Accounting for High Frequency Transmission Line Loss Effects in HFSS

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Transmission Line Refresher

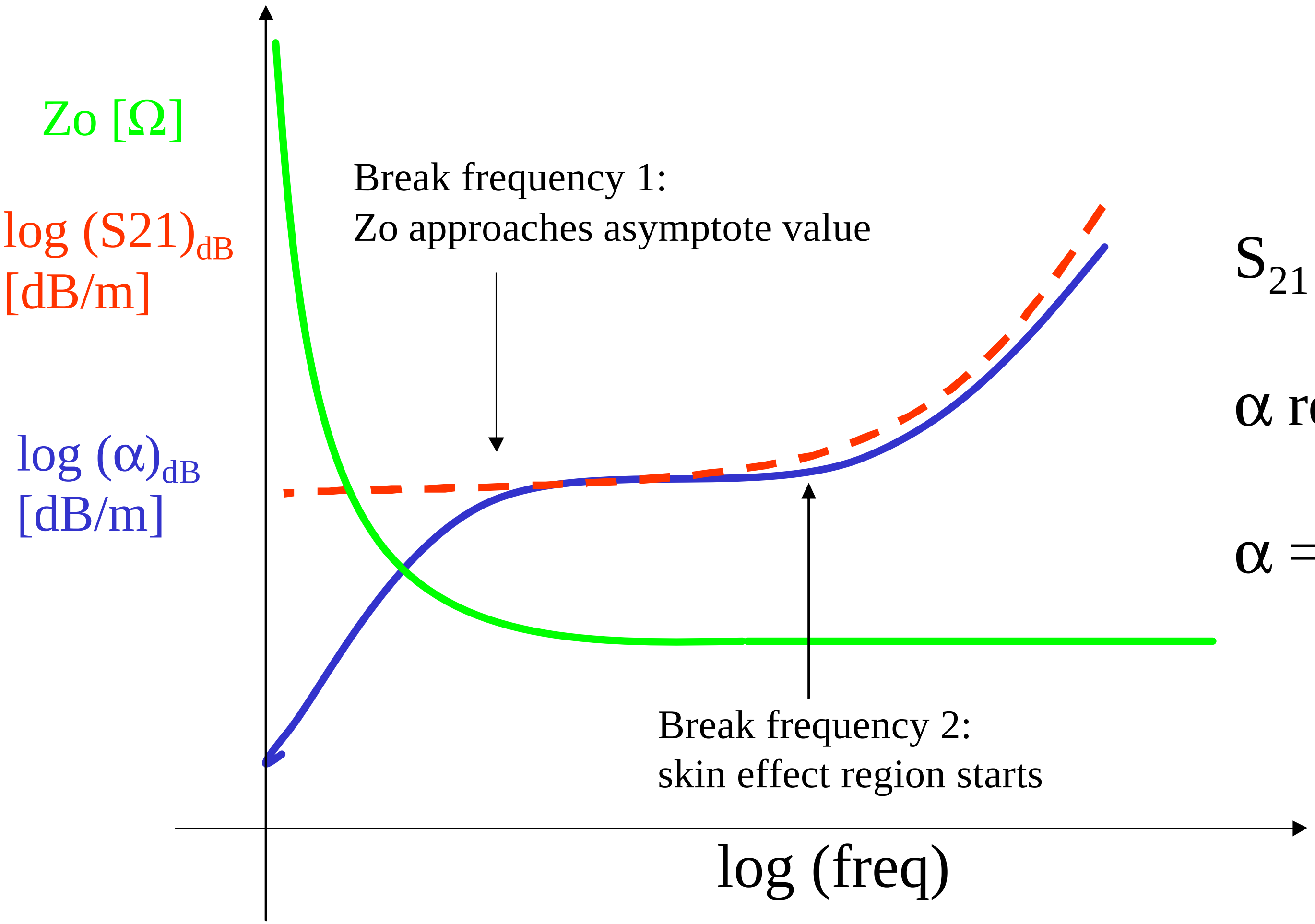
$$\gamma = \alpha + j\,\beta = \sqrt{(R + j\omega L) * (G + j\omega C)}$$

$$Zo = Zr + j\,Zi = \sqrt{(R + j\omega L) / (G + j\omega C)}$$

Transmission line characteristics describe a particular ***mode***
Number of modes = number of conductors -1

α = attenuation constant (loss in either metal or dielectric)
β = propagation constant (dependent on ε_o and μ_o)
R, L, C, G = frequency dependent equivalent circuit parameters

Transmission Line Refresher



S_{21} referenced to 50Ω

α referenced to Zo(f)

$\alpha = (R/2Z_o)$

“log-log” scale reference: National Bureau of Standards Tech Note 1042

Frequency-dependent Loss Mechanisms in Transmission Lines

Dielectric Loss

- function of dielectric loss tangent, tan δ
- dielectric loss dominates in PCB environments
  on FR4-like substrates
- loss is directly proportional to frequency and tanδ

Frequency-dependent Loss Mechanisms in Transmission Lines

Conductor Losses

- Current crowds to surface of transmission line as frequency increases
- Resistance of line inversely proportional to current-carrying cross-section: $R = \rho/A$
- As the current approaches the "skin depth", the resistance of the line begins to increase with the *square root of frequency:*

