

# Contents

<b>Contents</b>	<b>V</b>
<b>List of Figures</b>	<b>VIII</b>
<b>List of Tables</b>	<b>XIII</b>
<b>List of Publications</b>	<b>XV</b>
<b>ABSTRACT</b>	<b>XIX</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background	1
1.2 Motivation	3
1.2.1 oDPSK and oQPSK Transmission	3
1.2.2 High-Speed Integrated Circuits for xPSK Transmission	4
1.3 Organization of Thesis	5
<b>2 oDPSK Transmission System</b>	<b>7</b>
2.1 oDPSK signal generation	8
2.1.1 Differential Encoding and Decoding	8
2.1.2 Optical Phase Modulation	11
2.1.3 40 Gbit/s (CS)RZ-DPSK transmitter	16
2.1.4 Experimental Results	21
2.2 oDPSK signal detection	21
2.2.1 Mach-Zehnder Interferometer Modelling	22
2.2.2 40 Gbit/s RZ-DPSK receiver	23
2.2.3 Measurement results	25
2.3 Signed On Line Chromatic Dispersion Detection	27
2.3.1 Chromatic Dispersion in Single Mode Fibers	27
2.3.2 Measurement Setup for Chromatic Dispersion Detection	28
2.3.3 Experimental results	29
2.4 Chromatic Dispersion Compensation	31
2.4.1 Adaptive Tunable CD Compensation	33

2.5	Conclusion	38
<b>3</b>	<b>oDPSK Transmission System</b>	<b>39</b>
3.1	Introduction to oDPSK	39
3.2	oDPSK signal generation	41
3.2.1	DQPSK Precoding	41
3.2.2	Optical Encoder	42
3.2.3	40 Gbaud DQPSK Transmitter	47
3.3	oDPSK signal detection	48
3.3.1	DQPSK Decoding	48
3.3.2	40 Gbaud DQPSK Receiver	49
3.4	2×40 Gbit/s DQPSK Transmission Experiment	49
3.4.1	Transmission setup	49
3.4.2	Measurement Results and Discussion	50
3.5	RZ-DQPSK Polarization Multiplex Transmission	53
3.5.1	Transmission Setup	53
3.5.2	Transmission Results	55
3.6	Conclusion	58
<b>4</b>	<b>High-Speed Integrated Circuits for oDPSK Transmission</b>	<b>59</b>
4.1	Differential Amplifier for 10 and 40 Gbit/s CS(RZ)-DPSK system	59
4.2	Differential Distributed Amplifier	60
4.2.1	Distributed Amplification	61
4.2.2	Circuit Design	63
4.2.3	Result Discussion	68
4.3	10 Gbit/s CMOS Differential Amplifier	68
4.3.1	Design of Transmission Line Structures	69
4.3.2	Circuit Design	74
4.3.3	Result Discussion	77
4.4	Conclusion	77
<b>5</b>	<b>Result Discussion and Future Scope</b>	<b>79</b>
5.1	DPSK Transmission	79
5.2	DQPSK Transmission	80
5.3	High-Speed Integrated Circuit for oDPSK Transmission	81
5.4	Conclusion	82
<b>A</b>	<b>Definitions</b>	<b>83</b>
A.1	Bit Error Rate	83
A.2	Receiver sensitivity	84
A.3	Optical signal-to-noise ratio	84
<b>B</b>	<b>Theory of the Traveling Wave Amplifier</b>	<b>87</b>

<b>C Extraction of Transmission Line Parameters</b>	<b>93</b>
<b>References</b>	<b>96</b>
<b>Acknowledgements</b>	<b>107</b>

