Simbeor Application Note #2009_04, April 2009

Micro-strip line characteristic impedance and TDR

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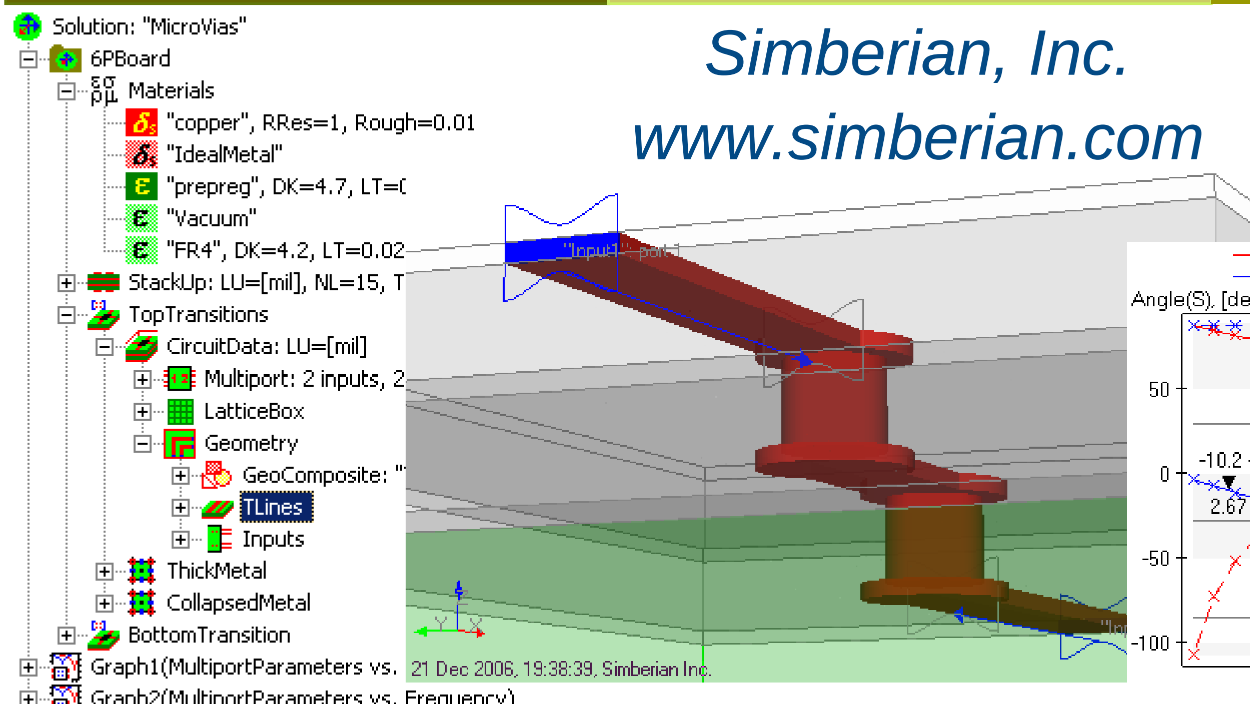

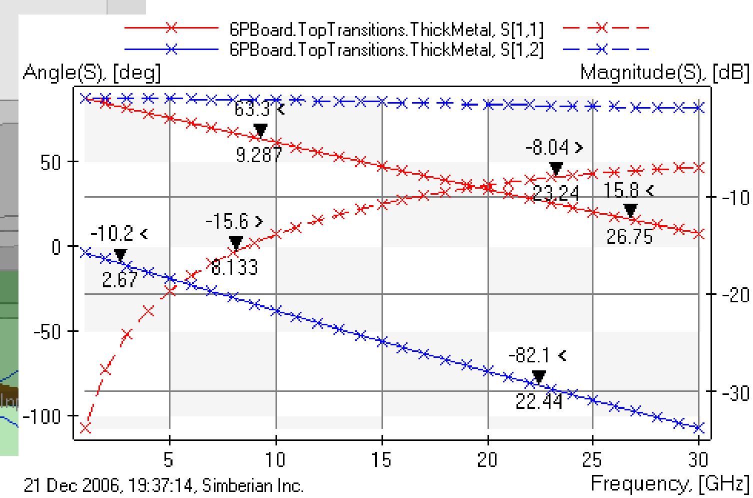

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Overview

- Introduction
- Transmission line parameters
- Micro-strip line geometry
- Characteristic impedance in frequency domain
- Possible ways to do correlation
- S-parameters of the line segment
- Impedance on TDR with different rise times
- Conclusion
- Solutions and contacts
- Backup slides – loss-less dispersive microstrip

Introduction

- Characteristic impedance of a micro-strip line is a complex value that changes with the frequency due to:
  - Dispersive dielectric with DK and LT changing with frequency
  - Conductor dispersion because of skin effect and roughness
  - High-frequency dispersion because of inhomogeneous dielectric
- Impedance changes over the frequency spectrum of a multi-gigabit signal and usually measured using Time Domain Reflectometry (TDR)
- **What impedance value is actually visible on TDR of a line segment?**
- **Does the observed impedance value depend on the rise time?**
- This is a simple numerical investigation of a dispersive micro-strip line segment to correlate impedances in frequency and time-domains
- One of the requirements for such investigation is the **full-wave electromagnetic analysis that accounts for dielectric, conductor and high-frequency dispersion effects over extremely wide frequency band**
- Simbeor 2008.01 built on April 7, 2009 has been used for all computations

Transmission line parameters

Generalized Telegrapher's equations describe t-line segment and work at microwave and optical frequencies with appropriately extracted impedance and admittance per unit length (p.u.l.)

