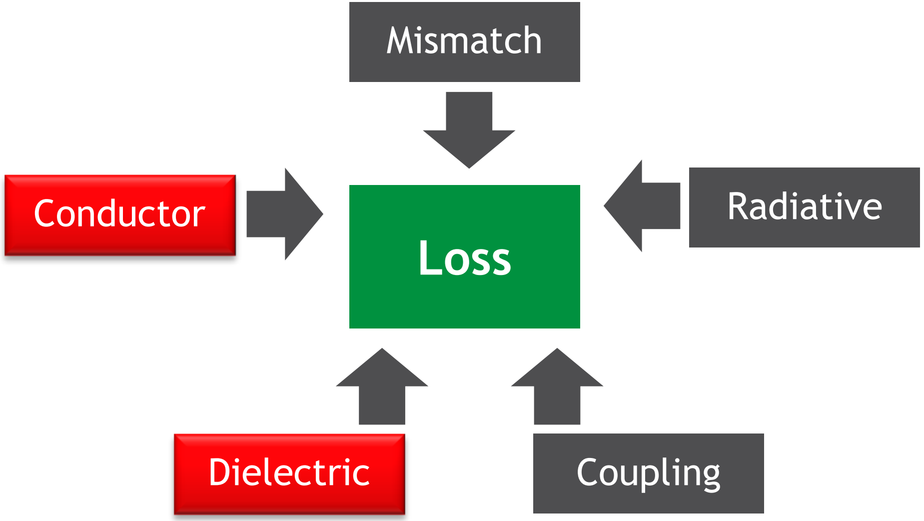
Simulating Dielectric and Conductor Loss Including surface roughness

Tracey Vincent

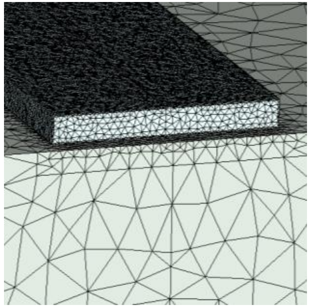
Overview

- Loss components
  - **Conductor**:
    - Skin effect
    - Simulating surface roughness:
      - Tabulated surface impedance: Hammerstad, Huray
      - 3D models- Periodic surface, random surface
      - Effective Dielectric method – (Dr. M. Koledintseva)
  - **Dielectric**:
    - Theory and parameters
      - N^{th} order curve fitting
    - Using Measurements and Simulation to extract material parameters
  - Discussion and conclusion

Loss Components



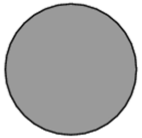
Simulating Conductor Loss



Skin Effect Theory

Current density increases at extremities at RF frequencies

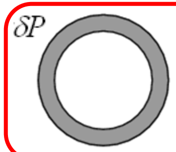
Cross-sectional area of round conductor



At DC
Current density fills cross-section

$$R_{DC} = \frac{1}{\sigma S} \text{ ohms/meter}$$

At AC
Current density moves toward extremities



At GHz frequencies
Current density concentrated at extremities

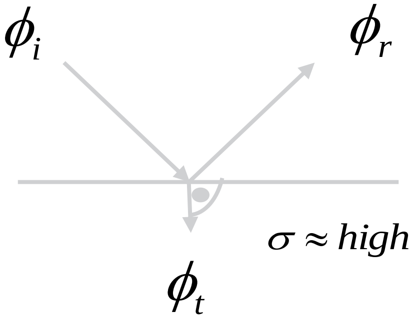
$$R_{AC} = \frac{1}{\sigma \delta P} \text{ ohms/meter} = \frac{R_S}{P} \text{ ohms/meter}$$

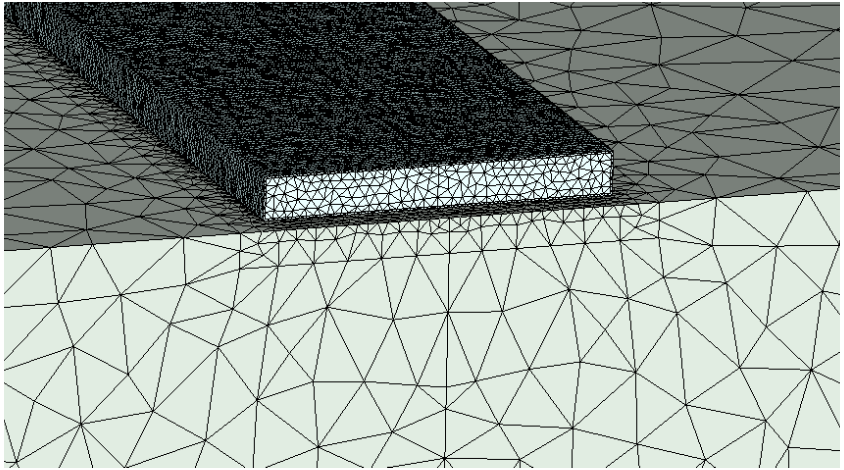
S is the cross-section area of the conductor.
σ is the volume conductivity.
Current is homogenous.

P is the *circumference* of the conductor, δ is skin depth. The δP is the equivalent cross-section area.

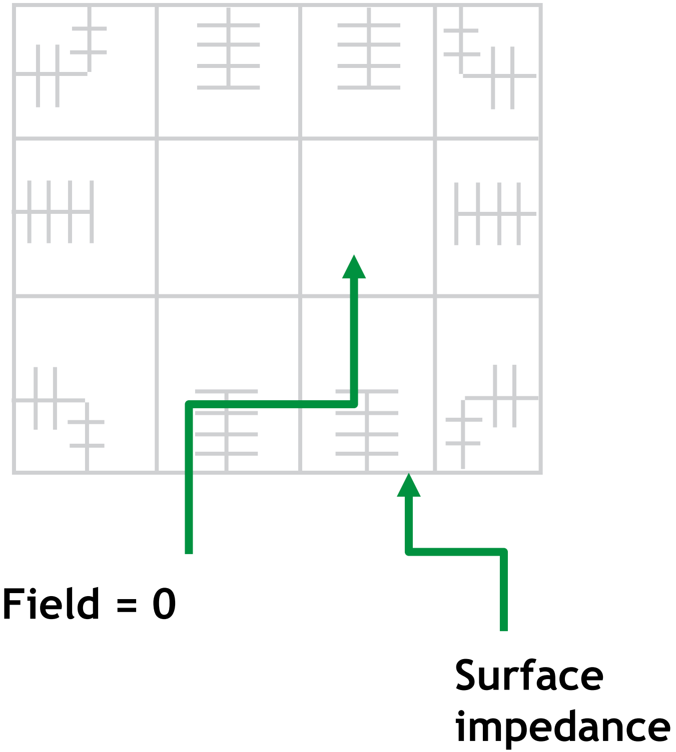
$$\delta = \sqrt{\left(\frac{2}{\omega \mu_o \sigma}\right)}$$

Skin Effect - Lossy Metal



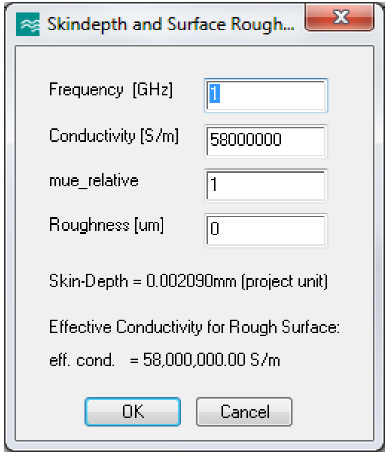


Alternative

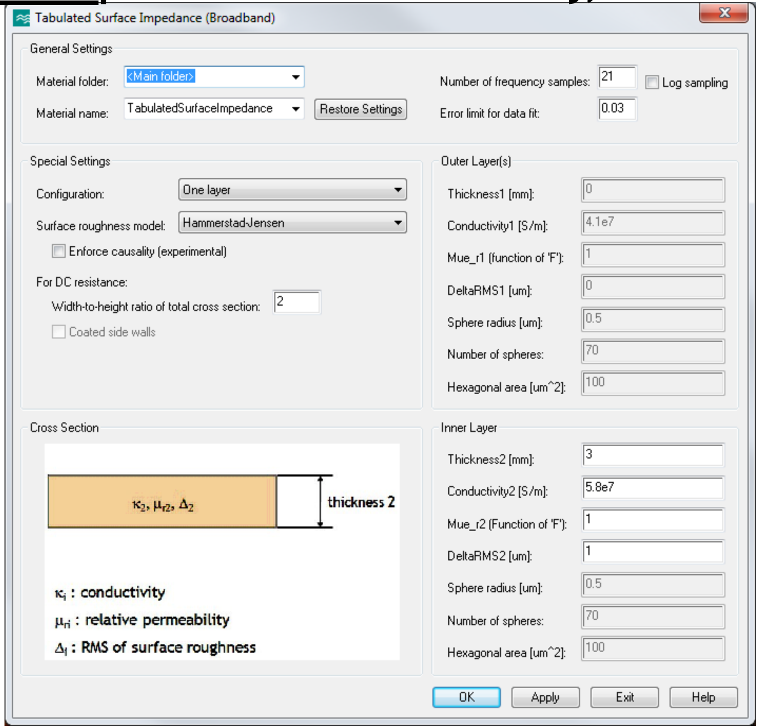


Surface Roughness Parameterization - Features

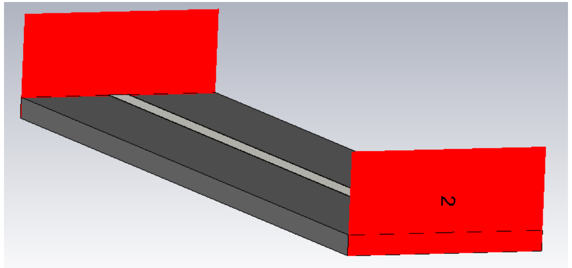
Change conductivity. Narrow band "quick" parameterization:

