SW Test Workshop
Semiconductor Wafer Test Workshop
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Probe Pin Wideband Electrical Circuit Model

Mohamed Eldessouki

SV TCL – An SV Probe Company

Overview

- Motivation and Objective
- Introduction
- Closed Form Circuit Model
- Probe Pin Measurements and Simulation
- Probe Pin Modeling and Verification
- Summary and Conclusion

Motivation & Objective

Motivation

Customers are looking for Probe Head (PH) circuit model to be able to:

Simulate and Predict Bandwidth (BW)

Simulate and Predict Power Plane Input Impedance

Reduce risk probe hardware not to meet test expectations

Objective

Develop Close Form Accurate Circuit Model

Verify Developed Model Using:

Measured S-parameters

Ansoft HFSS Simulation Tool (Field Analysis)

Introduction

Trio Probe & Spring Pin

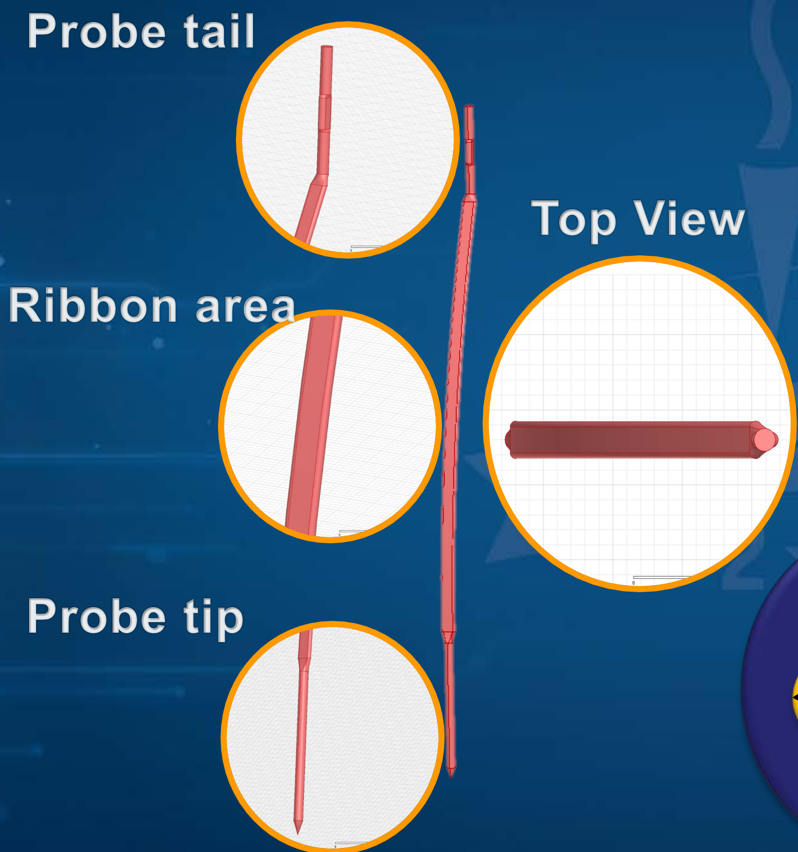
Proximity and Skin Effect

Circuit Model Comparison

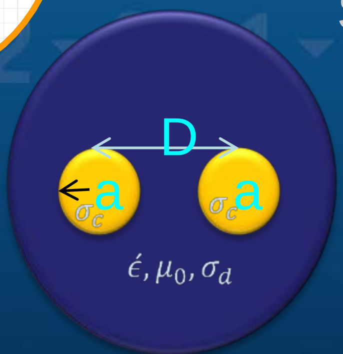
Transmission Line (TL) Model

Introduction

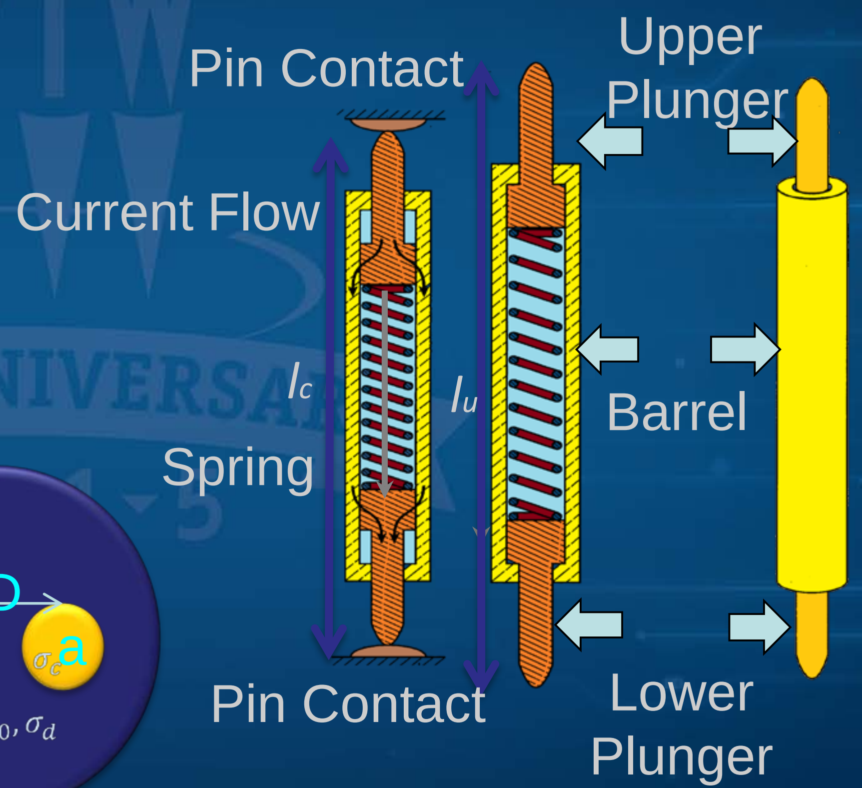
Probe Pin Structure



Trio-probe



Probe Head



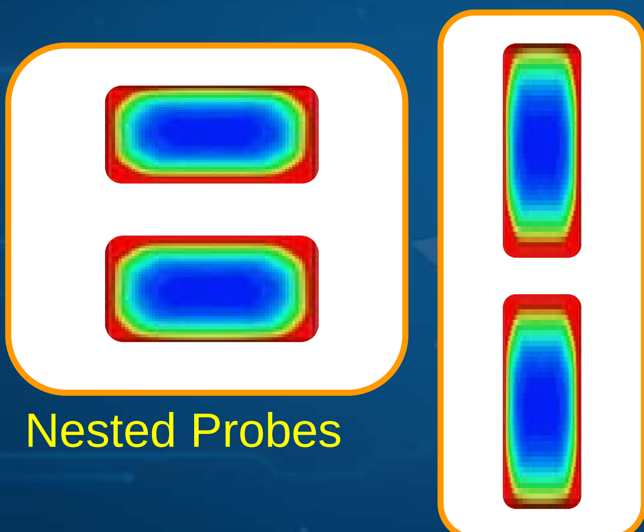
Spring Pin probe

Introduction

Proximity and Skin Effect

Current density distribution in parallel wire.

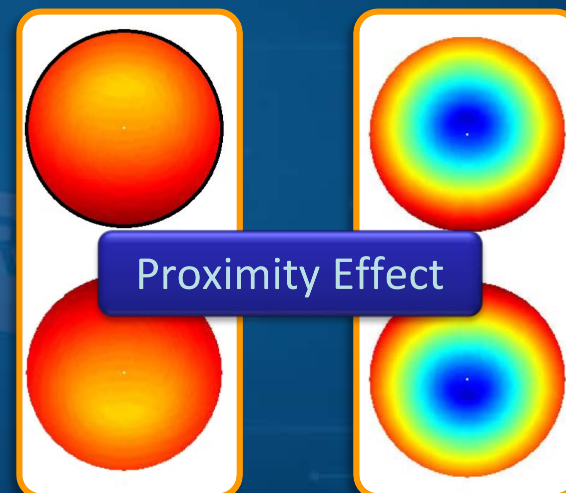
Unbalanced current distribution due to proximity effect.



Nested Probes

Side by Side Probes

Rectangular cross-section



Low Frequency High Frequency

Circular cross-section

Low current density **High current density**

Introduction

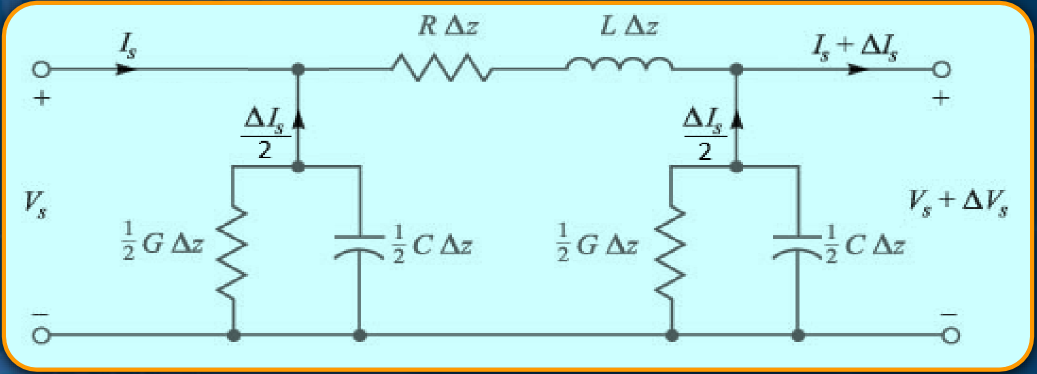
Fundamental Equations

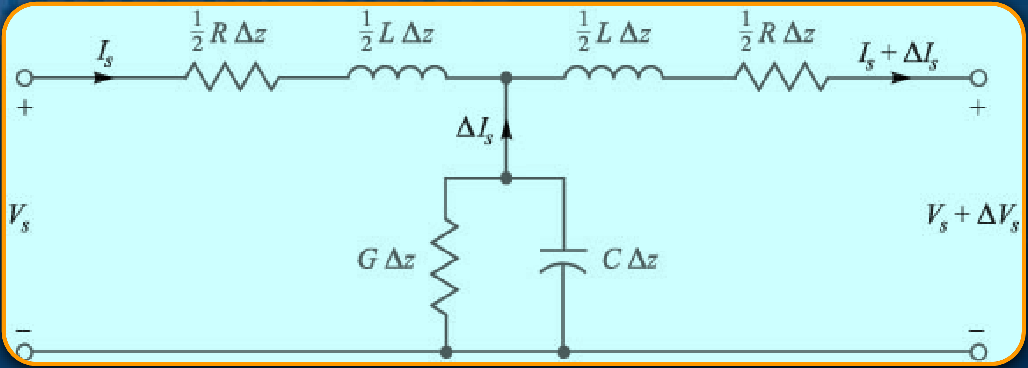
$$L = \frac{\mu}{I_0 I_0^*} \int_s \overline{H}.\overline{H}^* \, dS$$

$$C = \frac{\varepsilon'}{V_0 V_0^*} \int_s \overline{E}.\overline{E}^* \, dS$$

$$R = \frac{R_s}{I_0 I_0^*} \oint_{S_1+S_2} \overline{H}.\overline{H}^* \, dl$$

$$G = \frac{\omega \varepsilon''}{V_0 V_0^*} \int_s \overline{E}.\overline{E}^* \, dS$$





