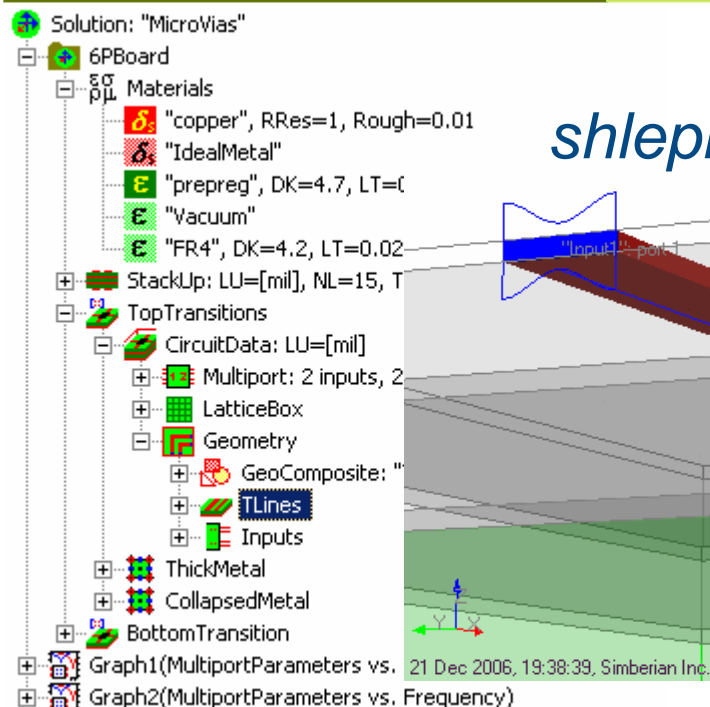
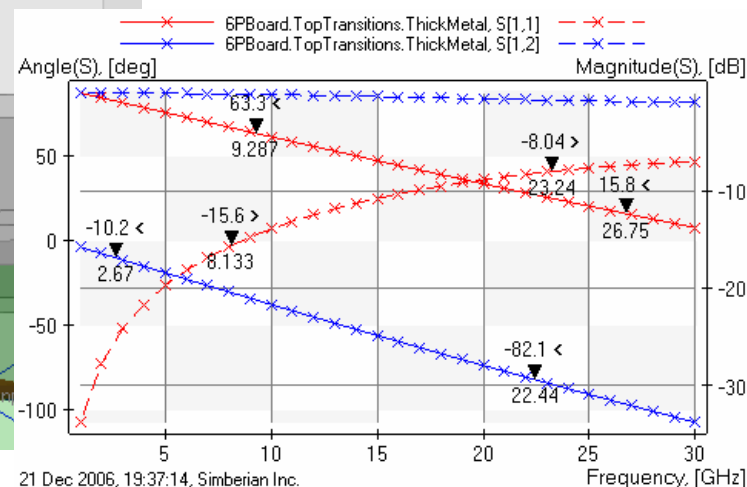
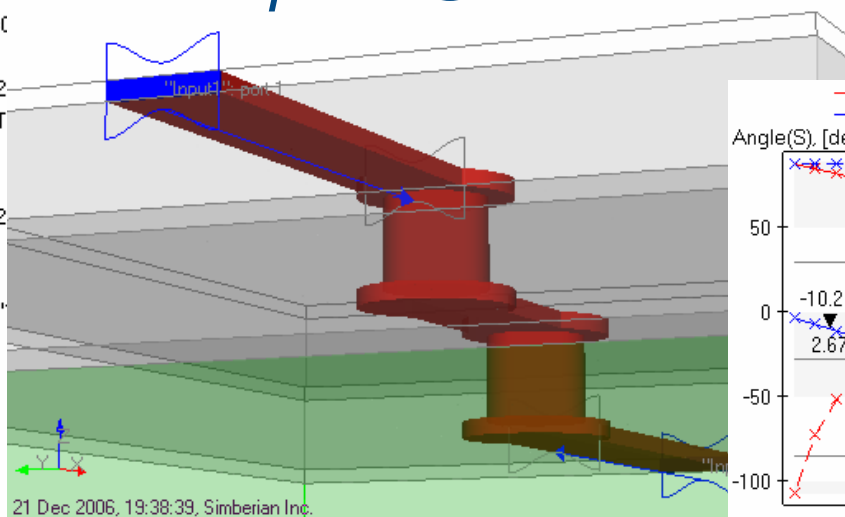


Quality metrics for S-parameter models

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Agenda

- Introduction
- Reciprocity metric
- Passivity metric
- Causality metrics
- Global quality metrics
- Examples
- Conclusion
- Contacts and resources

Introduction

- ❑ S-parameter models are becoming ubiquitous in design of multi-gigabit interconnects
 - Connectors, cables, PCBs, packages, backplanes, ... can be characterized with S-parameters from DC to daylight
- ❑ Such models come from measurement or electromagnetic analysis
- ❑ And very often have some quality issues
 - Passivity and reciprocity violations
 - Causality problems

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 anisotropic materials)

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

- ❑ Passive (interconnects do not generate energy)

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

- ❑ Causal – no response before the excitation

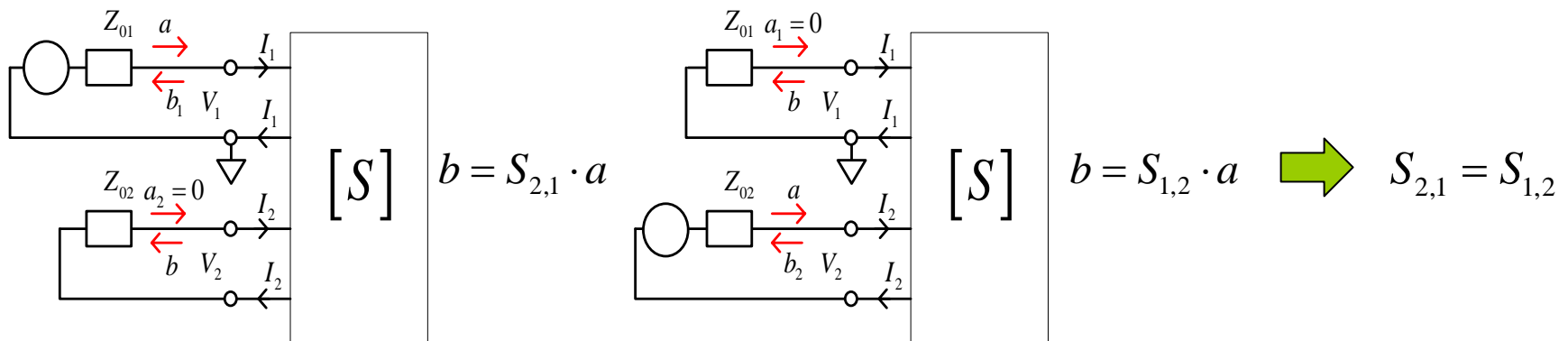
$$S_{i,j}(t) = 0, \quad t < T_{ij}$$

- ❑ Stable analysis in time domain
- ❑ What if some of those properties are violated – can we still use such model and trust the results?
- ❑ This presentation introduces metrics to distinguish good models from bad ones and methodology to improve the model quality for consistent frequency and time-domain analyses

Reciprocity

- Linear circuits with linear isotropic 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

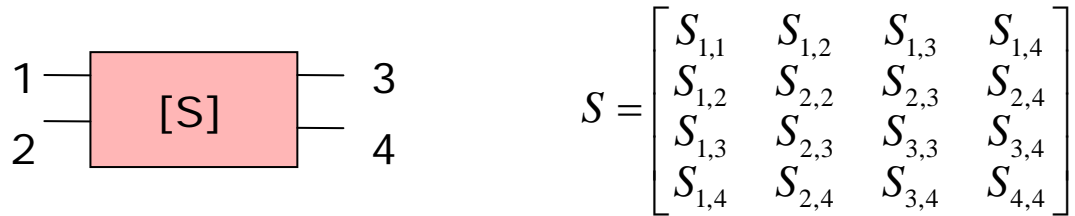


- In general it means that **the scattering matrices are symmetric**

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

Reciprocity estimation and enforcement

- Example of S-parameters of reciprocal 4-port interconnect (symmetric matrix):



