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Qualification of tabulated scattering parameters

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Why S-parameters

- S-parameters are always defined
  - Impedance or admittance may not
- S-parameters are normalized
  - Good numerical properties in simulation
- S-parameters are easily measured
  - Even at very high frequency, good reliability
- Standard format for S-parameters
  - Touchstone files from measurement hardware
  - All field solvers provide S-parameters on output
- Tabulated frequency data
  - Intrinsic IP protection for vendors
  - Do not disclose design details, but only I/O electrical properties
- Best way to represent broadband EM/circuit interactions
  - The essence of Signal and Power Integrity
- Is this characterization complete?
  - Yes, but…

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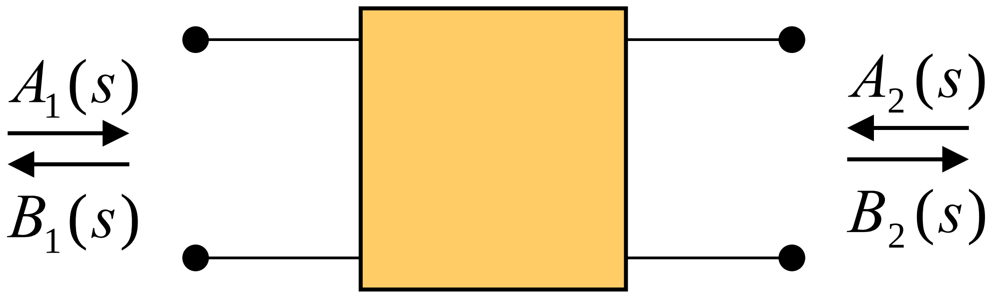
Scattering network functions

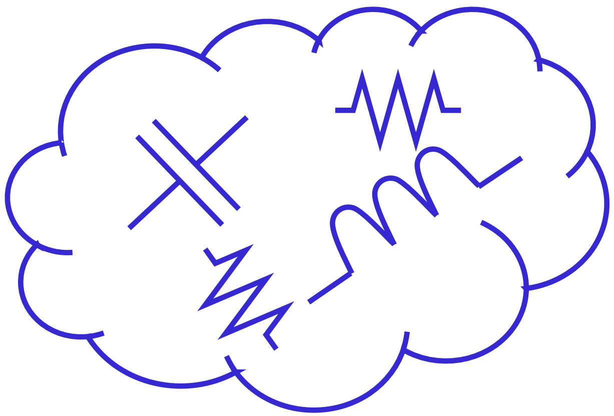


power waves

complex frequency

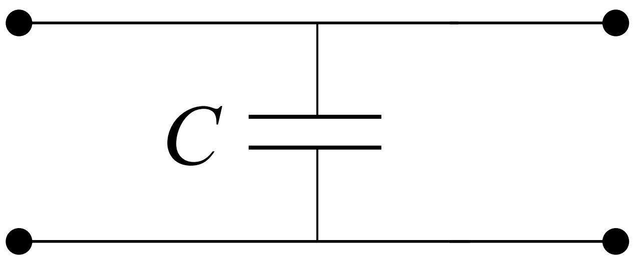
$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11}(s) & S_{12}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix}}_{\text{Scattering matrix}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

For circuits: real rational functions



$$S_{ij}(s) = \frac{a_0 + a_1 s + \cdots + a_n s^n}{b_0 + b_1 s + \cdots + b_n s^n}$$

- For lumped circuits: S-parameters are real rational functions
  - Valid for all complex frequencies in the entire complex plane



$$\mathbf{S}(s) = \begin{bmatrix} \dfrac{-sCR_0}{2+sCR_0} & \dfrac{2}{2+sCR_0} \\ \dfrac{2}{2+sCR_0} & \dfrac{-sCR_0}{2+sCR_0} \end{bmatrix}$$

R_0 = reference resistance

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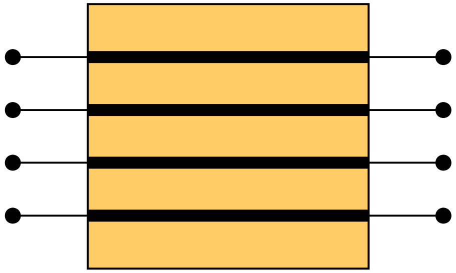
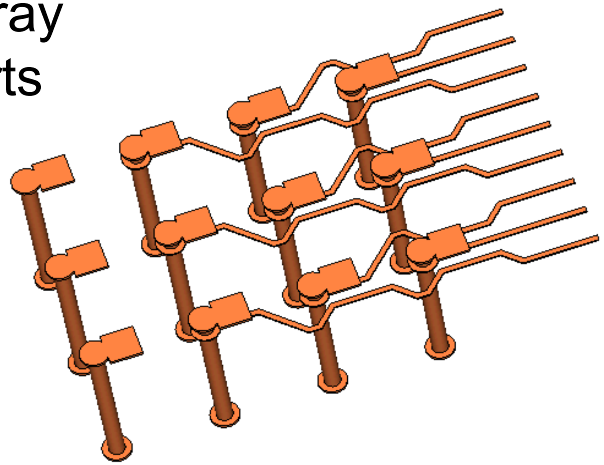
Examples of S-parameter data

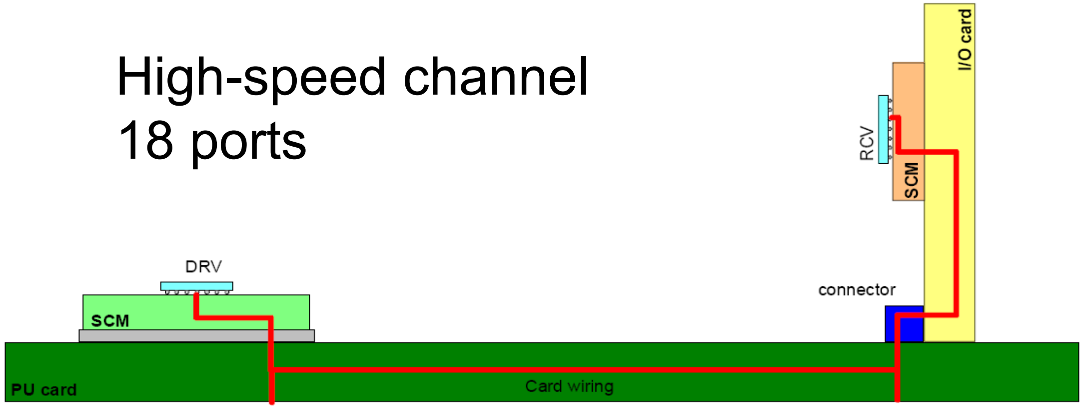


Via array
12 ports



Wiring harness
8 ports

High-speed channel
18 ports



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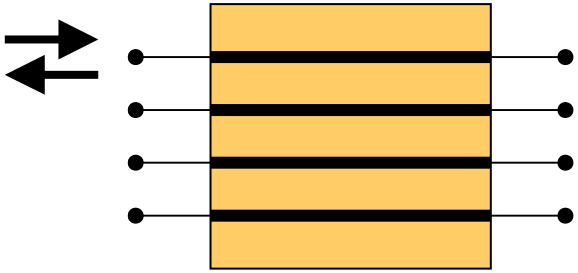

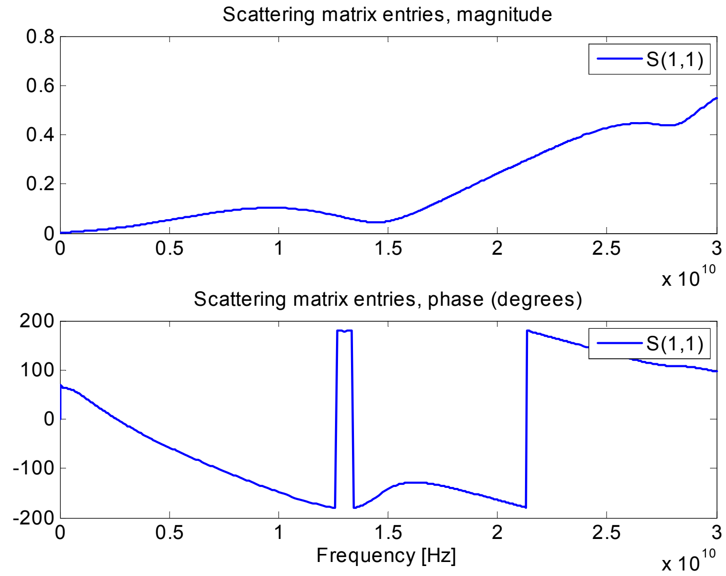

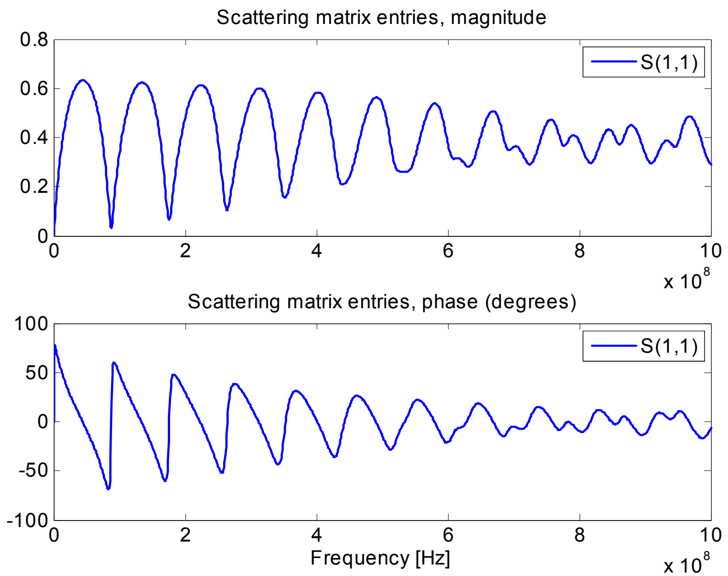

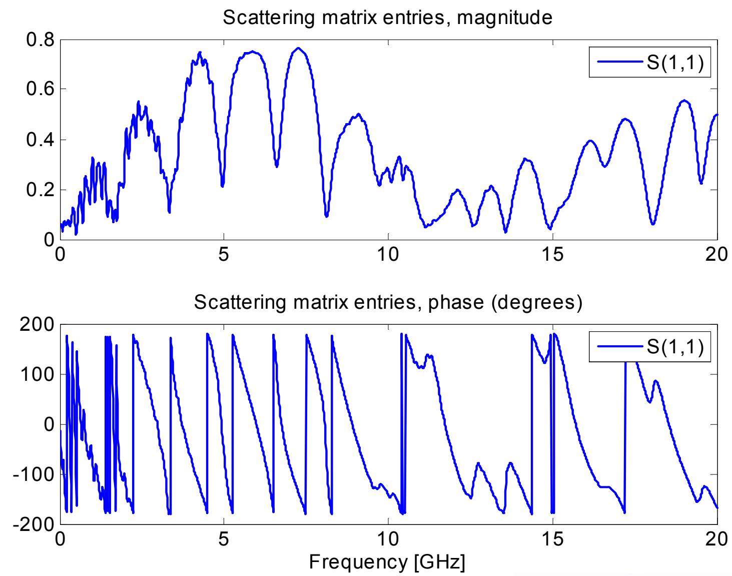

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From frequency to time-domain: impulse response

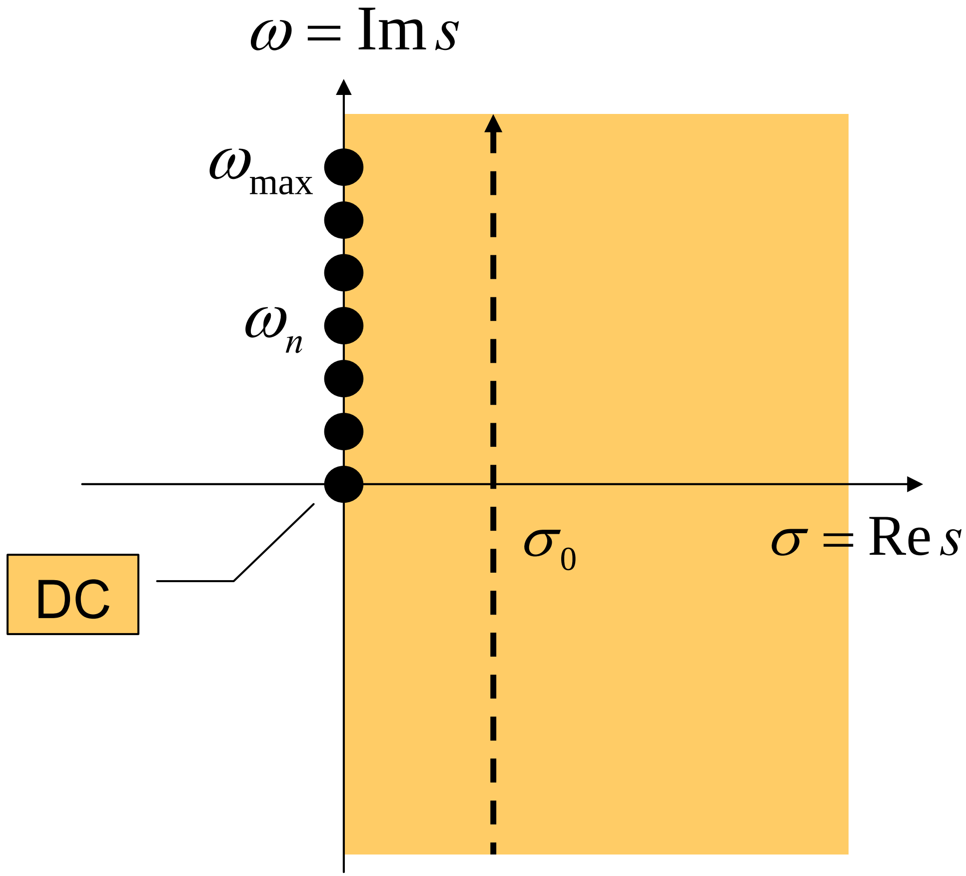
Inverse Fourier transform

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(j\omega) e^{j\omega t} d\omega$$

$$s \leftrightarrow j\omega$$

Inverse Laplace transform

$$h(t) = \frac{1}{2\pi j} \int_{\sigma_0 - j\infty}^{\sigma_0 + j\infty} S(s) e^{st} ds$$