π and T Equivalent Circuit TL Model

Introduction

Models Comparison

Model	Advantages (Account for)	Disadvantages
Low Frequency	• Internal and External Inductance • Proximity effect	• No Skin Effect
High Frequency	• Skin Effect	• No Internal Inductance • No Proximity Effect in inductance calculation
Wide Band	• Skin Effect • Internal Inductance • Proximity Effect in Inductance Calculation	• No Proximity Effect on Resistance Calculation Only

Closed Form Circuit Model

Models Comparison for Cylindrical Probe

$$L = \frac{\mu_0}{\pi}\left[\frac{1}{4} + \cosh^{-1}\left(\frac{D}{2a}\right)\right]$$

$$R = \frac{2}{\pi a^2 \sigma_c}$$

Low Frequency

$$L_{ext} = \frac{\mu_0}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right)$$

$$R = \frac{R_s}{\pi a}\frac{D/2a}{\sqrt{(D/2a)^2 - 1}}$$

High Frequency

$$L = \mathrm{Im}(Z)$$

$$R = \mathrm{Re}(Z)$$

Wide Band

Where

$$Z = 2Z_{\mathrm{int}} + j\omega L_{ext}$$

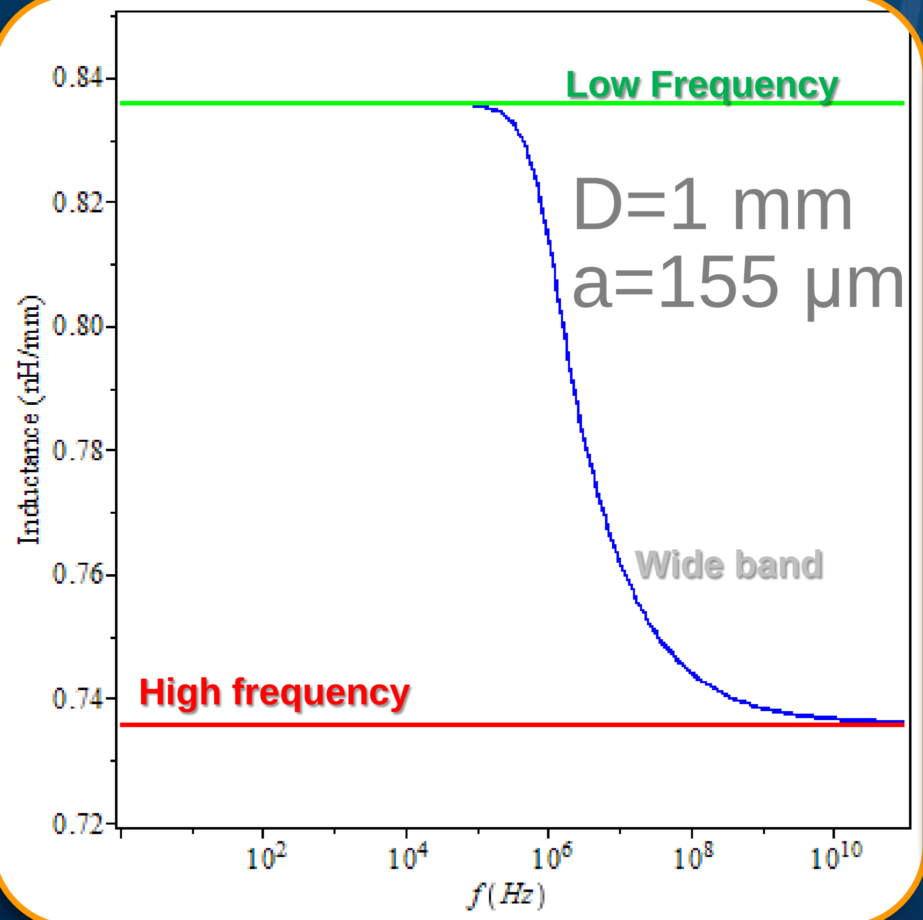
$$Z_{\mathrm{int}} = \frac{R_s}{\sqrt{2}\pi a}\frac{ber(\zeta) + jbei(\zeta)}{bei'(\zeta) - jber'(\zeta)}$$

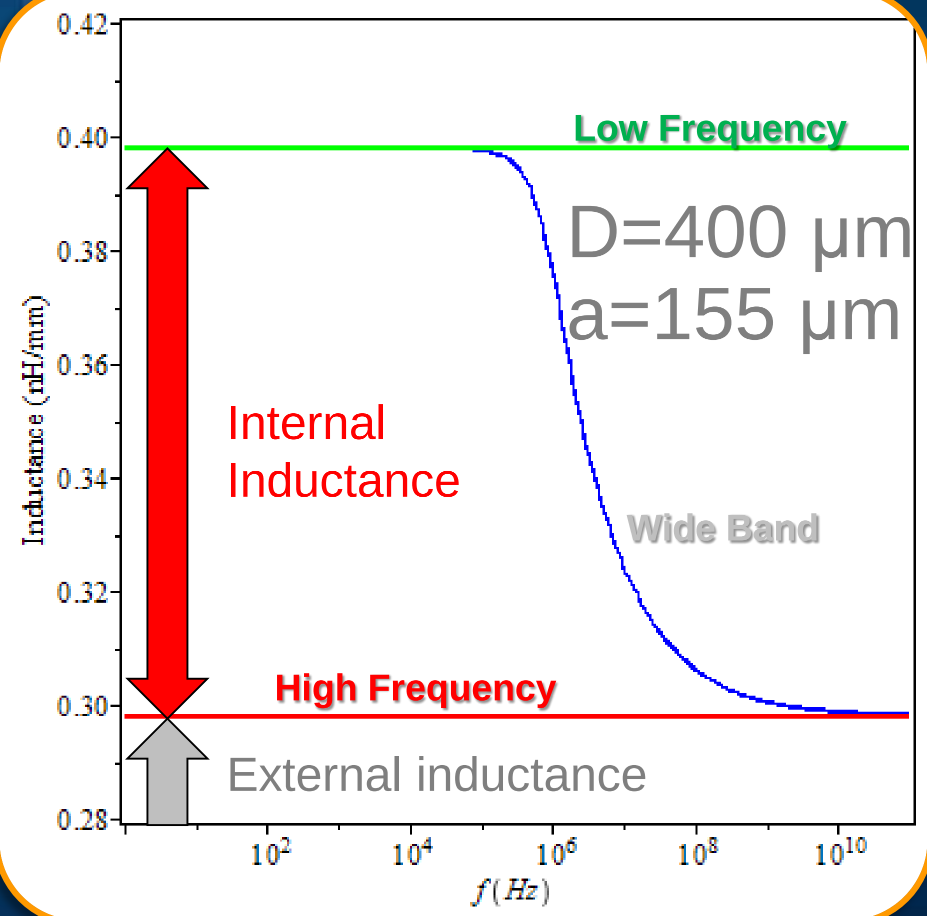
$$L = \frac{R_s}{\pi a}\frac{ber(\zeta)ber'(\zeta) - jbei(\zeta)bei'(\zeta)}{\sqrt{2}\omega\left([bei'(\zeta)]^2 + [ber'(\zeta)]^2\right)} + \frac{\mu_0}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right)$$

$$R = \frac{R_s}{\pi a}\frac{ber(\zeta)bei'(\zeta) - jbei(\zeta)ber'(\zeta)}{\sqrt{2}\left([bei'(\zeta)]^2 + [ber'(\zeta)]^2\right)}$$