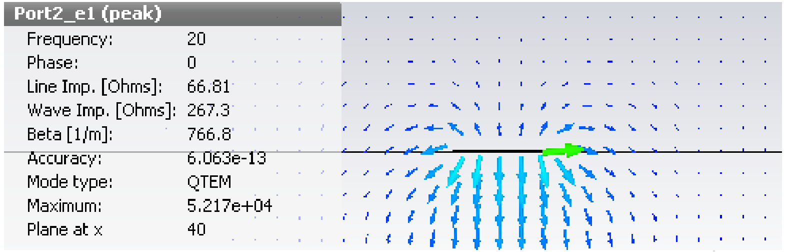


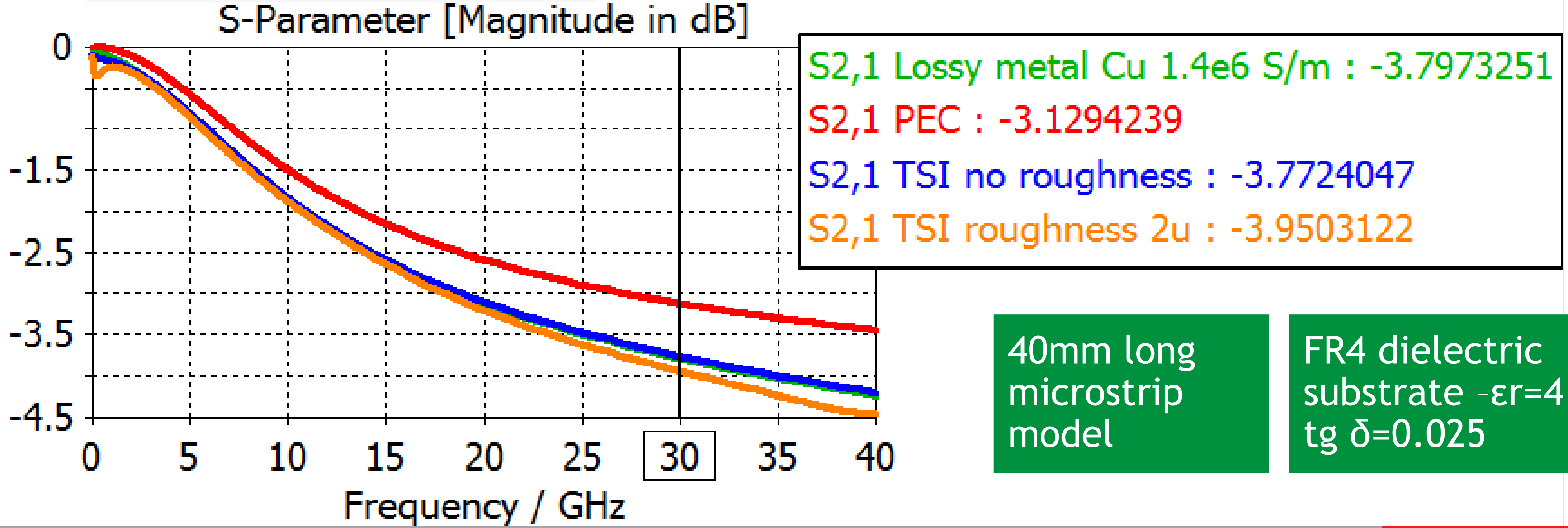
Broadband material type: <u>tabulated surface impedance parameterization</u>. Huray, Hammerstad models



Comparison of Results for Simple Model



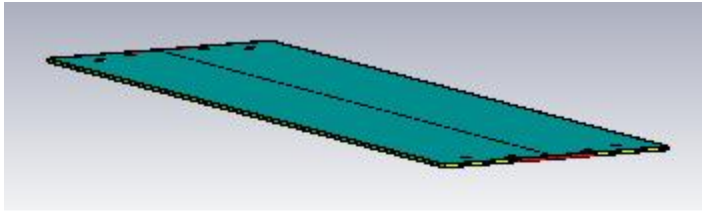


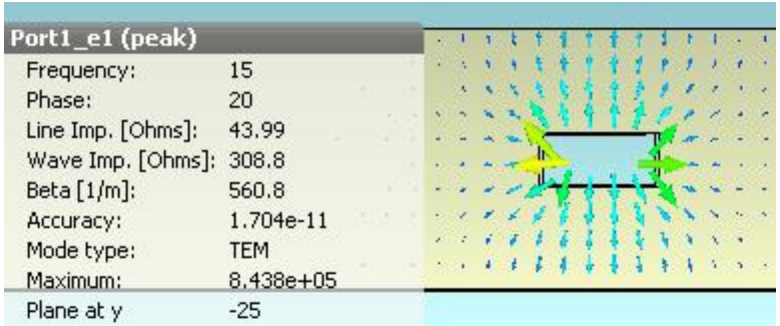


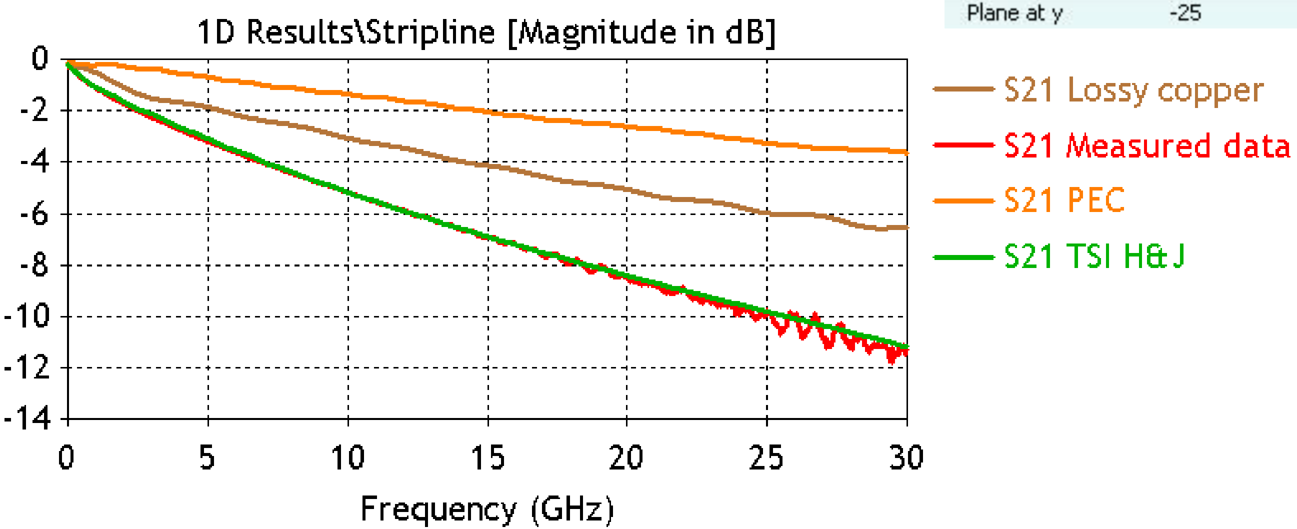
40mm long microstrip model

FR4 dielectric substrate –εr=4.3, tg δ=0.025

Measured and Simulated Data for Stripline





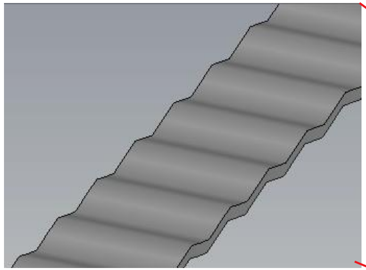


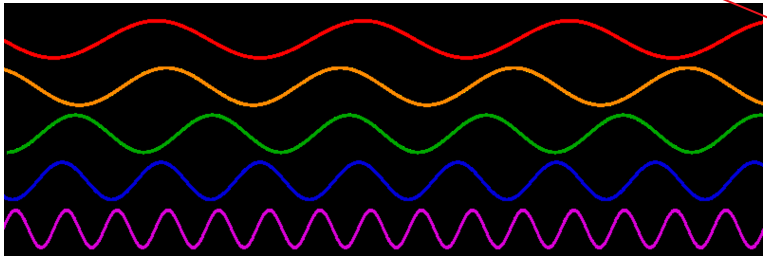
FR4 dielectric substrate –εr=3.5, tg δ=0.06

50mm long stripline model

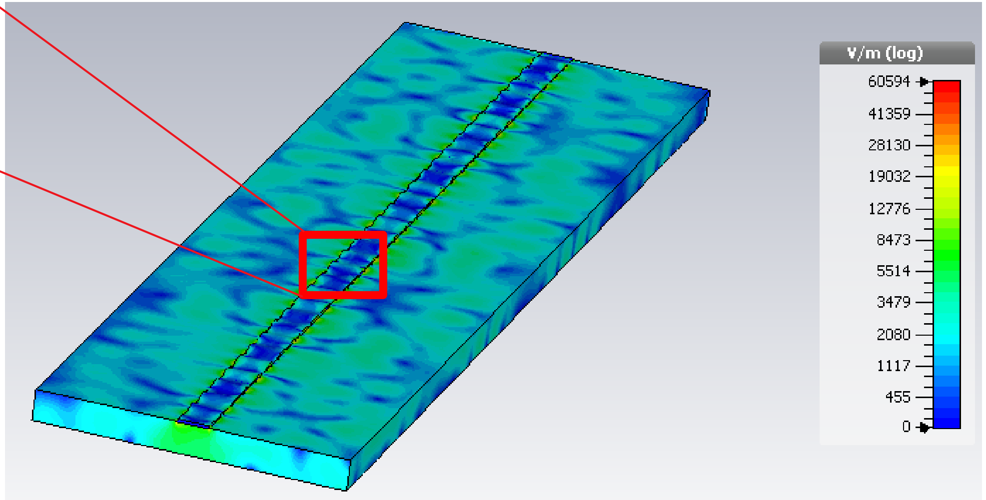
Analytical Face surface. Periodic example.

- Equation, such as polynomial can be used to generate non-smooth trace.
- Example is periodic trace: w=*Ra**sin(b00u).



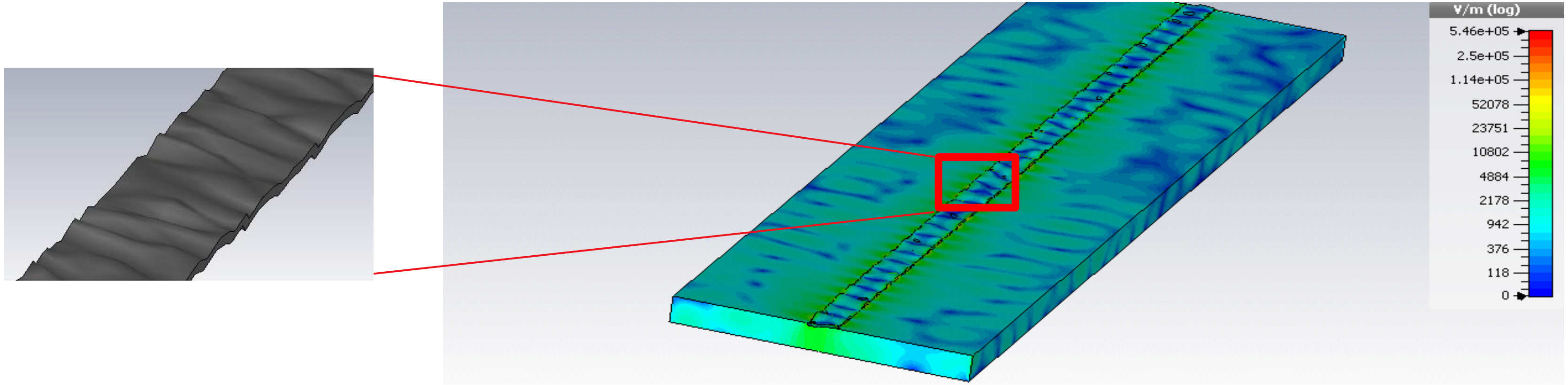


All of these waveforms have same average roughness Ra



Face Distortion Surface

Trace generated has random distortions, specifications are: peak to peak height, average distance between peaks



