A Causal Conductor Roughness Model and its Effect on Transmission Line Characteristics

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Principal engineer at Mentor Graphics Corporation. He has developed a number of advanced models and novel simulation methods used in the company's products. His current work includes development of efficient methods of circuit/system simulation in the time and frequency domains, transformation and analysis of multi-port systems, and statistical and time-domain analysis of SERDES links. He received Ph.D. and D.Sc. degrees (1986, 1998) based on his work on circuit and system simulation methods. The results have been published in numerous papers and conference proceedings.

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Graduated from Mohawk College of Applied Arts and Technology, Hamilton, Ontario Canada, as an Electronic Engineering Technologist. Over a 32-year career, working at Bell Northern Research/Nortel, in Ottawa, Canada, he helped pioneer several advanced technology solutions into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane architectures. After leaving Nortel in 2009, he founded Lamsim Enterprises Inc., where he continues to provide innovative signal integrity and backplane solutions as a consultant. He has also authored and coauthored several publications; posted on his web site at www.lamsimenterprises.com. His current research interests include: high-speed signal integrity, modeling and characterization of high-speed serial link architectures.

How We Model Metal Roughness: Brief Overview

Perfectly smooth metal

- Skin depth defines how far a wave propagates into a conductor, hence the thickness of the conducting layer. For metal it is: $\delta(f) = 1/\sqrt{\pi f \mu \sigma}$
- An internal impedance of a metal conductor with smooth surface is described by: $Z_{smooth}(f) = (1+i)\sqrt{\pi f}\, R_s$ with $R_s = const$
- Real (resistive) and imaginary (inductive) parts of $Z_{smooth}(f)$ are equal.
- It is also a function of complex frequency $Z_{smooth}(s) = \sqrt{s}\, R_s \quad s = i(2\pi f)$, for which exists an inverse Laplace transform, thus is a causal function.

How We Model Metal Roughness: Brief Overview

Rough metal

- Roughness is modeled by applying a frequency-dependent factor to the impedance of the smooth metal:

$$Z_{rough}(f) = K(f) Z_{smooth}(f) = K(f)(1+i)\sqrt{\pi f} R_s$$

- $K(f)$ is a real function that changes from 1 (at DC) to $K_{max}>1$ at infinite frequency.
- Resistive and inductive portions of the complex internal impedance become larger than for the smooth metal, but remain equal to each other
- Causality is not preserved, because real non-constant function of frequency cannot be a causal function.

  (Real and imaginary parts of a causal dependence must be mutually related by Hilbert transform. However, Hilbert transform from zero imaginary part may only produce a constant real part)

Loss Increase Due to Metal Roughness: Some Models

Modified Hammerstad:

$$K_{hmst}(f) = 1 + A_1 \frac{2}{\pi} \arctan(1.4(\Delta / \delta(f))^2)$$

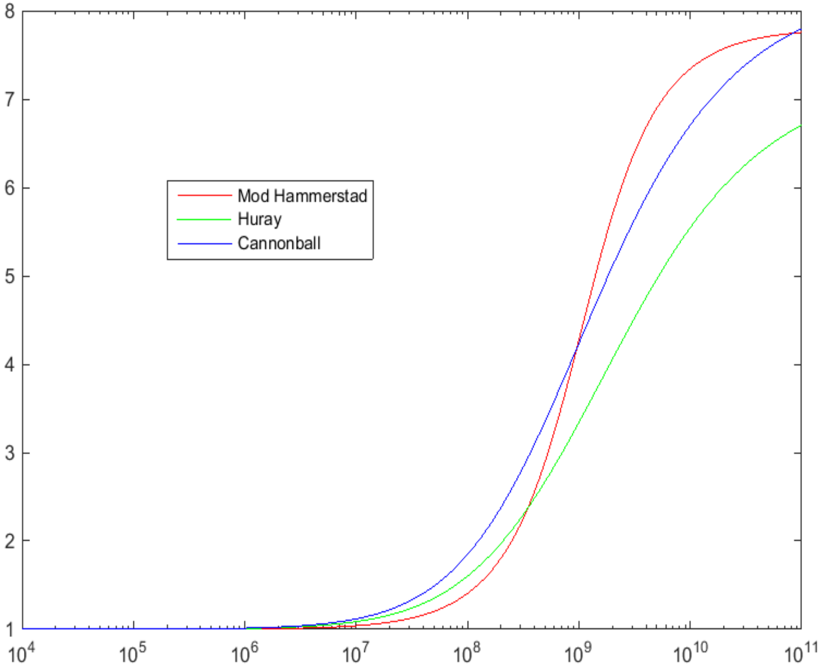
Huray:

$$K_{sph}(f) = A_0 + \sum_{n=1}^{N} \frac{A_n}{1 + \frac{\delta(f)}{a_n} + \frac{\delta^2(f)}{2a_n^2}}$$

Cannonball-Huray:

$$K_{cnnbl}(f) = 1 + \frac{(7/3)\pi}{1 + \frac{\delta(f)}{a} + \frac{\delta^2(f)}{2a^2}}$$

A number of other models with *K(f)=>real functions*



How Textbooks Define “Roughness Correction Factor”

E.g. S. Hall, H. Heck, “Advanced signal integrity for high speed digital designs,” John Willey & Sons Inc., Hoboken, NJ, 2009.

“At high frequencies, surface roughness will increase the ohmic losses of a transmission-line conductor”

“A ratio of the power absorbed with and without a good conducting protrusion”

- The correcting factor was defined as a loss increase due to additional power dissipation/loss on a rough metal
- As such, it should be associated only with resistive portion of the complex impedance
- On what basis we keep applying this factor to the inductive portion (internal metal inductance)? This doesn’t seem right; makes the model non-causal

Have Been Any Steps Made to Fix Non-causal Roughness Models?

1) Same book of S. Hall and H. Heck. Appendix E. “Causal relationships between skin effect resistance and internal inductance for rough conductors”, 2009
   - *“In general, real and imaginary parts of internal impedance of rough metal are not equal, but must be mutual Hilbert transforms*”. However, this statement was not applied to existing models
2) This approach was first realized in [E. Bracken, A causal Huray model for surface roughness, DesignCon 2012]
   - Author shows a causal version of Huray roughness factor that uses components of the form:

$$K_{Huray}(\omega)=1+\sum_{i=1}^{N}K_H^{(i)}(j\omega)\text{, where } K_H^{(i)}(j\omega)=\frac{K_i}{1+\left(\dfrac{j2\omega}{\omega_i}\right)^{-1/2}}$$

Why Those Efforts Are Not Enough?

