Back to basics:
the onset of skin effect in circuit board traces

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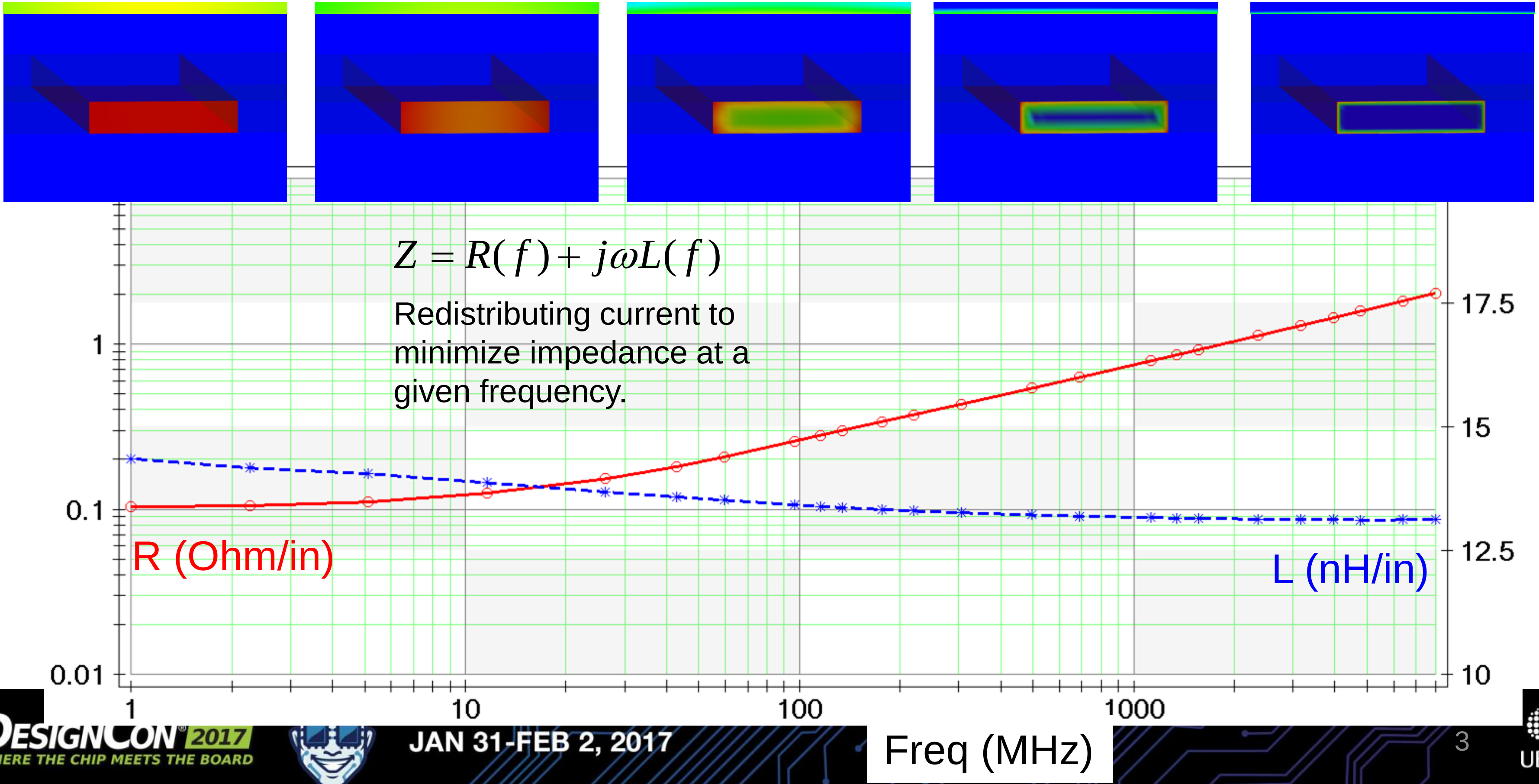
Agenda

- Skin effect in stripline environment
- Matching measurement of skin effect to simulation
  - Experiment setup
  - Measurement
  - Simulation
- Summary

The Skin effect and $R_{Len}(f)$, $L_{Len}(f)$ in stripline

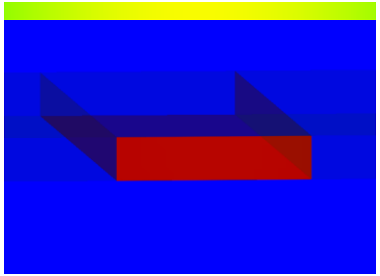


$$Z = R(f) + j\omega L(f)$$

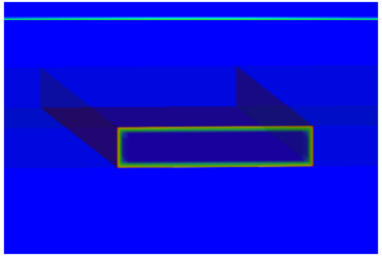
Redistributing current to minimize impedance at a given frequency.

How do we match measured skin effect to simulation?

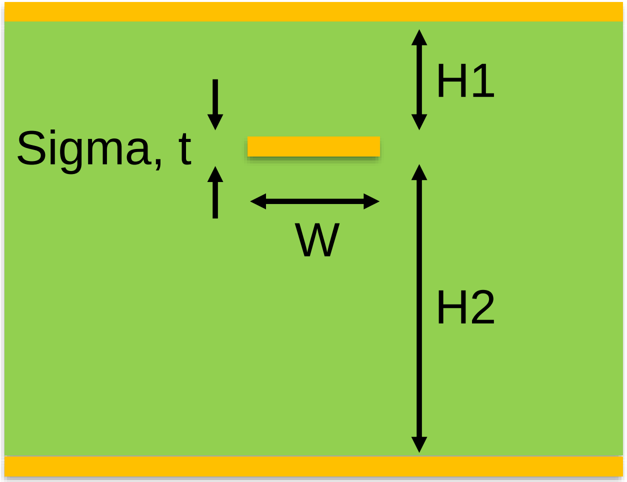
1 MHz



8 GHz



- It comes down to matching R_{Len}(f) and L_{Len}(f)
- What are the trace parameters that affect R_{Len} (f) and L_{Len}(f) ?



Expect to affect R_{Len} (f) to first order

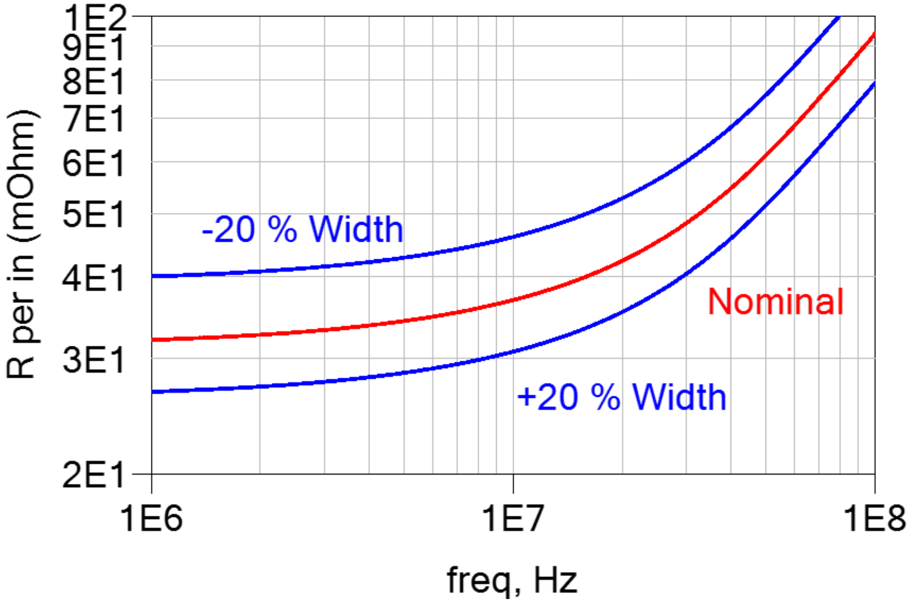
- Width of trace
- Thickness of trace
- Conductivity of copper

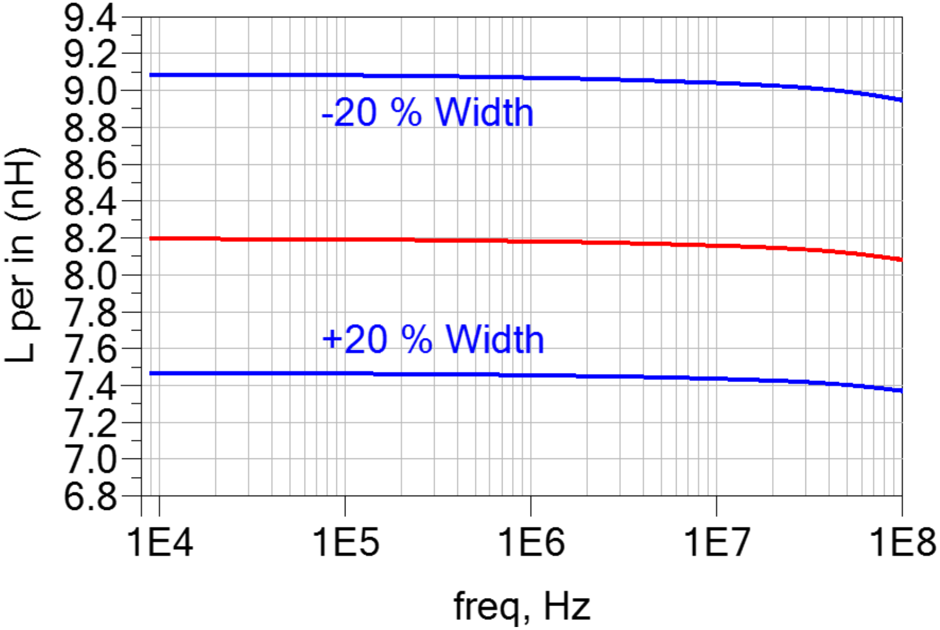
Expect to affect L_{Len}(f) to first order