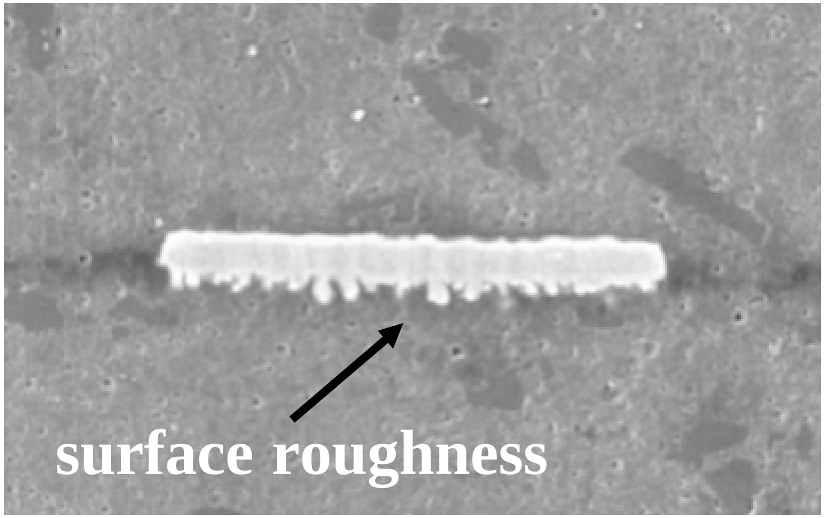
$$\delta_s = \sqrt{\frac{1}{\pi f \sigma \mu_o}}$$

- Conductor loss dominates in high-performance package and chip environment (low dielectric loss substrates or very thin metal)

Frequency-dependent Loss Mechanisms in Transmission Lines

Surface Roughness

- Surface of conductors can be "rough" - sometimes intentionally to aid in metal adhesion to substrate surface
- increase in total current travel distance will result in an increase in loss with frequency



$$\alpha'_c = \alpha_c \left[1 + 2/\pi \tan^{-1}\{1.4(\Delta/\delta_s)^2\}\right] \quad *$$

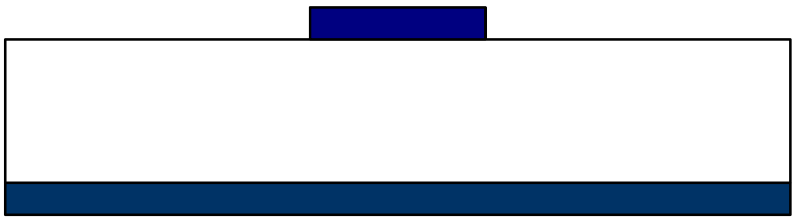
α'_c = attenuation for rough surface
α_c = attenuation for smooth surface
δ_s = skin depth
Δ = r.m.s. surface roughness height

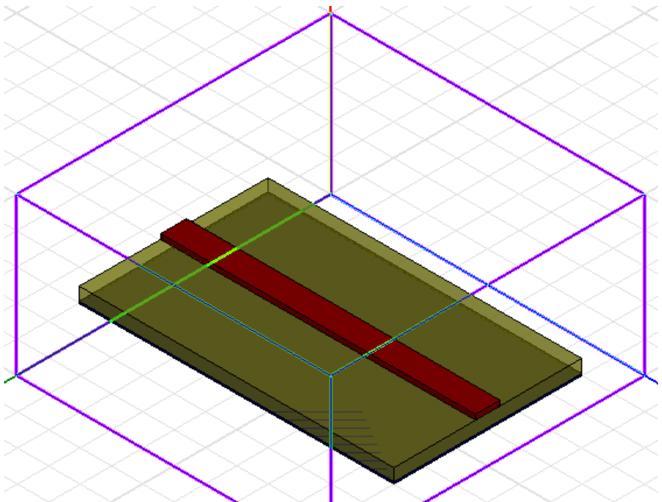
* Edwards, Terry. Foundations for Microstrip Circuit Design. John Wiley and Sons, 1992.