New Analytical Method “Roughness Dielectric”- Concept

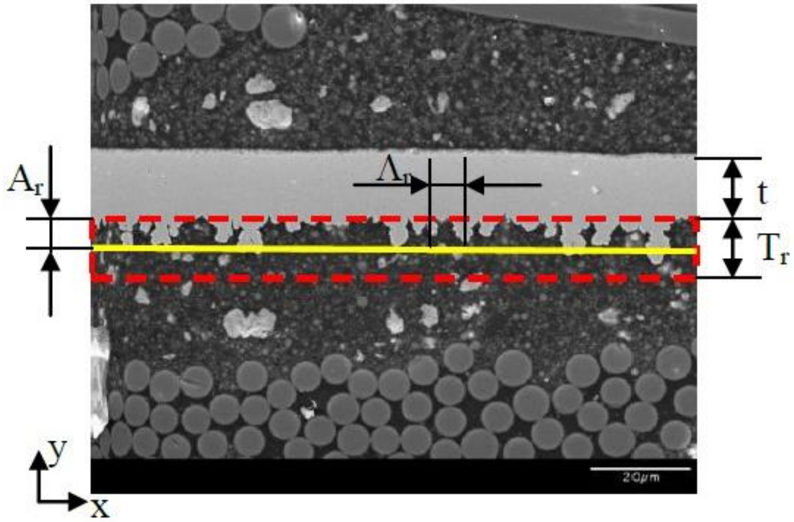
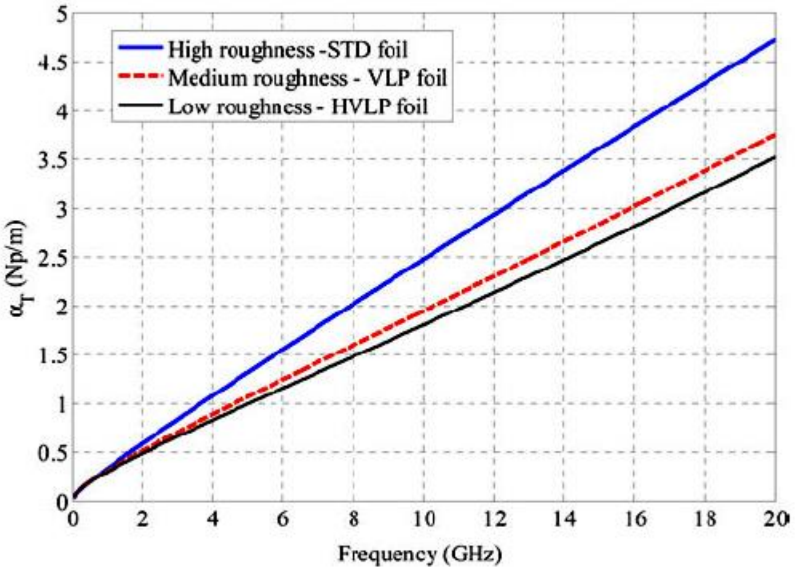


Fig. 6. Magnified section of the signal trace conductor in the SEM picture of the test line with STD foil. The region of the “roughness dielectric” is selected by a dashed line

	Ar (µm)	Λr (µm)	Ar/Λr	Ra (µm)	Rz (µm)	Rrms (µm)
STD	7.98	10.62	0.75	1.56	8.41	1.91
VLP	3.35	7.28	0.46	0.75	4.19	0.92
HVLP	1.65	4.69	0.35	0.35	2.29	0.44

Reference: Koledintseva, Razmadze, Gafarov, De, Drewniak, Hinaga “PCB Conductor Surface Roughness as a Layer with Effective Material Parameters” Electromagnetic Compatibility (EMC), 2012 IEEE International Symposium 2012

"Roughness Dielectric"- Extracting the parameters



Reference: Koul, Koledintseva, Hinaga, Drewniak "Differential Extrapolation Method for Separating Dielectric and Rough Conductor Losses in Printed Circuit Boards" IEEE Trans, 2012.

"smooth" conductor contribution /skin effect

Roughness contribution

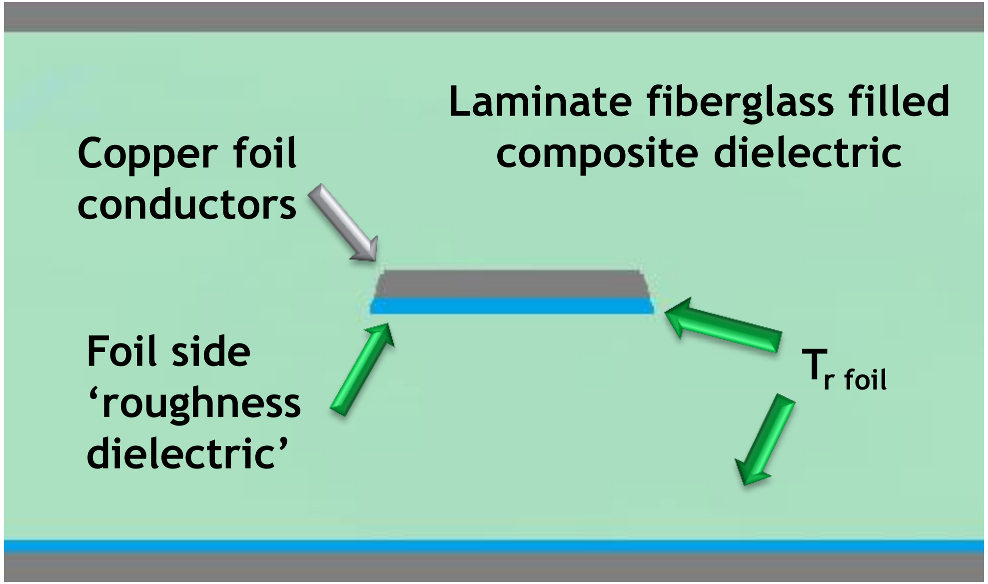
Dielectric contribution

$$\alpha_T = a\sqrt{\omega} + b\sqrt{\omega} + c\omega + d\omega^2 + e\omega + f\omega^2$$

a + b = K1 c + e = K2 d + f = K3

- Curve fitting co-efficients are generated K1 ~ √ω , K2 ~ ω, and K3 ~ ω²
- K1(0), K2(0), and K3(0) corresponds with smooth conductor, allow separation of surface roughness loss and dielectric loss. K co-efficients relate to Ar
- Dielectric material (smooth) 3D object with extracted "roughness" parameters can be included in simulation to simulate roughness impact

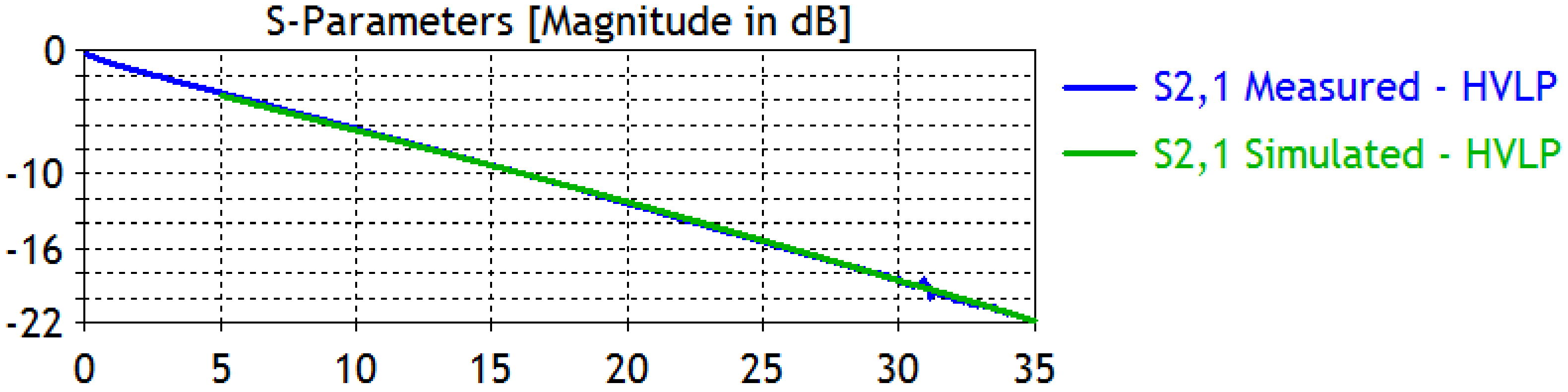
“Roughness Dielectric”- Concept

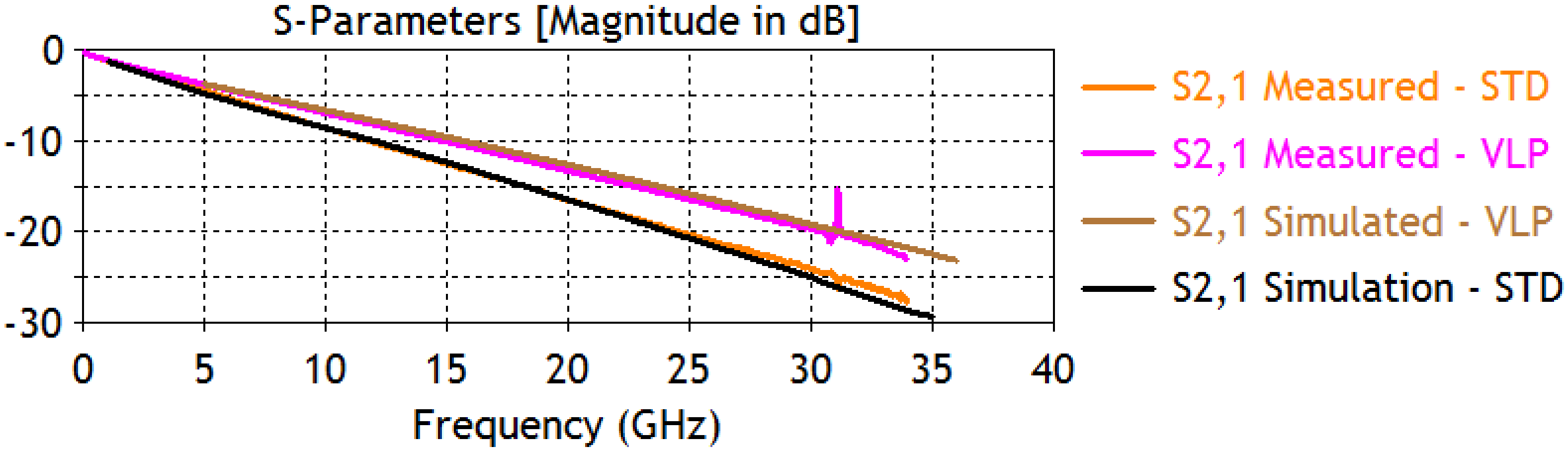


Cross section view - Not to scale for presentation purposes only

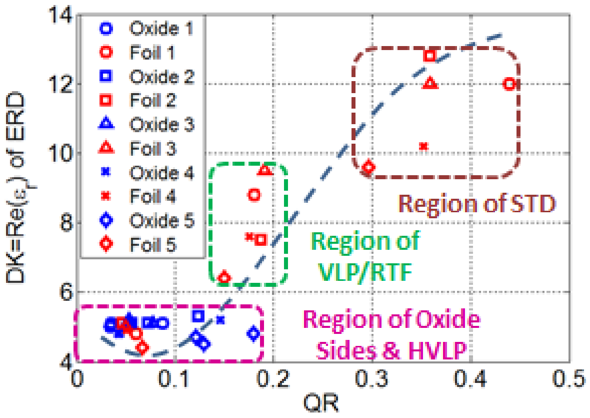
- Laminate dielectric parameters are extracted from DERM2 (for both α and β).
- Heights of ERD $T_{r\ foil}$ are taken $2A_{r\ foil}$, respectively.
- Line length for this model = 15,410 mils

