Experimental Determination of the Importance of Inductance in Sub-Micron Microstrip Lines

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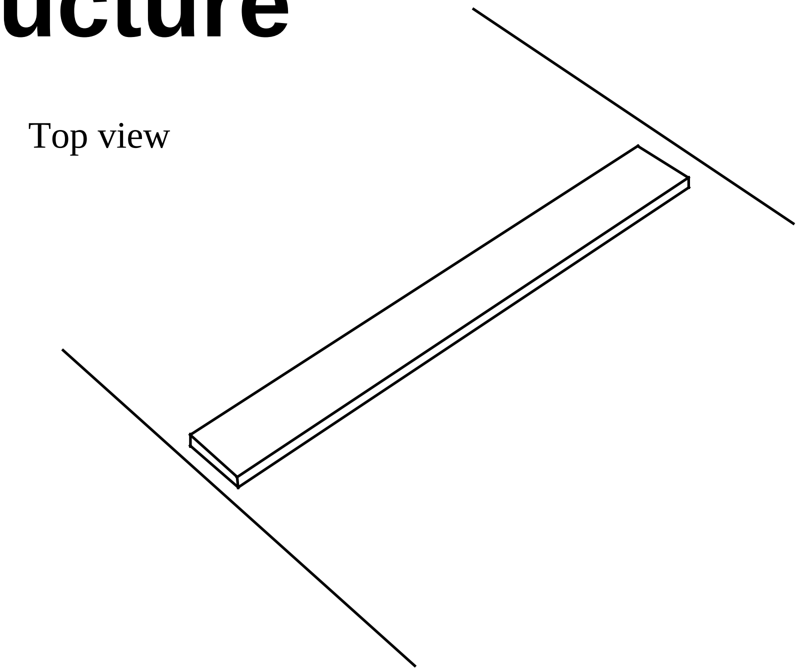
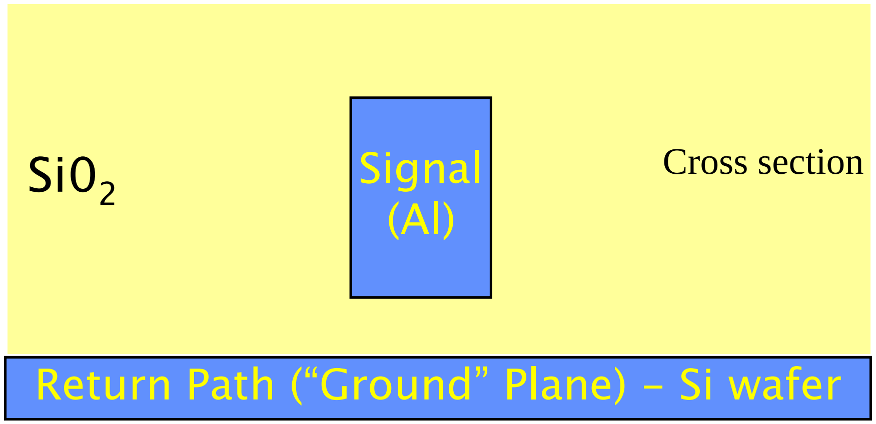
Impact of Inductance

- Delay
  - Affected by propagation constant
    - L affects β via series impedance term
    - Series term $R + j\omega L$
      - At low enough frequency, L does not matter
- Crosstalk
  - Signals propagating on one line produce signals on others
    - Mutual L important
    - Mutual C also important
- These experiments
  - Propagation on isolated lines
    - Attempt to assess relative importance of R and L
    - Measurements done in frequency domain

Test Structure

- **Microstrip**
  - **Distributed circuit**
  - **Isolated line**
- **Signal 0.7 μm thick Al**
- **3 widths**
  - **0.35 μm, 0.5 μm, 0.7 μm**
- **Lines 6400 μm long**
- **Embedded in SiO_2**
  - **Signal line 2.5 μm above ground**
- **Signal return via Si wafer**
- **Test structures fabricated by SEMATECH**
  - M. Steer and M. Harward, "Experimental Determination of On-Chip Interconnect Capacitances," SEMATECH, Technology Transfer 95072905A-XFR, August 31, 1995.
  - A. Karamcheti and R. Friar, "Final Report on TCAD Model/Validation for Interconnect Performance (Project ID: S85)," SEMATECH, 1998.