- Width of trace
- Substrate height

Sensitivity of $R_{Len}(f)$ and $L_{Len}(f)$ to W

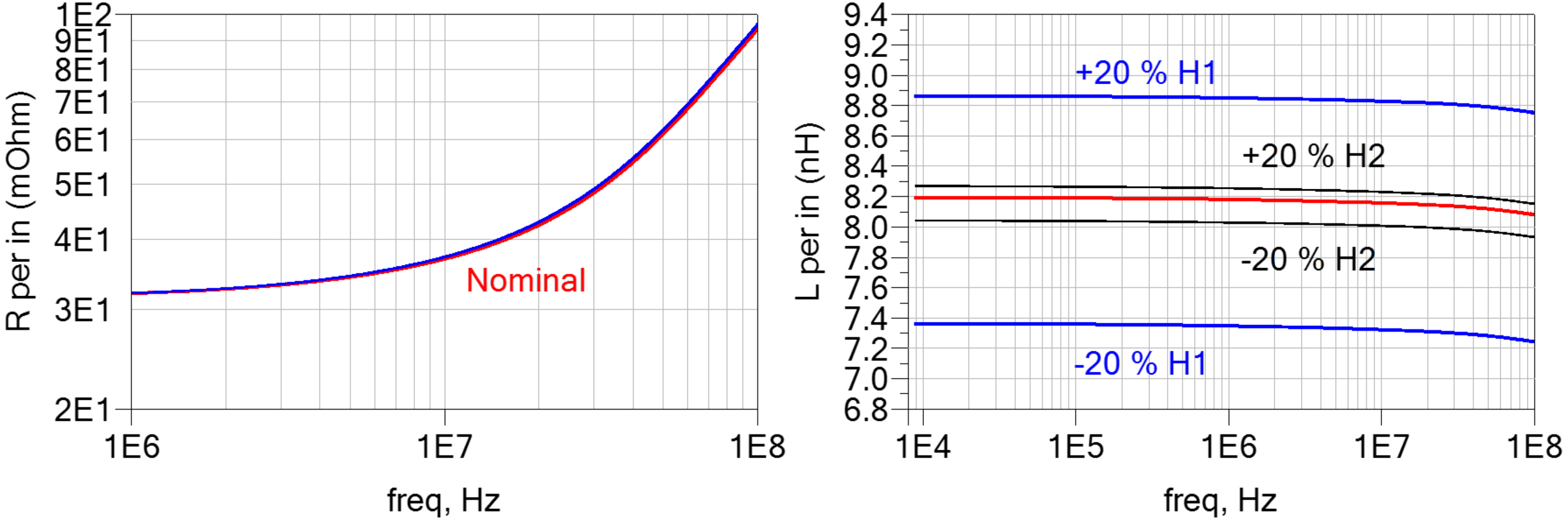
Both curves are sensitive to width change.
Need to extract the fabricated trace width.





Sensitivity of R_{Len}(f) and L_{Len}(f) to H1, H2

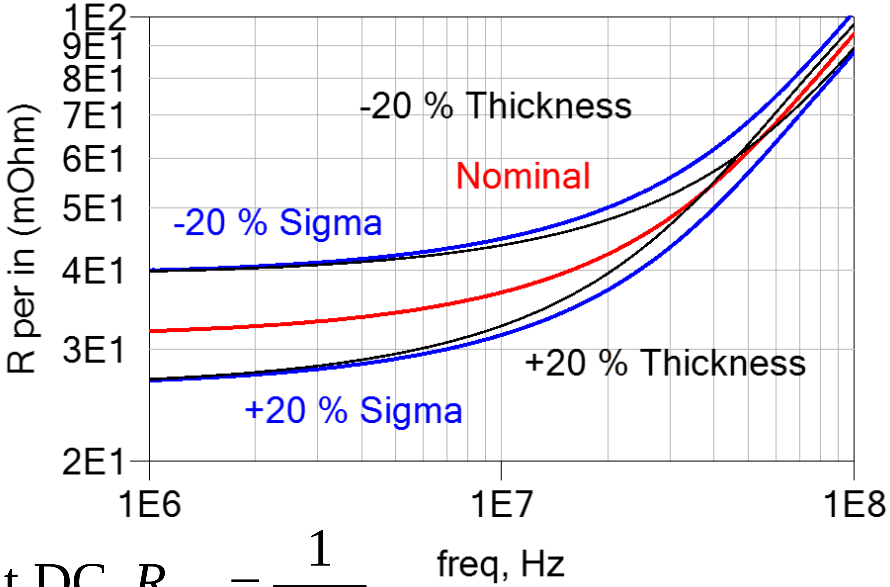
To first order, R_{Len}(f) is not sensitive to H changes, and L_{Len}(f) most influenced by H1.

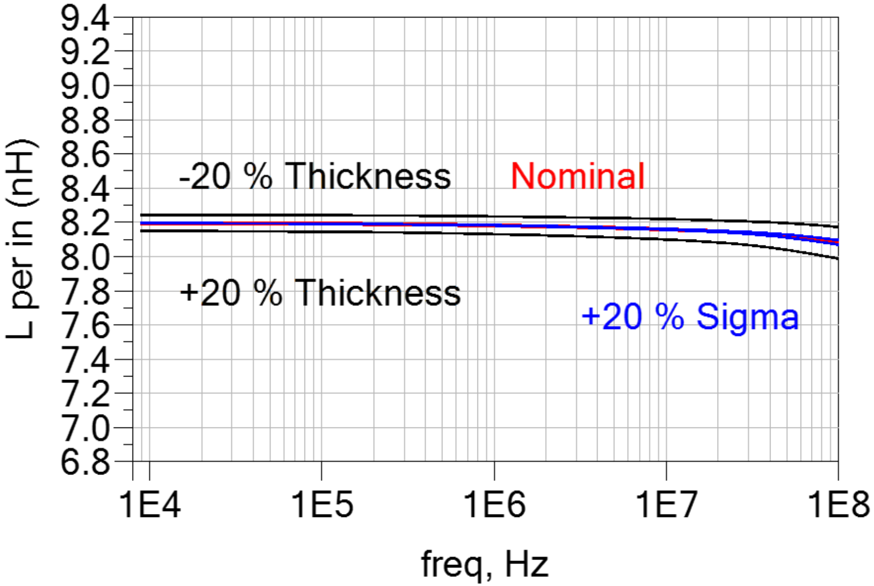


*less than 3% change from 20% H2 change

Sensitivity of $R_{Len}(f)$ and $L_{Len}(f)$ to Sigma and T

$R_{Len}(f)$ is sensitive to sigma and t change, but $L_{Len}(f)$ is insensitive to sigma.



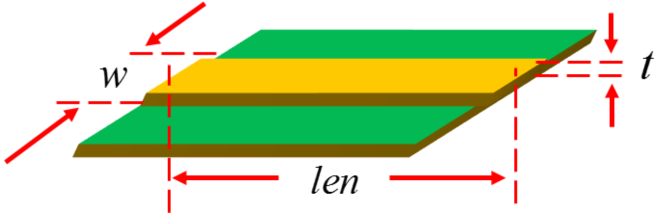


At DC, $R_{Len} = \dfrac{1}{w\sigma t}$

*less than 3% change from 20% Thickness change

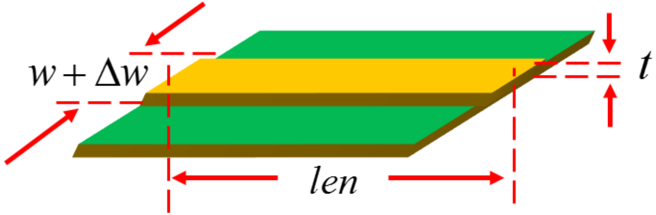
Reducing number of variables: divide and conquer

Variables: W, Sigma, T and H1.
Is there a way to reduce the number of variable?



$$R = \frac{1}{\sigma}\frac{len}{w\cdot t} = \frac{1}{\sigma t}\frac{len}{w} = R_{\square}\cdot\frac{len}{w} = R_{\square}\cdot n$$

Rule of thumb:
Rsheet = 0.5 mOhm/sq for 1 oz copper
Rsheet = 1 mOhm/sq for ½ oz copper

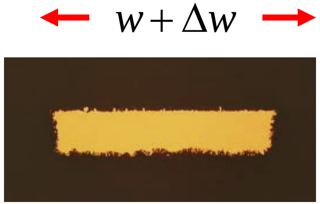


Measure R_{sheet} and delta w, but how?

$$R = R_{\square}\cdot\frac{len}{w+\Delta w}$$

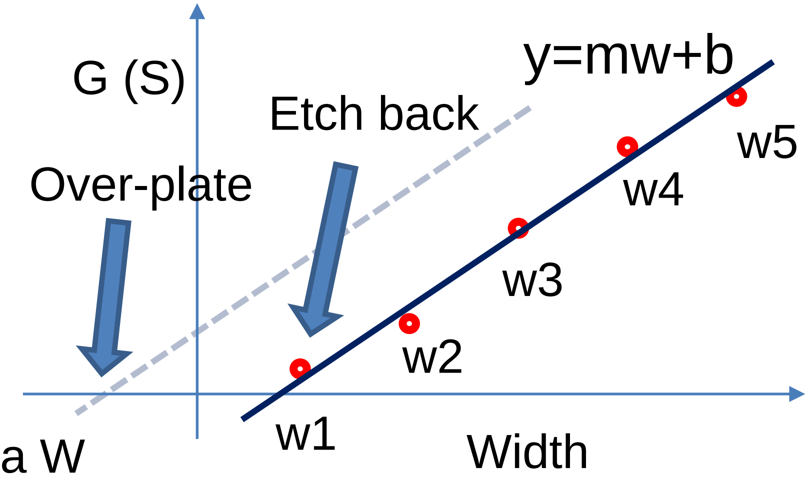
New technique to extract delta width and sheet resistance