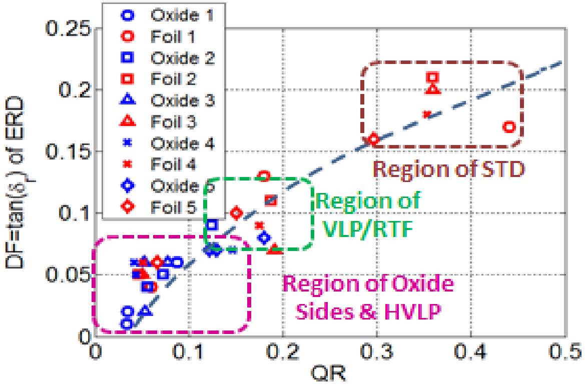
Comparison of S21 Results

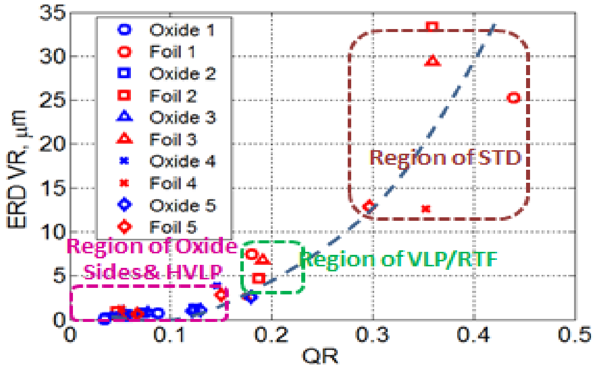




Design Curves

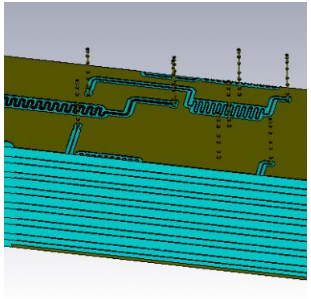




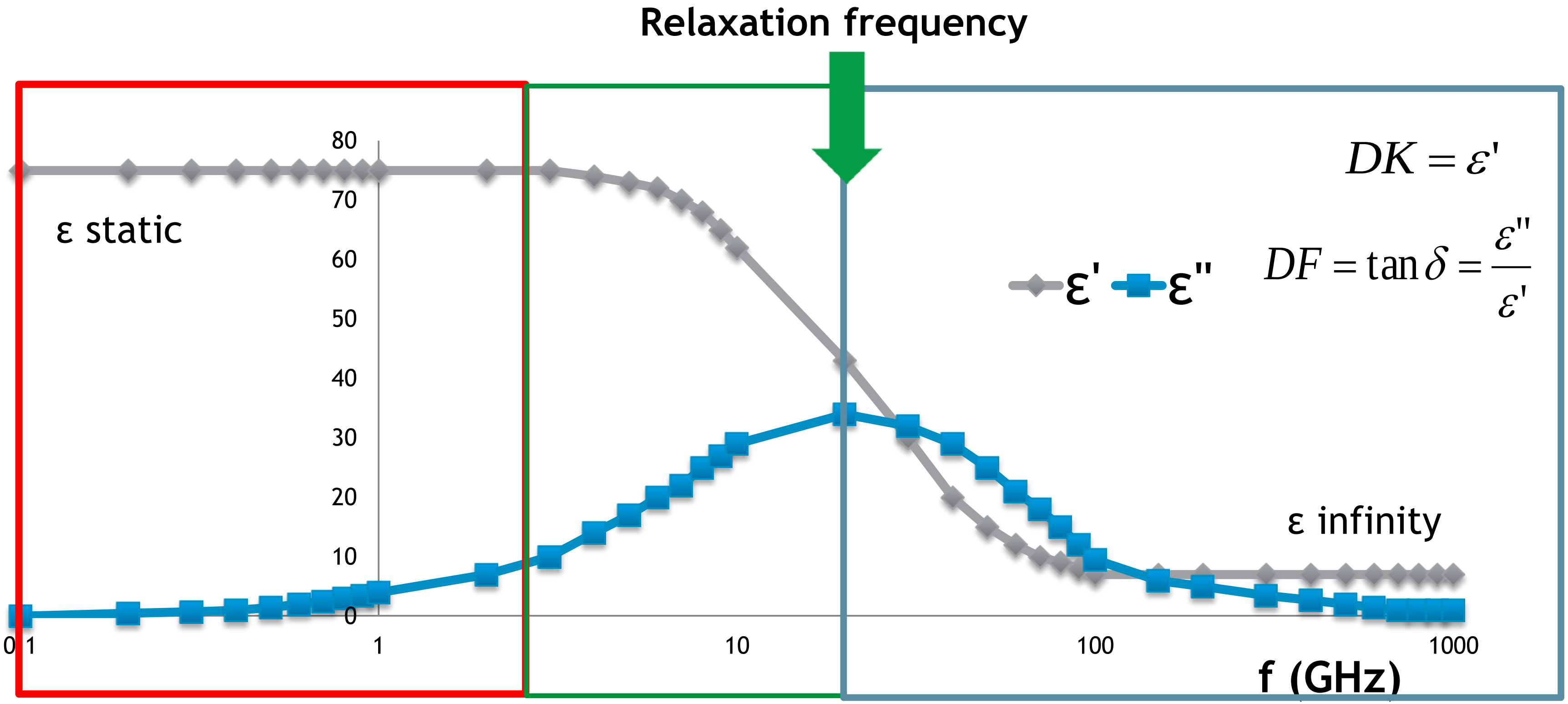


Design curves - can tie the ERD parameters to the roughness factor so design engineer does not have to do extrapolation

Simulating Dielectric Loss



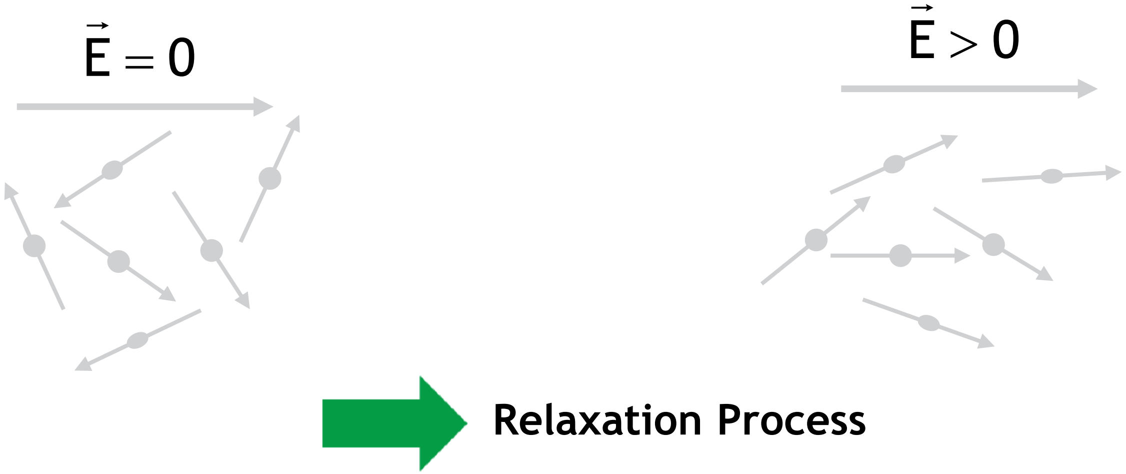
Dielectric Loss Theory - 1st Order Debye Dispersion



$$DK = \varepsilon'$$

$$DF = \tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

Dielectric Material Theory



- Such dielectric behavior can be modeled by including many relaxation terms, each localized around different frequency.
- Common PCB/package dielectric materials exhibit gradual change in dielectric constant over a very broadband frequency range.

Dielectric Loss - Causality

Definition: in any passive circuit, the effect always has to follow the cause.

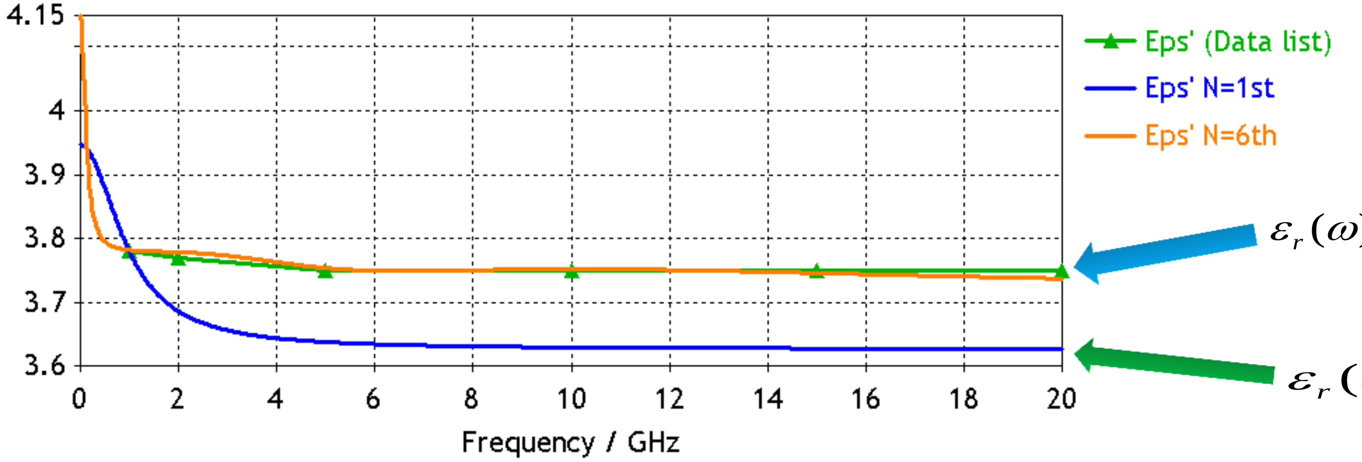
"The man who shoots faster than his **shadow**"
....."The shadow shoots the man?!?"

Sources of non-causality: Measurement, simulation (resonance, round error, interpolation, and extrapolation), and data manipulation.

Time domain solvers are broadband, curve fitting will retain causality.