Reciprocity measure can be computed as mean difference between elements that have to be equal (at each frequency point):

$$RM = \frac{1}{N_s} \sum_{i,j} |S_{i,j} - S_{j,i}| \quad \text{or max singular value of } S - S^t \text{ can be used}$$

RM is compared with a *threshold*: if $RM > \text{threshold}$, the multiport is reported as not reciprocal

Averaging can be used to “enforce” the reciprocity (**works only with noisy data**):

$$S_{j,i} = S_{i,j} = 0.5(S_{i,j} + S_{j,i})$$

Passivity (necessary but not sufficient conditions)

- Power transmitted to multiport is a difference of power transmitted by incident and reflected waves:

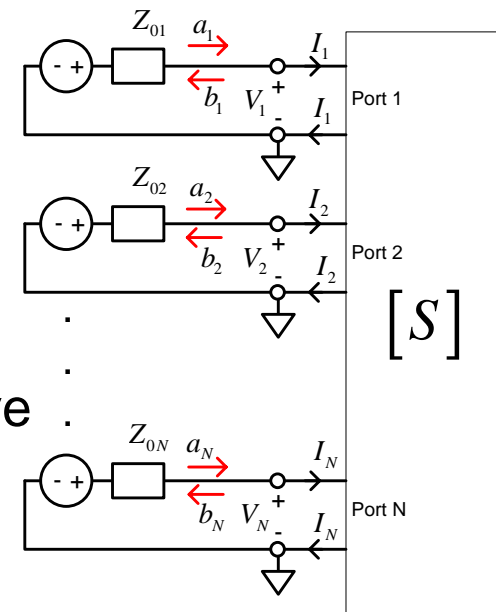
$$P_{in} = \sum_{n=1}^N |a_n|^2 - |b_n|^2 = [\bar{a}^* \cdot \bar{a} - \bar{b}^* \cdot \bar{b}]$$

or
$$P_{in} = \bar{a}^* \cdot \bar{a} - \bar{a}^* \cdot S^* S \cdot \bar{a} = \bar{a}^* \cdot [U - S^* S] \cdot \bar{a}$$

- Transmitted power is defined by Hermitian quadratic form and must be not negative for passive multiport for any combination of incident waves

- Quadratic form is non-negative if eigenvalues of the matrix are non-negative (Golub & Van Loan):

$$\text{eigenvals}[U - S^* \cdot S] \geq 0 \quad \Rightarrow \quad \text{eigenvals}[S^* \cdot S] \leq 1 \quad (U \text{ is unit matrix})$$



More on passivity

- Maximal singular value of S can be used for passivity estimation, because of non-zero singular values of S are square roots of eigenvalues of S^*S (Golub & Van Loan)

$$\delta_i = \sqrt{\lambda_i}, \quad \lambda_i = \text{eigenvals}(S^* \cdot S) \quad \lambda_i \in R, \lambda_i \geq 0$$

- Passivity of symmetric S can be estimated with eigenvalues as $|\text{eigenvals}(S)| \leq 1$
 - It is possible due to the fact that singular values of symmetric matrices are equal to the magnitudes of the eigenvalues

- Common mistake is to estimate passivity as:

$$\sum_{k=1}^N |S_{i,k}|^2 \leq 1 \quad \text{or} \quad |S_{i,k}| \leq 1 \quad \text{This is necessary but not sufficient condition!}$$

Passivity estimation and enforcement

- Passivity conditions for S-parameters (energy dissipation condition):

$$\text{eigenvals}(U - S^* \cdot S) \geq 0 \quad \Rightarrow \quad \text{eigenvals}(S^* \cdot S) \leq 1$$

Passivity measure is computed at each frequency point as:

$$PM = \sqrt{\max[\text{eigenvals}(S^* \cdot S)]}$$
 is equal to max singular value of S

PM is compared with a *threshold*: if $PM > \text{threshold}$, the multiport is reported as not passive

Normalization at each frequency point can be used to “enforce” the passivity (works only with minor violations):

$$\begin{aligned} \text{if } PM > 1.0 &\Rightarrow S_p = \frac{S}{PM} \\ \text{else } S_p &= S \end{aligned}$$

Alternatively a rational filter can be used

Causality in frequency-domain

- Condition $H(t) = 0$ at $t < 0$ for the unit pulse response matrix and

$$H(i\omega) = \int_{-\infty}^{\infty} H(t) \cdot e^{-i\omega t} \cdot dt, \quad H(i\omega) \in C^{N \times N}$$

leads to Kramers-Kronig relations for the frequency-domain parameters (Hilbert transform)

$$H(i\omega) = \frac{1}{i\pi} PV \int_{-\infty}^{\infty} \frac{H(i\omega')}{\omega - \omega'} \cdot d\omega', \quad PV = \lim_{\varepsilon \rightarrow 0} \left(\int_{-\infty}^{\omega - \varepsilon} + \int_{\omega + \varepsilon}^{+\infty} \right)$$

$$H_r(\omega) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{H_i(\omega')}{\omega - \omega'} \cdot d\omega', \quad H_i(\omega) = \frac{-1}{\pi} PV \int_{-\infty}^{\infty} \frac{H_r(\omega')}{\omega - \omega'} \cdot d\omega'$$

Kramers, H.A., Nature, v 117, 1926 p. 775..

Kronig, R. de L., J. Opt. Soc. Am. N12, 1926, p 547.

derivation

$$H(t) = \text{sign}(t) \cdot H(t),$$

$$\text{sign}(t) = \begin{cases} -1, & t < 0 \\ 1, & t > 0 \end{cases} \quad \begin{array}{c} \uparrow \\ \text{---} \\ \text{---} \end{array}$$

$$H(i\omega) = F\{H(t)\} =$$

$$= \frac{1}{2\pi} F\{\text{sign}(t)\} * F\{H(t)\}$$

$$F\{\text{sign}(t)\} = \frac{2}{i\omega}$$

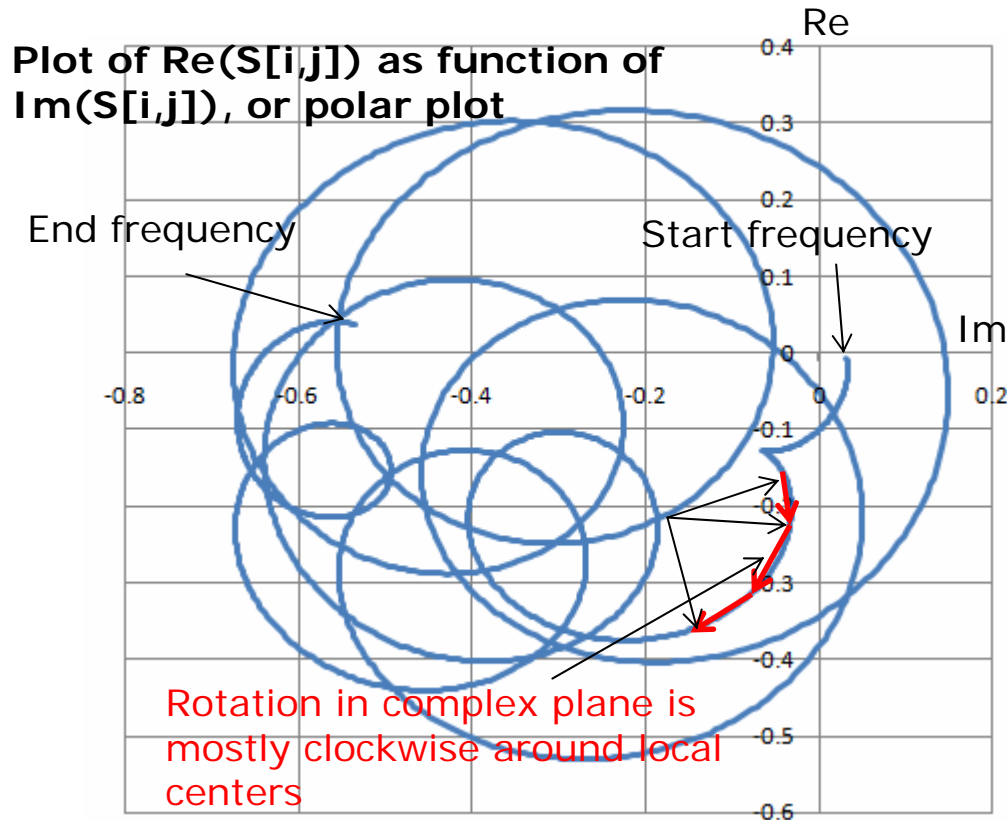
- Imaginary part can be derived from real (or vice versa), but the other part must be known from DC to infinity

Causality estimation - difficult way

- ❑ Kramers-Kronig relations **cannot be directly used** for the frequency-domain response known over **the limited bandwidth**
- ❑ Causality boundaries can be introduced to estimate causality of the tabulated and band-limited data sets
 - Milton, G.W., Eyre, D.J. and Mantese, J.V, *Finite Frequency Range Kramers Kronig Relations: Bounds on the Dispersion*, Phys. Rev. Lett. 79, 1997, p. 3062-3064
 - Triverio, P. Grivet-Talocia S., *Robust Causality Characterization via Generalized Dispersion Relations*, IEEE Trans. on Adv. Packaging, N 3, 2008, p. 579-593.