Complex s-plane

Finding impulse responses

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(j\omega) e^{j\omega t} d\omega$$

Strategy 1:
Discrete Fourier Transform
(Fast Fourier Transform, FFT)

$$\omega_m = j \frac{2\pi m}{N\Delta}$$

$$h(k\Delta) = \frac{1}{M} \sum_{m=0}^{M-1} S(j\omega_m) \exp\left(j \frac{2\pi mk}{M} \right)$$

Strategy 2:
Fit a parametric model allowing analytic Fourier/Laplace inversion

$$S(j\omega) \approx \sum_{n=1}^{N} \frac{R_n}{j\omega - p_n} + S_\infty$$

$$h(t) \approx \sum_{n=1}^{N} R_n \exp(p_n t) u(t) + S_\infty \delta(t)$$

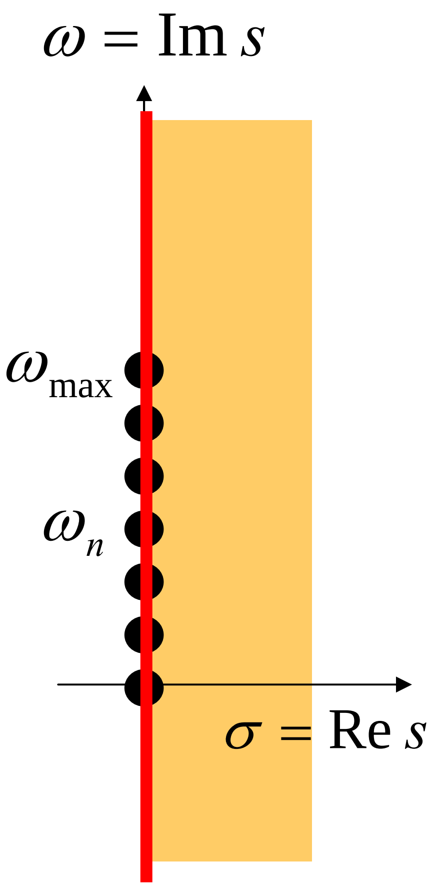
Qualification process

- The limited information in the Touchstone file must…
  - …describe the electrical behavior of the structure of interest
  - …have enough resolution: sampling
  - …cover a sufficient bandwidth
  - …fulfill fundamental passivity requirements
    - causality
    - energy gain, passivity
- Need a qualification methodology…
  - …based on rigorous theoretical foundation
  - …allowing robust numerical implementation
  - …checking all above conditions

Passivity conditions

$$\mathbf{S}(-j\omega) = \mathbf{S}^*(j\omega)$$

Guarantees real-valued impulse response.
Always assumed by construction



$$\|\mathbf{S}(j\omega)\| \le 1 \quad \text{or} \quad \max_i \sigma_i\{\mathbf{S}(j\omega)\} \le 1$$

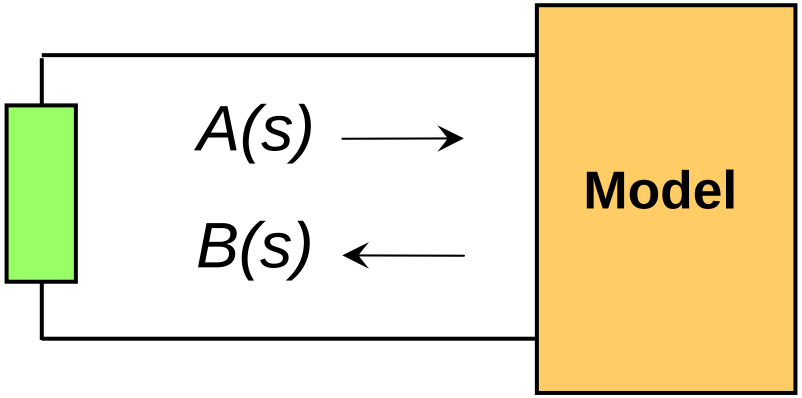
Energy condition: structure must not amplify signals.
Sometimes called simply “passivity” condition

$\mathbf{S}(j\omega)$ is causal

No anticipatory behavior in time-domain.
Note: causality is a prerequisite for passivity!

Passivity: a ping-pong match

Model: $B = S*A$
Load: $A = P*B$



One-port case

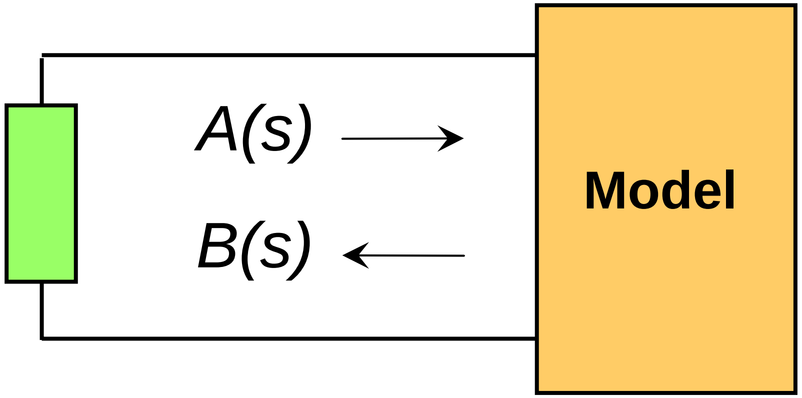
The poor man's illustration of passivity: iterate through signal reflections…

- Start with B=0 and A_0=1
- Model hits signal: $B_0 = S*A_0$
- Load hits signal: $A_1 = P*B_0 = (P*S)*A_0$
- Model hits signal: $B_1 = S*A_1 = S*P*S*A_0$
- Load hits signal: $A_2 = P*B_1 = (P*S)^2*A_0$
- …
- And the winner is… $A_N = (P*S)^N*A_0$

$$A = \sum_{N=0}^{\infty} A_N$$

Passivity: a ping-pong match

Model: $B = S^*A$
Load: $A = P^*B$



One-port case

$$A_N = (PS)^N A_0$$

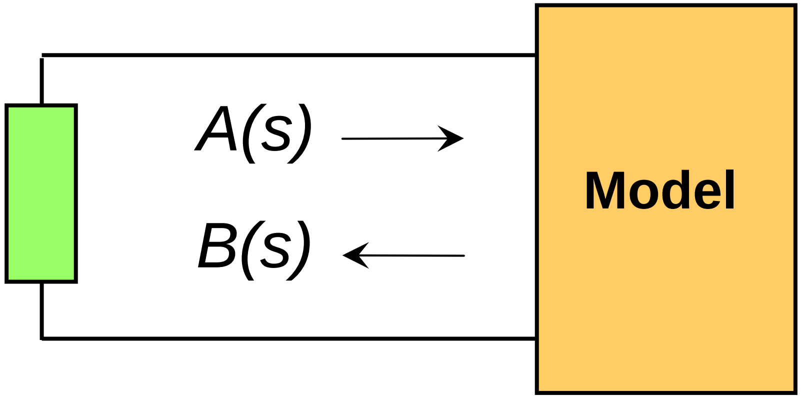
$$|P| < 1, |S| < 1 \quad \Rightarrow \quad A^N \text{ remains bounded}$$

$$|P| = 1, |S| > 1 \quad \Rightarrow \quad A^N \xrightarrow{N \to \infty} \infty \qquad \text{Blow-up!}$$

P is a reflection coefficient: for a passive load it does not exceed 1

Passivity: a ping-pong match

Model: $B = S*A$
Load: $A = P*B$

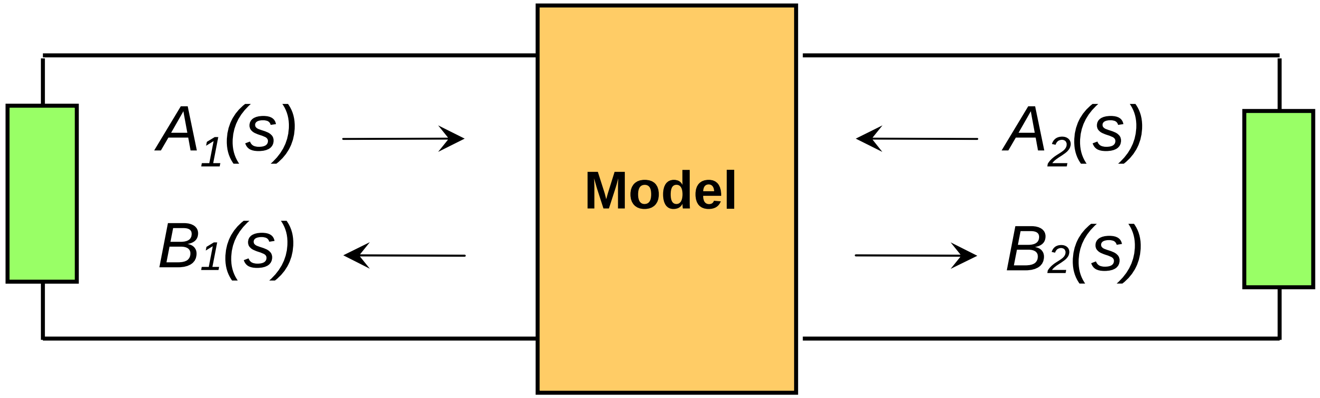


One-port case

Passivity requires that $$|S(j\omega)| \leq 1$$ for all frequencies!

(not just the modeling bandwidth… all means really all, from 0 to Inf)

Passivity: what?

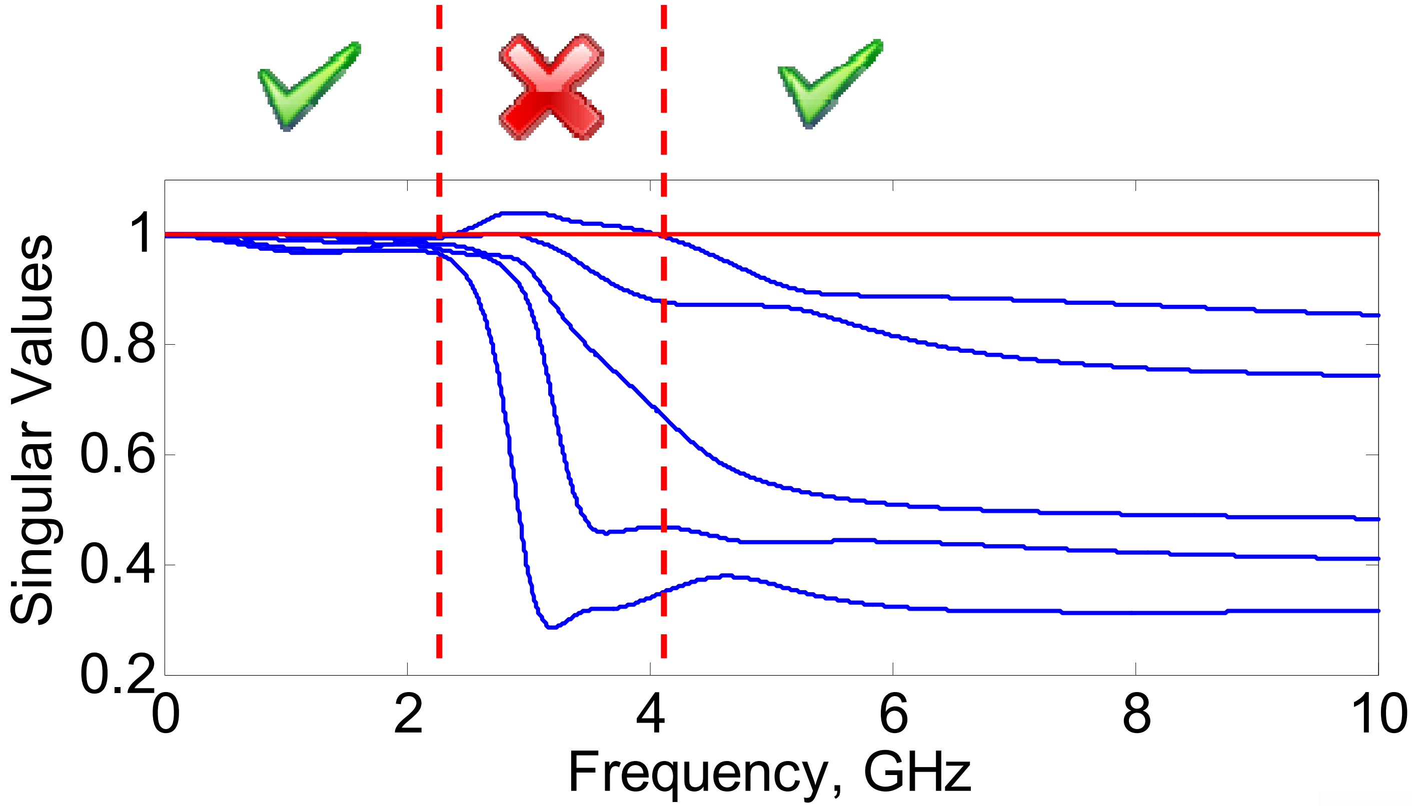


In case of matrices, math is more complicated…

… but visualization is simple and straightforward

Passivity: what?