Assume rectangular cross-section



$$R = R_\square \cdot \frac{len}{w+\Delta w}$$

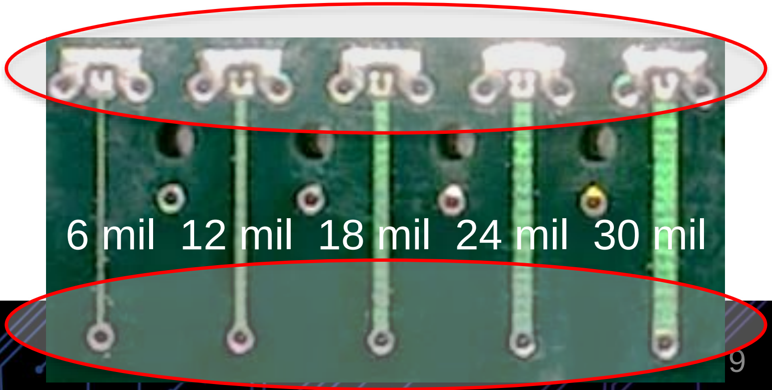
$R_\square$ = sheet resistance, Δw = etchback/overplate



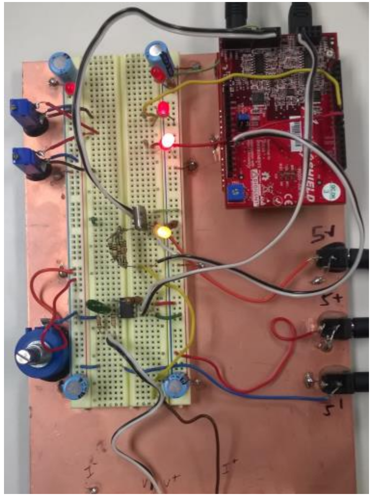
5 different trace widths to extract R_{sheet} and delta W

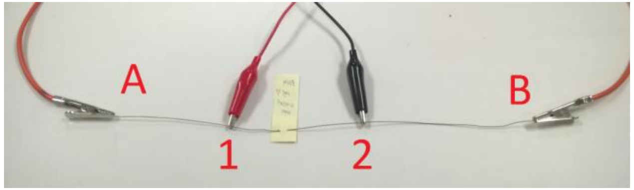
$$\frac{1}{R} = G = \frac{1}{R_\square \cdot len}(w+\Delta w) = mw+\mathrm{b}$$

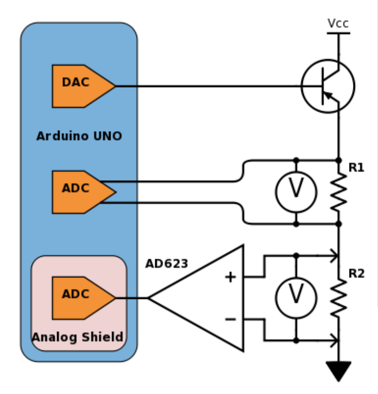
$$G = m\,(w+\frac{b}{m});\ R_\square = \frac{1}{m \cdot len};\ \Delta w = \frac{\mathrm{b}}{m}$$

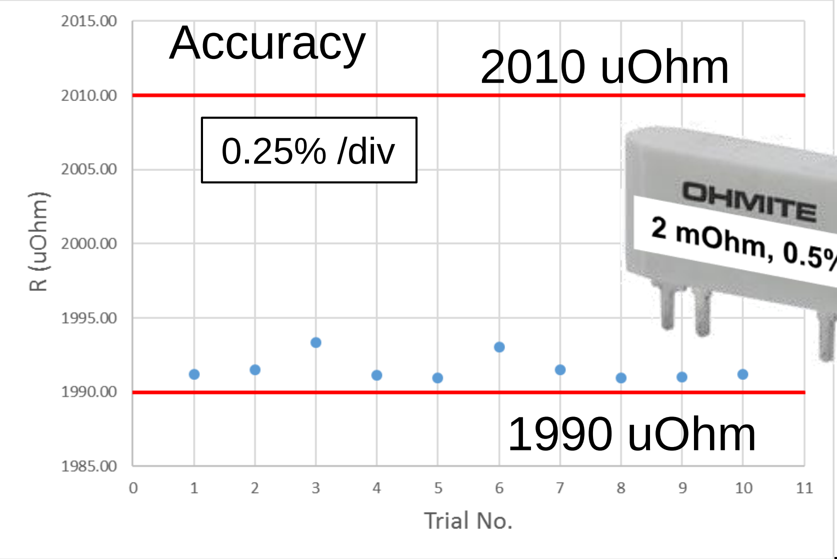


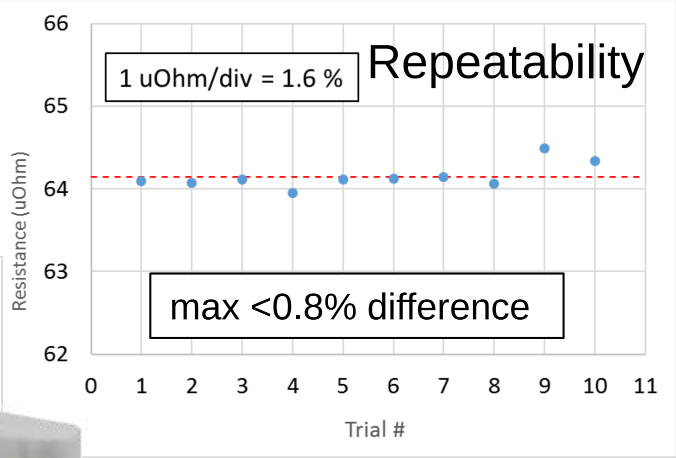
DC measurement with precision uOhm-meter

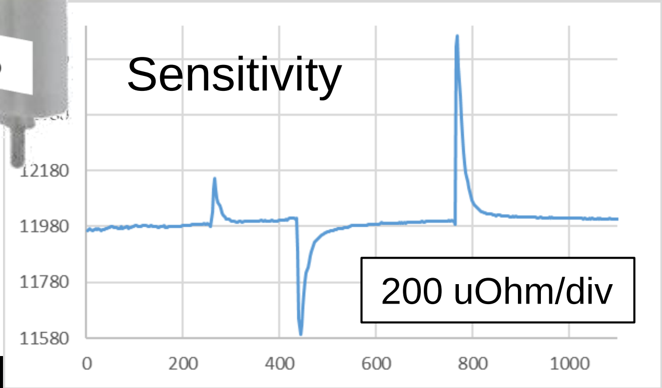




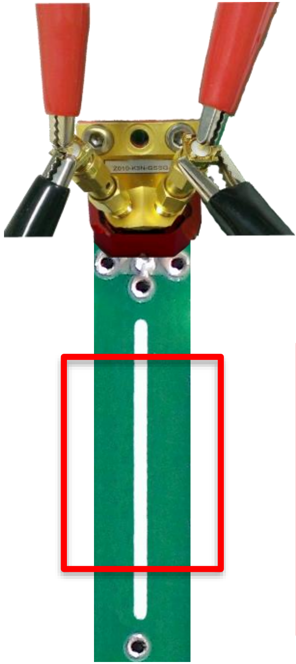








Extraction of R_{sheet} with DC measurement



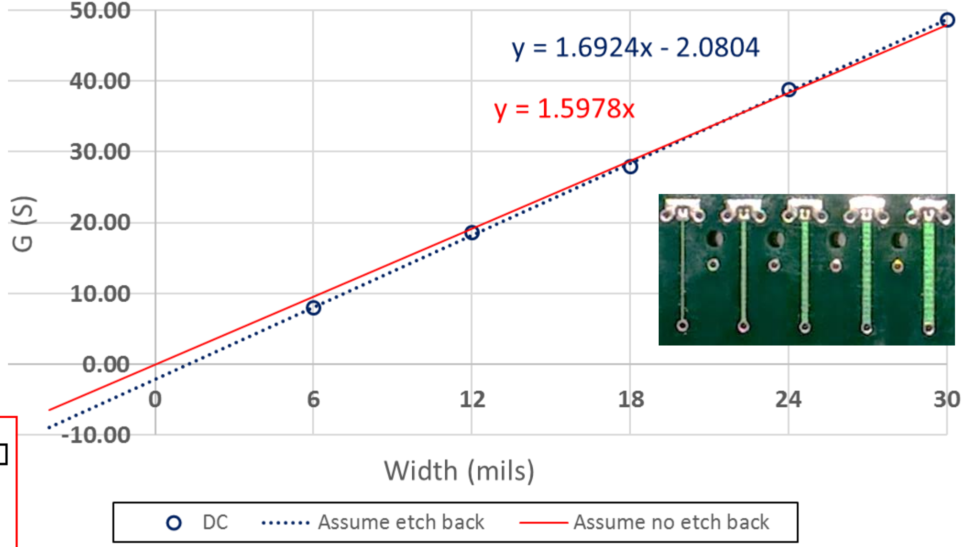
$$G = m\left(w + \frac{b}{m}\right)$$

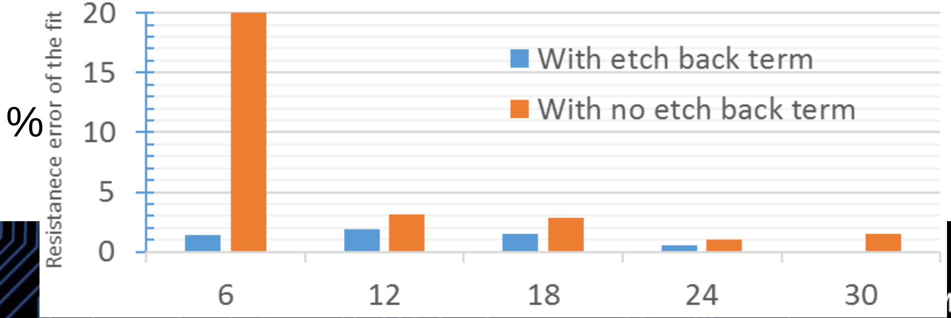
$$R_{\square} = \frac{1}{m \cdot len}; \Delta w = \frac{b}{m}$$