Causality estimation - easy way

- “Heuristic” causality measure based on the observation that polar plot of a causal system rotates mostly clockwise (suggested by V. Dmitriev-Zdorov)



Causality measure (CM) can be computed as the ratio of clockwise rotation measure to total rotation measure in %.

If this value is below 80%, the parameters are reported as suspect for possible violation of causality.

Causality improvement

- ❑ Filtration or decimating – the simplest technique, but may further degrade the response quality
- ❑ Artificially extend real or imaginary part, or magnitude of the frequency response to DC and to the infinity and restore the other part with the Kramers-Kronig equations
 - The restored part will strongly depend on the artificial extension
 - Iterative extension adjustment is possible to improve accuracy over the sampled frequency band - difficult to implement
- ❑ Fit the response with causal rational basis functions (use rational compact model)
 - Provides controlled accuracy over the sampled frequency band
 - Consistent results in both frequency and time domains
 - Can be extended to DC and to infinity

Use of Rational Compact Model (RCM) for S-parameters causality “improvement”

$$\bar{b} = S \cdot \bar{a}, \quad S_{i,j} = \frac{b_i}{a_j} \bigg|_{a_k=0, k \neq j} \Rightarrow S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}} \left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r_{ij,n}^*}{i\omega - p_{ij,n}^*} \right) \right] \cdot e^{-s \cdot T_{ij}} \quad \text{Continuous functions of frequency}$$

$s = i\omega$, d_{ij} – values at ∞ , N_{ij} – number of poles,

$r_{ij,n}$ – residues, $p_{ij,n}$ – poles (real or complex), T_{ij} – optional delay

□ Pulse response is real and delay-causal

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

$$S_{i,j}(t) = d_{ij} \delta(t - T_{ij}) + \sum_{n=1}^{N_{ij}} \left[r_{ij,n} \cdot \exp(p_{ij,n} \cdot (t - T_{ij})) + r_{ij,n}^* \cdot \exp(p_{ij,n}^* \cdot (t - T_{ij})) \right], \quad t \geq T_{ij}$$

□ Stable $\text{Re}(p_{ij,n}) < 0$

□ Passive if $\text{eigenvals}[S(\omega) \cdot S^*(\omega)] \leq 1 \quad \forall \omega, \text{ from } 0 \text{ to } \infty$

□ Reciprocal if $S_{i,j}(\omega) = S_{j,i}(\omega)$

May require enforcement

What are RCMs for?

- ❑ Improve quality of tabulated Touchstone models
 - Fix minor passivity and causality violations
 - Interpolate and extrapolate with guaranteed passivity
- ❑ Produce broad-band SPICE models
 - Much smaller model size
 - No artifacts and guaranteed stability of SPICE simulation
 - Consistent frequency and time domain analyses
- ❑ Compute time-domain response of a channel with a fast recursive convolution algorithm (exact solution for PWL signals)

Global quality metrics (0-100%)

- Passivity Quality Measure: PQM or zero if PQM<0

$$PQM = \frac{100}{N_{total}} \left[N_{total} - \sum_{n=1}^{N_{total}} PW_n \right] \% \quad PW_n = 0 \text{ if } PM_n < 1.00001; \text{ otherwise } PW_n = \frac{PM_n - 1.00001}{0.1}$$

should be >98%

$$PM_n = \sqrt{\max \left[\text{eigenvals} \left(S^* (f_n) \cdot S (f_n) \right) \right]}$$

- Reciprocity Quality Measure: RQM or zero if RQM<0

$$RQM = \frac{100}{N_{total}} \left[N_{total} - \sum_{n=1}^{N_{total}} RW_n \right] \% \quad RW_n = 0 \text{ if } RM_n < 10^{-6}; \text{ otherwise } RW_n = \frac{RM_n - 10^{-6}}{0.1}$$

should be >98%

$$RM_n = \frac{1}{N_s} \sum_{i,j} |S_{i,j}(f_n) - S_{j,i}(f_n)|$$

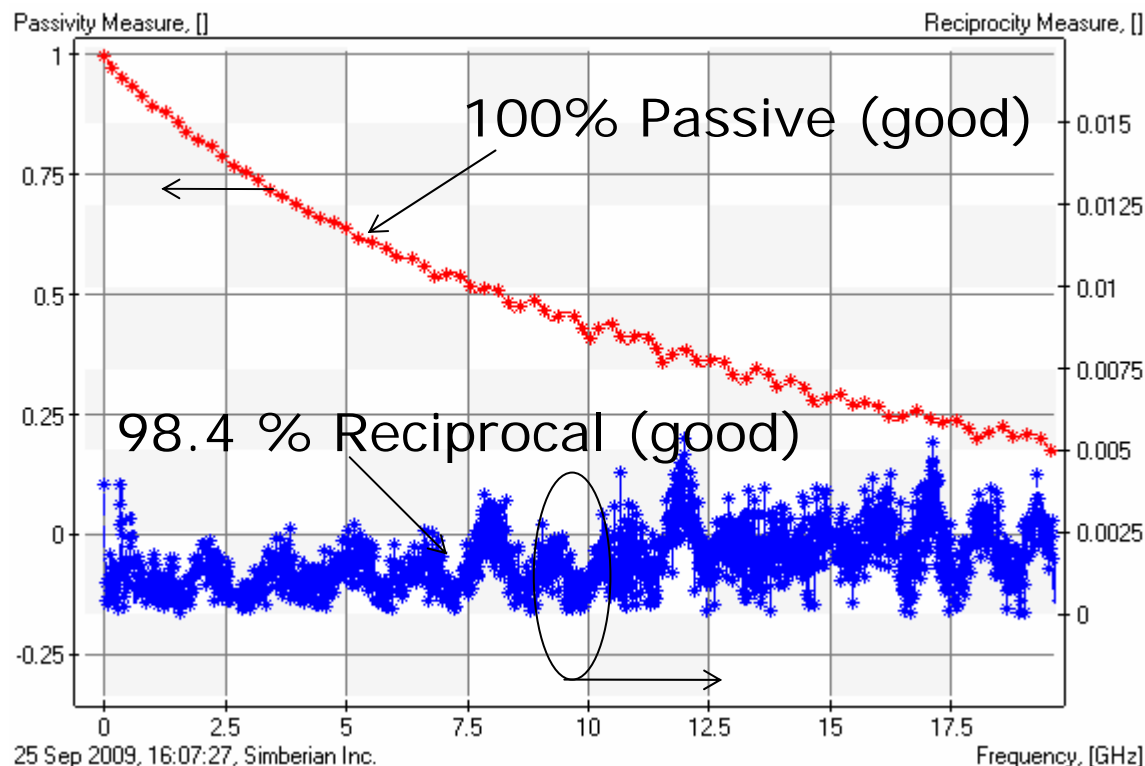
- Causality Quality Measure: Minimal ratio of clockwise rotation measure to total rotation measure in % (should be >80%)
- RMS error of the rational compact model can be also used to characterize the causality of the original data set