$$\mathbf{S}(s) \text{ is passive} \Rightarrow \{\text{singular values of } \mathbf{S}(j\omega)\} \le \mathbf{1}, \forall \omega$$



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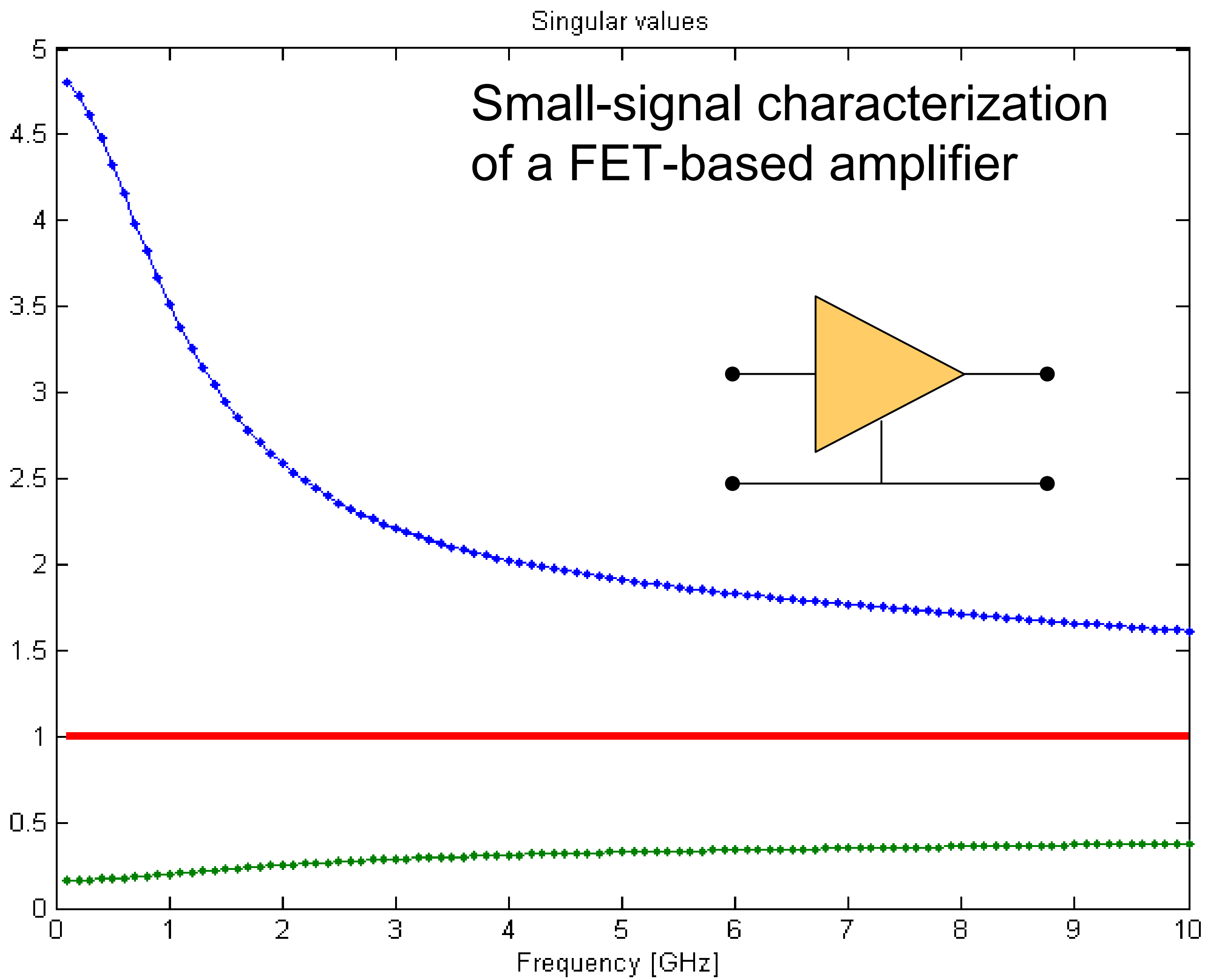
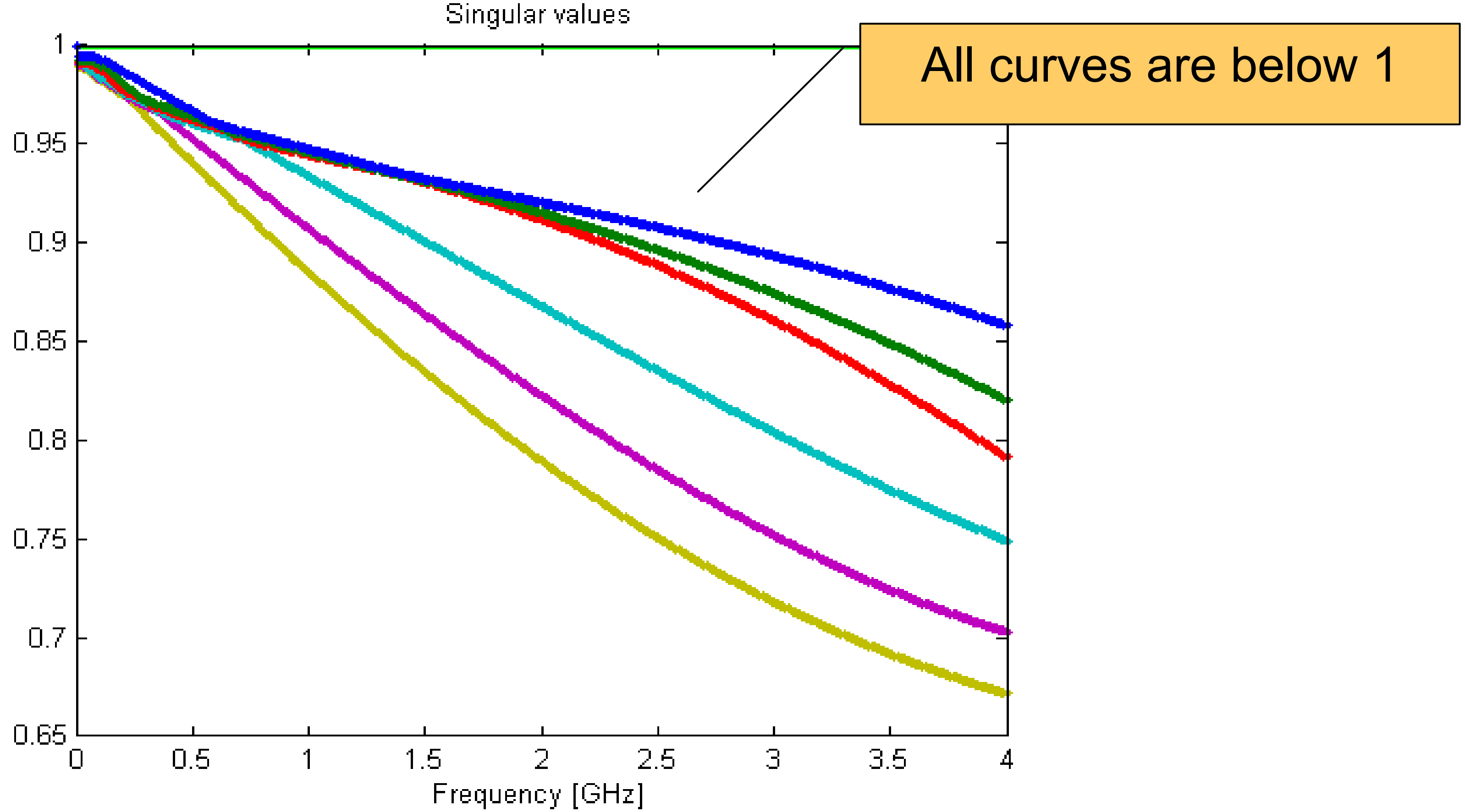
Not all S-parameter models should be passive



A passive interconnect model



Where do passivity violations come from?

- Data from measurement
  - Improper calibration and de-embedding
  - Human mistakes
  - Measurement noise
- Data from simulation
  - Poor meshing
  - Inaccurate solver
  - Bad models or assumptions on material properties
  - Poor data post-processing algorithms
  - Human mistakes
  - Putting together results from two solvers

Non-passive data: so what?

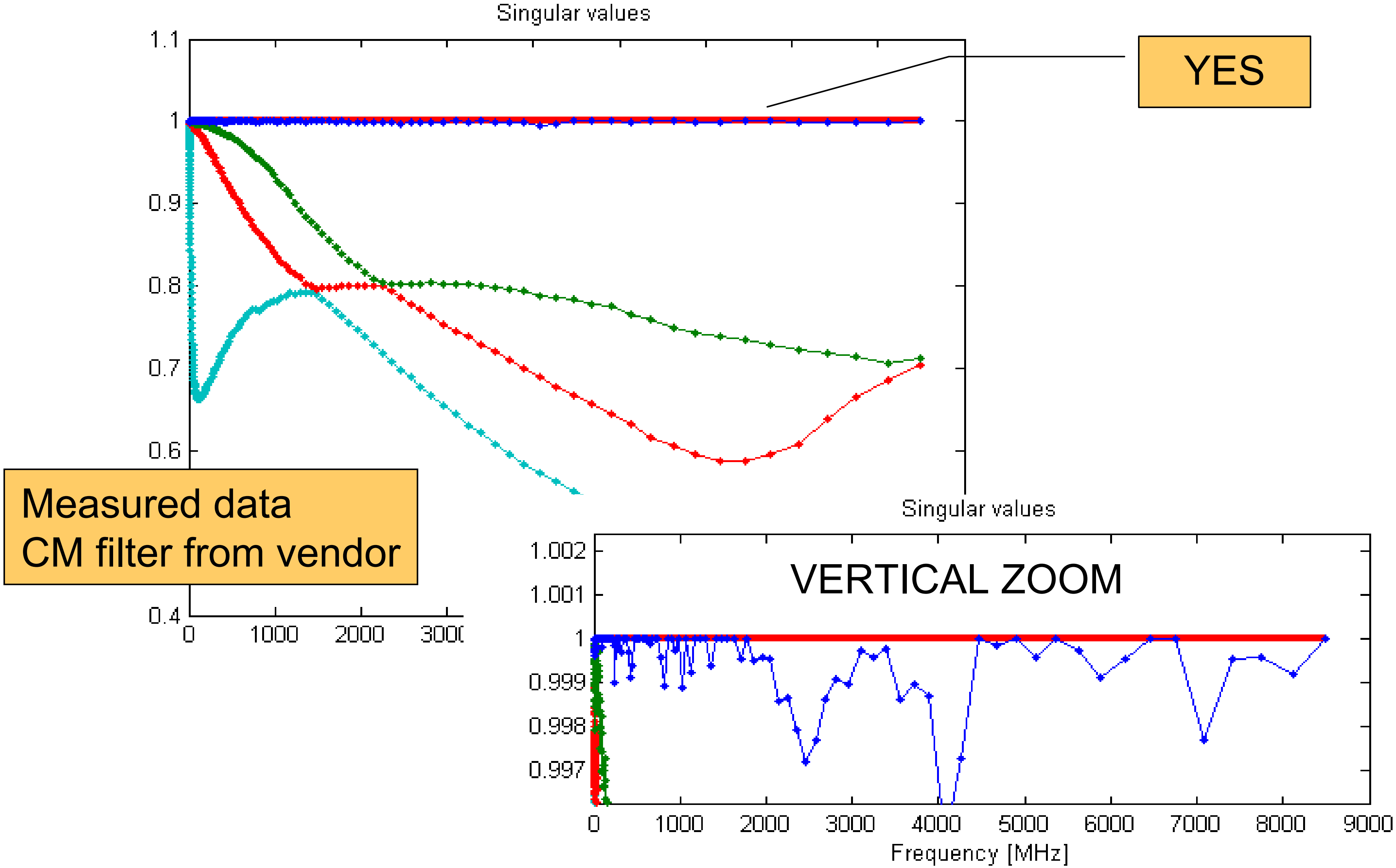
Non-passive data $\xrightarrow[\text{Accurate}]{\text{Fitting}}$ Non-passive model

Model may blow-up during transient analysis

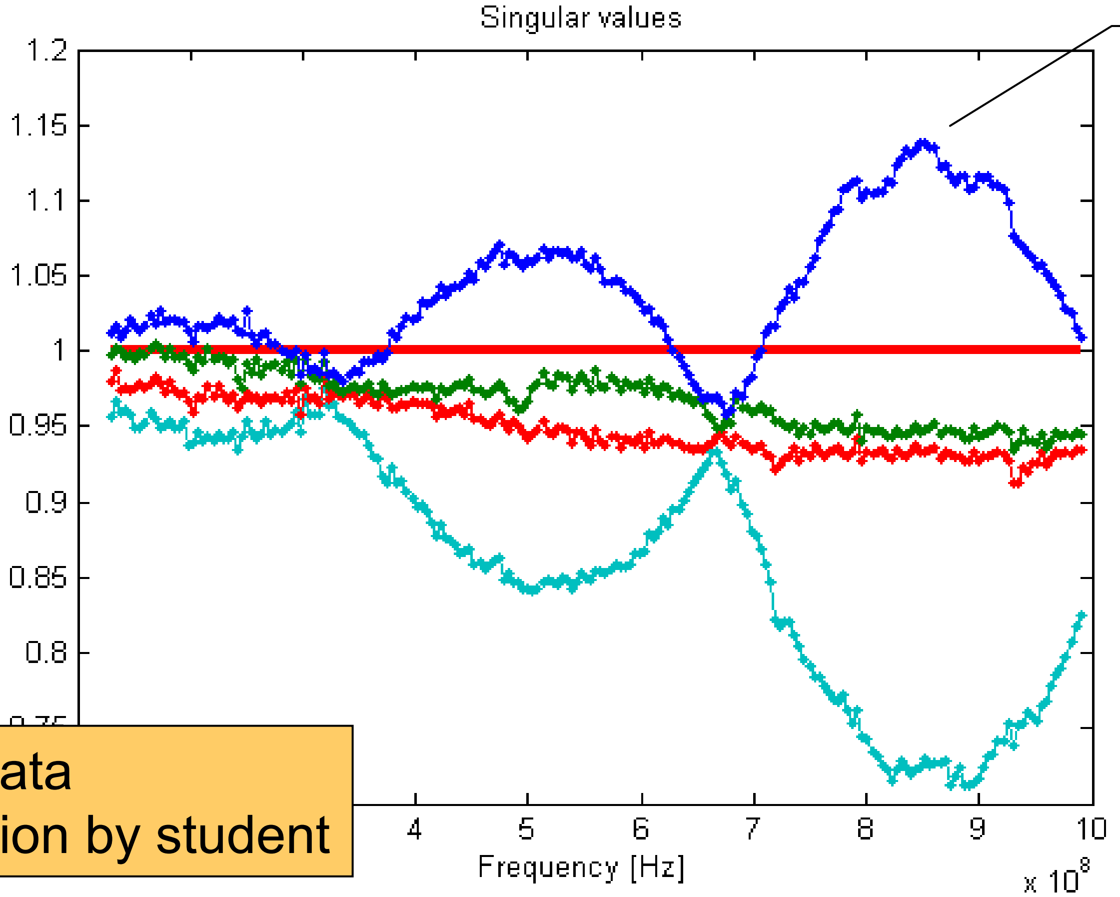
Non-passive data $\xrightarrow[\text{Passivity enforcement}]{\text{Fitting}}$ Passive model

Acceptable if passivity violations are “small”

Can we tolerate a passivity violation?