PCB Microstrip HFSS Simulations

Typical PCB dimensions: w=8mils, t=1.6mils, h=4mils, εr = 4

loss properties: tanδ = 0.04 σ = 5.8E7





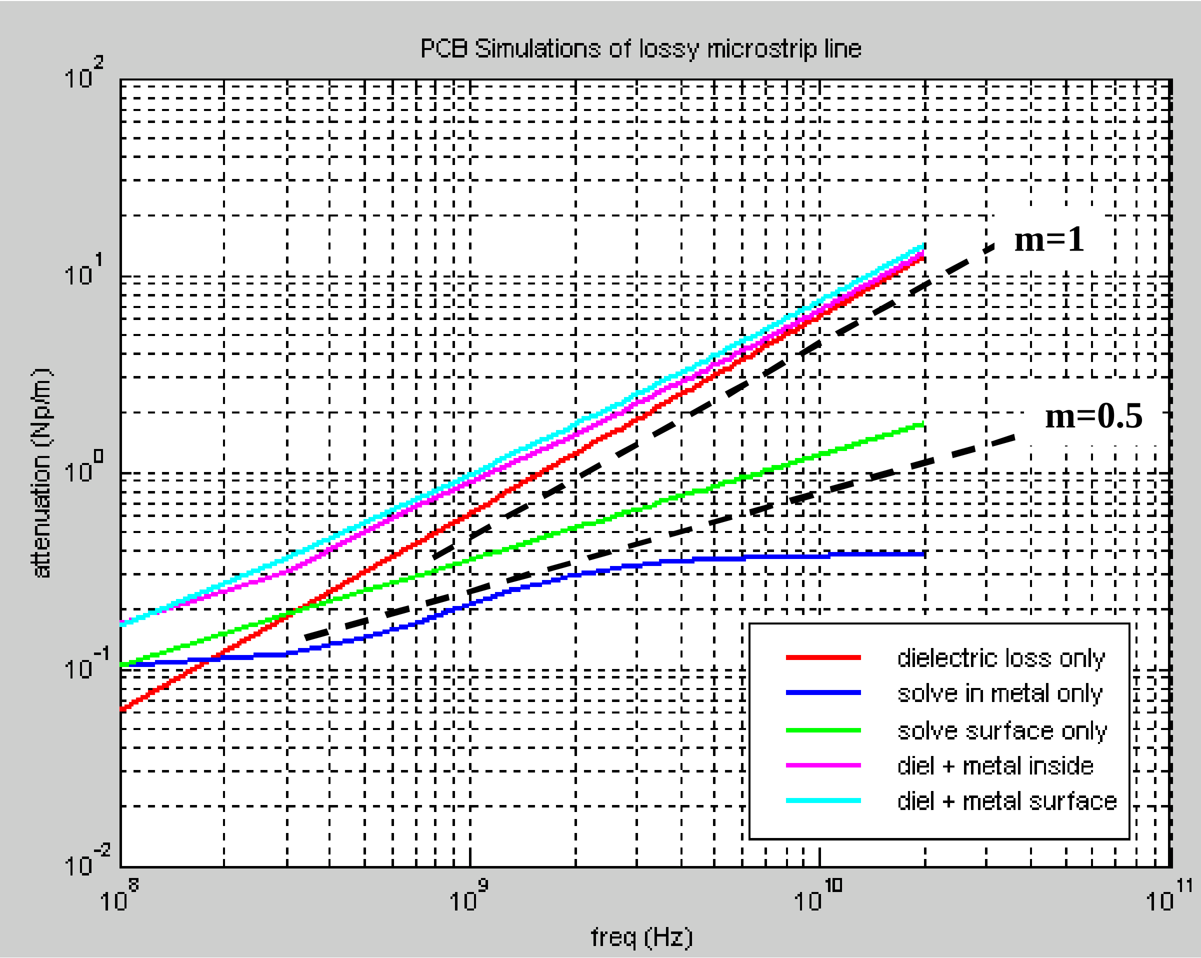
HFSS v9 view

HFSS Simulations:

- lossy dielectric only
- lossy metal (solve inside) only
- lossy metal (surface) only
- both lossy dielectric and metal (inside)
- both lossy dielectric and metal (surface)

inspect the attenuation constant, ***a****, to view loss characteristics ...*
[8.686dB/m = 1Np/m]

PCB Microstrip



SOME OBSERVATIONS:

Dielectric loss dominates at freq > 200MHz

Conductor loss DOES contribute at freq < 5GHz

Solving on surface only makes the skin depth approximation across all frequencies, ignoring the "transition region".

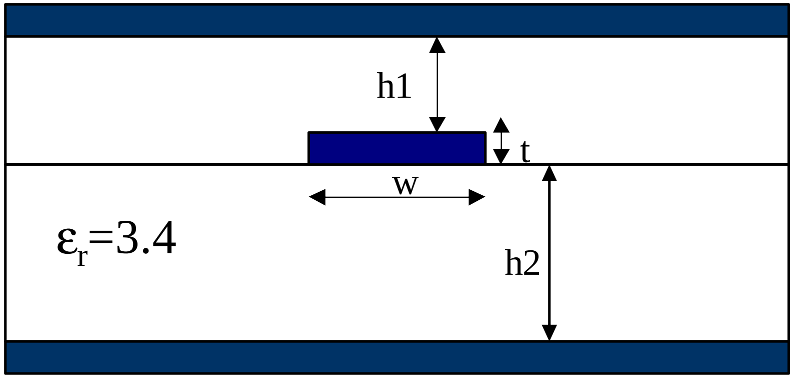
Solving inside the metal has an upper frequency limitation dependent on mesh density.

*** on a "log-log" scale, a slope of 1 is dielectric loss, a slope of 0.5 is skin effect loss**

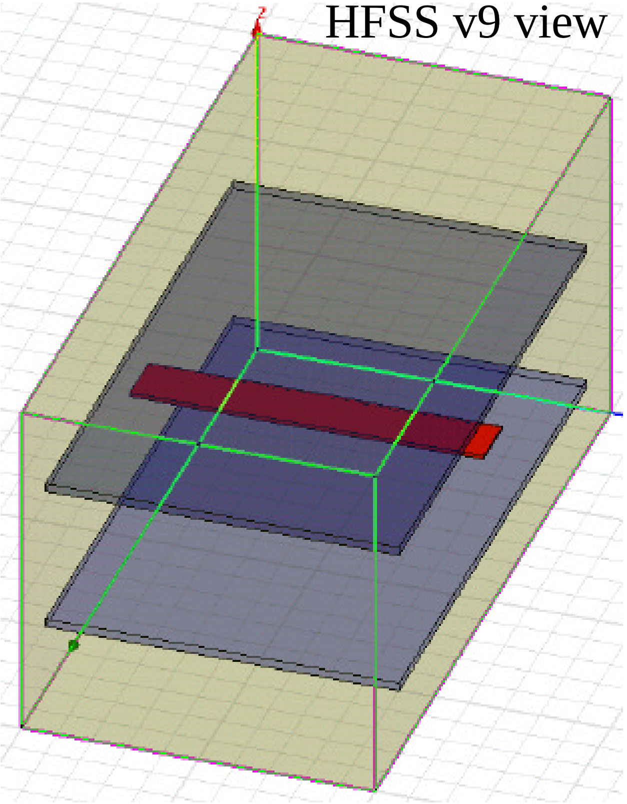
Package Stripline Simulations and Measured Data

