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Electromagnetic Solutions

Simbeor Application Note #2012_02, November 2012

Can conductor roughness effect be accounted for in dielectric model?

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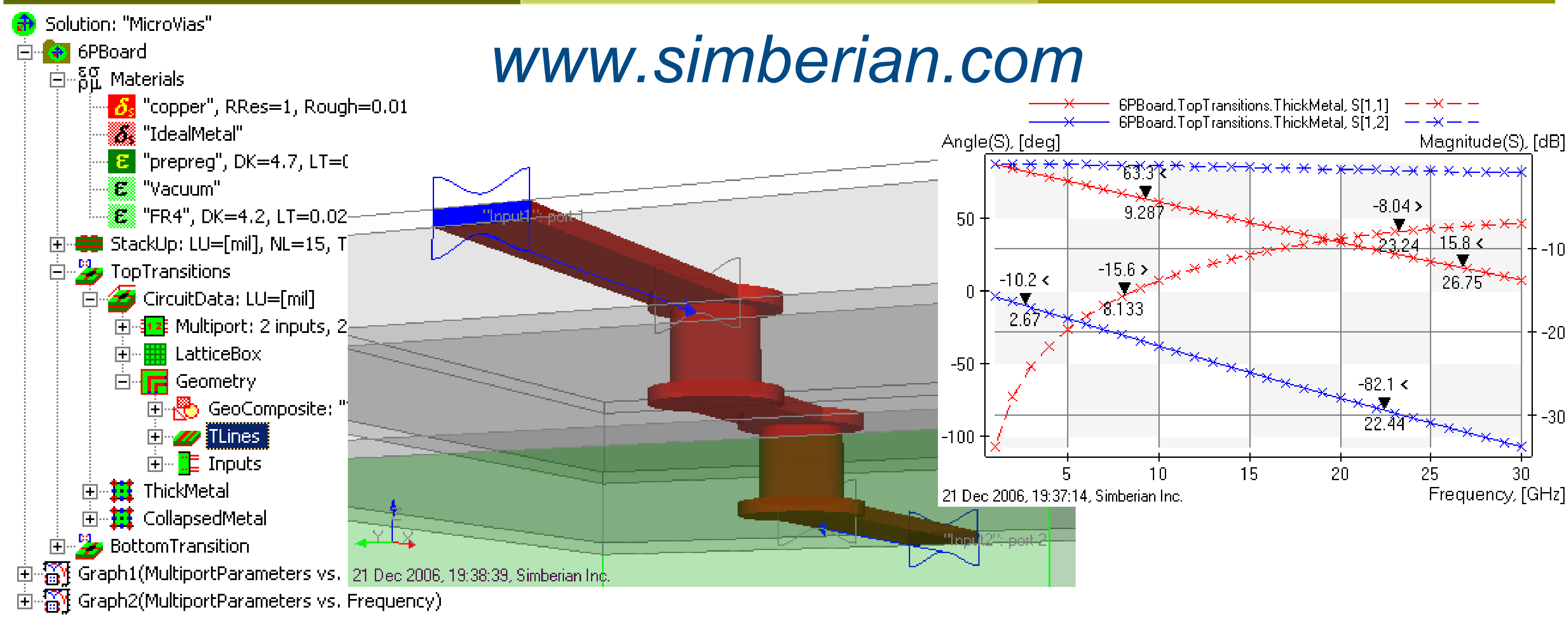

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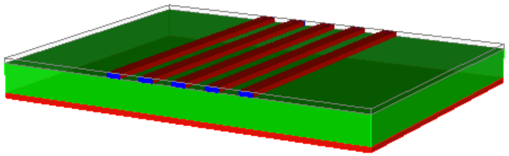
Outline

- Introduction
- Investigation of loss transfer consequences with a semi-analytical static model
- Investigation of loss transfer consequences with numerical electromagnetic model
- Appendix: On linearity of the total losses
- Conclusion
- Contacts and resources

Introduction

- A transmission line can be described by generalized Telegrapher's equations with complex impedance and admittance per unit length (matrices in general)
  - Conductor model with roughness should be accounted for in impedance per unit length (Z)
  - Dielectric model is accounted for in admittance per unit length (Y)
- What if roughness losses are inappropriately accounted for in dielectric model?
- In other words, what if Y is adjusted for roughness instead of Z?
  - If such adjustment keeps propagation constant (Γ) unchanged, what about characteristic impedance (Zo)?



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

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

One conductor case:

$$\Gamma(f) = \sqrt{Z(f)\cdot Y(f)}$$

$$Zo(f) = \sqrt{\frac{Z(f)}{Y(f)}}$$

To investigate the consequences

- Construct transmission line model with appropriate rough conductor model (accounted for in the impedance p.u.l.)
- Then, account for the roughness in the dielectric model (or in admittance p.u.l.) under condition of identical propagation constants and evaluate changes in characteristic impedances
- We will use
  - Huray snowball, modified Hammerstad and Simbeor roughness correction coefficients
  - Static analysis (semi-analytical model)
  - Electromagnetic analysis (numerical model)
- Do it for high-loss dielectric (LT~0.02), low loss (LT~0.002), normal and low profile copper

Static model for impedance p.u.l.

- Wideband cotangent model for smooth conductors:

$$Z(f) = Z_s + i2\pi f \cdot L(\infty) \quad \left[\frac{Ohm}{m}\right]$$

$$Z_s(f) = (1-i) \cdot R_{sn} \cdot \sqrt{f} \cdot \cot\left((1-i) \cdot \frac{R_{sn}}{R_{DC}} \sqrt{f} \right) \qquad R_{sn} = \frac{R_s(f_0)}{\sqrt{f_0}} \left[\frac{Ohm}{m\sqrt{Hz}}\right]$$

Resistance at f0

Converges to Rdc at low frequencies
and at high frequencies to $(1+i) \cdot R_{sn} \cdot \sqrt{f}$

- Model with causal roughness correction:

$$Z_r(f) = K_r \cdot Z_s + i2\pi f \cdot L(\infty) \quad \left[\frac{Ohm}{m}\right]$$

Kr is impedance roughness correction coefficient
(Huray, MHCC or Simbeor for instance)

- Linf, Rsn and Rdc are computed with a static field solver

Static model for admittance p.u.l.

- Complex capacitance model:

$$Y(f) = i2\pi f \cdot \hat{C}(f) \qquad Y(f) = 2\pi f \cdot \frac{\varepsilon''(f)}{\varepsilon'(\infty)} C(\infty) + i2\pi f \cdot \left(1 + \frac{\varepsilon'(f)}{\varepsilon'(\infty)}\right) \cdot C(\infty)$$

- Causal wideband Debye model:

$$\hat{C}(f) = C(\infty) + \frac{C_d}{(m_2 - m_1)\cdot \ln(10)} \cdot F(f) \qquad F(f) = \ln\left[\frac{f_2 + if}{f_1 + if}\right]$$

$$C_d = \frac{(m_2 - m_1)\cdot \ln(10)}{-2\pi \cdot \mathrm{Im}\left[F(f_0)\right]} \cdot G_d(f_0) \qquad C(\infty) = C(f_0) + \frac{\mathrm{Re}\left[F(f_0)\right]}{2\pi \cdot \mathrm{Im}\left[F(f_0)\right]} \cdot G_d(f_0)$$

- C(f0) and Gd(f0) are computed with a static field solver

The model is good only for homogeneous dielectric case!

Shift of roughness from Z to Y

- T-line with roughness accounted in Z

$$\Gamma(f)=\sqrt{Z_r(f)\cdot Y(f)} \qquad Zo(f)=\sqrt{\frac{Z_r(f)}{Y(f)}}$$

$$Z_r(f)=K_r\cdot Z_s+i2\pi f\cdot L(\infty)=\left(K_r-1\right)\cdot Z_s+Z_s+i2\pi f\cdot L(\infty)=\left(K_r-1\right)\cdot Z_s+Z(f)$$

- We can adjust Y: $Y_r(f)=Y(f)\cdot\left(1+\frac{K_r-1}{Z(f)}\cdot Z_s\right)=Y(f)\cdot\left(1+\frac{K_r-1}{Z_s+i2\pi f\cdot L(\infty)}\cdot Z_s\right)$

- Model with adjusted Y has identical propagation constant

$$\Gamma(f)=\sqrt{Z_r(f)\cdot Y(f)}=\sqrt{Z(f)\cdot Y_r(f)}$$

- But different characteristic impedance:

$$Zo(f)=\sqrt{\frac{Z_r(f)}{Y(f)}} \qquad Z1o(f)=\sqrt{\frac{Z(f)}{Y_r(f)}}$$

Let’s evaluate the difference

Impedance roughness correction coefficients

- Huray snowball model correction coefficient

$$K_{rhu} = 1 + \left(\frac{N \cdot 4\pi \cdot r^2}{A_{hex}}\right) \Big/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2 \cdot r^2}\right)$$

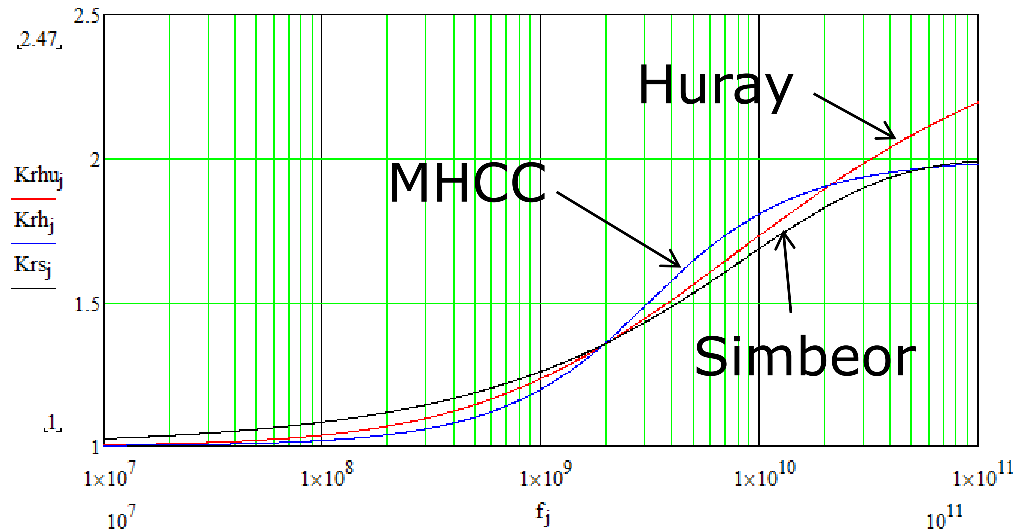
- Modified Hammerstad correction coefficient (MHCC)

$$K_{rh} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4\left(\frac{\Delta}{\delta}\right)^2\right]\right) \cdot (RF - 1)$$

- Simbeor correction coefficient

$$K_{rs} = 1 + \left(\tanh\left[0.56\frac{\Delta}{\delta}\right]\right) \cdot (RF - 1)$$

Regular treated copper
Huray model: r=0.85 um, At=65 um^2, N=11



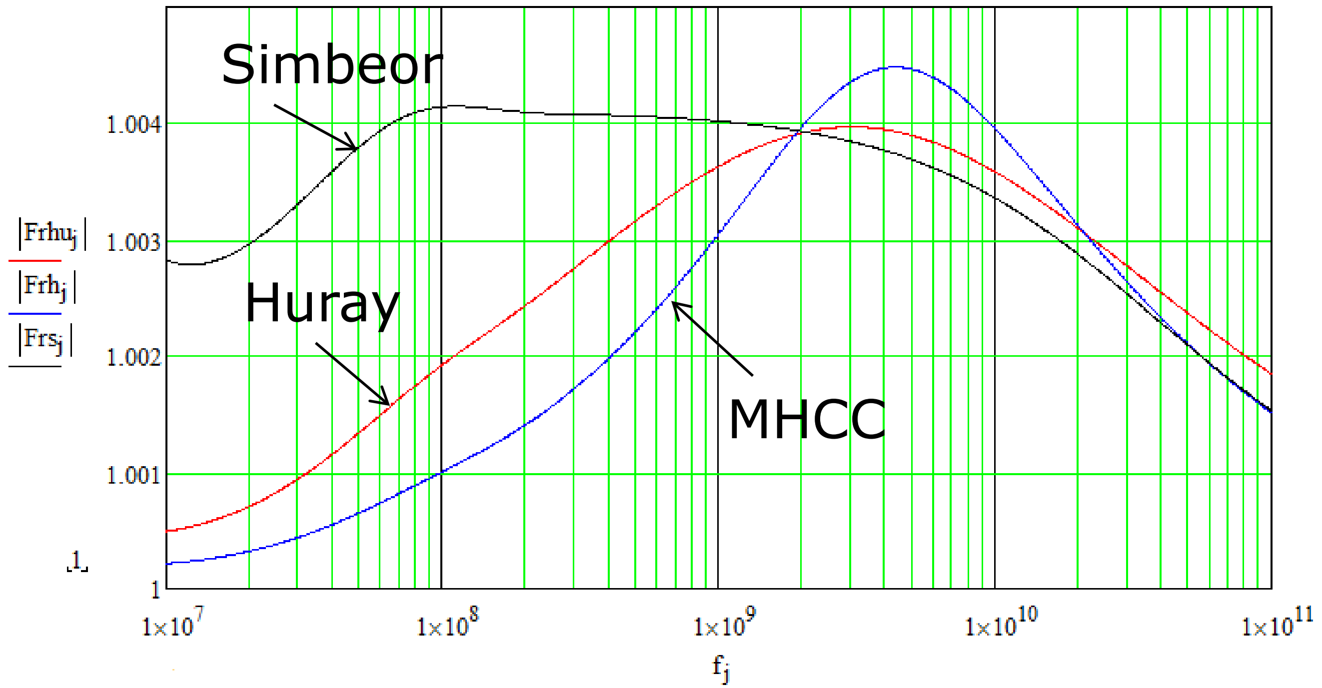
MHCC and Simbeor models: delta= 1um, RF=2

Admittance roughness correction coefficient (roughness moved into Y)

$$Y_r(f) = Y(f) \cdot F_r(f)$$

$$F_r(f) = \left(1 + \frac{K_r - 1}{Z(f)} \cdot Z_s\right) = \left(1 + \frac{K_r - 1}{Z_s + i2\pi f \cdot L(\infty)} \cdot Z_s\right)$$

$$Z_s(f) = (1-i) \cdot R_{sn} \cdot \sqrt{f} \cdot \cot\left((1-i) \cdot \frac{R_{sn}}{R_{DC}} \sqrt{f}\right)$$



Constructed to produce propagation constant identical to corrected impedance

Static model for evaluation

- Symmetric strip line, about 50 Ohm impedance, high loss dielectric (Dk=4.2, LT=0.02 at 1 GHz)

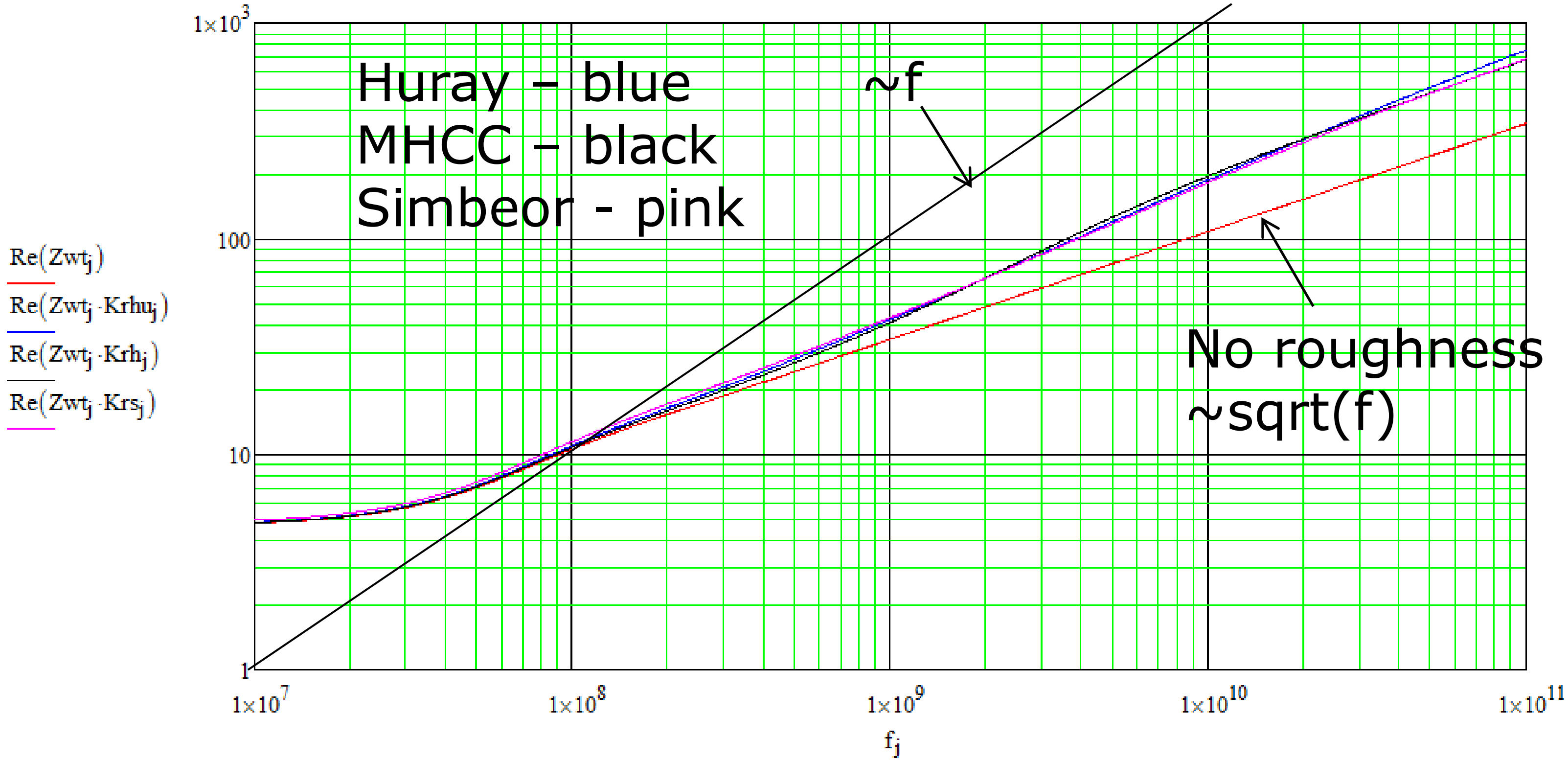
Linf=0.352 uH/m, Rsn=1.08 mOhm/(m*sqrt(Hz)), Rdc=4.7 Ohm/m
C(f0)=132.5 pF/m, **Gd(f0)=16.6 pS/m*Hz**, f0=1GHz

