

Copyright
by
Robert James Friar
2000

**Analysis, Design, and Measurement of On-Wafer Transmission Line
Test Structures**

by

Robert James Friar, B.S., M.S.E.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May 2000

**Analysis, Design, and Measurement of On-Wafer Transmission Line
Test Structures**

Approved by

Dissertation Committee:

To K.K., for patience, understanding, and love.

Acknowledgements

I wish to thank my supervising professor, Dean Neikirk, for his support and guidance. His technical insight and assistance was invaluable in completing this dissertation. I also wish acknowledge the members of my dissertation committee, Dr. Jack Lee, Dr. John Davis, and Dr. Mircea Driga of the ECE department and Dr. Bob Rogers of ARL for their assistance.

I also wish to recognize the support of the rest of Team Neikirk. The research conducted for this dissertation was funded by DARPA and SEMATECH. The author also wishes to thank Tod Courtney, Jim Hoffman, and David Gotthold for their advice and friendship. This thesis was edited by Kendra Kay Friar, the author's wife, and the author is grateful for this and all the other help she provided. This dissertation is dedicated to her and to James and Sue Friar, the author's parents.

Analysis, Design, and Measurement of On-Wafer Transmission Line Test Structures

Publication No. _____

Robert James Friar, Ph.D.
The University of Texas at Austin, 2000

Supervisor: Dean Neikirk

New dielectrics are being developed for integrated circuit applications, especially materials whose dielectric constant is less than that of silicon dioxide (i.e., so-called low-k dielectrics). The loss and relative dielectric constant of these materials needs to be characterized as a function frequency into the tens of GHz. It is desirable to characterize these materials in test structures with geometries that resemble integrated circuit interconnects.

This dissertation examines the effect of S-parameter measurement errors on the characterization of microstrip test structures. First, a perturbation technique is used to analyze the effect of S-parameter errors on the extraction of transmission line parameters; both magnitude and phase errors are considered. Next, derivative-based error propagation is used to design test structures that are minimally affected by the S-parameter errors. Finally, data from on-wafer microstrip test structures are compared to results from both the perturbation and derivative techniques.

The results of this study indicate that geometry significantly affects the transmission line parameter extraction error. The method presented designs test structures that minimize the extraction error for a set of geometrical and material constraints.

Table of Contents

List of Tables.....	ix
List of Figures	x
1. Introduction	1
Dielectric Constant	1
Loss Tangent	1
Measurement Error	2
Dissertation Overview	4
2. Transmission Lines	5
Introduction	5
Propagation Constant and Characteristic Impedance	5
RLCG	6
Loss Tangent	7
Measuring Transmission Lines	7
Impedance Spectroscopy	8
Network Analysis	10
Summary	13
3. Transmission Line Perturbation Analysis	14
Introduction	14
Methodology	15
Choice of Model	16
Types of Errors	18
Round-off Error	20
Length Offset Errors	31
Magnitude Limits	42
Magnitude Dependent Error	51
All Errors	58
Geometrical Considerations	63
Loss Tangent	72
Discussion	75
4. Test Structure Design Using Error Propagation.....	77
Introduction	77
Error Propagation	77
LC Example.....	78
Simulation Technique	81
Design Methodology	82
Design for R	83
Design for L	88
Design for C	93
Design for G	97

Summary of Design for R, L, C, and G.....	102
Width as a Design Variable.....	103
Design for R	104
Design for L	109
The Half Wavelength Resonance	114
Design for C	117
Design for G	122
Width Summary	126
Discussion	127
Pure Resistance Example	135
Design Goals	140
5. Measurement	142
Introduction	142
Extracted RLCG Data	142
Probe Pads and Pad Capacitance.....	147
Comparison of Perturbation Simulation Results and Actual Measurements	155
Predicting Error Bounds on Actual Structures	164
Discussion	170
6. Conclusions and Future Work	173
Analysis	173
Design.....	174
Measurement	175
Future Work	175
Bibliography	177
VITA	182