DC mOhm
1 in
125.61
53.80
35.76
25.81
20.55

$$R_{\square} = 0.591\,\mathrm{m}\Omega/\square$$

$$\Delta w = -1.23\ \mathrm{mils}$$



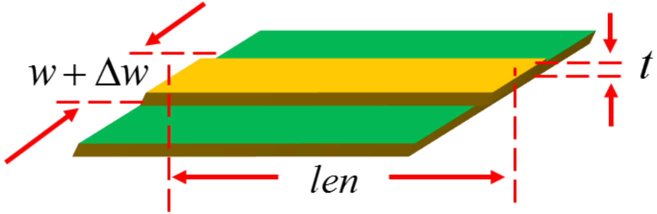


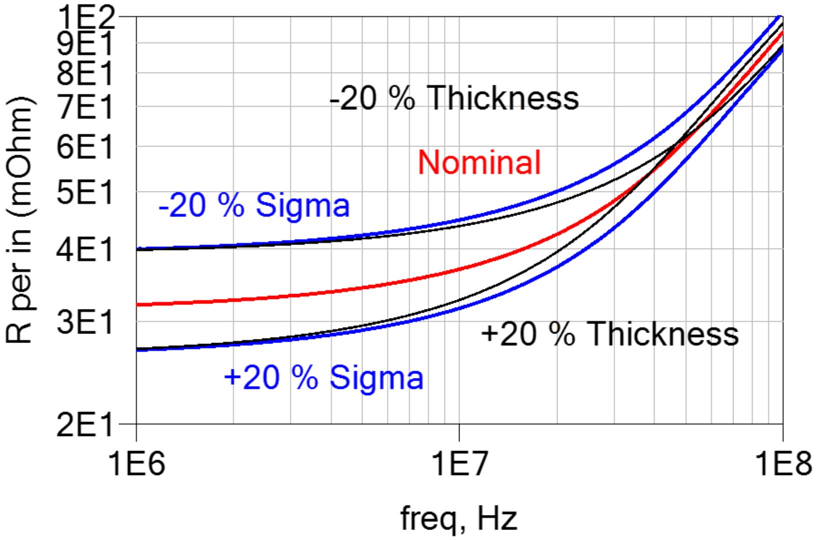
Rule of thumb:
Rsheet = 0.5 mOhm/sq for 1 oz copper

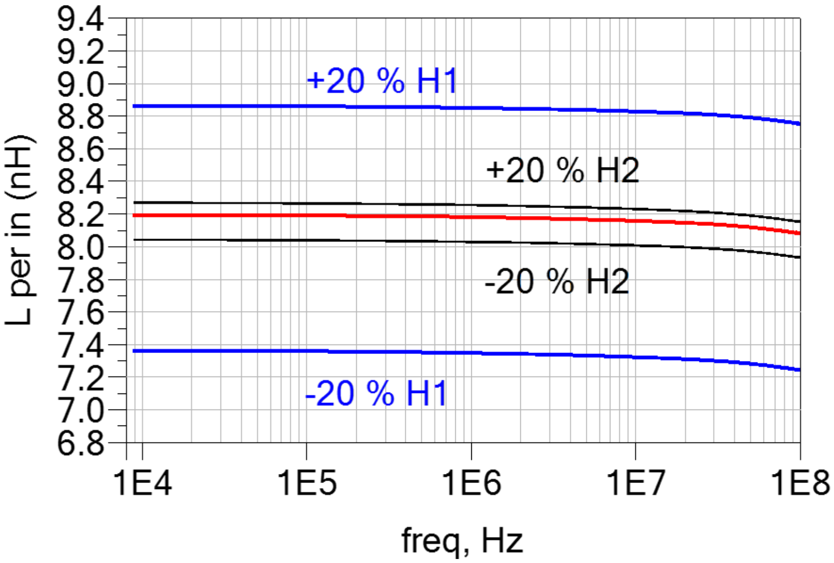
Reducing number of variables: divide and conquer

Variables: Sigma, T and H1.

$$R_{\square} = \frac{1}{\sigma t}$$







Road to R(f) & L(f)

Structures:

- Shorted transmission line
- 2X-thru

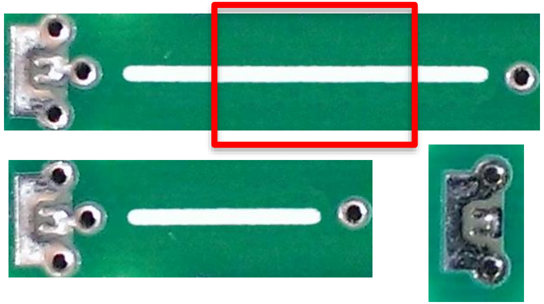
Measurement:

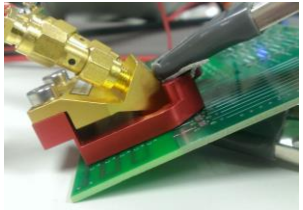
- S-parameter with 2 port technique
- What do we expect?

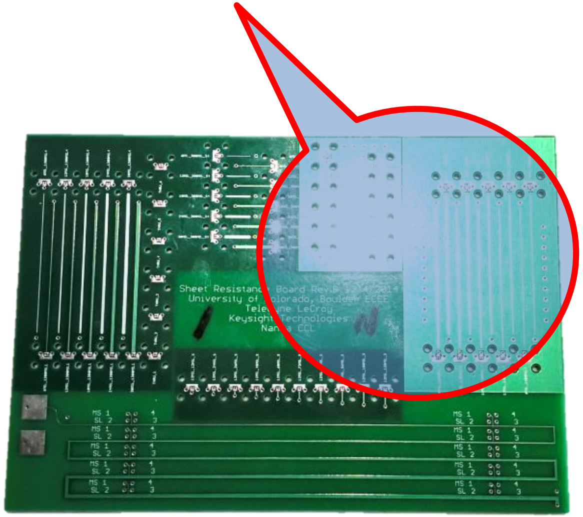
Data Process:

1. De-embedding and converting S-parameter to Zin
2. Extracting R(f)and L(f) from Zin
3. Takeingthe difference between two lengths
4. Fitting, sigma, T and H1 to the curves

SET2DIL
Footprint



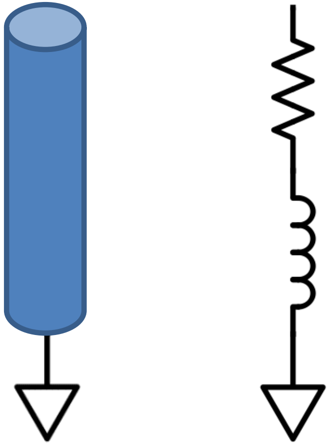




Low frequency behavior: Input impedance of shorted tline and the 2 port technique

At low frequencies, the input impedance of a transmission line is:

$$\tilde{Z}_{in} \Rightarrow R_{Len}(f) + j\omega L_{Len}(f)$$

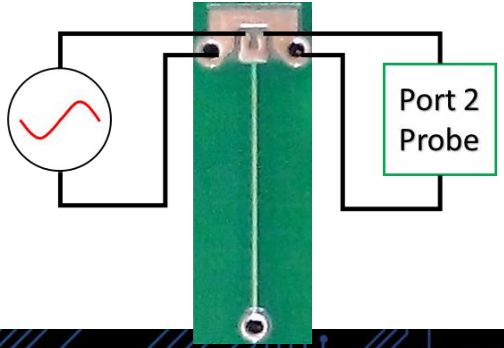


1 port measurement with estimated DC sheet resistance: R_{DC}=15 mOhm

$$S_{11} = \frac{R_{DC} - 50}{R_{DC} + 50} = -0.005\,\mathrm{dB}$$

Sensitive to Contact resistance > 15 mOhm

2 port technique for ultra low impedance measurement:

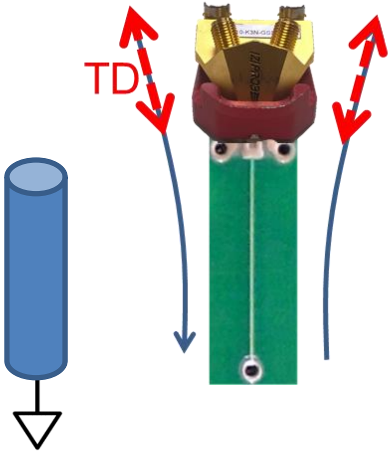


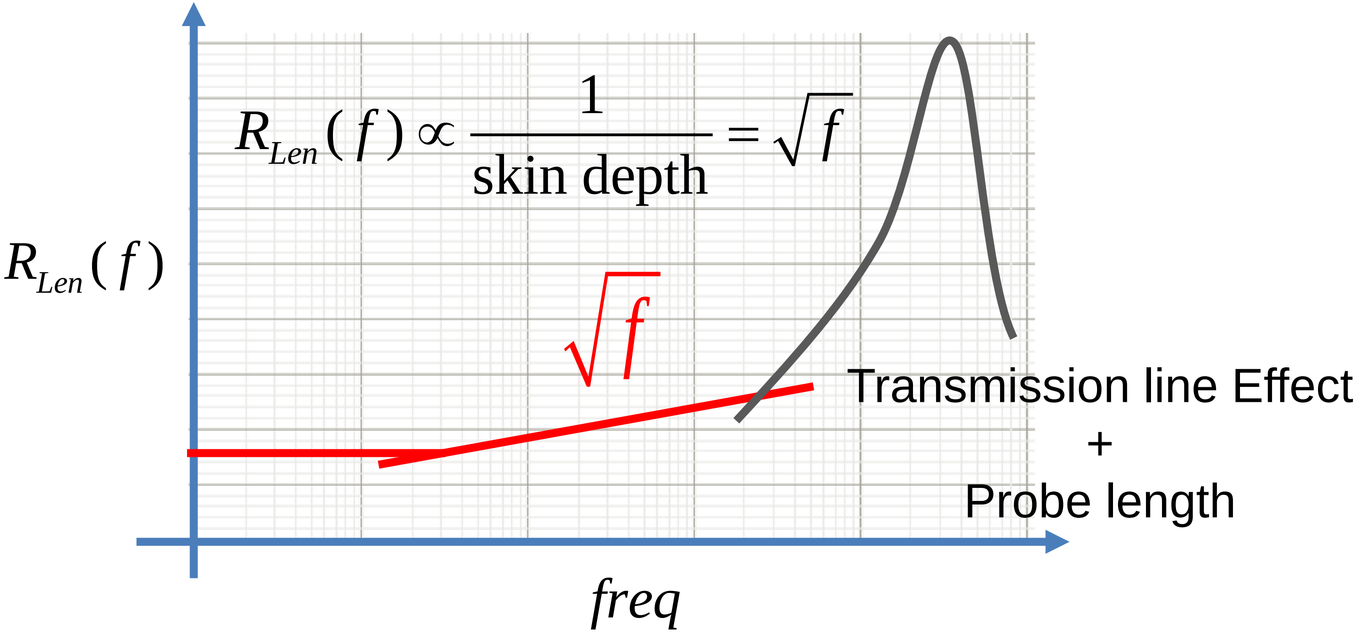
$$\tilde{Z}_{in} = 25\frac{\tilde{S}_{21}}{1-\tilde{S}_{21}} \Rightarrow \tilde{S}_{21} = \frac{\tilde{Z}_{in}}{25+\tilde{Z}_{in}}$$

$$|S_{21}| = -64\,\mathrm{dB}$$

Not sensitive to contact resistance!

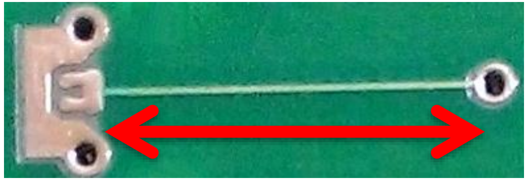
Applying Rule #9:
Expected R_{Len}(f) behavior and identifying artifacts



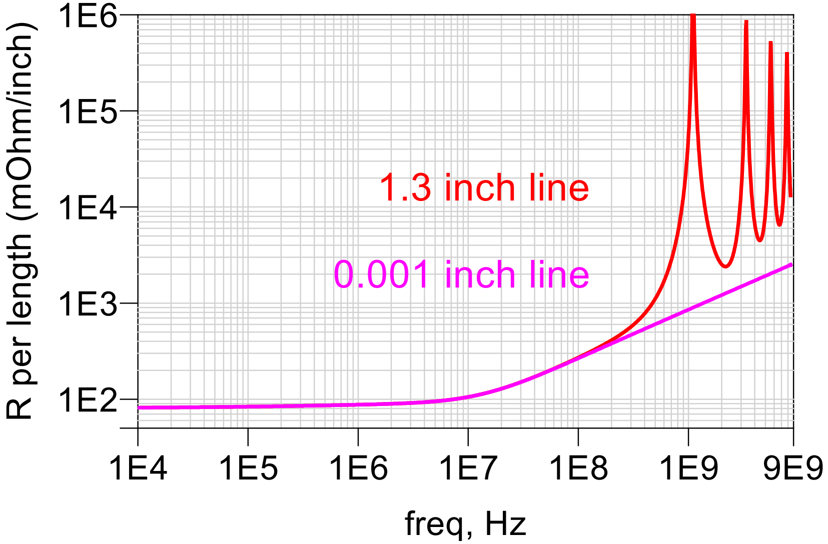


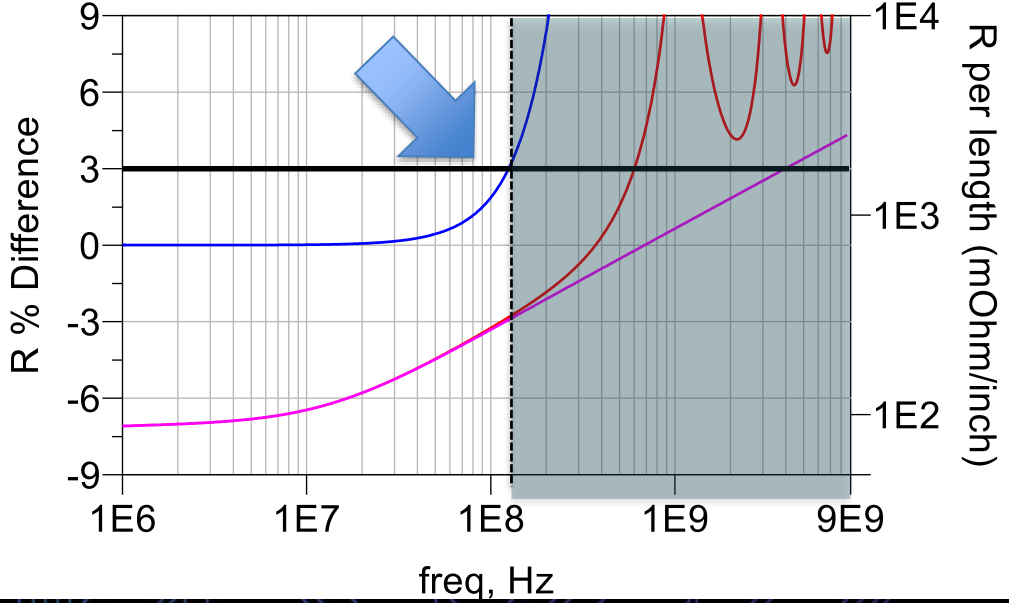
$$R_{Len}(f) \propto \frac{1}{\text{skin depth}} = \sqrt{f}$$

Artifact #1: Transmission line effect in R per len curve



Limiting factor: DUT is 1.3 inch.
At what frequency is measured data Tline effect free?
3% Resistance difference at 150 MHz

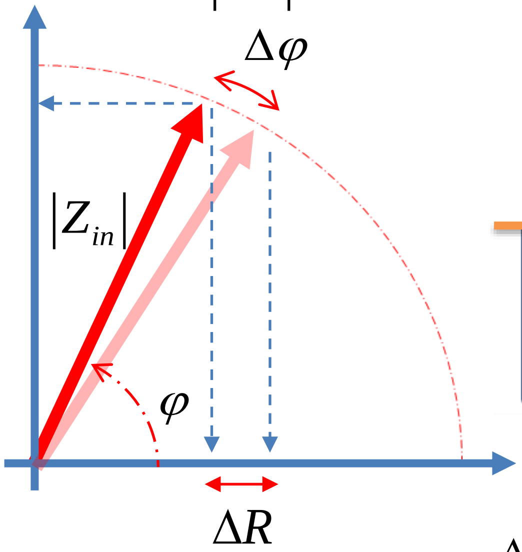


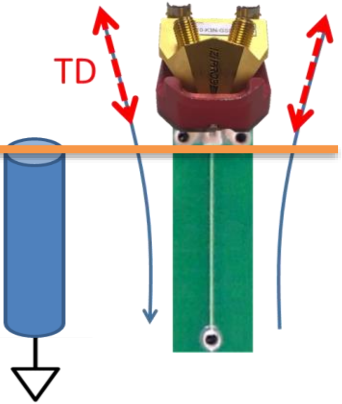


Artifact #2 phase introduced by probe length

$$\left|\tilde{Z}_{in}\right|e^{j\varphi} \approx 25\cdot\left|S_{21}\right|e^{j\theta_{21}}$$

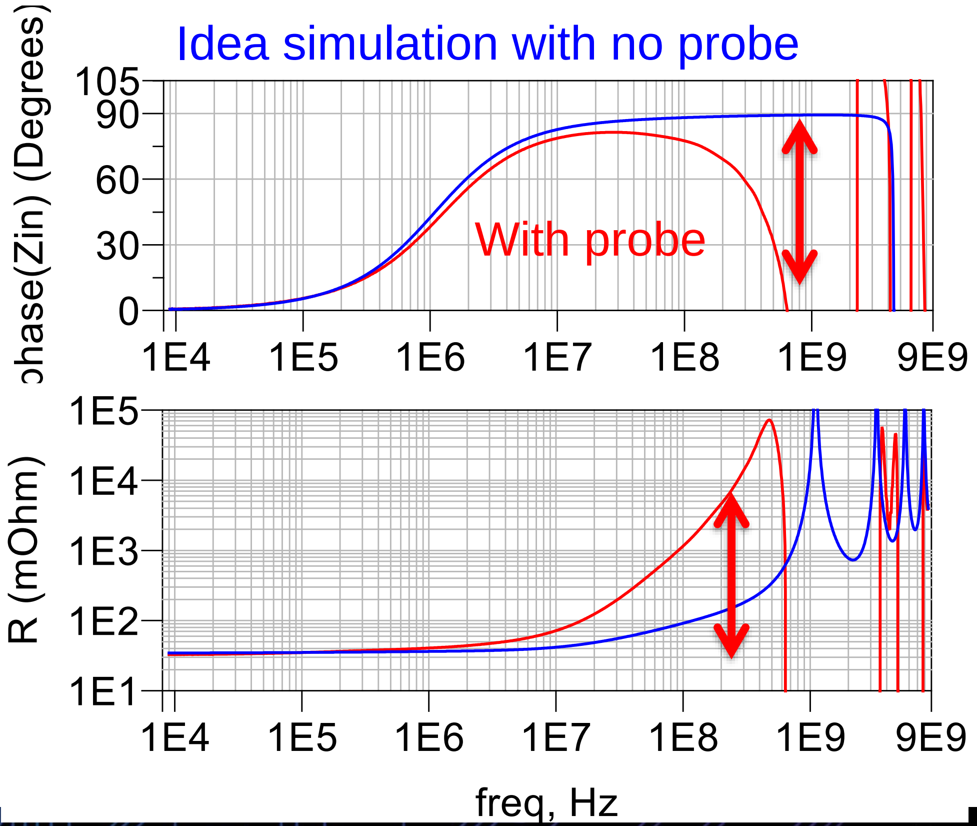
$$\left|\tilde{Z}_{in}\right|e^{j\varphi} = R_{Len}(f) + j\omega L_{Len}(f)$$