- Same line for low-loss dielectric (LT~0.002)

Linf=0.352 uH/m, Rsn=1.08 mOhm/(m*sqrt(Hz)), Rdc=4.7 Ohm/m
C(f0)=132.5 pF/m, **Gd(f0)=1.66 pS/m*Hz**, f0=1GHz

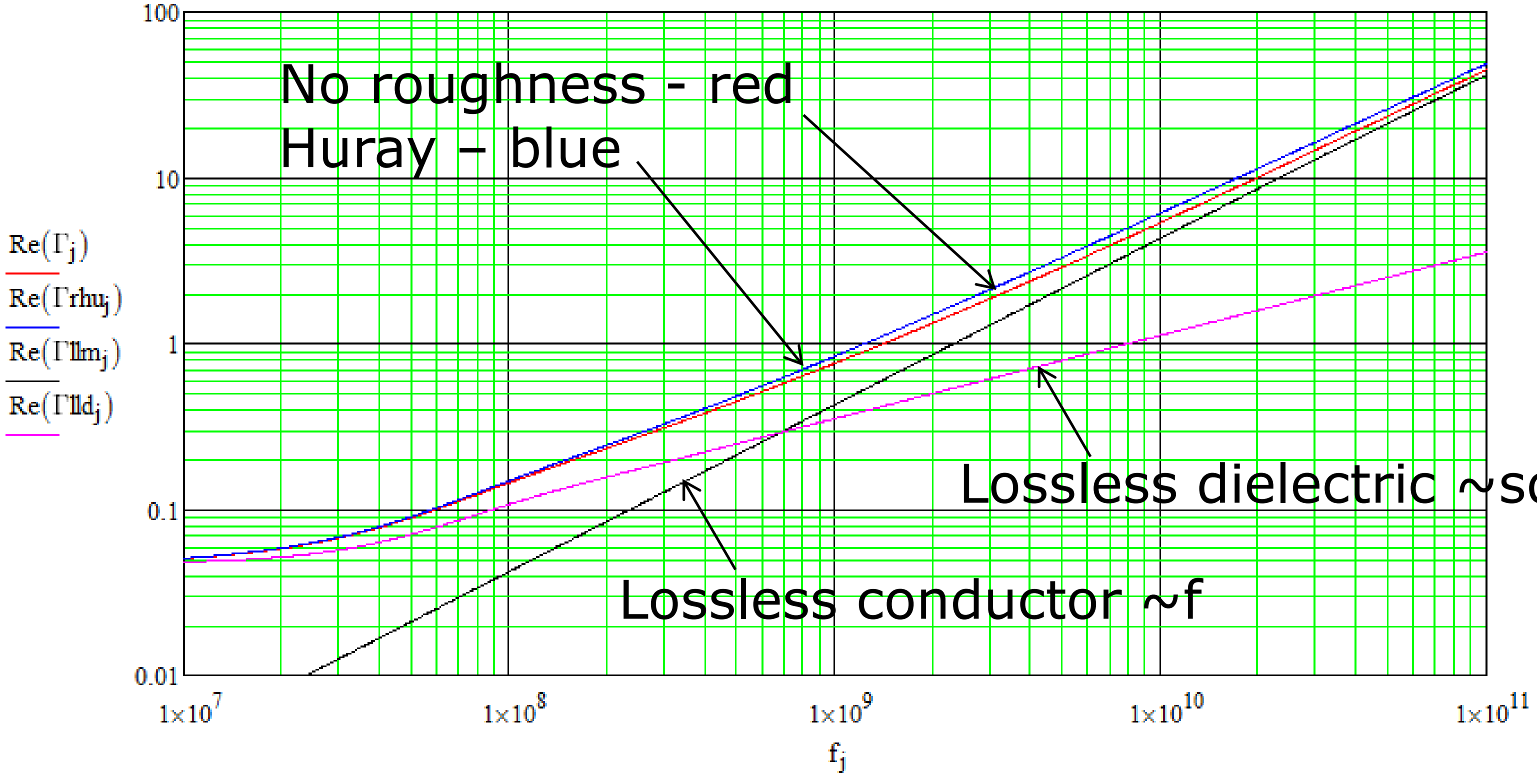
Increase in conductor impedance due to roughness

Real part of Kr*Zs is plotted – imaginary is identical



Non of the models predicts change of asymptotes from sqrt(f) to linear (typical roughness parameters)

Impact of roughness on overall losses (high loss dielectric case LT~0.02)

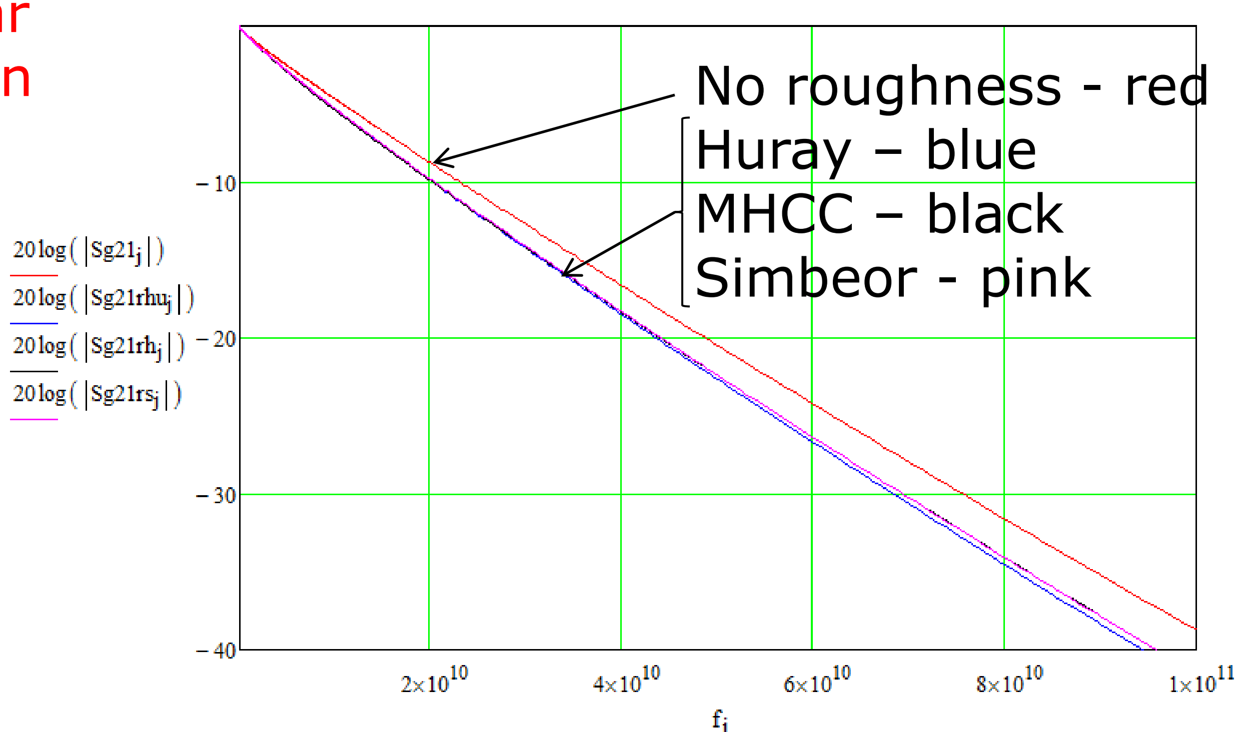


All other roughness models produce Γ very close to Huray model
Absolute values for different roughness models is difficult to compare – relative can be used

Does it produce linear insertion loss?

- 10 cm segment of line, 50-Ohm normalized S-parameters (small reflections due to mismatch with characteristic impedance)

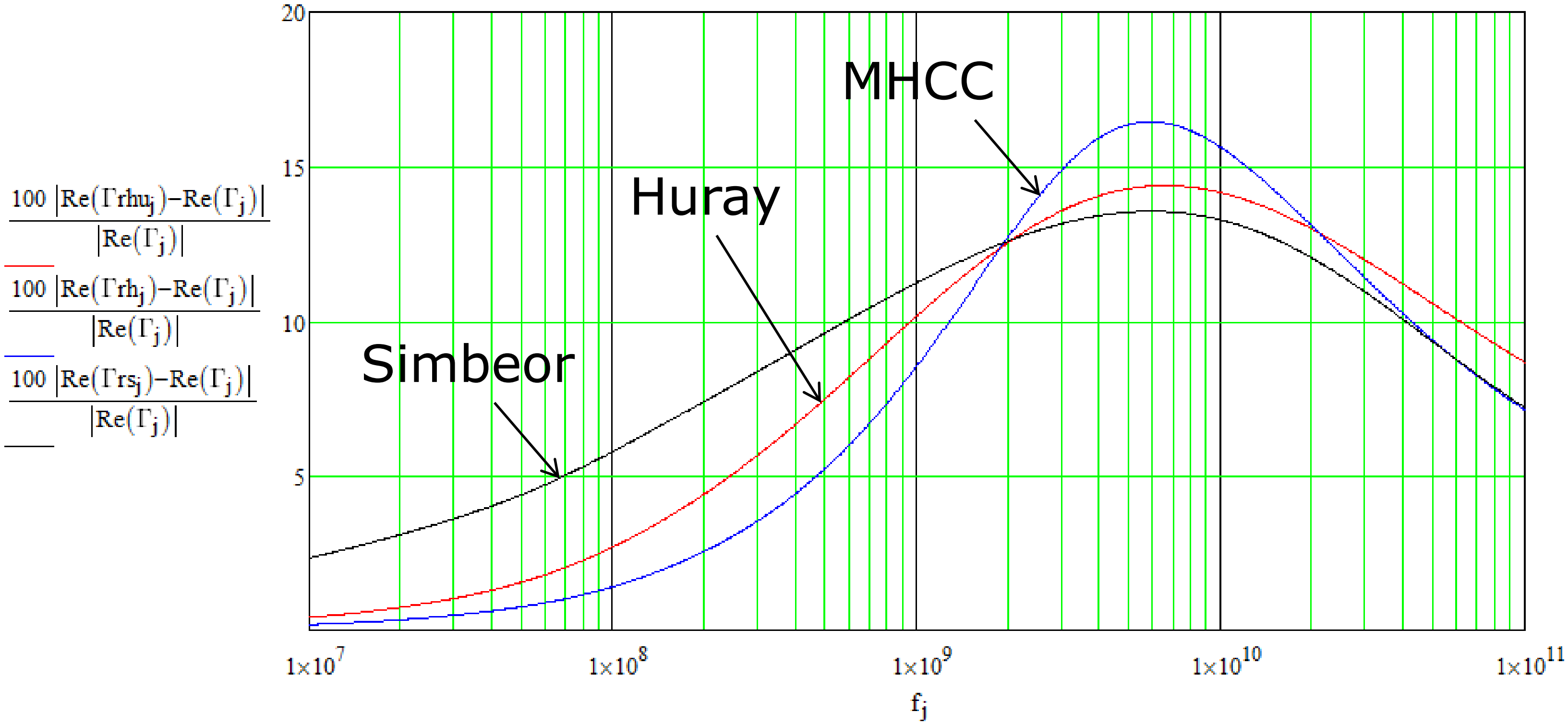
Possible linear approximation



On Log scale on vertical axis, the curve shape is similar to attenuation on the previous slide

Impact of roughness on attenuation

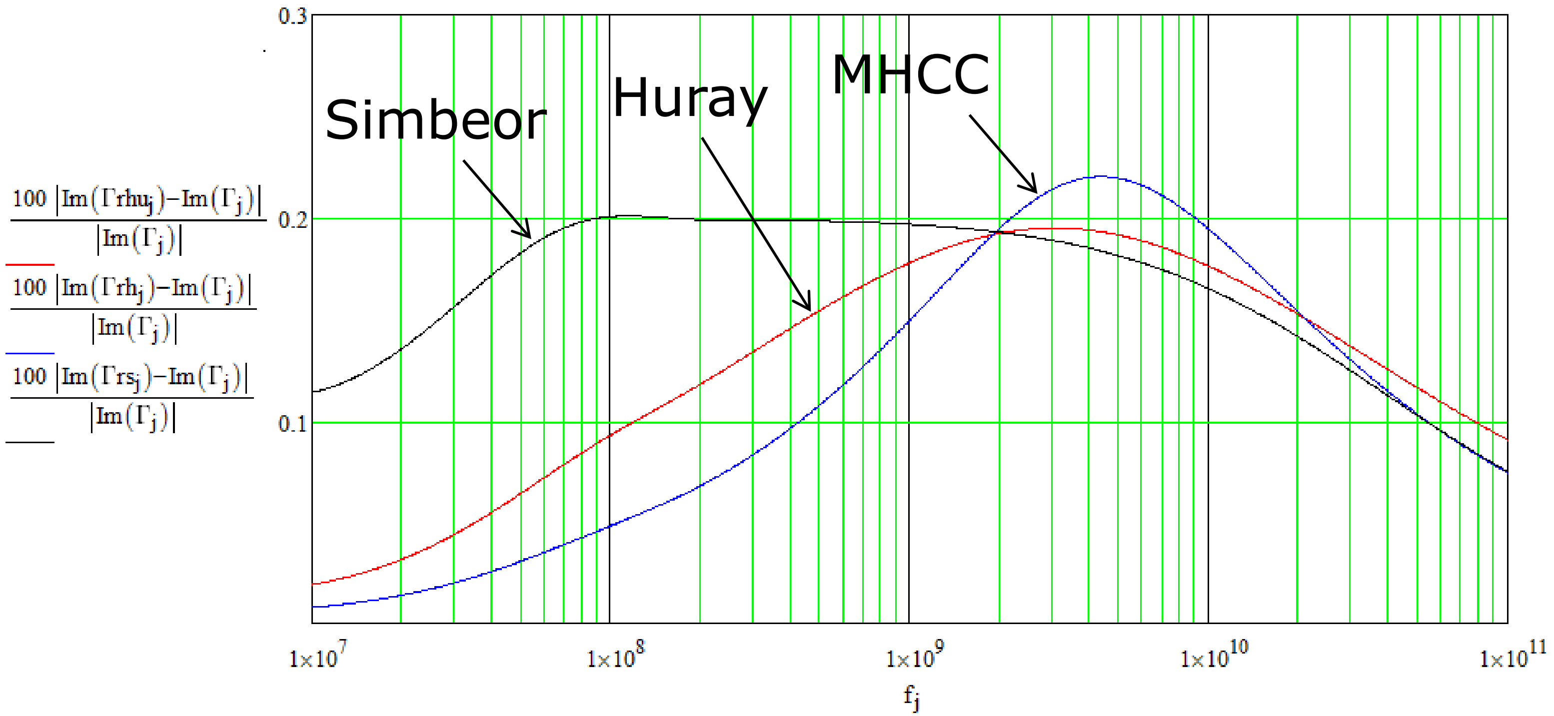
- Increase in attenuation in % relative to case with smooth conductor (wanted)



Up to about 15% increase in attenuation due to roughness

Impact of roughness on phase constant

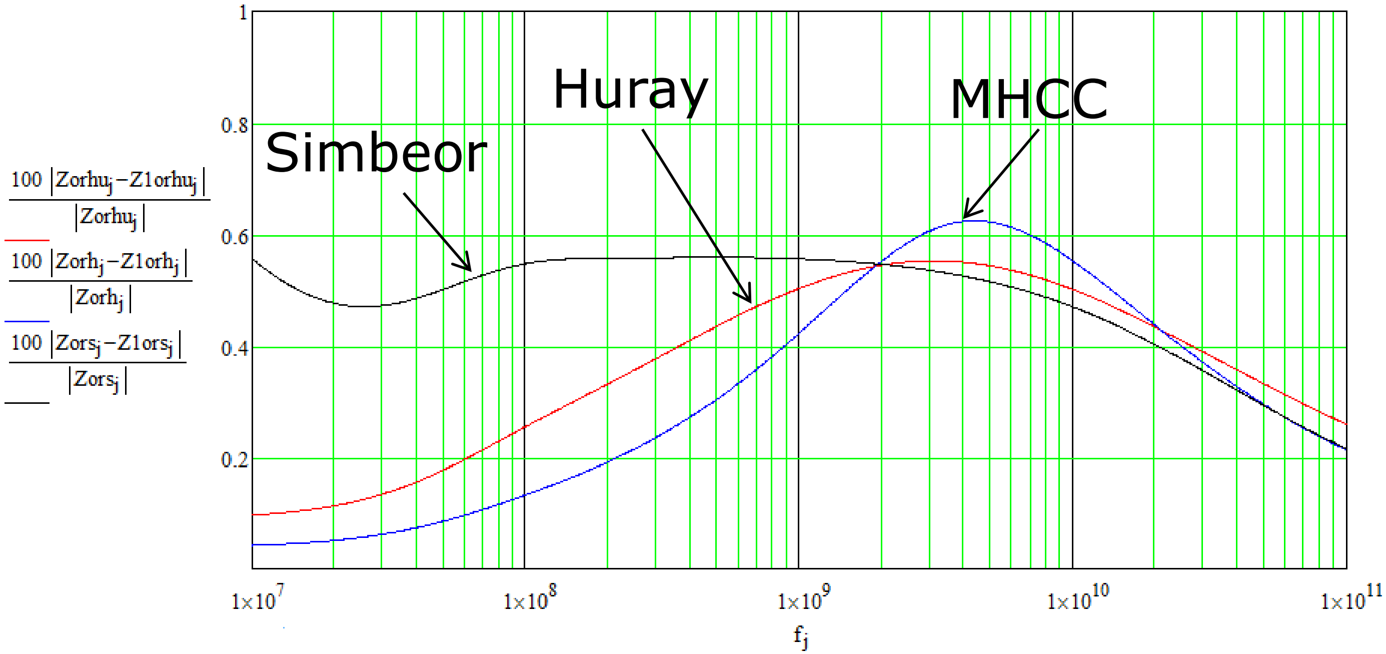
- Increase in phase constant in % relative to case with smooth conductor (maintains causality)



Up to about 0.2% difference (small correction)