List of Tables

Table 3.1: Magnitude dependent error.	20
Table 4.1: Minimum errors in R at 1 GHz and 10 GHz and associated lengths for three cross-sections. The error is normalized to the correct value of per unit length R.	84
Table 4.2: Minimum errors in L at 1 GHz and 10 GHz and associated lengths for three cross-sections. The error is normalized to the correct value of per unit length L.	89
Table 4.3: Minimum errors in C at 1 GHz and 10 GHz and associated lengths for three cross-sections. The error is normalized to the correct value of per unit length C.	93
Table 4.4: Minimum errors in G at 1 GHz and 10 GHz and associated lengths for three cross-sections. The error is normalized to the correct value of per unit length G.	98
Table 4.5: Minimum errors in R, L, C, and G at 1 GHz and 10 GHz and associated lengths for three cross-sections. The error is normalized to the correct parameter value.	102
Table 4.6: Minimum errors in R at 1 GHz and 10 GHz and associated lengths and widths for three cross-sections. The error is normalized to the correct value of per unit length R.	105
Table 4.7: Minimum errors in L at 1 GHz and 10 GHz and associated lengths and widths for three cross-sections. The error is normalized to the correct value of per unit length L.	110
Table 4.8: Width and length for minimum error structures in L at 39.81 GHz and 40.74 GHz for the 1 μm thickness.....	114
Table 4.9: Minimum errors in C at 1 GHz and 10 GHz and associated lengths and widths for three cross-sections. The error is normalized to the correct value of per unit length C.	118
Table 4.10: Minimum errors in G at 1 GHz and 10 GHz and associated lengths and widths for three cross-sections. The error is normalized to the correct value of per unit length G.....	123
Table 4.11: Minimum errors in R, L, C, and G at 1 GHz and 10 GHz and associated lengths for two thicknesses. The error is normalized to the correct parameter value.	127

List of Figures

Figure 2.1: Circuit diagram of an infinitesimal length of transmission line.	7
Figure 2.2: Circuit diagram of a lumped circuit equivalent for an electrically short, RC transmission line.	9
Figure 2.3: Block representation of a 2-port network.	10
Figure 3.1: Cross-section of an embedded microstrip transmission line	14
Figure 3.2: Phase of S_{11} with and without 0.1° round-off; $0.3\ \mu\text{m}$ cross-sectional geometry, 1 mm long, 10^{-2} loss tangent, and no other sources of error.	21
Figure 3.3: Phase of S_{21} with and without 0.1° round-off; $0.3\ \mu\text{m}$ cross-sectional geometry, 1 mm long, 10^{-2} loss tangent, and no other sources of error.	22
Figure 3.4: Extracted R per unit length for two phase round-off limits; $0.3\ \mu\text{m}$ cross- sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	23
Figure 3.5: Extracted R per unit length for three lengths; 0.1° round-off, $0.3\ \mu\text{m}$ cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.....	24
Figure 3.6: Extracted L per unit length for two phase round-off limits; $0.3\ \mu\text{m}$ cross- sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	25
Figure 3.7: Extracted L per unit length for three lengths; 0.1° round-off, $0.3\ \mu\text{m}$ cross- sectional geometry, 10^{-2} loss tangent, and no other sources of error.	25
Figure 3.8: Extracted C per unit length for two phase round-off limits; $0.3\ \mu\text{m}$ cross- sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	26
Figure 3.9: Extracted C per unit length for three lengths; 0.1° round-off, $0.3\ \mu\text{m}$ cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.....	27
Figure 3.10: Extracted G per unit length for two phase round-off limits; $0.3\ \mu\text{m}$ cross- sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	28
Figure 3.11: Extracted G per unit length for three lengths; 0.1° round-off, $0.3\ \mu\text{m}$ cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.....	28
Figure 3.12: Extracted loss tangent per unit length for two phase round-off limits; $0.3\ \mu\text{m}$ cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	30
Figure 3.13: Extracted loss tangent per unit length for three lengths; 0.1° round-off, $0.3\ \mu\text{m}$ cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	30
Figure 3.14: Phase of S_{11} with and without a $100\ \mu\text{m}$ length offset. $0.3\ \mu\text{m}$ cross- sectional geometry, 1 mm long, 10^{-2} loss tangent, and no other sources of error.	32

Figure 3.15: Phase of S_{21} with and without a 100 μm length offset. 0.3 μm cross-sectional geometry, 1 mm long, 10^{-2} loss tangent, and no other sources of error.	32
Figure 3.16: Extracted R per unit length for two length offsets; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	33
Figure 3.17: Extracted R per unit length for three lengths; 100 μm length offset, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	34
Figure 3.18: Extracted L per unit length for two length offsets; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	35
Figure 3.19: Extracted L per unit length for three lengths; 100 μm length offset, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	36
Figure 3.20: Extracted C per unit length for two length offsets; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	37
Figure 3.21: Extracted C per unit length for three lengths; 100 μm length offset, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	37
Figure 3.22: Extracted G per unit length for two length offsets; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	39
Figure 3.23: Extracted G per unit length for three lengths; 100 μm length offset, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	39
Figure 3.24: Extracted loss tangent per unit length for two length offsets; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	41
Figure 3.25: Extracted loss tangent per unit length for three lengths; 100 μm length offset, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	41
Figure 3.26: Magnitude (dB) of S_{11} with and without a -80 dB magnitude limit. 0.3 μm cross-sectional geometry, 5.5 mm long, 10^{-2} loss tangent, and no other sources of error.	43
Figure 3.27: Magnitude (dB) of S_{21} with and without a -80 dB magnitude limit. 0.3 μm cross-sectional geometry, 5.5 mm long, 10^{-2} loss tangent, and no other sources of error.	43
Figure 3.28: Extracted R per unit length for two magnitude limits; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	44
Figure 3.29: Extracted R per unit length for two lengths; -60 dB magnitude limit, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	45
Figure 3.30: Extracted L per unit length for two magnitude limits; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	46
Figure 3.31: Extracted L per unit length for two lengths; -60 dB magnitude limit, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	46