Example 1: High-quality model



Single controlled via
from PLRD-1 benchmark
board – SOLT calibration

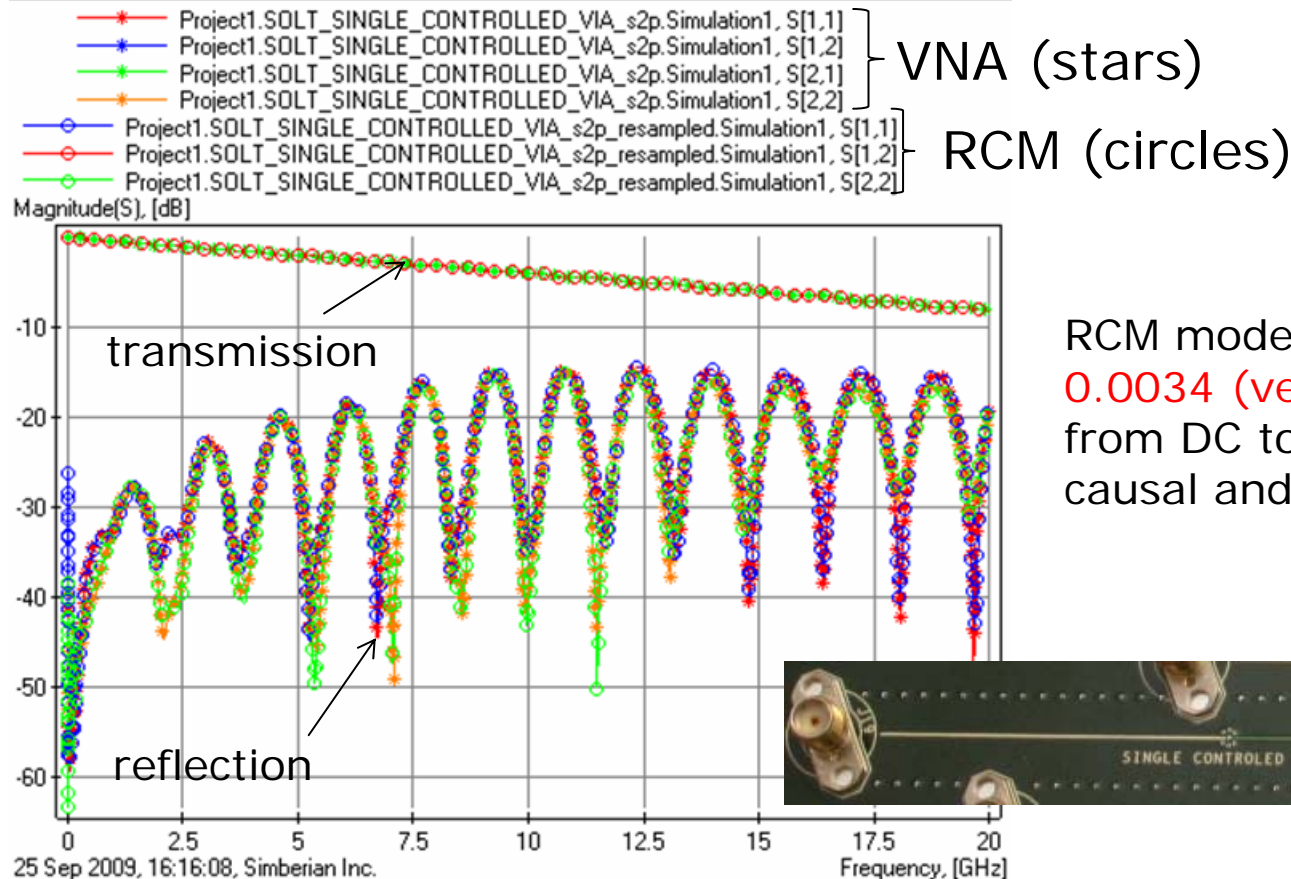
Project1.SOLT_SINGLE_CONTROLLED_VIA_s2p.Simulation1
MultiportParameters: S(Zo=50), Y, Z; ReciprocityQM=98.38%; SymmetryQM=72.05%; CausalityQM=9.5%



Causality problem,
but it can be
restored with RCM

*Data provided by Teraspeed
Consulting Group*

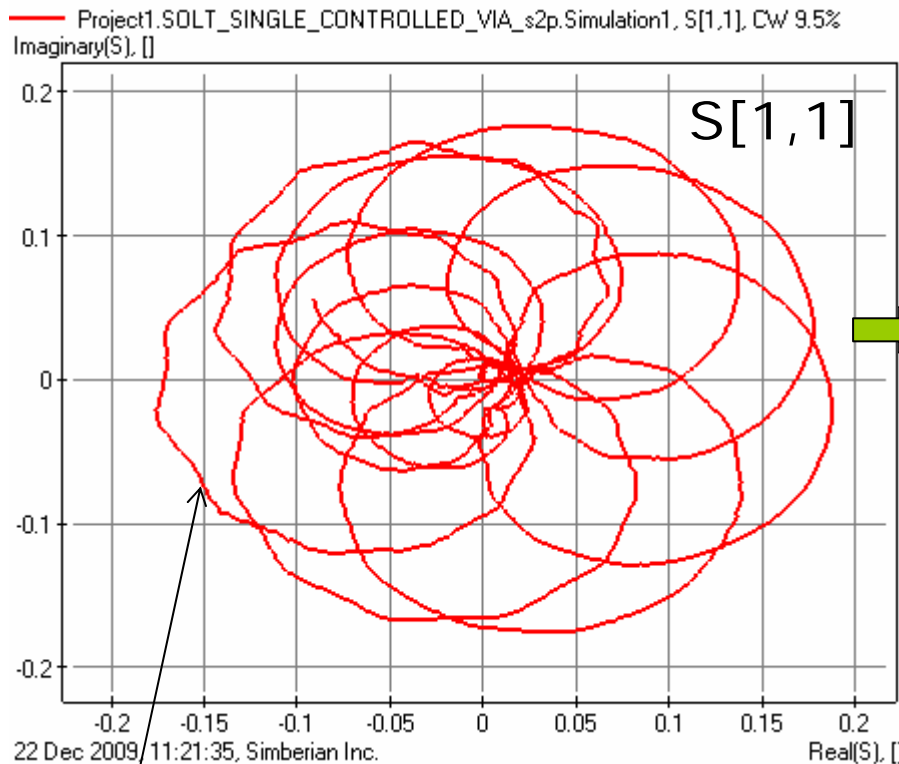
Single controlled via (SOLT): Improving S-parameters with RCM



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

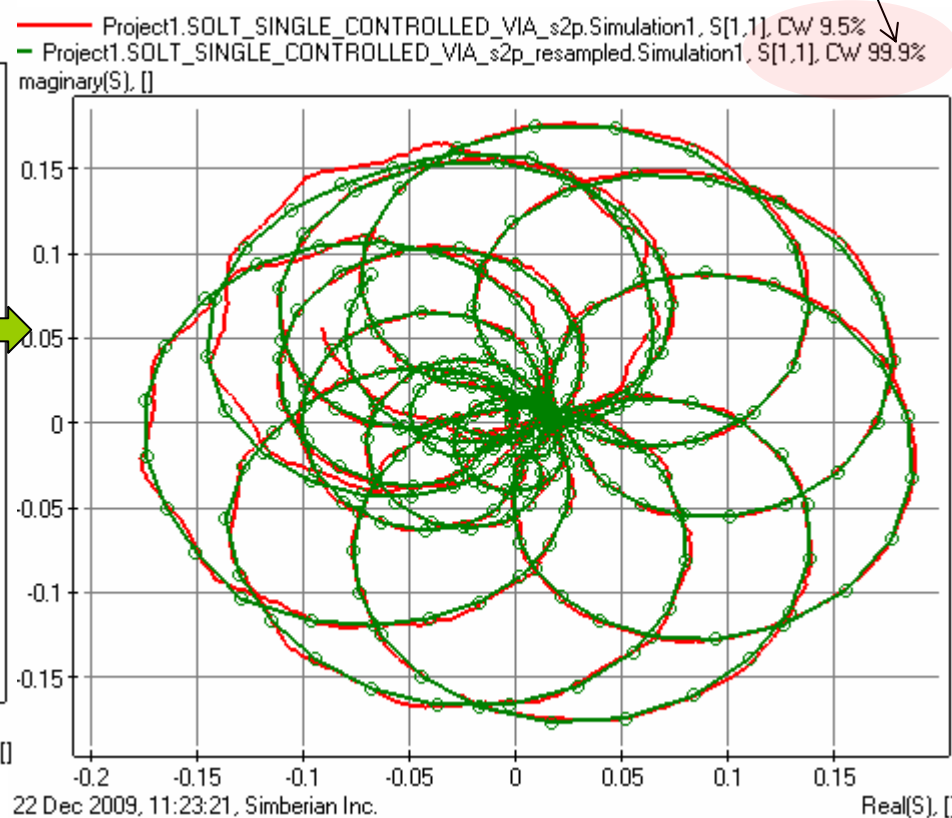
Single controlled via (SOLT): Original S[1,1] and RCM