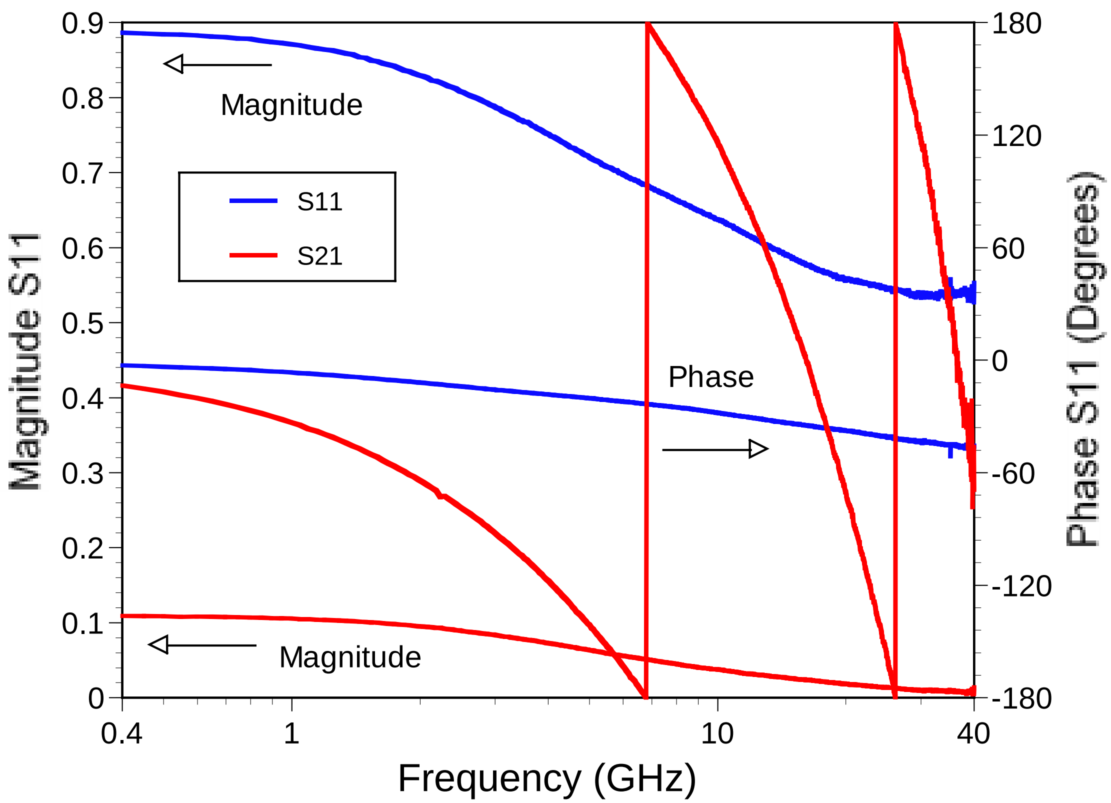
Measurements

- 2 port S-parameters measured
  - Travelling wave measurement
    - Reflection
    - Transmission
  - Convert for interpretation
  - HP 8510B Network Analyzer
    - Cascade wafer probes
    - SOLT (short, open, load, thru) calibration
      - Used impedance wafer
      - Probe pads not removed
- Frequency range 400 MHz - 40 GHz

S-Parameters: 0.5 μm Width Line

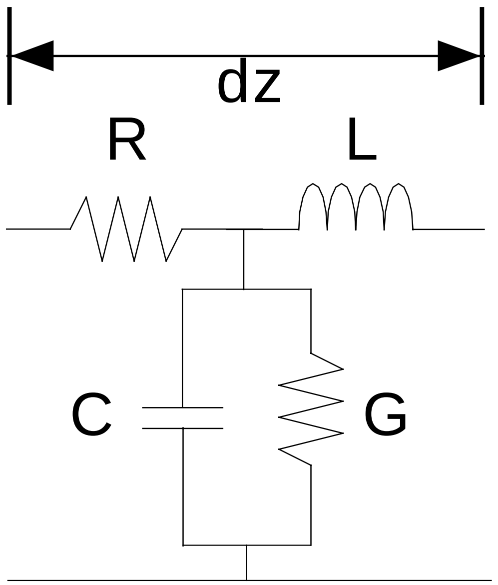
$$\gamma\ell = \mathrm{a}\cosh\left[\frac{-1}{2}\frac{S_{11}{}^2 - S_{21}{}^2 - 1}{S_{21}}\right]$$

$$Z_0 = \pm 50\sqrt{\frac{S_{11}{}^2 - S_{21}{}^2 + 1 + 2S_{11}}{S_{11}{}^2 - S_{21}{}^2 + 1 - 2S_{11}}}$$