- The authors didn’t show how a causal model could be derived; didn’t outline a general approach that works for different models (including those given by tables)
- Didn’t analyze the consequences of using causal model vs non-causal for Transmission lines, and more complicated structures
- Causal roughness models didn’t get into commercial simulators yet; except for a couple of tools that have been updated this year (2017)
- Although some folks understand the need for causal roughness models, this is not a common knowledge or concern since we don’t know otherwise

The Goals of This Work

- Get back to basics, introduce “loss correction factor” (applies to resistance), “inductance correction factor” (to internal metal inductance), and complex correction factor, establish dependences between them
- Outline a general approach of deriving a causal complex correction factor for a given loss correction dependence, analytical or table
- Apply this method to Cannonball/Huray and Hammerstad formulas and find causal correction factors in “Laplace” form. Compare the models side-by-side
- Analyze the impact of using causal roughness models on internal metal inductance
- Predict the changes causal models bring into characteristics of lossy transmission lines

Proposed Terminology: Complex Roughness Correction Factor, Loss and Inductance Correction Factors

Let roughness correction factor be complex: $K(if) = K_{re}(f) + iK_{im}(f)$

After multiplying it on a complex “skin impedance”, we get:

$$Z_{rough}(if) = \overbrace{\underbrace{K(if)}_{\text{Complex roughness correction factor}}(1+i)\sqrt{\pi f}\,R_s}^{\text{Complex impedance of rough metal}} = \overbrace{\underbrace{[K_{re}(f) - K_{im}(f)]}_{\text{Loss correction factor}}\sqrt{\pi f}\,R_s}^{\text{Real part of internal impedance of rough metal}} + \overbrace{i\underbrace{[K_{re}(f) + K_{im}(f)]}_{\text{Inductance correction factor}}\sqrt{\pi f}\,R_s}^{\text{Imaginary part of internal impedance of rough metal}}$$

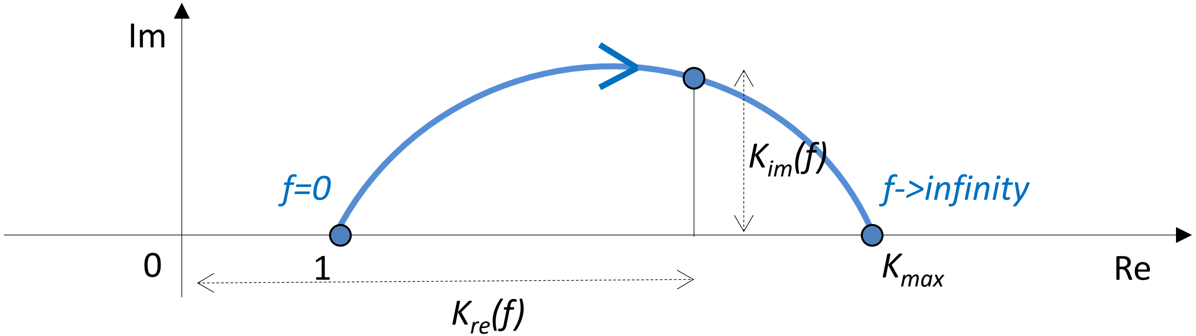
This is what we used to call “roughness correction” factor

Complex Roughness Correction Factor, Loss and Inductance Correction Factors

Let's represent complex correction factor by a polar plot. As a causal function, it should demonstrate clockwise direction of rotation. It changes from $K(0)=1$ to $K(inf)=K_{max}>1$. From here, it follows that $K_{im}(f)>0$ and therefore, inductive component of rough impedance exceeds resistive, because

$$K_{re}(f)+K_{im}(f)>K_{re}(f)-K_{im}(f)$$

Conclusion: non-causal roughness model (real correction factor) underestimates internal inductance of rough metal



How Can We Derive a Causal Complex Correction Factor?

From above definitions we get: $Z_{rough}(if) = K_{loss}(f)\sqrt{\pi f}R_s + iK_{induct}(f)\sqrt{\pi f}R_s$

- The first summand on the left is known because $K_{loss}(f)$ is given by a model formula
- Since $Z_{rough}(if)$ is causal, real and imaginary parts on the right should be related by Kramers-Kronig (K-K) integral relation
- Unfortunately, K-K integral requires that the integrand disappears at infinity, but it grows as *sqrt(f)*
- To overcome this problem, we find a complex inductance, which is also a causal function:

$$L_{rough}(if) = Z_{rough}(if)/(2\pi if) = \frac{R_s}{2\sqrt{\pi}}[K_{induct}(f)/\sqrt{f} - iK_{loss}(f)/\sqrt{f}]$$

- Now, imaginary part (blue) is known and disappears at infinity. Real part (pink) can be found by K-K integral:

$$Q_{real}(x) = \frac{2}{\pi} v.p.\int_0^\infty \frac{yQ_{imag}(y)dy}{(y^2 - x^2)}$$

Derivation of Causal Cannonball-Huray model

- Take general formula for the loss correction factor, eliminate a constant from the sum, consider just one summand, normalized.

$$K_{sph}(f) = A_0 + \sum_{n=1}^{N} \frac{A_n}{1+\frac{\delta(f)}{a_n}+\frac{\delta^2(f)}{2a_n^2}} \quad \Longrightarrow \quad K_0(f) = \frac{1}{1+\frac{\delta(f)}{a}+\frac{\delta^2(f)}{2a^2}}$$

- Introduce a normalized frequency $x = \omega\mu_0\sigma a^2$. Then, the normalized factor becomes: $K_0(x) = \dfrac{x}{x+\sqrt{2x}+1}$

- Resistive (real) portion of rough impedance, normalized: $\dfrac{x\sqrt{x}}{x+\sqrt{2x}+1}$

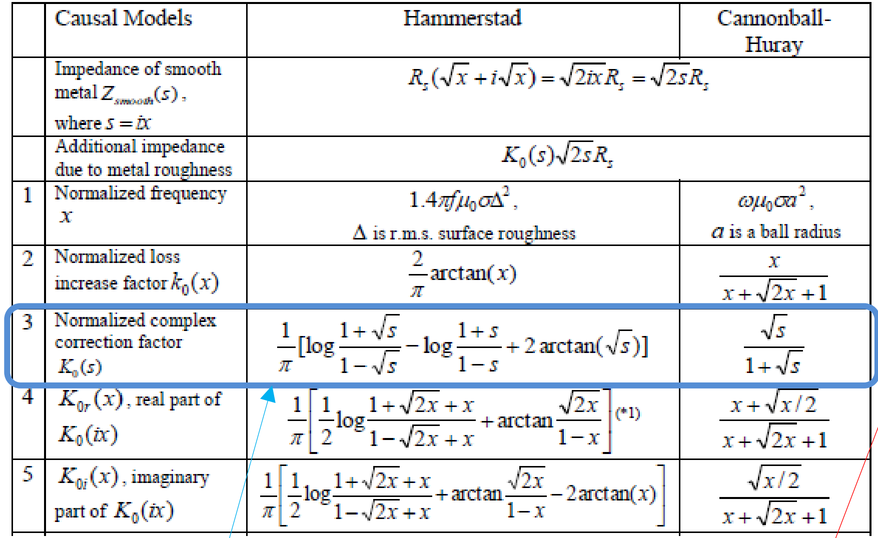
- Imaginary part of the complex inductance, normalized: $-\dfrac{\sqrt{x}}{x+\sqrt{2x}+1}$

- Real part of the complex inductance, normalized: $L_{0,re}(x) = \dfrac{2}{\pi} v.p.\displaystyle\int_0^{\infty} \frac{y\sqrt{y}}{(y^2-x^2)(y+\sqrt{2y}+1)}dy = \frac{\sqrt{2}+\sqrt{x}}{x+\sqrt{2x}+1}$