VNA Measurement: 3201 points
starting from 300 KHz



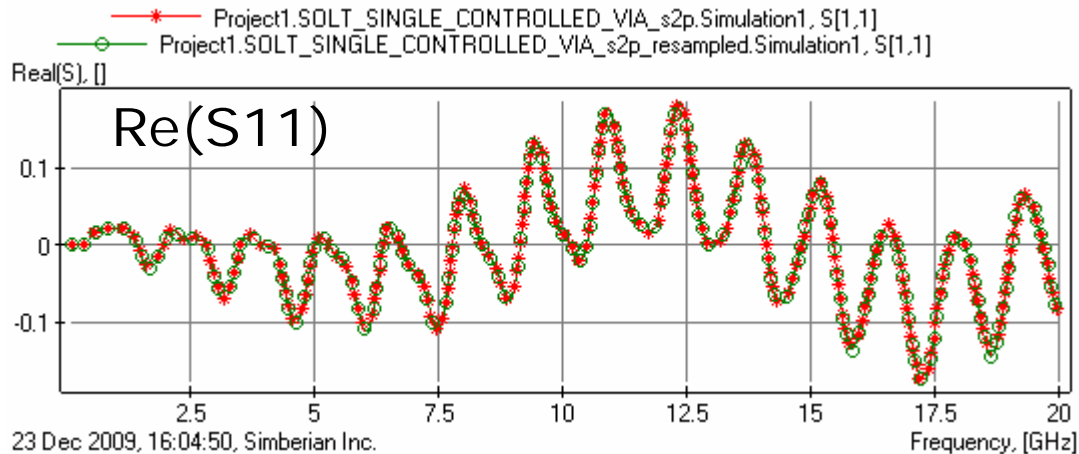
Visible noise and large segments
with counter-clockwise rotation

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



Red line – original VNA
Green line with circles - RCM

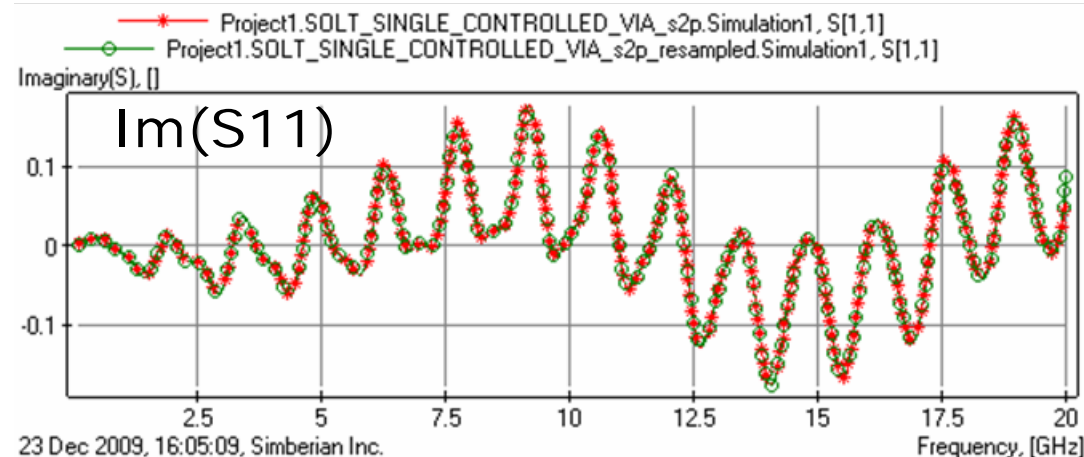
Single controlled via (SOLT): Original S[1,1] and RCM



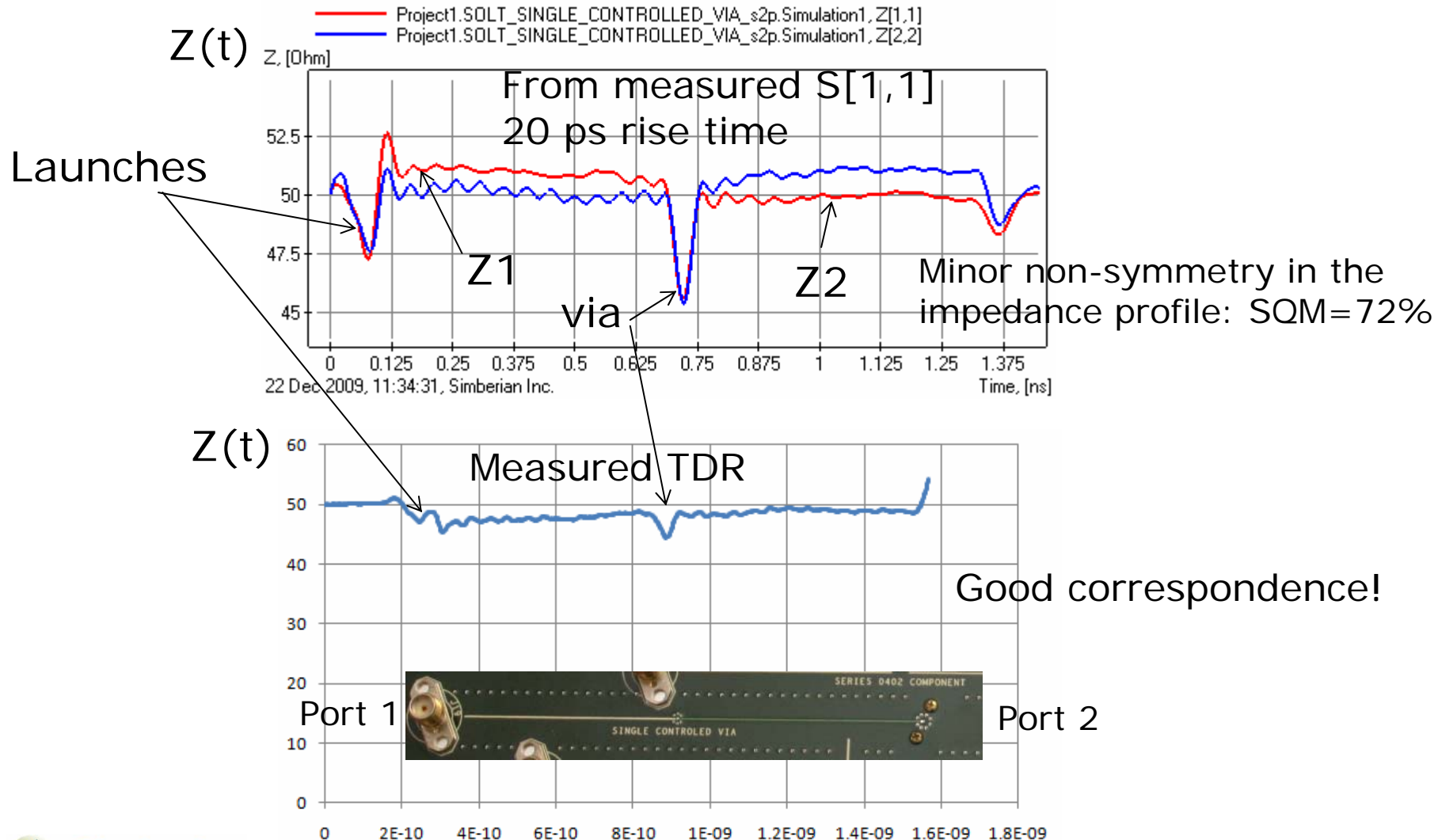
Stars – VNA data
Circles – RCM

RCM: 46 poles,
RMS Error 0.0034

Practically
indistinguishable!



