

Contents

1	Optical Networks	1
D.B. Payne		
1.1	Introduction	1
1.2	Background to Optical Communications Networks	4
1.2.1	Optical Fibre Transmission Systems	4
1.2.2	Fibre Attenuation	5
1.2.3	Fibre Dispersion	6
1.2.4	Non-linear Effects in Optical Fibre	8
1.2.5	A Simple Point-to-point Fibre Link	12
1.2.6	Receiver Sensitivity	13
1.2.7	Coherent Optical Systems	15
1.3	Why Optical Networks?	19
1.3.1	Physical Limits	19
1.3.2	Commercial Considerations	21
1.3.3	Service and Bandwidth Growth	24
1.4	Financial Barriers to All-optical Networking	27
1.4.1	Network Bandwidth Growth	27
1.4.2	Bandwidth Growth vs. Revenue Growth	29
1.4.3	Implications for Bandwidth Price Decline	30
1.5	Impact on Network Architecture	32
1.5.1	Options for Optical Networks	33
1.5.2	Long-reach Access	41
1.5.3	Metro Network	44
1.5.4	Core Networks	46
1.6	Summary – Future Evolution of Optical Networking	50
References		52
2	Optical Fibers	55
P. Nouchi, P. Sillard and D. Molin		
2.1	Introduction	55
2.2	Fiber Basics	56

2.2.1	Principle of Light Propagation in Optical Fibers	56
2.2.2	Modal Theory of Light Propagation in Optical Fibers . . .	57
2.2.3	Fiber Fabrication	60
2.2.4	Fiber Loss	61
2.2.5	Fiber Dispersion	62
2.3	Multimode Fibers	63
2.3.1	Key Characteristics	64
2.3.2	Different Types of Multimode Fibers	67
2.3.3	Standardization	70
2.4	Single-mode Fibers	71
2.4.1	Key Characteristics	71
2.4.2	Standardization	73
2.4.3	Fiber Types	77
2.5	Optical Fiber Cables	83
2.5.1	Basic Elements of a Cable	83
2.5.2	Cable Environment and Cable Types	86
2.6	New Developments	87
2.6.1	Microstructured Optical Fibers	87
2.6.2	Bragg Fibers	89
2.6.3	Fibers Mixing Glass and Semiconductors	89
2.6.4	Multicore and Multimode Fibers	90
	References	91
3	Laser Components	99
	M. Moehrle, W. Hofmann and N. Grote	
3.1	Introduction	99
3.2	Materials for “Long-wavelength” Laser Diodes	100
3.3	Laser Diode Structures	102
3.3.1	Layer Structure	102
3.3.2	Lateral Structure	103
3.4	Active Medium	105
3.4.1	Quantum-well Layers	105
3.4.2	Strained QWs	107
3.4.3	Quantum Dots	109
3.5	Fabry-Pérot Lasers	110
3.6	Single-mode Laser Diodes	113
3.6.1	Distributed Feedback Lasers	114
3.6.2	Advanced Single-mode Laser Structures	121
3.7	Surface-emitting Laser Diodes	125
3.7.1	Vertical-cavity Surface-emitting Laser	125
3.7.2	Horizontal Cavity Surface-emitting Laser Concepts . . .	132
3.8	Concluding Remarks	134
	References	134