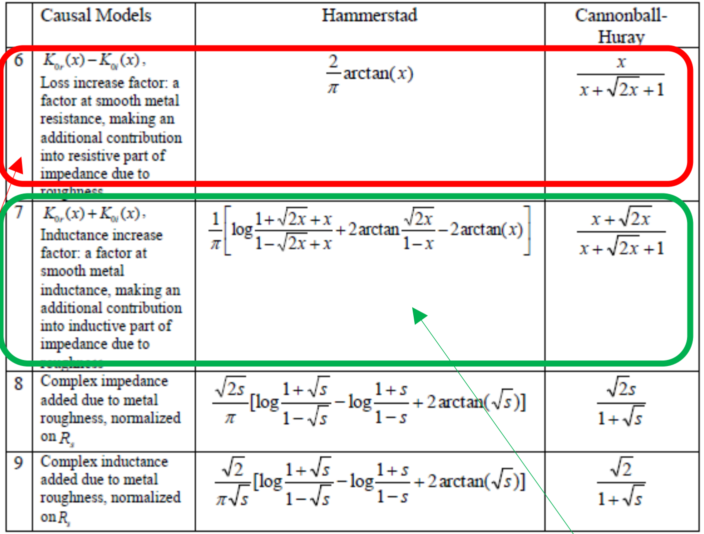
Derivation of Causal Cannonball-Huray Model

- Full complex inductance, normalized: $L_0(ix)=\dfrac{\sqrt{2}+\sqrt{x}-i\sqrt{x}}{x+\sqrt{2x}+1}$
- Introduce a normalized complex frequency: $s=ix,\quad \sqrt{s}=\sqrt{ix}=\dfrac{1}{\sqrt{2}}(1+i)\sqrt{x}$
- From here: $x=-is,\quad \sqrt{x}=\dfrac{1}{\sqrt{2}}(1-i)\sqrt{s}$
- Substitute above into complex inductance and get: $L_0(s)=\dfrac{\sqrt{2}}{1+\sqrt{s}}$
- Complex internal impedance, normalized on R_s: $Z_0(s)=\dfrac{\sqrt{2}s}{1+\sqrt{s}}$
- Complex roughness correction factor: $K_0(s)=\dfrac{\sqrt{s}}{1+\sqrt{s}}$

Summary: Causal Cannonball-Huray and Hammerstad Models



	Causal Models	Hammerstad	Cannonball-Huray
	Impedance of smooth metal $Z_{smooth}(s)$, where $s = ix$	$R_s(\sqrt{x} + i\sqrt{x}) = \sqrt{2ix}R_s = \sqrt{2s}R_s$	
	Additional impedance due to metal roughness	$K_0(s)\sqrt{2s}R_s$	
1	Normalized frequency x	$1.4\pi f\mu_0\sigma\Delta^2$, Δ is r.m.s. surface roughness	$\omega\mu_0\sigma a^2$, a is a ball radius
2	Normalized loss increase factor $k_0(x)$	$\frac{2}{\pi}\arctan(x)$	$\frac{x}{x+\sqrt{2x}+1}$
3	Normalized complex correction factor $K_0(s)$	$\frac{1}{\pi}[\log\frac{1+\sqrt{s}}{1-\sqrt{s}} - \log\frac{1+s}{1-s} + 2\arctan(\sqrt{s})]$	$\frac{\sqrt{s}}{1+\sqrt{s}}$
4	$K_{0r}(x)$, real part of $K_0(ix)$	$\frac{1}{\pi}\left[\frac{1}{2}\log\frac{1+\sqrt{2x}+x}{1-\sqrt{2x}+x} + \arctan\frac{\sqrt{2x}}{1-x}\right]$ (*1)	$\frac{x+\sqrt{x/2}}{x+\sqrt{2x}+1}$
5	$K_{0i}(x)$, imaginary part of $K_0(ix)$	$\frac{1}{\pi}\left[\frac{1}{2}\log\frac{1+\sqrt{2x}+x}{1-\sqrt{2x}+x} + \arctan\frac{\sqrt{2x}}{1-x} - 2\arctan(x)\right]$	$\frac{\sqrt{x/2}}{x+\sqrt{2x}+1}$



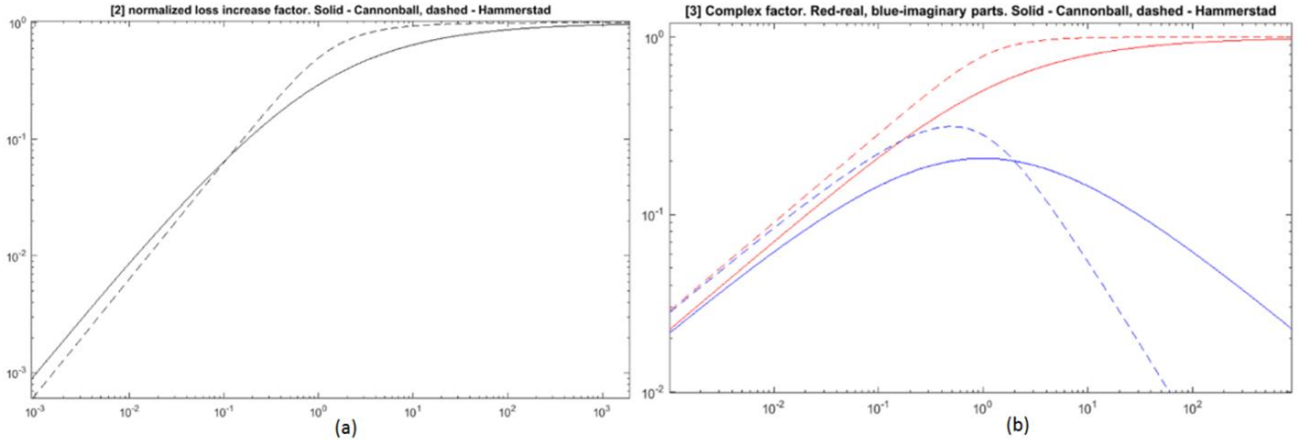
	Causal Models	Hammerstad	Cannonball-Huray
6	$K_{0r}(x) - K_{0i}(x)$, Loss increase factor: a factor at smooth metal resistance, making an additional contribution into resistive part of impedance due to roughness	$\frac{2}{\pi}\arctan(x)$	$\frac{x}{x+\sqrt{2x}+1}$
7	$K_{0r}(x) + K_{0i}(x)$, Inductance increase factor: a factor at smooth metal inductance, making an additional contribution into inductive part of impedance due to roughness	$\frac{1}{\pi}\left[\log\frac{1+\sqrt{2x}+x}{1-\sqrt{2x}+x} + 2\arctan\frac{\sqrt{2x}}{1-x} - 2\arctan(x)\right]$	$\frac{x+\sqrt{2x}}{x+\sqrt{2x}+1}$
8	Complex impedance added due to metal roughness, normalized on R_s	$\frac{\sqrt{2s}}{\pi}[\log\frac{1+\sqrt{s}}{1-\sqrt{s}} - \log\frac{1+s}{1-s} + 2\arctan(\sqrt{s})]$	$\frac{\sqrt{2s}}{1+\sqrt{s}}$
9	Complex inductance added due to metal roughness, normalized on R_s	$\frac{\sqrt{2}}{\pi\sqrt{s}}[\log\frac{1+\sqrt{s}}{1-\sqrt{s}} - \log\frac{1+s}{1-s} + 2\arctan(\sqrt{s})]$	$\frac{\sqrt{2}}{1+\sqrt{s}}$