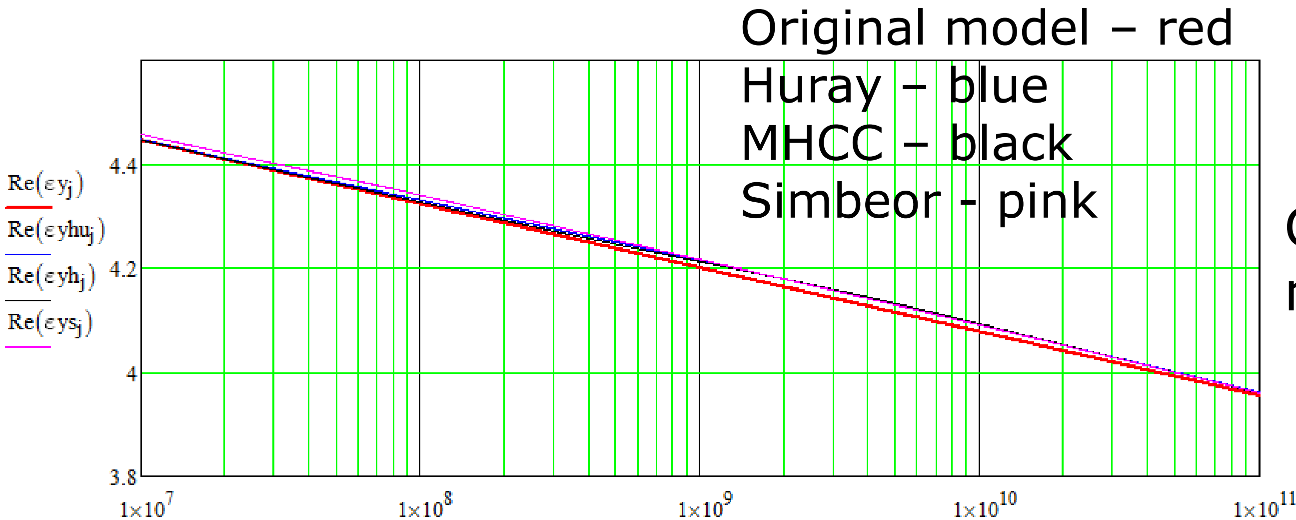
Model with roughness correction in Y

- Propagation constant is identical to the case with corrected Z
- Characteristic impedance decreases – **unwanted effect**

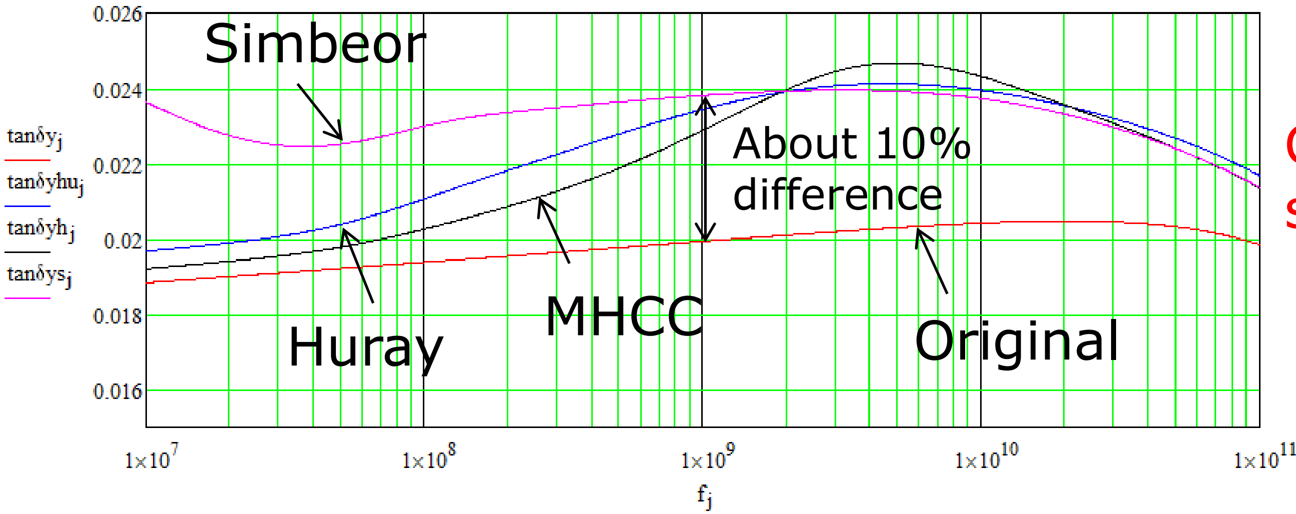


Less then 0.6% difference – not significant!
We can move roughness effect into dielectric model for high-loss dielectrics

Dielectric model that "accounts for" the roughness – Dk and LT computed from Y

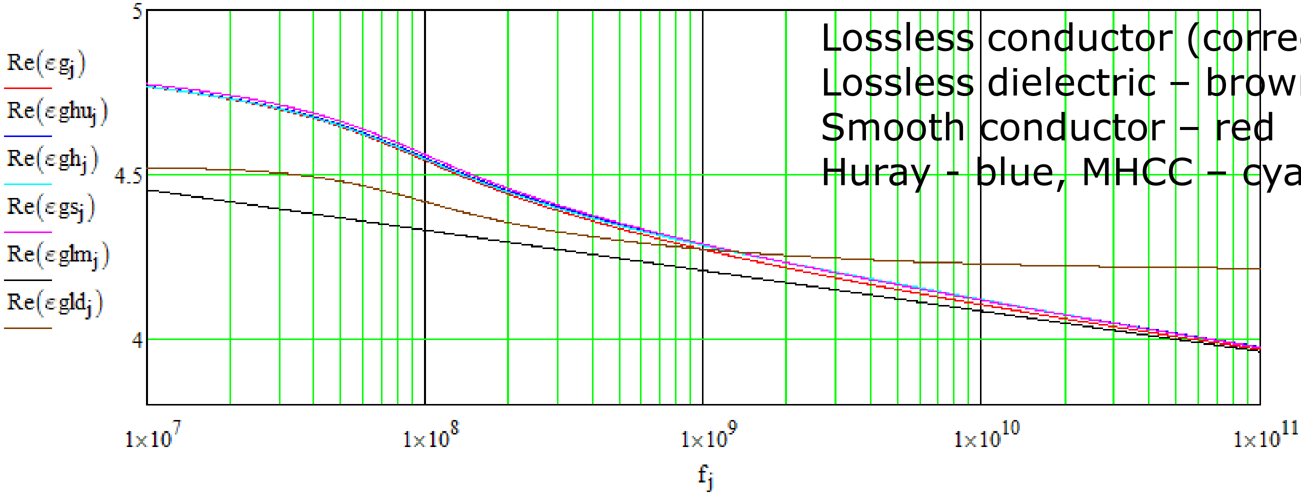


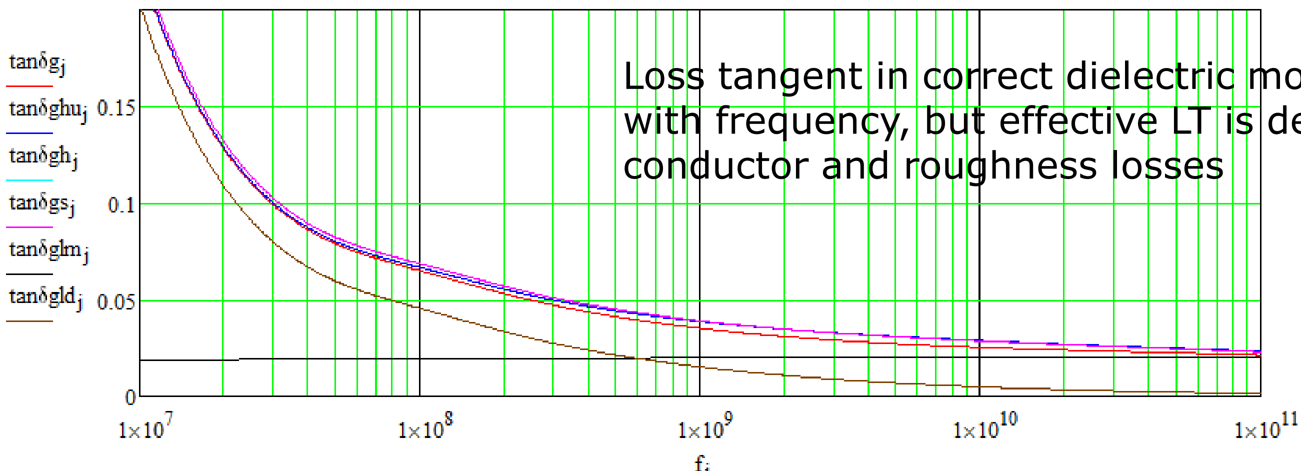
Changes in Dk are not significant



Changes in LT are significant

What if we compute Dk and LT directly from the propagation constant (Γ)?

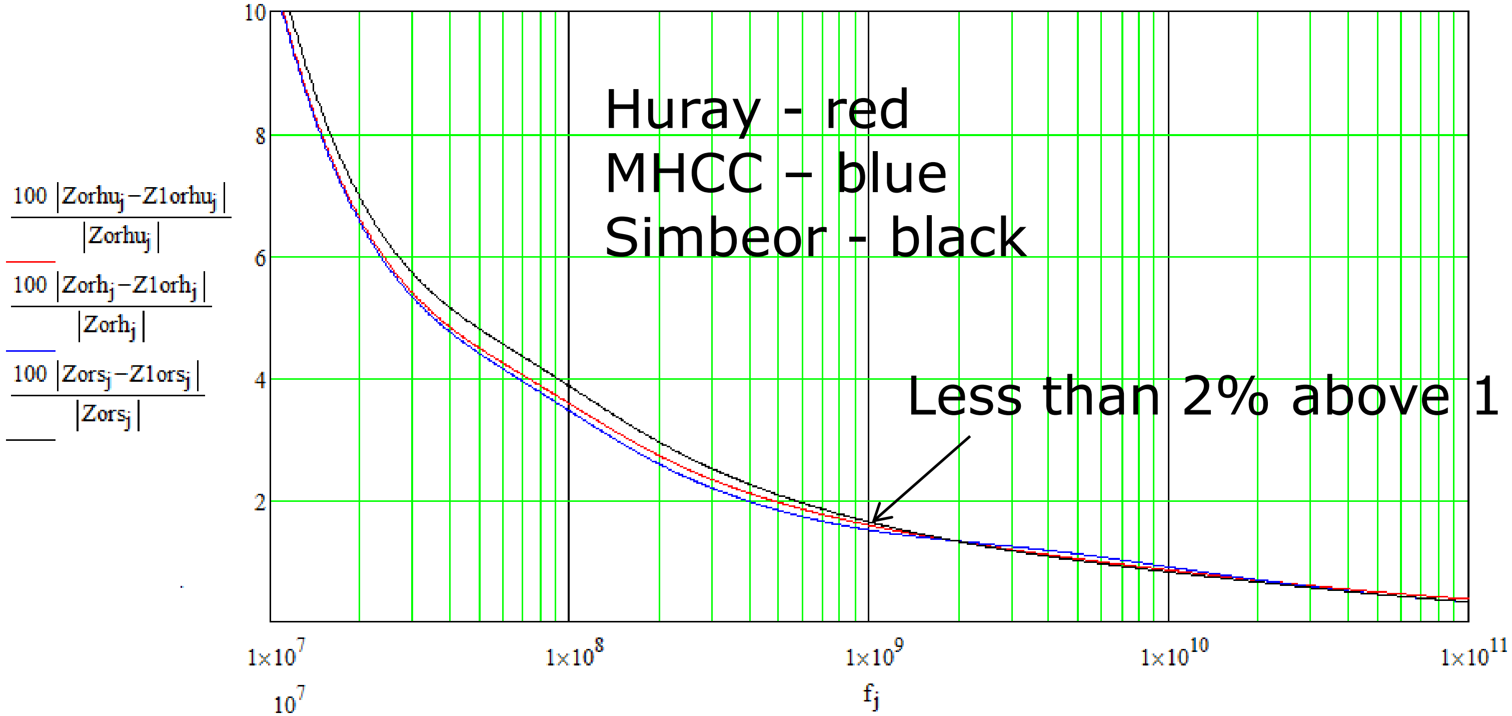




Effective Dk and LT extracted from Γ with all losses are similar to observed in A. Blankman, E. Bogatin, D. DeGroot, DesignCon 2012 paper

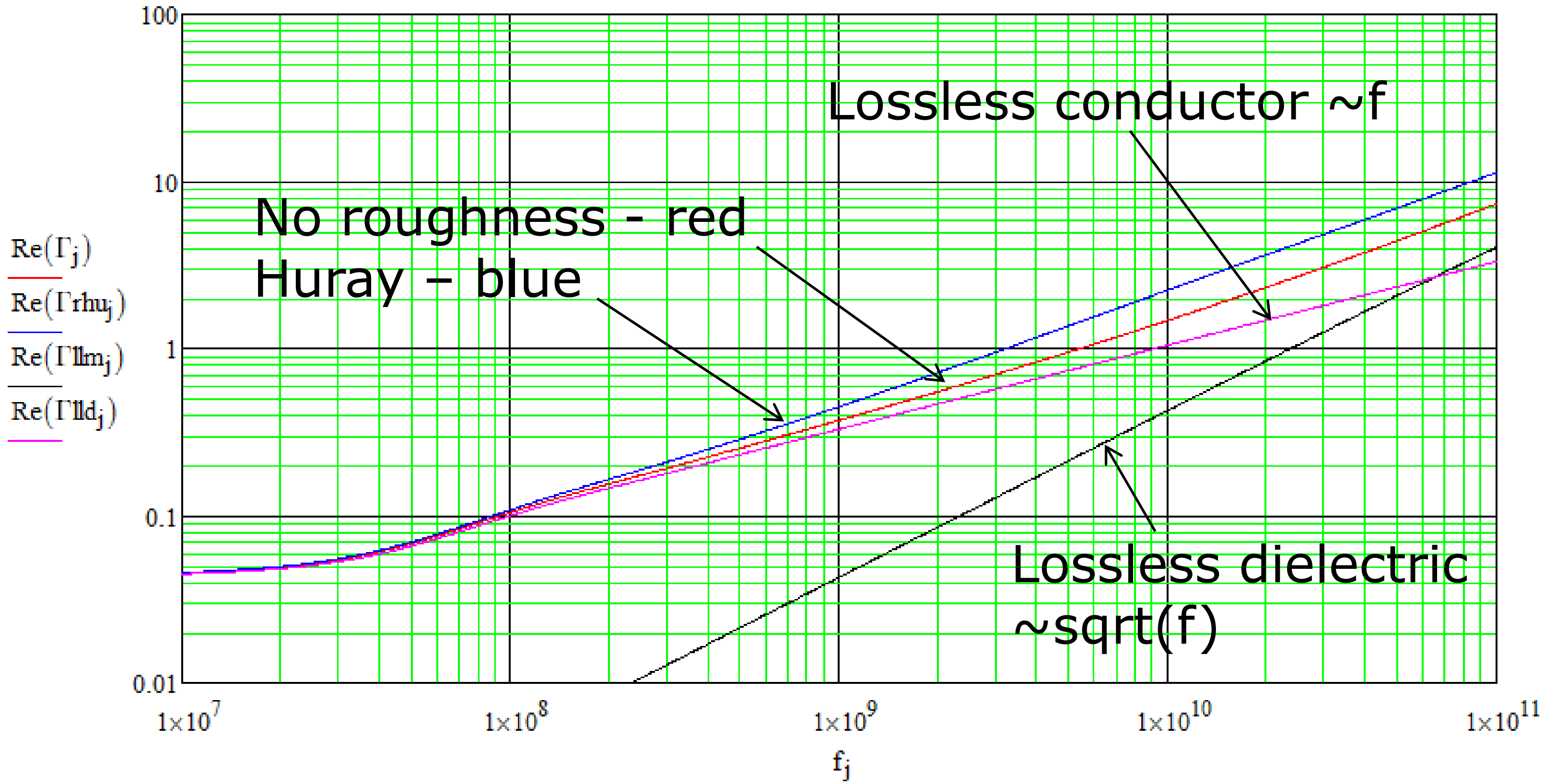
What if we use the effective Dk and LT model (move all conductor losses into Y)?

- Propagation constant stays unchanged
- Characteristic impedance decreases more:



May be acceptable in this case of high-loss dielectric (considering other factors that can change the impedance)

Impact of roughness on overall losses (low loss dielectric case, LT~0.002)

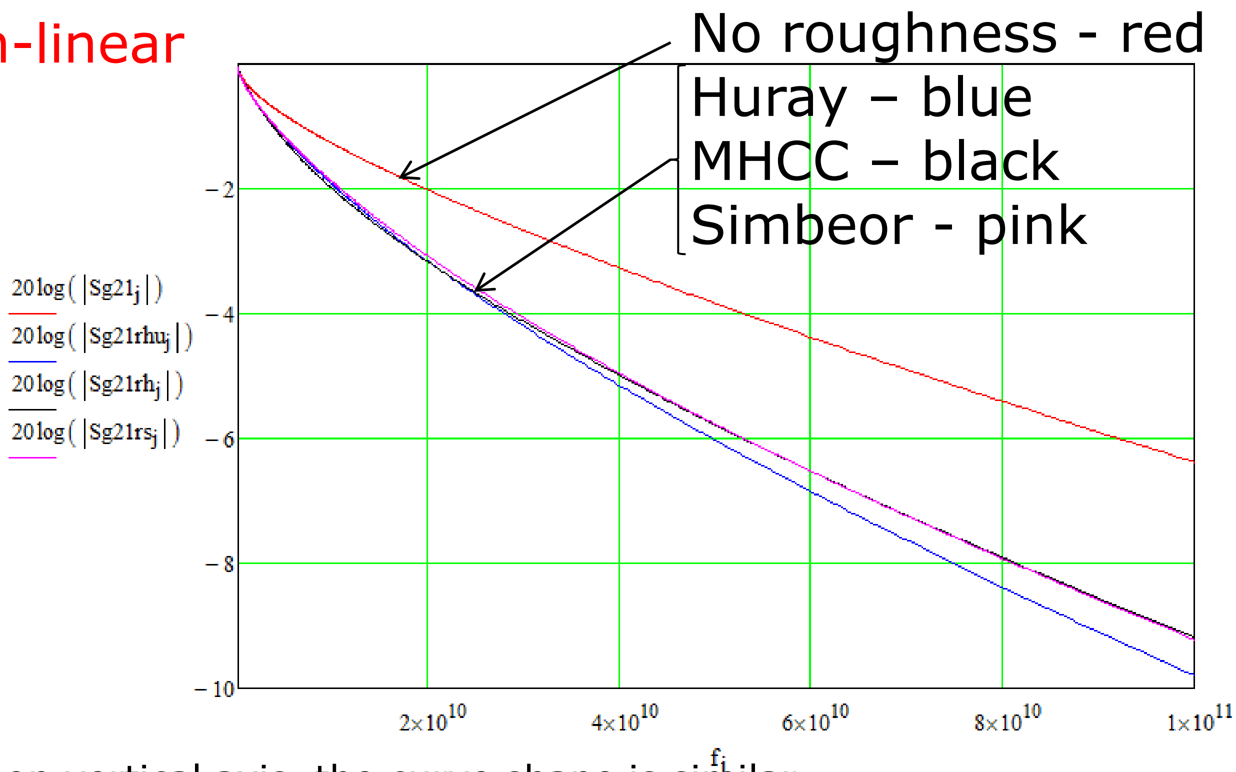


All other roughness models produce Γ very close to Huray model
Again, let's compare relative differences between roughness models

Does it produce linear insertion loss?