Single controlled via TDR from RCM (SOLT)



Example 2: Model that needs improvement

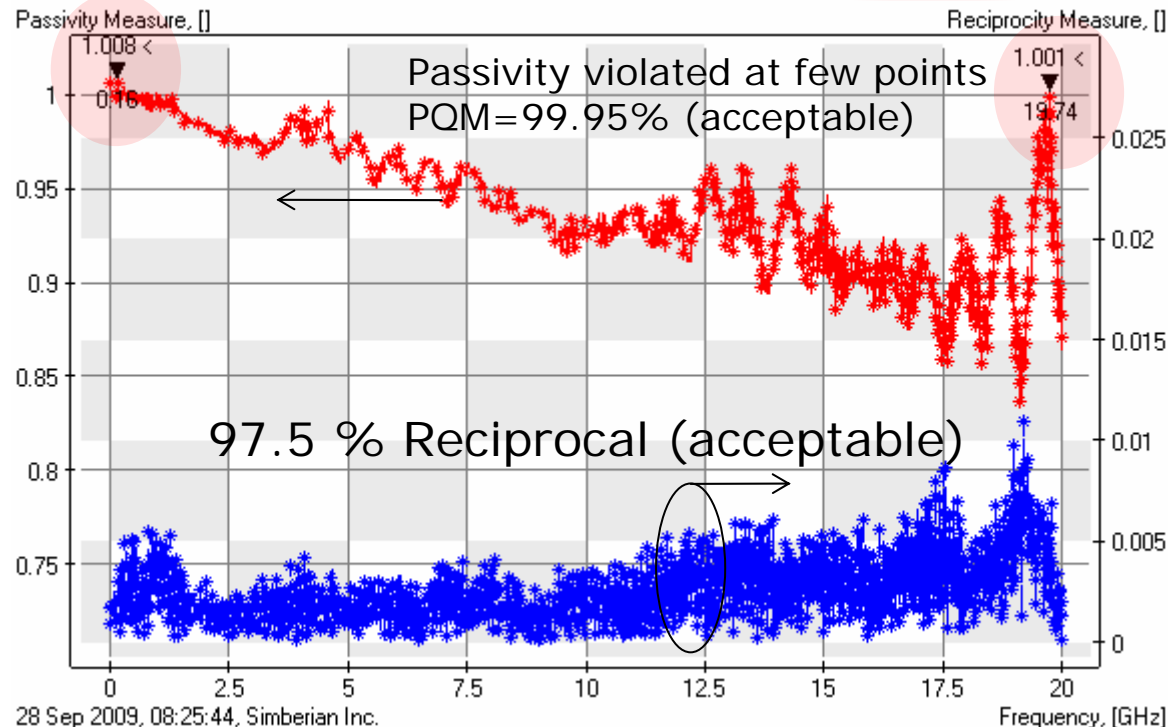
TRL Reference Planes (250 mil from via)



Single controlled via from PLRD-1 benchmark board – TRL calibration

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%



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

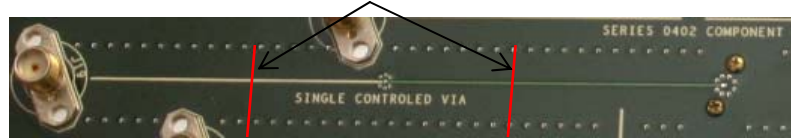
Passivity and reciprocity worsened comparing to SOLT, but still OK

Data provided by Teraspeed Consulting Group

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

TRL Reference Planes (250 mil from stubs)

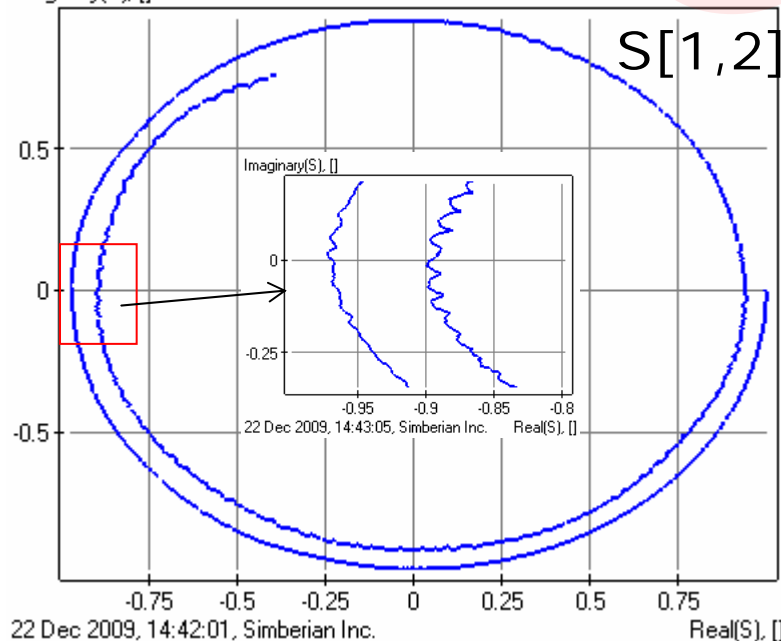
Port 1



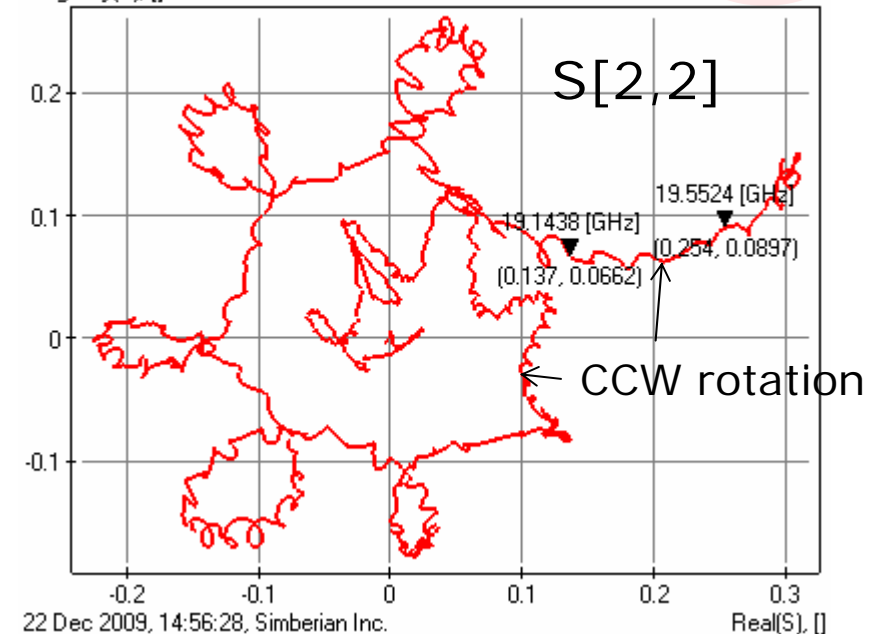
Port 2

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

Project1.TRL_SINGLE_CONTROLLED_VIA_s2p.Simulation1, S[1,2], CW 24.8%
Imaginary(S), []



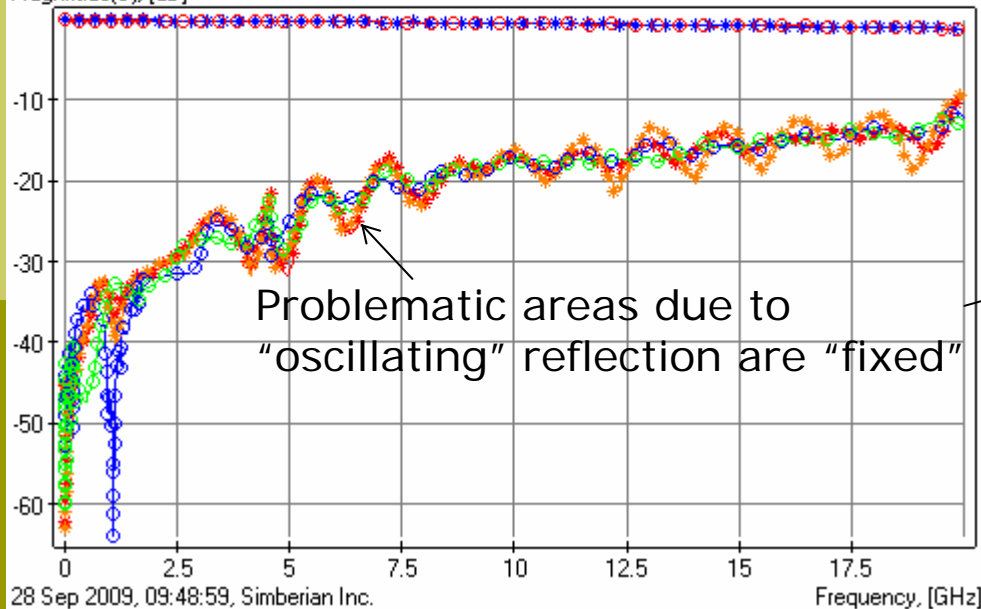
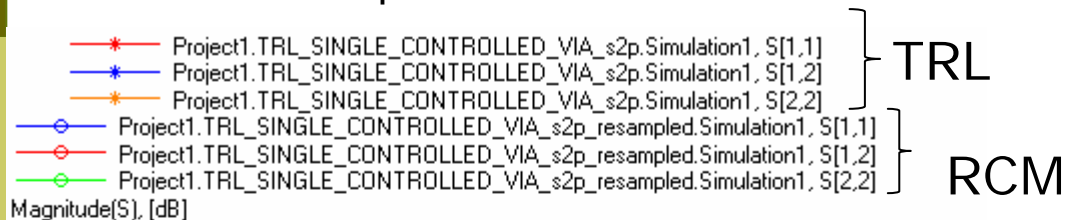
Project1.TRL_SINGLE_CONTROLLED_VIA_s2p.Simulation1, S[2,2], CW 46.4%
Imaginary(S), []