Closed Form Circuit Model

Inductance Comparison for Cylindrical Probe

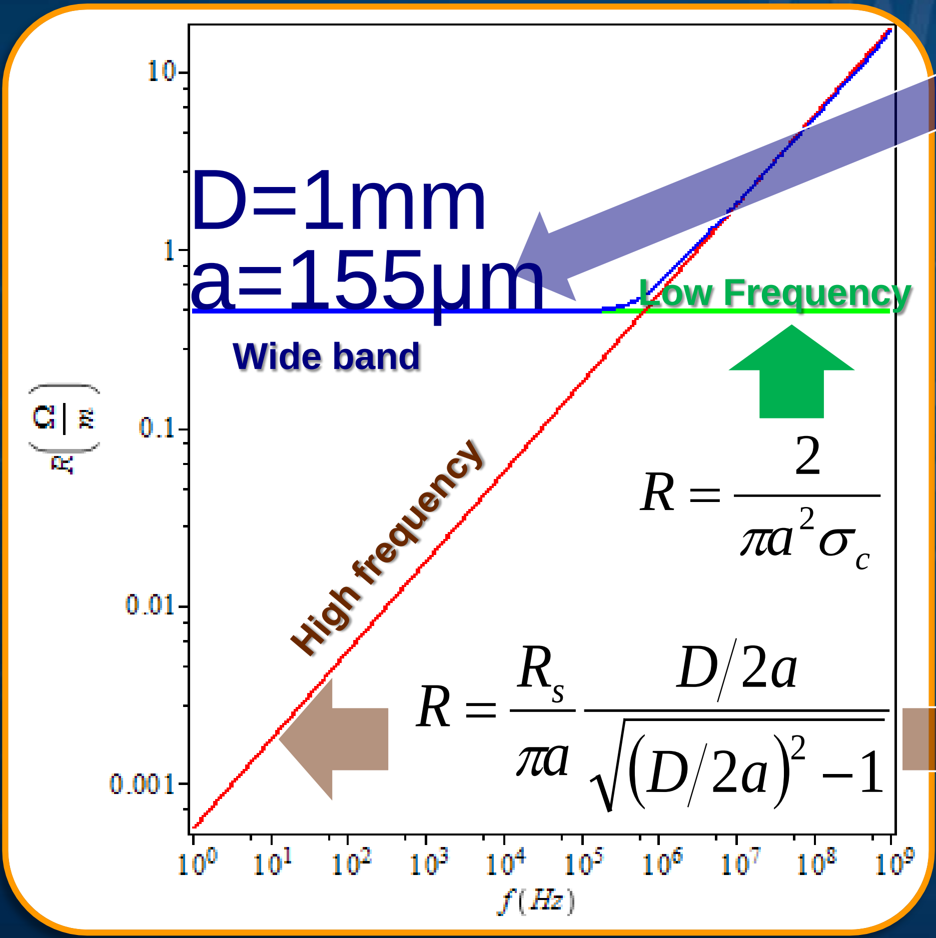


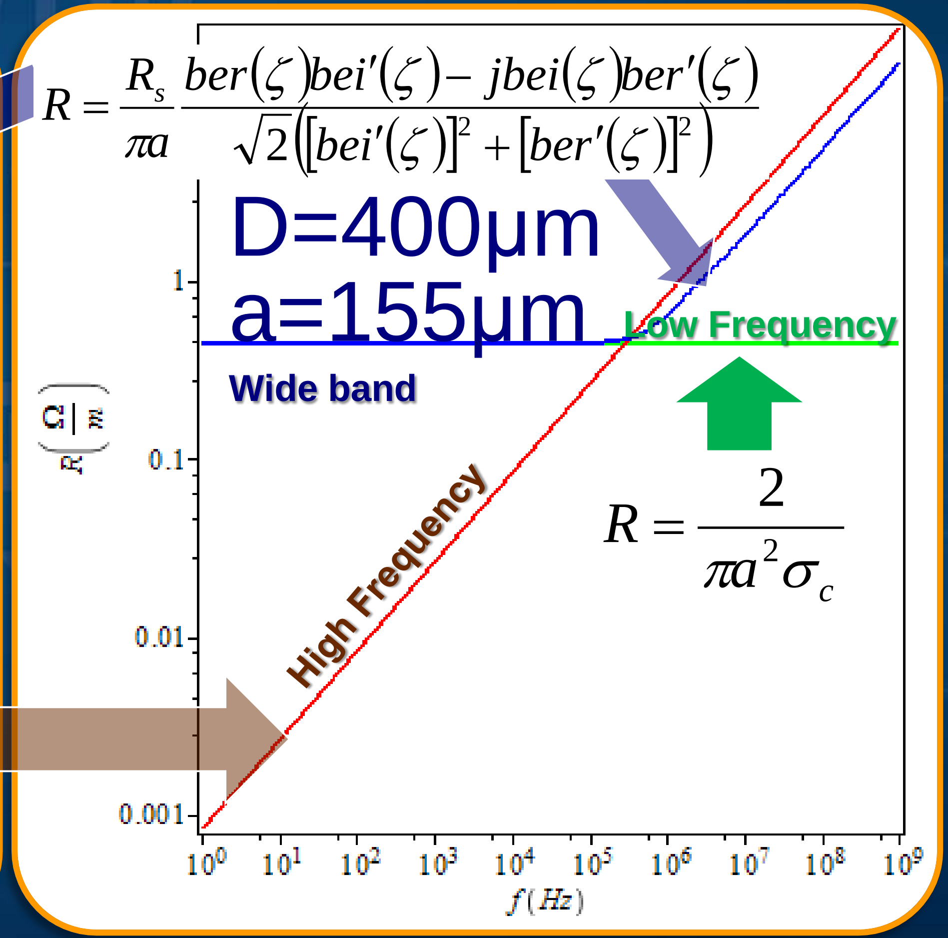


Calculated based on spring pin dimensions

Closed Form Circuit Model

Resistance Comparison for Cylindrical Probe





Calculated based on spring pin dimensions

Closed Form Circuit Model

Models Development for Rectangular Probe

Loop Inductance calculation
$L_{loop} = 2L_{self} - 2M$

$$L = \frac{\mu_0}{\pi}\left[\ln\left(\frac{d}{w+t}\right)\right] + \frac{3}{2}$$

$l >> w > t$

↓

Internal Inductance calculation L_{int}

$$L_{int} = \frac{\mu_0}{6}\frac{t}{w}$$

$w >> t$

$$L_{int} = \frac{\mu_0}{8\pi}$$

$w = t$

↓

Find the external inductance
$L_{ext} = L_{loop} - L_{int}$

↓

Add frequency dependent internal inductance
$L_{loop} = L_{ext} + L_{int}(f)$

$$Z_{int}(f) = \frac{R_s}{\sqrt{2}\pi a}\frac{ber(\zeta) + j\,bei(\zeta)}{bei'(\zeta) - j\,ber'(\zeta)}$$

↓

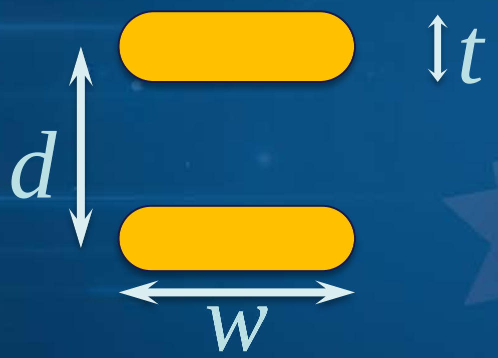
Calculate wideband R &L

$R = \mathrm{Re}(Z)$ $L = \mathrm{Im}(Z)$ Where $Z = 2Z_{int} + j\omega L_{ext}$

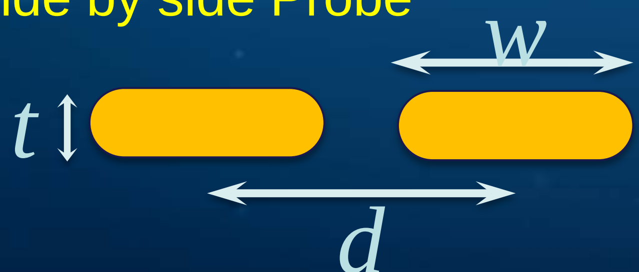
Closed Form Circuit Model

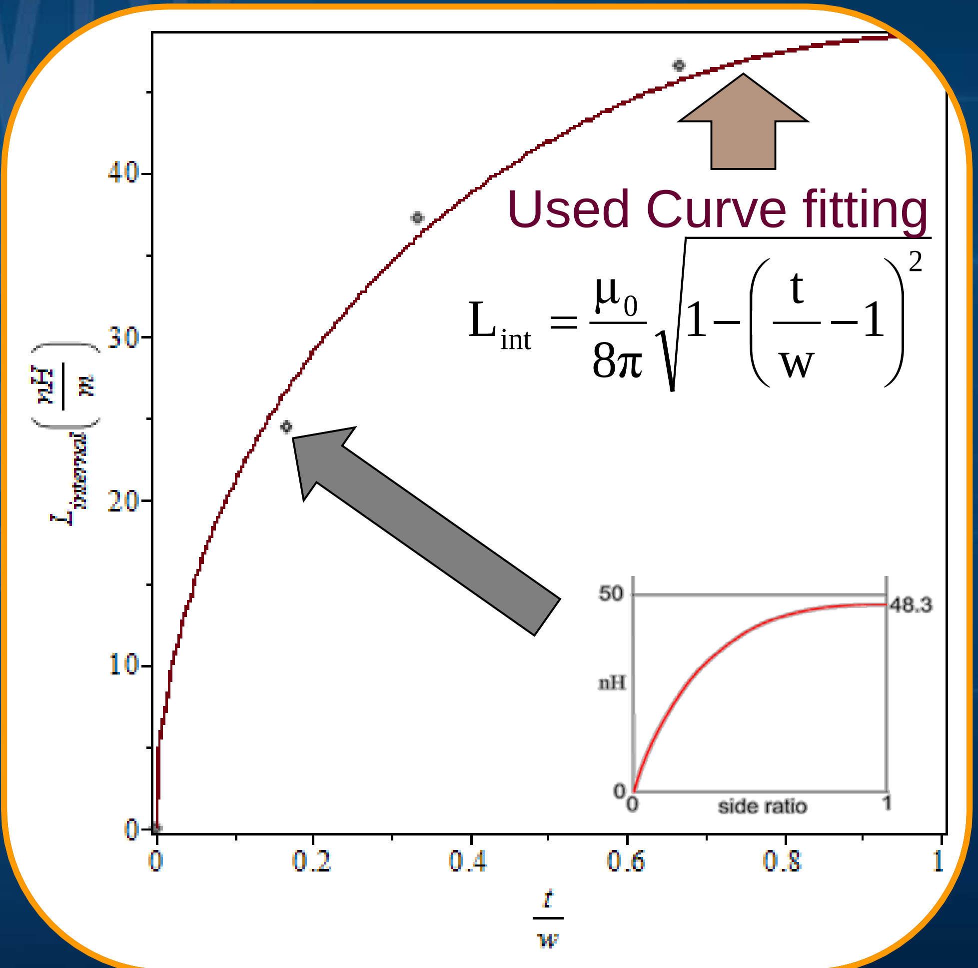
Internal Inductance Correction Factor for Stamped Probe