Dielectric Loss – Curve fitting Nth Orders

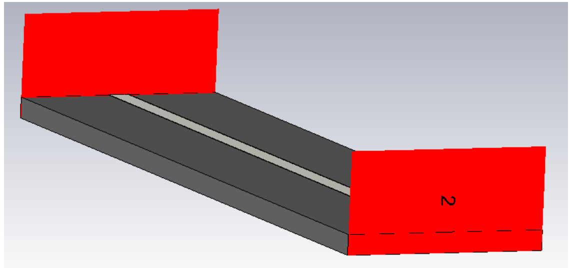
- Why nth order?
  - The transient solver is broadband (often more broadband that device modeled), dispersive materials: fit required.
  - nth order Debye/Lorentz fit more accurate than simple Debye or Lorentz models.



$$\varepsilon_r(\omega) = \varepsilon_\infty^{'} + \sum_i^N \frac{\Delta\varepsilon_i^{'}}{1 + j\dfrac{\omega}{\omega_i}} - j\frac{\sigma}{\omega\varepsilon_0}$$

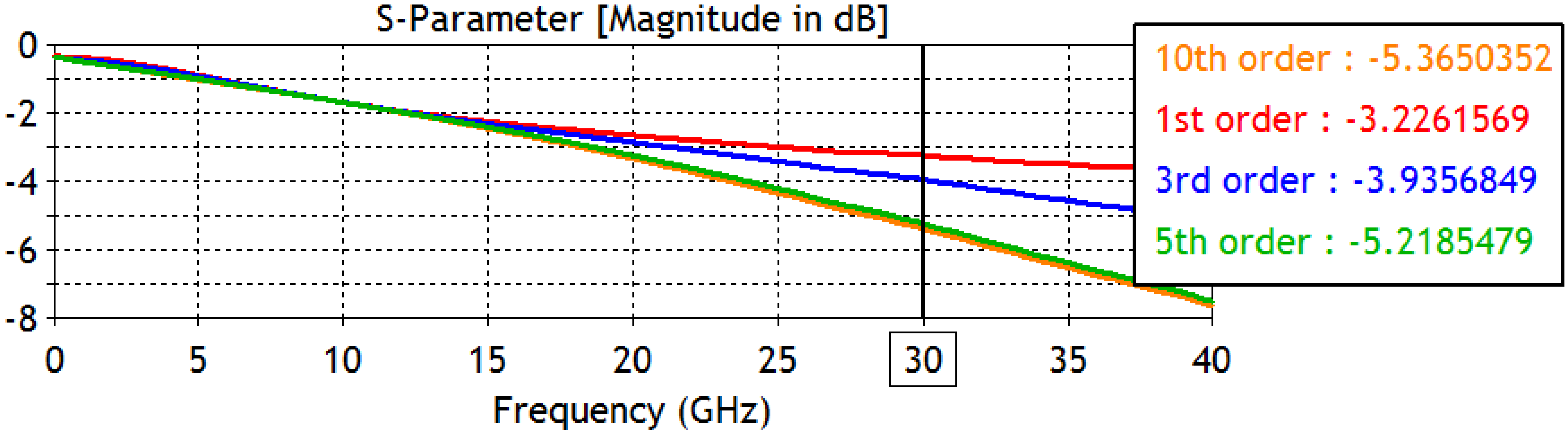
$$\varepsilon_r(\omega) = \varepsilon_\infty^{'} + \frac{\Delta\varepsilon^{'}}{1 + j\dfrac{\omega}{\omega_0}}$$

Curve Fitting Comparison - S21 Results

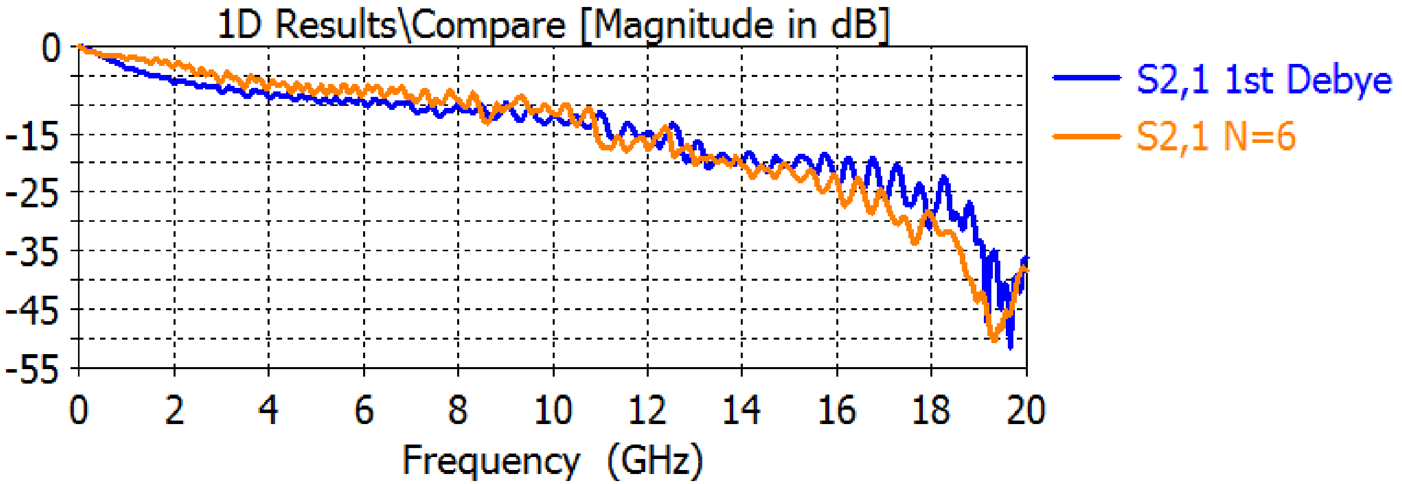


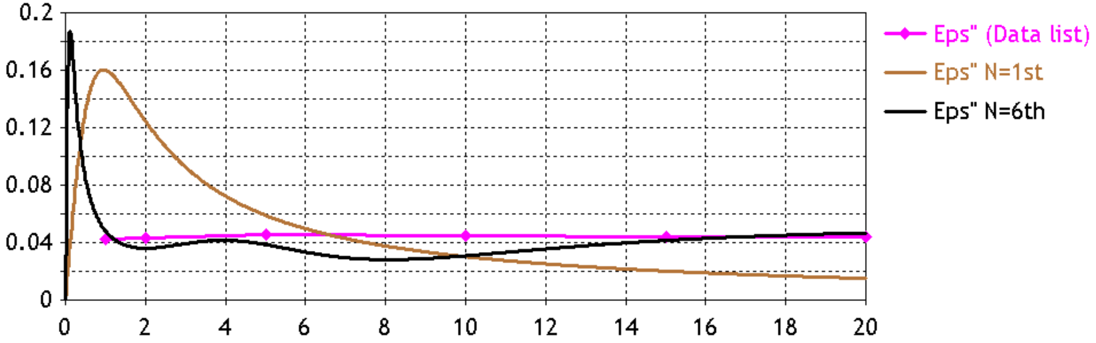
40mm long microstrip model

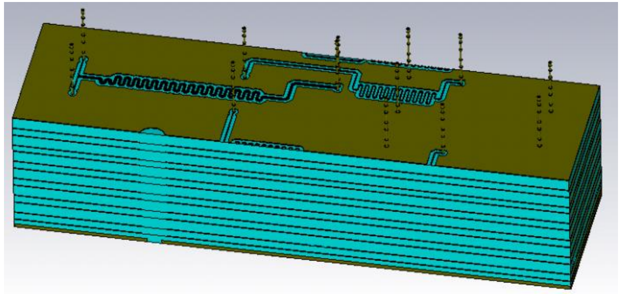
FR4 dielectric substrate –εr=4.3, tg δ=0.025



Dielectric Loss – Curve Fitting Nth Orders – S21 Results







Dielectric Loss Characterization

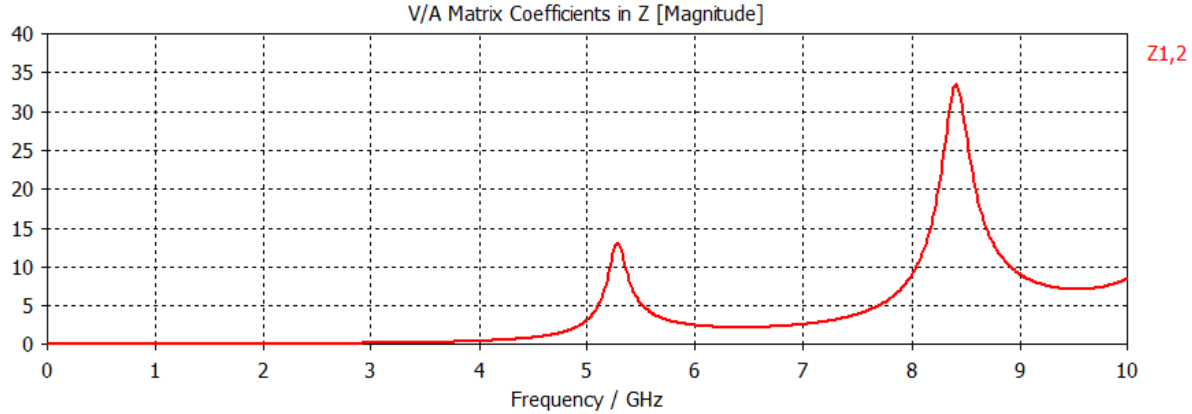
- What if you don’t have sufficient material properties for your simulation?

They can be extrapolated (and simulation can help)

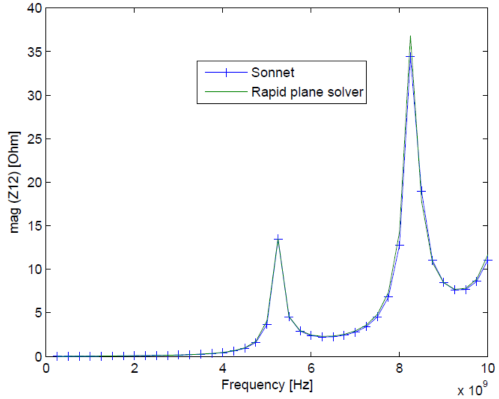
- Simulation can be used to Characterize Dielectric properties.

Different methods: Full Sheet Method, Ring Resonator, 2 through lines

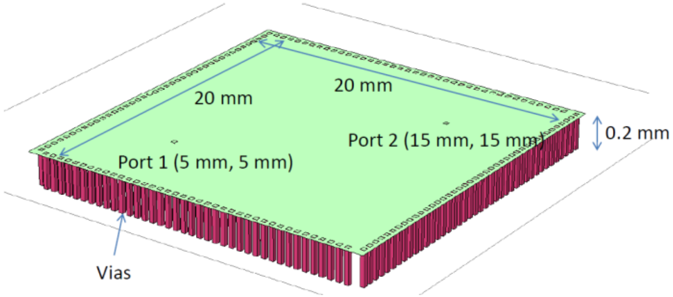
FSR with Electric Shield - Results



CST

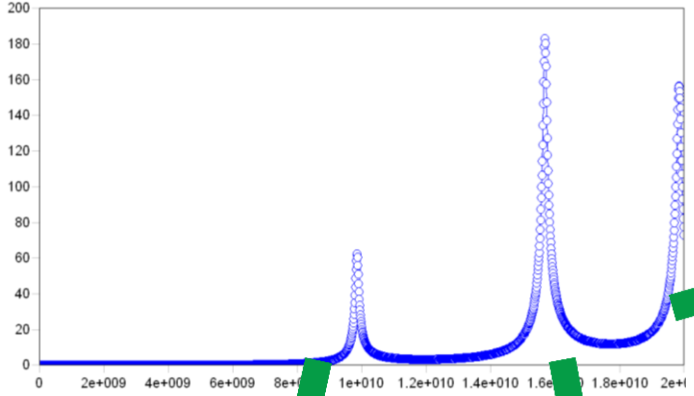


Reference: E. Engin "Extraction of Dielectric Constant and Loss Tangent Using New Rapid Plane Solver and Analytical Debye Modeling for Printed Circuit Boards", IEEE MTT 2010.