- 10 cm segment of line, 50-Ohm normalized S-parameters (small reflections due to mismatch with characteristic impedance)

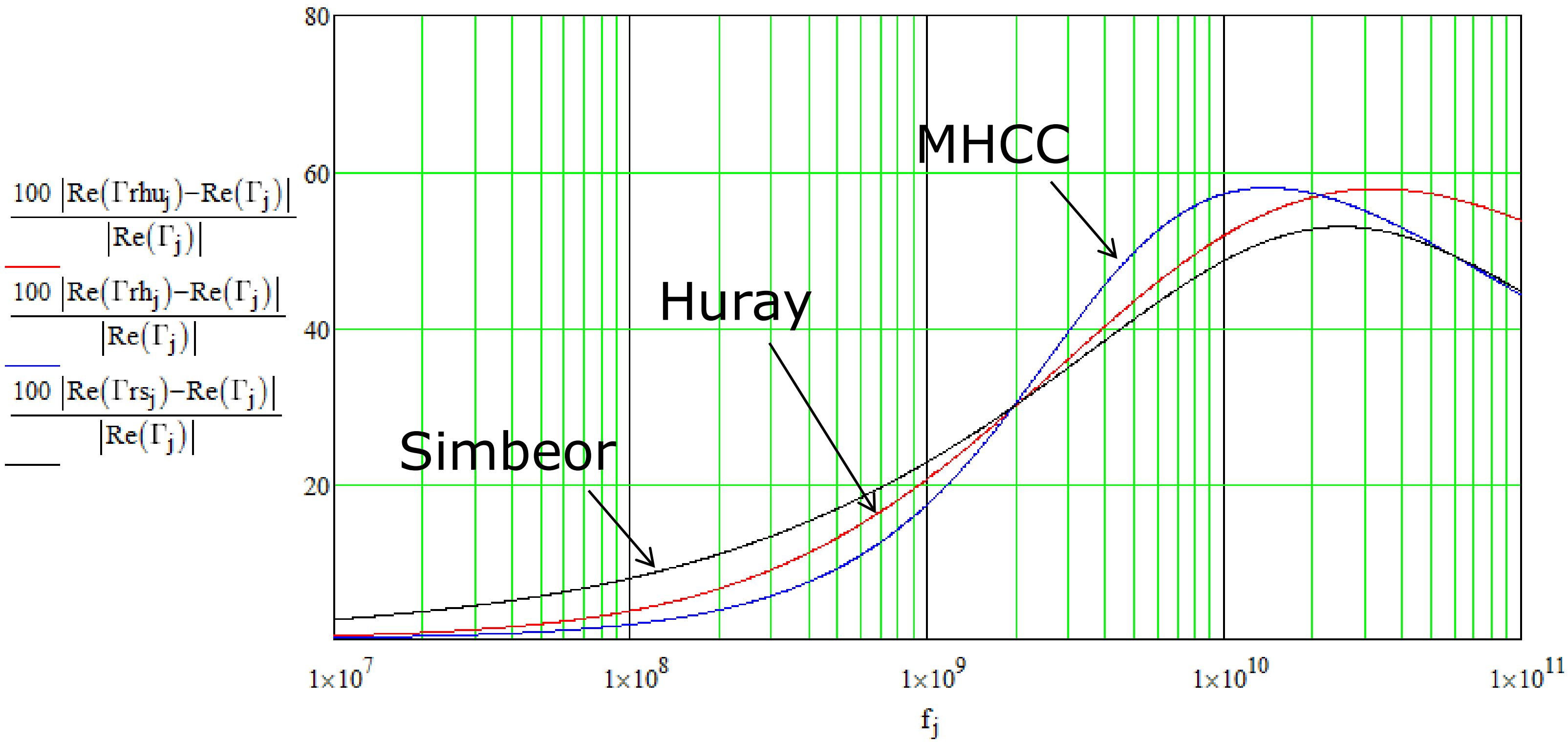
Clearly non-linear



On Log scale on vertical axis, the curve shape is similar to attenuation on the previous slide

Impact of roughness on attenuation

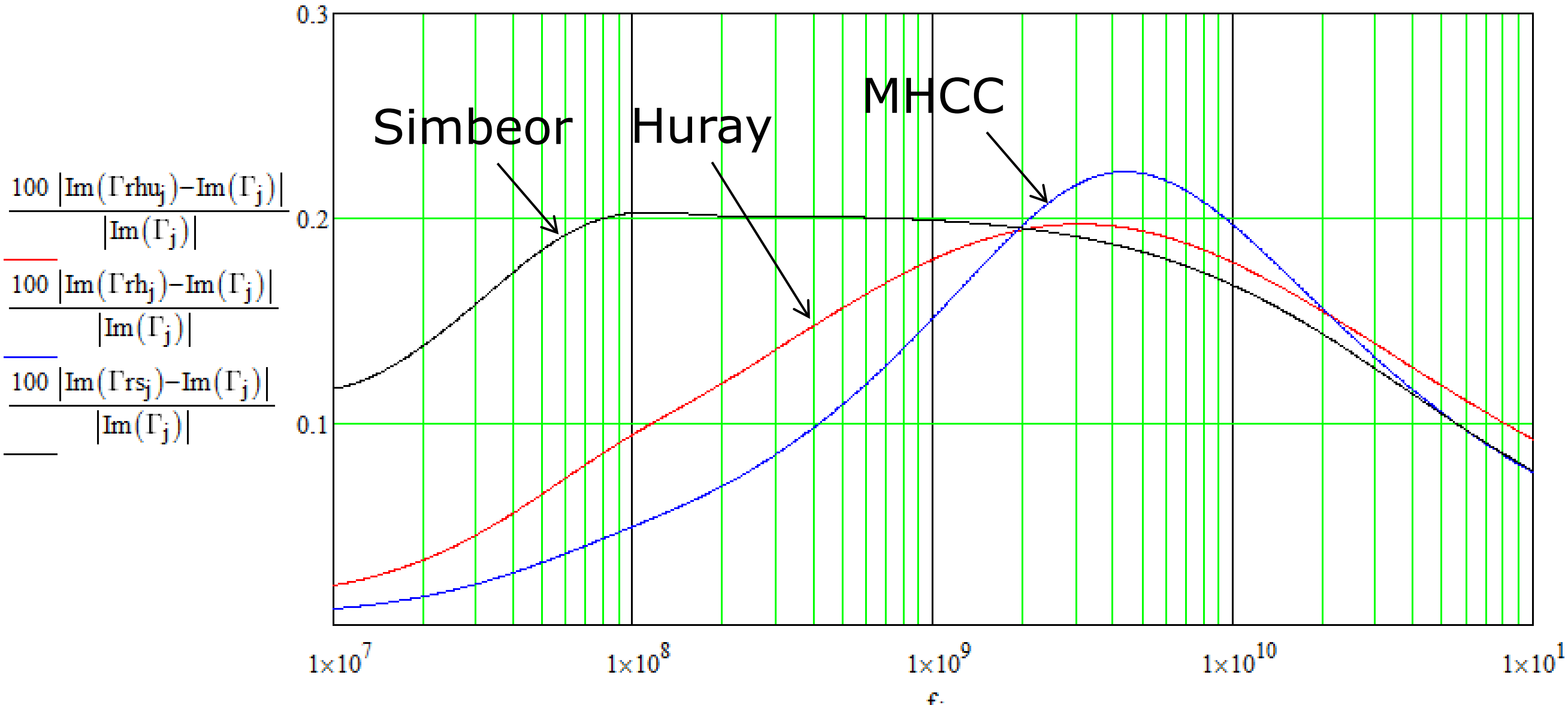
- Increase in attenuation in % relative to case with smooth conductor (wanted)



Up to about 60% increase in attenuation due to roughness

Impact of roughness on phase constant

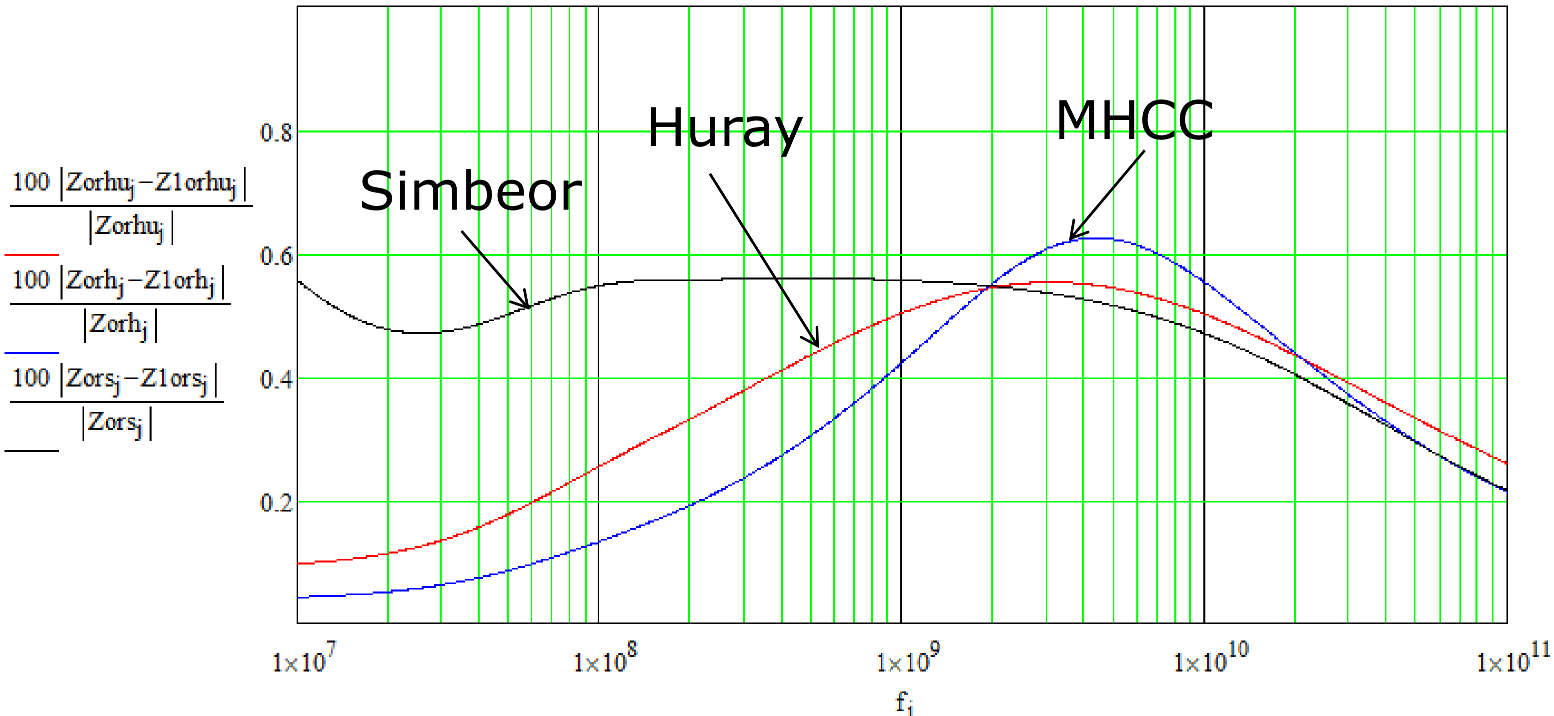
- Increase in phase constant in % relative to case with smooth conductor (maintains causality)



Up to about 0.2% difference (small correction – about the same as in high LT case)

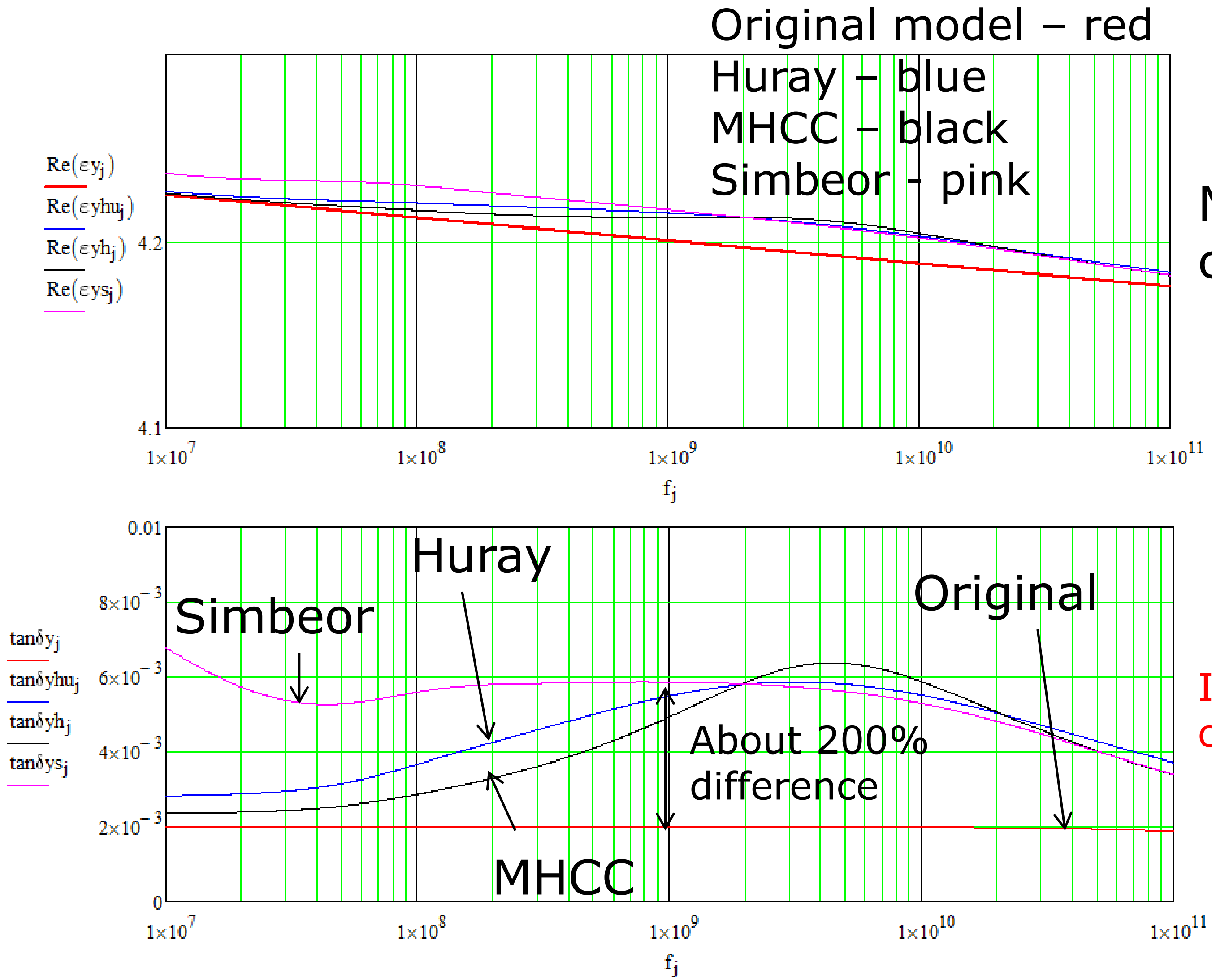
Model with roughness correction in Y

- Propagation constant is identical to the case with corrected Z
- Characteristic impedance decreases – **unwanted effect**



Less than 0.6% difference – not significant as in case of high LT!
We can move roughness effect into dielectric model for low-loss dielectrics too

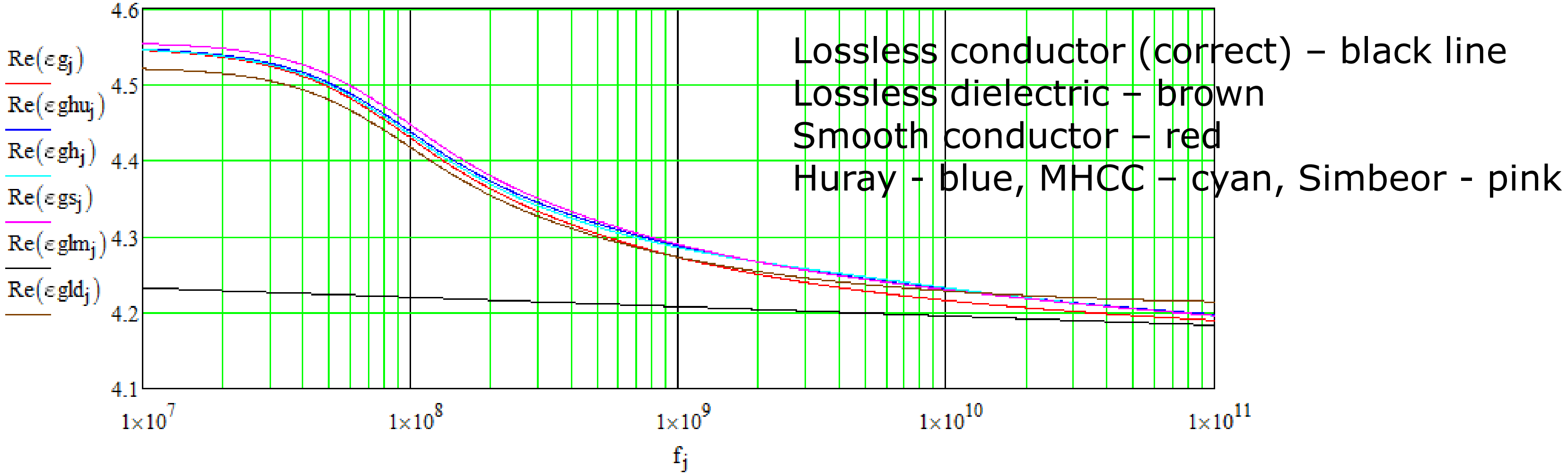
Dielectric model that "accounts for" the roughness – Dk and LT computed from Y

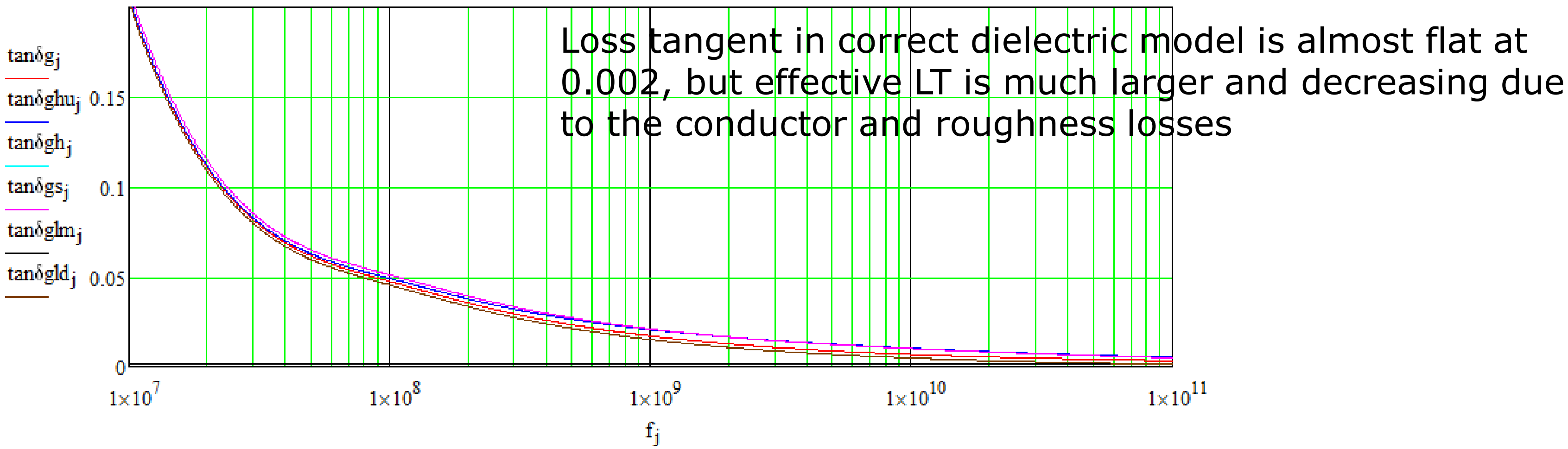


More visible changes in Dk

Impact of roughness on effective LT is huge!

