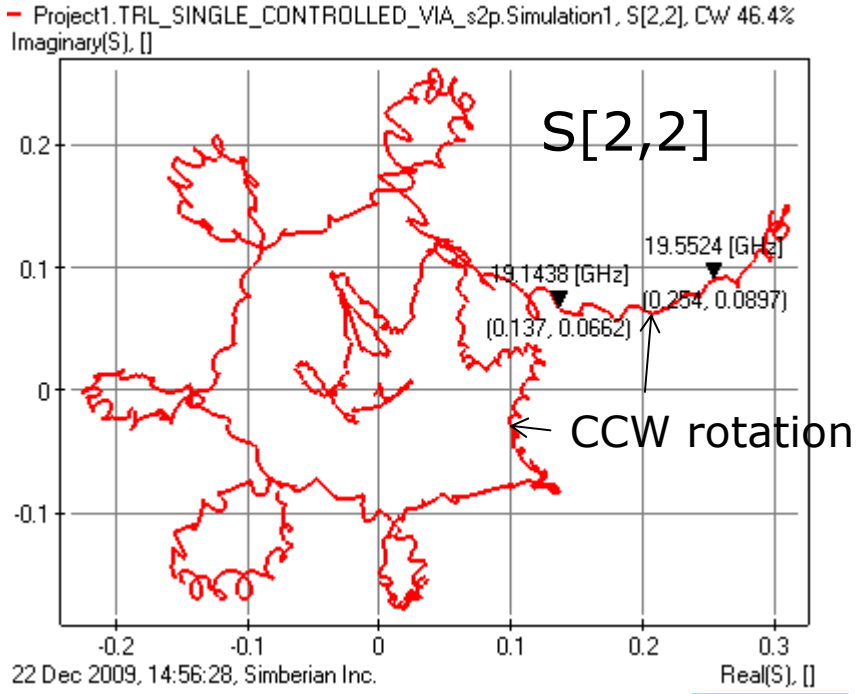
Single controlled via (TRL): Causality problems both in transmission and reflection

TRL Reference Planes (250 mil from stubs)



Some problems both in the transmission and reflection parameters (can be fixed):



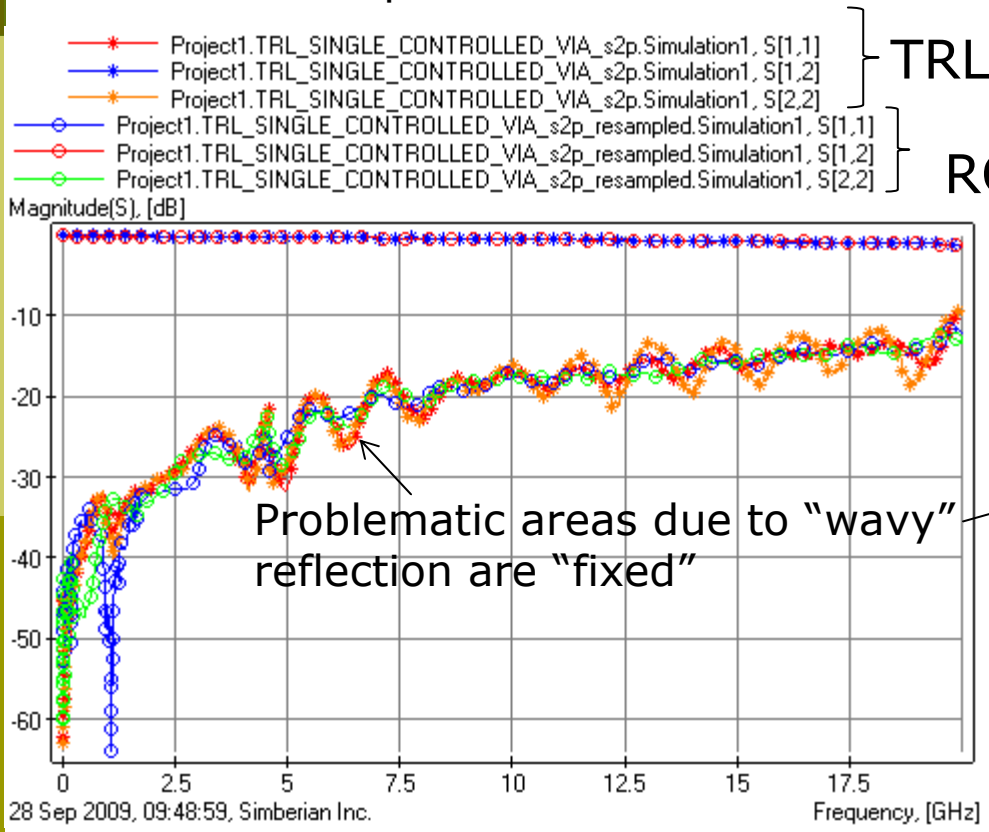


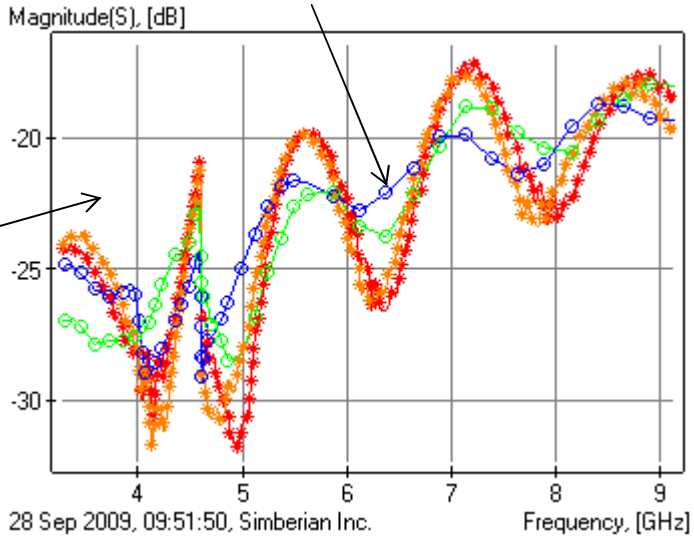
Single controlled via (TRL): Improving S-parameters with RCM

RCM RMS Error is 0.045 (still OK)
Passive from DC to infinity,
Causal and reciprocal

Transmission and group delay is OK

Problem is in the reflection parameters and RCM "fixes" it with the best possible fit