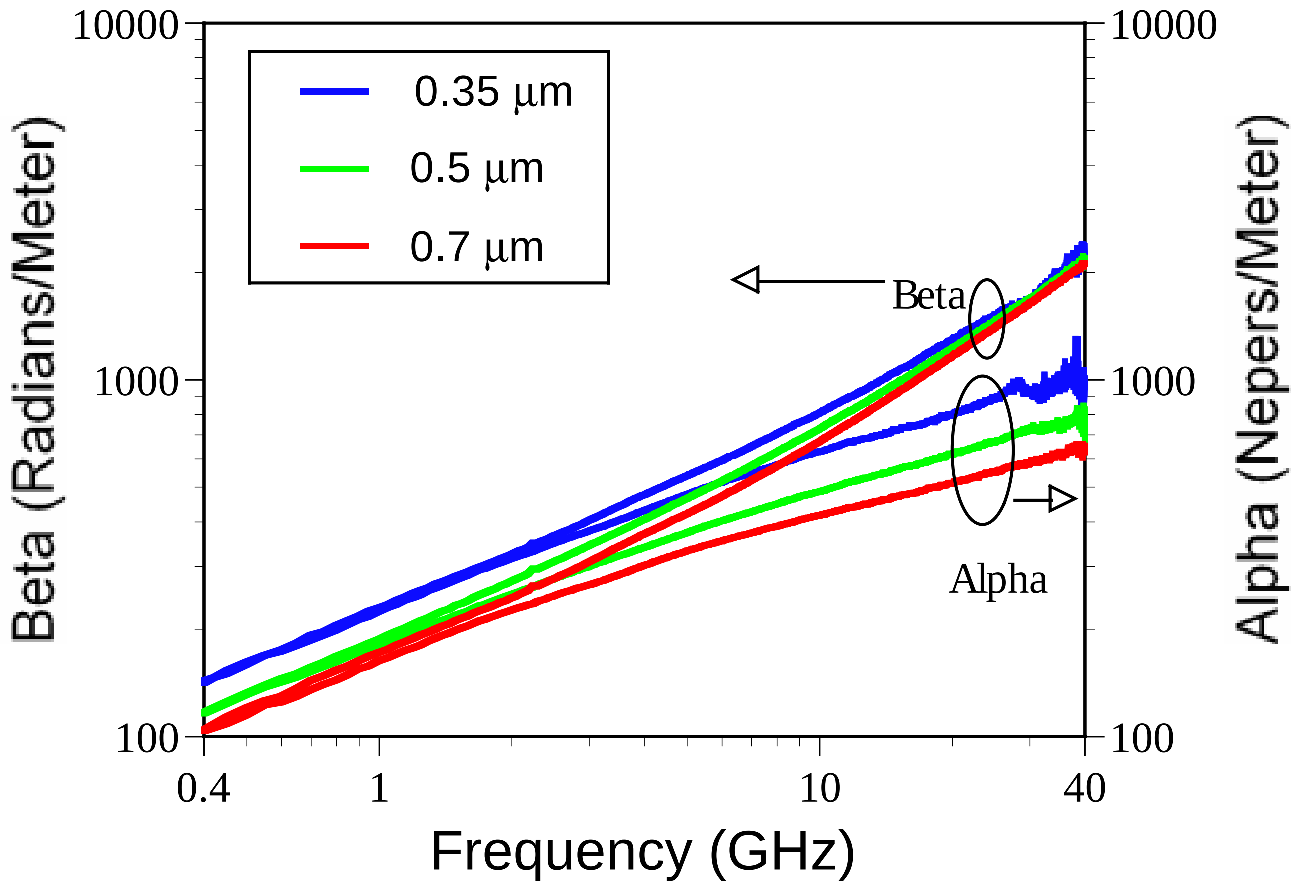
Transmission Lines

- **Characterized by 4 quantities**
  - α **attenuation constant**
  - β **phase constant**
  - Z_0 **characteristic impedance (real and imaginary)**
  - **All quantities may be functions of frequency**
- **Can be interpreted using distributed circuit model**
  - **Series R and L**
  - **Shunt C and G**

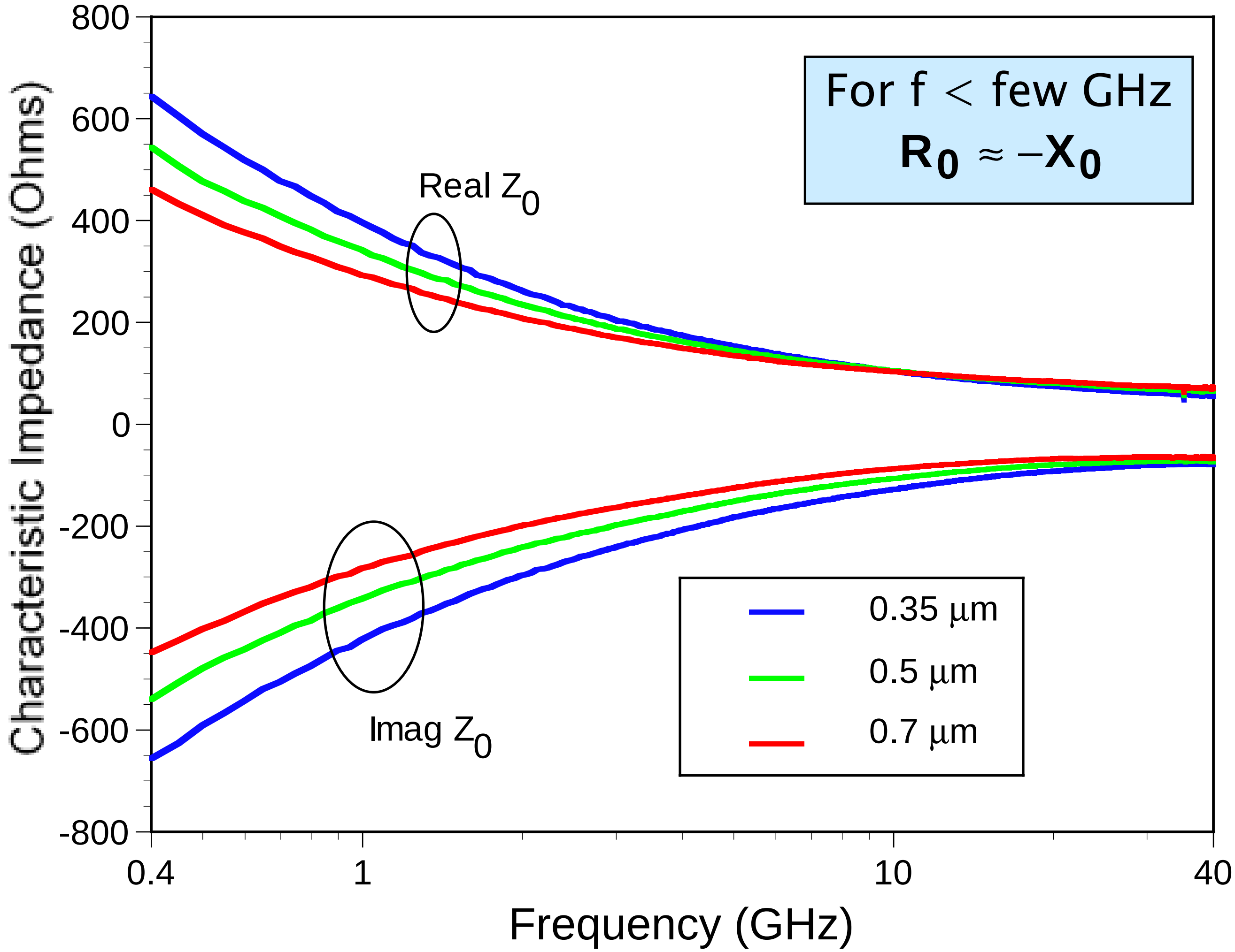


$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad Z_0 = R_0 + jX_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