$$\frac{\partial \bar{V}(x)}{\partial x} = -Z(\omega) \cdot \bar{I}(x)$$

$$\frac{\partial \bar{I}(x)}{\partial x} = -Y(\omega) \cdot \bar{V}(x)$$

Simbeor extracts frequency dependent impedance Z and admittance Y per unit length,

$$Z(\omega) = R(\omega) + i\omega \cdot L(\omega)$$

$$Y(\omega) = G(\omega) + i\omega \cdot C(\omega)$$

as well as frequency-dependent modal parameters such as characteristic impedance Zo and propagation constant Γ of micro-strip line dominant mode

$$Z_0(\omega) = \sqrt{\frac{Z(\omega)}{Y(\omega)}}$$

$$\Gamma(\omega) = \sqrt{Z(\omega) \cdot Y(\omega)} = \alpha + i\beta$$

All this can be done for multi-conductor lines in general and over extremely wide frequency band with practically all types of dispersion and losses include and **without TEM-wave assumption**

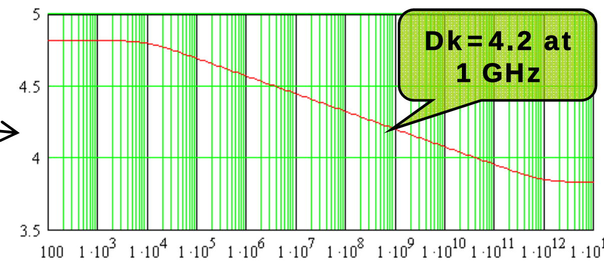
To learn more on advanced analysis of t-lines, sign up for Simberian's webinar at http://www.simberian.com/Seminars.php

Micro-strip line geometry

Solution: "Simple TDR Experiment"
- Project1
  - Materials
    - "Copper", RR=1
    - "FR4", Dk=4.2, LT=0.02, PLM=WD
    - "Air"
  - StackUp: LU=[mil], NL=4, T=32.94[mil]
    - 1| Signal: "Signal1", T=1.2, Ins="Air"
    - 2| Medium: T=4.5, Ins="FR4"
    - 3| Plane: "Plane1", Cond="Copper", T=0.77, Ins="FR4"
    - 4| Medium: T=20, Ins="FR4"
    - 5| Plane: "Plane2", Cond="Copper", T=0.77, Ins="FR4"
    - 6| Medium: T=4.5, Ins="FR4"
    - 7| Signal: "Signal2", T=1.2, Ins="Air"

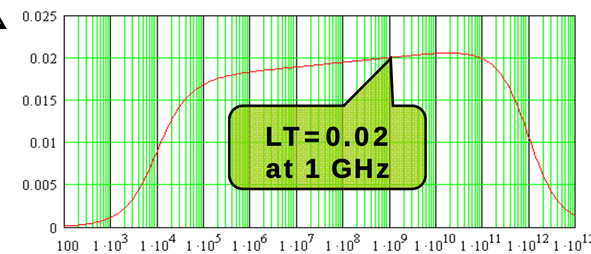
Wideband Debye dielectric model (Djordjevic-Sarkar)

Dielectric Constant (Dk)

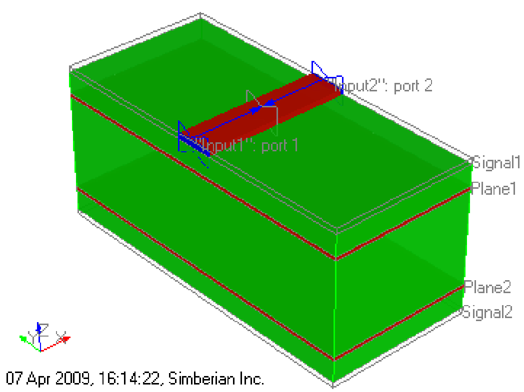


Changing more than 10%

Loss Tangent (LT)



A segment of line with strip width 8 mil (about 50 Ohm) is simulated to extract modal and p.u.l. parameters