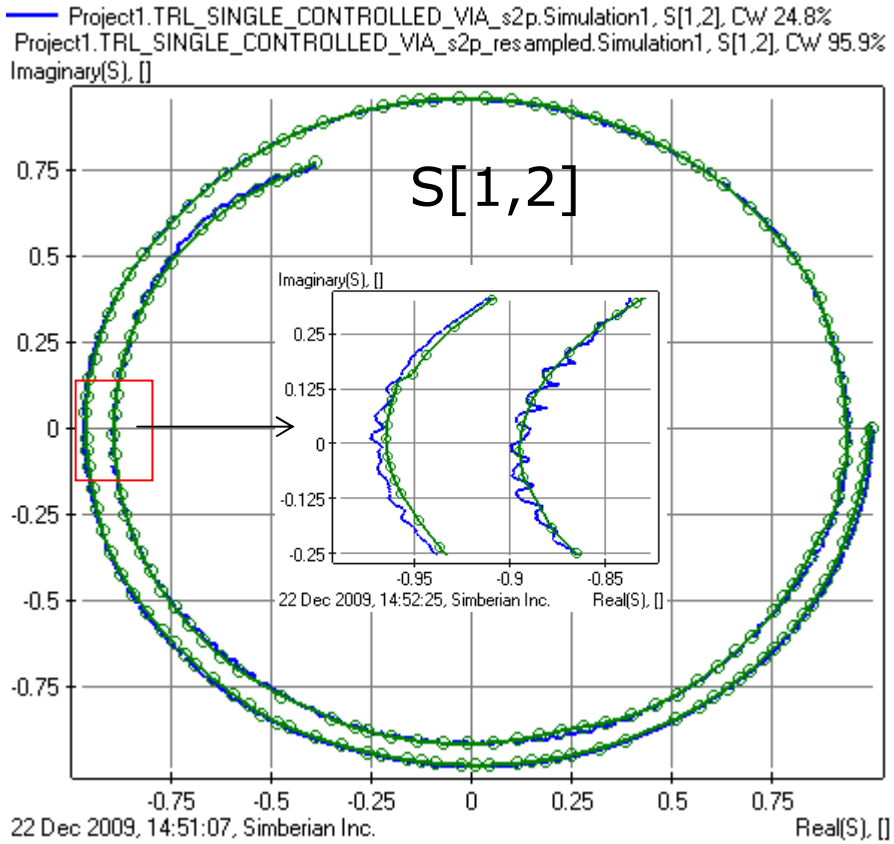




Single controlled via (TRL): Original S[1,2] and RCM

VNA Measurement: 3201 points starting from 300 KHz

Re-sampled RCM: 633 points distributed adaptively starting from 0 Hz

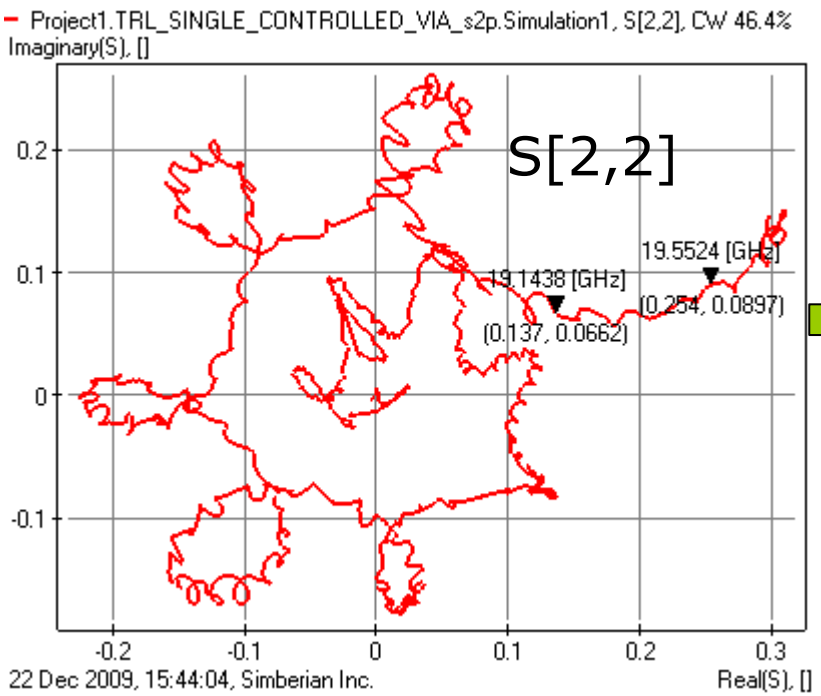


CAUSAL!

Very noisy data is corrected with RCM!

Single controlled via (TRL): Original S[2,2] and RCM

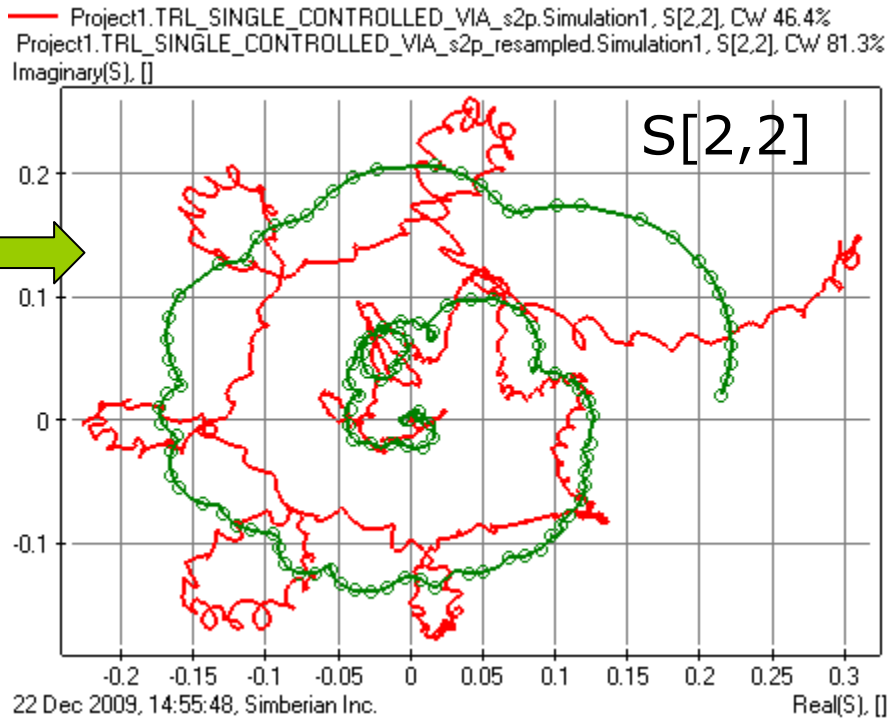
VNA Measurement: 3201 points starting from 300 KHz



Very noisy non-causal data with wrong rotation!

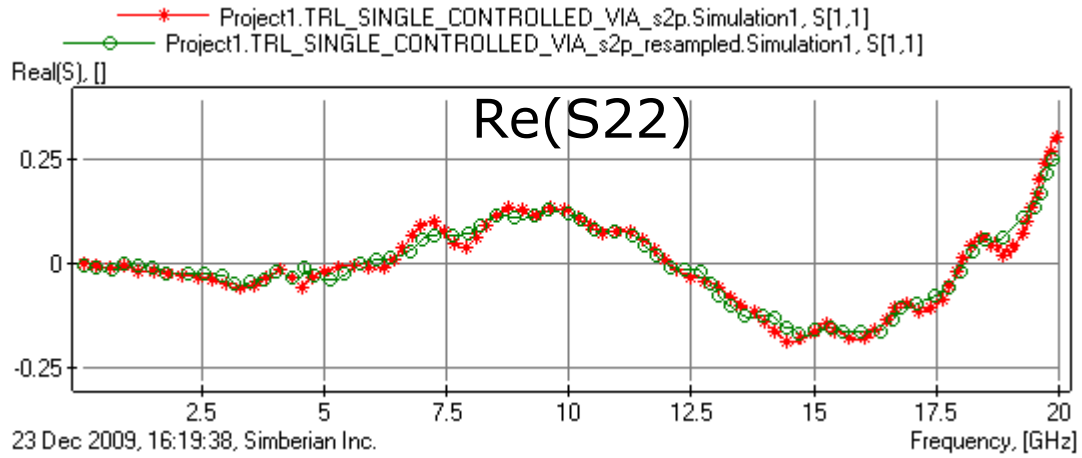
Re-sampled RCM: 633 points distributed adaptively starting from 0 Hz

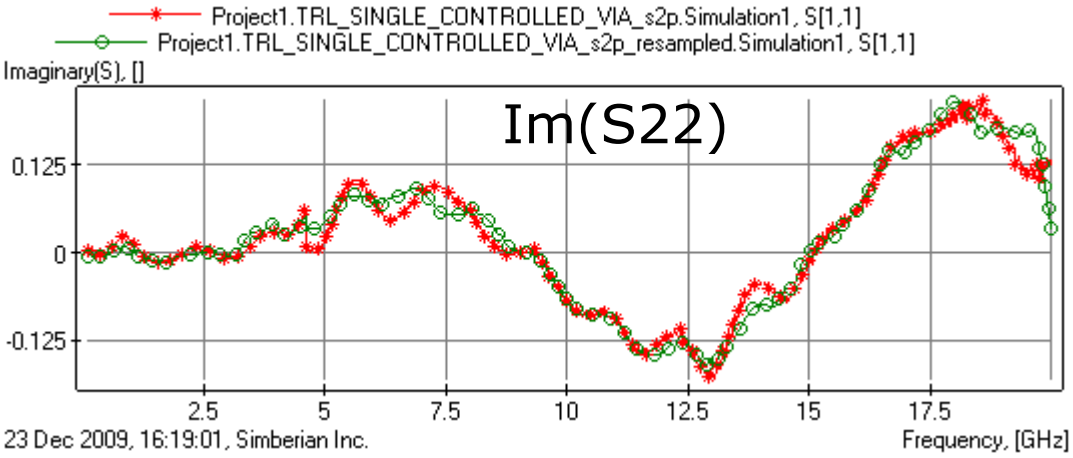
Does not match well but CAUSAL ☺



Red line – original TRL data
Green line with circles - RCM

Single controlled via (TRL): Original S[2,2] and RCM





Stars – original TRL data

Circles – RCM model

RMS Error 0.045,
44 poles

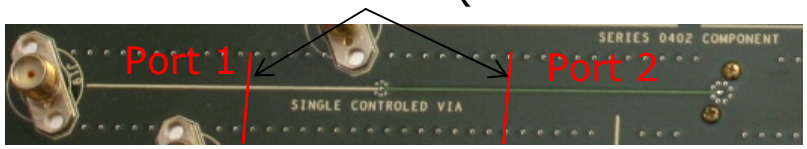
Problematic non-causal areas are fitted as close as possible

Does the corrected data contain information about the via?