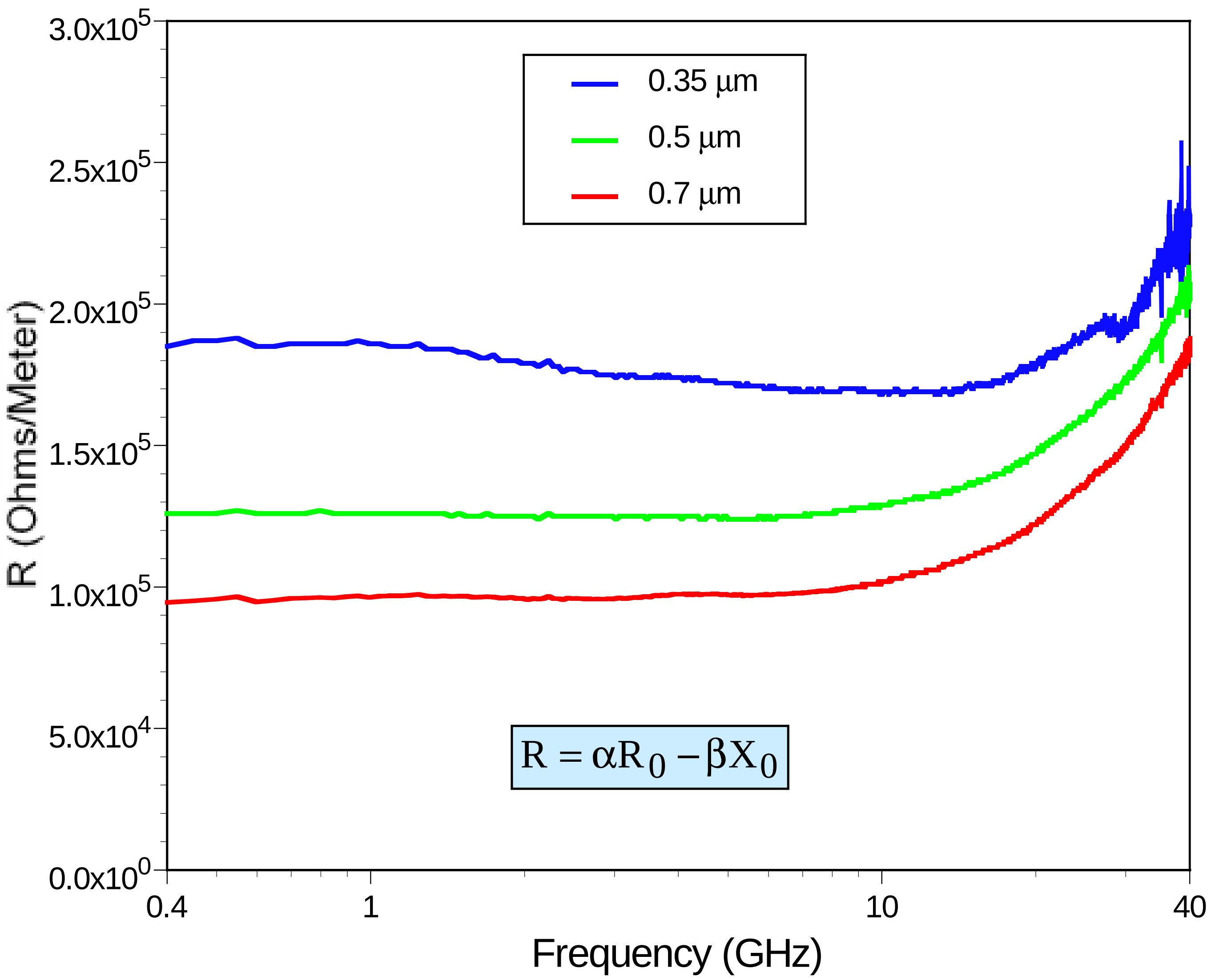
Beta and Alpha for Three Widths



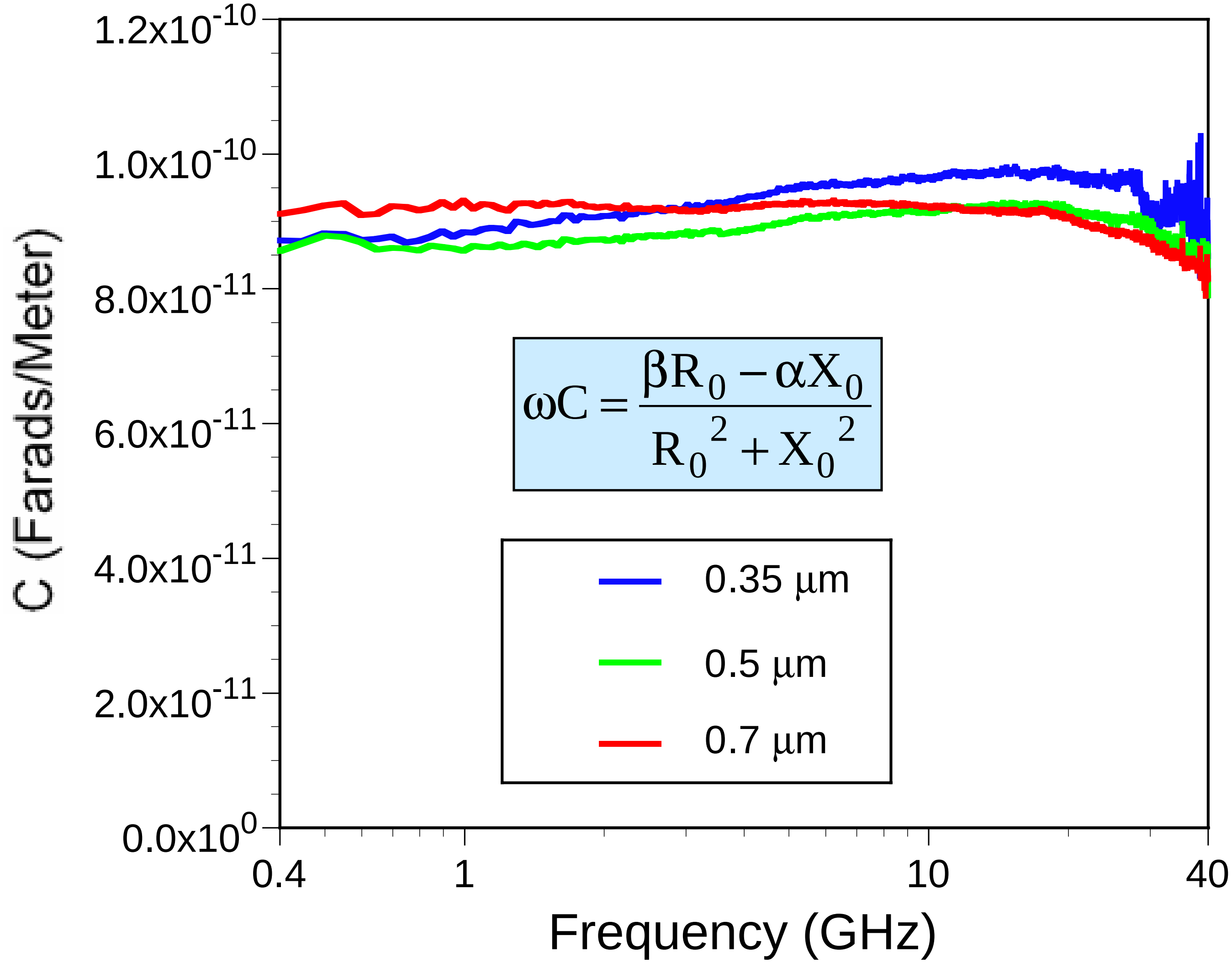
Z_0


For f < few GHz
$R_0 \approx -X_0$
Real Z_0
Imag Z_0
0.35 µm
0.5 µm
0.7 µm
Characteristic Impedance (Ohms)
800
600
400
200
0
-200
-400
-600
-800
0.4
1
10
40
Frequency (GHz)