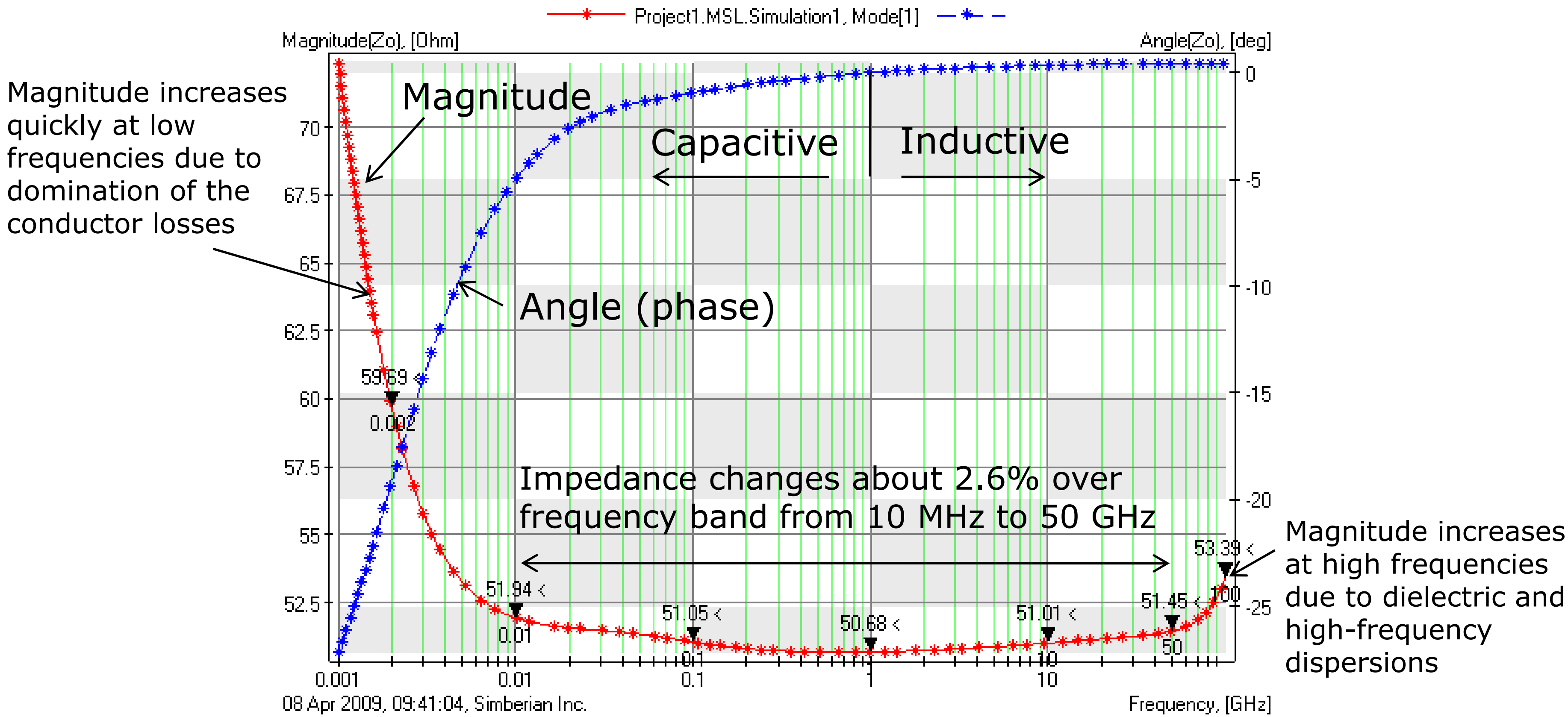


Such model is verified for PCB applications by multiple comparisons with experimental data – see App. Note 2009_03 at www.simberian.com for instance

Roughness, conductor plating, and solder mask can be easily accounted for, but are not specified here to keep it simple (not critical for the purpose of this investigation)

Multi-pole Debye and multi-pole Lorentz models are also available to simulate dielectrics with more complex behavior

Micro-strip line impedance profile in frequency domain

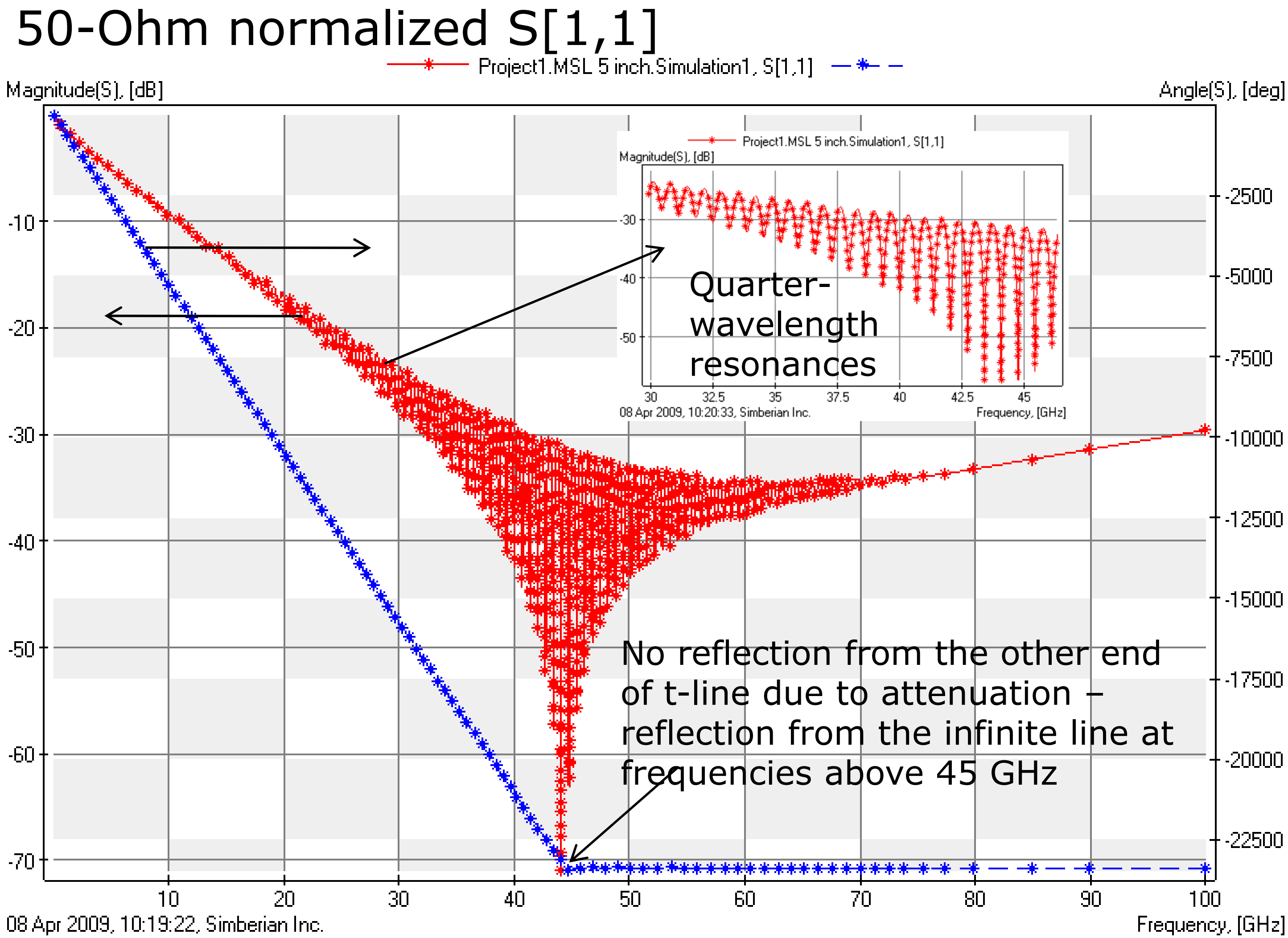


- Characteristic impedance is a complex function of frequency
- **What value we actually observe on TDR plot?**