4 Ultrafast Semiconductor Laser Sources	139
M. Aoki	
4.1 Introduction	139
4.2 Ultrafast Directly Modulated Laser Sources	141
4.2.1 High-speed Characteristics of Directly Modulated Lasers	141
4.2.2 Large-signal Dynamic Analysis of Rate Equations	144
4.2.3 Chirp Characteristics of Directly Modulated Lasers	145
4.2.4 High-gain Active Materials for Ultrafast Uncooled Lasers	146
4.2.5 Short-cavity Ultrafast Lasers	151
4.3 Ultrafast, Low-chirp Externally Modulated Laser Sources	157
4.3.1 High-speed Characteristics of Externally Modulated Lasers	158
4.3.2 Chirp Characteristics of Externally Modulated Lasers	160
4.3.3 Facet-reflection Induced Chirp in Externally Modulated Lasers	161
4.3.4 Transmission Simulation of Externally Modulated Lasers Considering Facet-reflection Induced Chirp	163
4.3.5 Effect of Photogenerated Current on Modulation Characteristics	168
4.3.6 Packaged High-speed Externally Modulated Lasers	171
4.3.7 Uncooled, High-speed, Low-chirp Externally Modulated Lasers	172
4.4 New Challenges for Ultrafast Semiconductor Light Sources	175
4.4.1 High-speed Active/Passive Feedback Diode Lasers	175
4.4.2 EA/DFB Laser Devices with Traveling-wave Modulator	177
4.4.3 Directly IC-driven High-speed Modulators	180
References	181
5 Widely Tunable Laser Diodes	189
H. Debrégeas-Sillard	
5.1 Basics of Current Injection Tuning, DBR Lasers	191
5.1.1 Current Injection Tuning Mechanisms	191
5.1.2 DBR Lasers: Principle of Operation	195
5.2 Widely Tunable Lasers by Current Injection	200
5.2.1 Sampled Gratings	200
5.2.2 SG-DBR Lasers	202
5.2.3 SSG-DBR Lasers	204
5.2.4 Y-Lasers	205
5.2.5 Multiple Peak Grating and Tunable Wide Filter Lasers (GCSR, DS-DBR)	205
5.2.6 DBR-MMI	207
5.3 Control Issues	208
5.3.1 Control Algorithms	208
5.3.2 Influence of Cavity Length and Nonlinear Effects	210
5.3.3 Fast Tuning	213

5.4	Other Wavelength Tunable>Selectable Lasers	213
5.4.1	Thermally Tuned DFB Array	214
5.4.2	Tunable Vertical Cavity Surface Emitting Lasers	214
5.4.3	External Cavity Tunable Lasers	216
5.4.4	Tunable Lasers with Ring Resonators	218
5.5	Subsystems and Tunable Photonic Integrated Circuits	219
5.5.1	Tunable Laser Integrated with Modulator	220
5.5.2	Tunable Subsystems	221
5.6	Conclusion	222
	References	224
6	Semiconductor-based Modulators	227
	H. Yasaka and Y. Shibata	
6.1	Overview of the Methods to Generate a Digital Optical Signal	228
6.1.1	Direct Modulation of Semiconductor Lasers	229
6.1.2	Electroabsorption Modulators (EAMs)	231
6.1.3	Mach-Zehnder Interferometer (MZI) Modulators	233
6.2	Semiconductor-based MZI Modulators	239
6.2.1	Fundamentals/Refractive Index Control of Semiconductor Materials	239
6.2.2	GaAs- and InP-based MZI Modulators	245
6.3	High-speed Modulator Design	246
6.4	Performance of Current MZI Modulators	251
6.4.1	n-i-n Structure MZI Modulators	251
6.4.2	Advanced MZI Modulator Modules	258
6.5	High Performance Modulators for Advanced Modulation Formats	262
6.5.1	Optical Duobinary (ODB) Modulation	263
6.5.2	Optical DPSK Modulation	266
6.5.3	Semiconductor Optical DQPSK Modulators	269
6.5.4	Semiconductor Multilevel Modulators	273
6.6	Summary and Future Issues	273
	References	273
7	Photodetectors	281
	A. Beling and J.C. Campbell	
7.1	Introduction	281
7.1.1	Fundamentals	281
7.1.2	Material Systems	286
7.2	Photodiode Types	287
7.2.1	p-i-n Photodiode	287
7.2.2	Metal–semiconductor–metal Photodetector	289
7.2.3	Avalanche Photodiodes	291
7.3	High-speed Photodetectors	296
7.3.1	Advanced Photodiode Structures	296
7.3.2	High-speed Side-illuminated Photodiodes	300