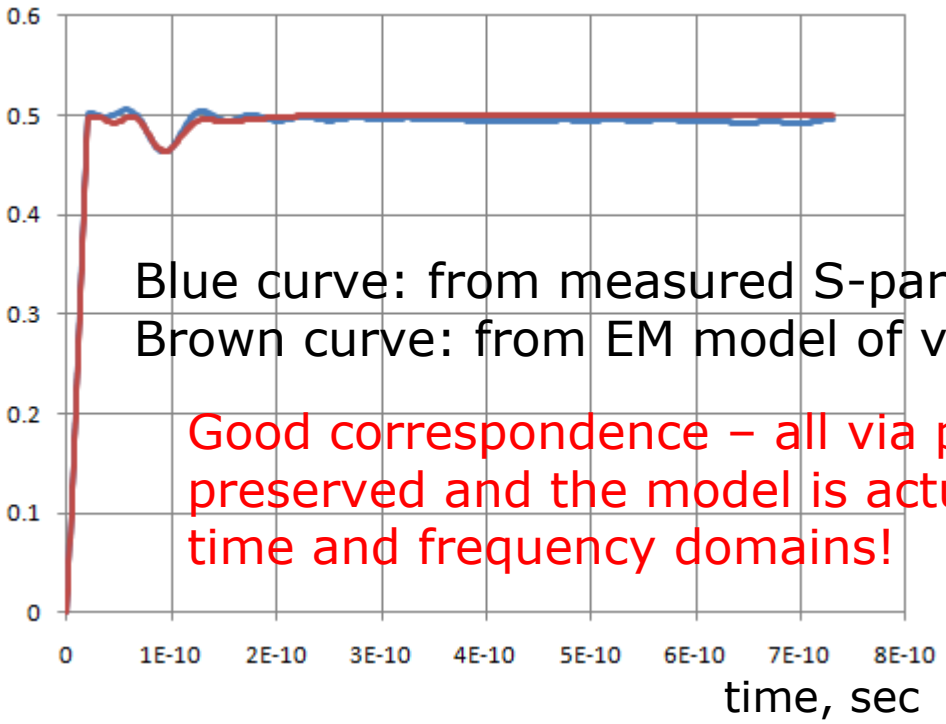
Single controlled via TDR from RCM (TRL)

Pure via in a t-line:
no connector and launch discontinuities

TRL Reference Planes (250 mil from stubs)



V(t)



Blue curve: from measured S-parameters
Brown curve: from EM model of via

Good correspondence – all via properties are preserved and the model is actually usable in the time and frequency domains!

Conclusion

- Always verify reciprocity, passivity and causality of interconnect component models before use
  - Measured models may be not acceptable for the analysis
  - Electromagnetic models may have violations too
- Distinguish minor “fixable” violations with acceptable accuracy degradation from severe violations
- Build macro-models with controllable accuracy to “improve” tabulated models and to correct minor violations of passivity and causality
- Verify macro-model both in frequency and time domains for consistency of the results

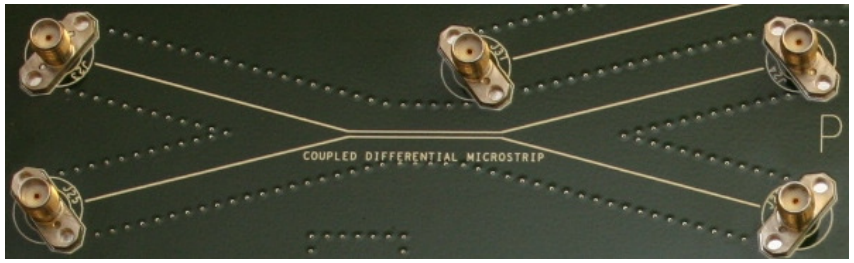
Please visit us

- Simberian Inc.
  - Booth #915 – Simbeor software and PLRD-1 board
  - www.simberian.com
- Teraspeed Consulting Group
  - www.teraspeed.com

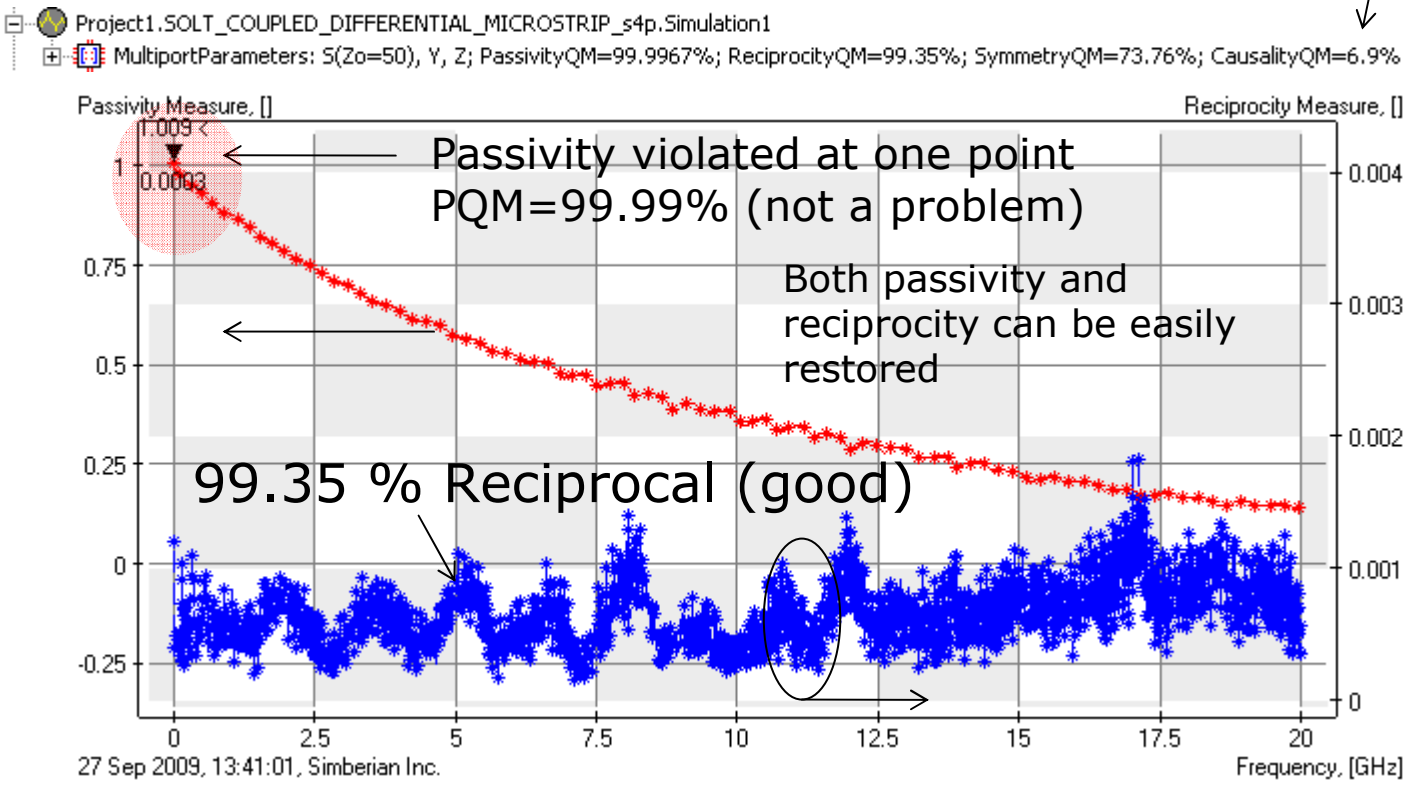
Backup slides

- SOLT-calibrated differential line segment
- TRL-calibrated differential line segment