Complex roughness correction factor

Loss correction factor

Inductance correction factor

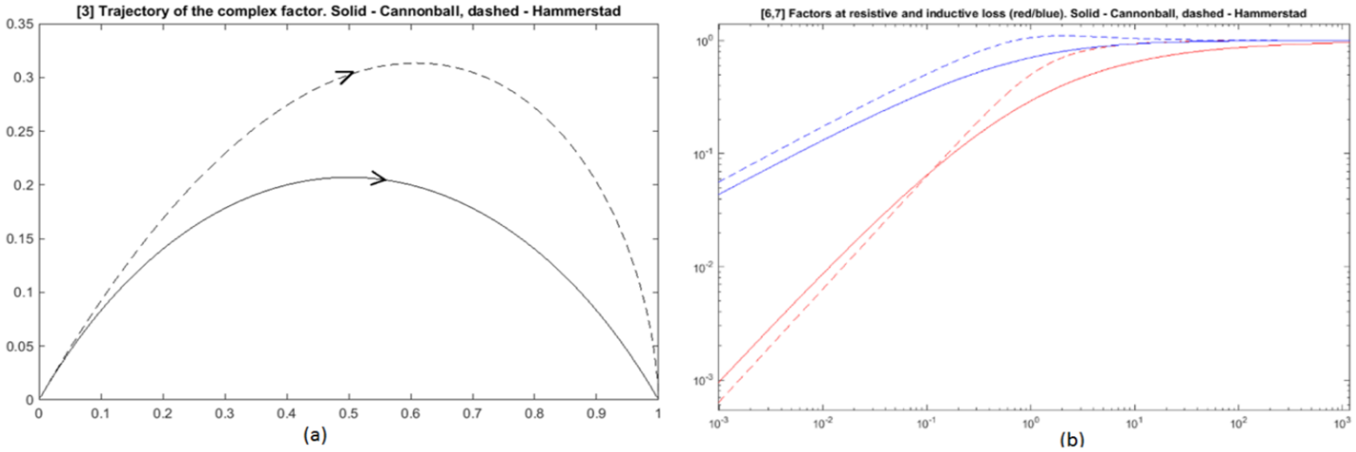
Loss Increase Factor and Complex Correction Factor for Normalized Cannonball-Huray(solid) and Hammerstad (dashed)



(a) Hammerstad and Cannonball-Huray loss correction factor [#2]
(b) Real/imaginary parts of the complex correction factor [#4, #5]

Loss correction factor (a) equals the difference between real and imaginary parts in (b)

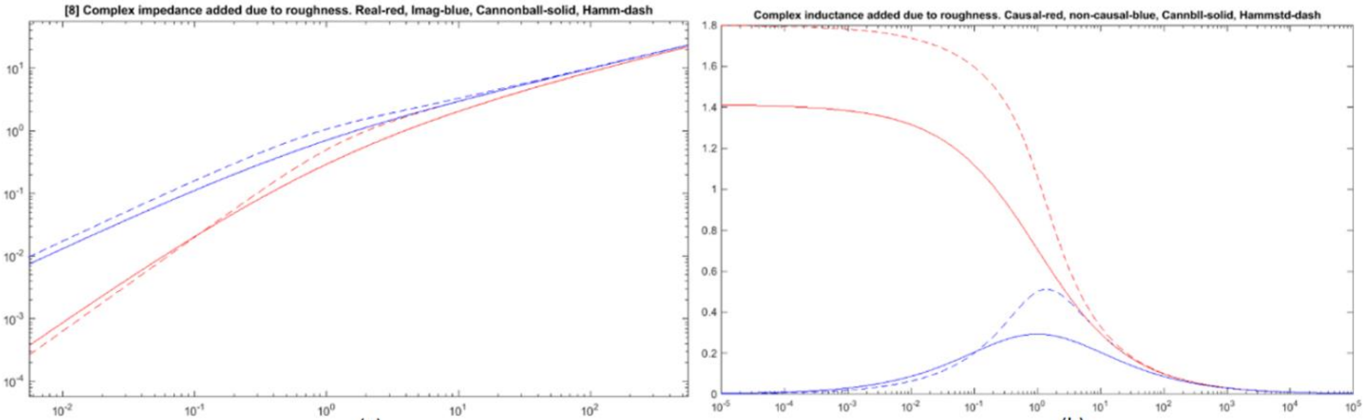
Complex Correction Factor, Loss Increase, & Inductance Increase Factors



(a) Trajectory (polar) plots for Hammerstad and Cannonball-Huray complex factor [#3]
(b) Loss and inductance correction factors [#6, #7]

Note how much inductance correction factor (blue) exceeds loss factor (red). Non-causal model assumes them equal (same as red)

Internal Complex Impedance and Complex Inductance Added Due to Metal Roughness



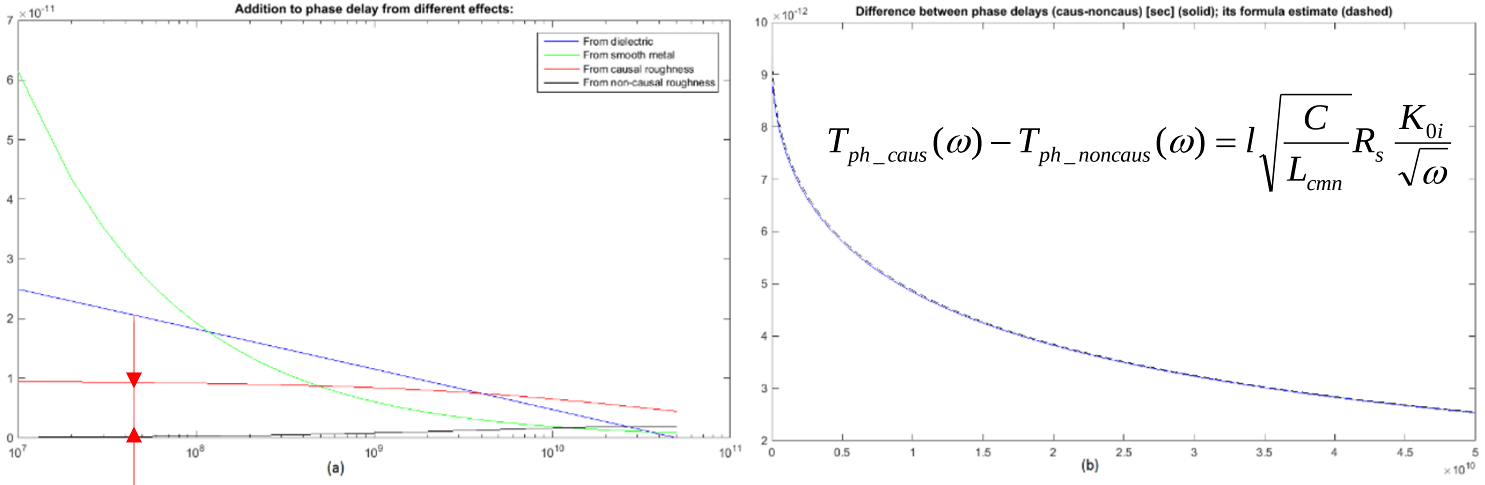
(a) (b)

(a) Complex impedance [#8]. Note how much inductive component (**blue**) exceeds resistive (**red**). Non-causal model would increase them identically (as **red**)
(b) Addition complex inductance [#9]. Non-causal model would add an inductance shown **blue**.