Figure 3.32: Extracted C per unit length for two magnitude limits; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	47
Figure 3.33: Extracted C per unit length for two lengths; -60 dB magnitude limit, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error. .	48
Figure 3.34: Extracted G per unit length for two magnitude limits; 0.3 μm cross-sectional geometry, 5.5 mm length, no other error sources. Actual loss tangent used was 10^{-2}	49
Figure 3.35: Extracted G per unit length for two lengths; -60 dB magnitude limit, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error. .	49
Figure 3.36: Extracted loss tangent per unit length for two magnitude limits; 0.3 μm cross-sectional geometry, 5.5 mm length, 10^{-2} loss tangent, and no other sources of error.	50
Figure 3.37: Extracted loss tangent per unit length for two lengths; -60 dB magnitude limit, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	51
Figure 3.38: Magnitude (dB) of S_{11} with and without a magnitude dependent error. 0.3 μm cross-sectional geometry, 5.5 mm long, 10^{-2} loss tangent, and no other sources of error.	52
Figure 3.39: Magnitude (dB) of S_{21} with and without a magnitude dependent error. 0.3 μm cross-sectional geometry, 5.5 mm long, 10^{-2} loss tangent, and no other sources of error.	53
Figure 3.40: Extracted R per unit length for three lengths; 0.3 μm cross-sectional geometry, magnitude dependent error, 10^{-2} loss tangent, and no other sources of error.	54
Figure 3.41: Extracted L per unit length for two lengths; magnitude dependent error, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	55
Figure 3.42: Extracted L per unit length for 10 mm length; magnitude dependent error, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	55
Figure 3.43: Extracted C per unit length for three lengths; magnitude dependent error, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	56
Figure 3.44: Extracted G per unit length for three lengths; magnitude dependent error, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	57
Figure 3.45: Extracted loss tangent per unit length for three lengths; magnitude dependent error, 0.3 μm cross-sectional geometry, 10^{-2} loss tangent, and no other sources of error.	58

Figure 3.46: Extracted R per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	60
Figure 3.47: Extracted L per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	61
Figure 3.48: Extracted C per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	61
Figure 3.49: Extracted G per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	62
Figure 3.50: Extracted loss tangent per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	62
Figure 3.51: Extracted R per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 10 ⁻² loss tangent.	65
Figure 3.52: Extracted L per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 10 ⁻² loss tangent.	65
Figure 3.53: Extracted C per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 10 ⁻² loss tangent.	66
Figure 3.54: Extracted G per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 10 ⁻² loss tangent.	66
Figure 3.55: Extracted loss tangent per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 10 ⁻² loss tangent.	67
Figure 3.56: Extracted R per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 3.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	68
Figure 3.57: Extracted L per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 3.3 μm cross-sectional geometry and 10 ⁻² loss tangent.	70

Figure 3.58: Extracted C per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 3.3 μm cross-sectional geometry and 10^{-2} loss tangent.	70
Figure 3.59: Extracted G per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 3.3 μm cross-sectional geometry and 10^{-2} loss tangent.	71
Figure 3.60: Extracted loss tangent per unit length for three lengths; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 3.3 μm cross-sectional geometry and 10^{-2} loss tangent.	71
Figure 3.61: Extracted loss tangent per unit length for two loss tangents; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 0.3 μm cross-sectional geometry and 3.2 mm long.	73
Figure 3.62: Extracted loss tangent per unit length for two loss tangents; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit, and magnitude dependent error; 1 μm cross-sectional geometry and 3.2 mm long.	74
Figure 3.63: Extracted loss tangent per unit length for two loss tangents; 0.1° phase round-off, 100 μm length offset, -60 dB magnitude limit and magnitude dependent error; 3.3 μm cross-sectional geometry and 3.2 mm long.	74
Figure 4.1: Minimum normalized error in R for three different cross-sectional geometries.	86
Figure 4.2: Length of line that produces the minimum normalized error in R for three different cross-sectional geometries.	86
Figure 4.3: Normalized error in R for the 0.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	87
Figure 4.4: Normalized error in R for the 1 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	87
Figure 4.5: Normalized error in R for the 3.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	88
Figure 4.6: Minimum normalized error in L for three different cross-sectional geometries.	90
Figure 4.7: Length of line that produces the minimum normalized error in L for three different cross-sectional geometries.	91
Figure 4.8: Normalized error in L for the 0.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	91
Figure 4.9: Normalized error in L for the 1 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	92