S-parameters from a low-reflective structure: Coupled differential micro-strip, SOLT

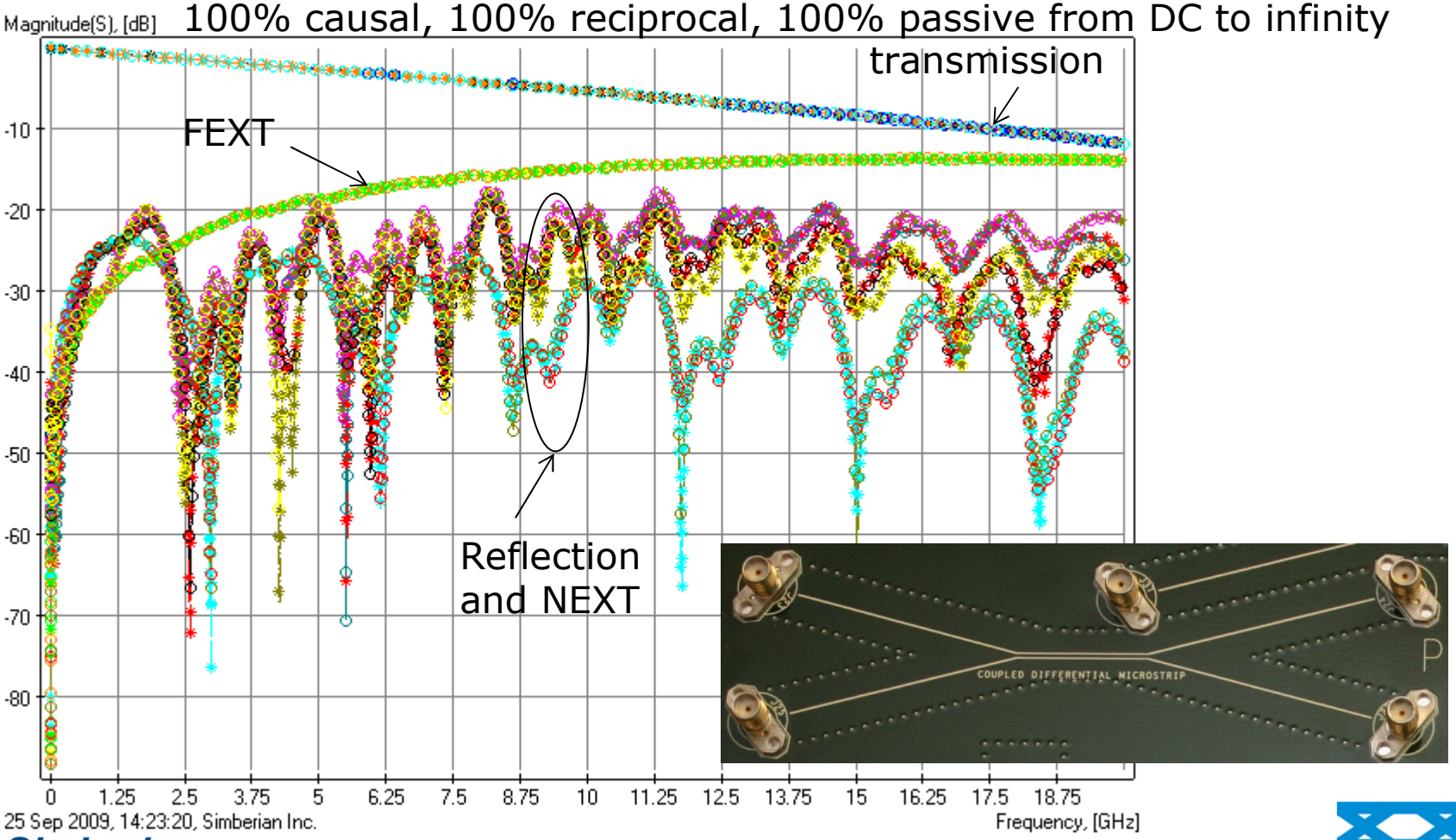


Causality, can be restored with RCM



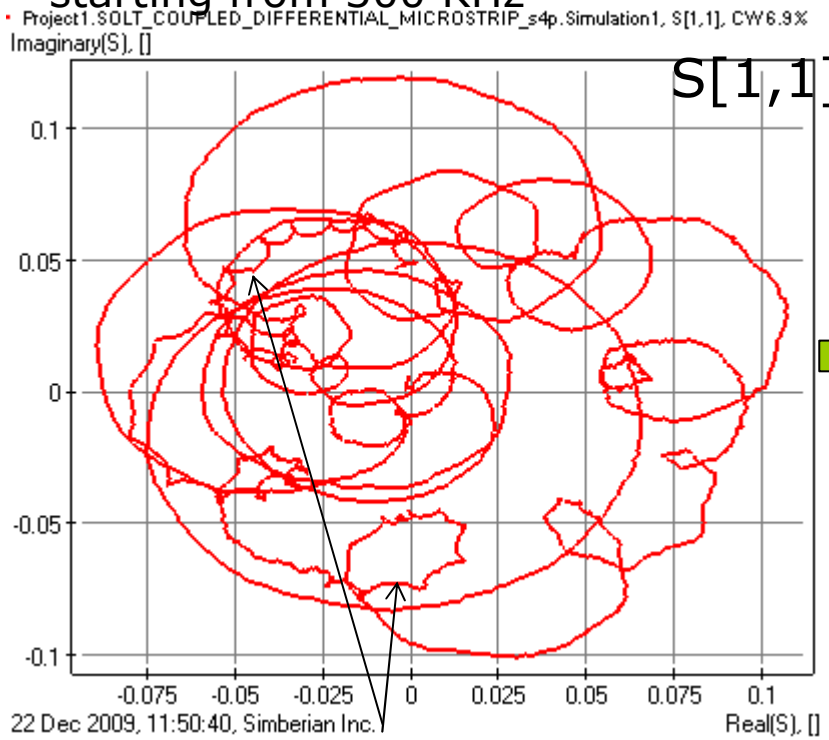
Coupled differential micro-strip (SOLT): Improving S-parameters with RCM

Stars - VNA
Circles – RCM with 27 to 165 poles per element, RMS Error 0.0024, 100% causal, 100% reciprocal, 100% passive from DC to infinity



Coupled differential micro-strip (SOLT): Original and improved S[1,1]

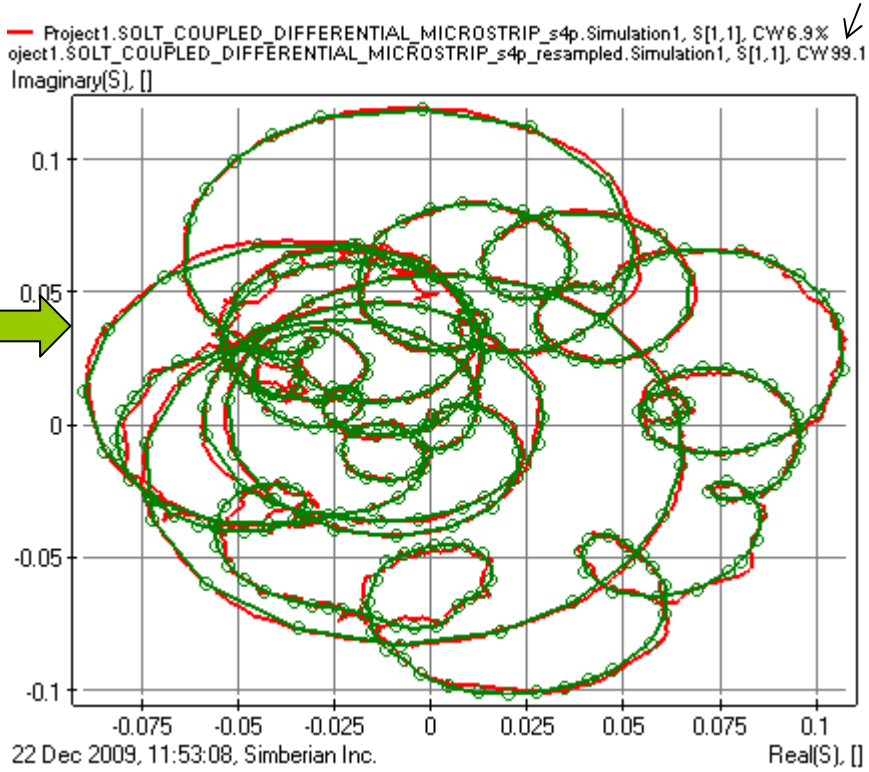
VNA Measurement: 3201 points starting from 300 KHz