# List of Figures

1.1	Traffic Growth Trends . . . . .	2
2.1	Schematic diagram of a differentially encoded (left) and decoded (right) bit	9
2.2	Proposal for regular differential encoding/decoding scheme with realizable feedback delays . . . . .	9
2.3	Simplified differential encoding/decoding scheme . . . . .	10
2.4	Realized scheme . . . . .	10
2.5	Principle of optical PSK signal modulation a) data signal b) carrier c) PSK signal . . . . .	11
2.6	Lithium Niobate-based Phase Modulator . . . . .	12
2.7	Waveguide based travelling-wave phase modulator using x- or z-cut LiNbO <sub>3</sub> materials . . . . .	13
2.8	X-cut Lithium Niobate-based Mach-Zehnder modulator . . . . .	14
2.9	Three different structures for Mach-Zehnder modulator using x- or z-cut LiNbO <sub>3</sub> . . . . .	15
2.10	Chromatic dispersion tolerance of DPSK using either a Mach-Zehnder modulator or a phase modulator at the data rate of 40 Gbit/s and chromatic dispersion of 0, 34, and 68 ps/nm . . . . .	16
2.11	40 Gbit/s CSRZ-DPSK transmitter . . . . .	17
2.12	Photograph of the data buffer board . . . . .	17
2.13	DPSK Transmitter using the MZMs . . . . .	19
2.14	DPSK signal generation . . . . .	20
2.15	a)Transmission characteristic of MZM b)Optical intensity generated signals	20
2.16	DSPK optical receiver . . . . .	21
2.17	Simplified Interferometer model with delay T and retardation R in the lower branch . . . . .	22
2.18	Block diagram of the lock-in amplifier's scheme . . . . .	25
2.19	Optical spectrum at the constructive port (left) and destructive port(right)	25
2.20	BER vs. power at optical preamplifier input for different CS-RZ DPSK modulation format . . . . .	26
2.21	40 Gbit/s eye diagrams back-to-back for NRZ-DPSK (left) and (CS)RZ-DPSK (right) . . . . .	26

2.22	Total dispersion $D$ and relative contributions of material dispersion $D_m$ and waveguide dispersion $D_w$ for a conventional single mode fiber . . . . .	28
2.23	Experimental 40 Gbit/s CSRZ-DPSK setup for chromatic dispersion detection . . . . .	29
2.24	Chromatic dispersion detection readout vs. actual dispersion. Inset: eye diagram resulting from interferometer output signal difference . . . . .	30
2.25	Standard deviation versus measurement interval, at zero actual dispersion . . . . .	30
2.26	CSRZ-DPSK eye diagrams at interferometer outputs (top), and difference signal (bottom) back to back (left) after transmission over the 91km (right) . . . . .	31
2.27	Illustration of a uniform grating with constant amplitude of refractive index modulation and grating period . . . . .	32
2.28	Principle of FBG CD compensator with circulator . . . . .	33
2.29	CDC Setup for 40 Gbit/s DPSK transmission . . . . .	34
2.30	Photograph of the TeraXion thermally tunable dispersion compensator . . . . .	35
2.31	Group delay versus wavelength in tunable CD compensator for dispersion settings . . . . .	35
2.32	OSNR needed for BER = $10^{-9}$ versus compensator CD . . . . .	36
2.33	BER versus OSNR. The OSNR is varied by an attenuator. . . . .	37
2.34	40 Gbit/s eye diagrams back-to-back (top) and after 263 km transmission (bottom), for NRZ-DPSK and CSRZ-DPSK (from left to right) . . . . .	37
3.1	DQPSK Constellations . . . . .	40
3.2	Schematic representation of Optical DQPSK signalling . . . . .	41
3.3	DQPSK signal generation using two Mach-Zehnder modulators . . . . .	43
3.4	DQPSK signal generation using Mach-Zehnder and phase modulator . . . . .	43
3.5	Single dual-drive MZM for DQPSK signal generation . . . . .	44
3.6	Procedure to find $\varphi_{i1}$ and $\varphi_{i2}$ for $s_i = r_i e^{j\theta_i}$ . . . . .	46
3.7	DQPSK signal generation using a dual-drive Mach-Zehnder modulator and interferometer . . . . .	46
3.8	$2 \times 40$ Gbit/s DQPSK Transmitter . . . . .	47
3.9	40 Gbaud intensity eye diagrams of NRZ-DQPSK (left) and CS(RZ)DQPSK signals (right) . . . . .	48
3.10	DQPSK Decoder . . . . .	48
3.11	$2 \times 40$ Gbit/s RZ-DQPSK transmission setup . . . . .	50
3.12	Measured BERs vs. optical preamplifier input power for RZ-DPSK, RZ-DQPSK, RZ-ASK . . . . .	51
3.13	$2 \times 40$ Gbit/s RZ-DQPSK I and Q eye diagrams back-to-back (top) and after 263 km of fiber (middle). Bottom diagram is back-to-back with wrong interferometer phase . . . . .	52
3.14	$4 \times 40$ Gbit/s per channel RZ-DQPSK PoIDM transmission . . . . .	53
3.15	Electrical interference spectra measured in the 12 GHz photoreceiver after the polarizer . . . . .	55