Nested Probe



Side by side Probe

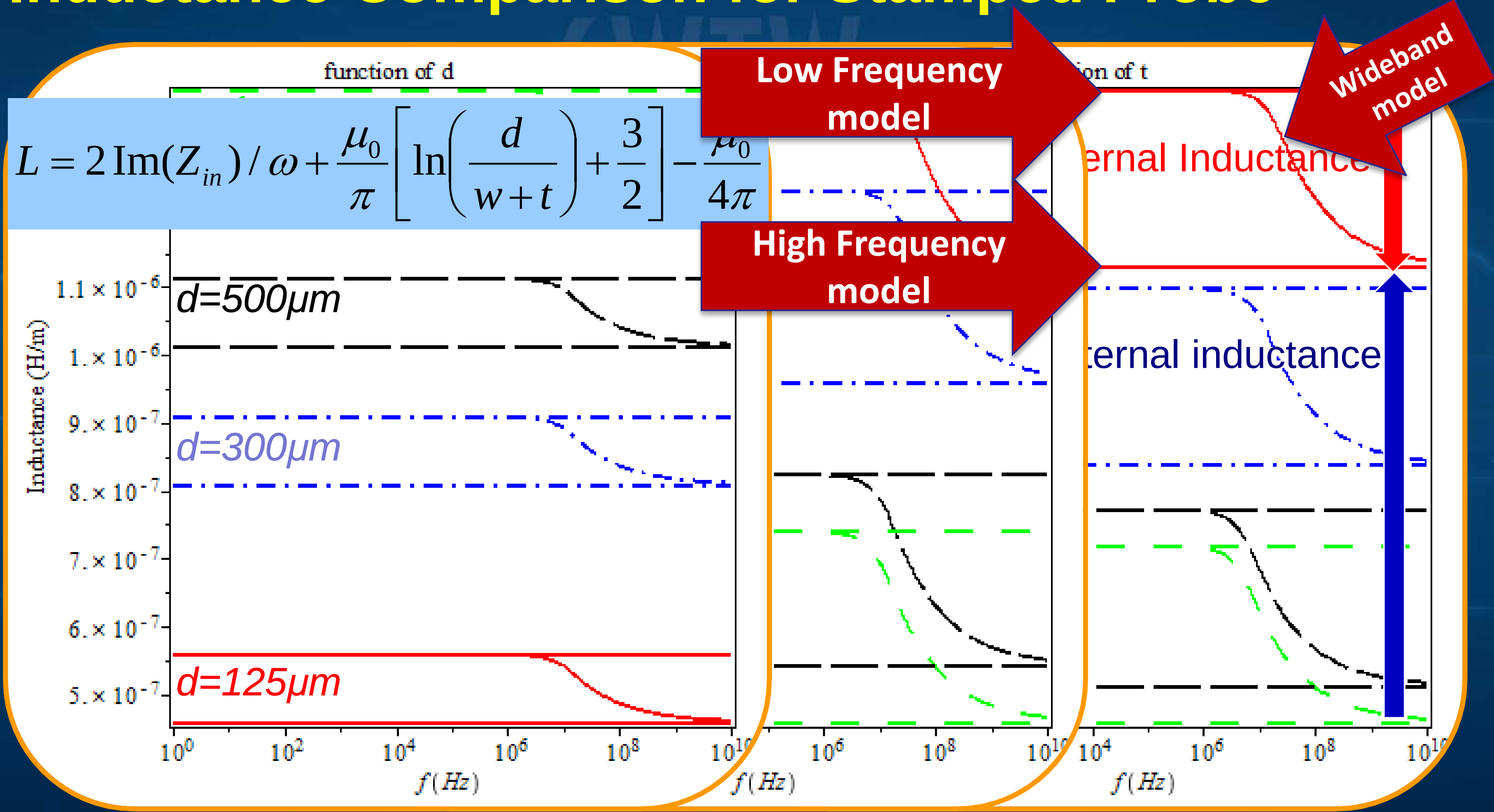




Closed Form Circuit Model

Inductance Comparison for Stamped Probe

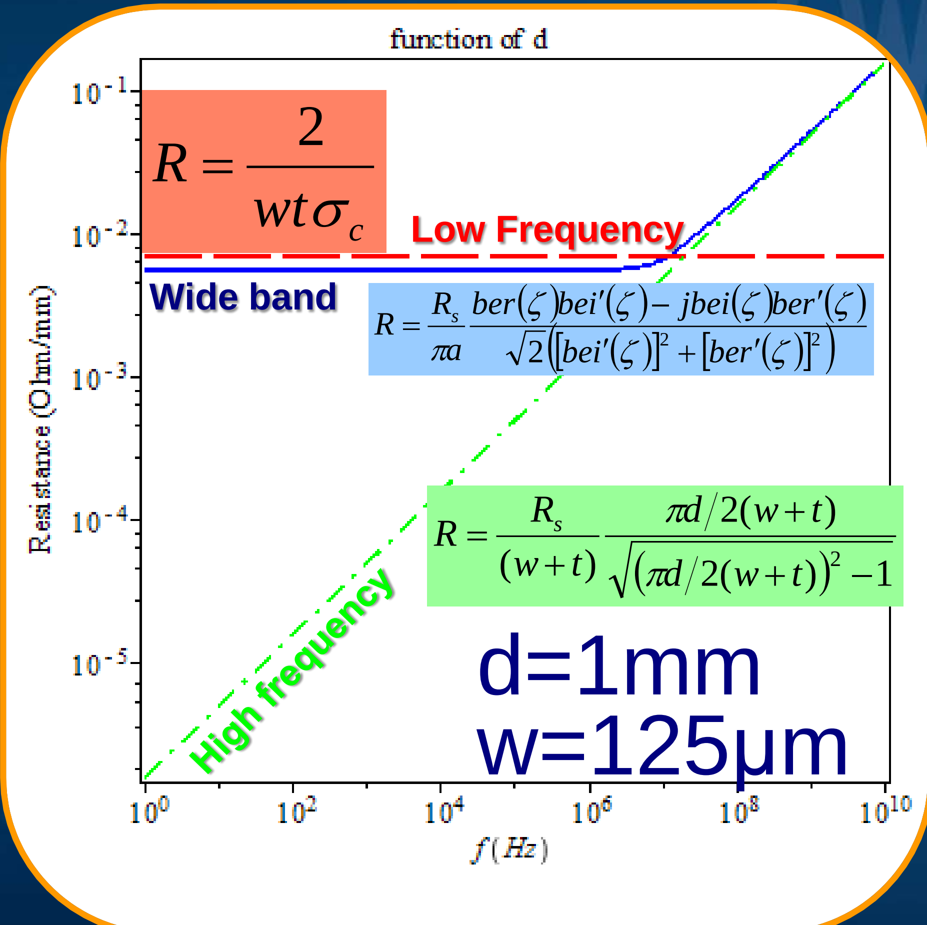
$$L = 2\,\mathrm{Im}(Z_{in})/\omega + \frac{\mu_0}{\pi}\left[\ln\left(\frac{d}{w+t}\right)+\frac{3}{2}\right] - \frac{\mu_0}{4\pi}$$

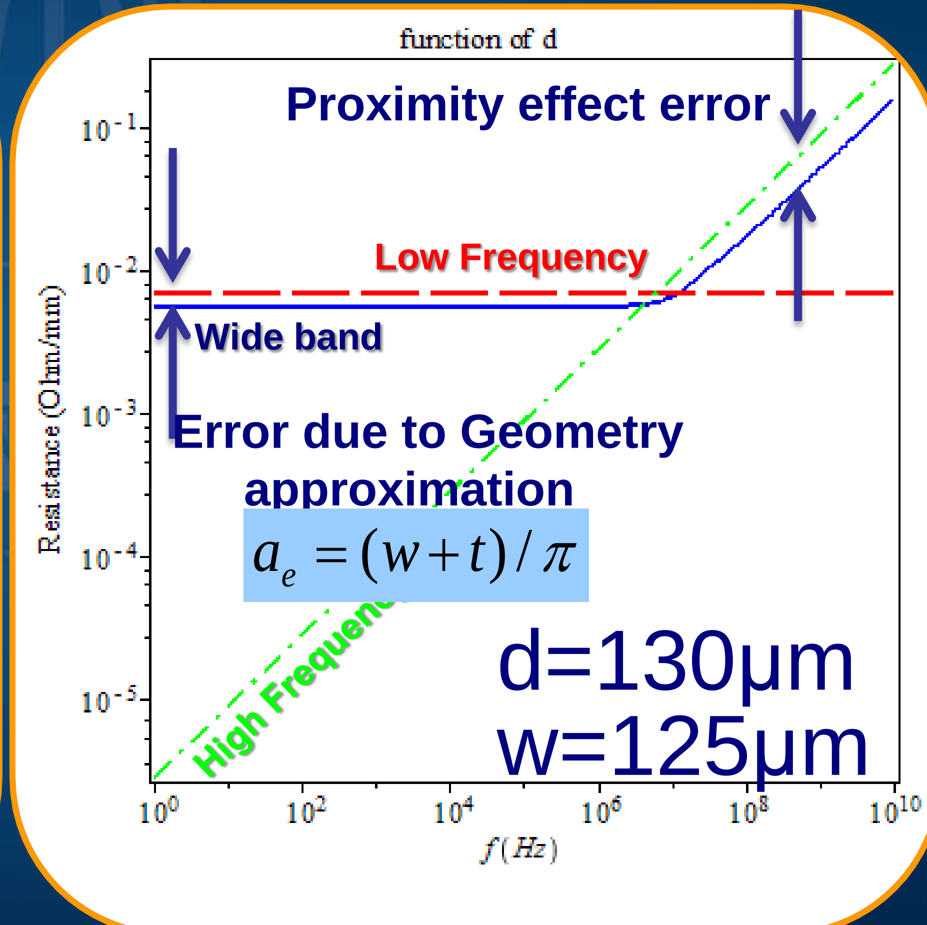


Calculated based on 3mil Trio-probe dimensions

Closed Form Circuit Model

Resistance Comparison for Stamped Probe





Calculated based on 3mil Trio-probe dimensions

Closed Form Circuit Model

Capacitance Calculation for Stamped Probe

Nested Probe

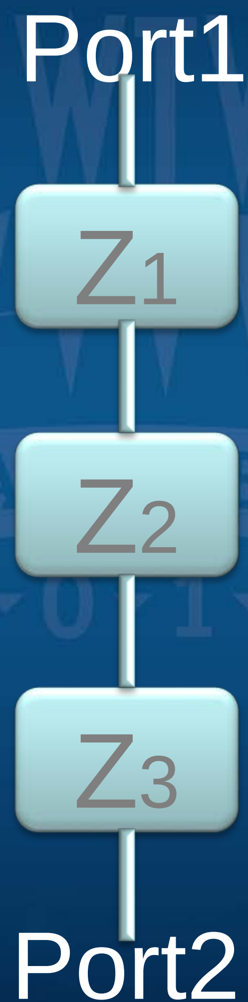
Side by side Probe

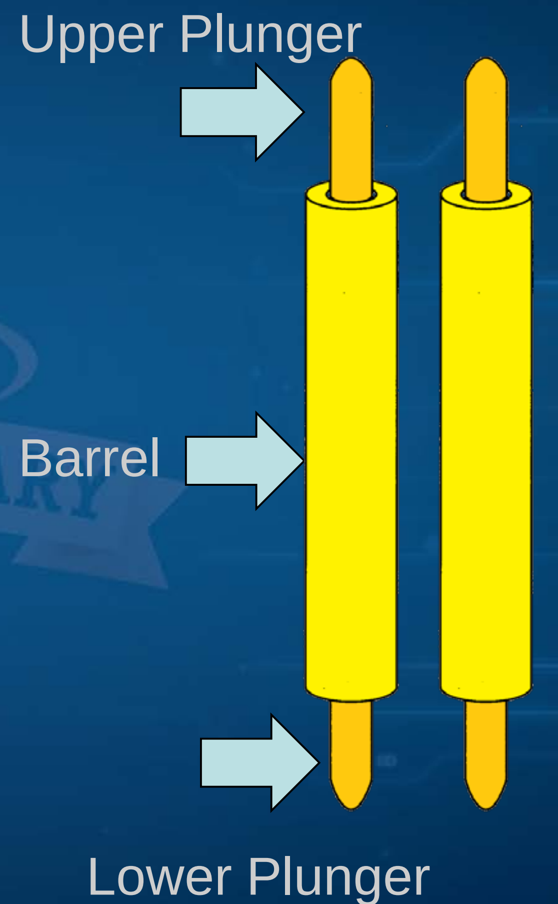
$$C = C_{pp} + C_{fringe} = \frac{w\varepsilon}{(d)} + \frac{\pi\varepsilon}{\cosh^{-1}(d/t)}$$