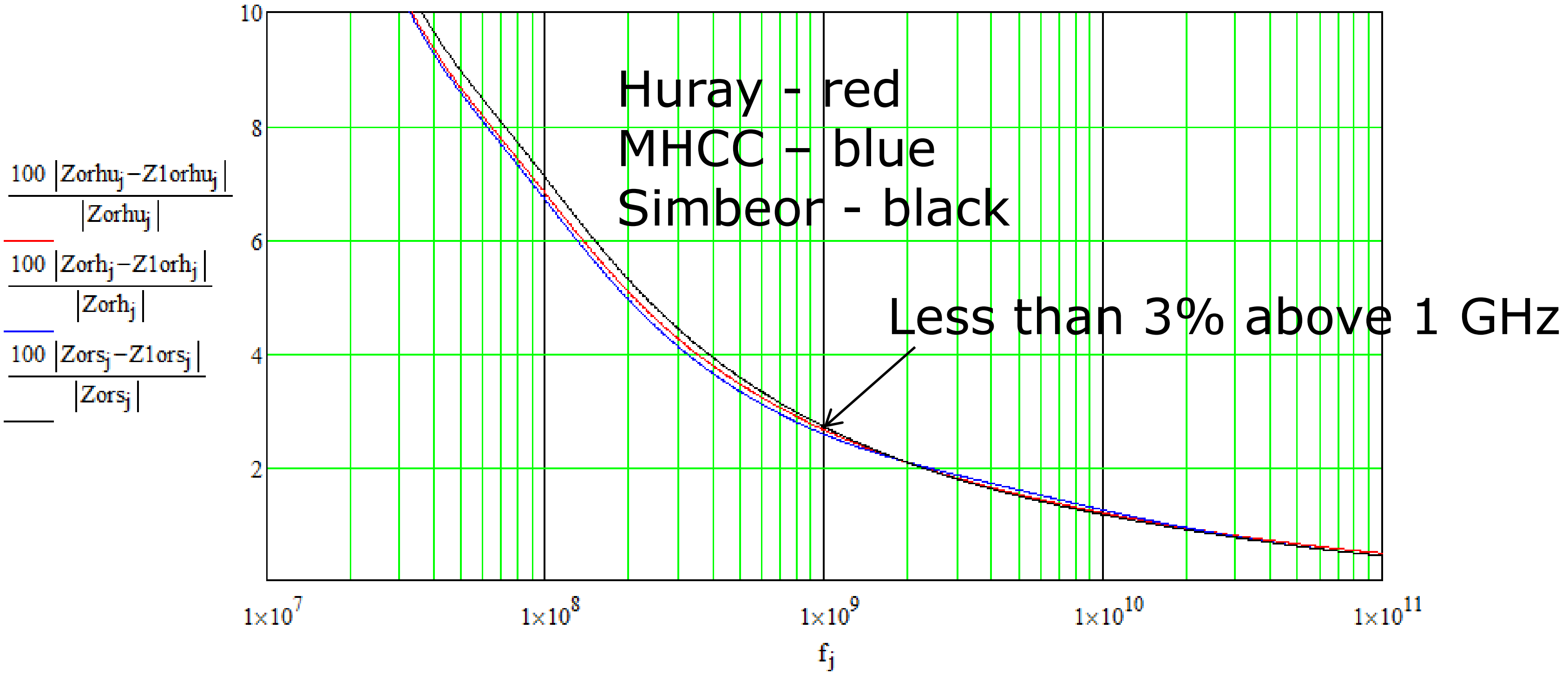
What if we compute Dk and LT directly from the propagation constant (Γ)?





What if we use the effective Dk and LT model (move all conductor losses into Y)?

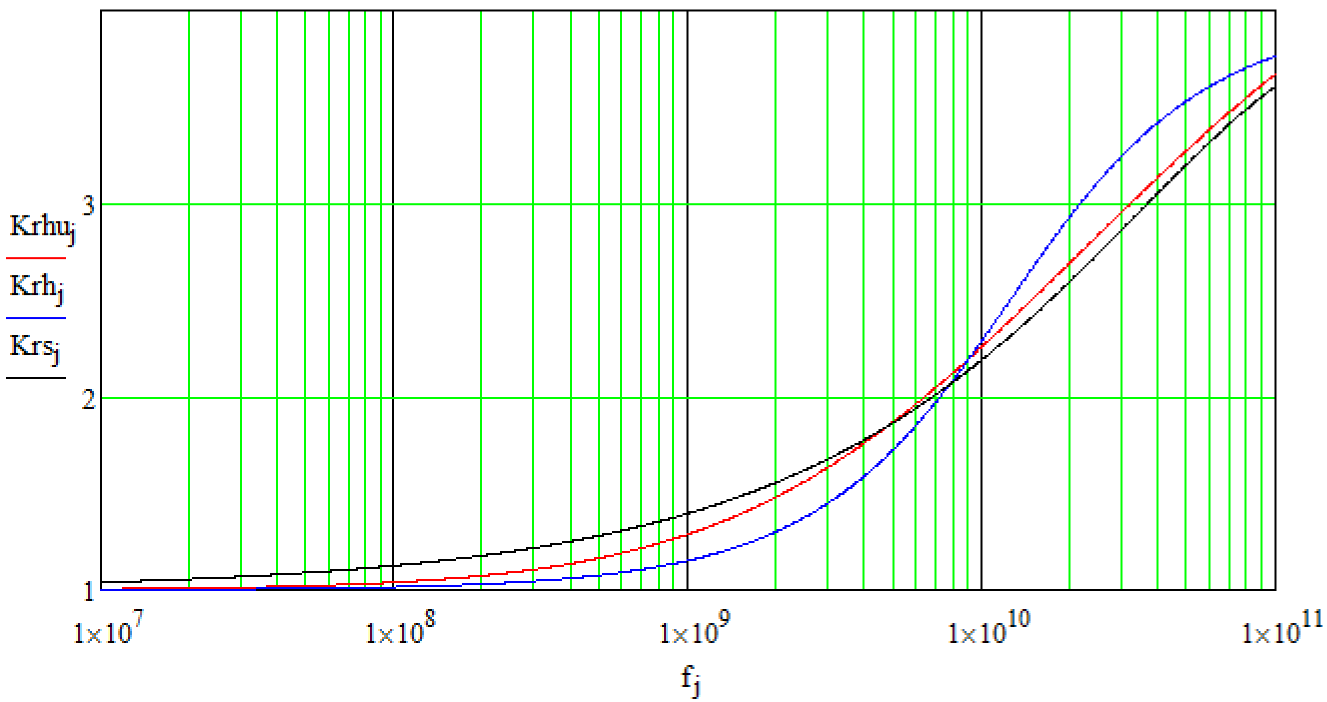
- Propagation constant stays unchanged
- Characteristic impedance decreases more:



May be not acceptable in this case of low-loss dielectric

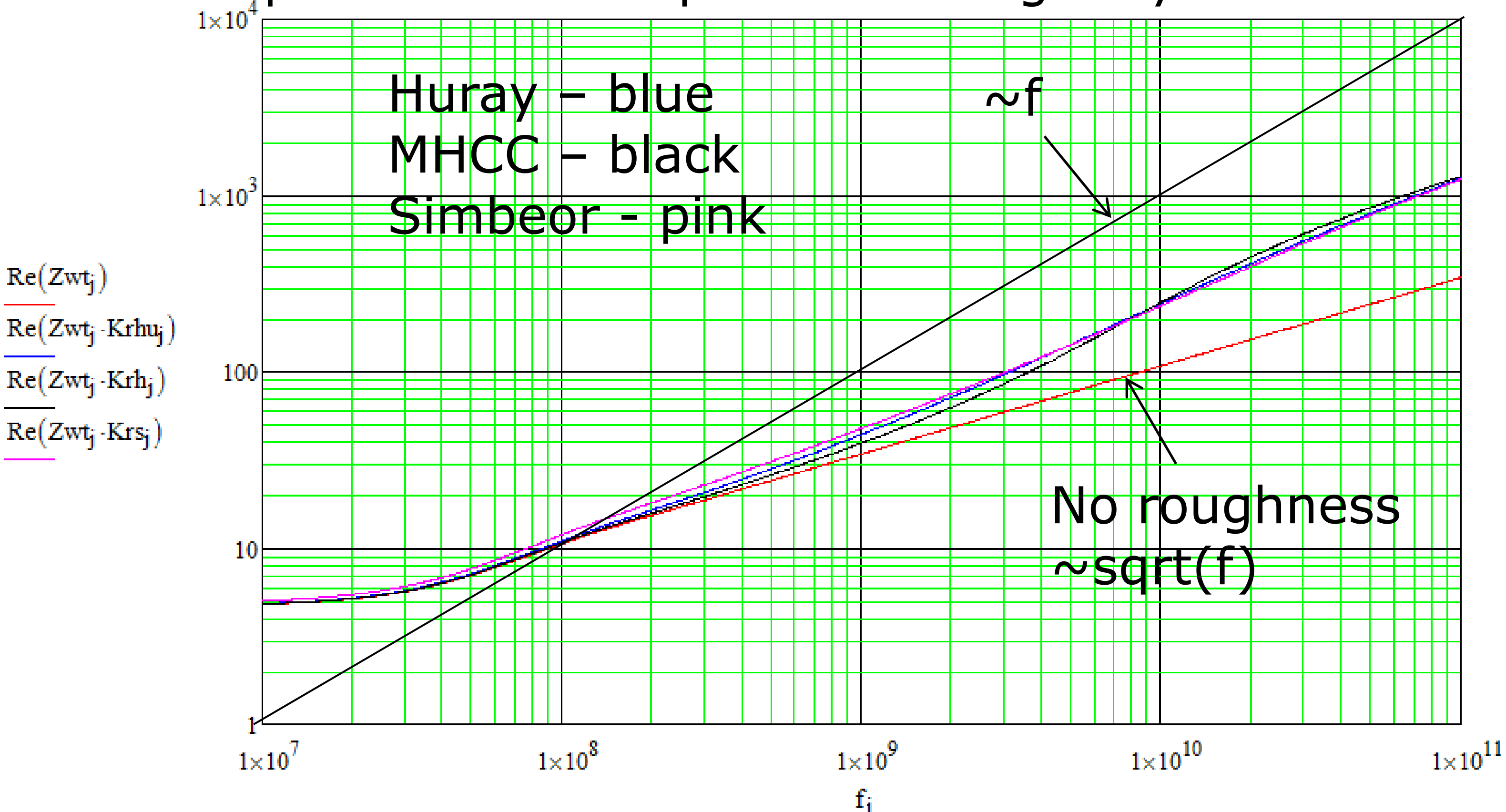
Roughness correction coefficients for low profile copper surface

- MHCC and Simbeor – delta=0.5 um, RF=4
- Huray model – r=0.5 um, At=25 um^2, N=32



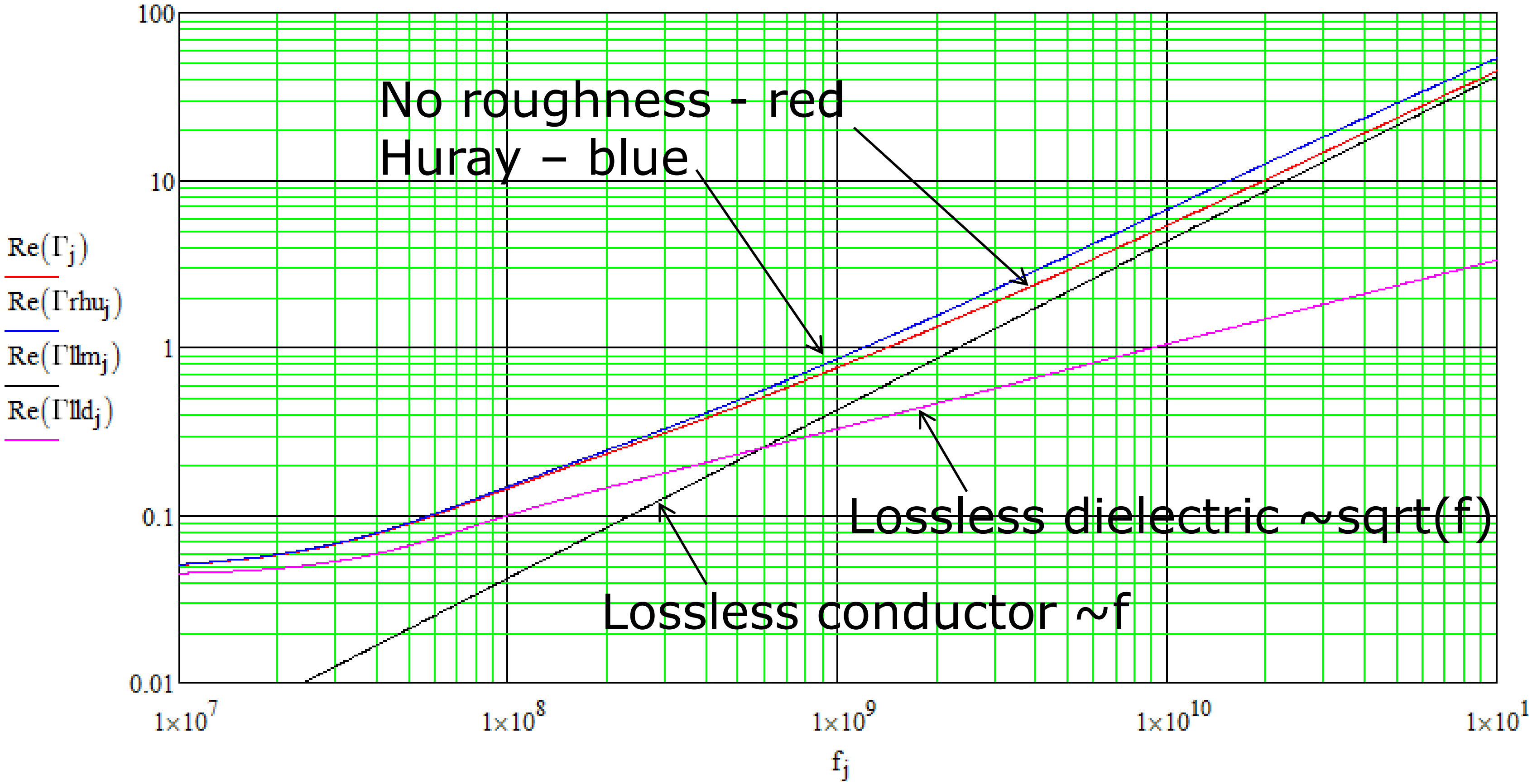
Increase in conductor impedance due to roughness

Real part of Kr*Zs is plotted – imaginary is identical



Non of the models predicts change of asymptotes from sqrt(f) to linear (though, it is closer now)

Impact of roughness on overall losses (high loss dielectric case)



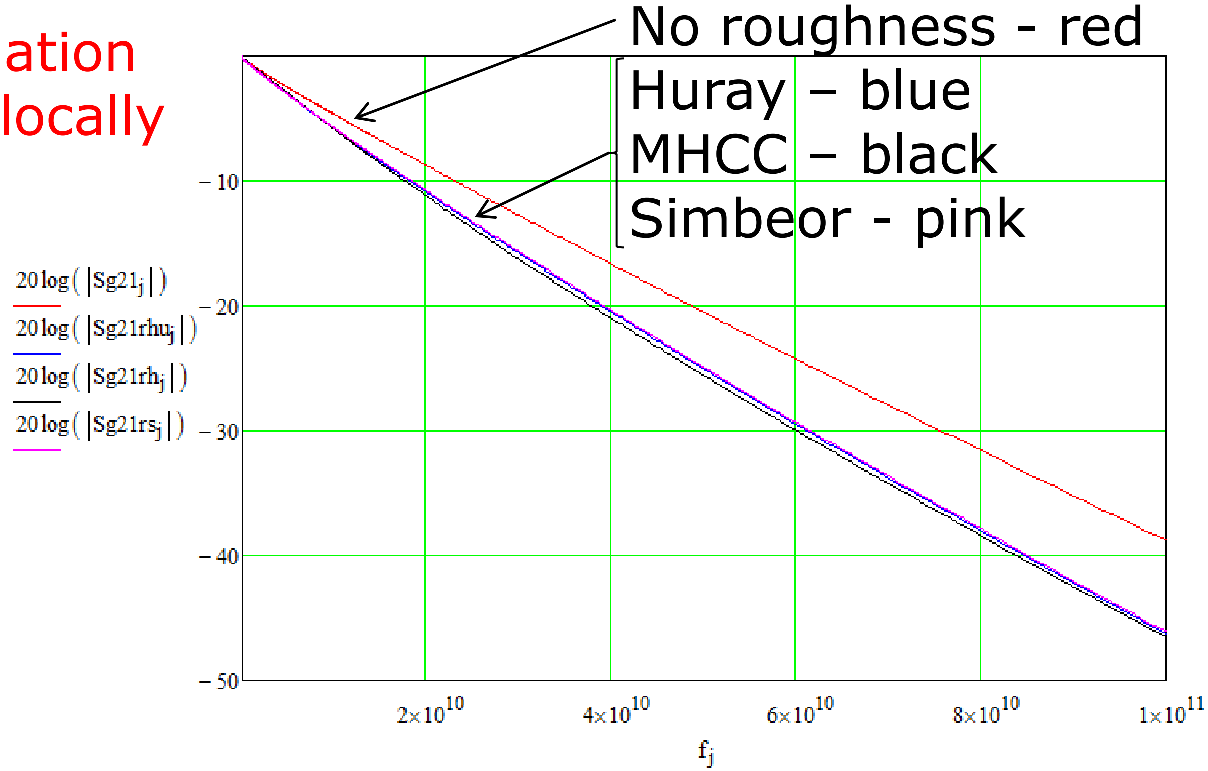
All other roughness models produce Γ close to Huray model and do not confirm linear attenuation growth concept

All other conclusions are similar to the case of regular copper

Does it produce linear insertion loss?