3.16	Back-to-back receiver sensitivity for both in-phase and quadrature data channels for one polarization. Optical power is given for aggregate 160 Gbit/s signal . . . . .	55
3.17	Back-to-back performance of $4 \times 40$ Gbit/s system . . . . .	56
3.18	Eye diagrams in one polarization, (top) back-to-back in I channel, Q channel and (bottom) after 230 km in I and Q channel . . . . .	56
3.19	Optical spectrum after 229 km of fiber . . . . .	57
3.20	Measured Q factors for I and Q data channels in both polarizations back-to-back for 8 WDM channels, and after transmission over 230 km fiber for the CD-compensated 192.5 THz channel . . . . .	57
4.1	Typical 40 Gbit/s CS(RZ)-DPSK balanced optical front end . . . . .	60
4.2	Simulated DC characteristics of the HEMT fabricated in OMMIC D01PH process . . . . .	61
4.3	Basic configuration of the travelling wave amplifier . . . . .	62
4.4	Typical schematic of the cascode amplifier . . . . .	64
4.5	Schematic of the differential pre-amplifier (left) and simulated magnitude of $S_{21}$ and CMRR (right) . . . . .	64
4.6	Schematic of a traveling wave amplifier using cascode as the main amplifying stage . . . . .	65
4.7	Stability factors $k$ and $\mu$ (left) and output reflection coefficient $S_{22}$ (right) . . . . .	65
4.8	Phases on the gate and drain line . . . . .	66
4.9	Layout details of the cascode cell . . . . .	66
4.10	Optimization of forward transmission as a function of number of stages $N$ (left) and group delay (right) . . . . .	67
4.11	Simulated eye diagram for $50\text{ mV}_{pp}$ input voltage . . . . .	67
4.12	Layout of the differential distributed amplifier at 40 Gbit/s . . . . .	67
4.13	Cross-section of the $0.18\ \mu\text{m}$ CMOS process (left) and n-MOS transconductance as a function of the gate-source voltage (right) . . . . .	69
4.14	Geometry of the microstripline in CMOS (left) and its characteristic impedance as function of the conductor width (right) . . . . .	70
4.15	Geometry of coplanar waveguide . . . . .	70
4.16	Characteristic impedance of the coplanar waveguide in function of the ratio $W/(W + 2G)$ (left) and conductor width (right) . . . . .	71
4.17	Measured attenuation for $50\ \Omega$ CPW versus width of signal line . . . . .	71
4.18	SL configuration (left) and characteristic impedance of the SL in function of the conductor width (right) . . . . .	72
4.19	Microphotograph of the fabricated MS, CPW and SL (from left to right) . . . . .	72
4.20	Comparison of measured MS, CPW and SL data for the magnitude $S_{21}$ and $S_{11}$ . . . . .	73
4.21	Comparison of measured, simulated and modelled MS data for the magnitude $S_{21}$ (top-left), phase $S_{21}$ (top-right) and magnitude $S_{11}$ (bottom) . . . . .	73

4.22	Comparison of measured, simulated and modelled CPW data for the magnitude $S_{21}$ (top-left), phase $S_{21}$ (top-right) and magnitude $S_{11}$ (bottom) . . .	74
4.23	Comparison of measured, simulated and modelled SL data for the magnitude $S_{21}$ (top-left), phase $S_{21}$ (top-right) and magnitude $S_{11}$ (bottom) . . . .	74
4.24	Schematic of the differential amplifier using striplines in CMOS . . . . .	75
4.25	Microphotograph of the realized chip . . . . .	75
4.26	Comparison of measured, simulated single phase and simulated differential magnitude of $S_{21}$ . . . . .	76
4.27	Comparison of measured, simulated single phase and simulated differential magnitude of $S_{11}$ . . . . .	76
4.28	Measured eye diagram at 10 Gbit/s for $2^7 - 1$ PRBS input signal . . . . .	77
B.1	Lumped transmission line with shunt loss . . . . .	87
B.2	One section of the drain line . . . . .	89
B.3	One section of the gate line . . . . .	89
B.4	Signal path from the input to the output via the 'k'-th transistor . . . . .	91
C.1	Single transmission line represented by a two-port network and described with distributed transmission line parameters R, L, C and $G \rightarrow 0$ . . . . .	93

# List of Tables

1.1	The frequencies of the optical carriers and the propagation losses in single mode optical fiber in the three most popular optical bands . . . . .	1
1.2	Optical carrier rates . . . . .	2
2.1	Selected long-haul 40 Gb/s DPSK transmission experiments . . . . .	7
2.2	The bit stream to be transmitted and bit stream generated for DPSK transmission . . . . .	8
3.1	Phase states for DQPSK signal . . . . .	40
3.2	Selected DQPSK transmission experiments with higher spectral efficiencies	41
4.1	Distributed circuit parameters for interconnect test structures . . . . .	73