What is Impact on Transmission Line Characteristics?

- We don’t expect noticeable difference for insertion loss (assuming modal basis). It is defined by “loss increase” factor that is the same as in a real-value non-causal correction.
- Phase delay of the propagation operator increases because of larger inductance
- T-line’s characteristic impedance also becomes larger

Phase Delay Increase When Considering Causal Roughness Model

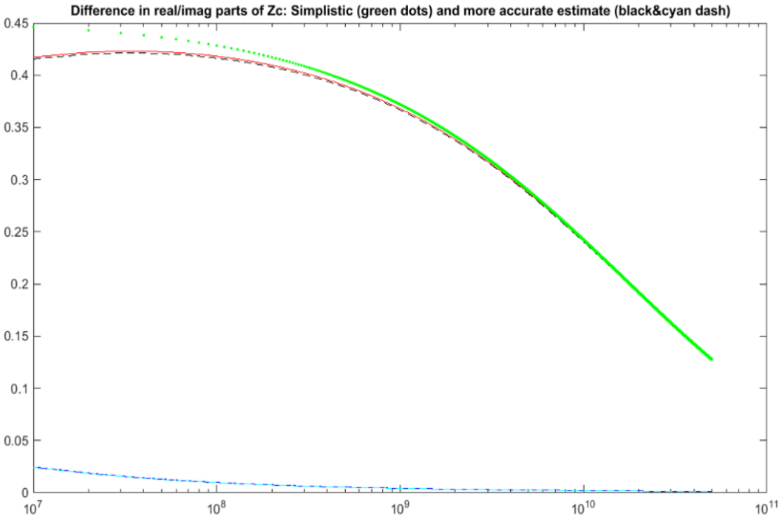


$$T_{ph\_caus}(\omega) - T_{ph\_noncaus}(\omega) = l\sqrt{\frac{C}{L_{cmn}}}R_s\frac{K_{0i}}{\sqrt{\omega}}$$

(a) Addition into phase delay from different losses. Arrows show contributions from causal and non-causal models

(b) Difference between phase delay added by causal and non-causal models (computed and evaluated by formula)

Characteristic Impedance With Causal Roughness Model



Simplistic (green dots on the plot):

$$Z_c(\omega) - Z_{nc}(\omega) \approx \frac{R_s}{\sqrt{L_{cmn}C}} \frac{K_{0i}}{\sqrt{\omega}}$$

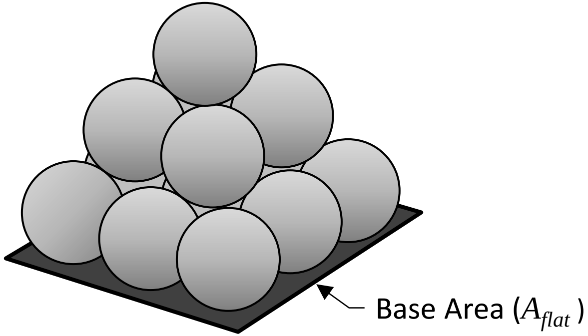
More accurate (red/blue dots):

$$Z_c(\omega) - Z_{nc}(\omega) \approx \frac{i\sqrt{\omega}R_s K_{0i}}{Z_{PUL}(i\omega)} Z_c(\omega) = \frac{i\sqrt{\omega}R_s K_{0i}}{\sqrt{Y_{PUL}(i\omega)Z_{PUL}(i\omega)}}$$

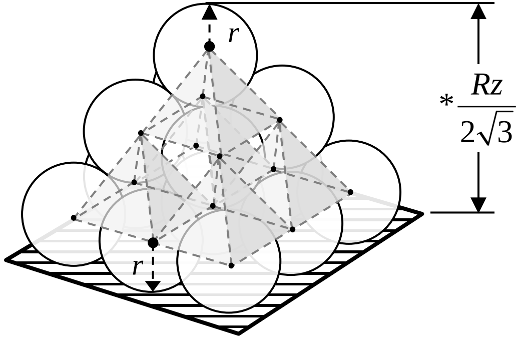
- Characteristic impedance becomes larger as well
- The addition can be evaluated by above formulas (simplistic and more accurate)
- Good match with computed characteristic impedance (dashed black)

Cannonball-Huray Model

Cannonball-Huray Model [11]



14 Spheres



$$K_{CH}(f) \approx 1 + 84\left(\frac{\left(\frac{\pi(r)^2}{A_{Flat}}\right)}{\left(1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2(r)^2}\right)}\right)$$

$$r \approx 0.06R_z;\ A_{flat} = 36r^2$$

$*Rz = $ 10-point mean roughness from data sheet

FR408HR/RTF Case Study [11]

CMP-28 Test Platform

Photo courtesy Wild River Technology [11]

Features:

- FR408HR material with reverse-treated foil (RTF)
- Assembled with 2.92mm (CMP-28) or 2.4mm (CMP-32) connectors
- 3D EM benchmark structures
  - Loss structures for material extraction
  - Resonators for measurement correspondence
  - Multi-impedance structures for VNA time transform analysis

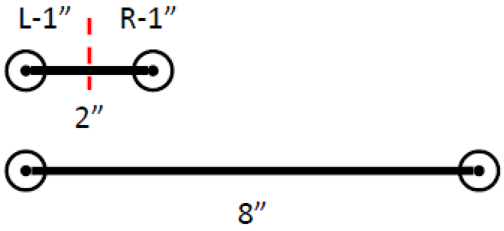
Applications:

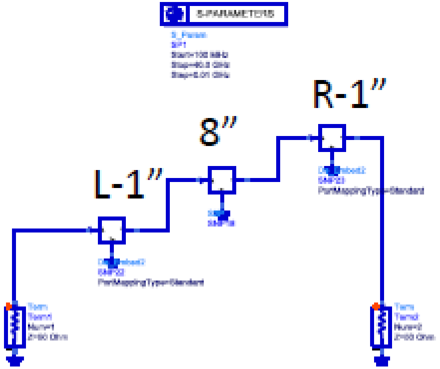
- 3D-EM and measurement assistance for the SI practitioner
  - Vias
  - Multimode Analysis
  - Meshing Analysis Structure
  - Advanced Material Extraction and Loss Modeling
- THRU Calibration, T-matrix de- embedding
- Advanced Crosstalk analysis
- TRL/LRM Calibration Verification/Benchmark