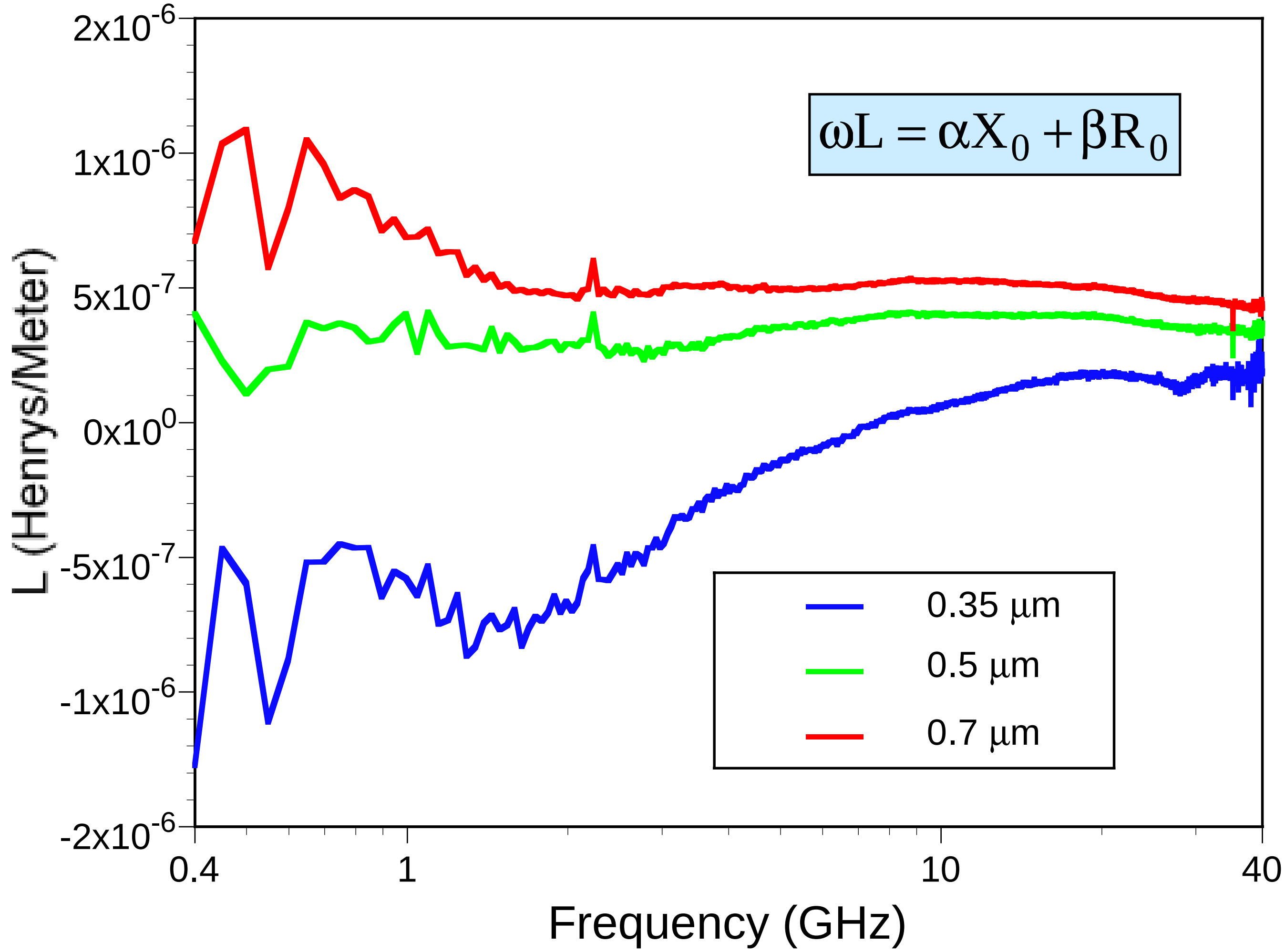
R Extracted


3.0x10^5
2.5x10^5
2.0x10^5
1.5x10^5
1.0x10^5
5.0x10^4
0.0x10^0
R (Ohms/Meter)
0.35 µm
0.5 µm
0.7 µm
$R = \alpha R_0 - \beta X_0$
0.4
1
10
40
Frequency (GHz)