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

RCM **RMS Error is 0.045** (still OK)

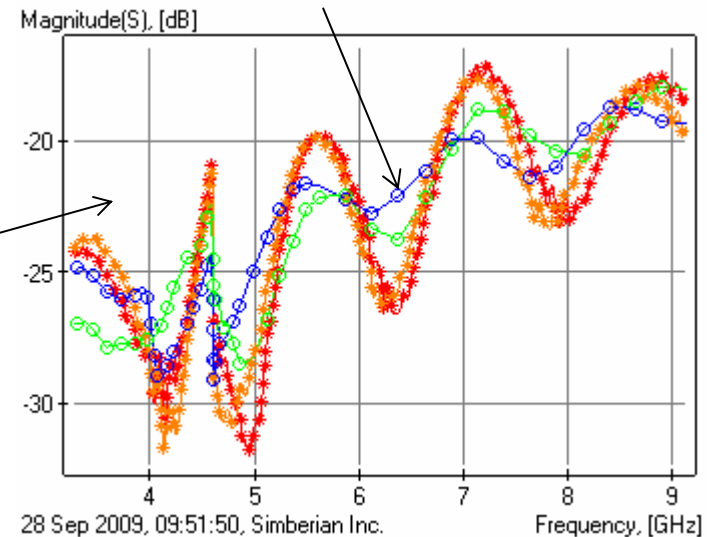
Passive from DC to infinity,
causal and reciprocal



28 Sep 2009, 09:48:59, Simberian Inc.

Transmission and
group delay is OK

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



28 Sep 2009, 09:51:50, Simberian Inc.

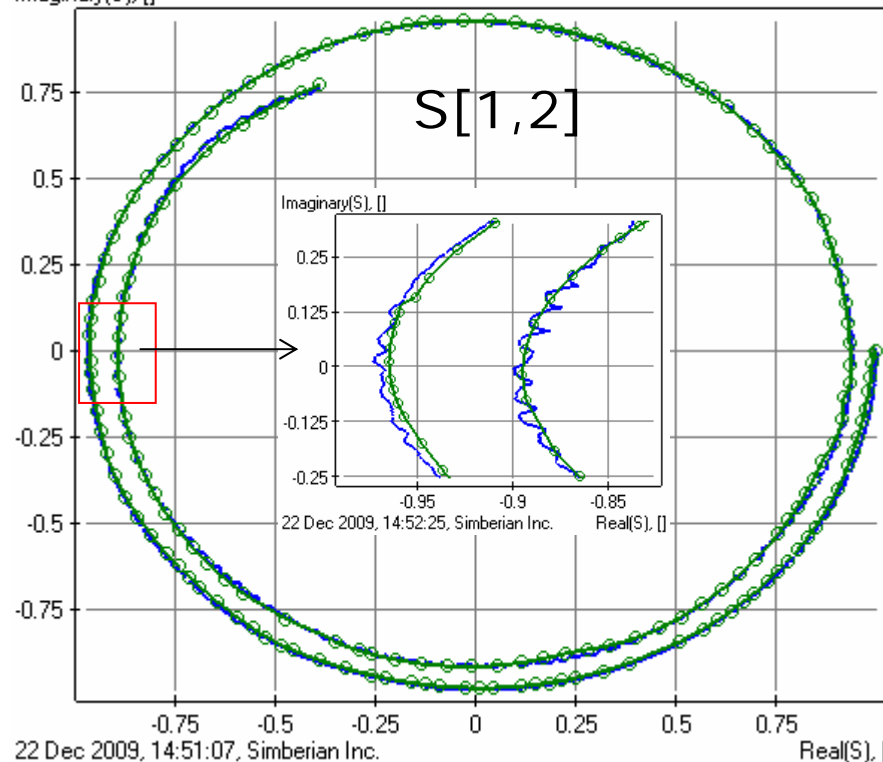
Single controlled via (TRL): Original S[1,2] and RCM

VNA Measurement: 3201 points
starting from 300 KHz

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

Project1.TRL_SINGLE_CONTROLLED_VIA_s2p.Simulation1, S[1,2], CW 24.8%
Project1.TRL_SINGLE_CONTROLLED_VIA_s2p_resampled.Simulation1, S[1,2], CW 95.9%
Imaginary(S), []

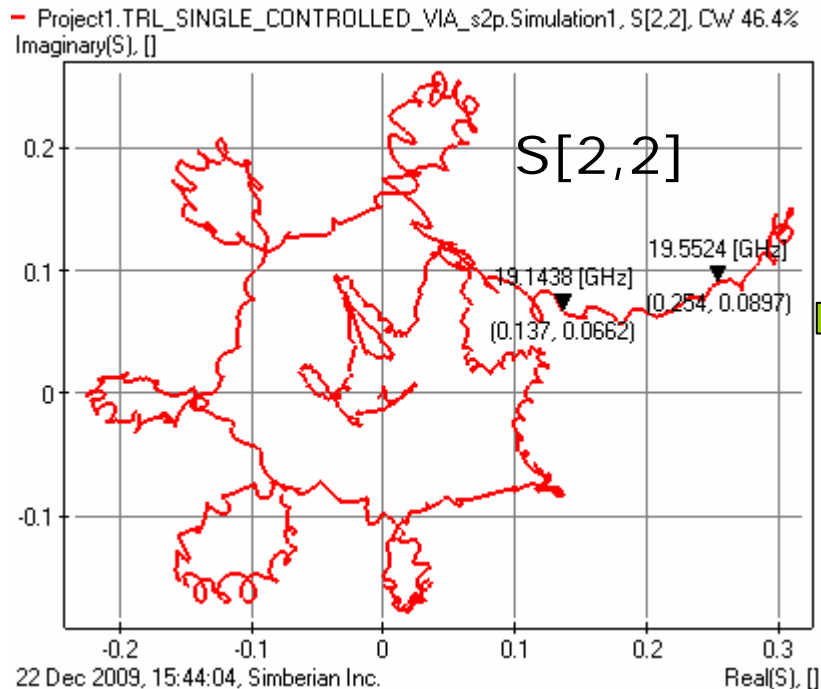
← CAUSAL!



Very noisy data is
corrected with RCM!