- 10 cm segment of line, 50-Ohm normalized S-parameters (small reflections due to mismatch with characteristic impedance)

Linear approximation may be applied locally



On Log scale on vertical axis, the curve shape is similar to attenuation on the previous slide

Conclusions from static model investigation

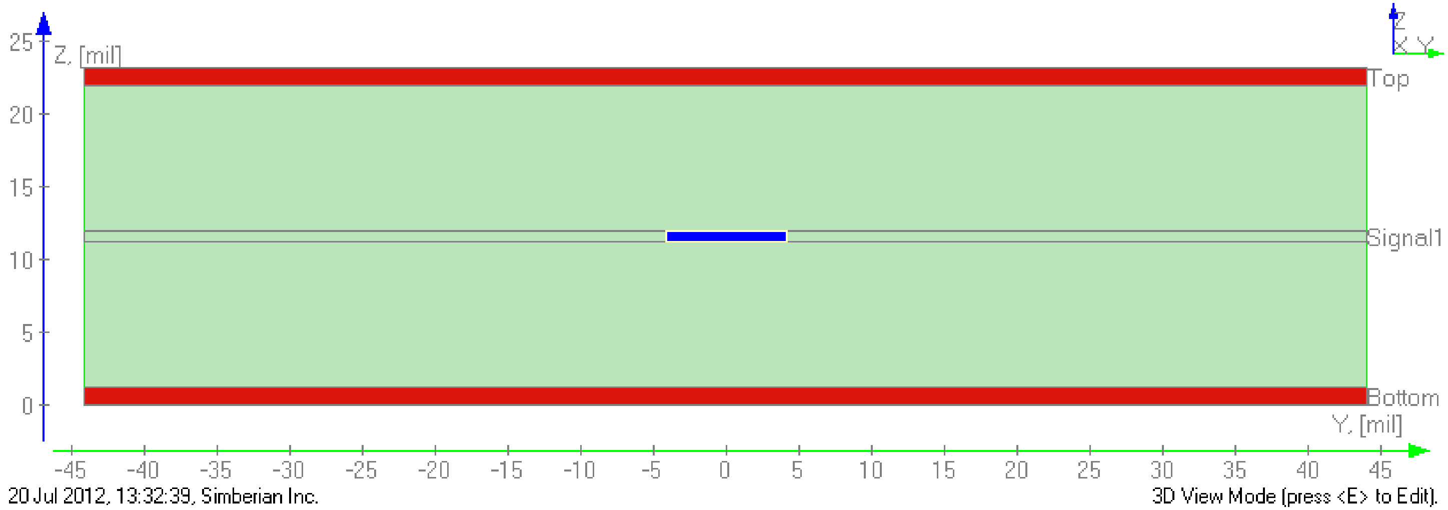
- It looks like the roughness effect can be safely accounted for in the dielectric model
- Smooth lossy conductor model must be always used to simulate conductor effect
  - Transfer of all conductor losses into dielectric model can significantly change characteristic impedance, especially for low-loss dielectrics – not acceptable!
- As the next step we will try to build dielectric models that account for the roughness and try to apply them to strips with different widths
  - Numerical electromagnetic analysis with Simbeor will be used

Numerical experiment outline

- Build dielectric model that includes roughness effect
  - Build electromagnetic model for strip line segment with roughness
  - Build model with smooth copper and adjust dielectric parameters to match insertion loss and phase to the model with roughness
- Change dielectric thickness and strip width and verify how new dielectric model with included roughness works
  - Build model for strip line segment with roughness
  - Build model without roughness and with new dielectric model and compare the results

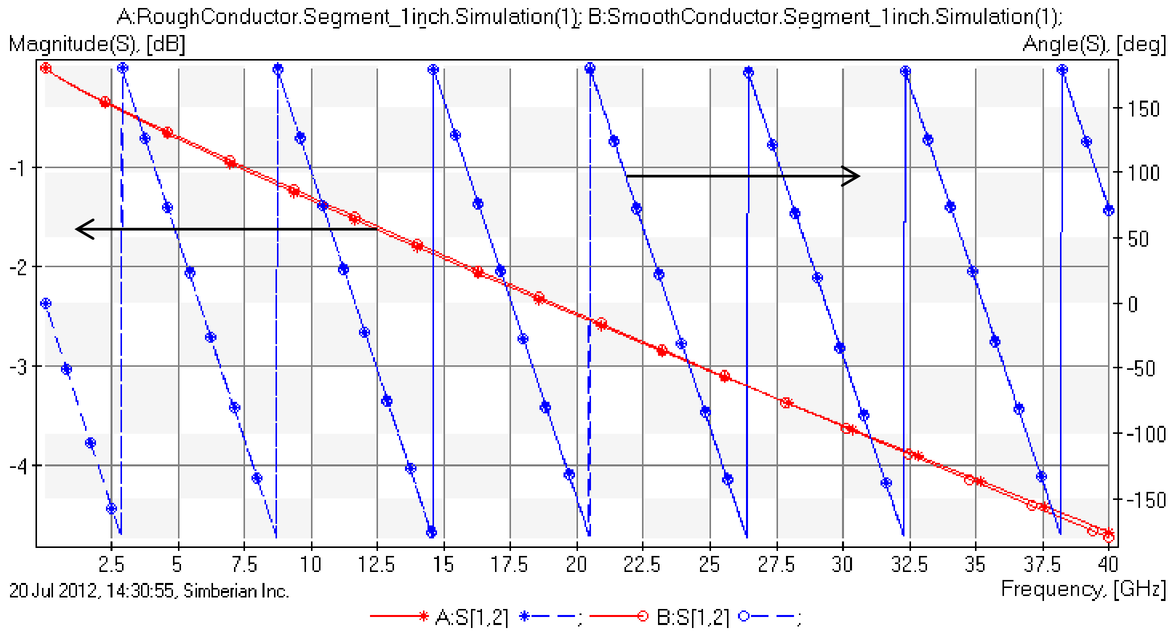
Strip line to identify dielectric model

- 8.3 mil strip, 0.73 mil thick, 10 mil dielectric above and below, 1.2 mil thick planes
- Wideband Debye dielectric model, Dk=4.2, LT=0.02 (high loss case) and LT=0.002 (low loss case)
- Conductor roughness for all surfaces: SR=1 um, RF=2



Dielectric identification (high-loss case)

- New wideband Debye model that includes roughness effect: **Dk=4.24, LT=0.022 (10% increase)**
- Insertion loss and phase match well (1 inch line segment)

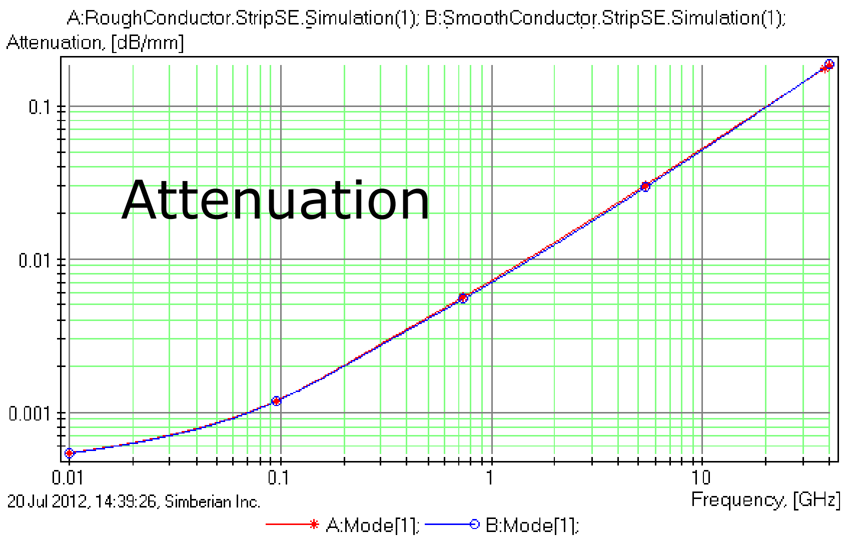


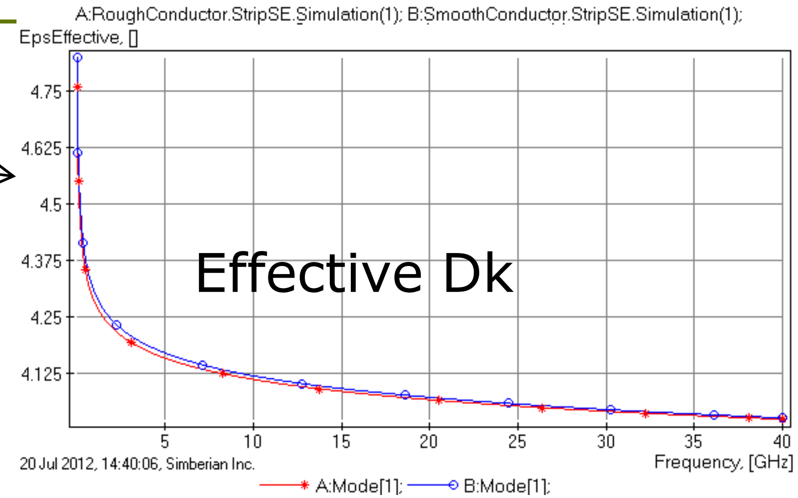
With Simbeor roughness model

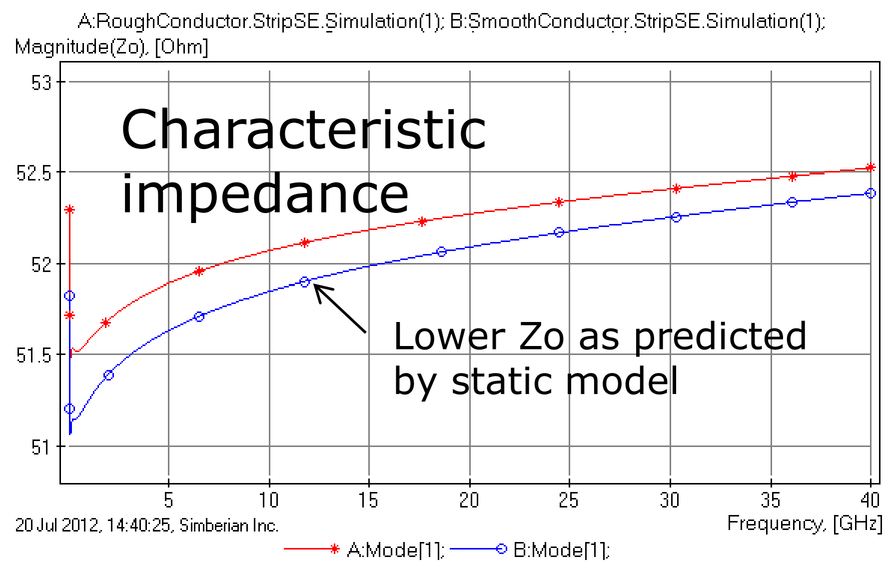
Model with rough conductor - stars
Model with smooth conductor and new dielectric - circles

Comparison of two models

- Good correspondence as expected



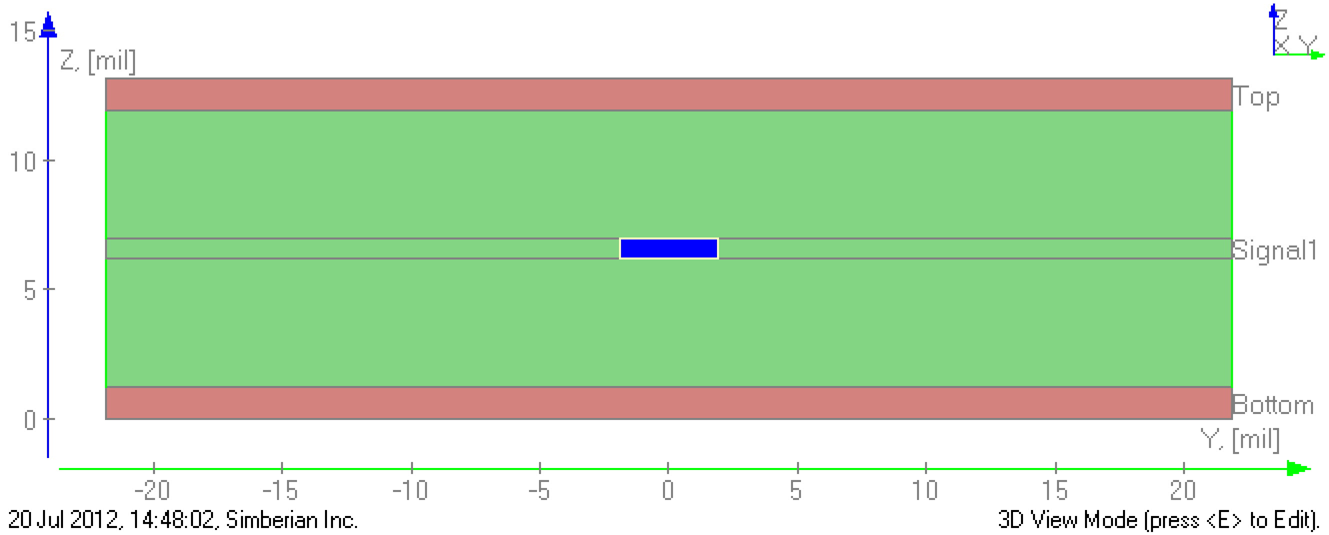




Model with rough conductor – red lines with stars
Model with new dielectric – blue lines with circles

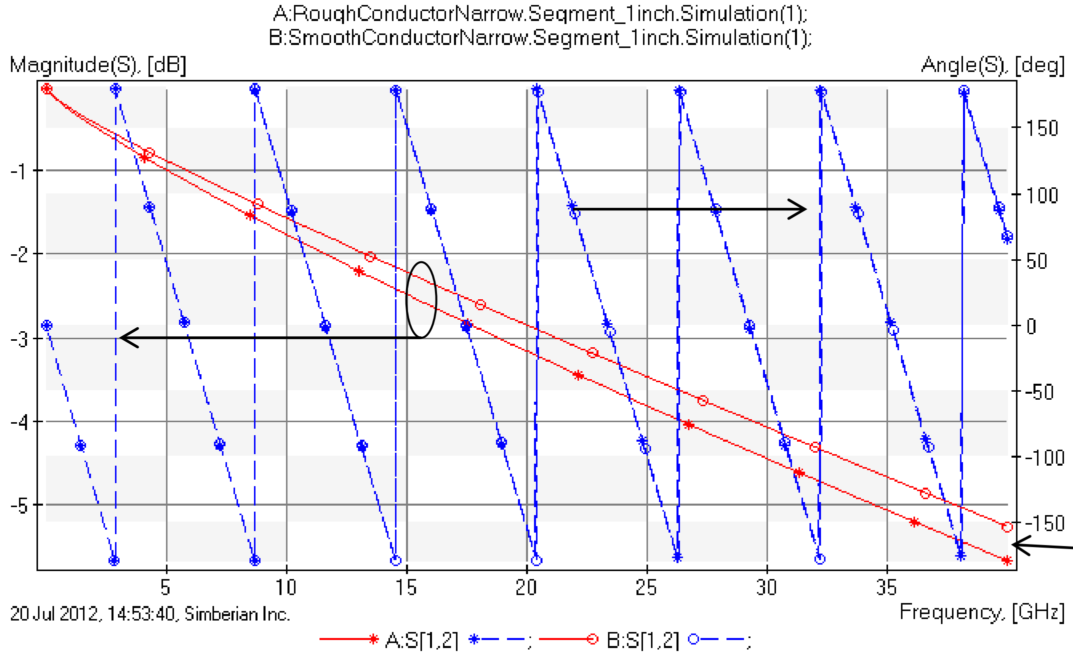
Can we use new dielectric model for different strip widths?

- Let's reduce dielectric thickness to 5 mil and narrow strip to 3.8 mil to have about 50 Ohm line



The model is not good!