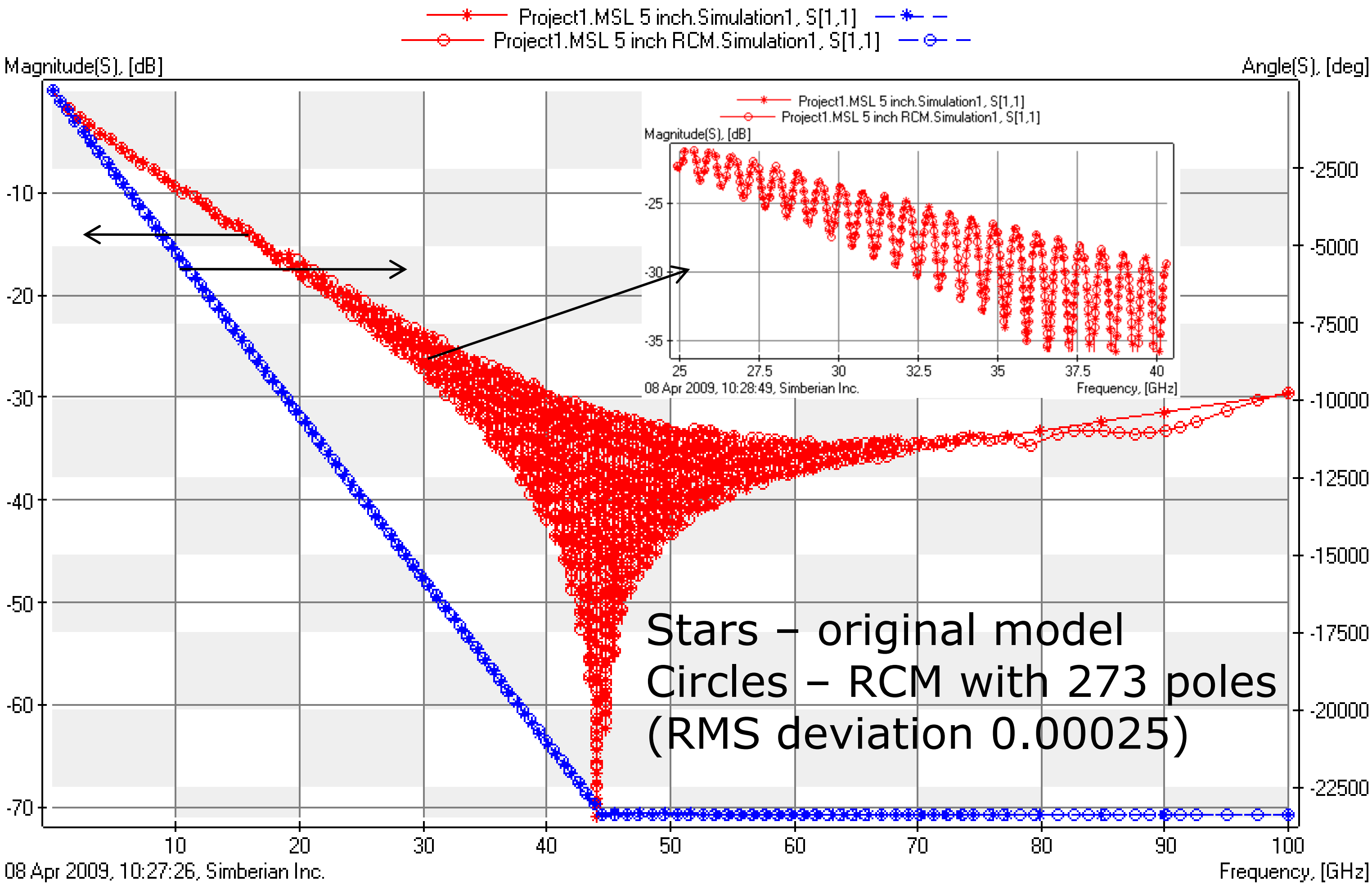
TDR investigation of a micro-strip line segment can be done in multiple ways

- Compute frequency-domain S-parameters of the line segment, then build Rational Compact Model (RCM) and compute step response in Simbeor
- Use RCM of the line segment generated in Simbeor and output it as the broad-band SPICE model for investigation in a SPICE solver
- Output W-element RLGC(f) model directly from the created t-line model and use a SPICE solver to compute step response of the segment
- Let’s explore all possibilities

Frequency-domain model of open-ended 5-inch micro-strip line segment in Simbeor



Rational Compact Model (RCM) of open-ended 5-inch micro-strip line segment

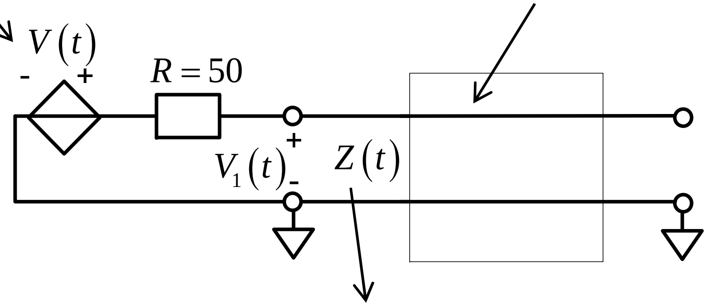


See "How to build rational compact model?" chapter in Simbeor Manual for more details