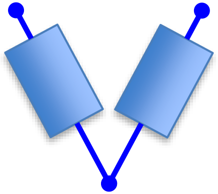
$$\left|Z_{in}\right|\cos(\varphi) = R$$

$$\Delta R = -\left|Z_{in}\right|\sin(\varphi)\Delta\varphi$$



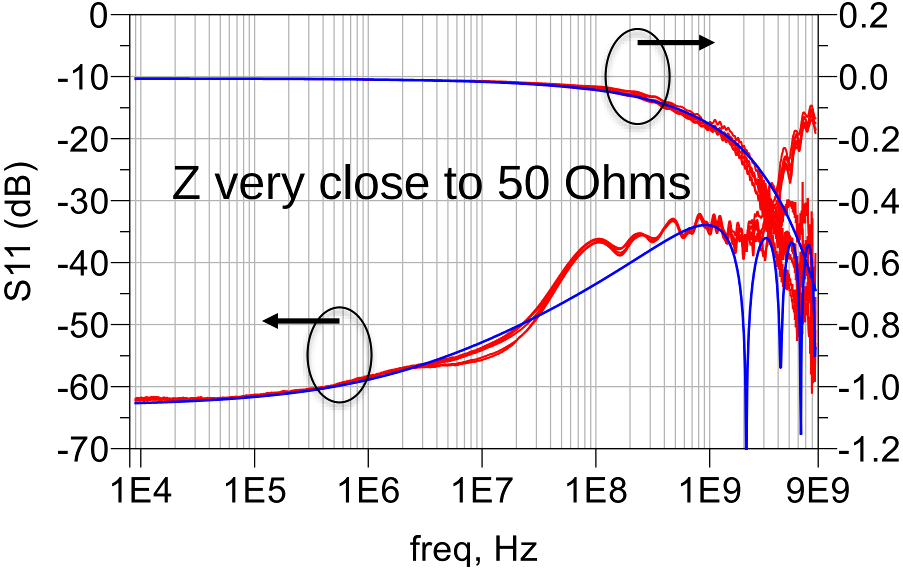
Variation in nominally identical thrus

Model of fixture built and simulated in ADS

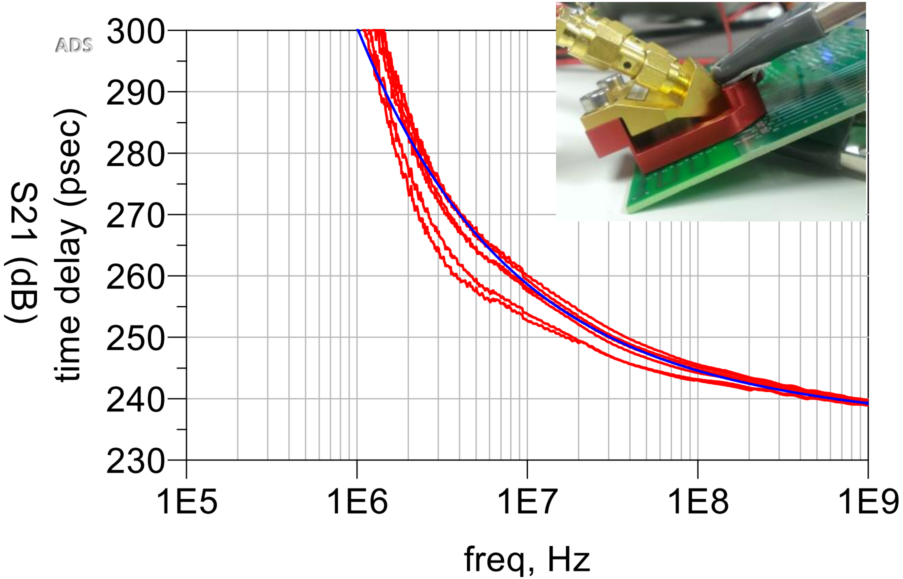


Nominal six same thrus

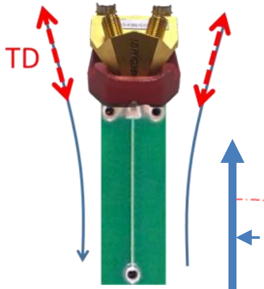
Estimated probe delay:
2 inches @ 8 inch/nsec
~250 psec



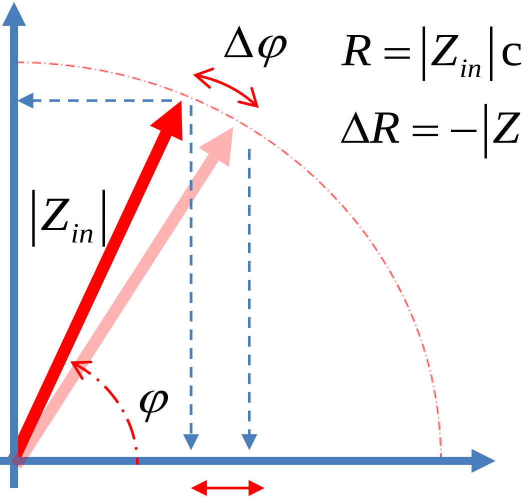
Z very close to 50 Ohms



For a given Time Delay, delta R increases with frequency



$$\left|\tilde{Z}_{in}\right| e^{j\varphi} = R_{Len}(f) + j\omega L_{Len}(f)$$



$$R = |Z_{in}|\cos(\varphi)$$

$$\Delta R = -|Z_{in}|\sin(\varphi)\Delta\varphi$$

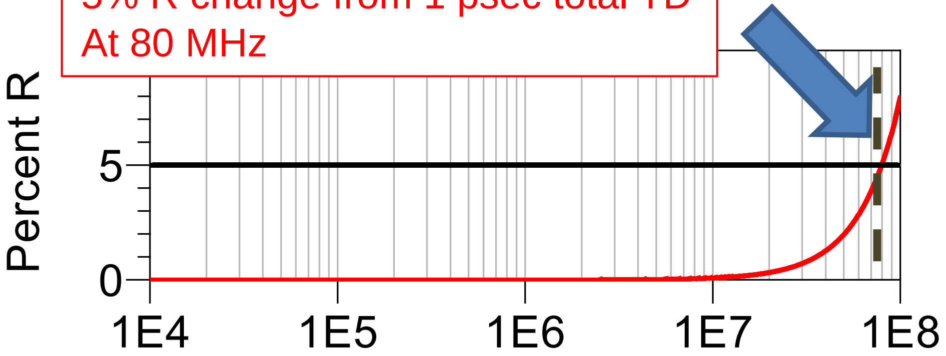
$$|Z_{in}|\cos(\varphi) = R \qquad \Delta R$$

$$\frac{\Delta R}{R} = -\tan(\varphi)\Delta\varphi;\ \Delta\varphi = \Delta TD \cdot 2\pi f$$

$$\frac{\Delta R}{R} = \frac{\omega L}{R}\Delta TD \cdot 2\pi f$$

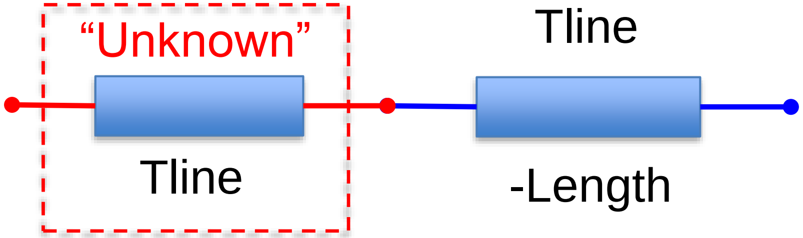
Estimated DC sheet resistance: 15 mOhm
Estimated Inductance strip line : 5 nH/in * 0.3 inch -> 1.5nH
Delta time delay (total) = 1 psec Freq = 100MHz
R %change = 4%

5% R change from 1 psec total TD
At 80 MHz



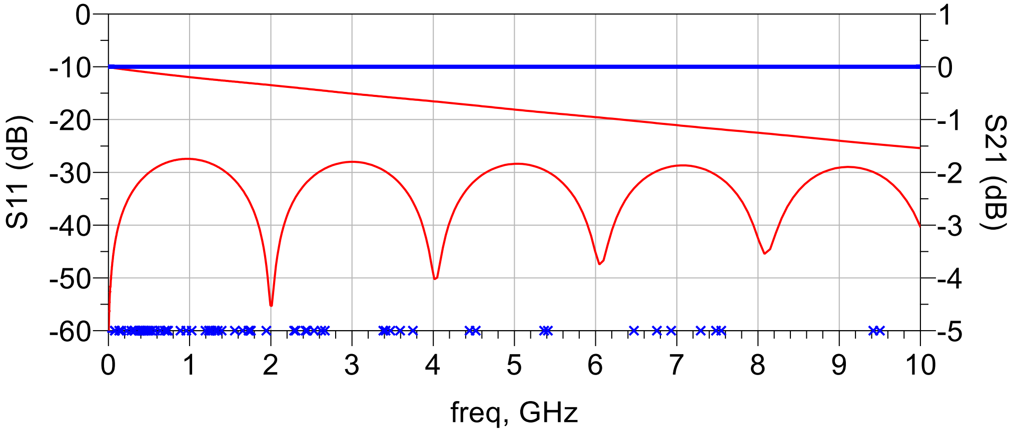
A new flexible deembedding technique: negative length