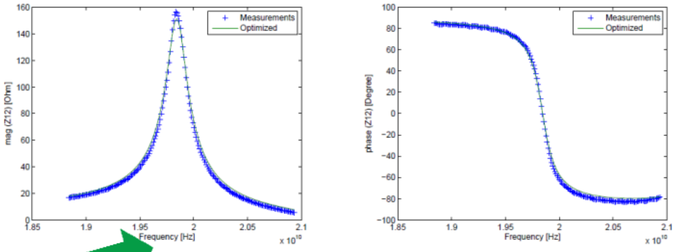


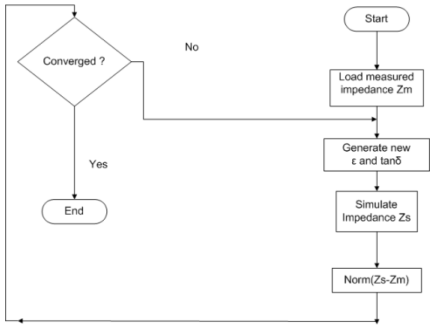
Extracting dielectric parameters with FSR

Cavity measurement

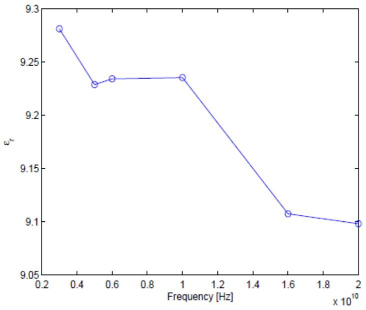


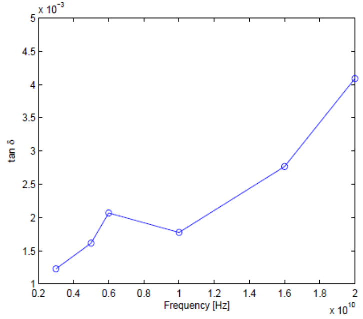
3rd resonance

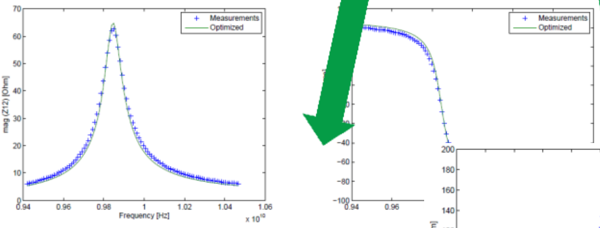




Extracted DK and DF

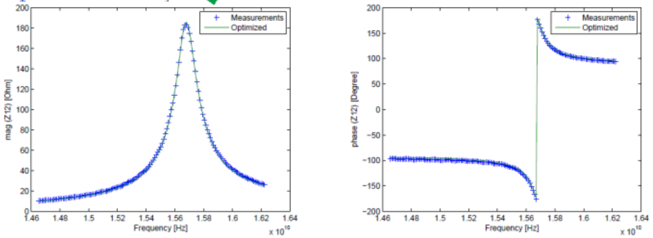






1st resonance

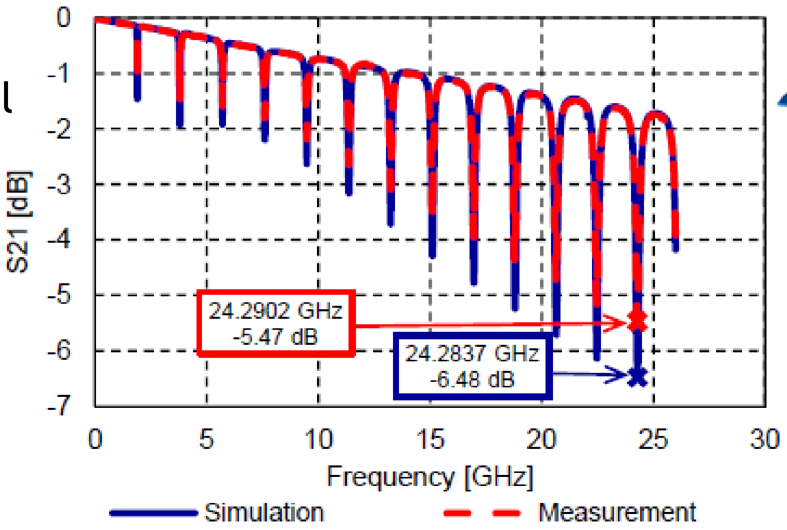
2nd resonance

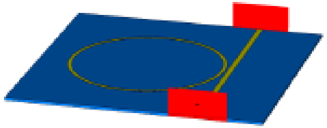


Dielectric Loss Characterization - Ring Resonator

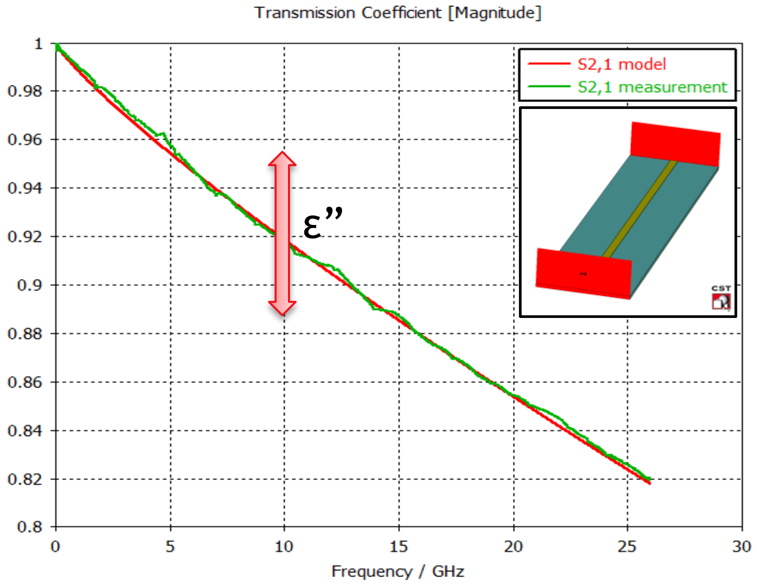
- Novel thru-line technique: calibration standards Thru and Line are much larger than $\frac{\lambda}{4}$
- Longer length increases sensitivity to substrate loss
- MACRO for automated extraction
- Research by CST and Czech Technical University in Prague.

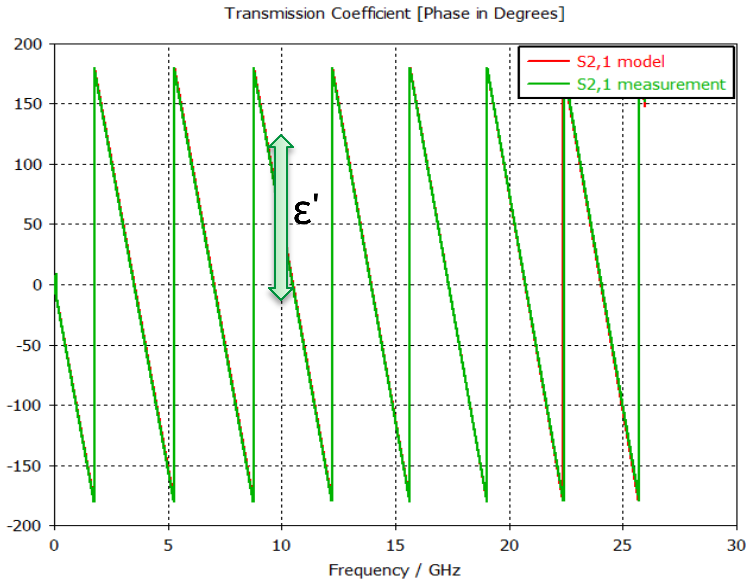
Verification

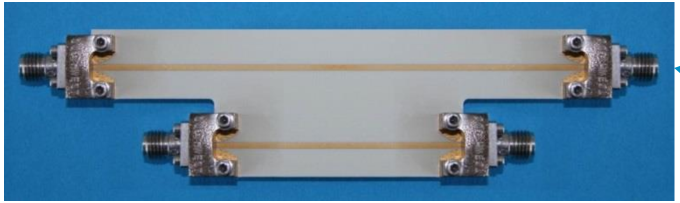




Dielectric Loss Characterization – Two Through lines

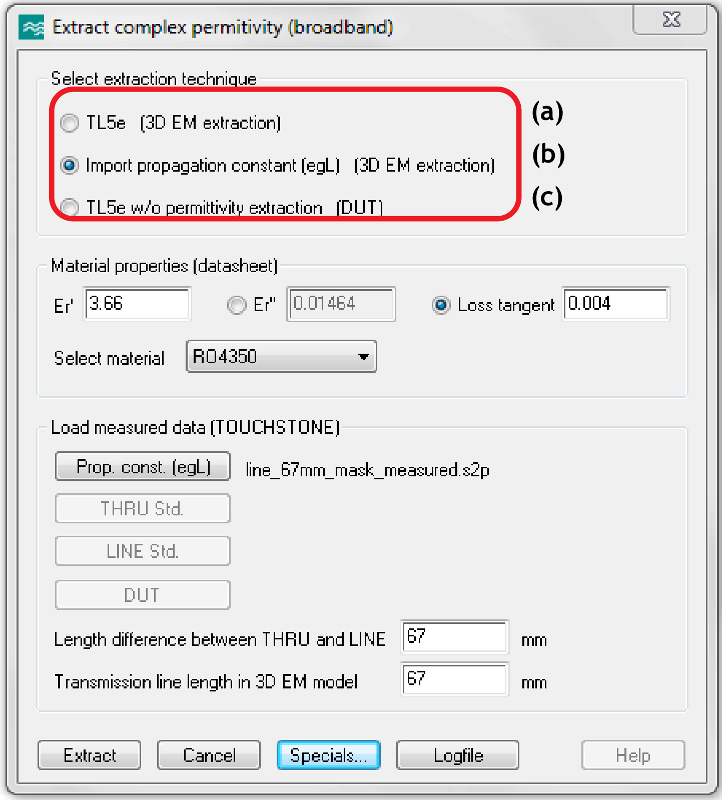






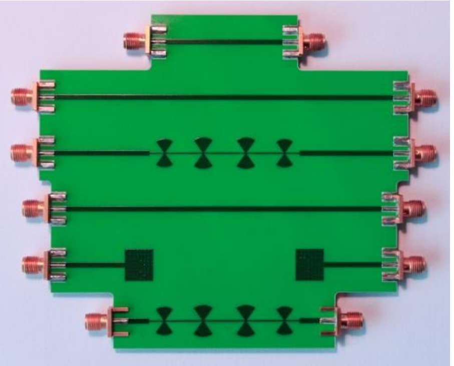
High quality end-launch connectors should be used in order to keep constant error model of the coaxial to microstrip line transition (NO soldering of the connectors!)