Simple numerical TDR experiment

Step voltage source

5-inch micro-strip line segment



Open-circuit termination

$$Z(t) = \frac{R \cdot V_1(t)}{V(t) - V_1(t)}$$

Visible impedance profile in time-domain (real value)

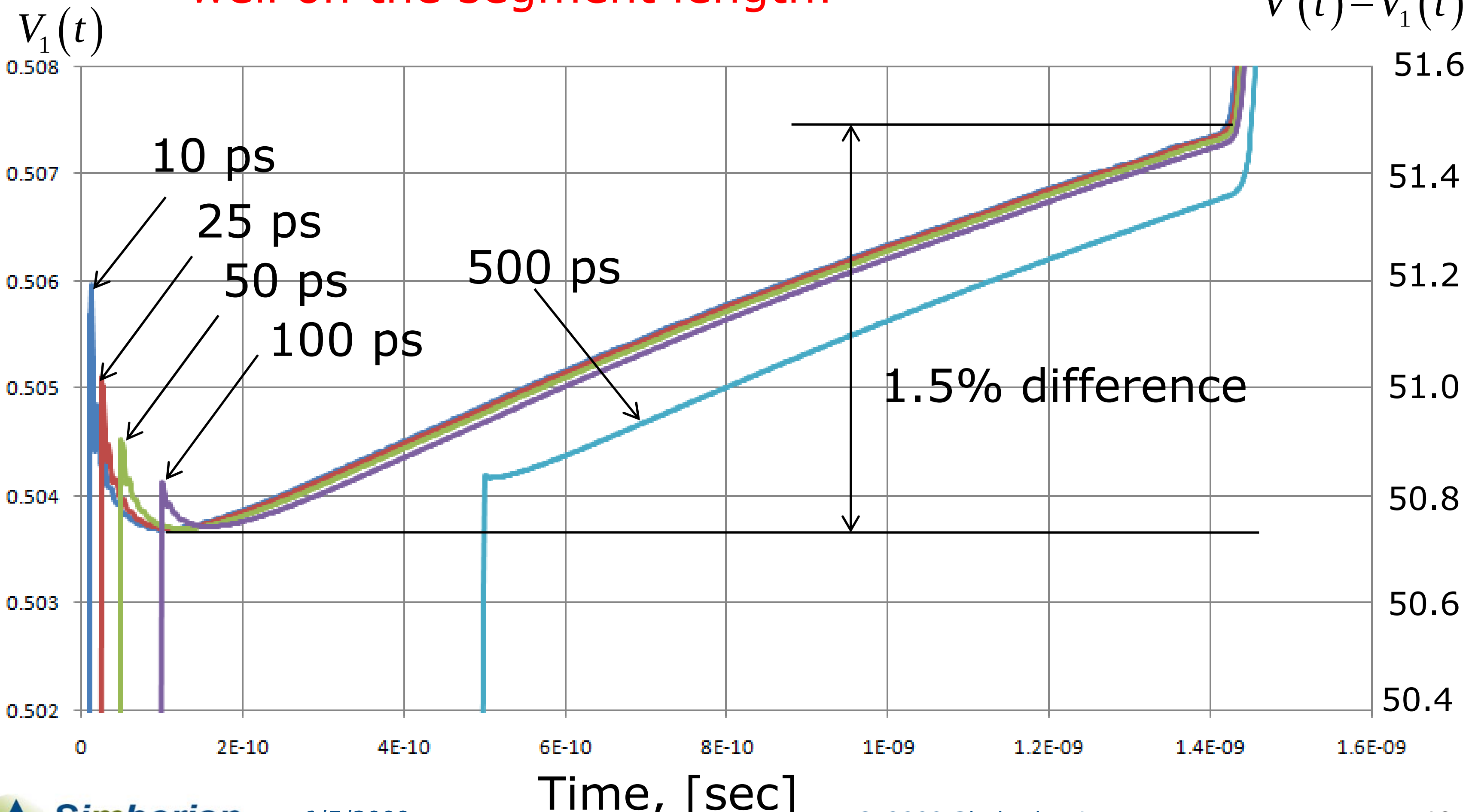
Using step source with different rise times we should be able to see the reflection from characteristic impedance of t-line before the wave is reflected from the open end (about 1.4 ns)

See "How to compute time domain response matrix?" chapter in Simbeor Manual for more details