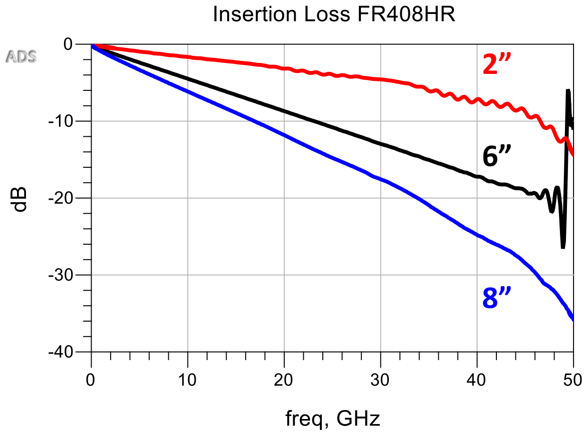
Measure and De-embed

Photo courtesy Anritsu

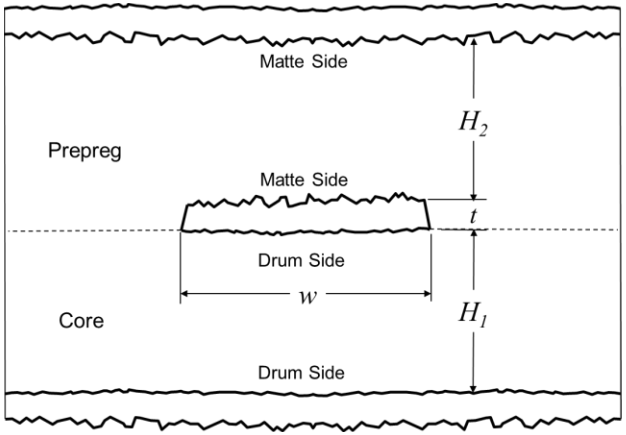
2x Thru





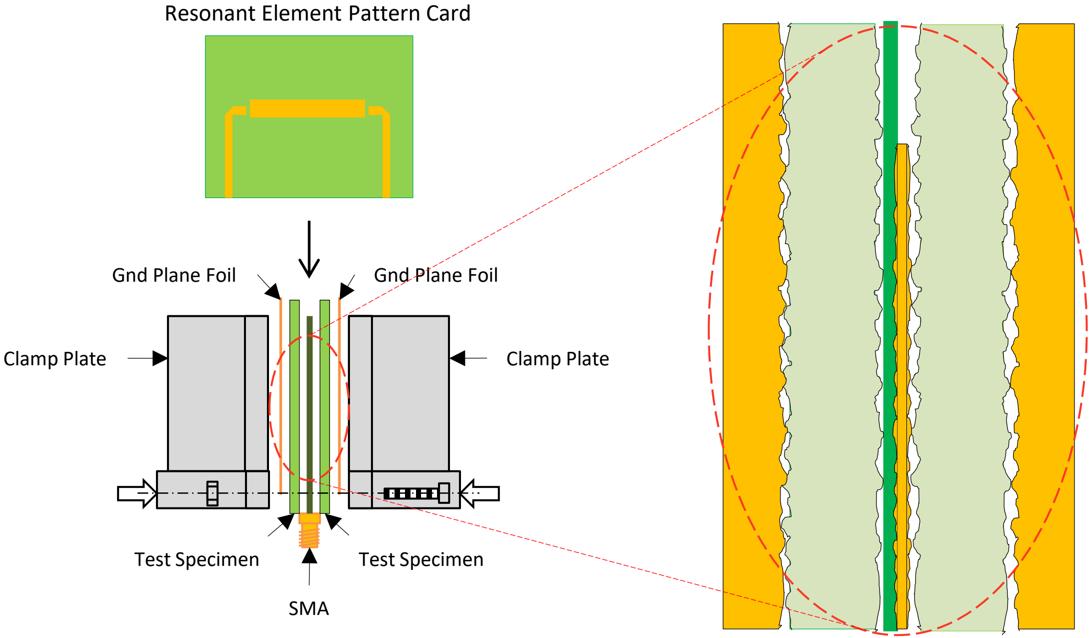


FR408HR/RTF Data Sheet & Test Board Design Parameters



Parameter	FR408HR/RTF
D_k Core/Prepreg @ f_o	3.68/3.62@1GHz
D_f Core/Prepreg @ f_o	0.0087/0.0089 @ 1GHz
R_z Drum side	3.048 μm
R_z Before Micro-etch-Matte side	5.715 μm
R_z After 50 μin (1.27 µm) Micro-etch treatment - Matte side	4.445 μm
Trace Thickness, t	1.25 mils (31.73 μm)
Trace Etch Factor	60 deg taper
Trace Width, w	11 mils (279.20 μm)
Core thickness, H1	12 mils (304.60 μm)
Prepreg thickness, H2	10.6 mils (269.00 μm)
De-embedded trace length	6.00 in (15.24 cm)

D_{keff} Due to Roughness Issue



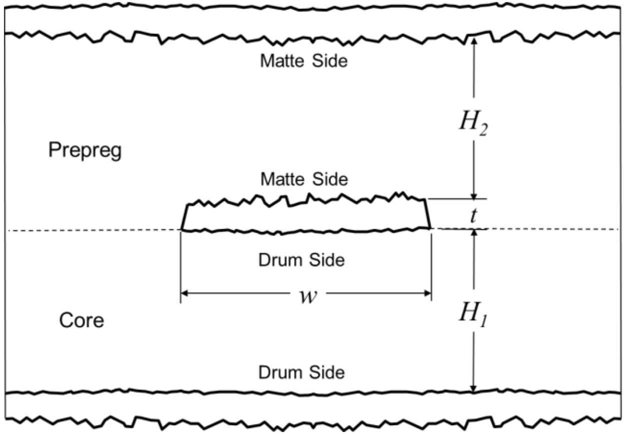
Side View (Unclamped) N.T.S.

Side View (Clamped) N.T.S.

- IPC-TM-650 [18] test method used to rapidly test dielectric material for permittivity and loss tangent in a production environment
- Since resonant element pattern card & material U.T. not physically bonded together => small air gaps between various layers & conductor roughness affects published results

Published D_k not same as D_{keff} due to roughness!