Automatic extraction Macro



1(a) Extracts complex permittivity from measurement of two lines* (Thru, Line) using 3D EM line model.

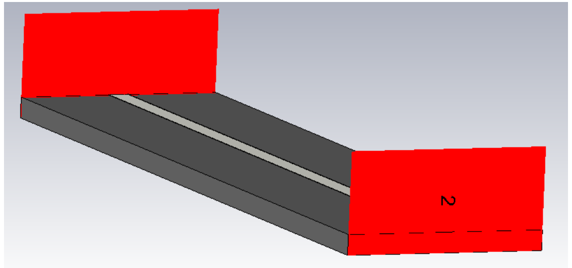
1(b) Extracts complex permittivity from directly measured S-parameters of a section of homogeneous transmission line (transmission coefficient egL) stored in Touchstone file using 3D EM line model. Multiline calkit and NIST Multiline TRL calibration technique is usually used for this option.



1(c) Extracts DUT S-parameters using just Thru and Line calibration standards*.

* 1st tier calibration at coaxial line is required.

Curve Fitting Comparison – S21 Results



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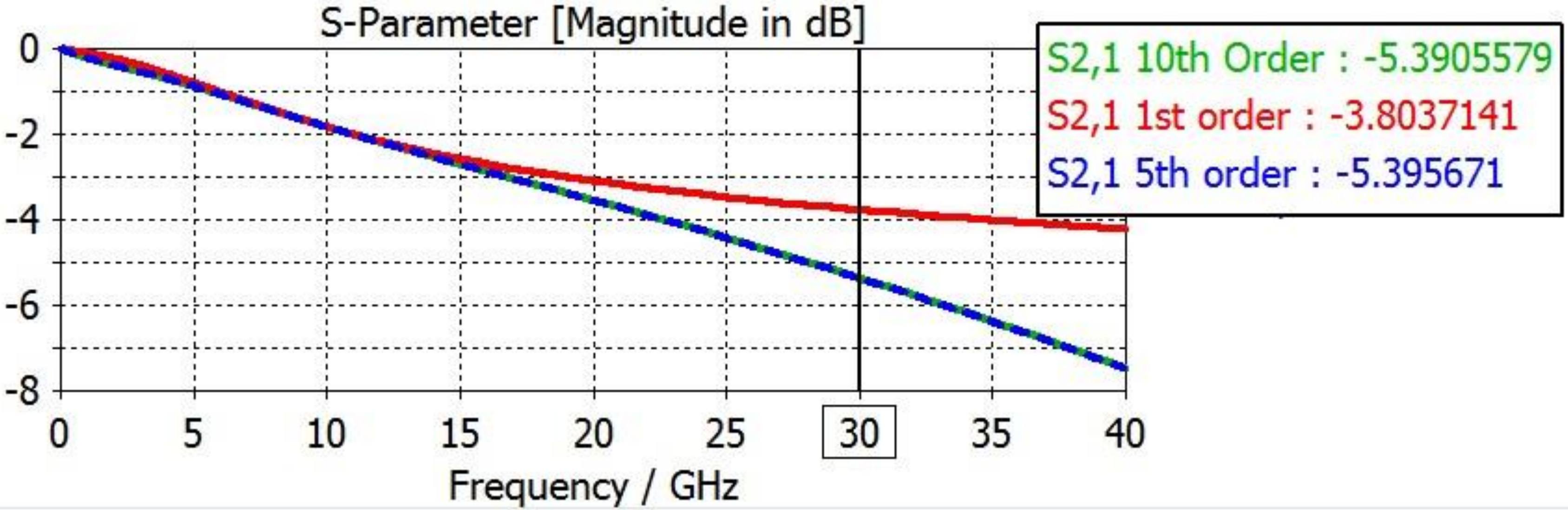
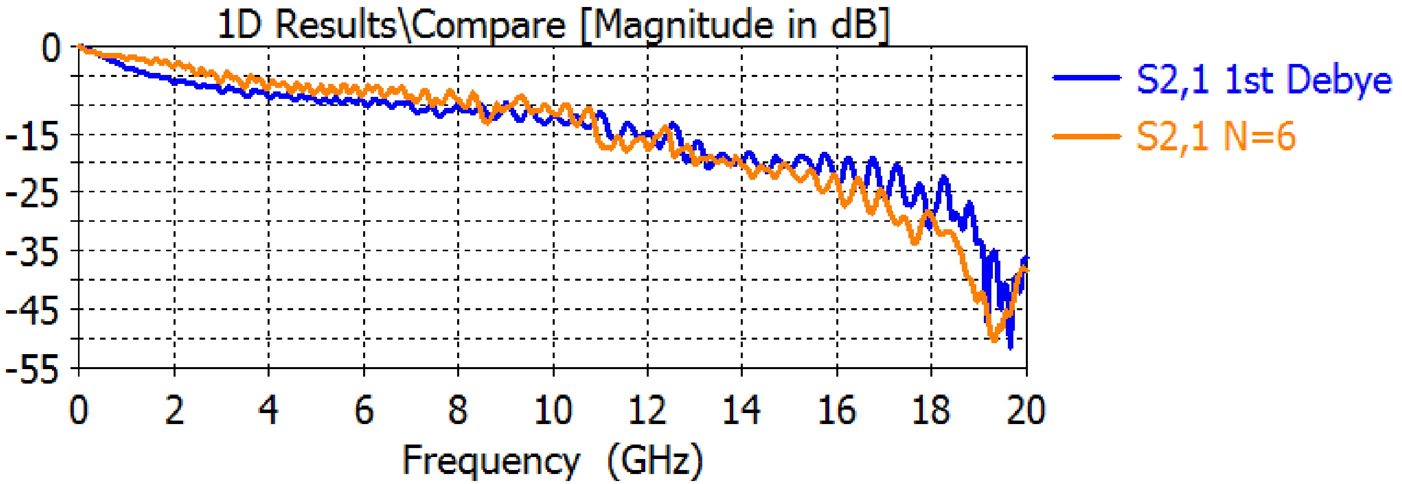
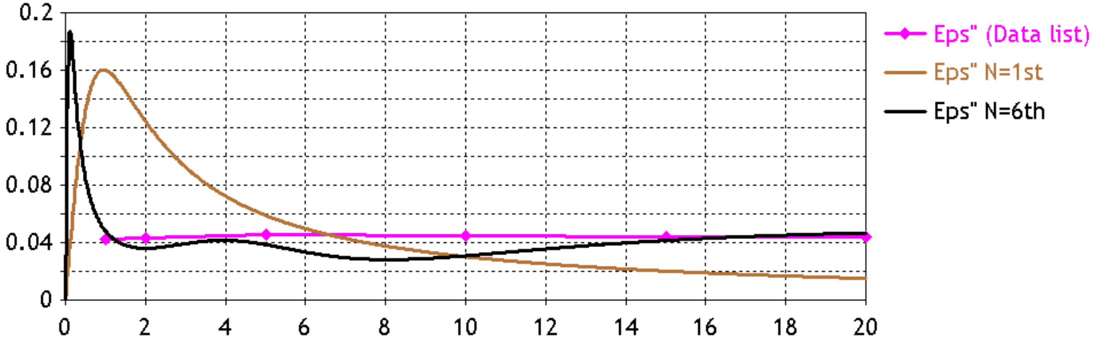
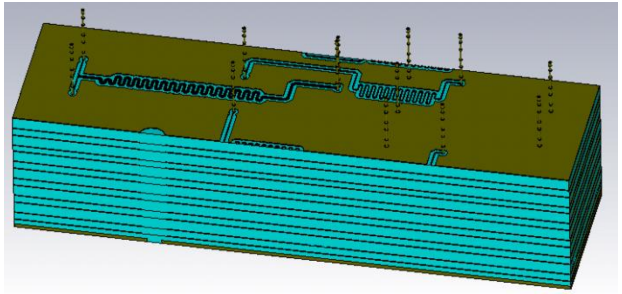


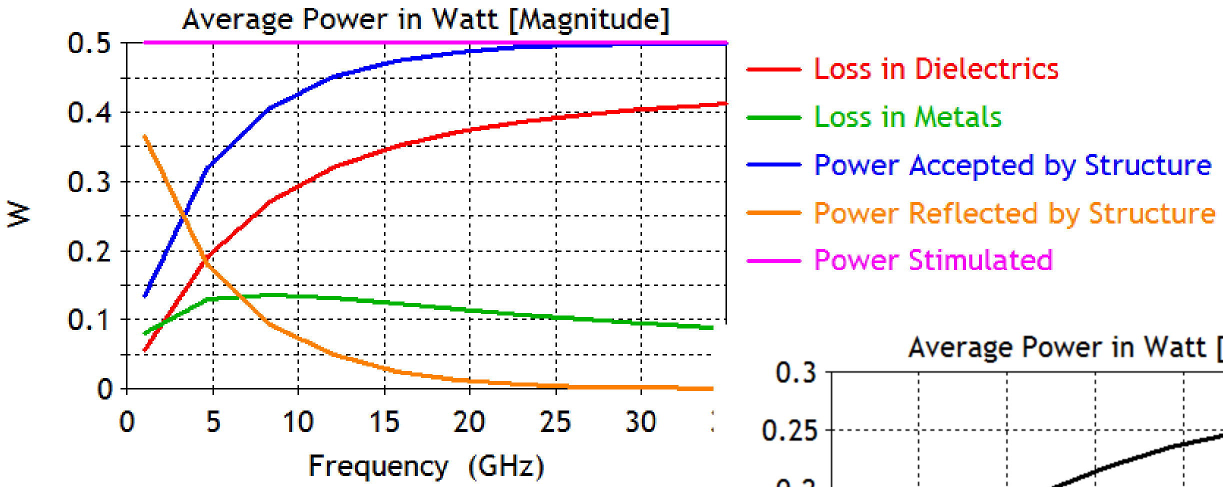
Dielectric Loss - Curve Fitting Nth Orders - S21 Results