Visible noise and counter-clockwise rotations

Re-sampled RCM: 687 points distributed adaptively starting from 0 Hz

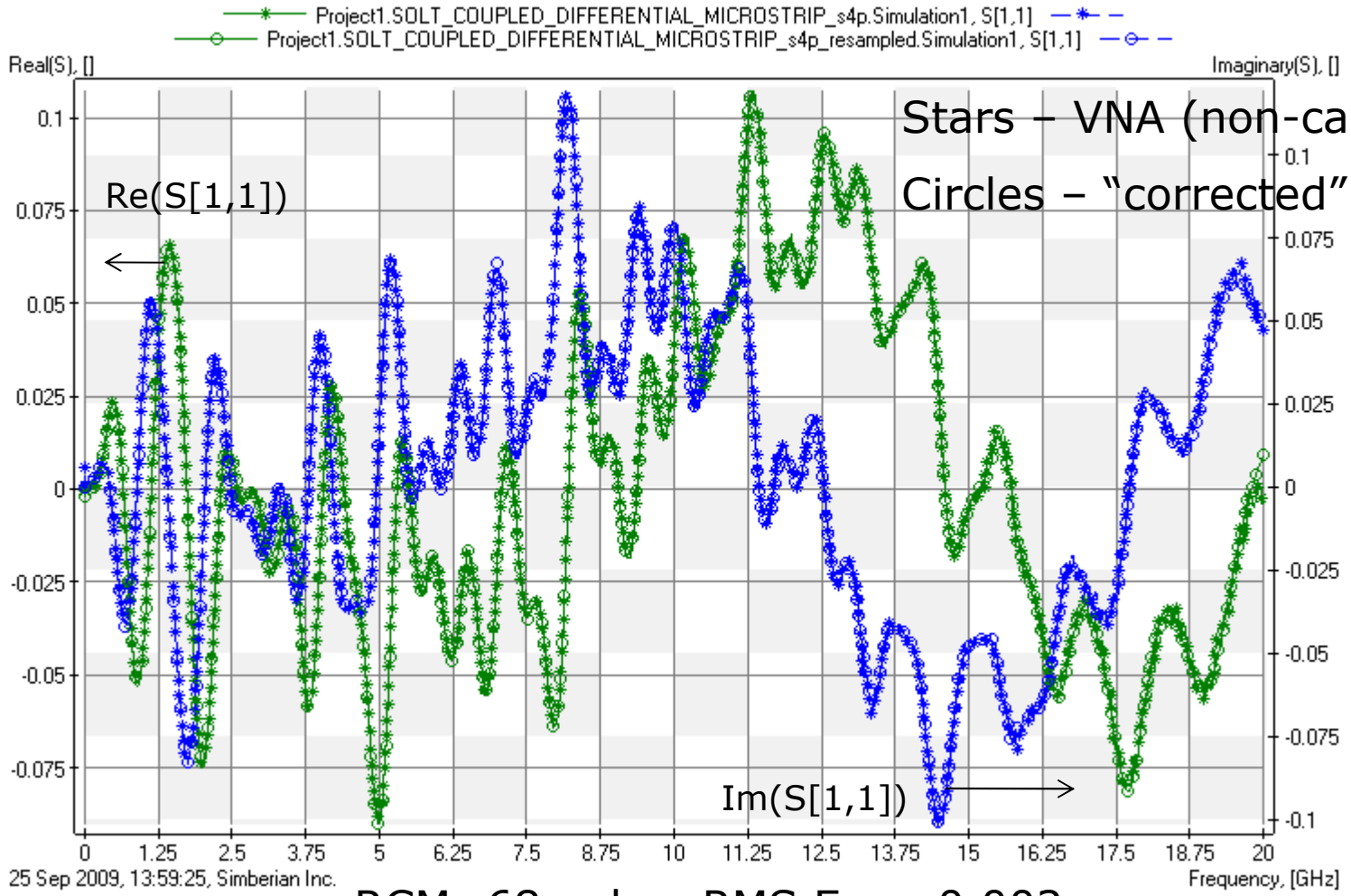
CAUSAL!



Red line – original
Green line with circles - corrected

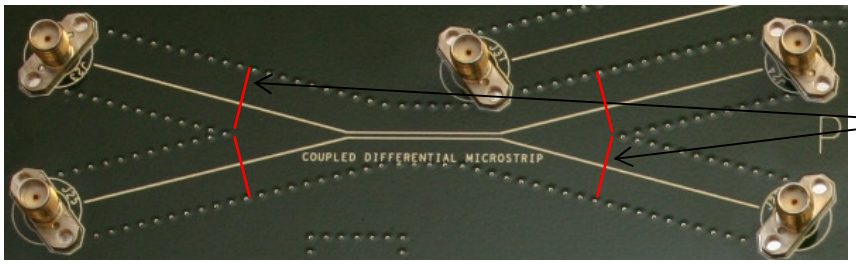
Reflections and NEXT are worst from the causality point of view due to smallness, but repairable with RCM

Coupled differential micro-strip (SOLT): Original and improved S[1,1]



RCM: 68 poles, RMS Error 0.002

S-parameters for a low-reflection structure: Coupled differential micro-strip, TRL-calibration

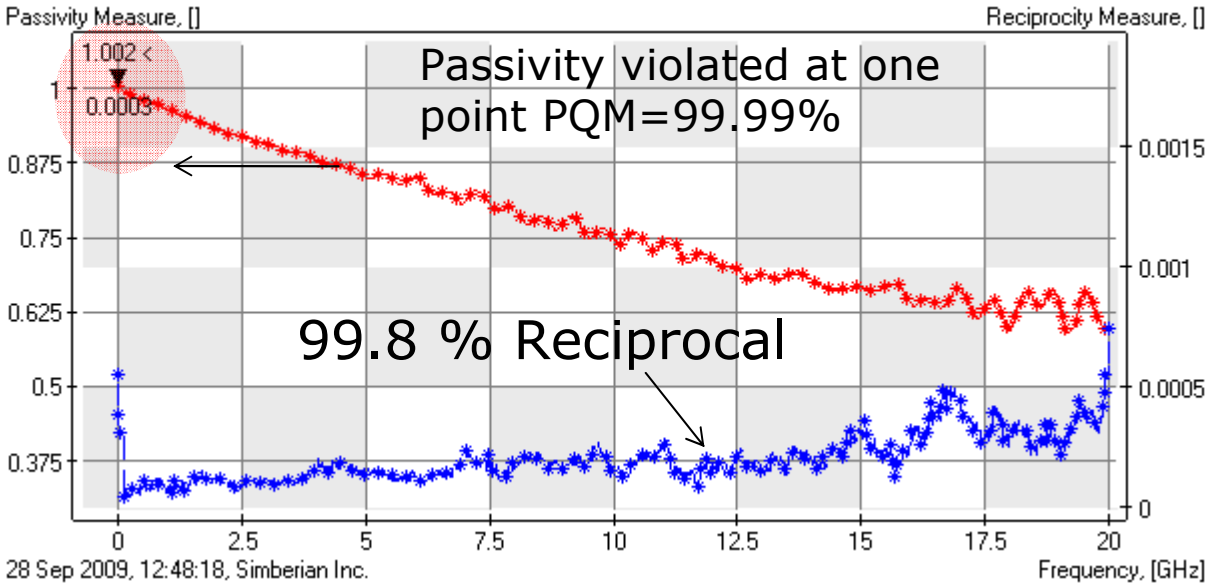


TRL Reference Planes (250 mil from differential section)