C Extracted

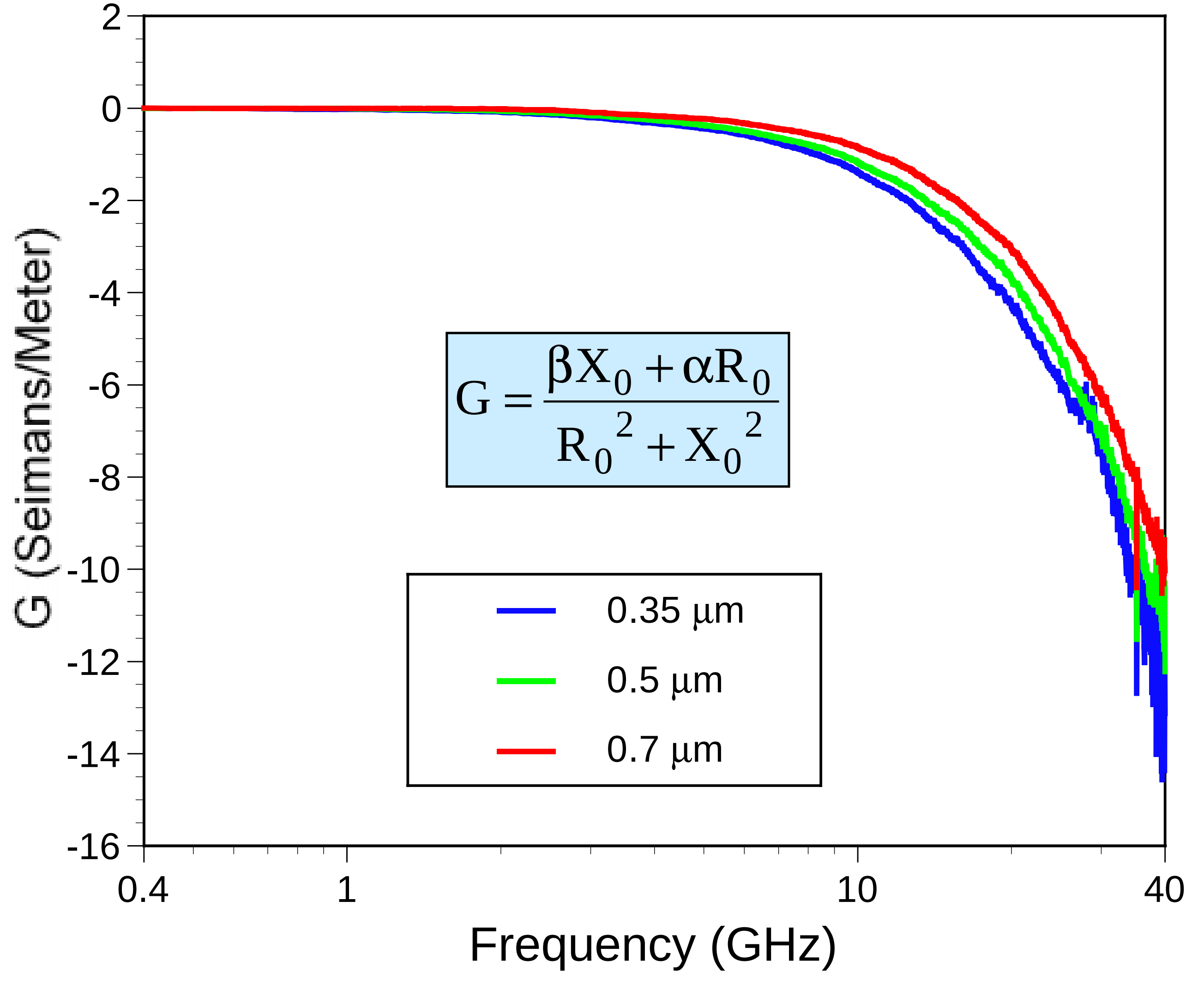

1.2x10^-10
1.0x10^-10
8.0x10^-11
6.0x10^-11
4.0x10^-11
2.0x10^-11
0.0x10^0
C (Farads/Meter)
0.4
1
10
40
Frequency (GHz)
$\omega C = \frac{\beta R_0 - \alpha X_0}{R_0^2 + X_0^2}$
0.35 µm
0.5 µm
0.7 µm