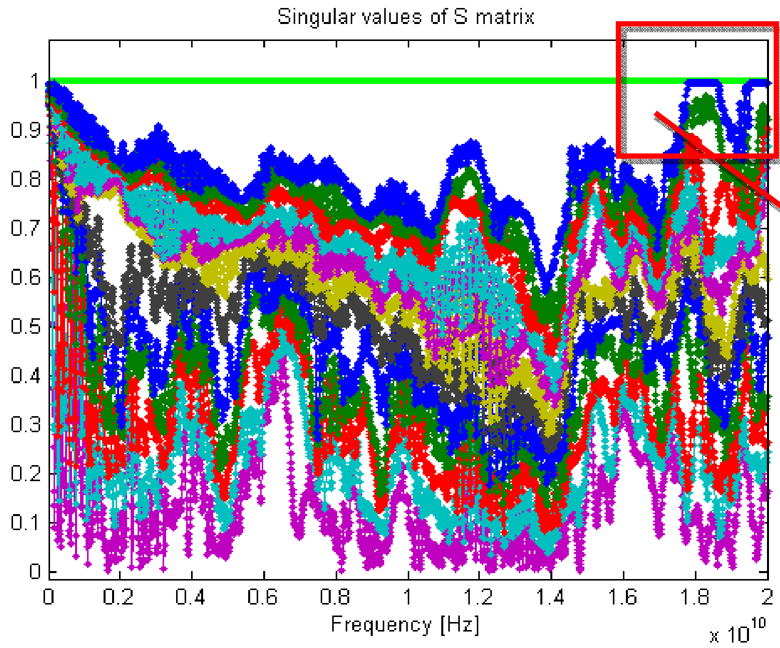
Can we tolerate a passivity violation?



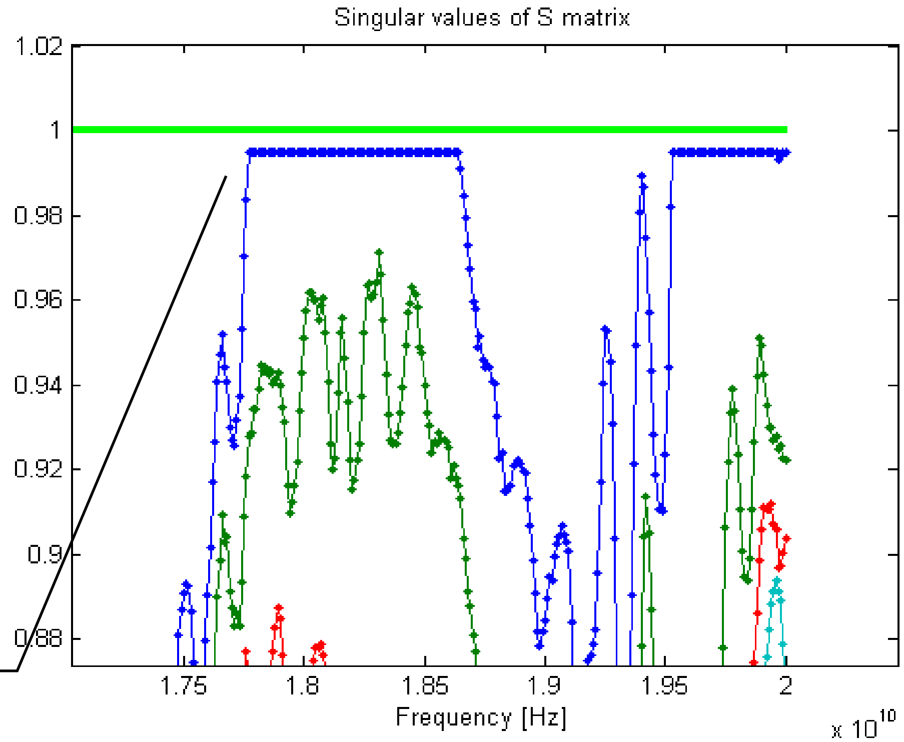
NO

Measured data
Bad calibration by student

Can we fix passivity violations?



Test case: measured cable



Although the responses present no energy gain, an artificial clipping is evident at high frequencies.

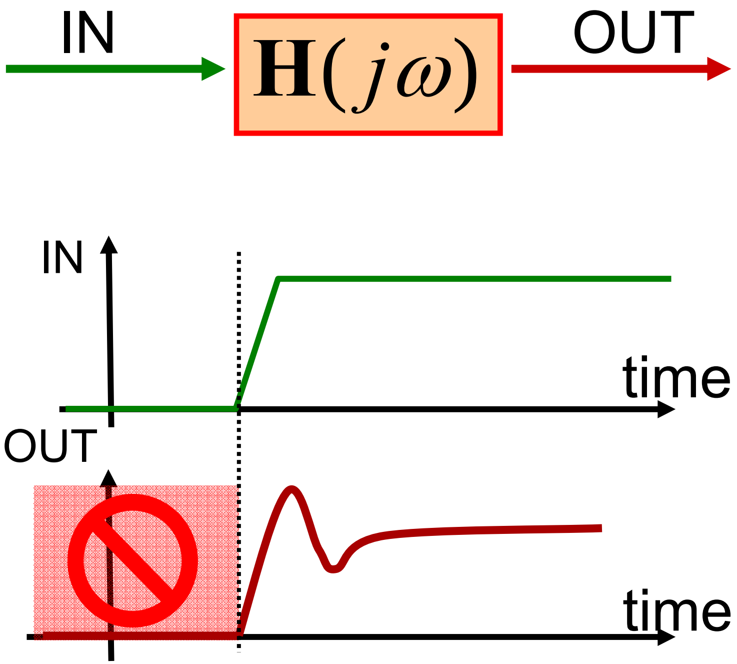
Is this clipping ok?

Causality qualification

Much more tricky…

Causality: definitions

Time-domain



Note: no delay extraction here

Frequency-domain

Hilbert transform

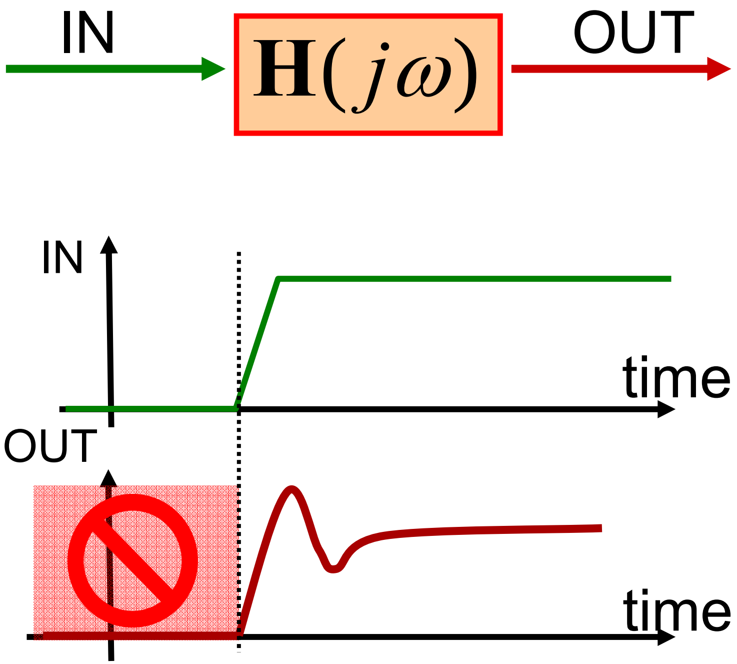
Kramers-Krönig dispersion relations

$$\begin{cases} U(\omega) = \dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} V(\omega')\dfrac{d\omega'}{\omega-\omega'} \\ V(\omega) = -\dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} U(\omega')\dfrac{d\omega'}{\omega-\omega'} \end{cases}$$

$$H(j\omega) = U(\omega) + jV(\omega)$$

Causality: definitions

Time-domain



Note: no delay extraction here

Frequency-domain

Hilbert transform

Kramers-Krönig dispersion relations

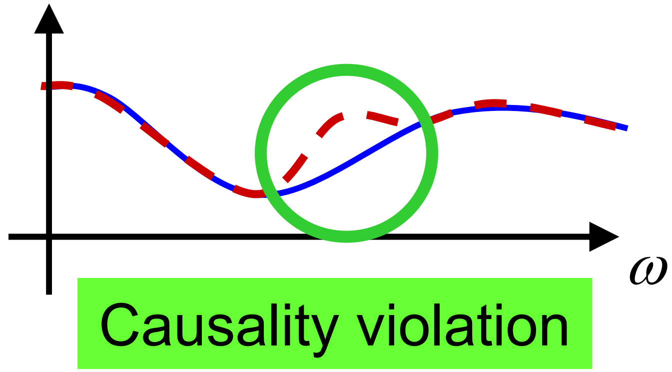
$$H(j\omega) = \frac{1}{j\pi} \mathrm{pv} \int_{-\infty}^{+\infty} H(j\omega') \frac{d\omega'}{\omega - \omega'}$$

Self-consistency

All samples are strongly related

Causality check via dispersion relations

$$\underbrace{\Delta(j\omega)}_{\text{reconstruction error}} = \underbrace{H(j\omega)}_{\text{true}} - \underbrace{\frac{1}{j\pi}\,\mathrm{pv}\int_{-\infty}^{+\infty} H(j\omega')\frac{d\omega'}{\omega-\omega'}}_{\text{reconstruction}} \neq 0$$



- But in practice reconstruction is difficult because data are:

  1. known only up to a maximum frequency Ω $\quad \int_{-\infty}^{+\infty} \rightarrow \boxed{\int_{-\Omega}^{+\Omega}}$ TRUNCATION ERROR

  2. tabulated $\quad \int \rightarrow \boxed{\sum}$ DISCRETIZATION ERROR

- Errors may hide causality violations... or point out bogus ones!
- Identification of causality violations must account for these errors.

Causality check (ideal)

$$\mathbf{H}(j\omega) \longrightarrow \boxed{\text{Hilbert transform}} \longrightarrow \mathbf{H}_{\mathrm{REC}}(j\omega)$$

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Causality check (ideal)

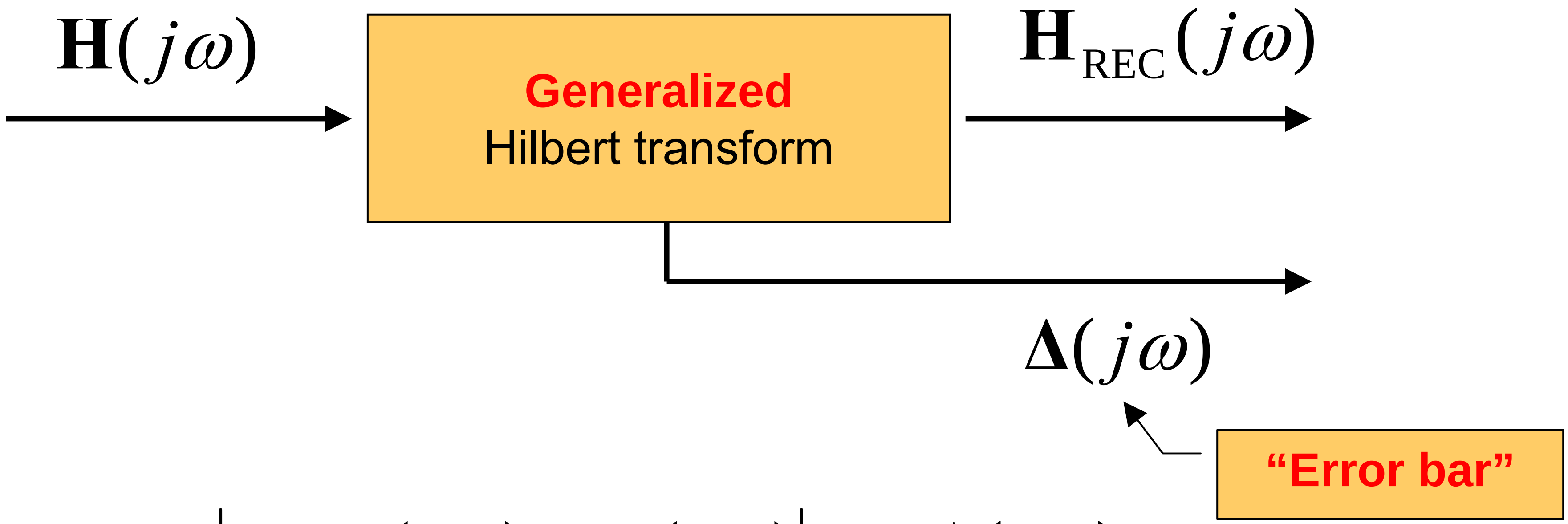
$$\mathbf{H}(j\omega) \longrightarrow \boxed{\text{Hilbert transform}} \longrightarrow \mathbf{H}_{\mathrm{REC}}(j\omega)$$

Never verified numerically!