Cross-section measured dimensions:
w=79um, h1=60um, h2=138um, t=5um

loss properties: $\tan\delta = 0.008$ $\sigma = 5.8E7$

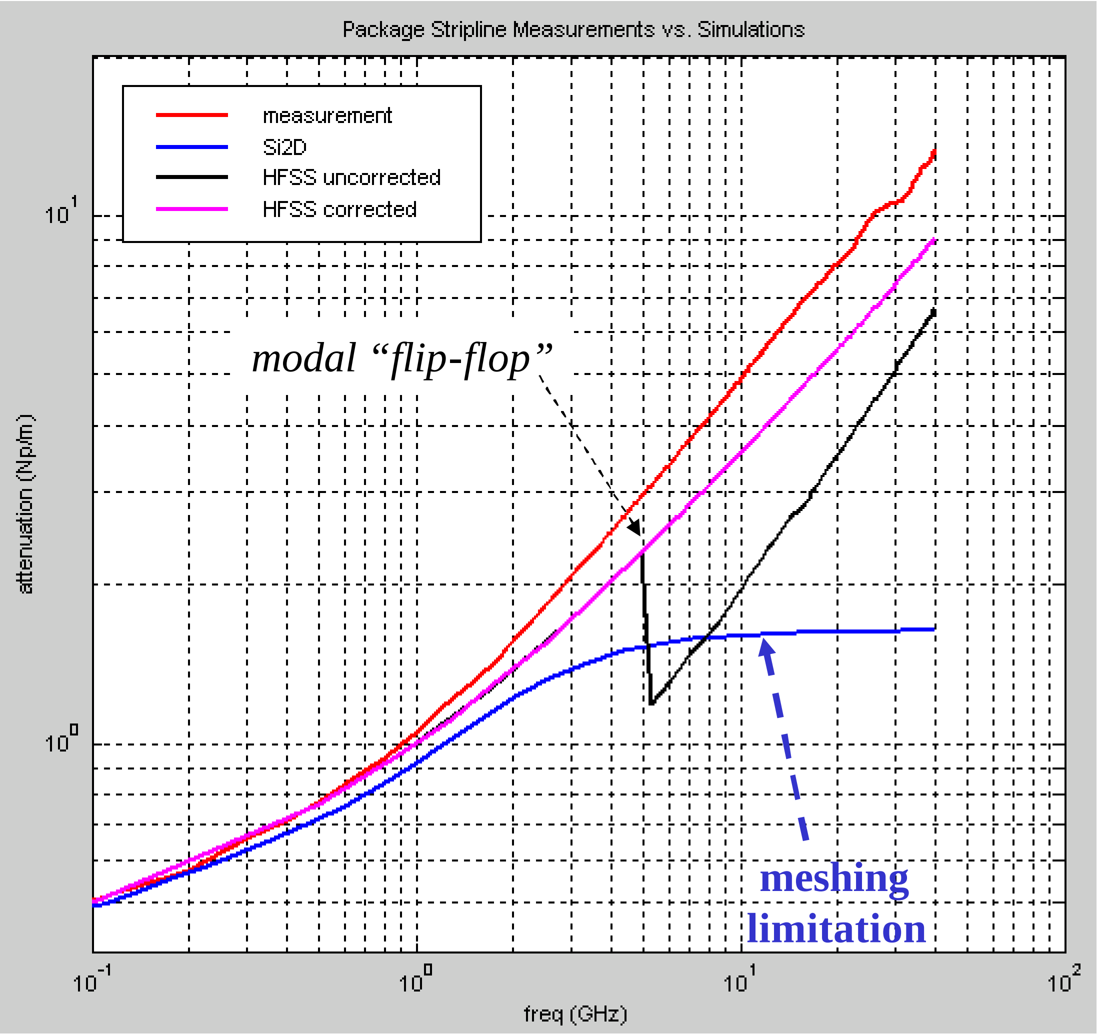


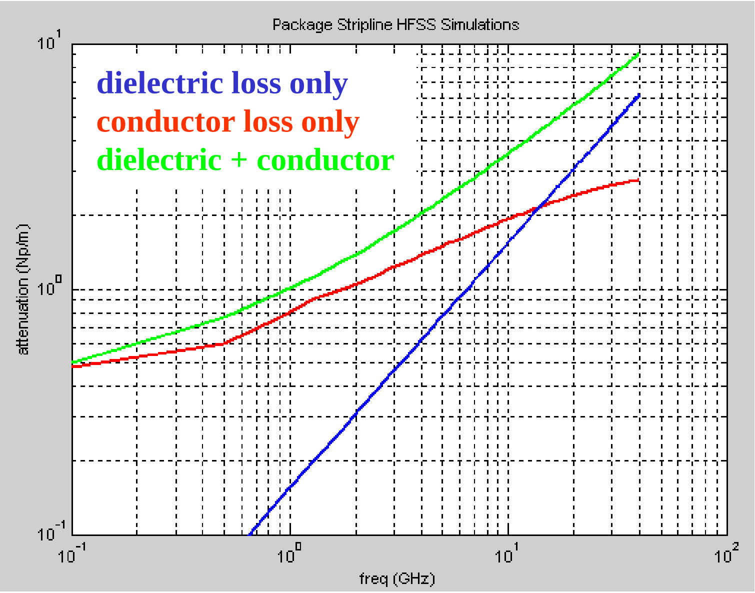
HFSS v9 view



Measured data taken on a test package using the 'TRL' calibration procedure to deembed the RF probe pads and extract the line characteristics.