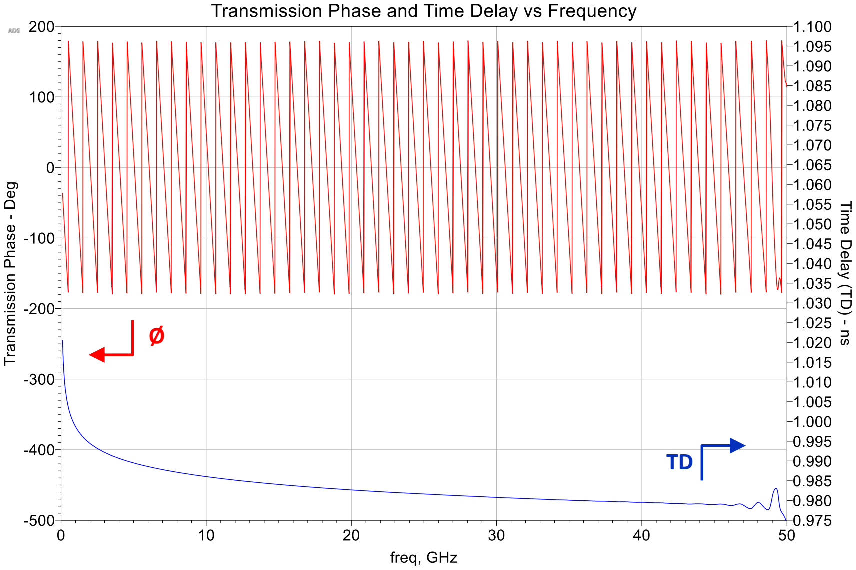
Determine D_{keff} Due to Roughness Core/Prepreg [13]



$$D_{keff\_core} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_z\right)} \times D_{k\_core} = \frac{304.6\mu m}{\left(304.6\mu m - 2\times 3.048\mu m\right)} \times 3.68 = 3.755@1GHz$$

$$D_{keff\_prepreg} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_z\right)} \times D_{k\_prepreg} = \frac{269\mu m}{\left(269\mu m - 2\times 4.445\mu m\right)} \times 3.62 = 3.744@1GHz$$

Phase Delay



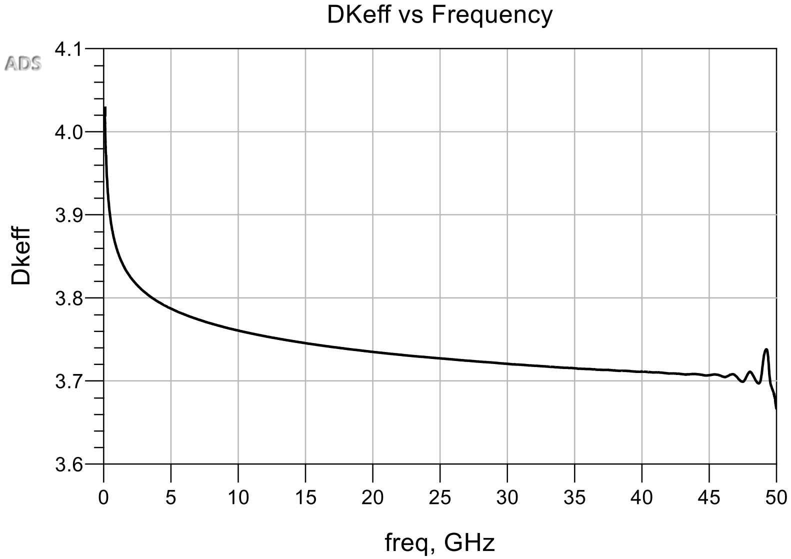
Simulated with Keysight ADS [15]

Phase delay a.k.a. time delay (TD) in seconds can be derived from the transmission phase angle [4]*

$$TD(f) = -1\left[\frac{unwrap(phase(S21))}{360\times freq}\right]$$

* Keysight ADS [15] equation syntax.

Effective Dielectric Constant (D_{keff})

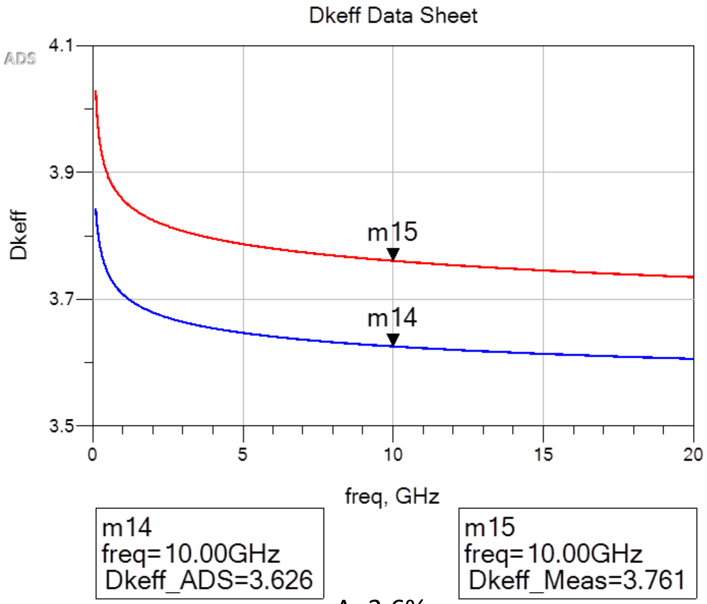


TD can be used to determine D_{keff}

$$D_{keff}(f) = \left(TD(f) \frac{c}{Length} \right)^2$$

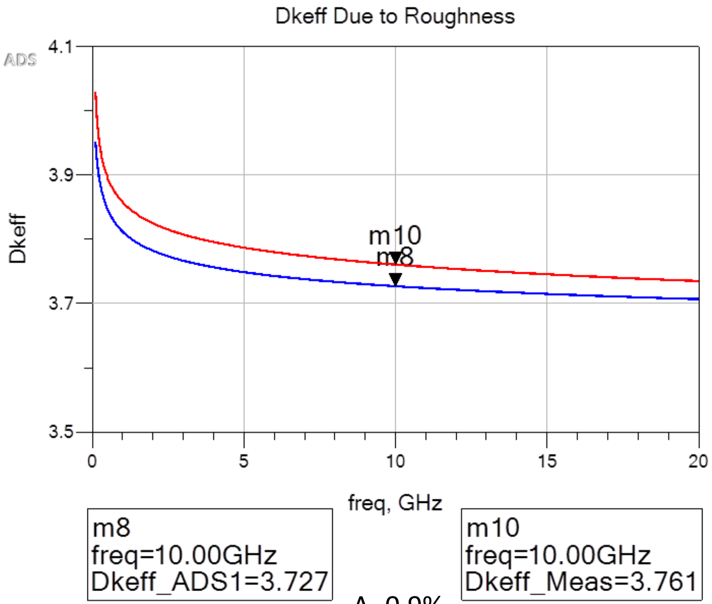
Simulated with Keysight ADS [15]

FR408HR Simulation Results for D_{keff} (Non-causal) [13]