L Extracted

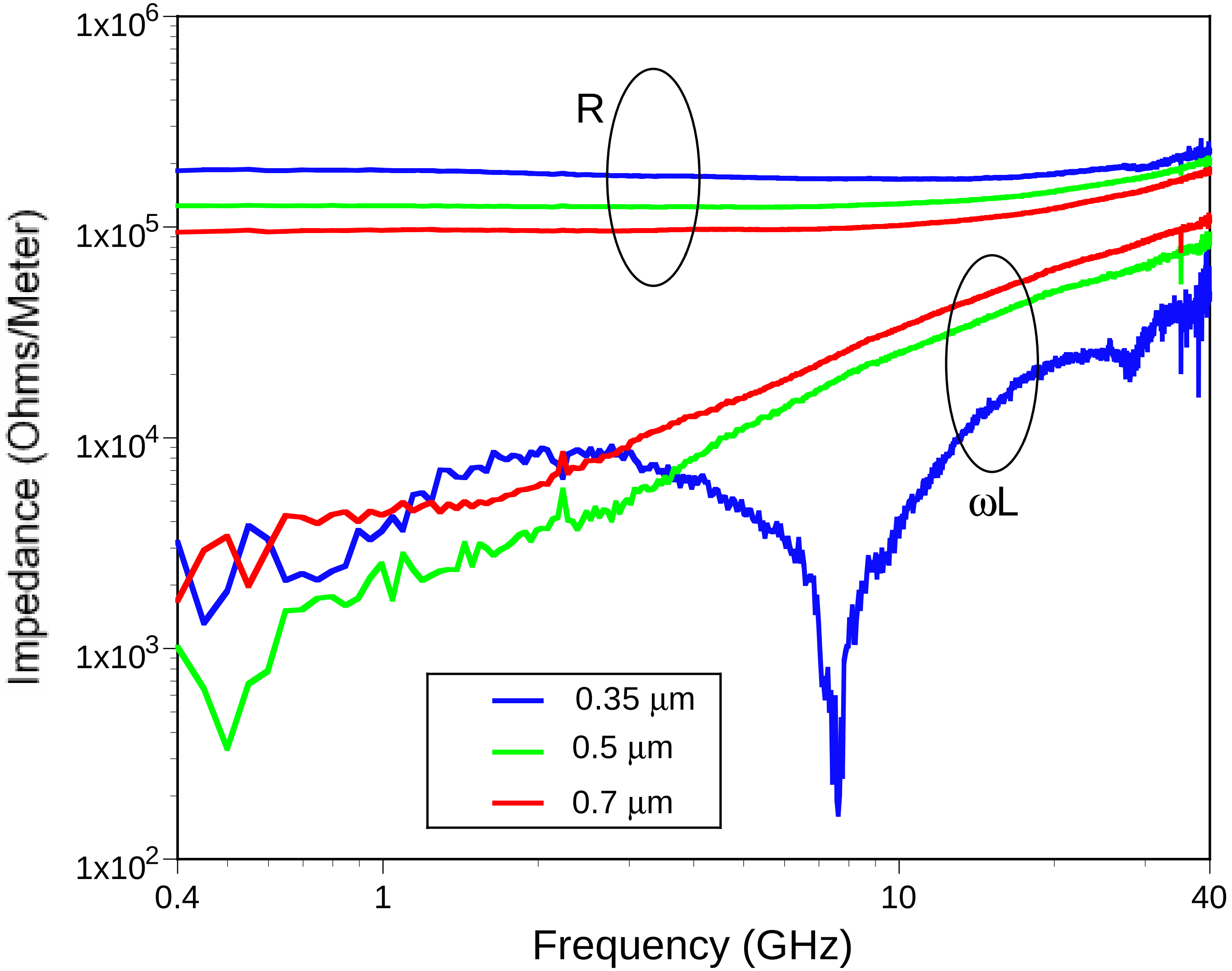


$\omega L = \alpha X_0 + \beta R_0$
2x10^-6
1x10^-6
5x10^-7
0x10^0
-5x10^-7
-1x10^-6
-2x10^-6
L (Henrys/Meter)
0.4
1
10
40
Frequency (GHz)
0.35 µm
0.5 µm
0.7 µm

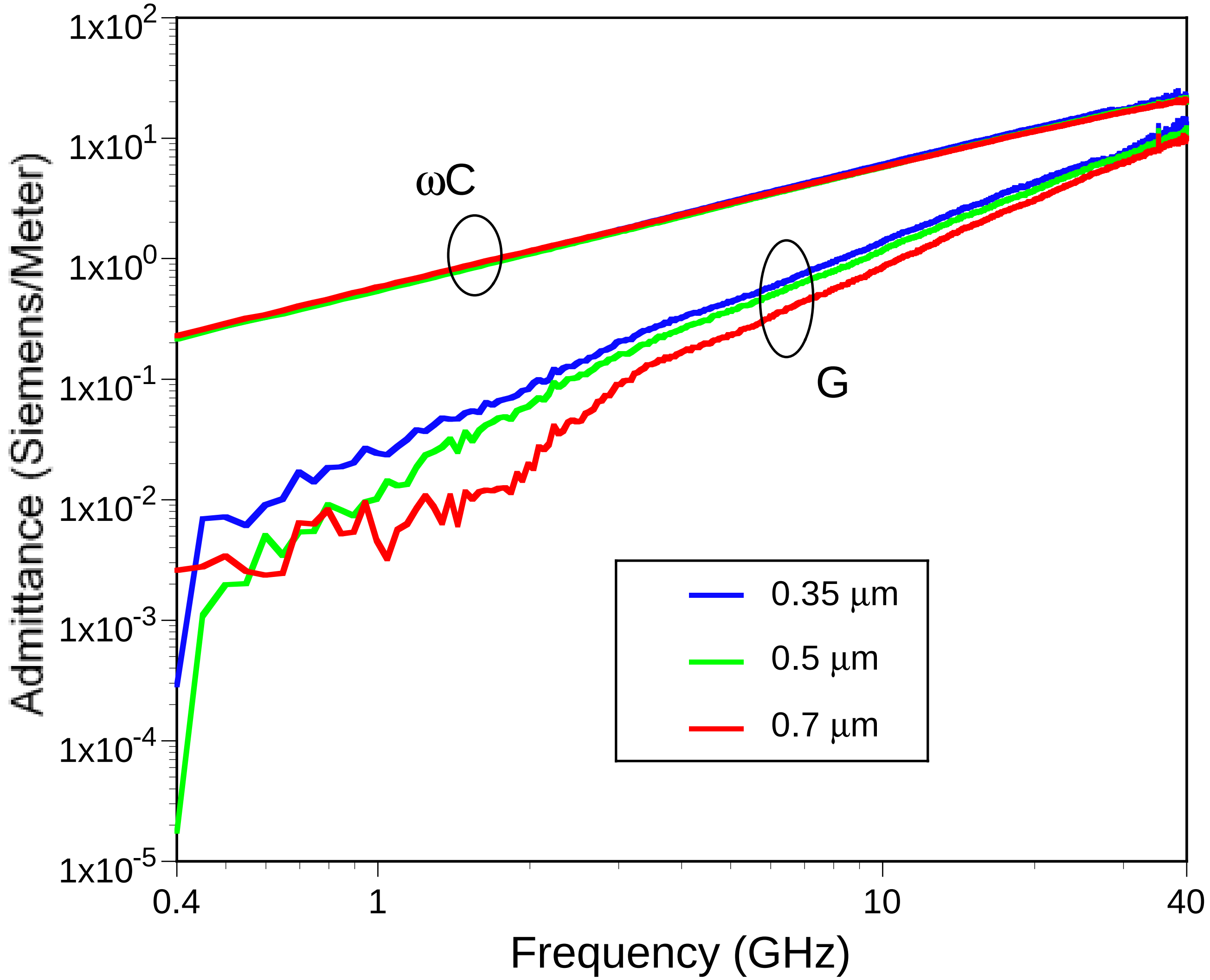
G Extracted


2
0
-2
-4
-6
-8
-10
-12
-14
-16
G (Seimans/Meter)
0.4
1
10
40
Frequency (GHz)
$G = \frac{\beta X_0 + \alpha R_0}{R_0^{\ 2} + X_0^{\ 2}}$
0.35 µm
0.5 µm
0.7 µm

R Vs. |ωL|


1x10^6
1x10^5
1x10^4
1x10^3
1x10^2
Impedance (Ohms/Meter)
R
ωL
0.35 μm
0.5 μm
0.7 μm
0.4
1
10
40
Frequency (GHz)

|G| Vs. ωC


1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
1x10^-5
Admittance (Siemens/Meter)
ωC
G
0.35 μm
0.5 μm
0.7 μm
0.4
1
10
40
Frequency (GHz)