Package Stripline Results



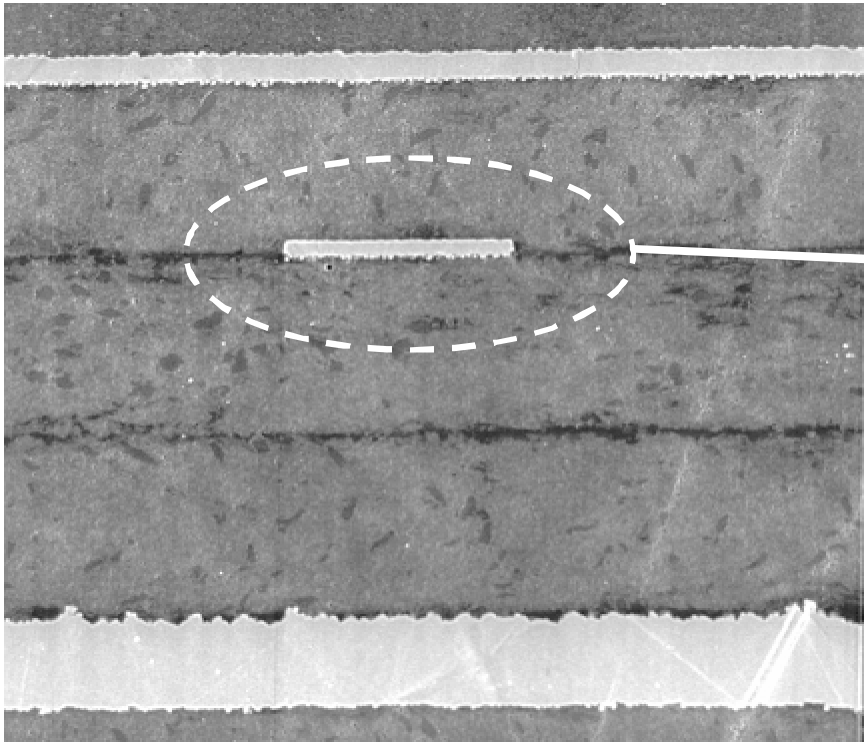


Uncorrected HFSS has two modes with nearly identical Beta values - at approximately 4 GHz, the modal results cross over and the recorded alpha effectively "flip-flops".

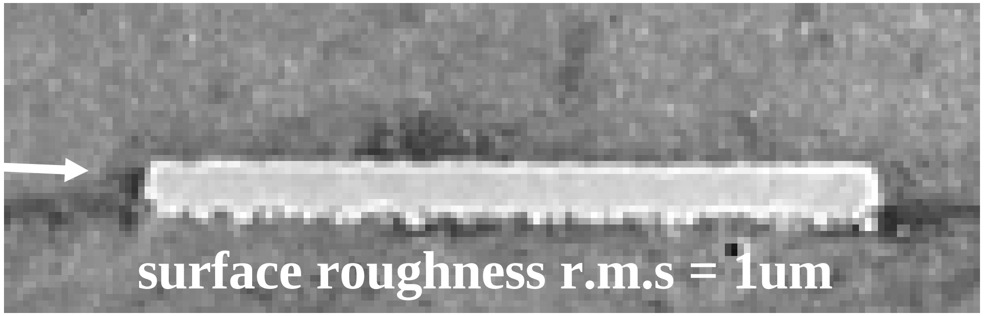
Corrected version uses mode 1 data before 4GHz, mode 2 data after 4GHz.

Measured data still shows more loss than the HFSS simulations...