$$C = \frac{\pi\varepsilon}{\cosh^{-1}((d-w+t)/t)}$$

Closed Form Circuit Model

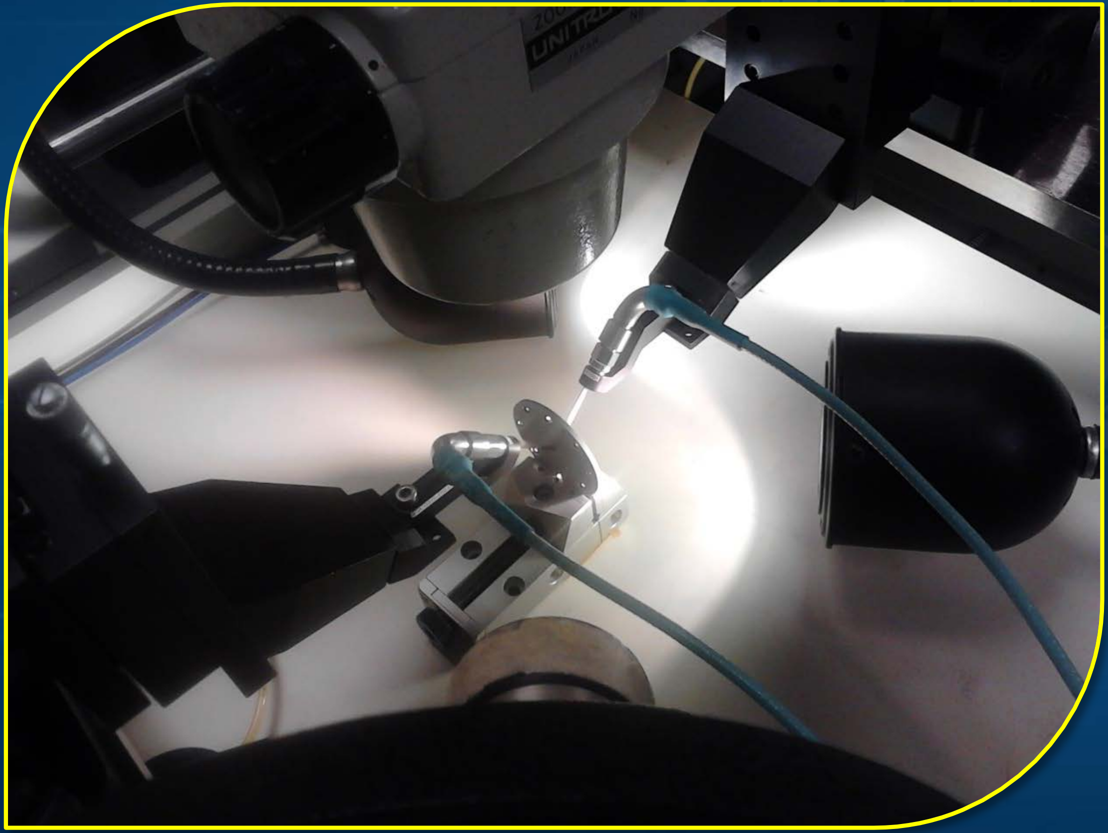
Circuit Model





Measurements & Simulation

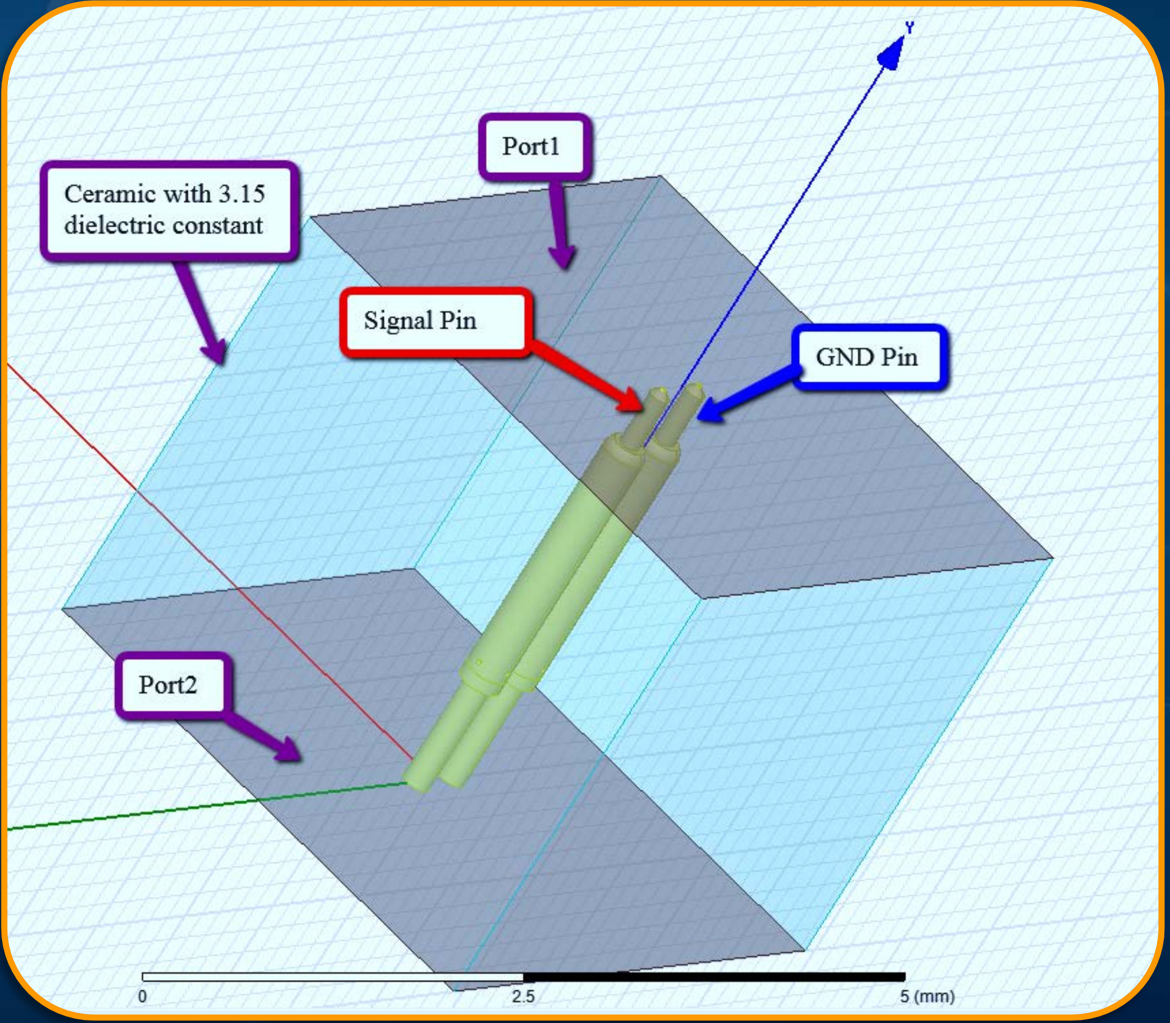
Measurement Setup



Measurements & Simulation

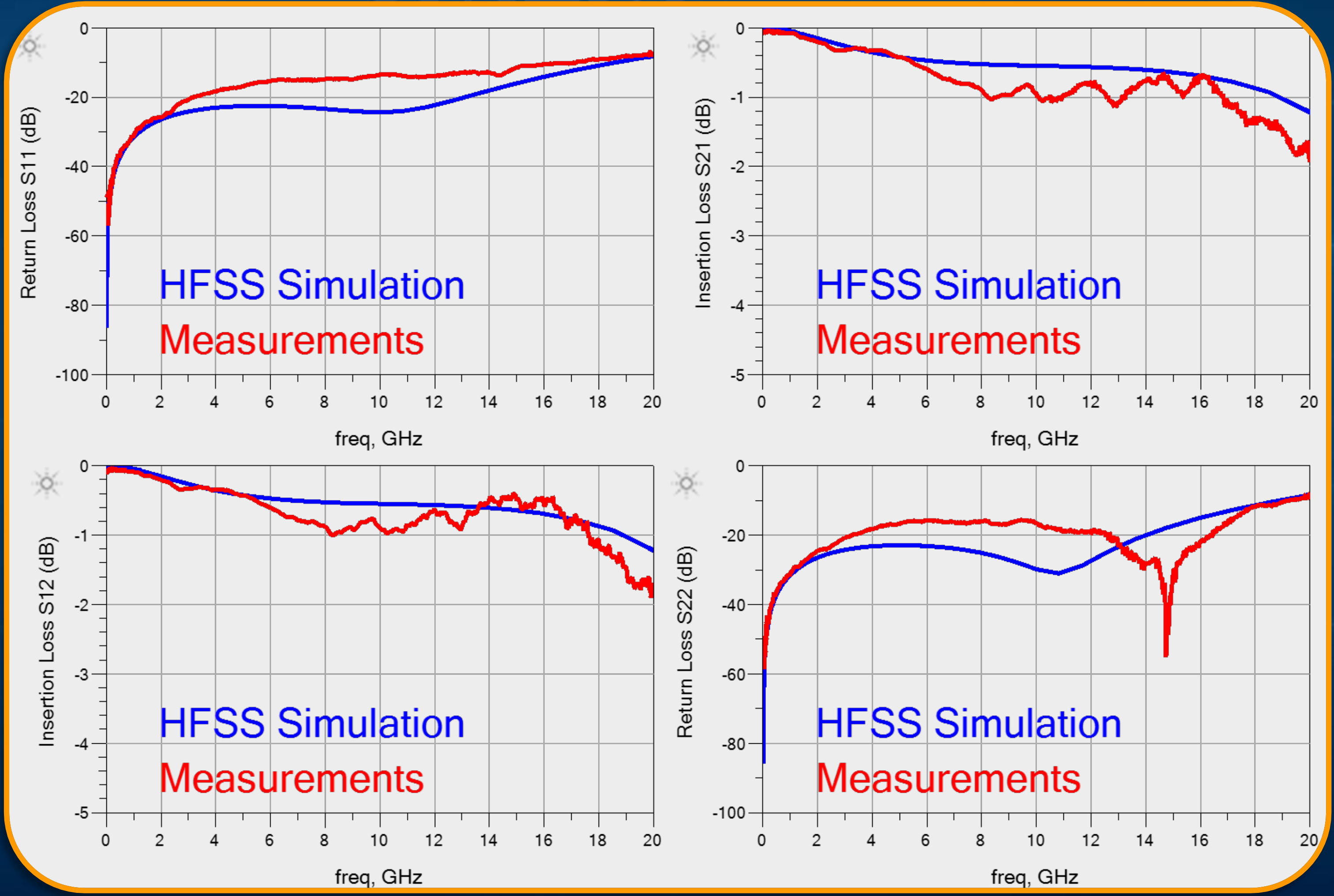
Ansoft HFSS Simulation

Structure and Boundary conditions.