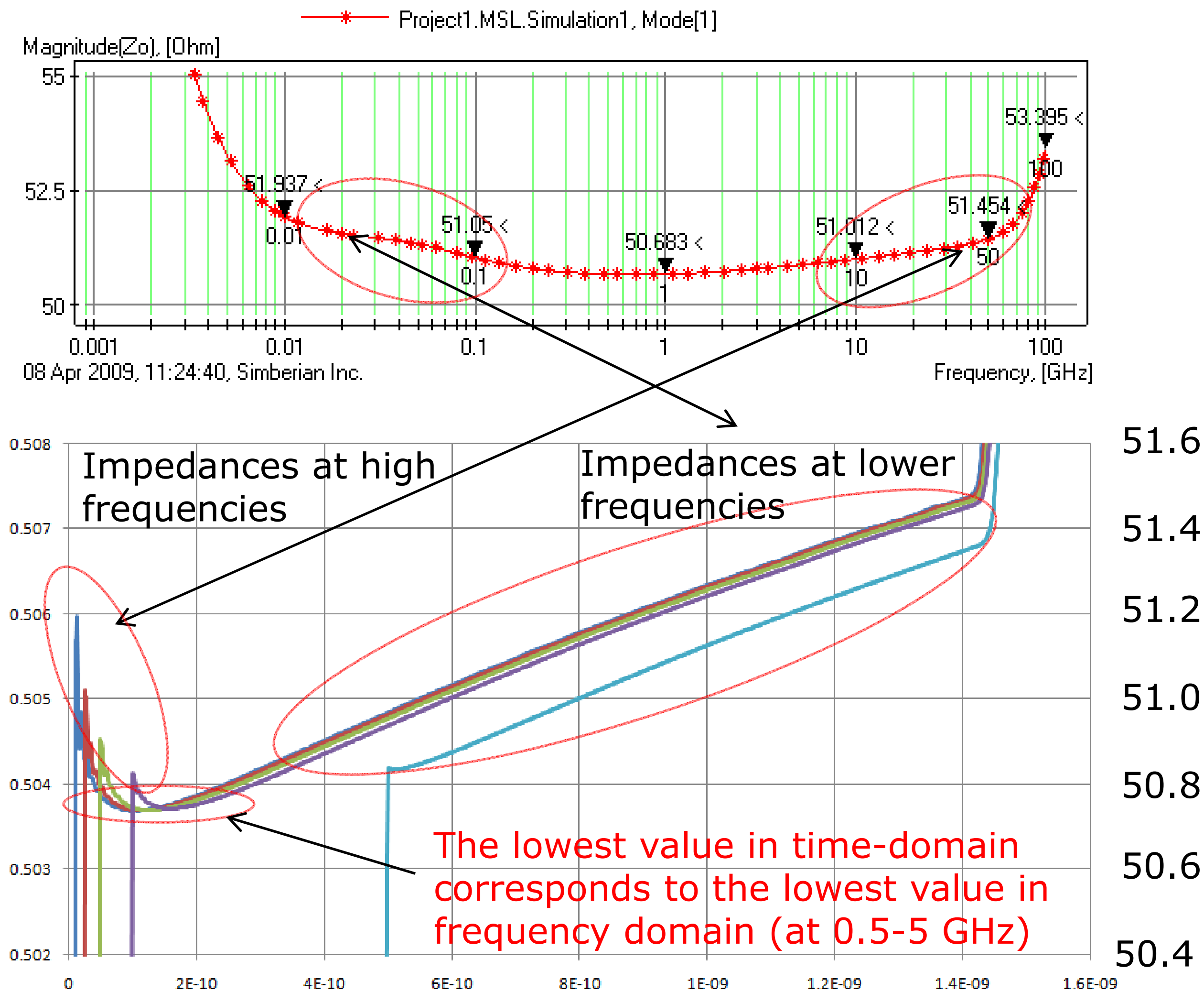
TDR in Simbeor with different rise times

Clear dependency on the rise time as well on the segment length!

$$Z(t) = \frac{R \cdot V_1(t)}{V(t) - V_1(t)}$$



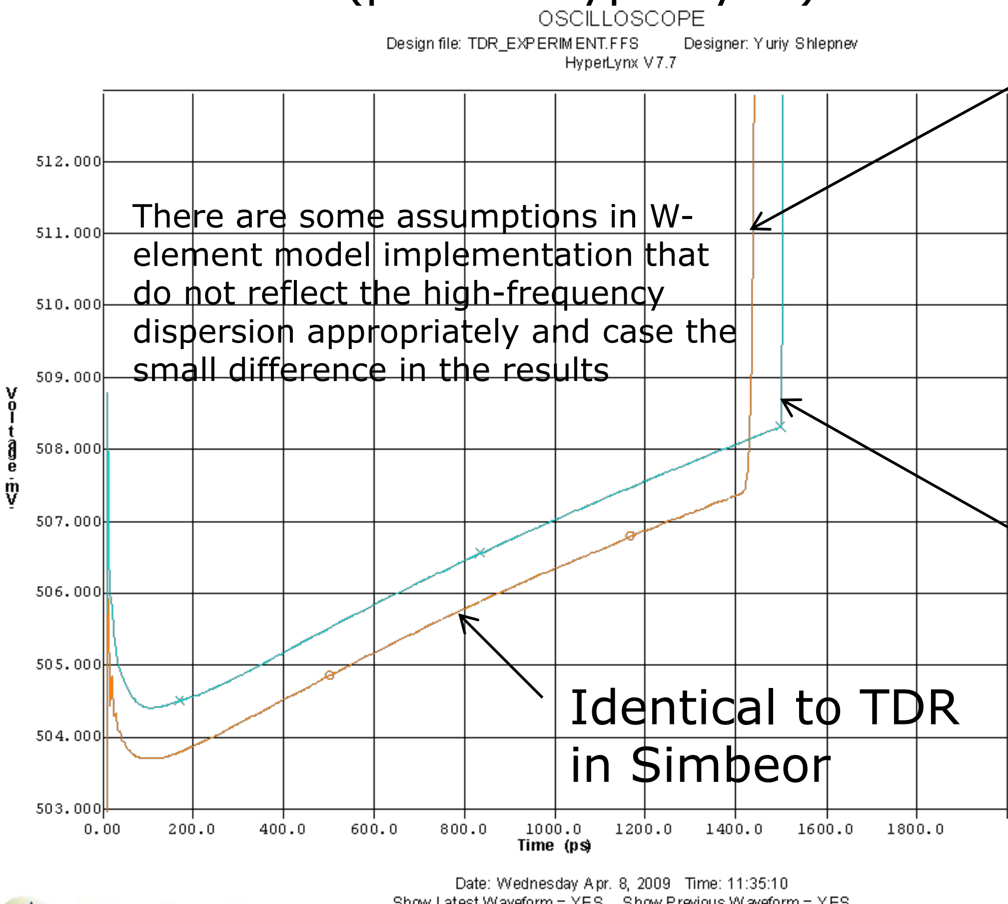
Is there correspondence between time and frequency domain profiles?