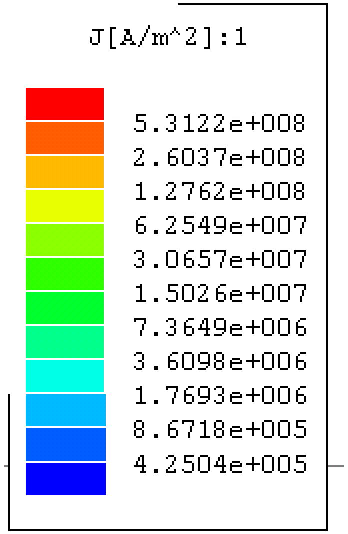
Package Stripline - Surface Roughness



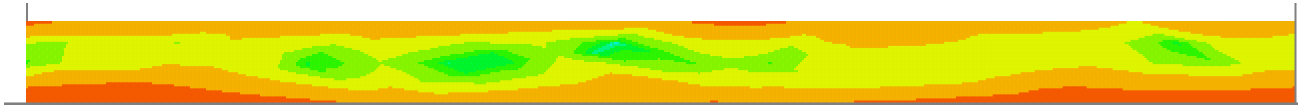
SEM cross sectional pictures



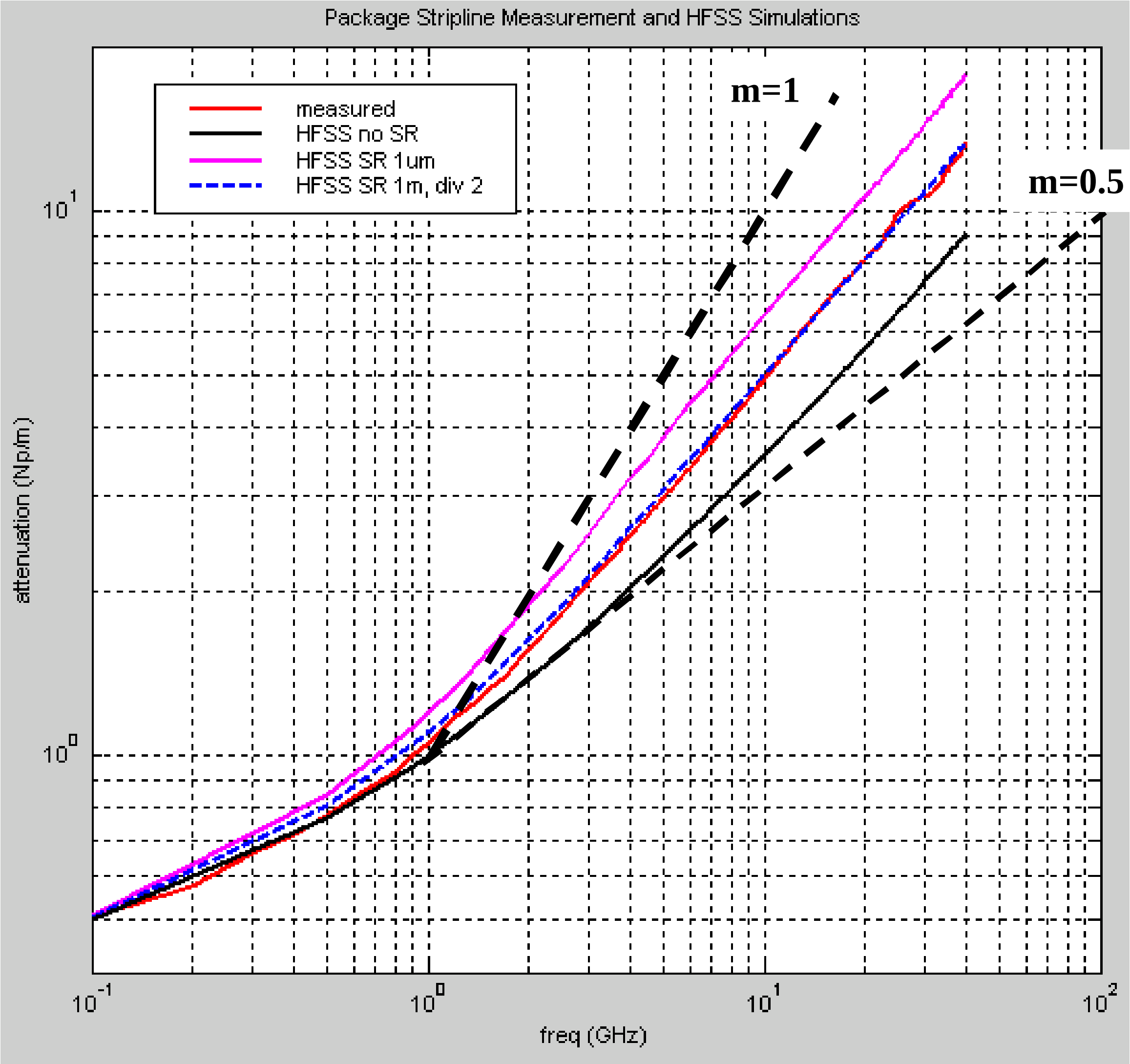
- Surface roughness on bottom side of stripline



- In the stripline configuration, current spreads on BOTH sides of stripline
- Adjust surface roughness calculation by half to account for current distribution



Package Stripline - Surface Roughness



HFSS simulation with no S.R. is not lossy enough.