Figure 4.10: Normalized error in L for the 3.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	92
Figure 4.11: Minimum normalized error in C for three different cross-sectional geometries.	95
Figure 4.12: Length of line that produces the minimum normalized error in C for three different cross-sectional geometries.	95
Figure 4.13: Normalized error in C for the 0.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	96
Figure 4.14: Normalized error in C for the 1 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	96
Figure 4.15: Normalized error in C for the 3.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	97
Figure 4.16: Minimum normalized error in G for three different cross-sectional geometries.	99
Figure 4.17: Length of line that produces minimum normalized error in G for three different cross-sectional geometries.	100
Figure 4.18: Normalized error in G for the 0.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	100
Figure 4.19: Normalized error in G for the 1 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	101
Figure 4.20: Normalized error in G for the 3.3 μm cross-sectional geometry and two lengths. Lengths used produce the minimum normalized error at 1 GHz and 10 GHz.	101
Figure 4.21: Minimum normalized error in R for two different metal thicknesses. .	106
Figure 4.22: Width that produces the minimum normalized error in R for two different metal thicknesses.	107
Figure 4.23: Length that produces the minimum normalized error in R for two different metal thicknesses.	107
Figure 4.24: Normalized error in R for the 0.3 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	108
Figure 4.25: Normalized error in R for the 1 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	108
Figure 4.26: Minimum normalized error in L for two different metal thicknesses. .	111

Figure 4.27: Width that produces the minimum normalized error in L for two different metal thicknesses.	112
Figure 4.28: Length that produces the minimum normalized error in L for two different metal thicknesses.	112
Figure 4.29: Normalized error in L for the 0.3 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	113
Figure 4.30: Normalized error in L for the 1 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	113
Figure 4.31: Normalized error in L for the 1 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 39.81 GHz and 40.74 GHz.	116
Figure 4.32: Comparison of the 40.74 GHz normalized error and the guided wavelength normalized by twice the line length.	116
Figure 4.33: Normalized error in L for both the derivative and perturbation methods. Structure used was the 40.74 GHz design structure.	117
Figure 4.34: Minimum normalized error in C for two different metal thicknesses. .	119
Figure 4.35: Width that produces the minimum normalized error in C for two different metal thicknesses.	120
Figure 4.36: Length that produces the minimum normalized error in C for two different metal thicknesses.	120
Figure 4.37: Normalized error in C for the 0.3 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	121
Figure 4.38: Normalized error in C for the 1 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	121
Figure 4.39: Minimum normalized error in G for two different metal thicknesses. .	124
Figure 4.40: Width that produces the minimum normalized error in G for two different metal thicknesses.	124
Figure 4.41: Length that produces the minimum normalized error in G for two different metal thicknesses.	125
Figure 4.42: Normalized error in G for the 0.3 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	125
Figure 4.43: Normalized error in G for the 1 μm thickness and two length and width pairs. Length and width pairs used produce the minimum normalized error at 1 GHz and 10 GHz.	126
Figure 4.44: Characteristic impedance for minimum normalized error in R.	129
Figure 4.45: Characteristic impedance for minimum normalized error in L.	129
Figure 4.46: Characteristic impedance for minimum normalized error in C.	130