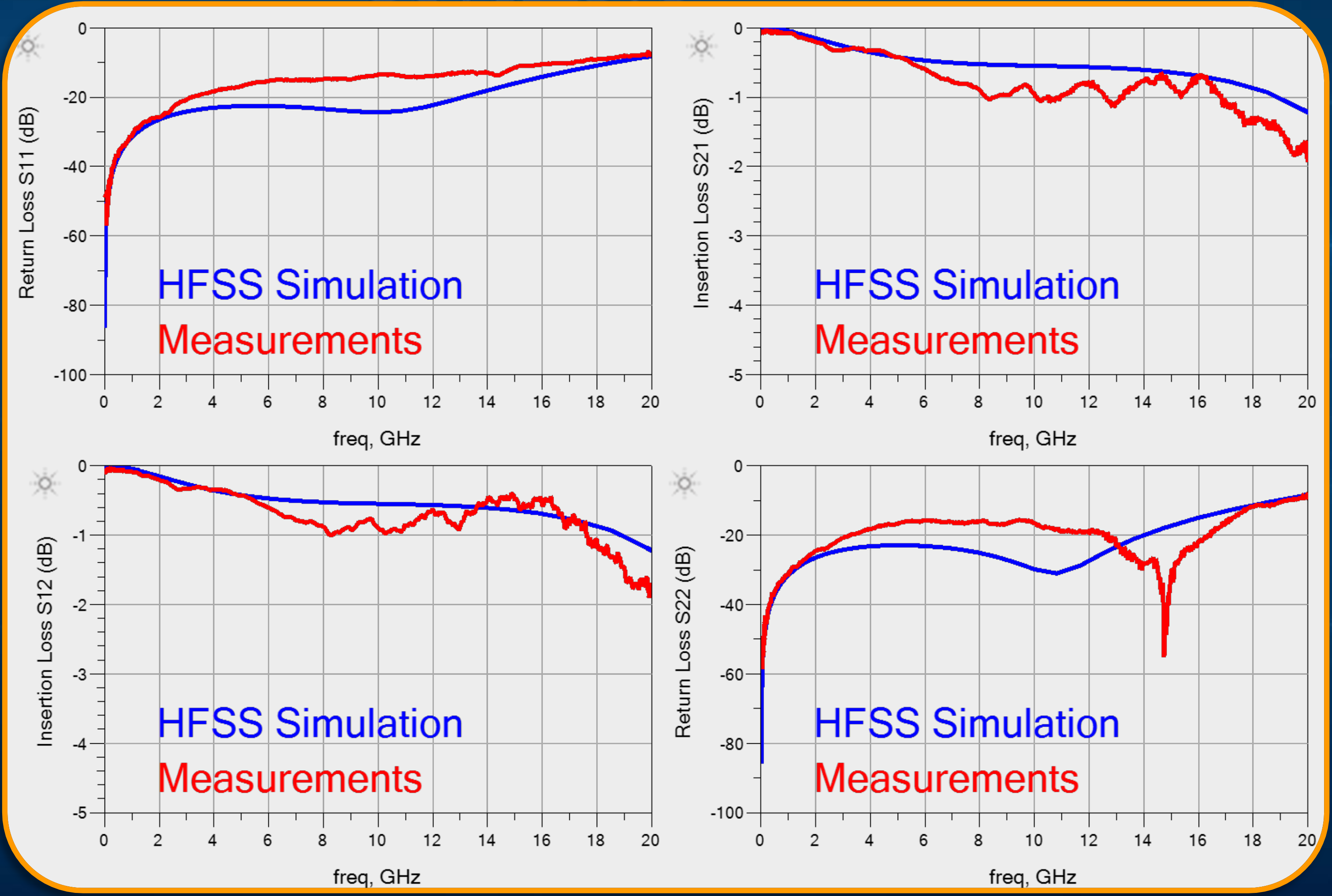
Measurements & Simulation

Insertion and Return Loss Magnitude



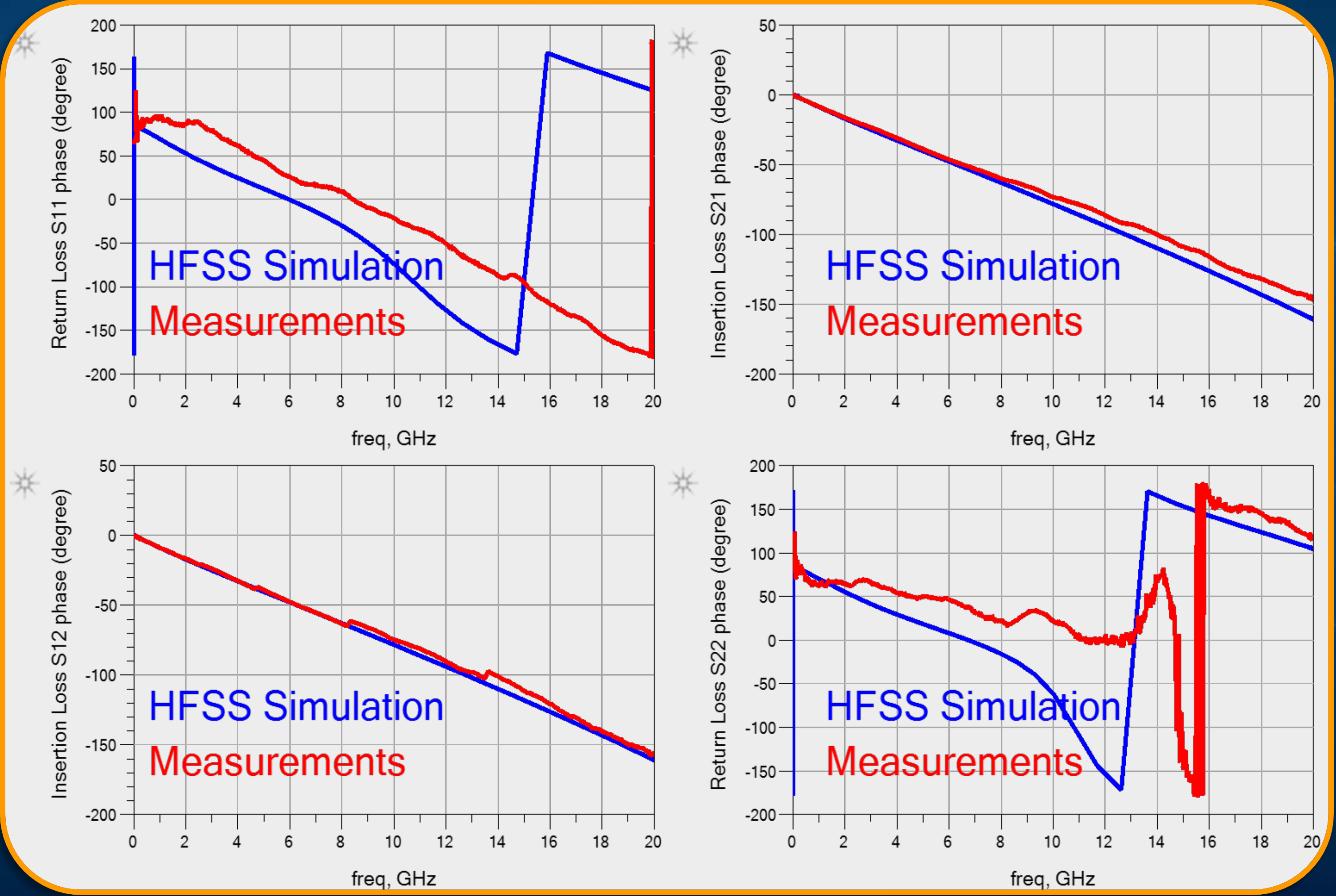
Measurements & Simulation

Insertion and Return Loss Magnitude



Measurements & Simulation

Insertion and Return Loss Phase



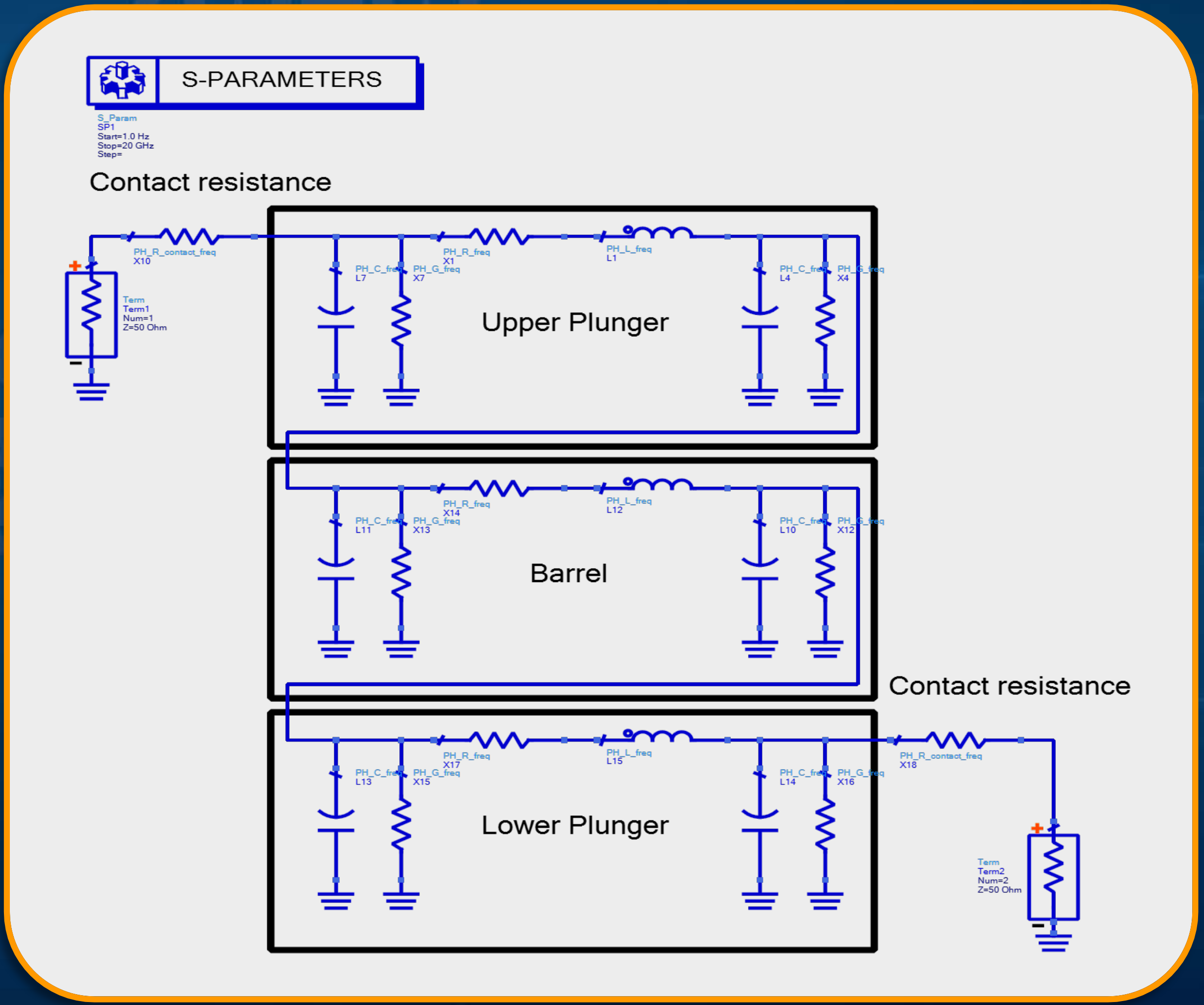
Circuit Model & Model Verification

Lumped Circuit π Model

Upper Plunger