7.3.3	Traveling Wave Photodetectors	307
7.3.4	Photoreceivers	312
7.4	Summary	314
	References	314
8	Systems with Higher-order Modulation	325
	Y. Achiam, A. Kaplan and M. Seimetz	
8.1	Introduction	325
8.1.1	Coherent Detection	327
8.1.2	Higher-order Optical Modulation	328
8.1.3	Coherent Optical Orthogonal Frequency-division Multiplexing	330
8.2	System Configurations	331
8.2.1	Transmitter Structures	331
8.2.2	Receiver Concepts	336
8.3	Key Components for Higher-order Modulation	342
8.3.1	Quadrature Modulators	342
8.3.2	Integrated Coherent Receivers	349
8.3.3	Integrated Balanced Four-branch Receivers	356
8.4	Trends in System Performance	362
8.5	Issues of Future Research	367
	References	368
9	Wavelength Filters	375
	H. Venghaus	
9.1	Introduction	375
9.2	Phase Effects	377
9.2.1	General Considerations	377
9.2.2	Phase Characterization Techniques	379
9.2.3	Typical Group Delay Characteristics	379
9.2.4	Group Delay Ripple	381
9.2.5	System Implications of Non-ideal Filter Characteristics	382
9.3	Fibre Couplers	383
9.3.1	Basics of Coupled Mode Theory	383
9.3.2	Fabrication of Fibre Couplers	385
9.3.3	Characteristics of Fibre Coupler-based Wavelength Filters	386
9.3.4	Applications Beyond Wavelength Channel Filters	386
9.4	Diffraction Gratings	387
9.4.1	Planar Diffraction Gratings	387
9.4.2	Relevant Parameters of Diffraction Gratings	388
9.4.3	Diffraction Gratings Used in Fibre Optic Communication	390
9.4.4	InP- and Si-based Planar Gratings	391
9.5	Arrayed Waveguide Gratings	392
9.5.1	Basics of AWGs	392
9.5.2	AWGs in Silica-on-Silicon	395

9.5.3	AWGs in InP	398
9.5.4	AWGs in Other Material Systems	399
9.6	Fibre Bragg Gratings	399
9.6.1	Generic Properties	399
9.6.2	Types of Gratings	401
9.6.3	Apodization	402
9.6.4	Temperature and Strain Dependence	402
9.6.5	Chirped Gratings	403
9.6.6	Long-period Fibre Bragg Gratings	403
9.6.7	Commercially Available Devices	404
9.7	Fabry-Pérot Interferometers	405
9.7.1	Multiple-reflection Cavities	405
9.7.2	Wavelength/Frequency Characteristics	407
9.7.3	Implementations	408
9.7.4	Typical Performance Characteristics	409
9.7.5	Applications	409
9.8	Thin-film Filters	410
9.8.1	Generic Functionalities of TFFs	410
9.8.2	Fabrication of TFFs	412
9.8.3	Filters for Telecom Applications	413
9.8.4	Filter Modules	415
9.9	Microrings	417
9.9.1	Key Features of Microring Resonators	418
9.9.2	Polarization-dependent Effects	420
9.9.3	Higher Order Filters	420
9.9.4	Experimental Results	421
9.9.5	Microring-based Filters with Extended FSR	422
9.9.6	Prospects and Further Developments of MR-based Filters	422
9.10	Interleavers	422
9.10.1	Operation Principle	422
9.10.2	Interleaver Types	423
9.10.3	Characteristics of Commercially Available Interleavers ..	424
9.11	Acousto-optic Tunable Filters	425
9.12	Filters for Silicon Photonics	426
9.12.1	General and Technological Aspects	426
9.12.2	Examples of CMOS-based Filters	427
9.13	Conclusions	428
	References	430
10	Passive Devices	441
	W. Coenning and F. Caloz	
10.1	Optical Connectors	442
10.1.1	Introduction	442
10.1.2	Connecting Different Types of Fibres	442
10.1.3	Basics of FO-Connectors	444

10.1.4	Relevant Standards for Optical Connectors	445
10.1.5	Optical Requirements for Single-mode FO-Connectors .	446
10.1.6	Mechanical and Climatic Requirements for FO-Connectors	449
10.1.7	Available Standard Connector Types	449
10.1.8	FO-cables for Patch Cords	449
10.1.9	Connectors for Special Fibres or Special Use	451
10.1.10	Cleaning and Inspection	456
10.2	Fibre-optical Couplers	457
10.2.1	Introduction	457
10.2.2	Modelling of Optical Directional Couplers/Power Splitters	457
10.2.3	Fibre Coupler Technologies	461
10.2.4	Classification	461
10.2.5	Star Couplers	463
10.3	Optical Circulators	464
10.4	Optical Isolators	466
10.4.1	General Characteristics	466
10.4.2	Polarisation-independent Optical Isolators	468
10.4.3	Planar Integrated Waveguide-based Optical Isolators .	470
	References	471
11	Fiber Amplifiers	473
	K. Rottwitt	
11.1	The EDFA	474
11.1.1	Energy Levels	475
11.1.2	Rate Equations	476
11.1.3	Signal Propagation	476
11.1.4	Emission and Absorption Cross Sections	478
11.1.5	Characteristics	479
11.1.6	Amplifier Performance	480
11.1.7	Recent Applications	483
11.2	Raman Amplifiers	485
11.2.1	Propagation Equations	486
11.2.2	The Raman Gain Coefficient	488
11.2.3	Characteristics	489
11.2.4	Amplifier Performance	491
11.2.5	System Considerations	494
11.2.6	Recent Applications	496
11.3	Parametric Amplifiers	498
11.3.1	Propagation Equations	498
11.3.2	Amplifier Gain Spectrum	500
11.3.3	Characteristics	501
11.3.4	Amplifier Performance	501
11.3.5	Application Issues	503