Project1.TRL_COUPLED_DIFFERENTIAL_MICROSTRIP_s4p.Simulation1

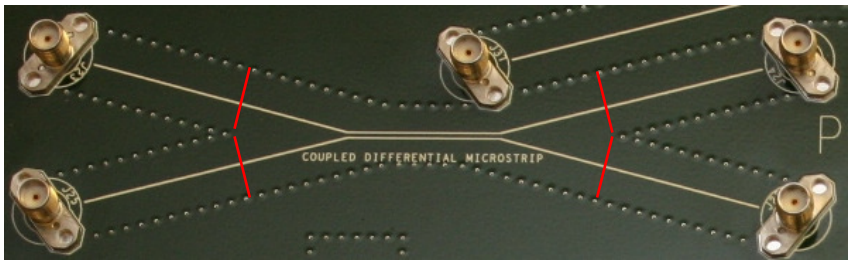
MultiportParameters: S(Zo=50), Y, Z; PassivityQM=99.9987%; ReciprocityQM=99.8%; SymmetryQM=64.5%; CausalityQM=0%

Big problems with causality in reflection parameters



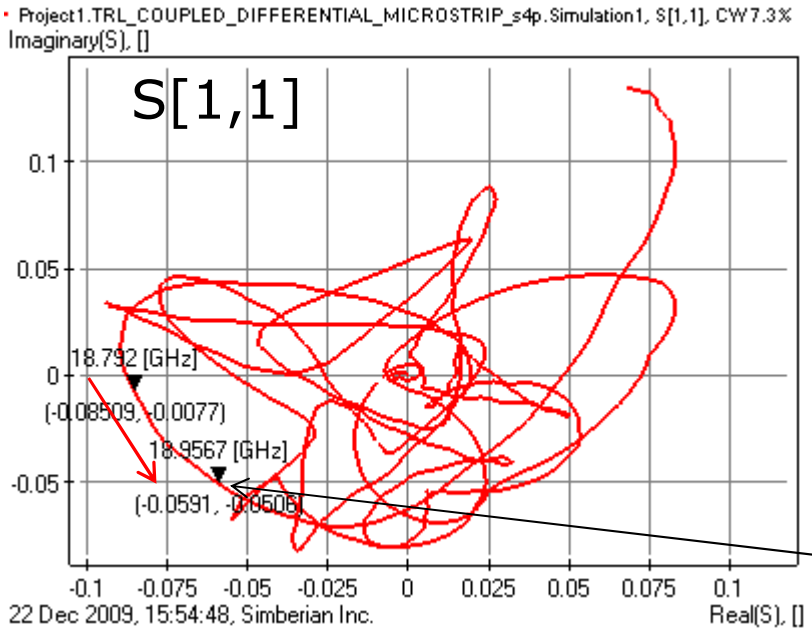
Passivity and reciprocity are practically same as in SOLT

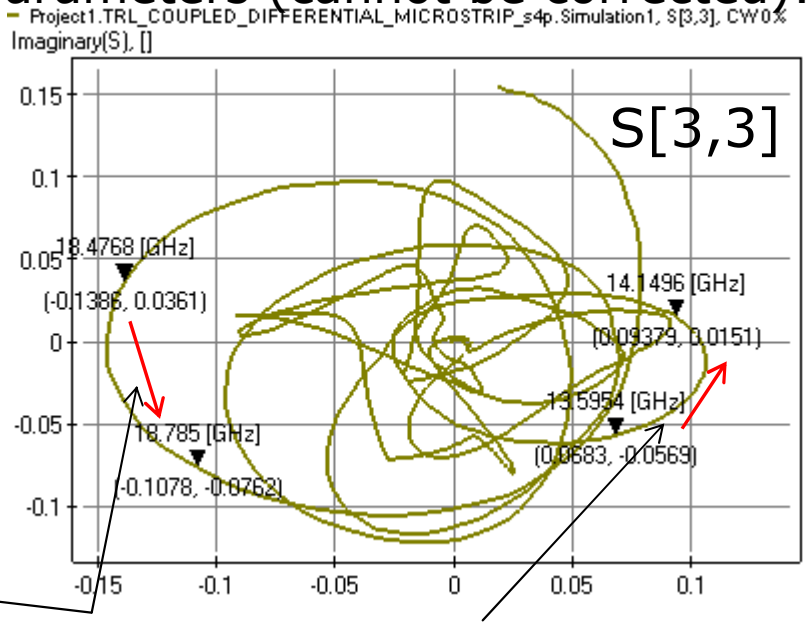
Coupled differential micro-strip (TRL): Causality problems in reflection



Transmission parameters are OK – minor noise problems

Severe problems in the reflection parameters (cannot be corrected):

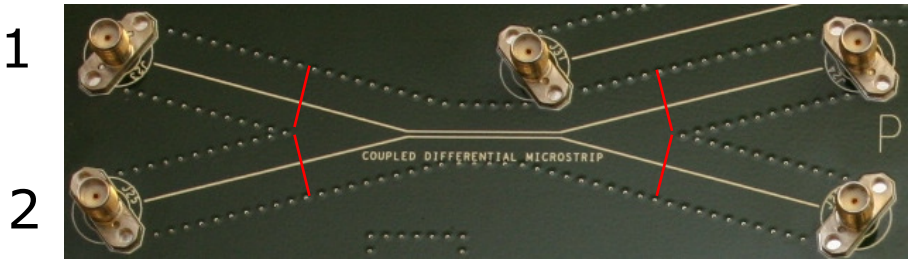




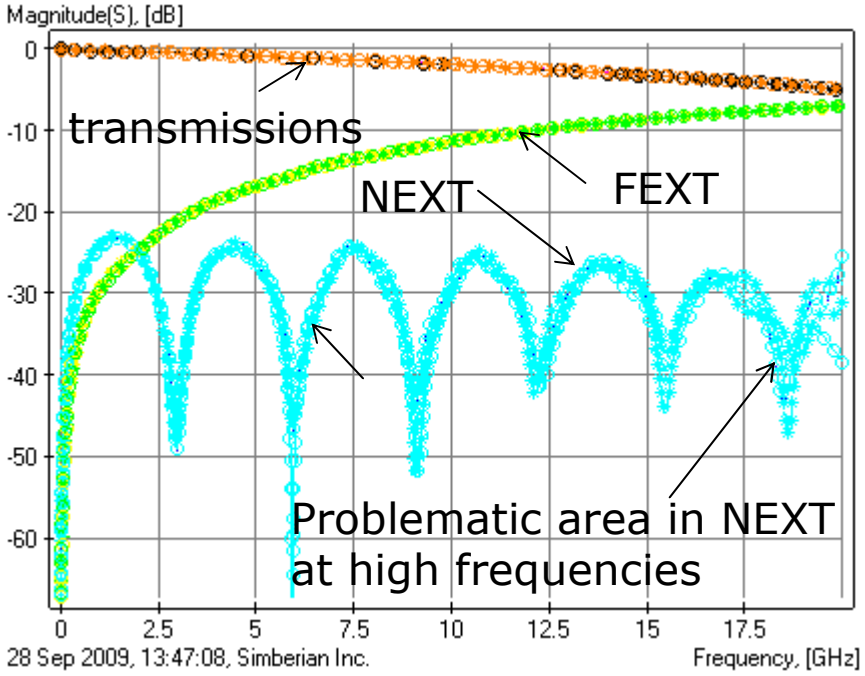
Rotates wrong way!