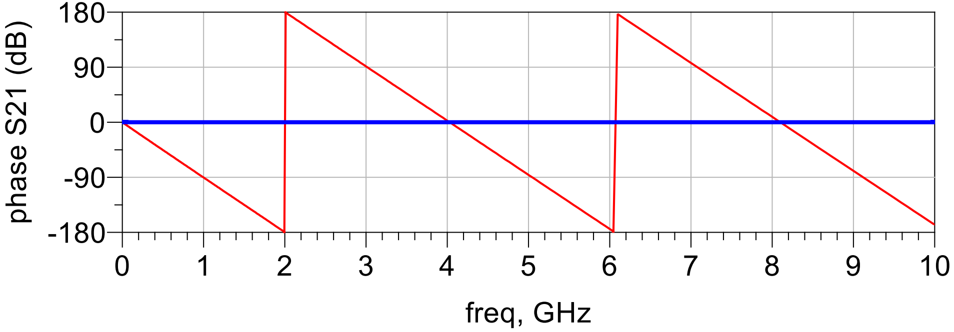
Virtual prototype



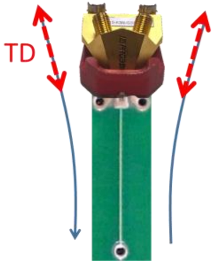
52 Ohm, 1.5 inch, FR4

Parameter	After De-embedding
S_{11}	No ripples
S_{21}	Flat
Phase S_{21}	0 degree





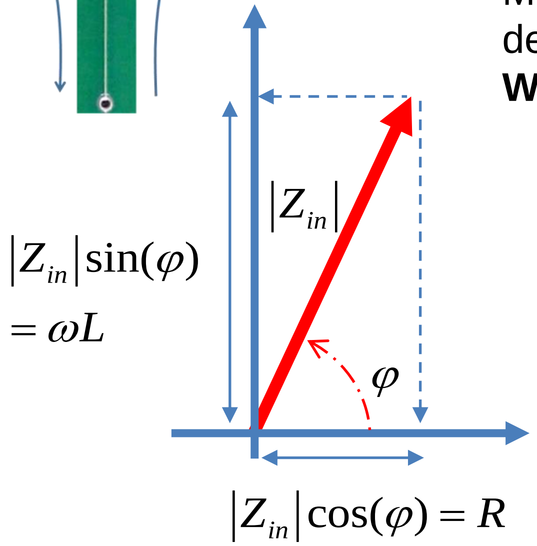
How do we know if we deembed enough/too much?

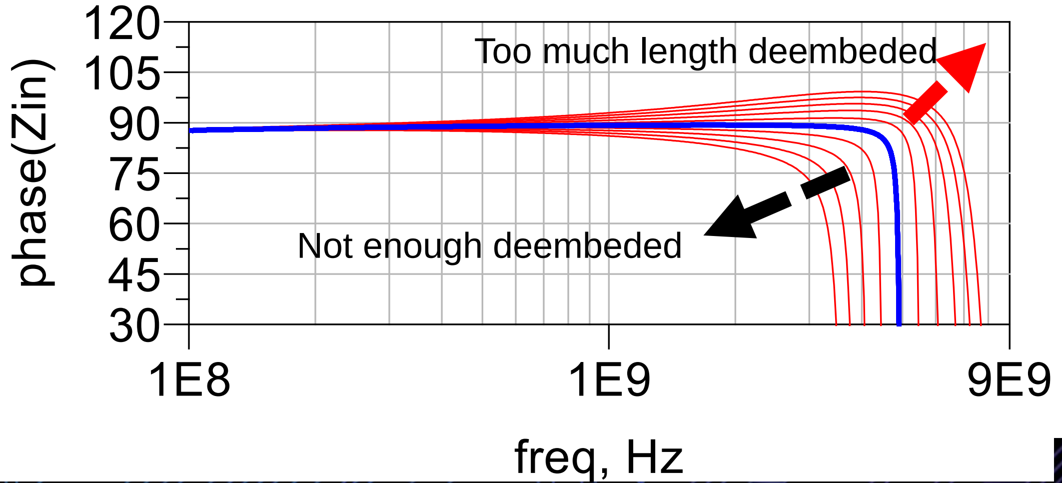


$$\tilde{Z}_{in} = 25\frac{\tilde{S}_{21}}{1-\tilde{S}_{21}} \Rightarrow \left|\tilde{Z}_{in}\right| = 25\frac{\left|\tilde{S}_{21}\right|}{\sqrt{1-2\left|\tilde{S}_{21}\right|\cos(\theta_{21})+\left|\tilde{S}_{21}\right|^{2}}}$$

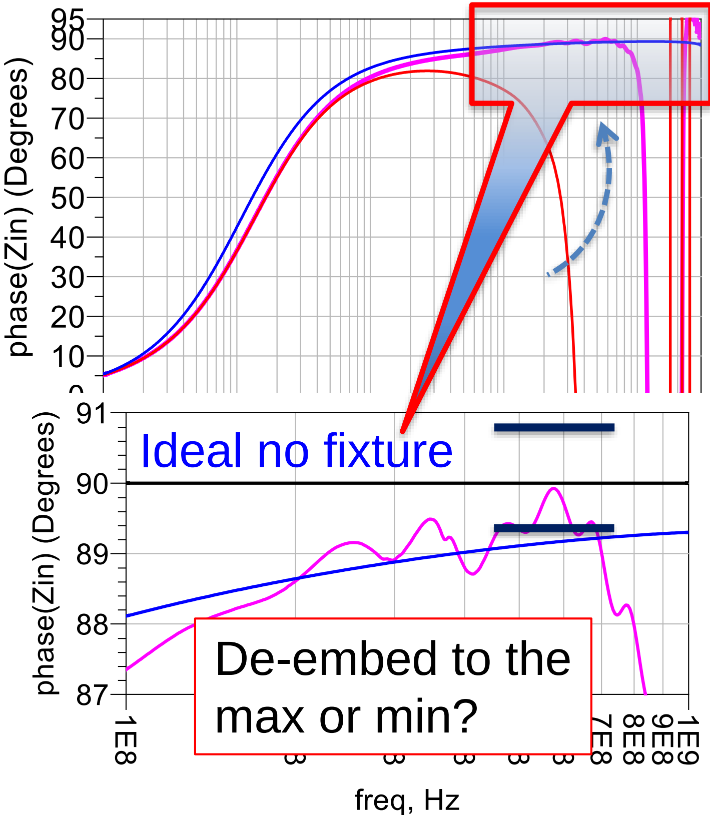
$$\varphi = \angle\tilde{Z}_{in} = \tan^{-1}\left(\frac{\sin(\theta_{21})}{\cos(\theta_{21})-\left|\tilde{S}_{21}\right|}\right)$$

Mathematically, -90 < phi < 90 because -90< arctan <90, but we are dealing with numerical simulations when de-embedding.
We need to make sure de-embedded result is physical.



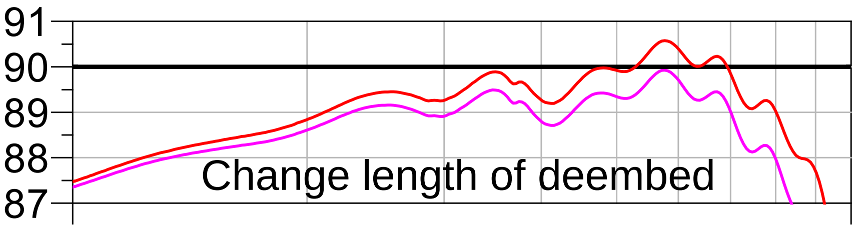


Hidden Artifact #3: noise in phase after deembedding



Ideal no fixture

De-embed to the max or min?

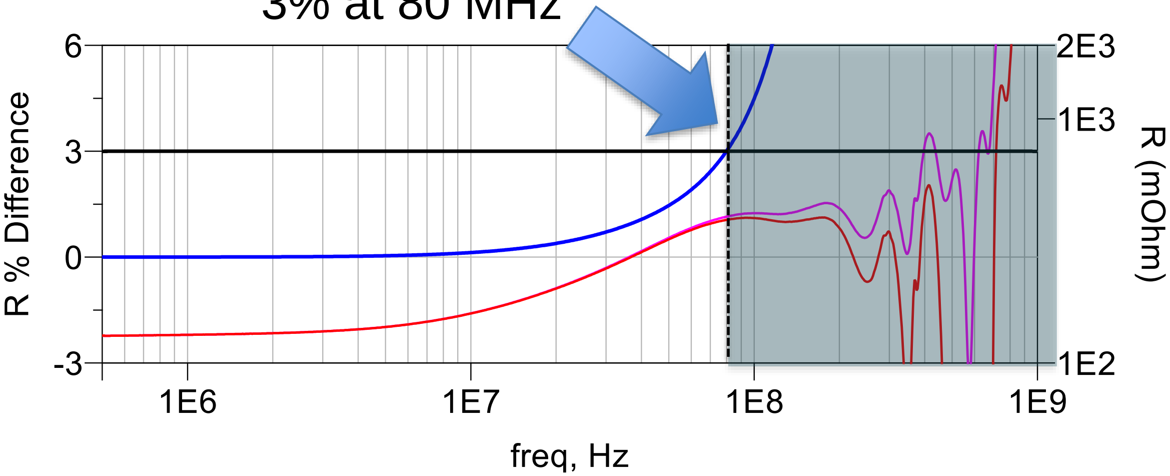


Change length of deembed

~1 psec Numerical noise

How much % difference is in R(f)?