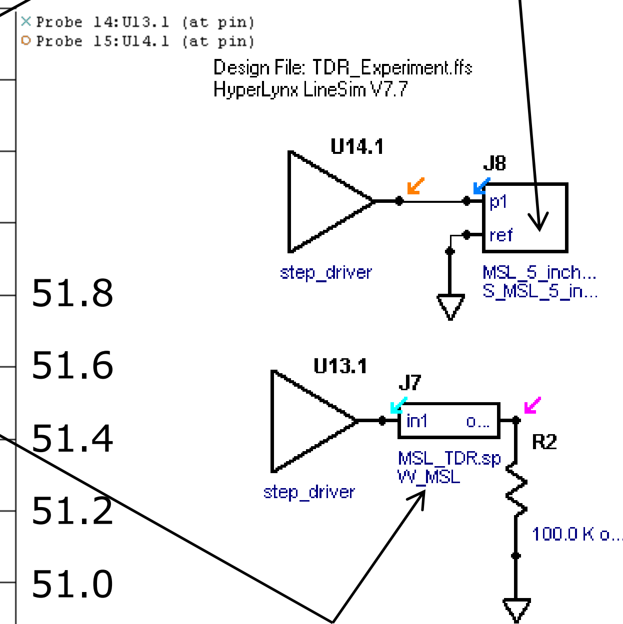


Alternative ways for TDR experiment

Simbeor models can be used in any HSPICE compatible solver – such as Mentor's Eldo (part of HyperLynx)

Broad-band SPICE model from Simbeor as SPICE sub-circuit





Broad-band W-element RLGC(f) model from Simbeor as SPICE sub-circuit

Conclusion

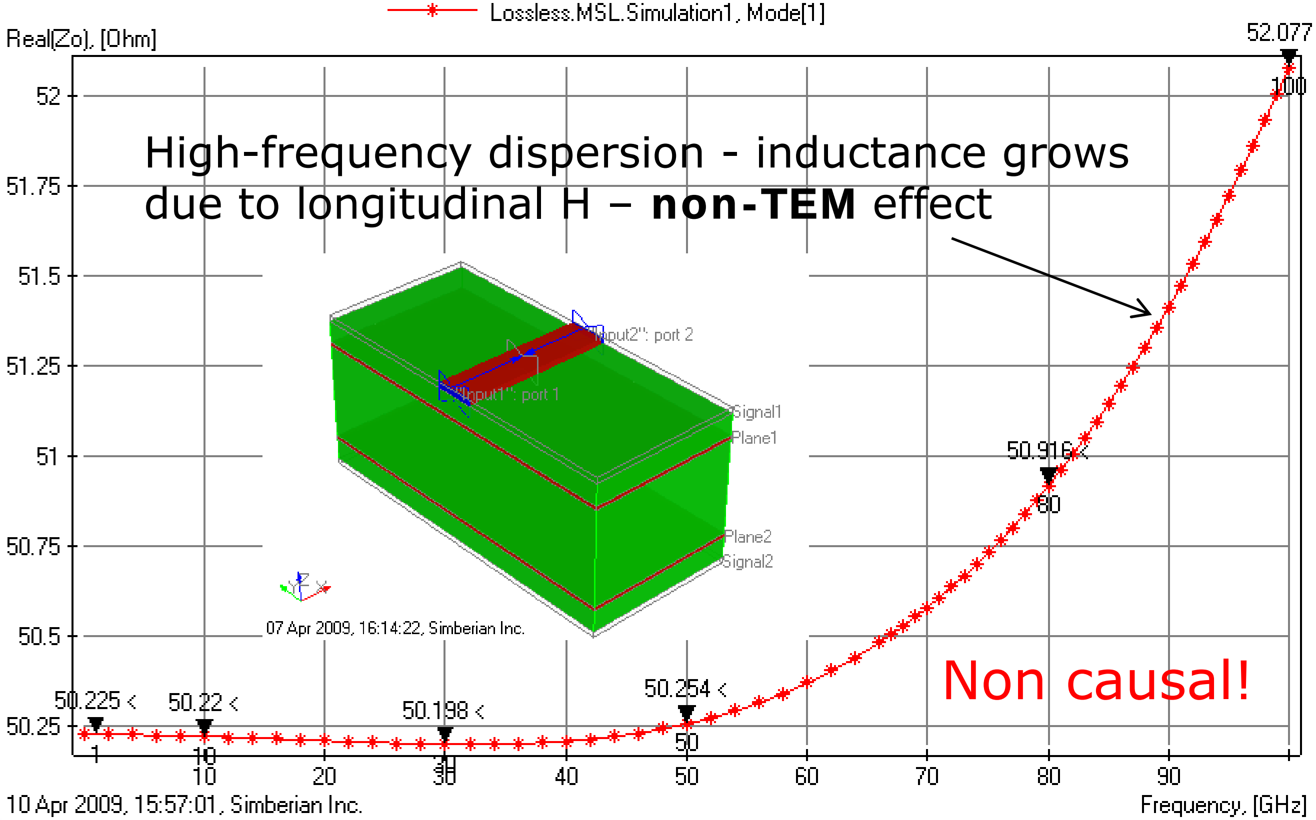
- It is observed that TDR with different rise times may be correlated to magnitudes of the characteristic impedance at different frequencies
- TDR with smaller rise time corresponds to impedances at higher frequencies, and with larger rise time corresponds to impedances at lower frequencies
- **The lowest value of the impedance on TDR is correlated with the lowest value of the characteristic impedance in the frequency domain – this value can be actually used to validate different models**
- Both TD and FD variations of the impedance may be comparable or even smaller than the expected variation due to the weave effect
  - Though it may be important to account for the variations on the impedance controlled boards with homogeneous dielectrics with smaller weave effect
- This is just a numerical experiment with homogeneous dielectric and wideband Debye dispersion model – TDR on real board may be different due to the weave effect, difference in dielectric behavior, and filtering effect of the measurement fixture (connectors, probes)