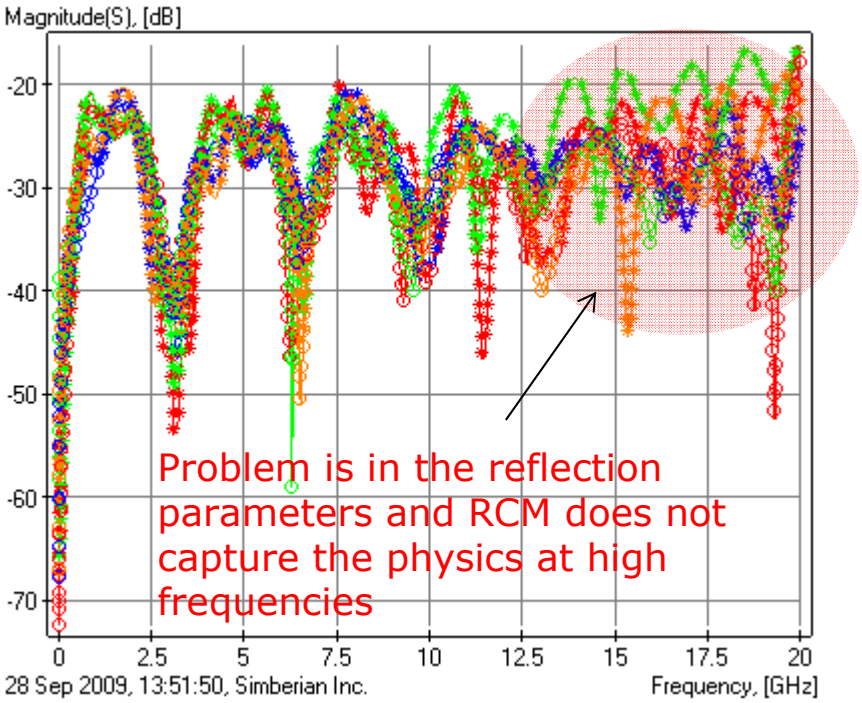
Coupled differential micro-strip (TRL): Improving S-parameters with RCM

RCM RMS Error is 0.057 (not good)
Passive from DC to infinity,
100% causal and reciprocal



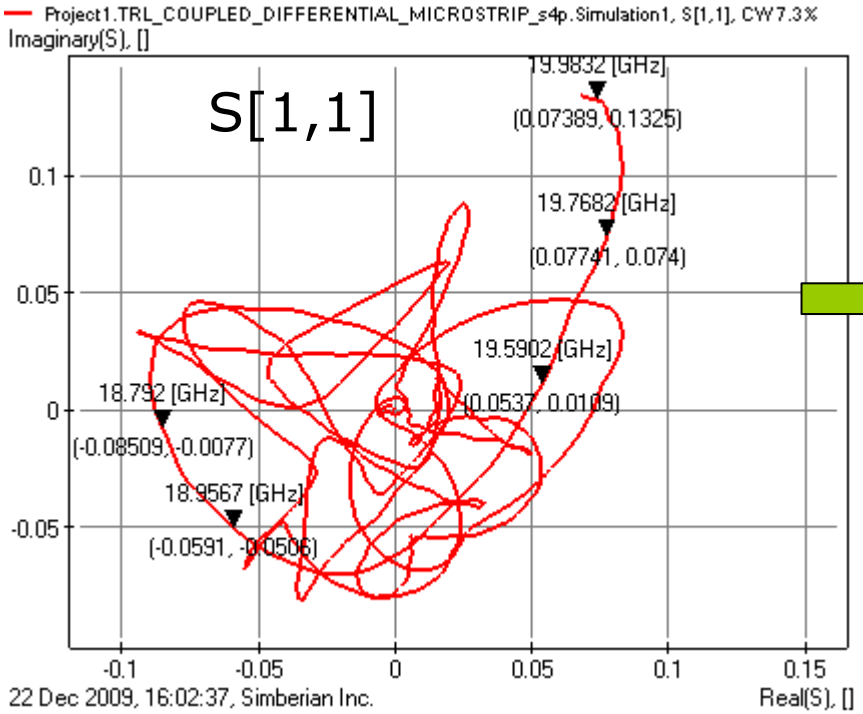
VNA - stars RCM - circles





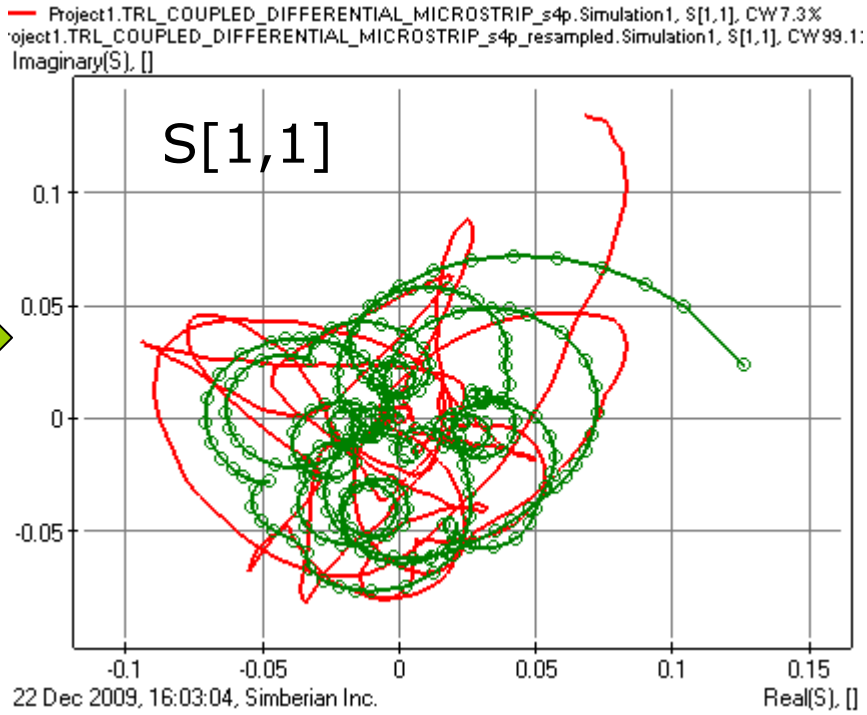
Coupled differential micro-strip (TRL): Original and improved S[1,1]

VNA Measurement: 3201 points starting from 300 KHz



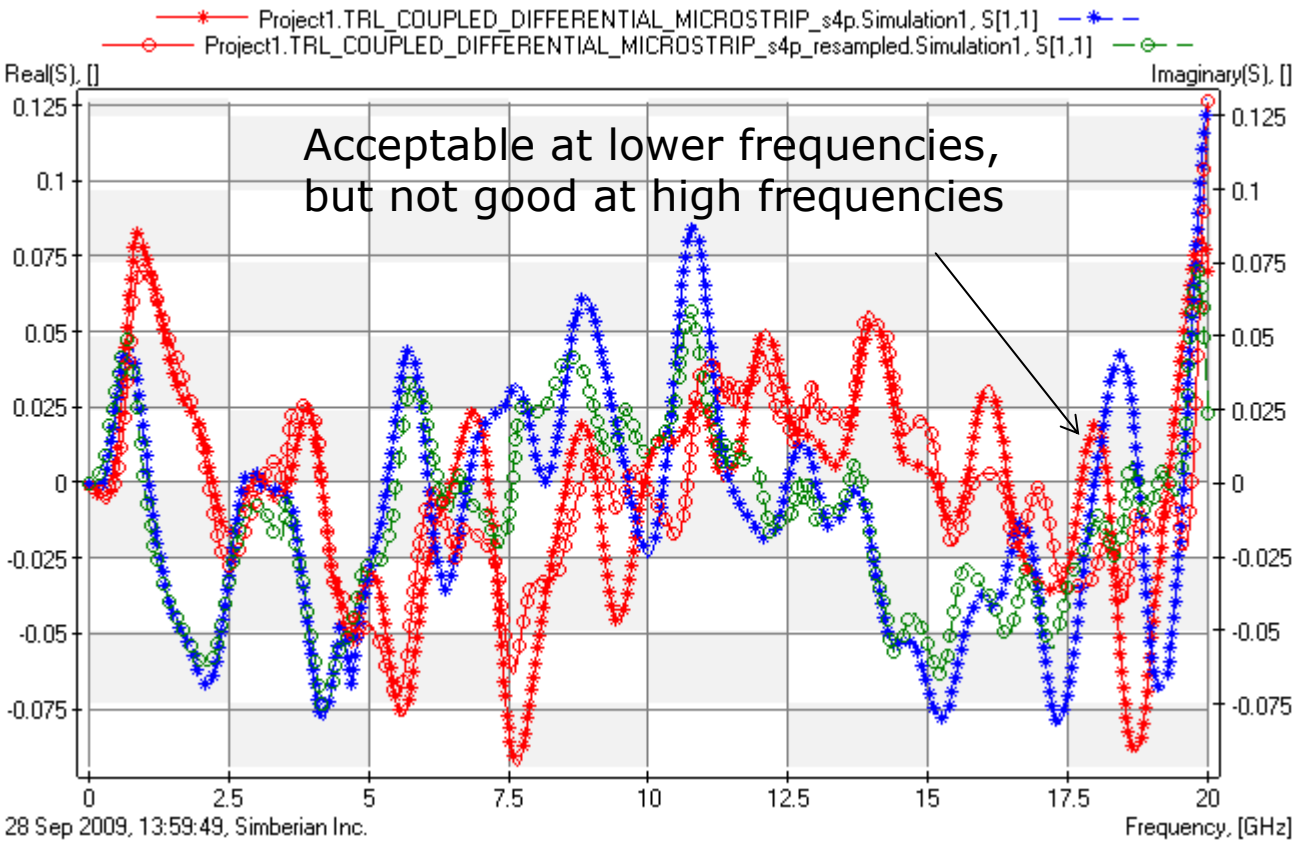
Non-causal data!