3% at 80 MHz



Review of Measurement procedure

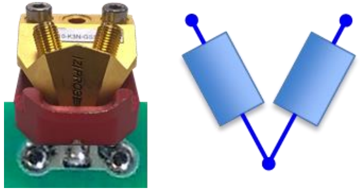
- 2 port measurement
  - Long structure
  - Short structure

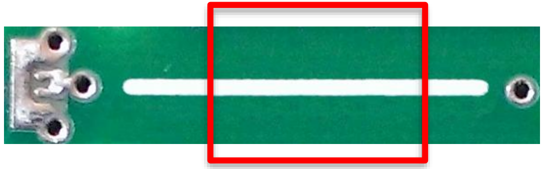
$$R_{Len}(f) = \frac{real(\tilde{Z}_{in})}{len}$$

$$L_{Len}(f) = \frac{imag(\tilde{Z}_{in})}{\omega}\frac{1}{len}$$

- Process
  - Convert to Zin to R(f) and L(f).
  - De-embed both structures with negative length transmission.
  - Take the difference between the R(f), L(f) results from long structure and short.

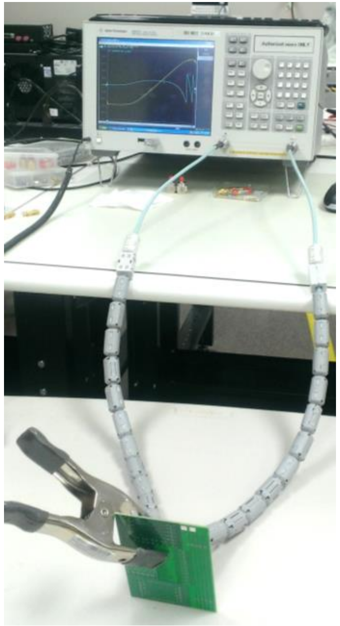
$$\tilde{Z}_{in} = 25\frac{\tilde{S}_{21}}{1-\tilde{S}_{21}}$$

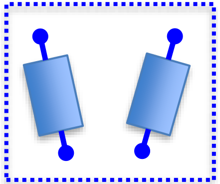


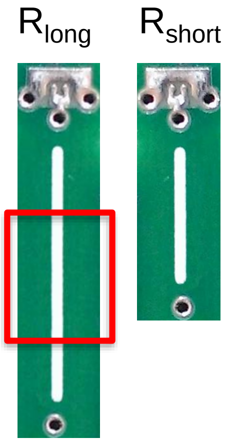


Deembedded RF Measurement and DC consistency test

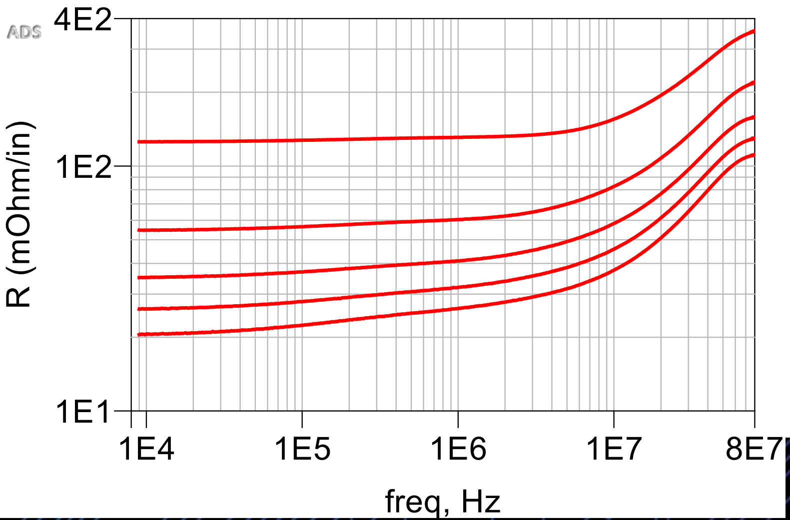
Keysight E5071C
9 kHz-8.5 GHz







	Resistance per inch (mOhm)	
w (mil)	DC	RF
6	125.6	125.5
12	53.8	54.7
18	35.8	35.0
24	25.8	26.0
30	20.6	20.5



	R sheet	delta W
DC	0.591	-1.23
RF	0.589	-1.26

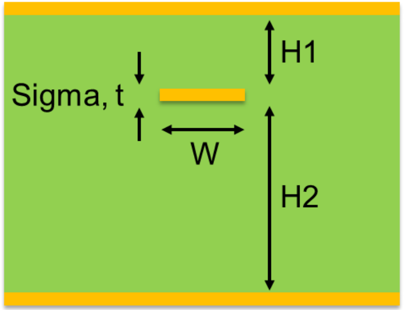
Difference from DC:
R_{sheet}: 0.3%,
Delta W: 2.7%

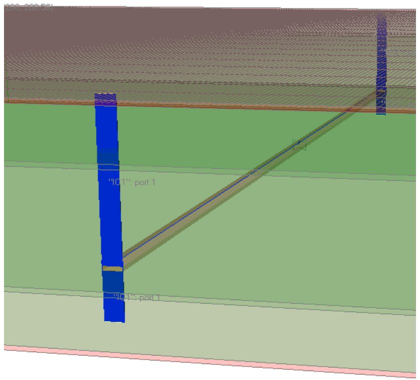
Fitting to the T With Simbeor

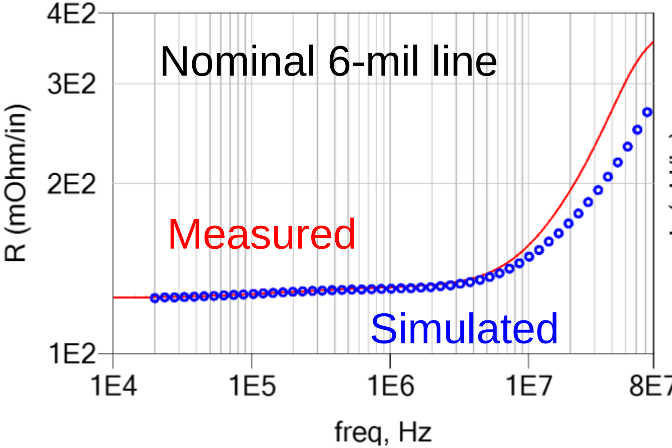
Param.	Vendor value	Input to Simbeor
Dk	4.3	4.3
Df	0.0165	0.0165
H1 (mil)	14.1	12.9
H2 (mil)	42.1	40.9
W (mil)	6	4.77
T (mil)	1.2	1.2
σ (S/m)	5.8e7	5.6e7

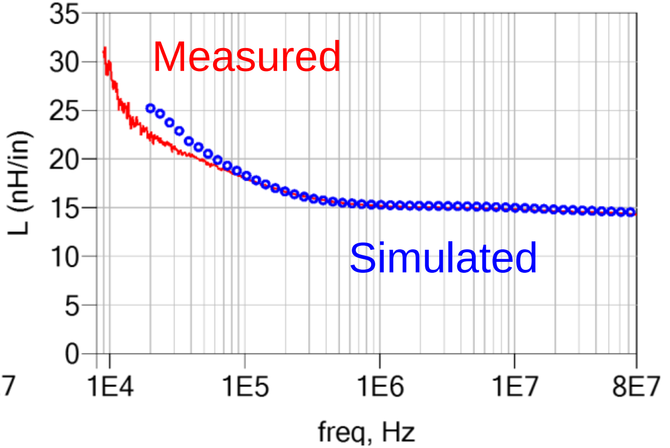
$$R_{\square} = 0.591\ \mathrm{m}\Omega/\square$$
$$\Delta w = -1.23\ \mathrm{mils}$$

$$\sigma = \frac{1}{R_{\square} t}$$



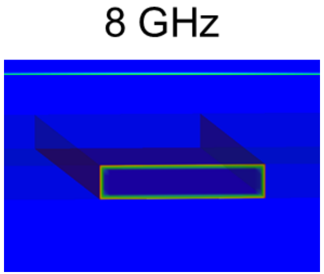


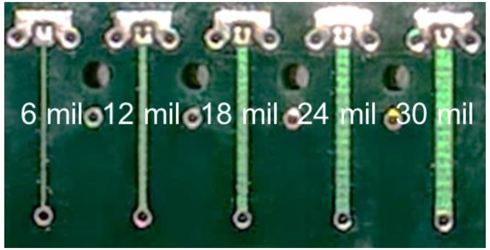


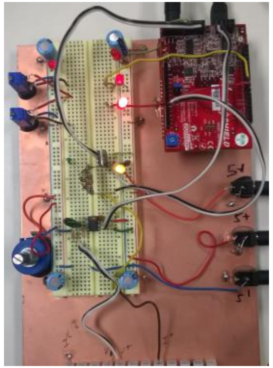


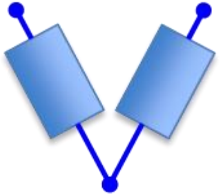
Summary

- Demonstrated skin depth and current distribution in a trace.
- Used 5x line technique to extract etch-back and sheet resistance.
- Built a low cost precision micro-Ohm meter for low level measurement.
- Used SET2DIL test pattern in designing test patterns.
- Performed 2-port technique for ultra-low resistance RF measurement.
- Achieved DC and RF resistance correlation within 3%.
- Illustrated the impact of probe length uncertainty.
- Introduced a new flexible negative length de-embedding technique.









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