- New dielectric model produces very close phase, but insertion loss is smaller than in the model with rough conductor as we can see from simulation of 1 inch segment



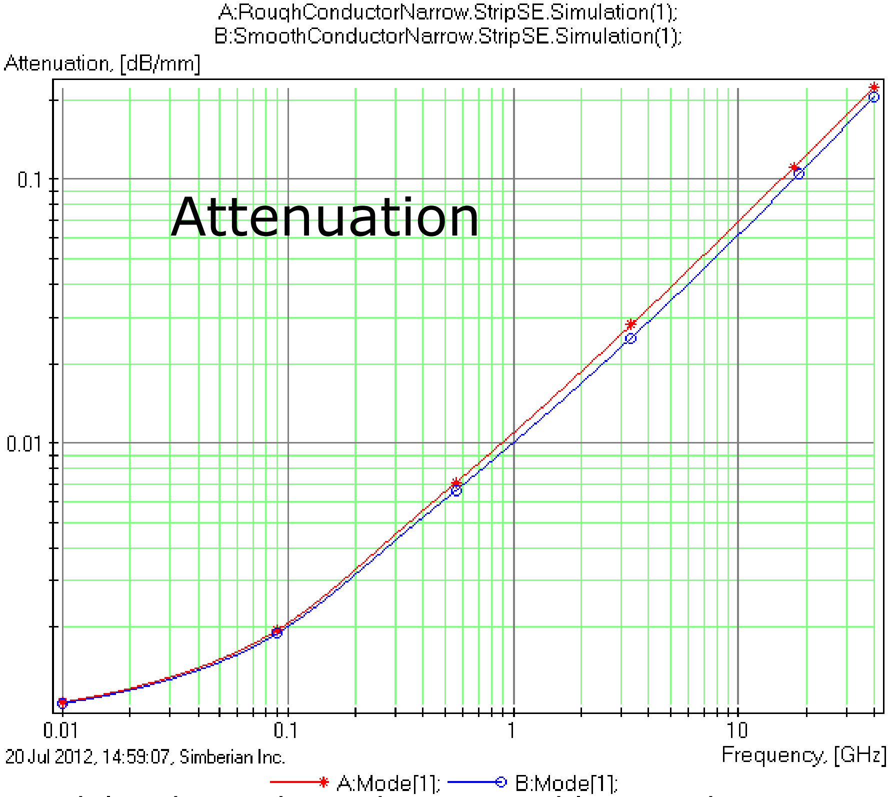
With Simbeor roughness model

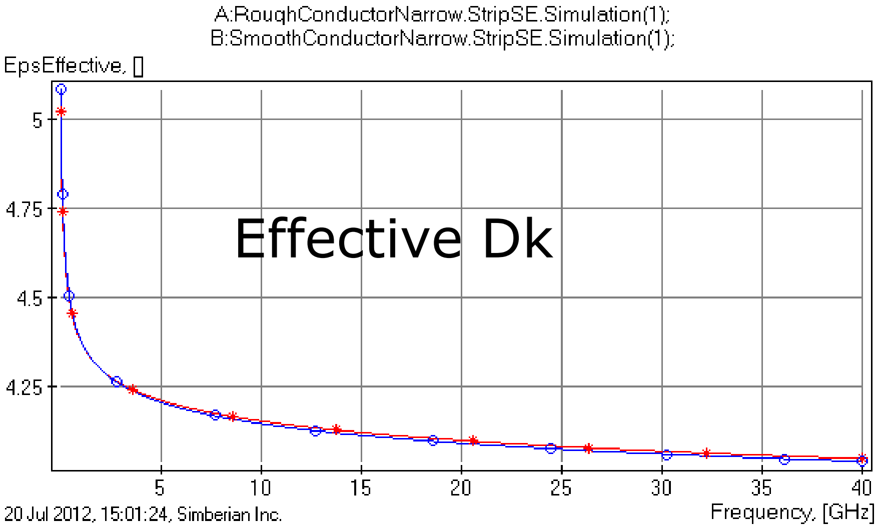
Another 10% increase in LT needed to match IL

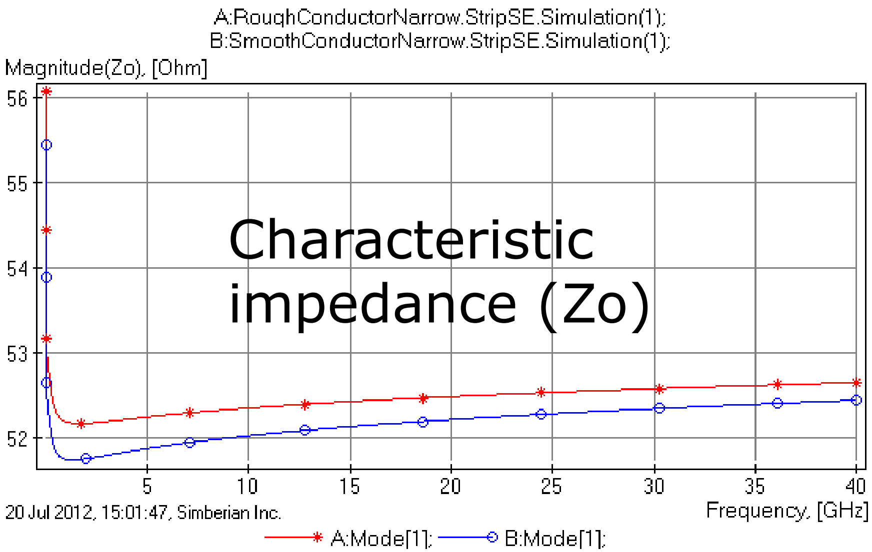
Model with rough conductor - stars
Model with smooth conductor and new dielectric - circles

Comparison of two models for narrow strip

- Unacceptable discrepancies in attenuation (and Zo)



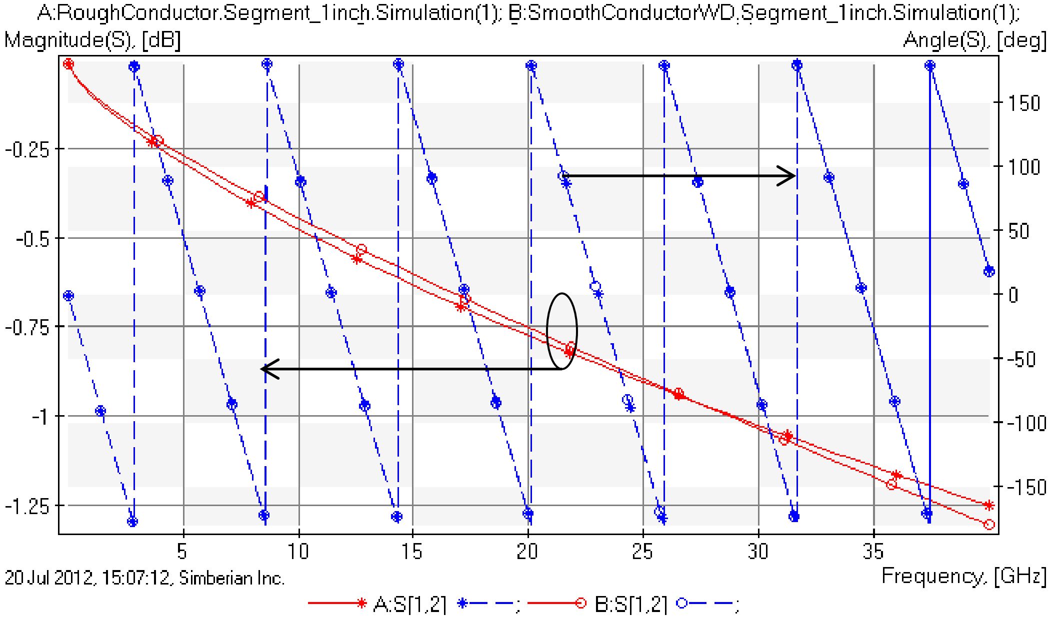




Model with rough conductor – red lines with stars
Model with new dielectric – blue lines with circles

Dielectric identification (low-loss case)

- New wideband Debye model that includes roughness effect: **Dk=4.24, LT=0.0045 (more than 100% increase)**
- Phase match well, but IL deviates a little (1 inch line segment)



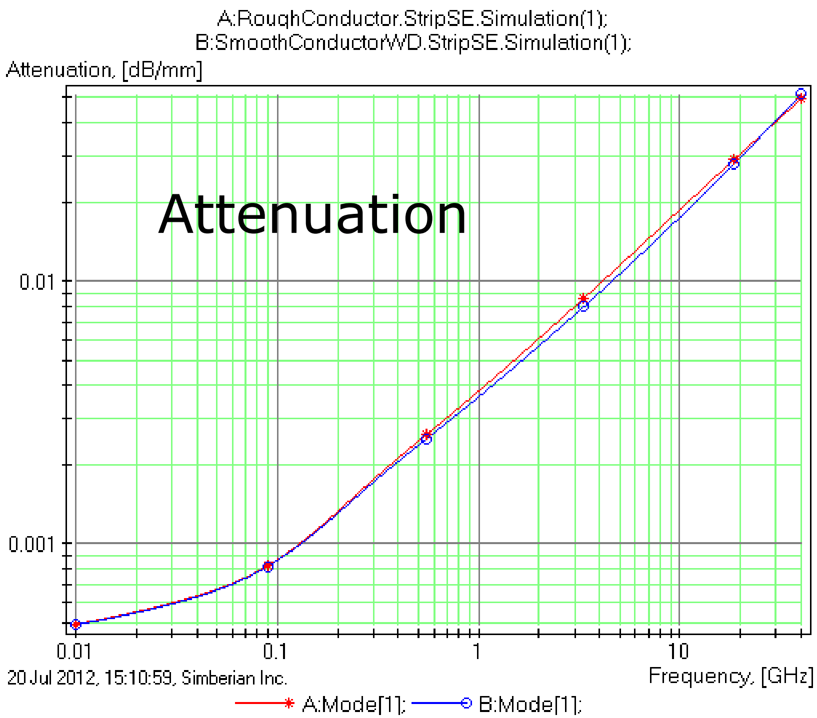
Multi-pole Debye model must be used to achieve better match!

With Simbeor roughness model

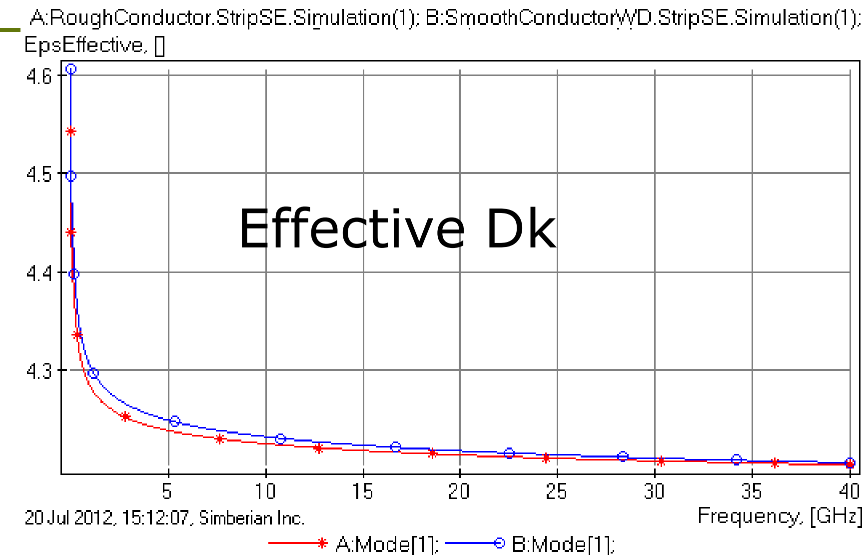
Model with rough conductor - stars
Model with smooth conductor and new dielectric - circles

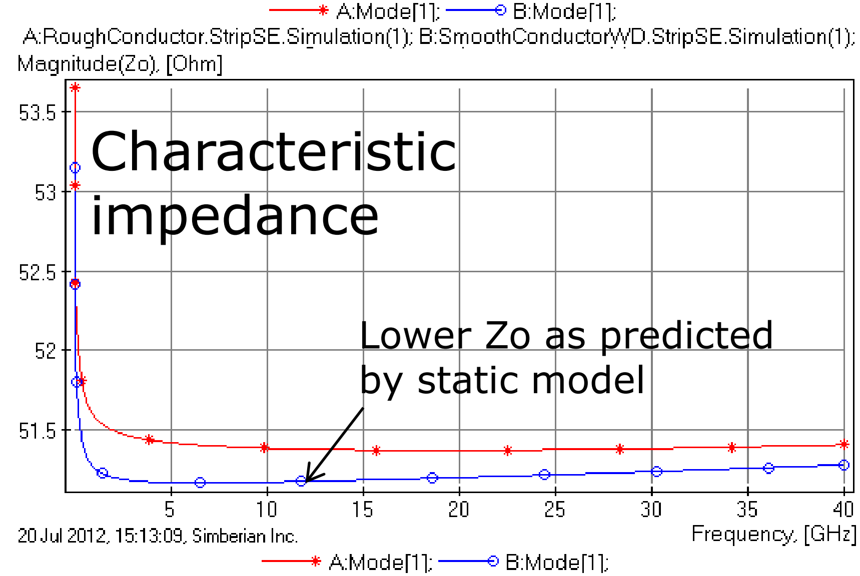
Comparison of two models

- Correspondence in attenuation is not so good



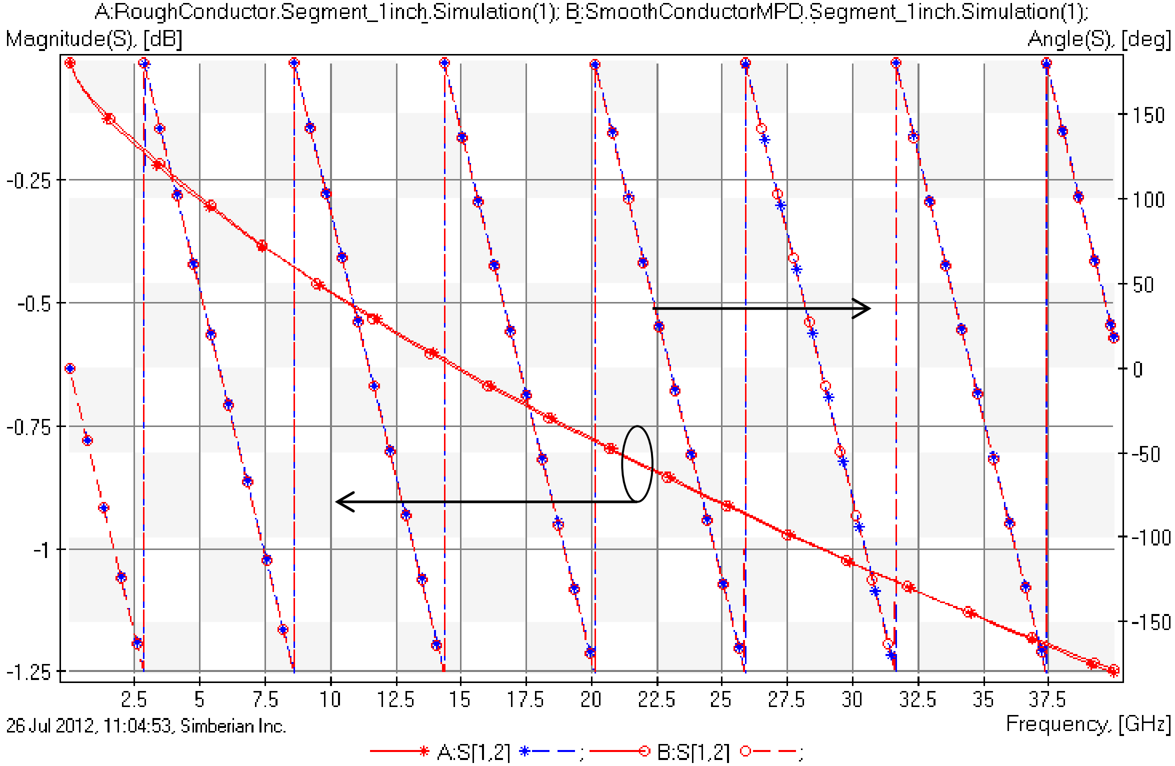
Model with rough conductor – red lines with stars
Model with new dielectric – blue lines with circles





Dielectric identification (low-loss case)

- Multipole Debye model with 8 poles fitted to have minimal least-square error

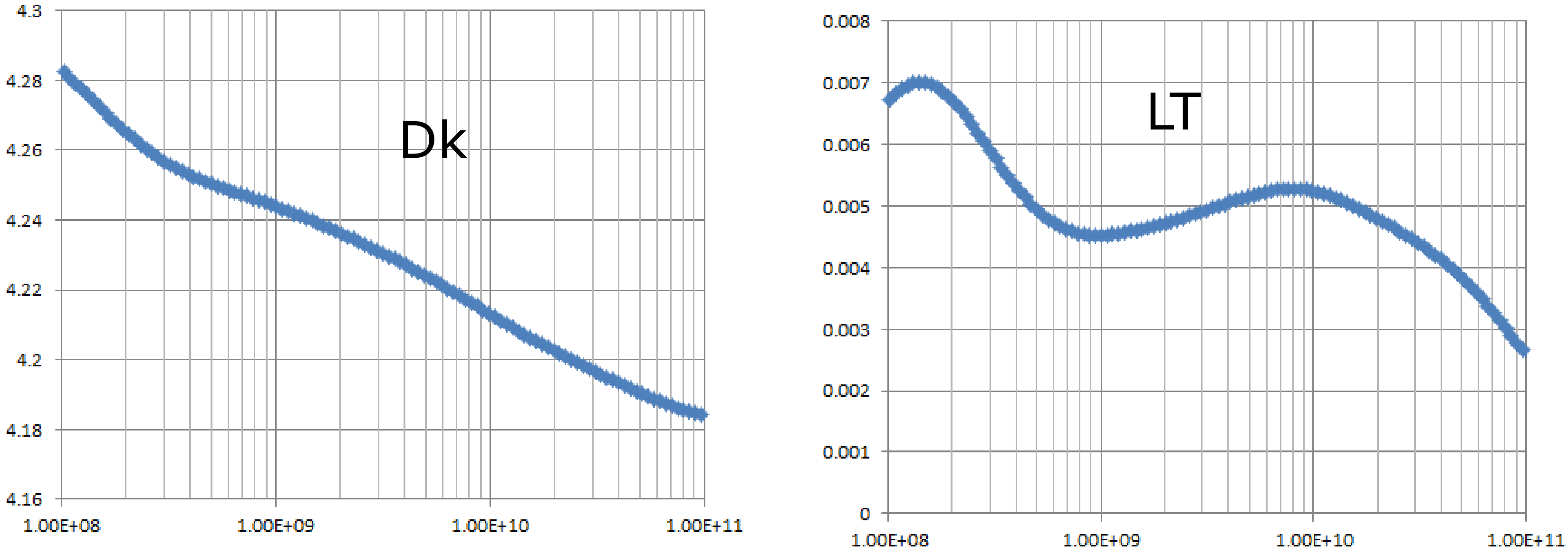


With Simbeor roughness model

Model with rough conductor - stars
Model with smooth conductor and new dielectric - circles

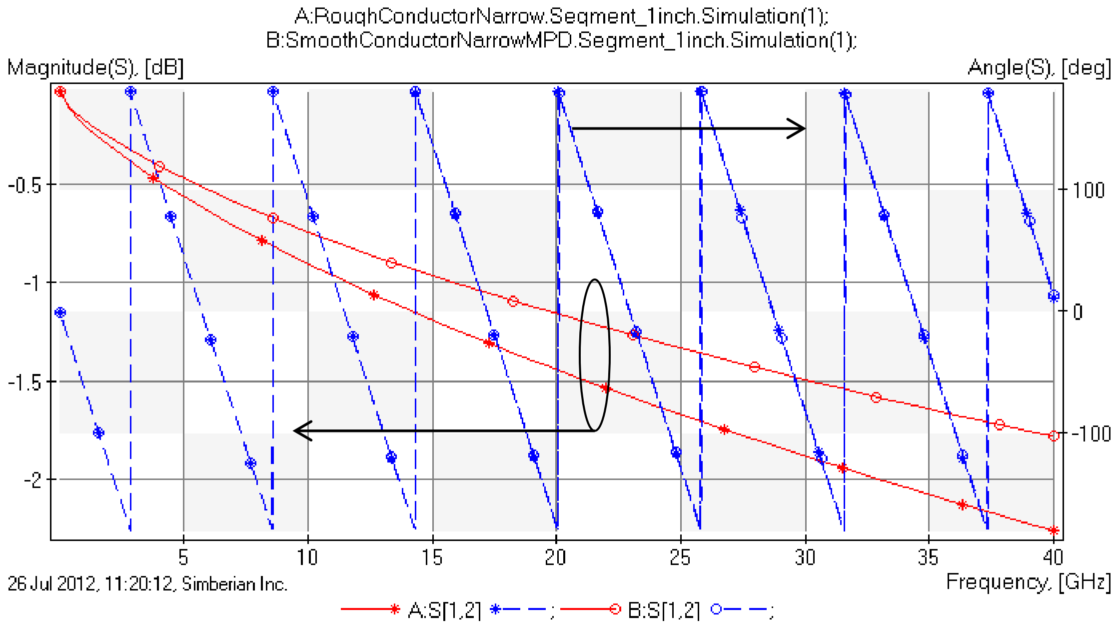
New dielectric model that includes roughness effect

- 8-pole model (may be further improved)
- Shows larger LT at lower frequencies – not what we typically see from experimental extraction for low-loss materials!!!