Δ -3.6%

Data Sheet Values

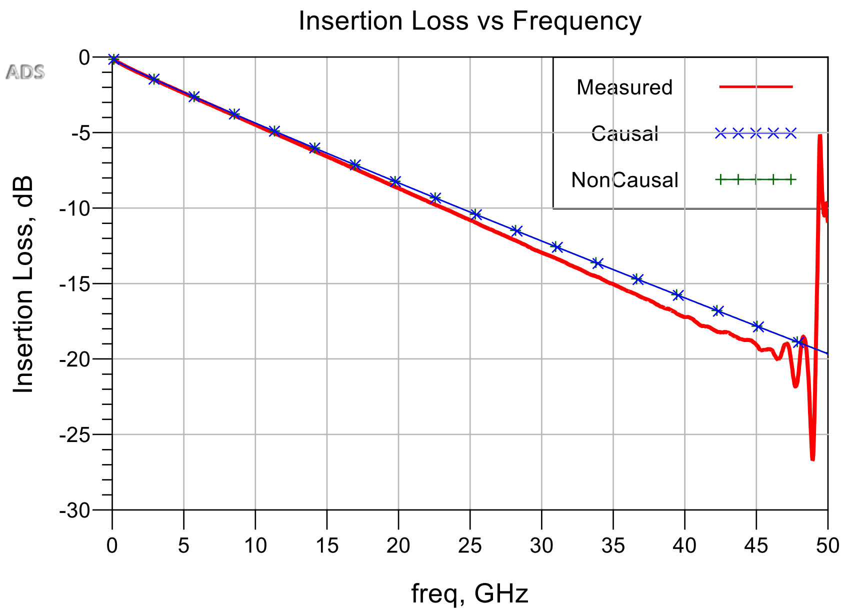


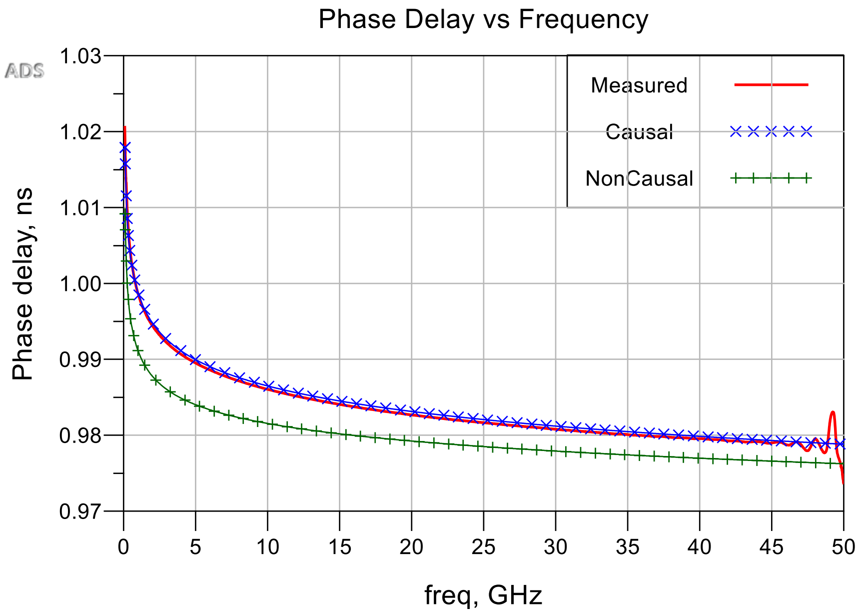
Δ -0.9%

D_{keff} Roughness Model

Simulated with Keysight ADS [15]

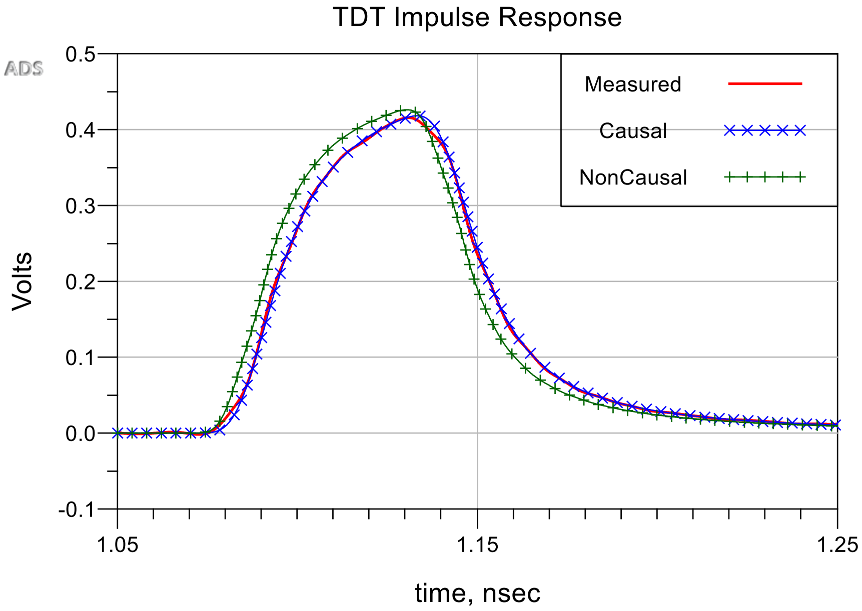
FR408HR Simulation Results for IL and Phase Delay

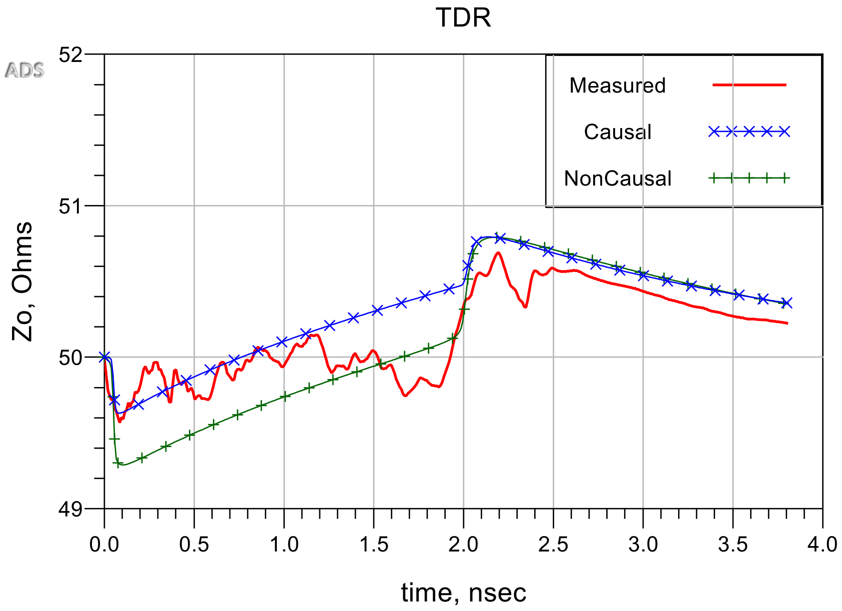




Modeled with Mentor Hyperlynx [14] and Simulated with Keysight ADS [15]

FR408HR Simulation Results for Impulse and TDR





Modeled with Mentor Hyperlynx [14] and Simulated with Keysight ADS [15]

Summary and Conclusions

- A causal version of the roughness correction factor associated with Hammerstad and Cannonball-Huray models has been presented in detail. This method also applies to other correction factors, given by formulas or tables.
- We have shown that T-line characteristic impedance and phase delay of the propagation operator increases because of larger inductance.
- By correcting effective D_k due to roughness and using causal version of the roughness correction factor from Cannonball-Huray model shows excellent results when compared to measured data without curve fitting.
- In the end, we note that causal and non-causal models of metal roughness are not just two versions of the same model. Causal models could be wrong in many ways, but at least they have a potential to correctly describe the relation between the current density and the electric field on metal's surface, which is a causal function. A non-causal model, on the other hand, is always wrong, and it's only a question of how large the error it brings into simulation.

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Thank You!

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