Causal $\mathbf{H}_{\mathrm{REC}}(j\omega) = \mathbf{H}(j\omega)$

Non-causal $\mathbf{H}_{\mathrm{REC}}(j\omega) \neq \mathbf{H}(j\omega)$

Causality check



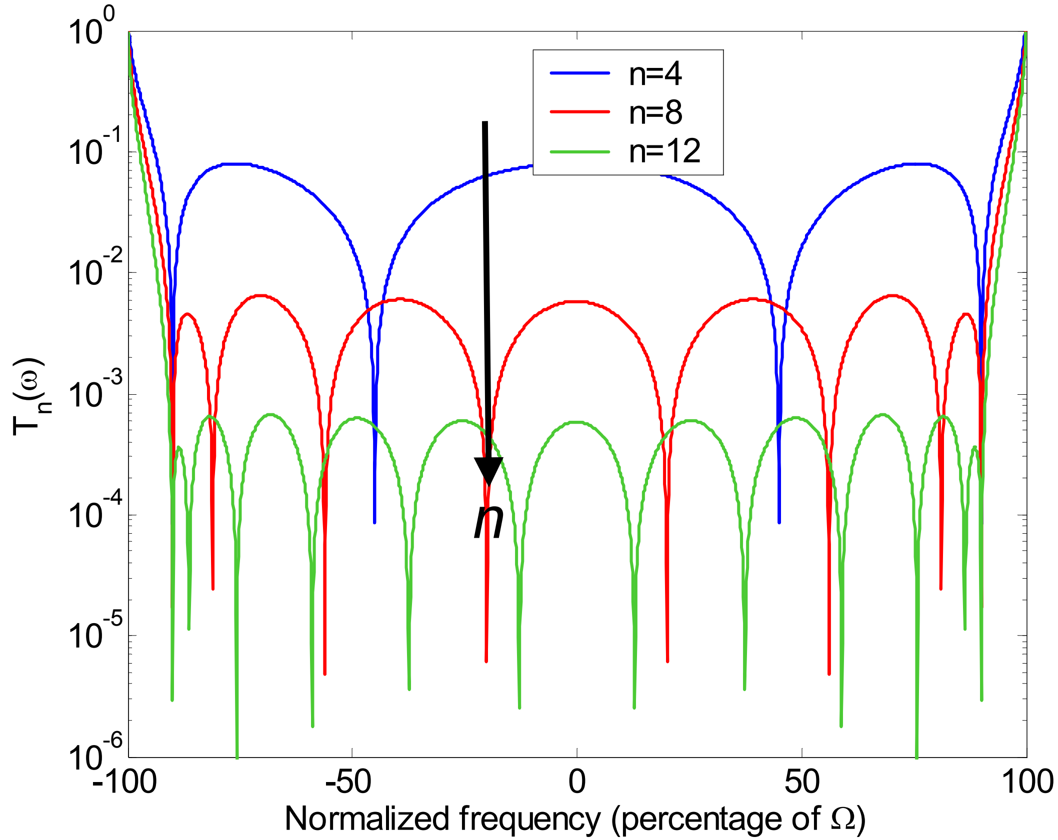
Causal $$\left|\mathbf{H}_{\mathrm{REC}}(j\omega)-\mathbf{H}(j\omega)\right| < \boldsymbol{\Delta}(j\omega)$$

Non-causal $$\left|\mathbf{H}_{\mathrm{REC}}(j\omega)-\mathbf{H}(j\omega)\right| > \boldsymbol{\Delta}(j\omega)$$

Truncation error

$$\left|E_n(j\omega)\right| = \left| \frac{\prod_{q=1}^{n}(\omega-\overline{\omega}_q)}{j\pi}\,\mathrm{pv}\int_{|\omega'|>\Omega} \frac{H(j\omega')-\cancel{\beta(j\omega')}}{\prod_{q=1}^{n}(\omega'-\overline{\omega}_q)}\,\frac{d\omega'}{\omega-\omega'} \right| \boxed{\le T_n(\omega)}$$

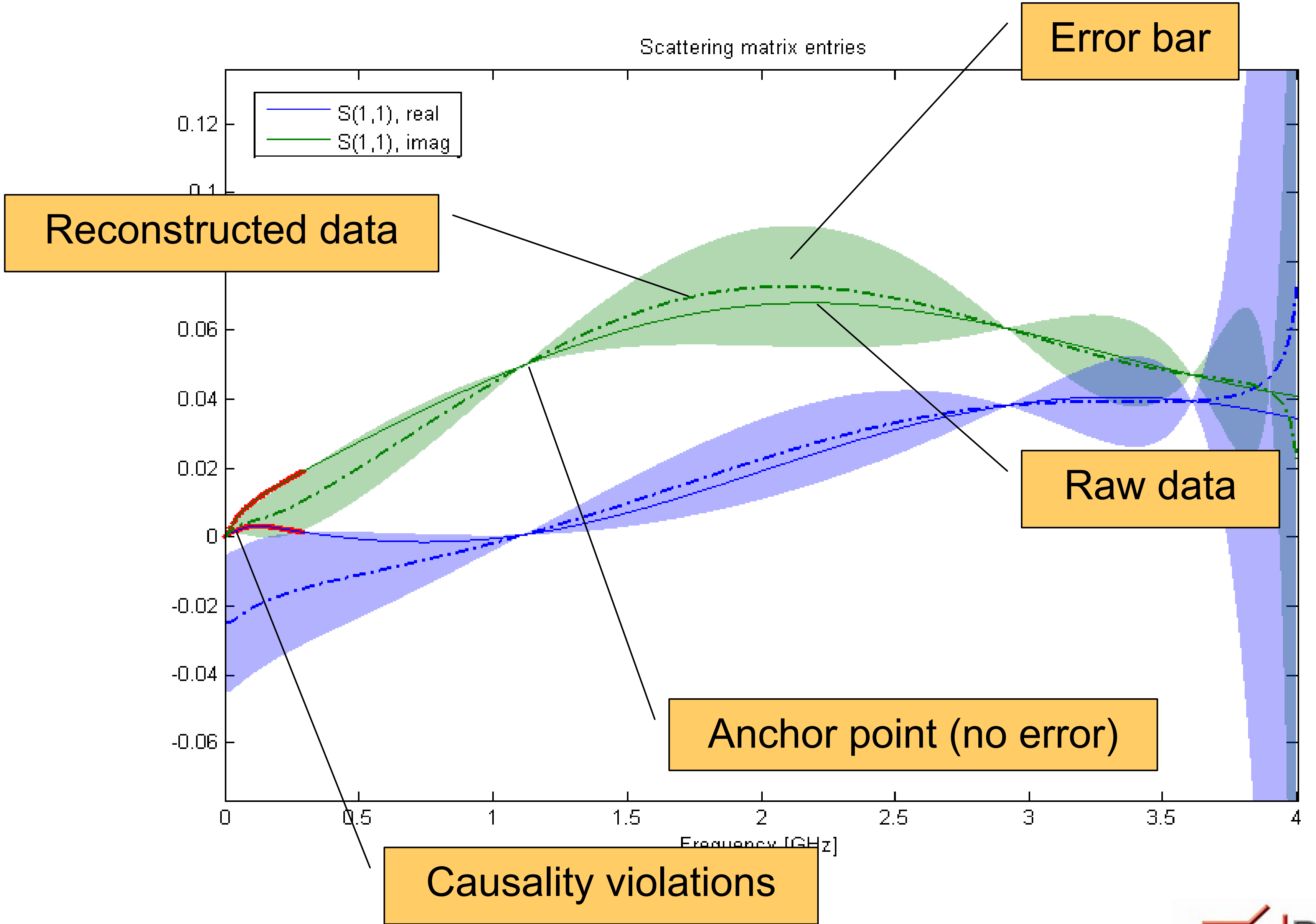
Analytic bound



Truncation error can be arbitrarily reduced

Full control of truncation effects!

Causality check results



Computed by IdEM R2009b

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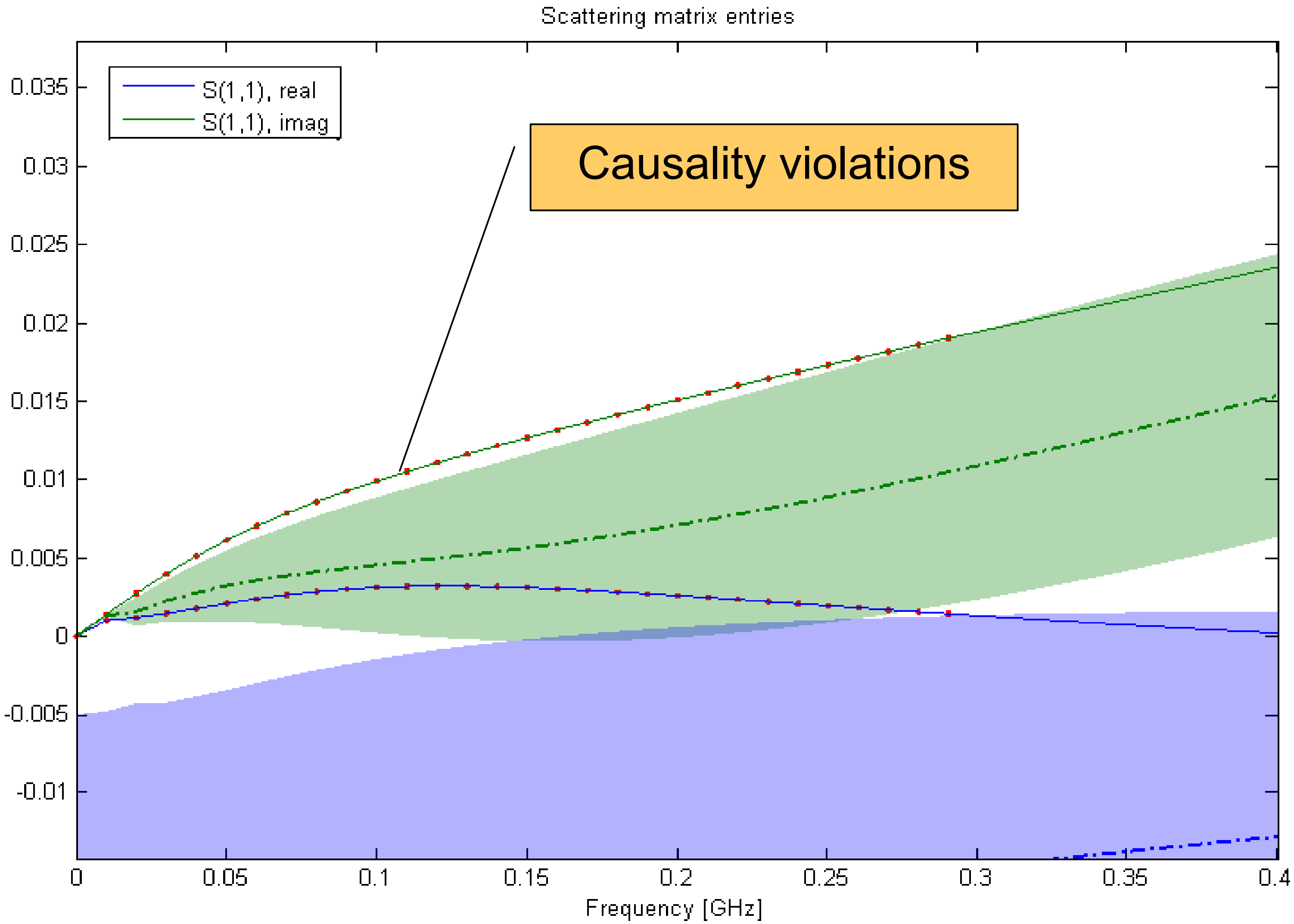
Causality check results



Computed by IdEM R2009b

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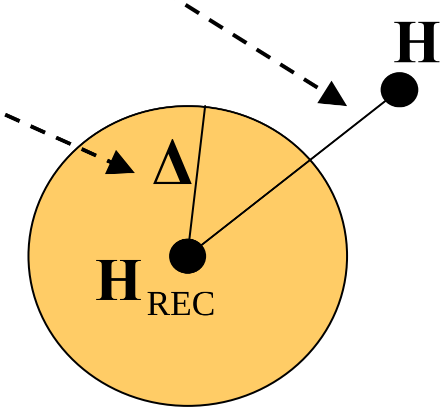
Causality check error