Thin dielectric and narrow strip

- New dielectric model produces very close phase, but insertion loss is **much** smaller than in the model with rough conductor as we can see from simulation of 1 inch segment



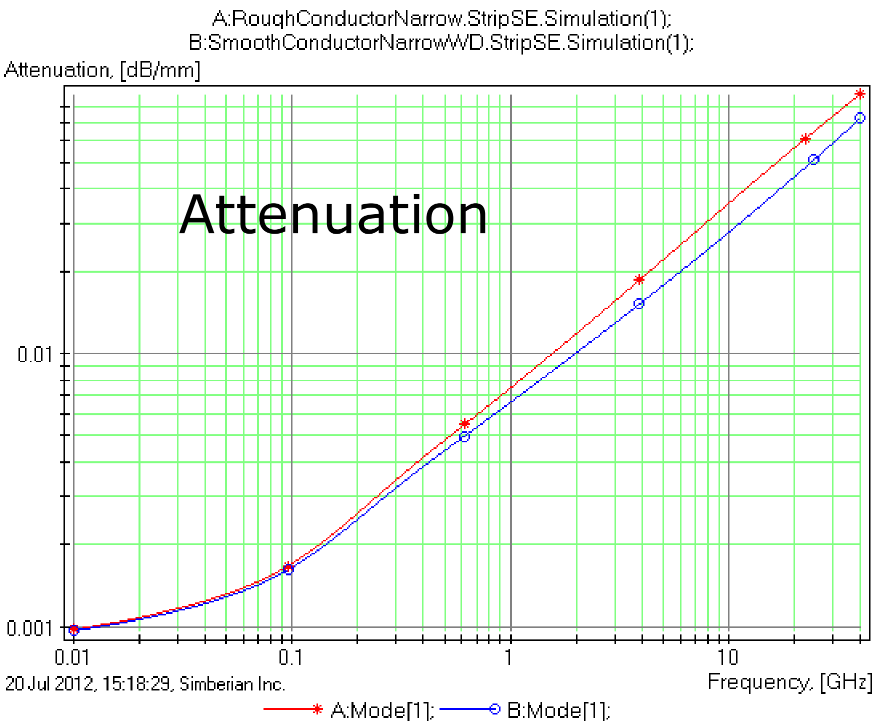
With Simbeor roughness model

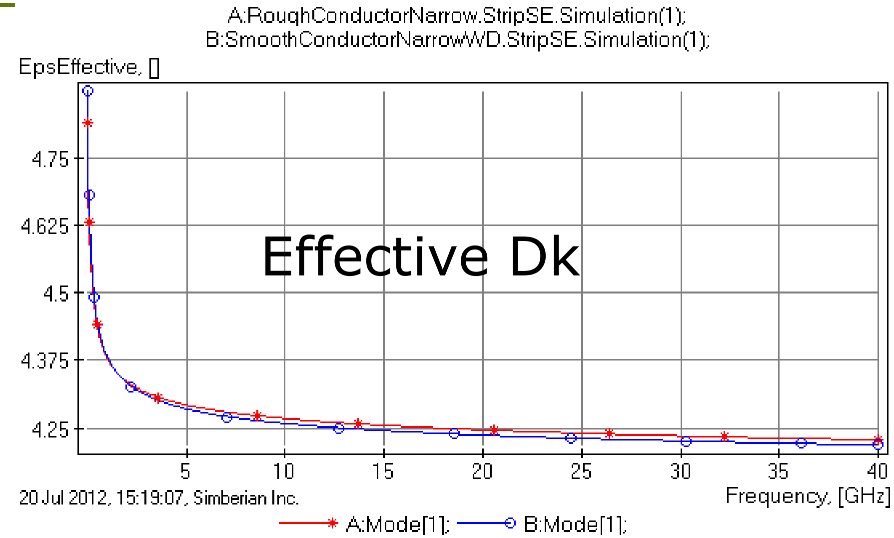
Another 100% increase in LT may be needed to match IL

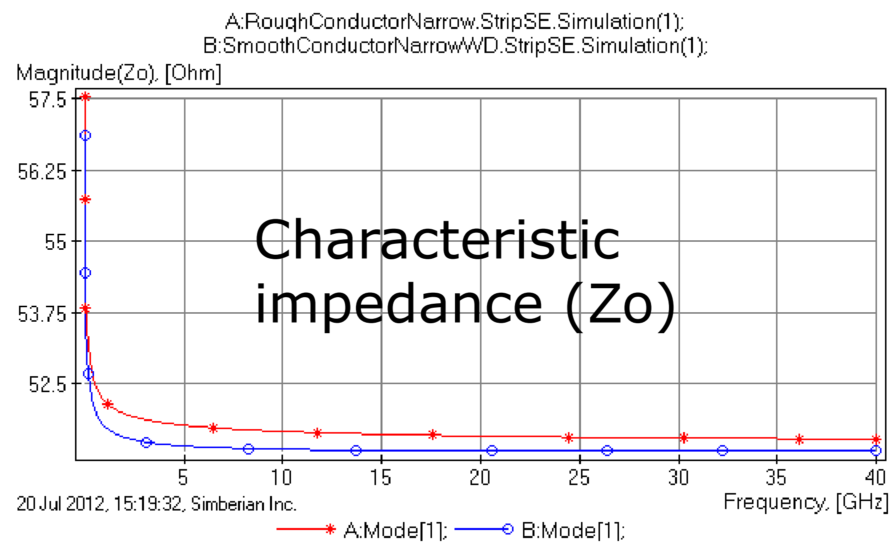
Model with rough conductor - stars
Model with smooth conductor and new dielectric - circles

Comparison of two models for narrow strip

- Unacceptable discrepancies in attenuation (and Zo)







Model with rough conductor – red lines with stars
Model with new dielectric – blue lines with circles

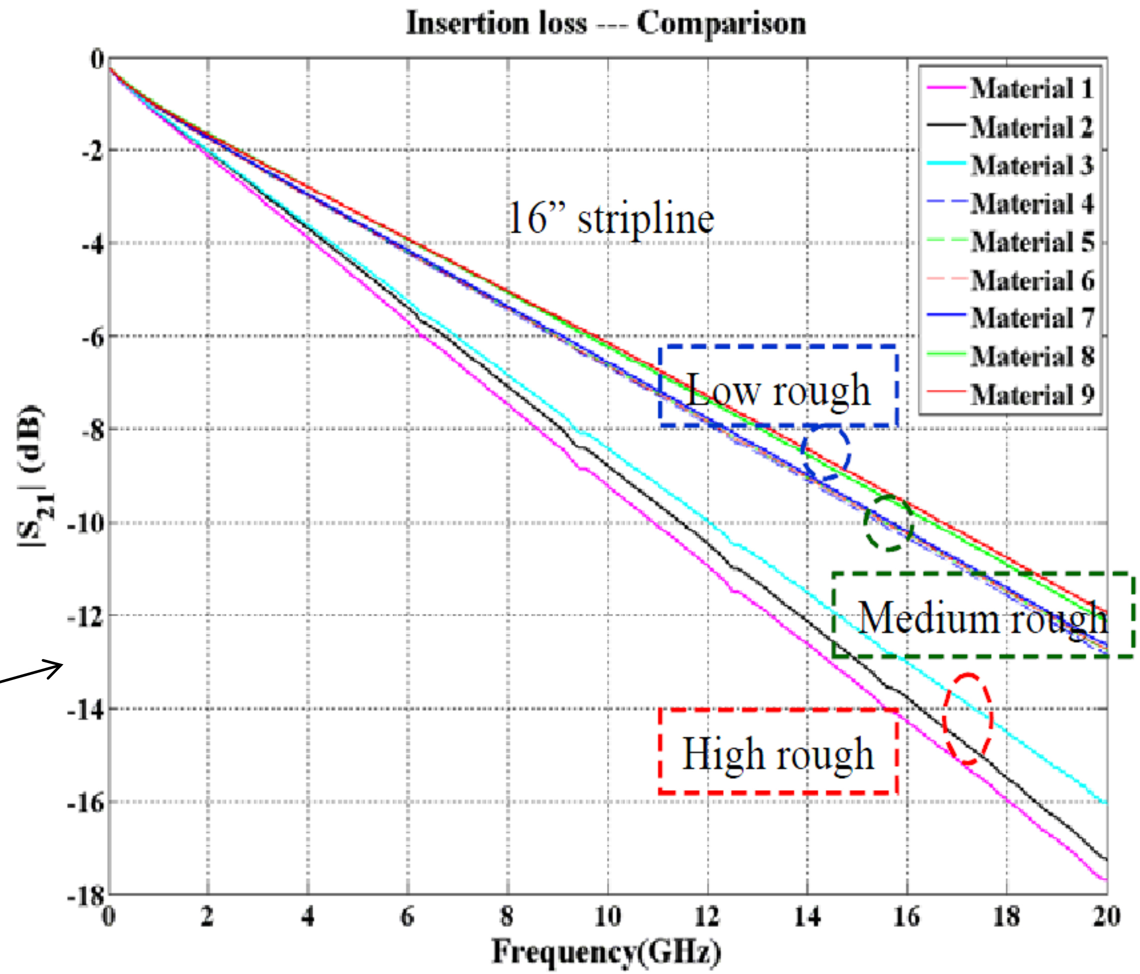
Conclusion

- Roughness effect can be transferred into dielectric model in some cases
- However,
  - Such model may be good only for a particular line type and small variations of strip width
  - It increases complexity of dielectric model, especially in case of low-loss dielectrics (multi-pole Debye should be used)
- All conductor losses cannot be transferred into dielectric model
  - Causes significant changes in characteristic impedance
  - Dielectric model becomes even more dependent on strip width and line time

Appendix: On linearity of the losses

- It is visual illusion! – see next slides

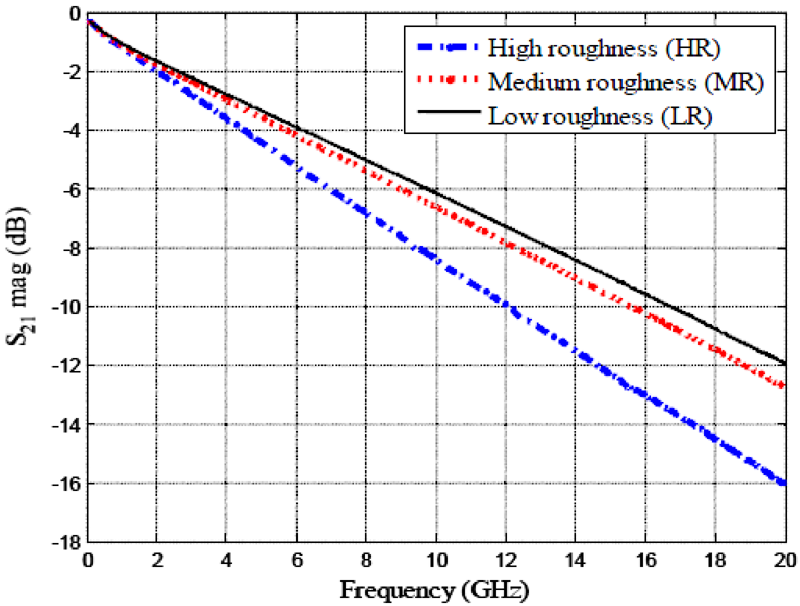
From M. Y. Koledintseva, J. L. Drewniak, S. Hinaga, F. Zhou, A. Koul, and A. Gafarov, Experiment-based Separation of Conductor and Dielectric Loss in PCB Striplines, DesignCon 2011

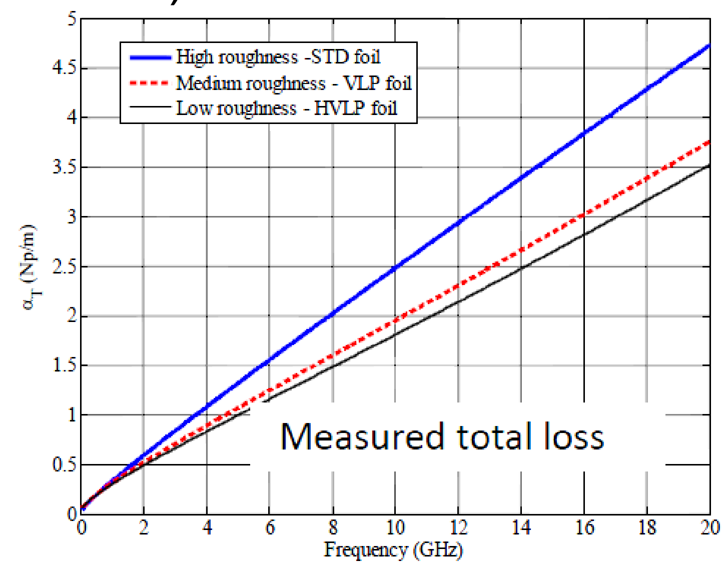


On log scale, curve is similar in shape to attenuation computed as ln(|S21|)/length

Visually linear IL produces attenuation with non-linear terms!

- S-parameters normalization and Zo mismatch may contribute to the linearity (not accounted in the extraction below)





Largest sqrt and square terms in the least lossy case!

$$\alpha_T^{STD} = 1.386\cdot 10^{-6}\sqrt{\omega} + 3.399\cdot 10^{-11}\omega - 2.682\cdot 10^{-24}\omega^2$$

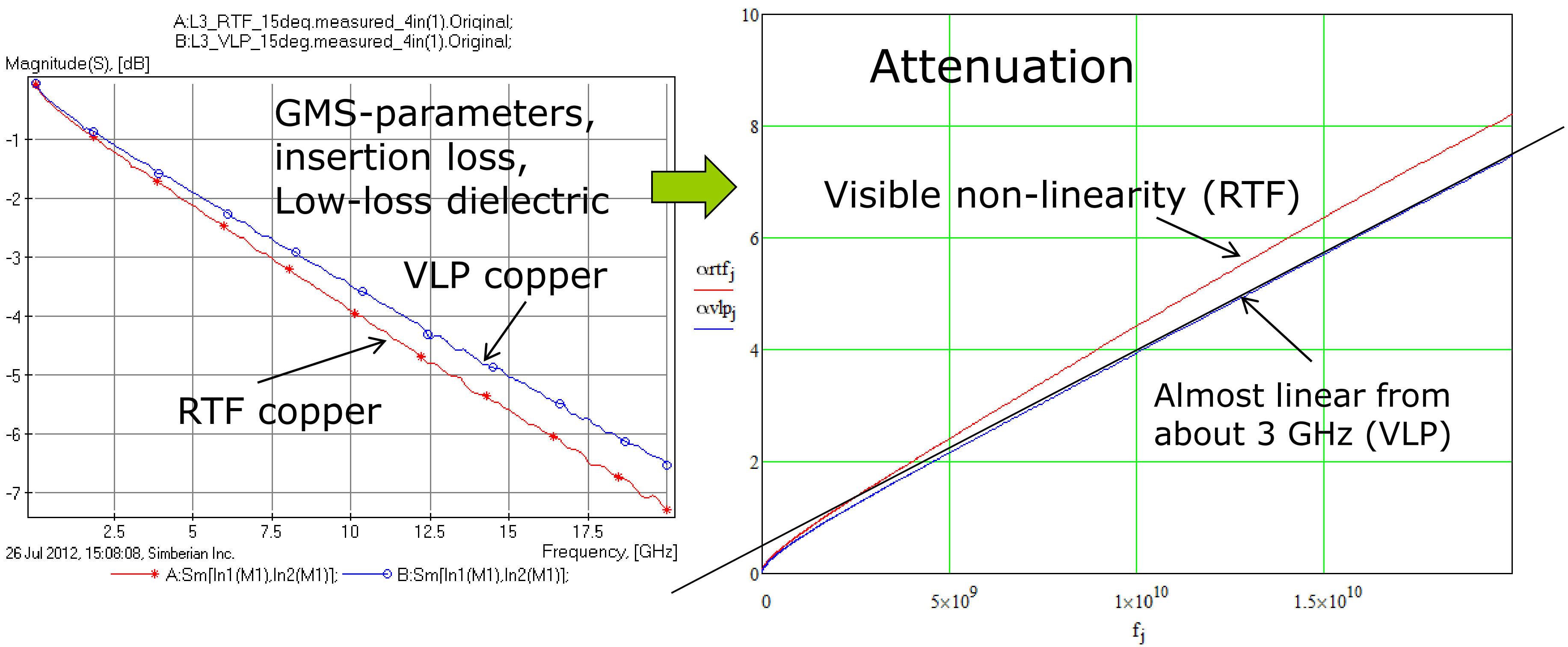
$$\alpha_T^{VLP} = 2.200\cdot 10^{-6}\sqrt{\omega} + 2.070\cdot 10^{-11}\omega + 2.334\cdot 10^{-23}\omega^2$$

$$\alpha_T^{HVLP} = 2.309\cdot 10^{-6}\sqrt{\omega} + 1.745\cdot 10^{-11}\omega + 3.192\cdot 10^{-23}\omega^2$$

From M. Y. Koledintseva, J. L. Drewniak, S. Hinaga, F. Zhou, A. Koul, and A. Gafarov, Experiment-based Separation of Conductor and Dielectric Loss in PCB Striplines, DesignCon 2011

Another example…

- Shlepnev, Nwachukwu, DesignCon 2012



Though, there is something in this linearity above 3 GHz for copper with very low profile copper – may be not much roughness effect?

Contact and resources

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- Download Simbeor® from www.simberian.com and try it on your problems for 15 days
- Simberian web site and contacts www.simberian.com
- Simbeor demo-videos http://www.simberian.com/ScreenCasts.php
- App notes http://www.simberian.com/AppNotes.php
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