Figure 4.47: Characteristic impedance for minimum normalized error in G.....	130
Figure 4.48: $R/\omega L$ for minimum normalized error in R.....	132
Figure 4.49: $R/\omega L$ for minimum normalized error in L.....	133
Figure 4.50: $R/\omega L$ for minimum normalized error in C.....	133
Figure 4.51: Optimum length for R for the 0.3 μm thickness. Length is normalized to the guided wavelength, λ_g	134
Figure 4.52: A lumped element RC ladder representation of a transmission line....	134
Figure 4.53: Total resistance and reactance for optimum R for the 0.3 μm thickness.	135
Figure 4.54: Single lumped element transmission line model for the zero phase case.	135
Figure 4.55: Single lumped element transmission line model and network analyzer circuit.....	136
Figure 4.56: Total resistance and reactance for optimum R for the 0.3 μm thickness. The magnitude error delta is constant, and the phase error delta is zero.	139
Figure 4.57: Width and Length that produce minimum error in R with no phase error. The thickness is 0.3 μm	140
Figure 5.1: Extracted R per unit length for three widths.....	145
Figure 5.2: Extracted L per unit length for three widths.....	145
Figure 5.3: Extracted C per unit length for three widths.....	146
Figure 5.4: Extracted G per unit length for three widths.....	146
Figure 5.5: Top-view of a three-tip microwave probe (not to scale). Drawing based on a Cascade Microtech probe.	147
Figure 5.6: Top-view of three probe pads for a microstrip transmission line test structure. SEM courtesy of SEMATECH [40].....	148
Figure 5.7: Network under test, including probe pads.	149
Figure 5.8: Comparison of extracted R for -175 μm length offset and 3 fF pad capacitance.	151
Figure 5.9: Comparison of extracted L for -175 μm length offset and 3 fF pad capacitance.	151
Figure 5.10: Comparison of extracted C for -175 μm length offset and 3 fF pad capacitance.	152
Figure 5.11: Comparison of extracted G for -175 μm length offset and 3 fF pad capacitance.	152
Figure 5.12: Comparison of extracted R for a 0.1° phase round-off, -175 μm length offset, -60 dB magnitude limit, magnitude dependent error, and 3 fF pad capacitance.	153
Figure 5.13: Comparison of extracted L for a 0.1° phase round-off, -175 μm length offset, -60 dB magnitude limit, magnitude dependent error, and 3 fF pad capacitance.	154

Figure 5.14: Comparison of extracted C for a 0.1° phase round-off, $-175\ \mu\text{m}$ length offset, $-60\ \text{dB}$ magnitude limit, magnitude dependent error, and $3\ \text{fF}$ pad capacitance.	154
Figure 5.15: Comparison of extracted G for a 0.1° phase round-off, $-175\ \mu\text{m}$ length offset, $-60\ \text{dB}$ magnitude limit, magnitude dependent error, and $3\ \text{fF}$ pad capacitance.	155
Figure 5.16: Extracted R for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $1200\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $50\ \text{fF}$ pad capacitance.	160
Figure 5.17: Extracted L for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $400\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $10\ \text{fF}$ pad capacitance.	160
Figure 5.18: Extracted C for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $550\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $20\ \text{fF}$ pad capacitance.	161
Figure 5.19: Extracted G for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $400\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $35\ \text{fF}$ pad capacitance.	161
Figure 5.20: Extracted R for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $475\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $20\ \text{fF}$ pad capacitance.	162
Figure 5.21: Extracted L for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $475\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $20\ \text{fF}$ pad capacitance.	162
Figure 5.22: Extracted C for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $475\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $20\ \text{fF}$ pad capacitance.	163
Figure 5.23: Extracted G for measurement and perturbation simulation. The errors are a 0.1° phase round-off, a $475\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, a magnitude dependent error, and a $20\ \text{fF}$ pad capacitance.	163
Figure 5.24: Normalized error in R for the $0.7\ \mu\text{m}$ ($0.8\ \mu\text{m}$) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a $100\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, and a magnitude dependent error.	166
Figure 5.25: Normalized error in L for the $0.7\ \mu\text{m}$ ($0.8\ \mu\text{m}$) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a $100\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, and a magnitude dependent error.	167
Figure 5.26: Normalized error in C for the $0.7\ \mu\text{m}$ ($0.8\ \mu\text{m}$) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a $100\ \mu\text{m}$ length offset, a $-60\ \text{dB}$ magnitude limit, and a magnitude dependent error.	167

- Figure 5.27: Normalized error in G for the 0.7 μm (0.8 μm) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a 100 μm length offset, a -60 dB magnitude limit, and a magnitude dependent error. 168
- Figure 5.28: Normalized error in R for the 0.5 μm (0.6 μm) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a 100 μm length offset, a -60 dB magnitude limit, and a magnitude dependent error. 168
- Figure 5.29: Normalized error in L for the 0.5 μm (0.6 μm) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a 100 μm length offset, a -60 dB magnitude limit, and a magnitude dependent error. 169
- Figure 5.30: Normalized error in C for the 0.5 μm (0.6 μm) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a 100 μm length offset, a -60 dB magnitude limit, and a magnitude dependent error. 169
- Figure 5.31: Normalized error in G for the 0.5 μm (0.6 μm) width for measurement and derivative simulation. The errors are a 0.1° phase round-off, a 100 μm length offset, a -60 dB magnitude limit, and a magnitude dependent error. 170