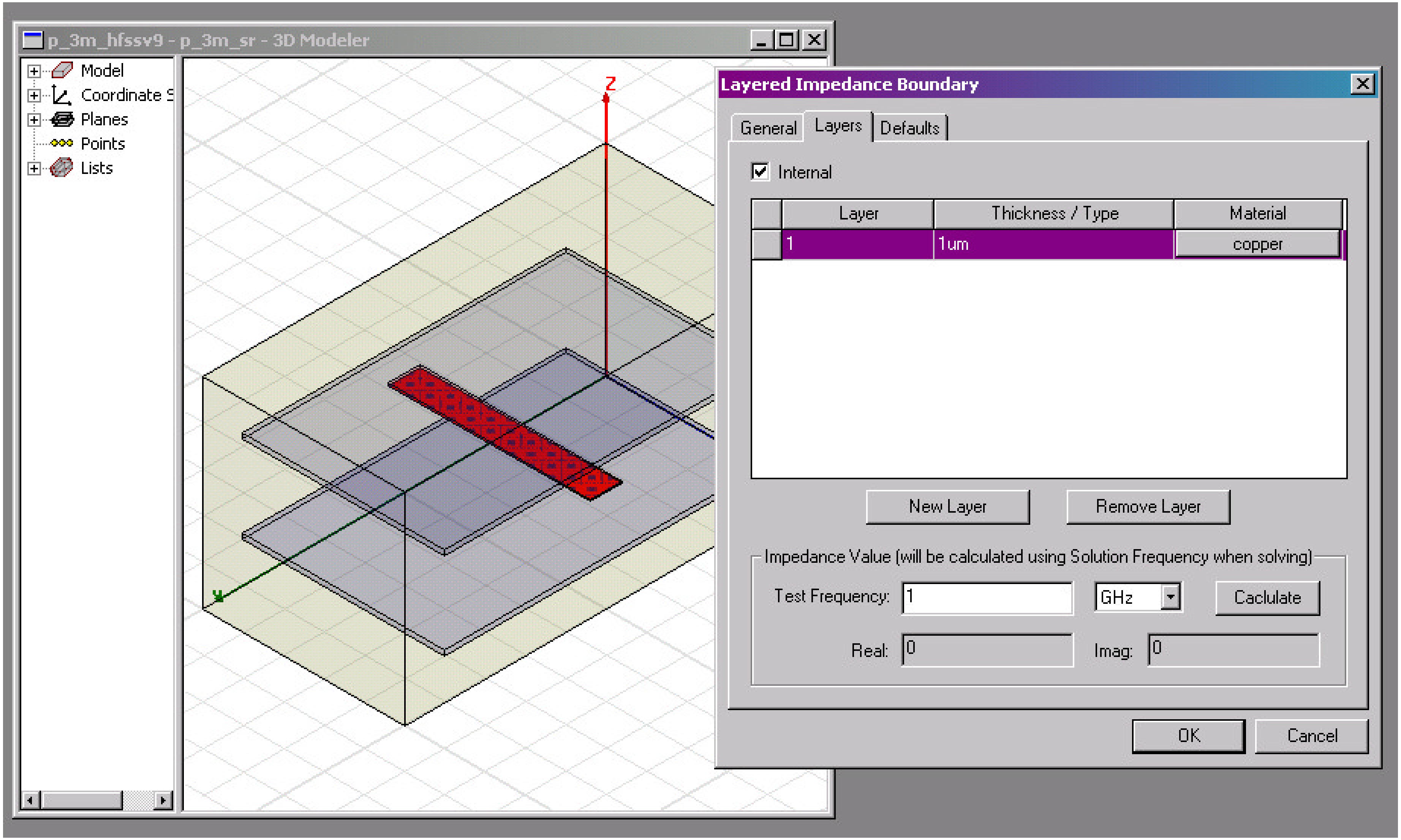
HFSS simulation with 1um S.R. calculation is too lossy.

$$\alpha'_c = \alpha_c \left[1 + \left(2/\pi \tan^{-1}\{1.4(\Delta/\delta_s)^2\}\right)\right]$$

HFSS simulation with 1um S.R. calculation, assuming half current distribution on rough side, fits measured data very well.

$$\alpha'_c = \alpha_c \left[1 + 0.5*\left(2/\pi \tan^{-1}\{1.4(\Delta/\delta_s)^2\}\right)\right]$$

Package Stripline - Surface Roughness



Package Stripline - Surface Roughness

(from HFSS v9 help)

Surface Roughness Calculation for Layered Impedance Boundary

The surface roughness is measured as the RMS deviation of the conductor surface from a plane. Surface roughness increases conduction losses. Ansoft HFSS calculates surface roughness by modifying the conductivity as follows:

$$\sigma_c = \frac{\sigma}{K_w^2}$$

where

- σ is the material's conductivity.

$$K_w = 1 + \exp\left(-\frac{s}{2h}\right)^{1.6}$$

-

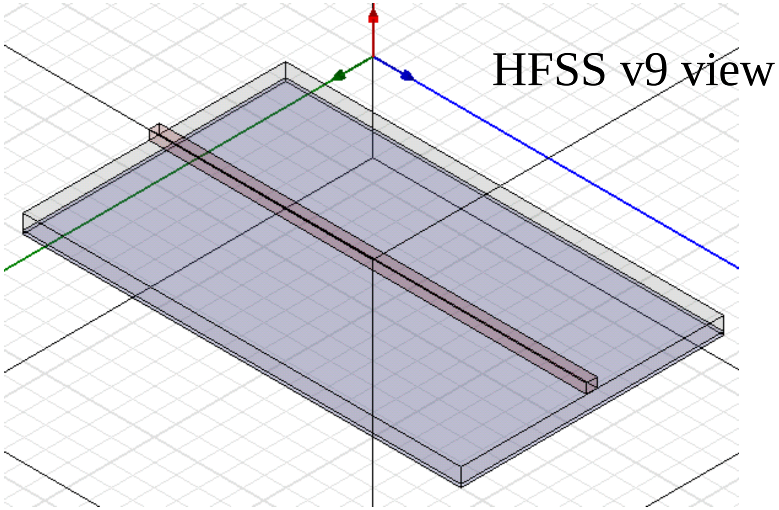
  where

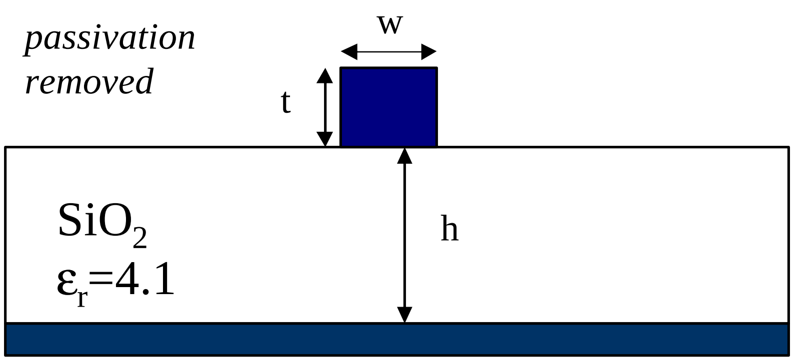
  - h is the surface roughness.
  - s is the skin depth.