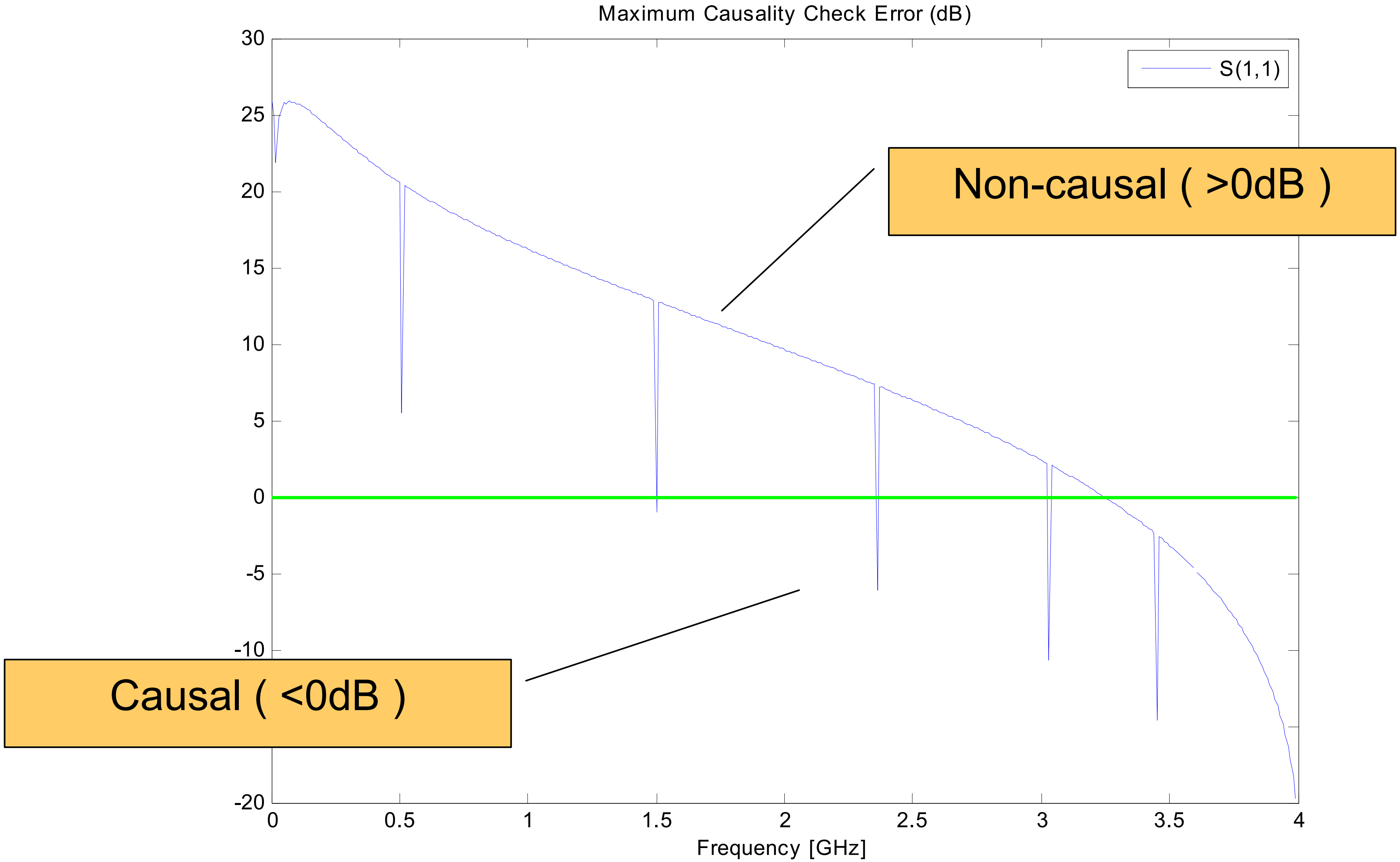
Difference between reconstructed and raw data

$$E_{dB}(j\omega) = 20\log_{10}\frac{\left|H_{\mathrm{REC}}(j\omega) - H(j\omega)\right|}{\Delta(j\omega)}$$

Numerical resolution (“error bar”)



Causality check error



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Non-causal data: so what?

$$\text{Non-causal data} \xrightarrow[\text{Stable poles}]{\text{Fitting}} \text{Bad accuracy}$$

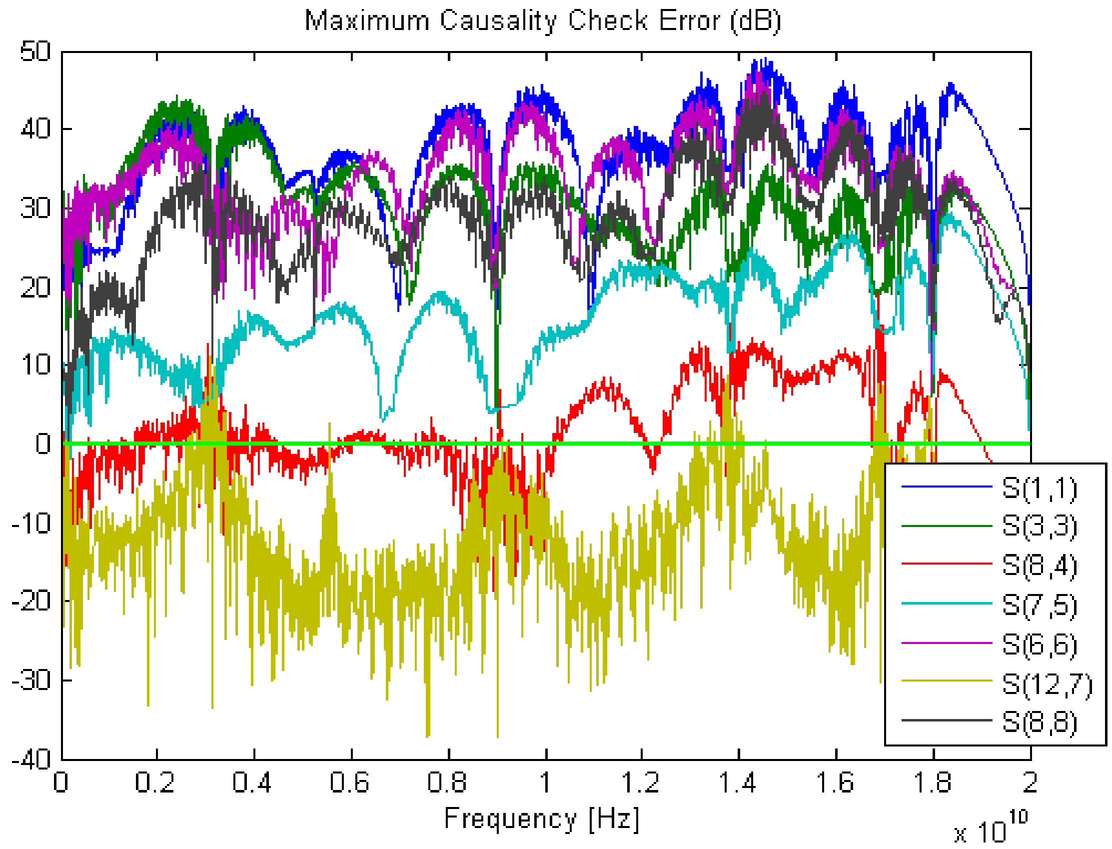
Model is not representative of the real structure

$$\text{Non-causal data} \xrightarrow[\text{Good accuracy}]{\text{Fitting}} \text{Unstable poles}$$

Model cannot be simulated (will blow-up)

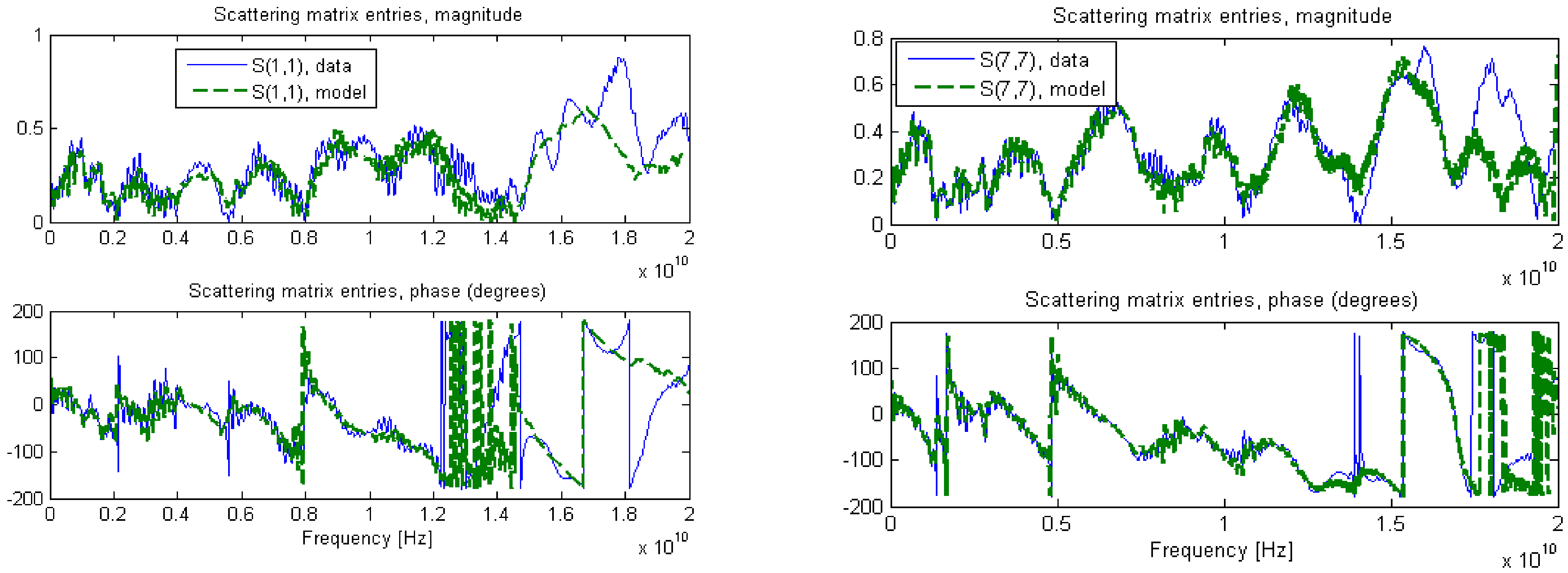
Cable test case – again

Several causality violations are detected. Such violations are very large and spread throughout the entire band, especially for the diagonal responses of the S-matrix (return losses at all ports)



Trying to extract a macromodel…

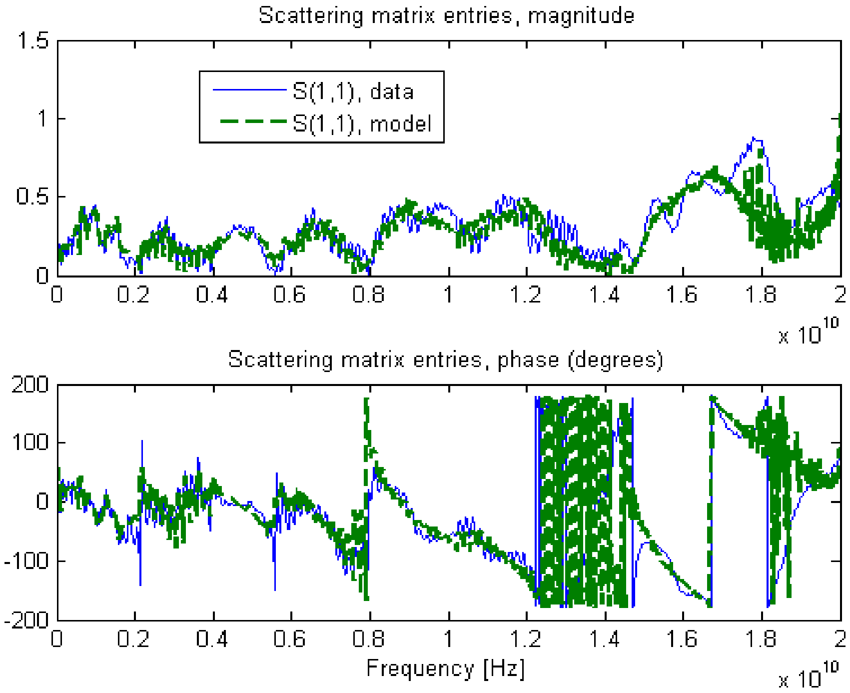
Due to the data inconsistencies, it is impossible to obtain an accurate model after the fitting process.

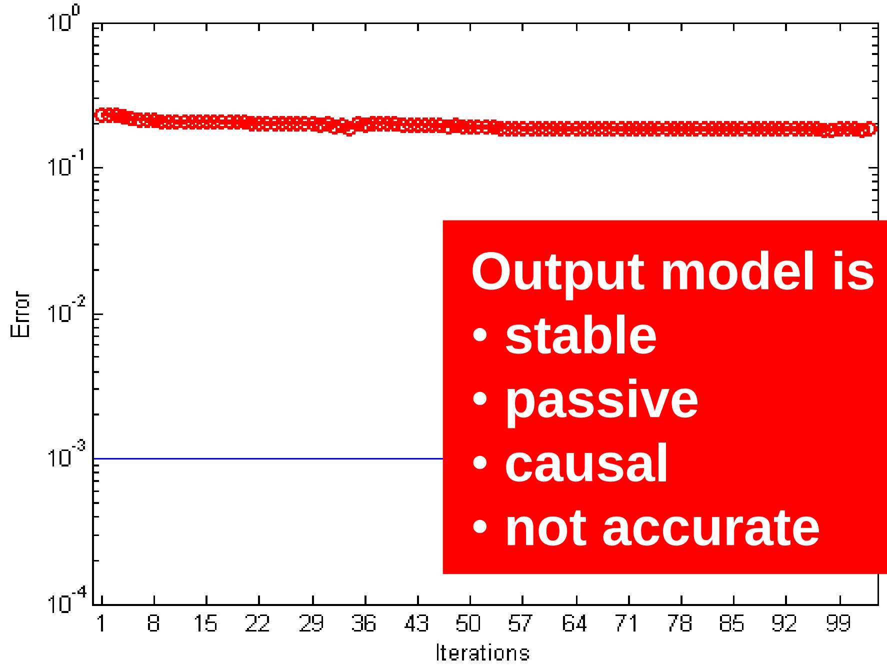


Note that the model accuracy is very poor, especially for the responses where the largest causality violations have been detected.