Re-sampled RCM: 798 points distributed adaptively starting from 0 Hz



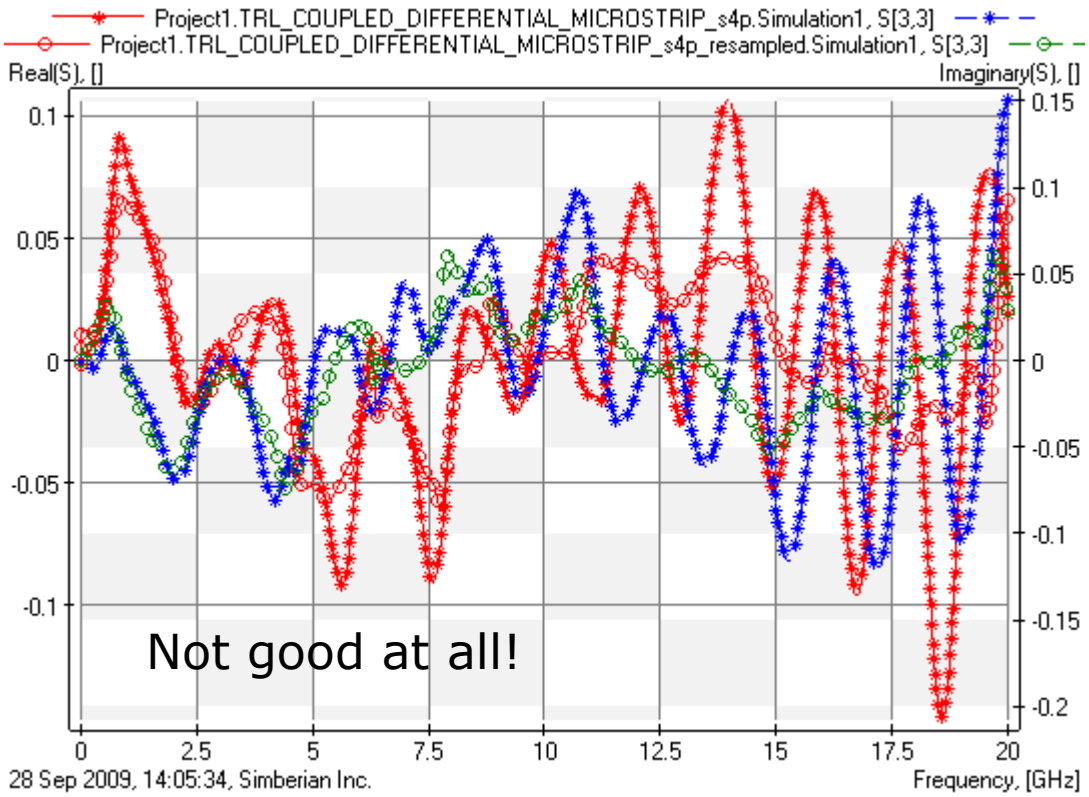
Causal, but may be does not capture the physics!

Coupled differential micro-strip (TRL): Re-sampled RCM vs. original S[1,1]

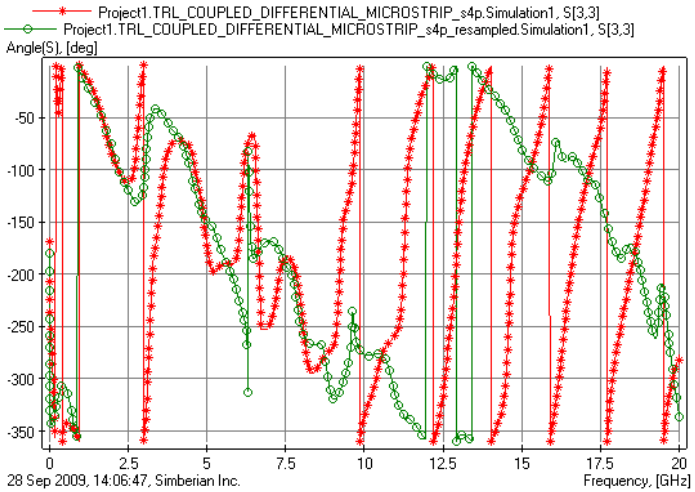


RMS Error 0.031, 40 poles

Coupled differential micro-strip (TRL): Re-sampled RCM vs. original S[3,3]

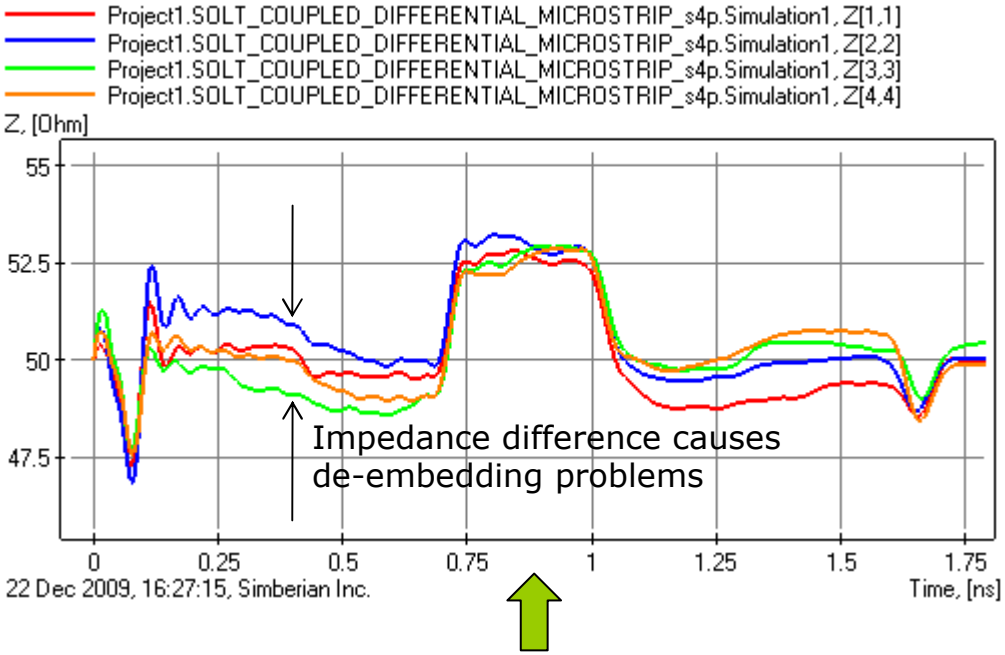


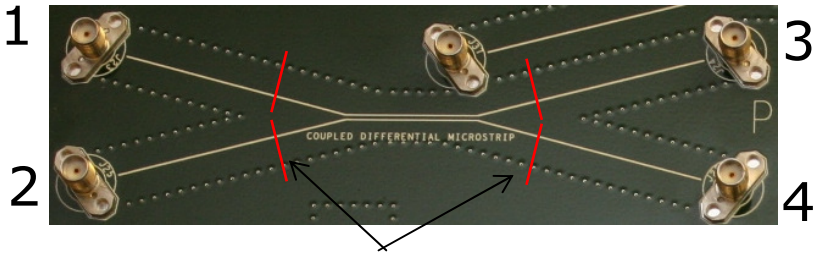
Phase of measured S[3,3] goes wrong way starting from about 4 GHz



RMS Error 0.057, 29 poles – more poles does not help

Coupled differential micro-strip (TRL): TDR/TDT from RCM





TRL reference planes

TDR from SOLT calibrated data (accurate and reliable)

TDR from TRL calibrated data (may be acceptable)