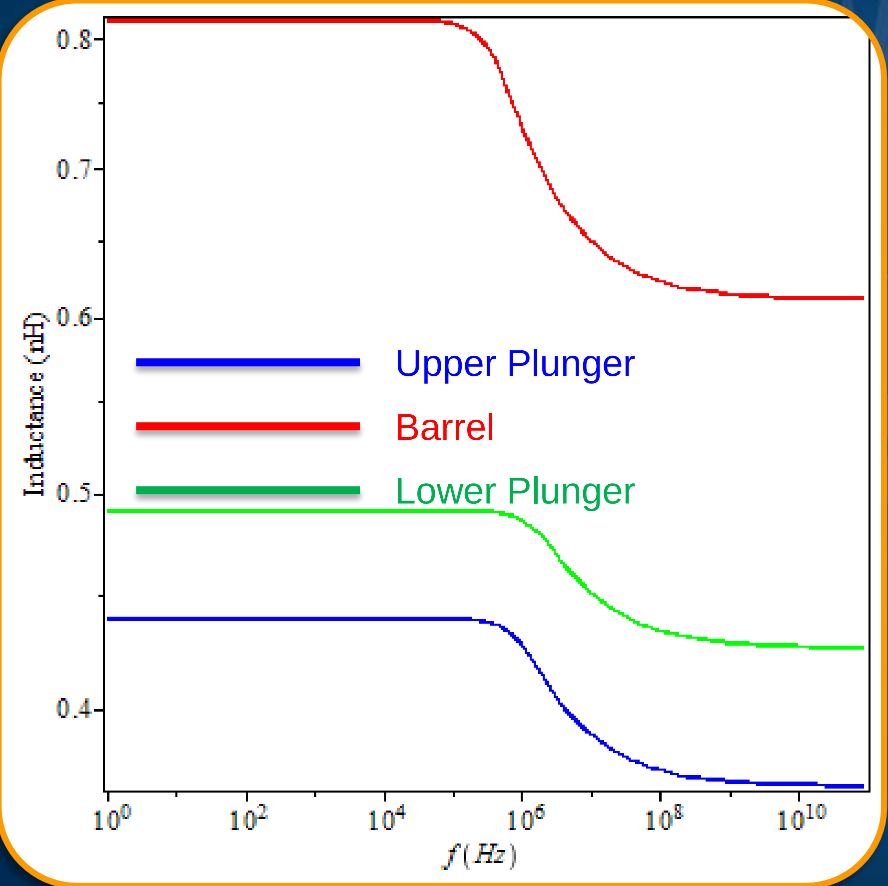
Barrel

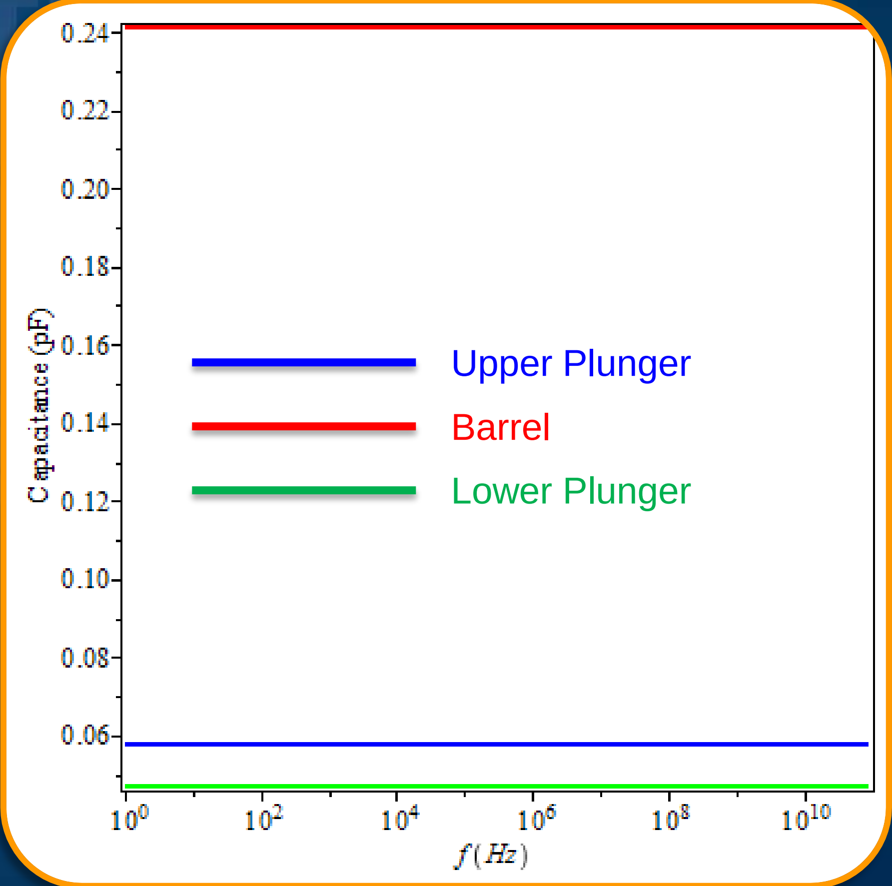
Lower Plunger



Circuit Model & Model Verification

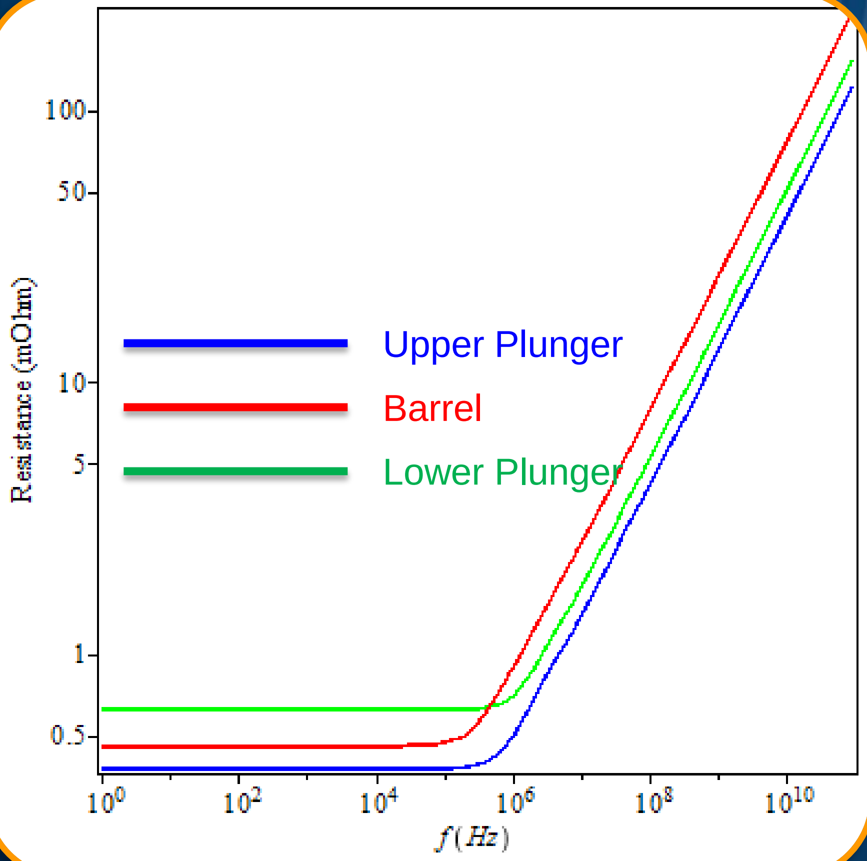
Circuit Model Parameters (Total L & C)

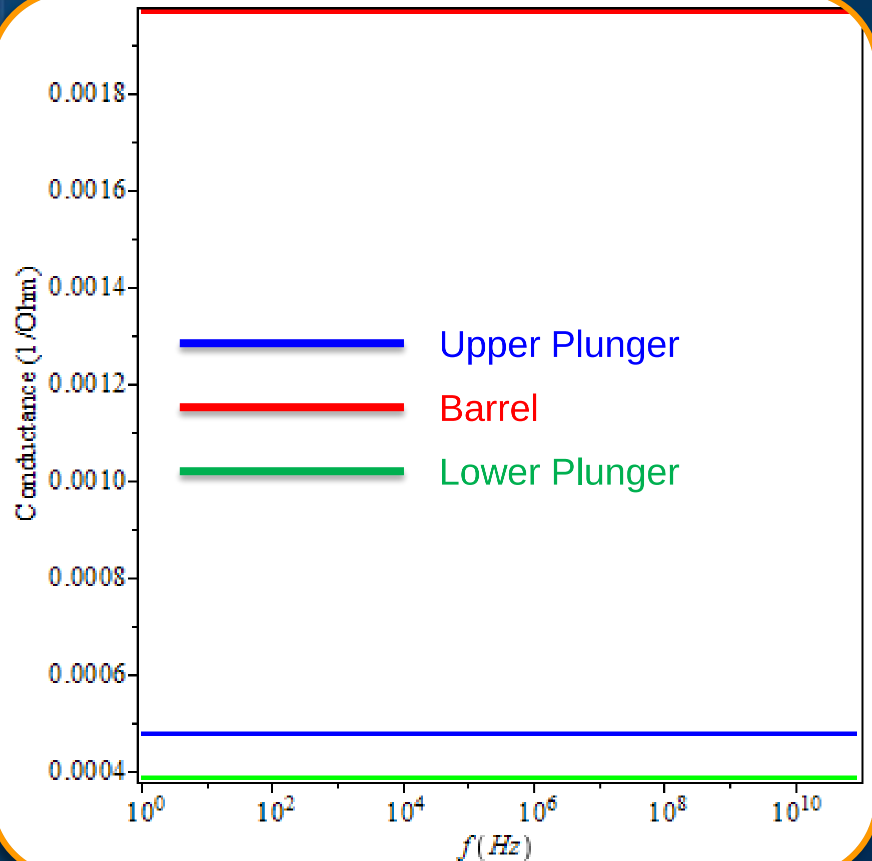




Circuit Model & Model Verification

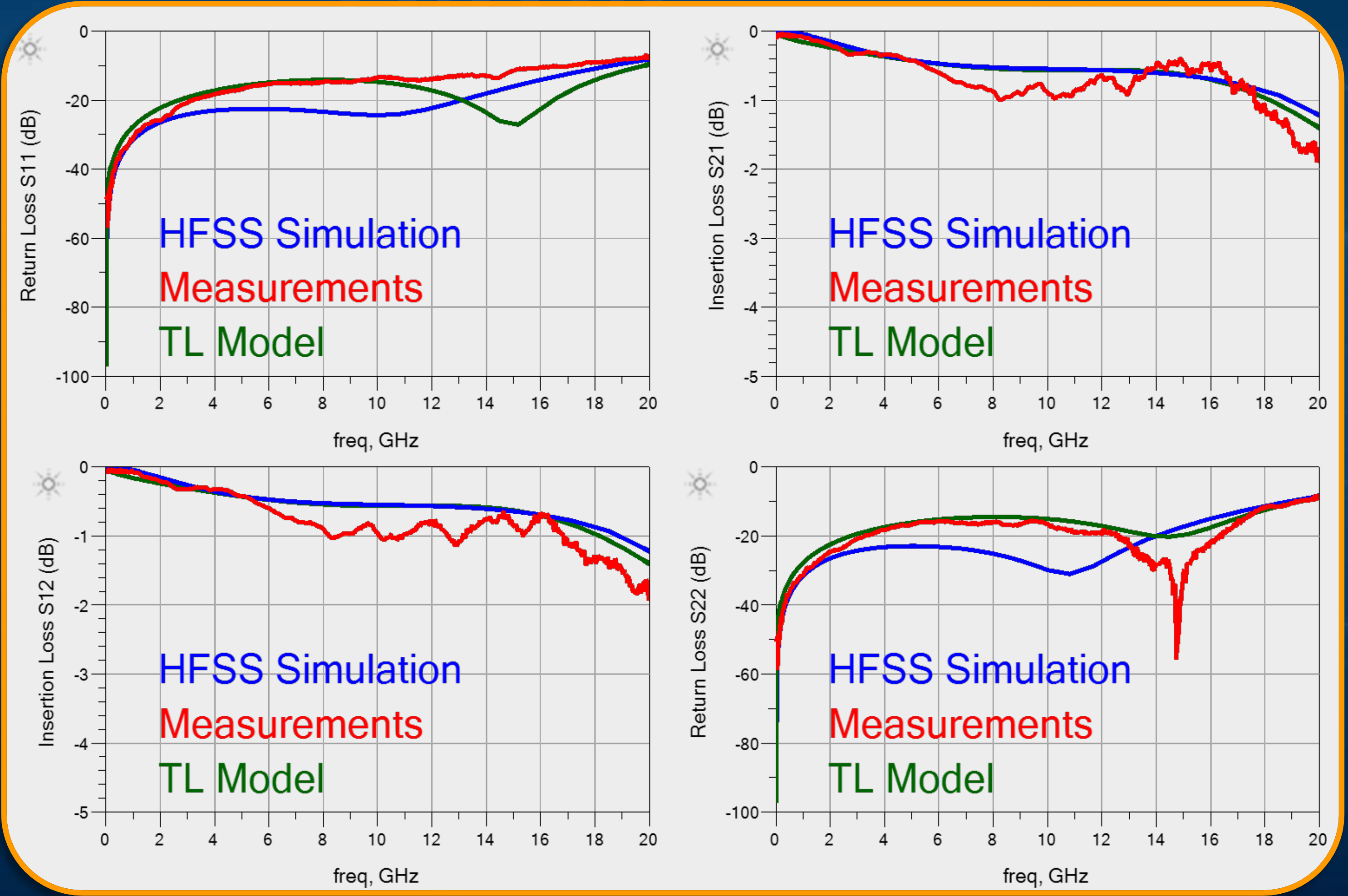
Circuit Model Parameters (total R & G)