Effects of causality violations

Causality violations in the data affect the fitting. The approximation error does not decrease even if a very large number of poles is used.

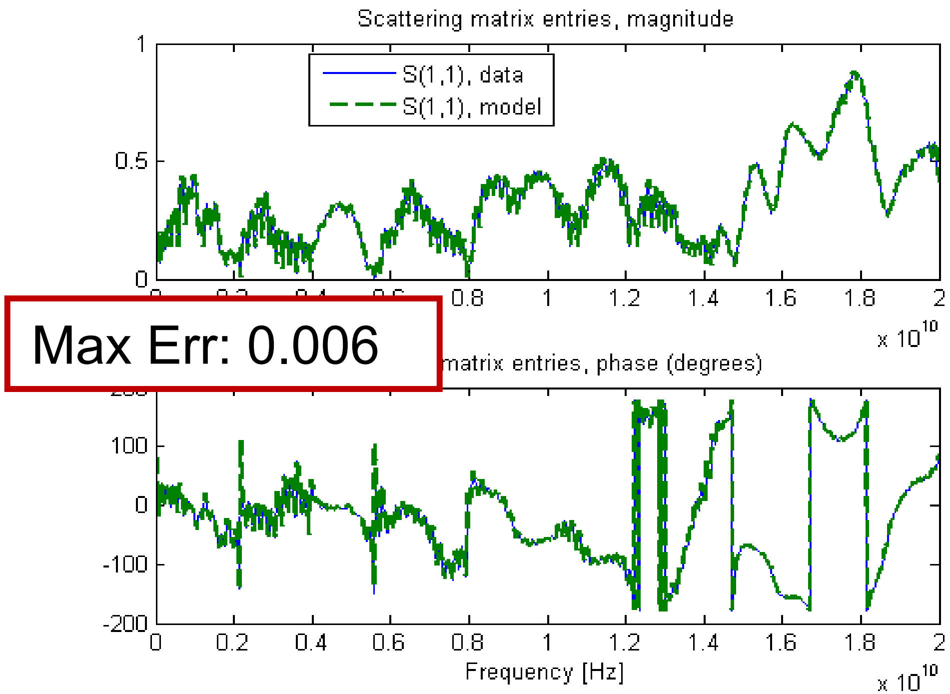


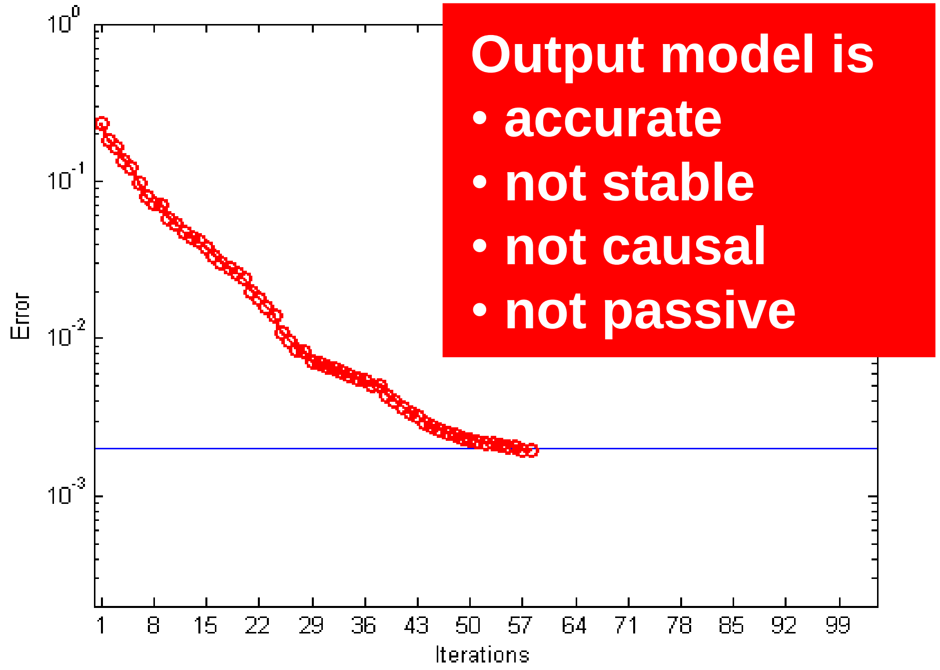


Output model is
- **stable**
- **passive**
- **causal**
- **not accurate**

Effects of causality violations

Removing the stability condition during the fitting (allowing poles in the right half plane), the fitting converges with good accuracy, but the final model is unstable.





S. Grivet-Talocia and P. Triverio, “Modeling and Simulation of High-Speed Interconnects: Approaches, Challenges and Solutions”, SPI 2010 Tutorial, 9 May 2010, Hildesheim, Germany

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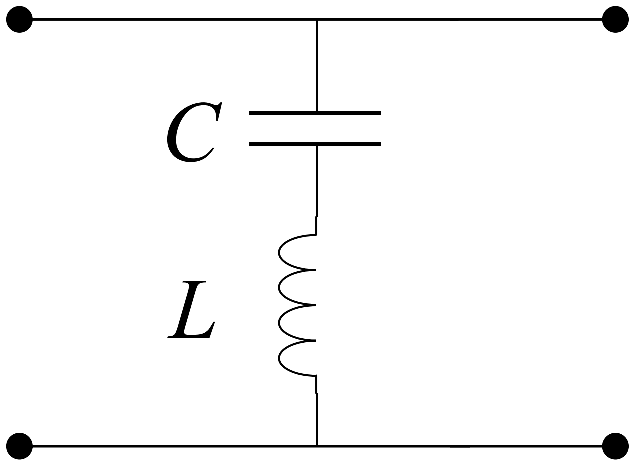
Sampling: a trivial case



$$S_{21}(s) = \frac{s^2 + \omega_0^2}{s^2 + \alpha s + \omega_0^2}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