Solutions and contact

- Setting up all simulations and analysis took less than 1 hour
- Simbeor solution file used to illustrate these notes is available for download from Simberian web site
  - http://www.simberian.com/AppNotes/Solutions/MicrostripImpedanceAndTDR_2009_04.zip
- Send questions and comments to
  - General: info@simberian.com
  - Sales: sales@simberian.com
  - Support: support@simberian.com
- Web site www.simberian.com

Lossless micro-strip (out of curiosity)

- Conductor is specified as “Lossless”, dielectric is specified as “Lossless” with DK=4.2 (constant or independent of frequency)
- Same geometry as in the lossy case, but characteristic impedance is pure real function (imaginary part is zero)

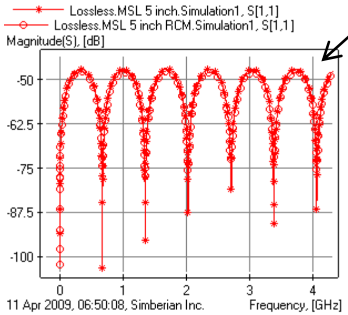


Without the high-frequency dispersion the impedance is constant or independent of frequency

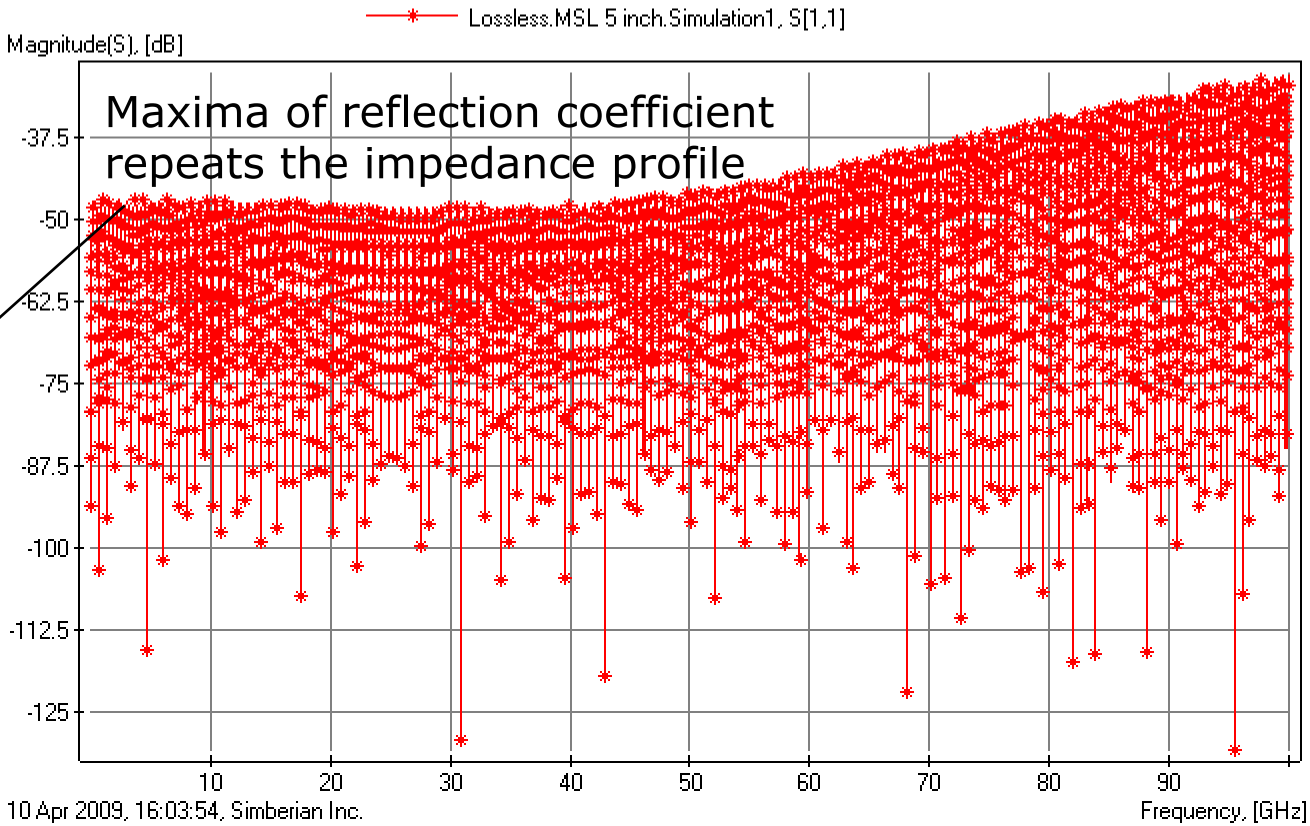
Frequency-domain model of 5-inch lossless micro-strip line segment

- Segment is terminated with 50 Ohm impedance (instead of open-ended) to reduce the stiffness of the system

RCM with 312 poles and RMS deviation 0.0054 is constructed to compute step response



More difficult to build RCM because of non-causality



TDR of loss-less micro-strip segment with different rise times

$$Z(t) = \frac{R \cdot V_1(t)}{V(t) - V_1(t)}$$