On-chip Microstrip Simulations and Measured Data

Design dimensions:
w=2.4um, h=3.25um, t=2.07um

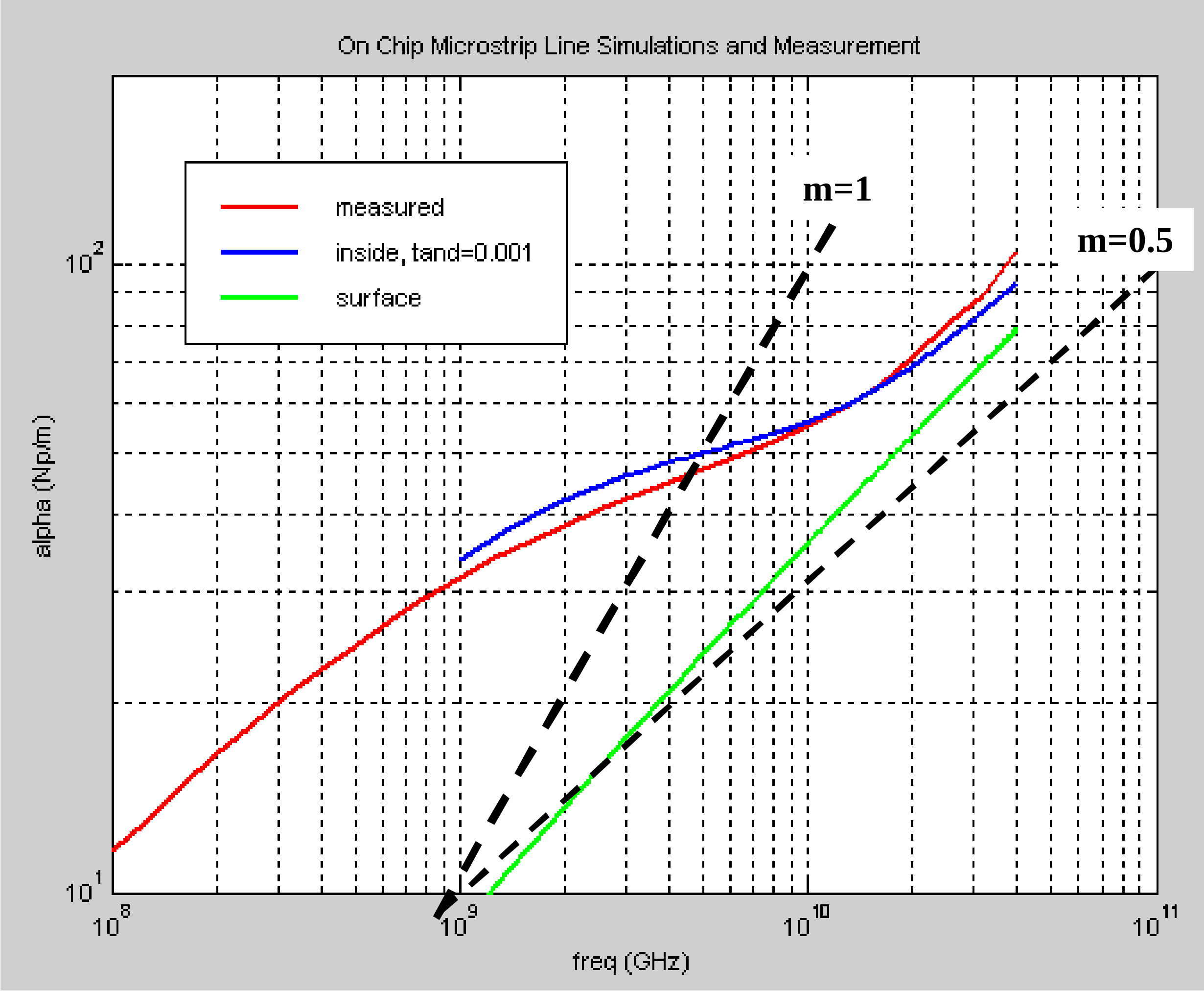
$\tan\delta = 0.001 \quad \sigma = 3.22E7$





Measured data taken directly on a test wafer using the 'TRL' calibration procedure to deembed the RF probe pads and extract the line characteristics.

On-chip Microstrip



SOME OBSERVATIONS:

Skin effect mechanism dominates up to measurement frequency limit of 40GHz.

Slope of measured data starts to increase after 30 GHz, could be start of dielectric loss component.

Solving inside metal is necessary whenever line dimensions are close to skin depth.

Solving inside captures the "transition region", which is dependent on the trace geometry.

Closing Remarks

- Different transmission environments = different dominant loss mechanisms -> the beauty of log-log plots

- Solving for surface currents only -> know your skin depth

- The surface roughness adjustment - got teeth?

- Be aware of “transition region” to skin effect -> might be smack dab in the middle of your bandwidth!

- Other possible loss mechanisms include:
    - radiation from discontinuities
    - proximity effect - current crowding in diff pairs
    - dispersion and higher-order mode propagation