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

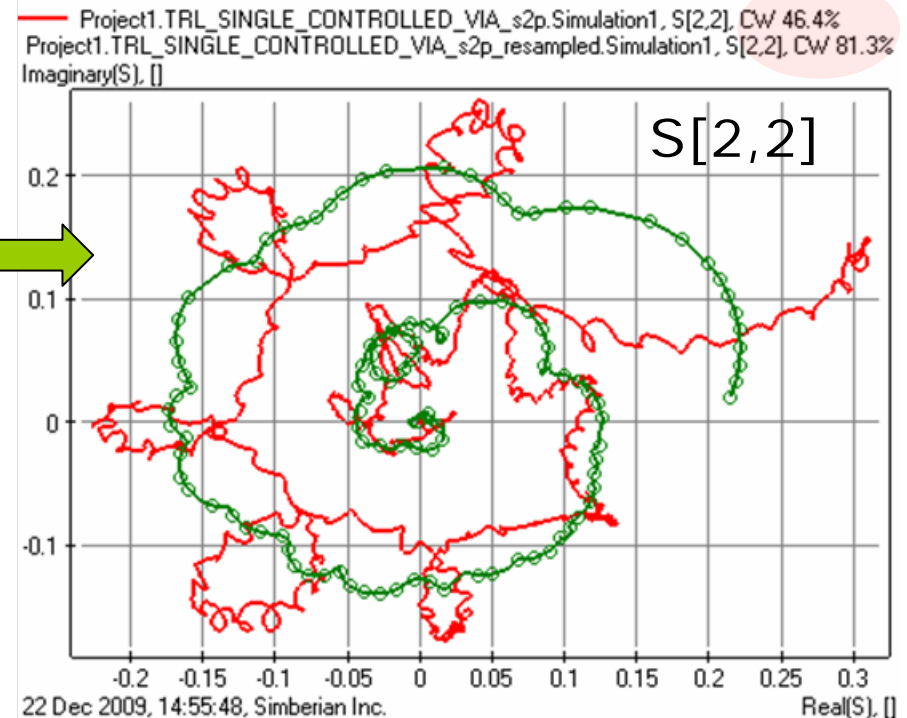
VNA Measurement: 3201 points
starting from 300 KHz



Very noisy non-causal data with
wrong rotation!

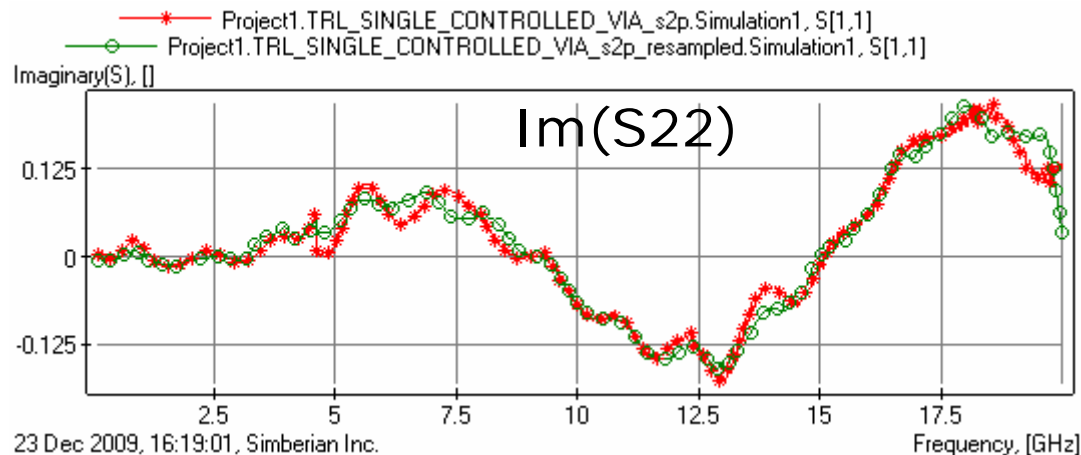
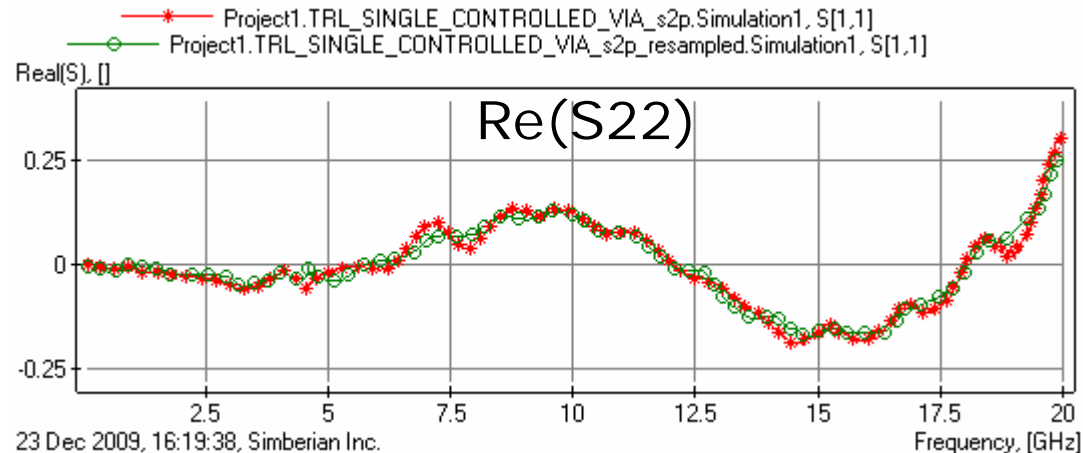
Re-sampled RCM: 633 points distributed
adaptively starting from 0 Hz

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

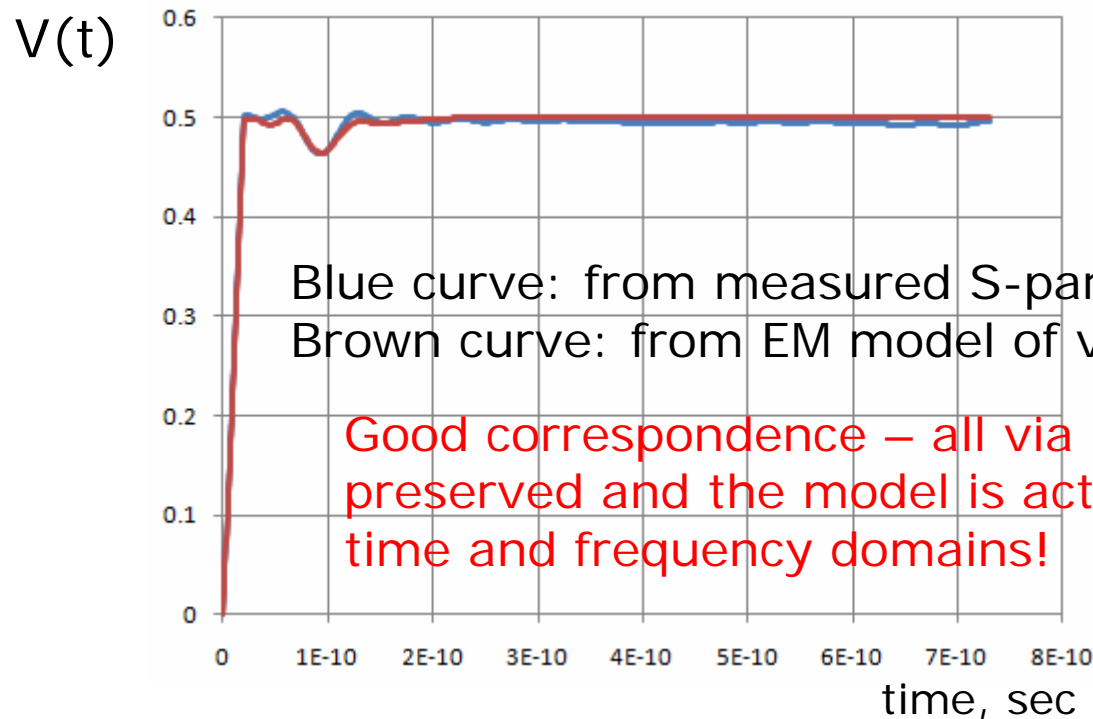
Problematic non-causal areas
are fitted as close as possible

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)



Conclusion

- ❑ Reciprocity, passivity and causality of interconnect component models must be verified before use
 - Measured models may be not acceptable for the analysis
 - Electromagnetic models may have severe problems too
- ❑ Quality metrics allow distinguishing minor “fixable” violations with acceptable accuracy degradation from severe violations
- ❑ Rational macro-models with controllable accuracy can be used to “improve” tabulated models and to correct minor violations of passivity and causality
- ❑ **Standardization of the quality metrics and exchange formats for rational compact models are needed**

Contact and resources

- ❑ Yuriy Shlepnev, Simberian Inc.
shlepnev@simberian.com
Cell: 206-409-2368
- ❑ Free version of Simbeor 2008.L0 used to plot and estimate quality of S-parameters is available at www.simberian.com
- ❑ To learn on quality metrics further see slides from DesignCon2010 tutorial (also available on request)
 - TF-MP12 H. Barnes, Y. Shlepnev, J. Nadolny, T. Dagostino, S. McMorro, Quality of High Frequency Measurements: Practical Examples, Theoretical Foundations, and Successful Techniques that Work Past the 40GHz Realm