Table of contents

List of Symbols **xv**

List of Figures **xix**

List of Tables **xxix**

1 Introduction **1**

1.1 Fiber-Optic Communications 1

1.2 Modulator Performance Criteria 5

1.2.1 Electrical Bandwidth 7

1.2.2 Optical Loss 8

1.2.3 Switching Voltage 9

1.2.4 Optical Bandwidth 9

1.2.5 Chirp 10

1.2.6 Extinction Ratio and Other Eye Measurements . . 10

1.3 Optical Phase Modulation 11

1.4 The Mach-Zehnder Modulator 11

1.5 Nested MZMs 14

1.6 Material Systems 14

1.6.1 Inorganic crystals 15

1.6.2 Polymers 17
1.6.3 Semiconductors 17
1.7 Comparison of the Material Technologies 19
1.8 Thesis Outline 23

2 The Mach-Zehnder Modulator Model 25
2.1 Mathematical Model 25
2.2 Driving Schemes 28
2.3 MZM with Linear Phase Shifter 29
2.4 MZM with Non-Linear Phase Shifter 33
2.5 Quantification of the Chirp 35
2.6 IQ MZM 36

3 Silicon MZMs 41
3.1 Si Waveguide Technology 41
3.2 Modulation Effects in Si 44
3.2.1 Electro-Optic Effect 44
3.2.2 Thermo-Optic Effect 44
3.2.3 Plasma Dispersion Effect 44
3.3 Si Phase Shifters 50
3.3.1 Carrier Injection-Based 50
3.3.2 Carrier Depletion-Based 52
3.3.3 Carrier Accumulation-Based 55
3.4 Performance Comparison of Si MZMs 57

4 Performance Limits of Depletion-Type Phase Shifters 59
4.1 Phase Shifter Geometries 60
4.2 Simulation Technique 62
4.3 Characteristic Curves 65
4.4 Comparison of the Non-linearity 70
4.5 MZM Loss Analysis 74
4.6 Comparison of the RC 76

5 Traveling-Wave Electrode Analysis 79
5.1 Need for the TWE Design . . . 79
5.2 Transmission Line Types . . . 80
5.3 Transmission Line Simulation . . . 82
5.4 Transmission Line Design Issues . . . 84
5.4.1 Impedance Matching . . . 84
5.4.2 Velocity Matching . . . 86
5.4.3 Microwave Loss . . . 88
5.5 Fabricated Device Description . . . 90
5.6 Experimental Bandwidth Dependencies . . . 93
5.7 Simulation Assumptions . . . 95
5.8 Bandwidth Dependence on the V_{bias} . . . 96
5.9 Bandwidth Dependence on the V_{π} . . . 99
5.10 Loss Trade-off . . . 101
5.11 Phase Shifter Optimization Figure . . . 103
5.11.1 Qualitative Discussion . . . 103
5.11.2 Comparison of the Optimization Figure . . . 103
5.12 Co-Simulation Technique . . . 106
5.12.1 Motivation . . . 106
5.12.2 MZM Implementation . . . 107
5.12.3 Time-Domain Response . . . 109

6 Segmented MZMs Integrated in Photonic BiCMOS 113
6.1 Monolithic Integration in Photonic BiCMOS . . . 114
6.2 Linear Segmented MZM . . . 115
6.2.1 Device Description . . . 115
6.2.2 Measurement Setup . . . 119
6.2.3 Measurement Results . . . 122
6.2.4 Comparison of Integrated Si OOK Transmitters . . . 125
6.3 Segmented MZM with Integrated DAC . . . 129
6.3.1 Device Description . . . 130
6.3.2 Measurement Results . . . 131
6.3.3 Comparison of Si Transmitters with DAC . . . 132

Conclusions **134**

Publications **138**

Bibliography **143**