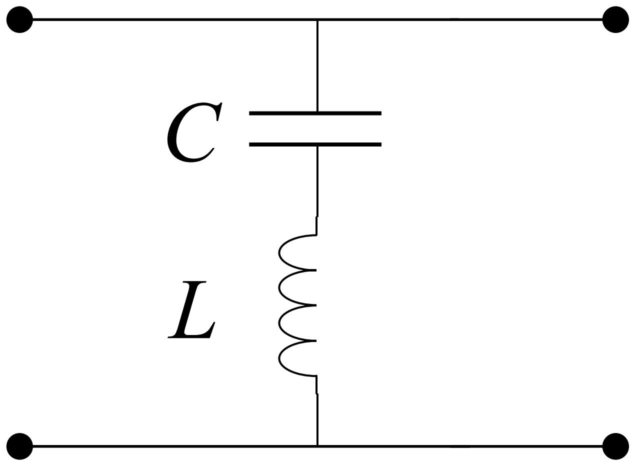
R_0 = reference resistance

$$\alpha = \frac{R_0}{2L}$$

$$C = 5\,\mathrm{pF}$$

$$L = 2\,\mathrm{nH}$$

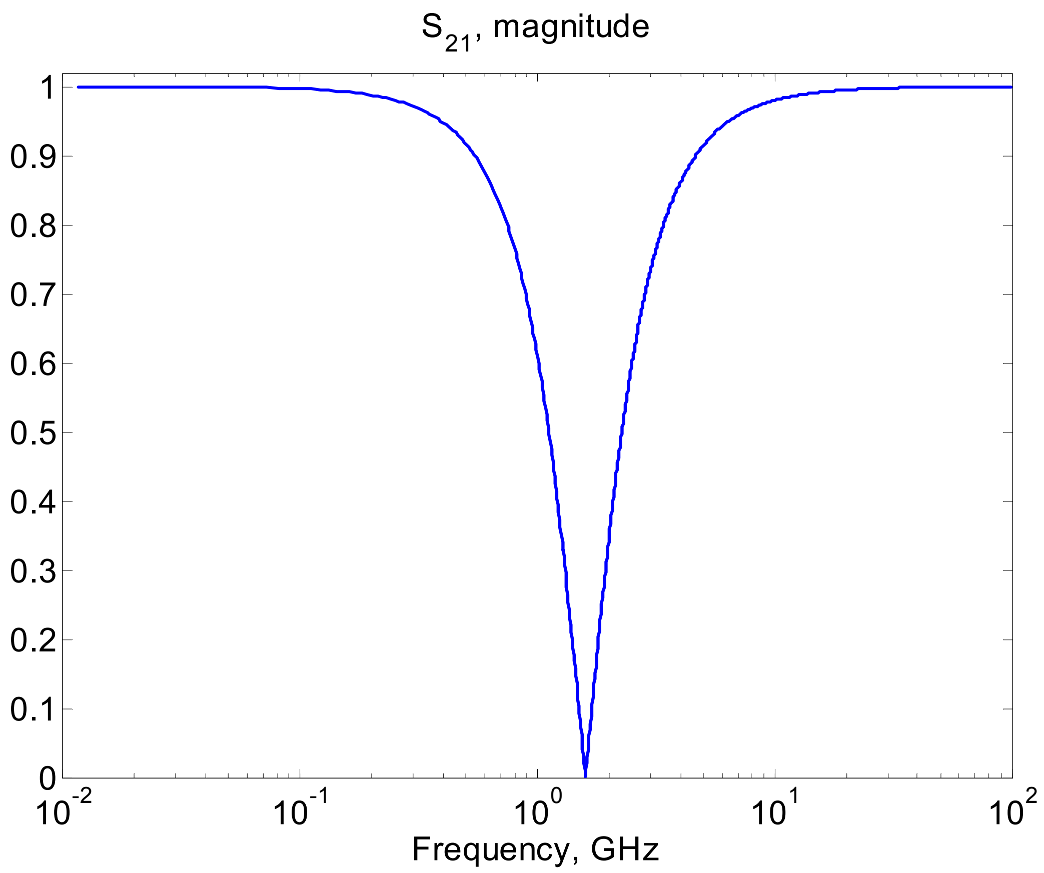
Sampling: a trivial case



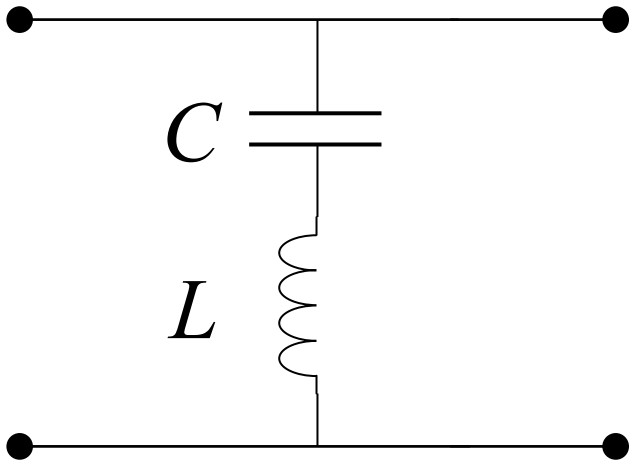
$$R_0 = 50\,\Omega$$

$$C = 5\,\mathrm{pF}$$

$$L = 2\,\mathrm{nH}$$



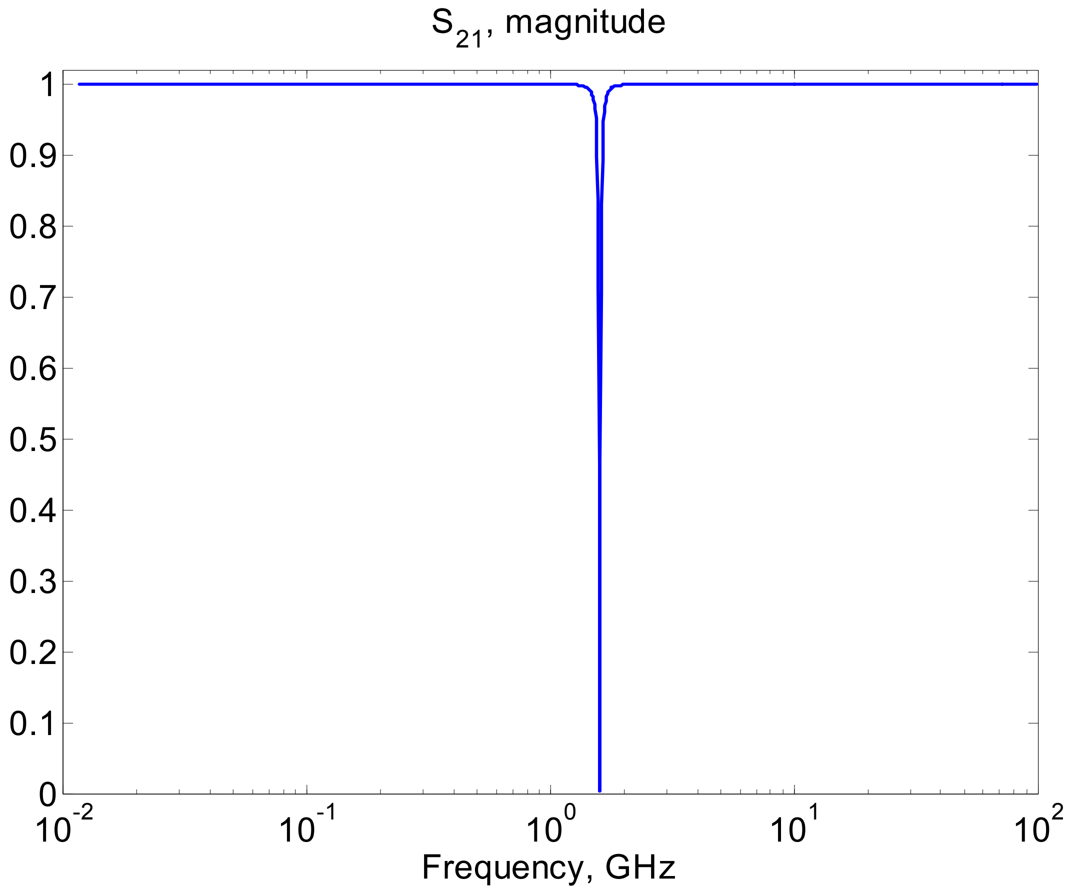
Sampling: a trivial case



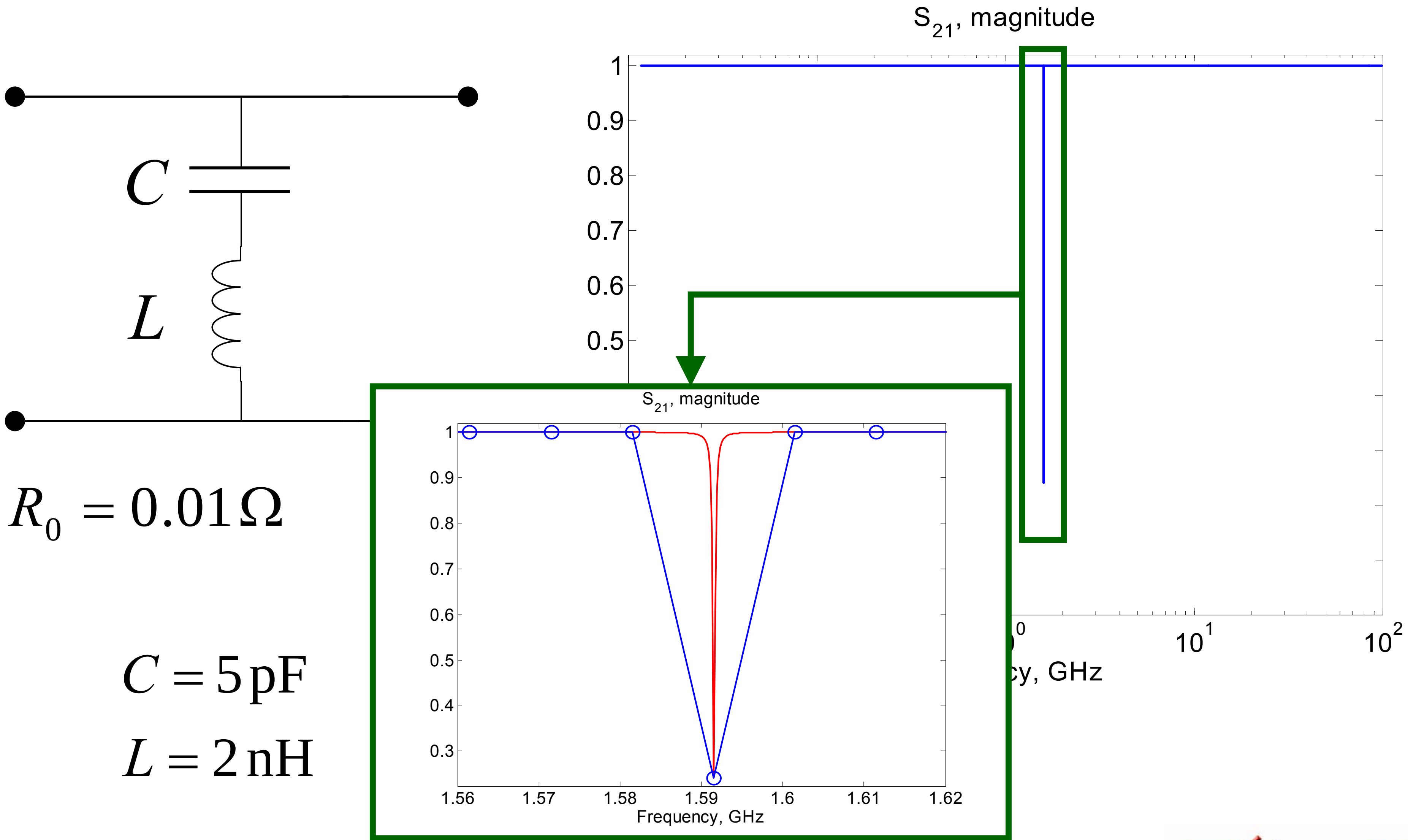
$$R_0 = 1\Omega$$

$$C = 5\,\mathrm{pF}$$

$$L = 2\,\mathrm{nH}$$



Sampling: a trivial case



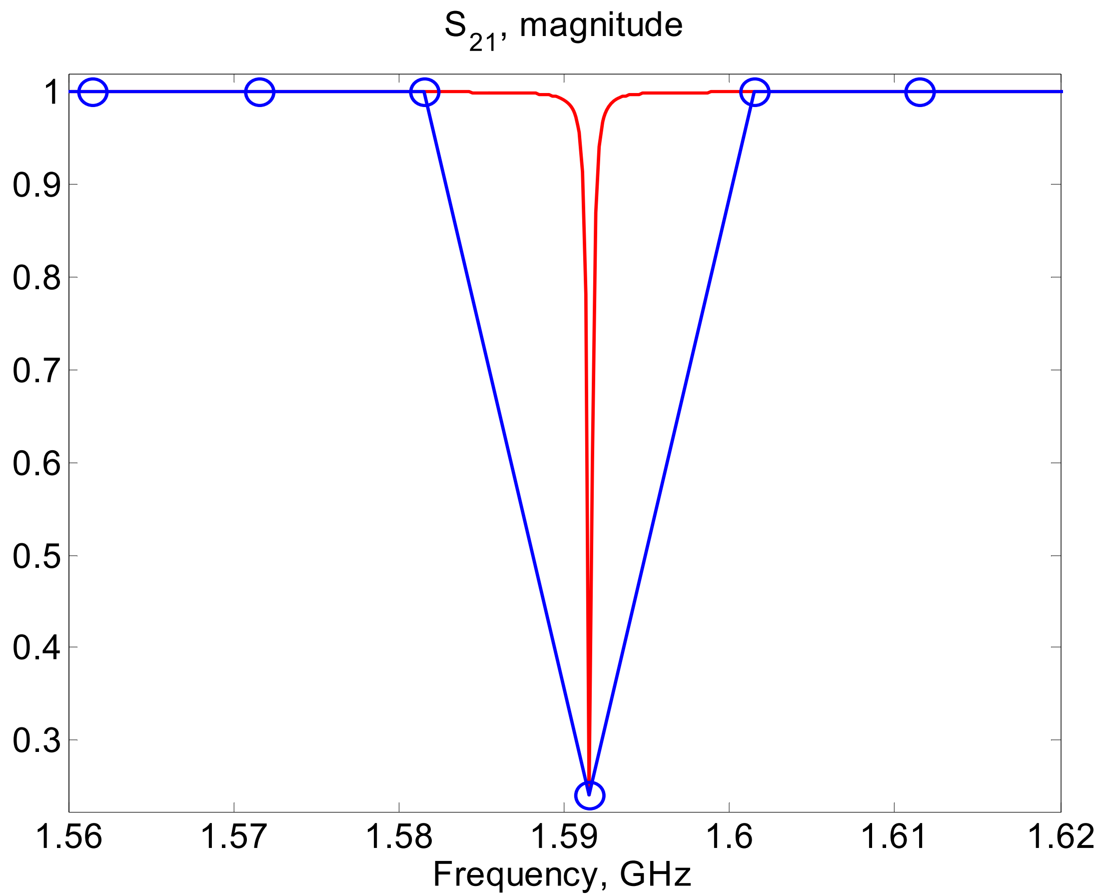
$$R_0 = 0.01\,\Omega$$

$$C = 5\,\mathrm{pF}$$

$$L = 2\,\mathrm{nH}$$

Sampling: a trivial case

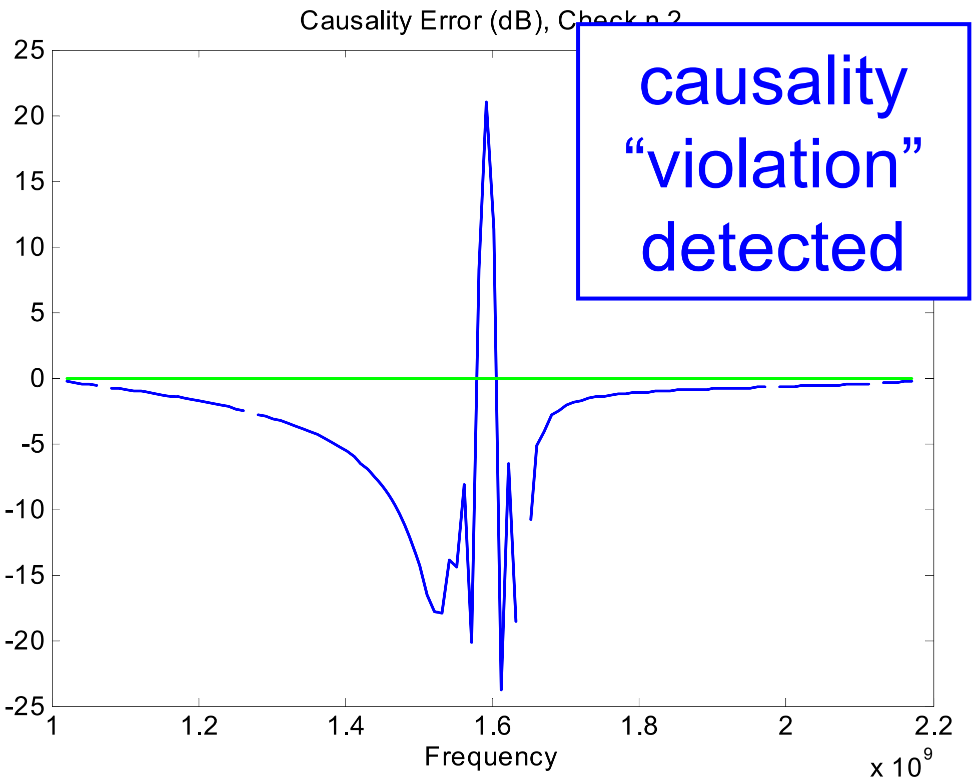
How do we expect a solver will interpret the blue samples?

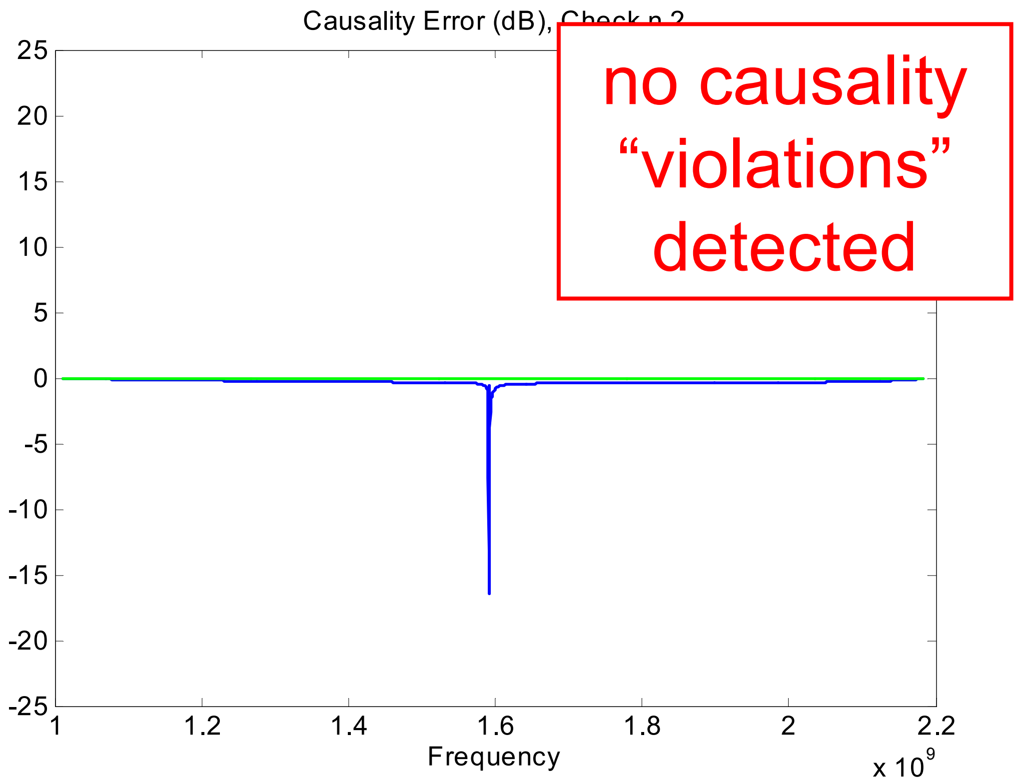


Detecting undersampled data via "causality" check

undersampled

well sampled





Conclusions

- Tabulated S-parameter data may hide serious issues
  - Passivity (energy gain) violations
    - Easily checked at individual frequencies (singular value test)
  - Causality violations
    - Can be detected using Generalized Hilbert Transform
    - Theoretically sound
    - Robust numerical implementation
  - Bad or insufficient sampling
    - Also detectable via Generalized Hilbert Transform
- If not detected (and corrected)
  - Any of these issues will lead to problems in simulation
    - With any tool or method (see SPI 2010 tutorial)

Thank you

http://www.emc.polito.it

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