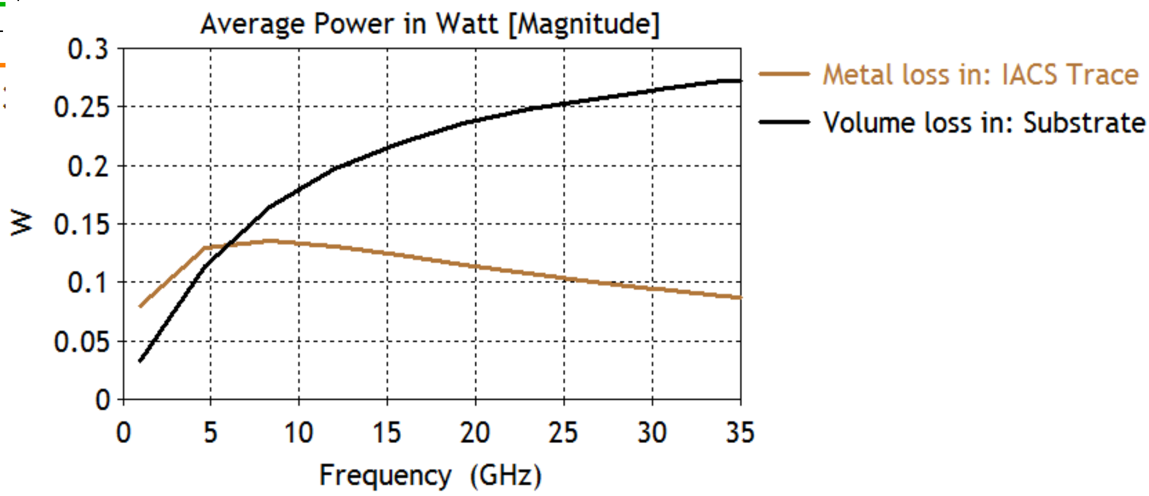




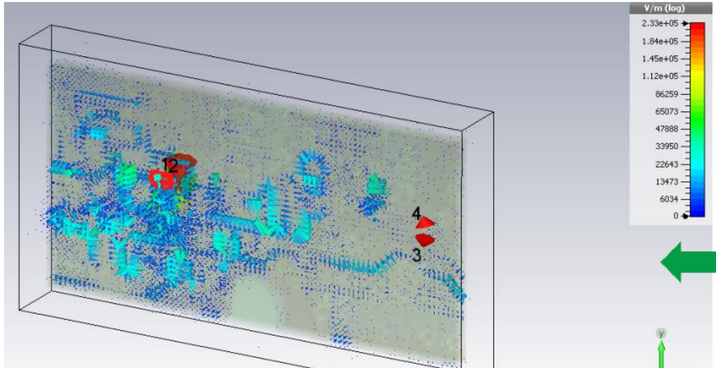


Where Does the Power go? Separating the Components

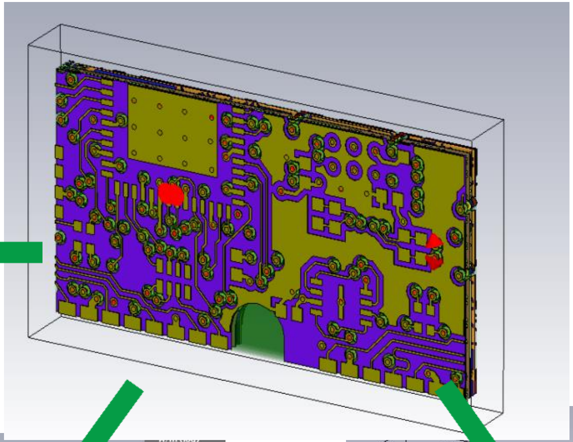


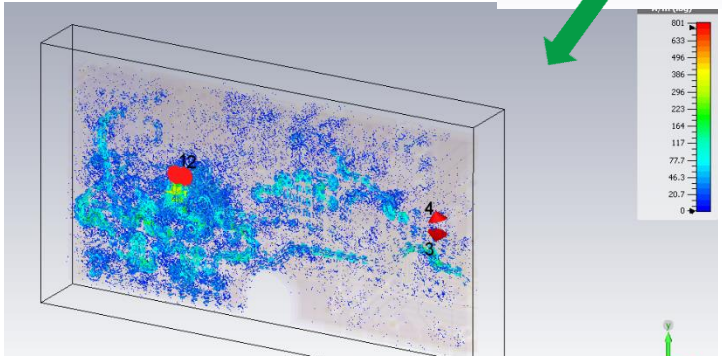


Where Does the Power go? Monitoring the Fields

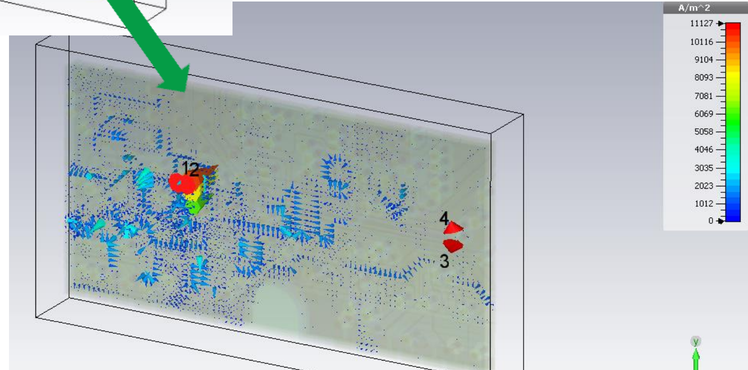


E field



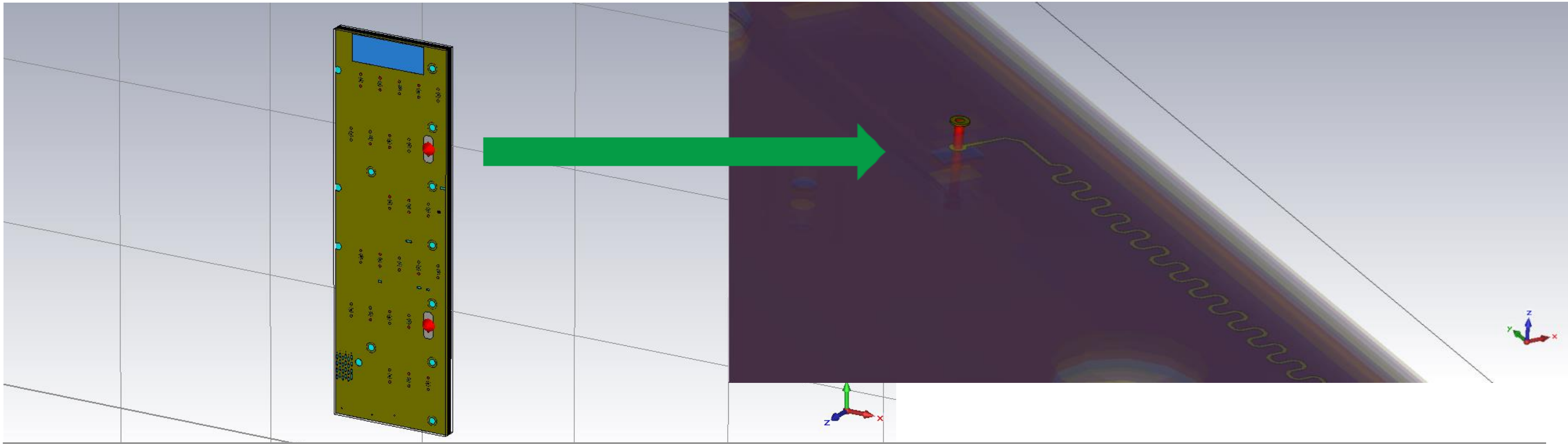


Surface current



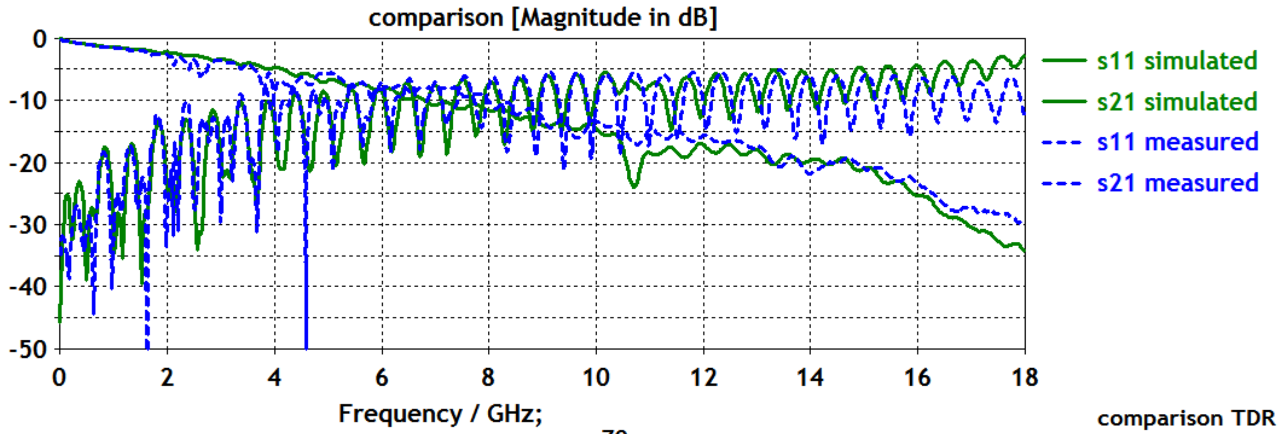
Current density

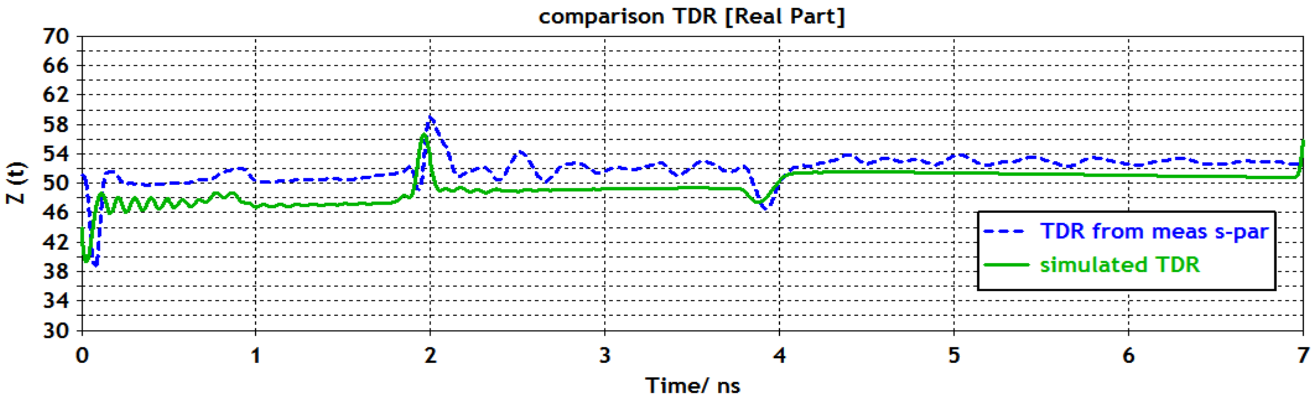
Real Case Example



Materials properties
Dielectric: eps=3.6, tgd=0.01 Debye 3rd order
Copper = 4.1e7 S/m with inclusion of surface roughness with TSI (H&J model)

S-Parameter and TDR Results





More information: webinars

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Questions?