Discussion

- Below 3 GHz data shows lines are RC dominated
  - $\alpha \approx \beta$
  - $R_0 \approx -X_0$
  - $R >> |\omega L|$
  - $\omega C >> |G|$
- Above 3 GHz
  - $R > |\omega L|$, but not order of magnitude greater
  - In tens of GHz, R and ωL comparable
  - RLC line
    - Never reaches LC limit
- Extraction of L limited by finite precision / accuracy of the measurements

Discussion

- Extracted C is within 10% for all three widths
  - High aspect ratio
    - Square at best
    - Not in parallel plate limit
  - Fringe fields important
- Extracted G
  - Negative (non-physical)
  - Increase rapidly above 10 GHz
  - Extraction of G limited by finite precision / accuracy of the measurements

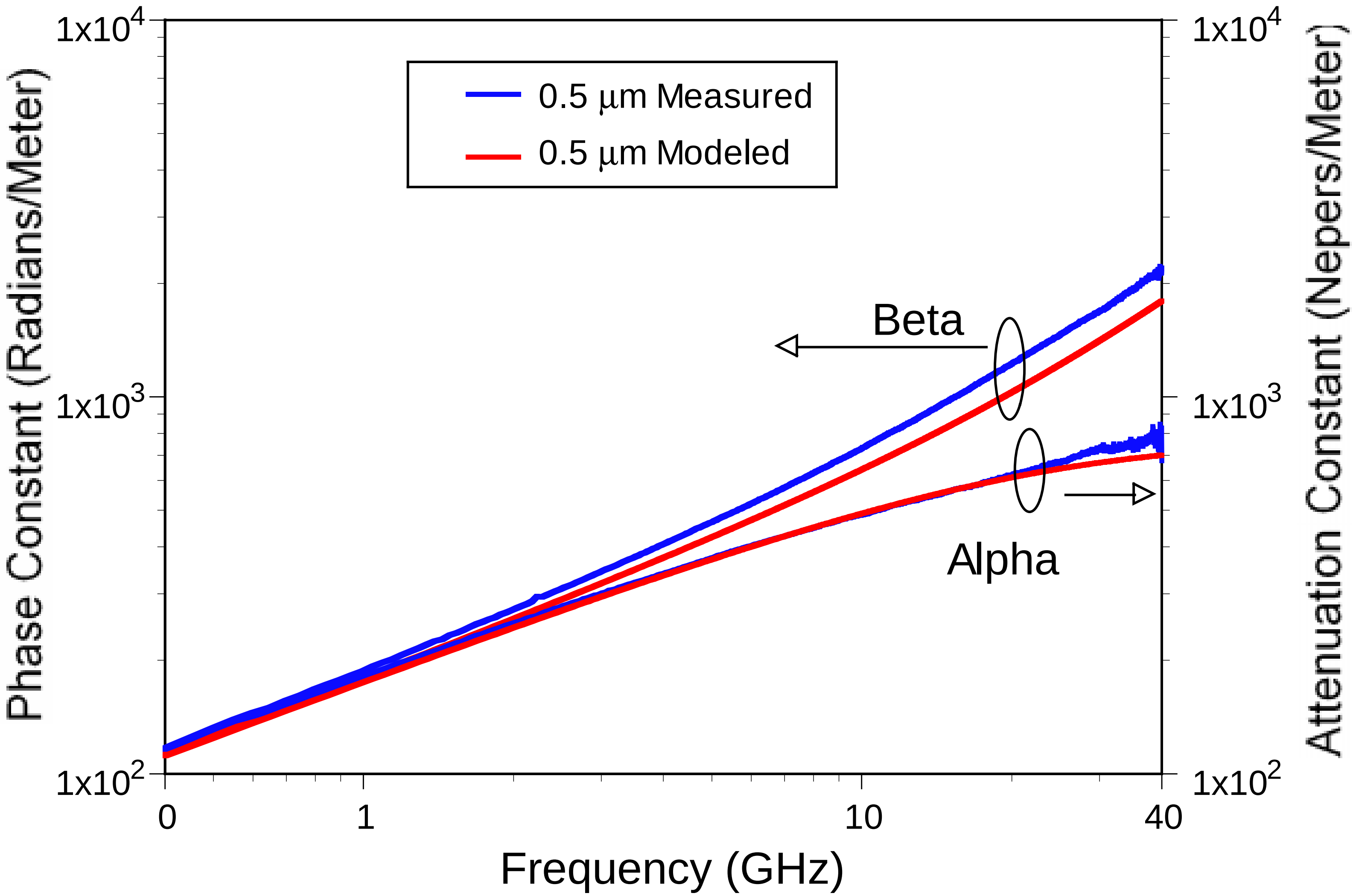
Wheeler Model

- Closed form model of microstrip
- 2-D Model
  - Allows “thick” conductor
  - No probe pads
- Assumes perfect ground plane
  - No substrate effects
- Allows calculation of L and C
- Does not include R
  - Use measured DC R
  - No skin effect

H. Wheeler, “Transmission-line properties of a strip on a dielectric sheet on a plane,” *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-25, pp. 631-647, 1977.

	DC R	Wheeler C	Wheeler L
0.35 μm	1192 Ω	478 fF	3.71 nH
0.5 μm	817 Ω	502 fF	3.54 nH
0.7 μm	593 Ω	531 fF	3.35 nH

Wheeler Example: 0.5 μm Case



Evaluation of Simple Model

- Fit using Wheeler L and C and measured DC R
- Alpha fits very well
  - R dominated
  - DC R measured
- Beta fits with some error
  - Exact dimensions and material parameters unknown
  - Trend still correct
- Simple quasi-static model predicts well
  - Skin effect not needed (and not expected)
  - Substrate effects not needed

Conclusions

- L not important to series impedance <3 GHz for line widths < 1 μm
- L comparable to R only in tens of GHz
  - Even though present not dominant
  - >40 GHz needed for LC behavior
- Wheeler with DC R predicts well
  - Model does not need substrate or skin effect
  - Simple quasi-static model works to 40 GHz
- To predict delay must get DC R and C right