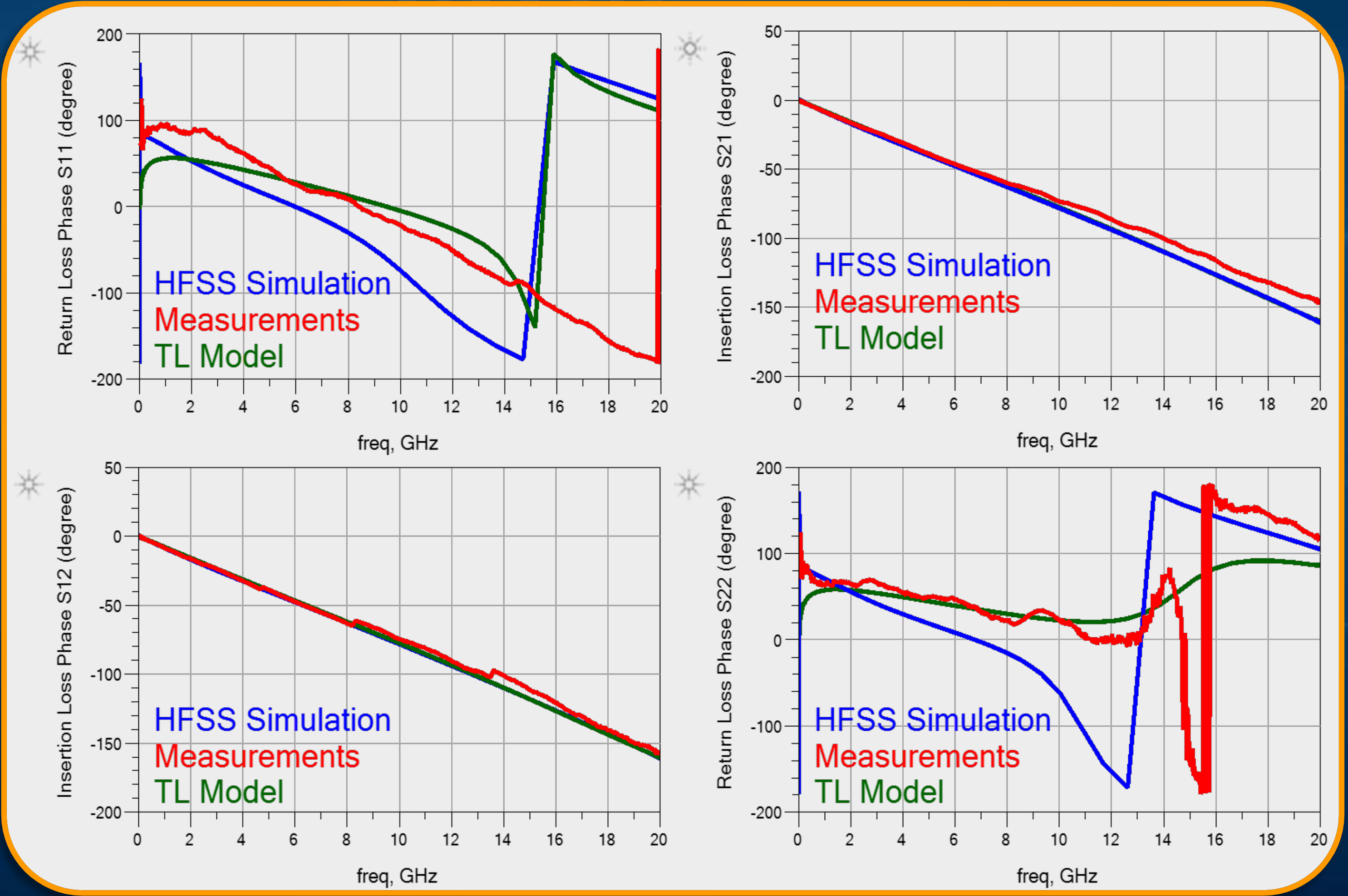
Circuit Model & Model Verification

TL Circuit Model S-Parameters



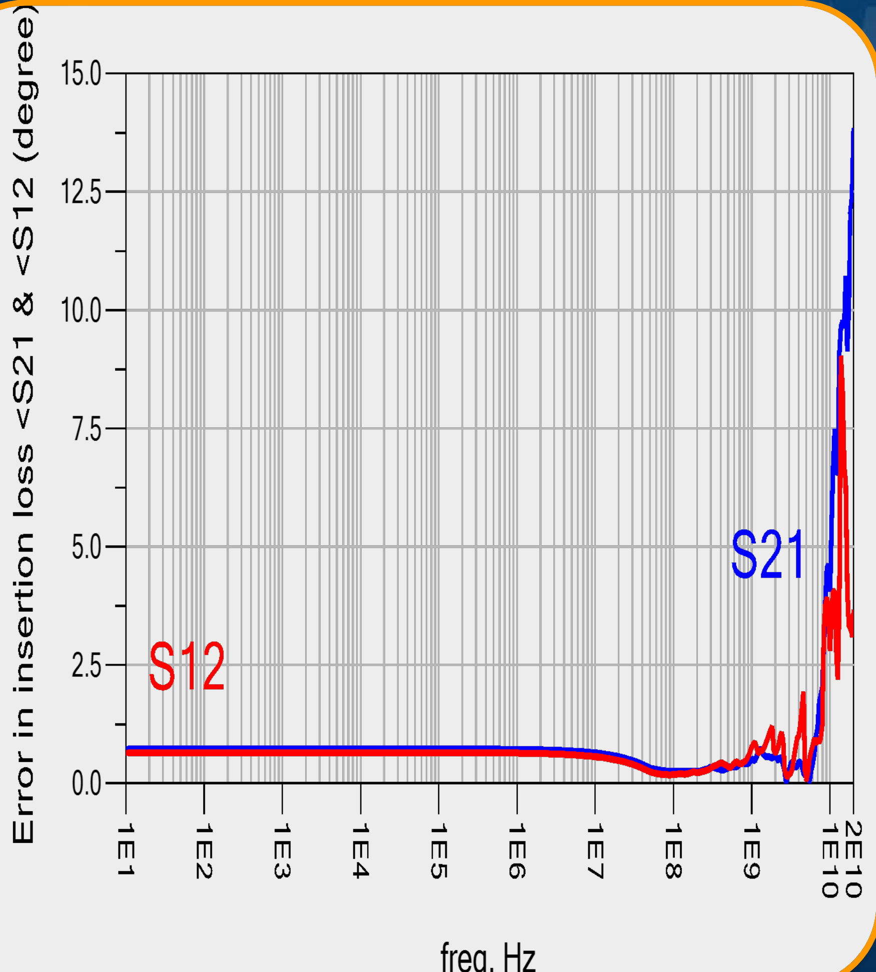
Circuit Model & Model Verification

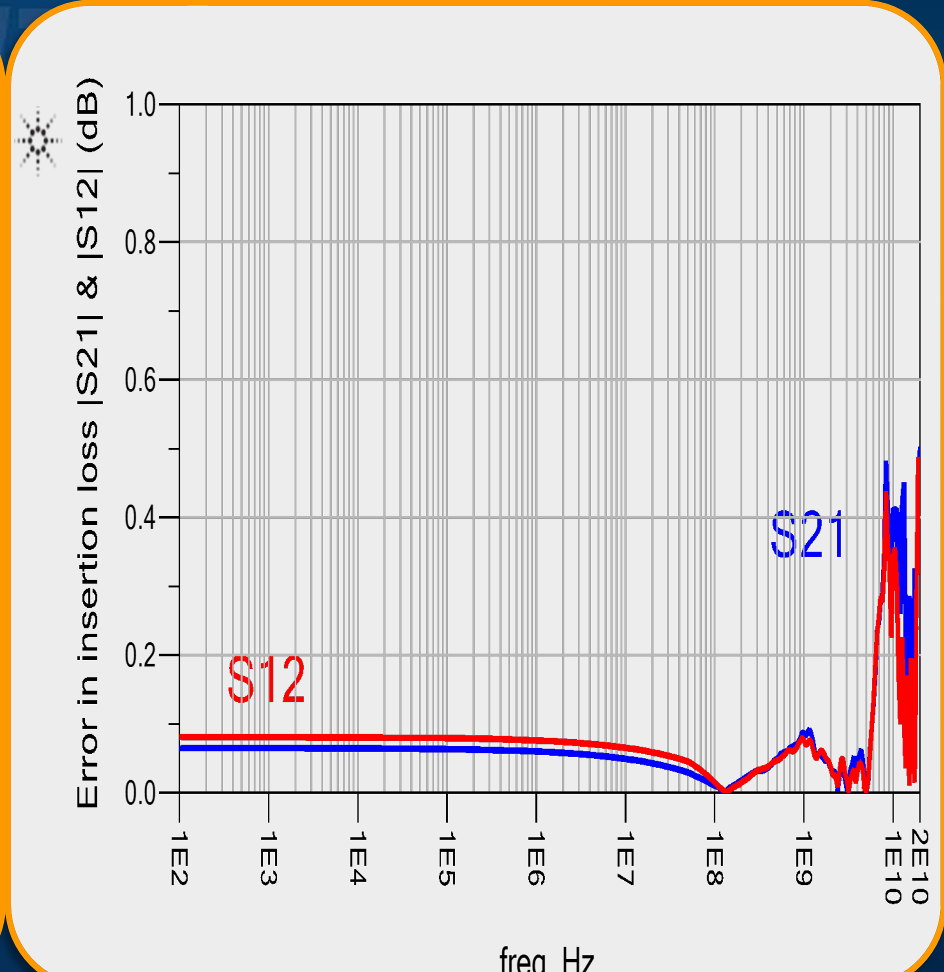
TL Circuit Model S-Parameters



Circuit Model & Model Verification

Measurements vs. Model Magnitude & Phase





SUMMARY

- Lumped and TL circuit models had been developed using close form Wideband solution.
- Two models were developed. One for circular cross section and one for rectangular cross section
- Models had been analyzed for 400um probe spacing.
- Models were verified against Spring pin measurements and field analysis simulation results.
- Results show a good match with maximum magnitude error of 0.5dB and phase error of 12 degree at high frequency

CONCLUSION

- Using a closed form model, minimize simulation time and cost.
- Closed form model can be used for quick product feasibility
- Model can be integrated with other probe card components to obtain a full performance prior to manufacturing to minimize risks and design optimization time delays.
- TL model provides better results compared with lumped circuit model, where distribution effect takes place.

References

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