11.3.6	Recent Applications	504
11.4	Conclusion	506
	References	507
12	Linear Semiconductor Optical Amplifiers	511
	R. Bonk, T. Vallaitis, W. Freude, J. Leuthold, R.V. Penty, A. Borghesani and I.F. Lealman	
12.1	Introduction	512
12.2	SOA Basics	513
12.2.1	Absorption and Emission of Light.....	513
12.2.2	Compound Semiconductors and Heterostructures	516
12.2.3	Properties of the Active Region	519
12.2.4	SOA Structures and Devices	523
12.2.5	Packaging and Photonic Integrated Circuits	525
12.2.6	Applications as Booster, Inline and Preamplifiers	526
12.3	Parameters of Semiconductor Optical Amplifiers	527
12.3.1	Physics of Media with Gain	527
12.3.2	Gain and Phase	530
12.3.3	Noise Figure.....	532
12.3.4	Gain Saturation	536
12.3.5	SOA Dynamics	539
12.3.6	Alpha-factor	545
12.4	Linear SOAs in Optical Networks.....	549
12.4.1	Parameters of SOAs for Network Applications	549
12.4.2	Linear Amplification Range	552
12.4.3	SOA Dynamic Range for Different Modulation Formats ..	554
12.5	Commercial SOAs	559
12.5.1	SOAs for High Data Rate Signal Amplification.....	560
12.5.2	Extended Wavelength Range and Multi-wavelength Operation	563
12.5.3	Reflective SOAs for WDM-PON Applications	564
12.6	Conclusion	566
	References	566
13	Optical Signal Processing for High-speed Data Transmission	573
	H.G. Weber and R. Ludwig	
13.1	Introduction	573
13.2	OTDM Transmission Systems	576
13.2.1	OTDM Transmission System Using OOK Modulation ..	576
13.2.2	1.28 Tbit/s OTDM Transmission System with Conventional Receiver	577
13.2.3	1.28 Tbit/s OTDM Transmission System with Coherent Receiver	578
13.3	Introduction to Optical Signal Processing for OTDM Systems	579

13.3.1	Self-phase Modulation (SPM) and Cross-phase Modulation (XPM)	580
13.3.2	Four-Wave Mixing (FWM)	582
13.4	OTDM Transmitter	583
13.4.1	Optical Pulse Generator	583
13.4.2	Optical Pulse Compressor and Pulse Cleaner	585
13.4.3	Characterization of Optical Pulses	587
13.4.4	Modulation of an Optical Pulse Train	588
13.4.5	OTDM-multiplexer	592
13.5	Conventional OTDM Receiver	594
13.5.1	NOLM as the Optical Gate	595
13.5.2	SOA- and EAM-based Optical Gates	597
13.5.3	Timing Extraction Devices	601
13.5.4	Optoelectronic Base Rate Receiver	602
13.6	Coherent OTDM Receiver	604
13.6.1	Principle of the Phase-diversity Homodyne Receiver	604
13.6.2	Coherent Receiver as an OTDM Demultiplexer	607
13.6.3	Postdetection Electrical Signal Processing	608
13.7	Optical Signal Processing for Combating Impairments in the Fiber Link	609
13.7.1	Fiber Nonlinearity and Choice of Appropriate Transmission Fiber	609
13.7.2	Compensation of Chromatic Dispersion by DCF	610
13.7.3	Compensation of Higher Order Chromatic Dispersion	612
13.7.4	Compensation of Polarization-mode Dispersion	613
13.8	Concluding Remarks	616
	References	617
14	Silicon Lasers and Photonic Integrated Circuits	625
	Di Liang, A.W. Fang and J.E. Bowers	
14.1	Silicon as a Platform for PICs	626
14.2	Lasers (Emitters) and Amplifiers on Silicon	628
14.2.1	Low-dimensional Silicon Approaches	630
14.2.2	Raman Effect	636
14.2.3	Monolithic Integration Approaches	638
14.2.4	Hybrid Integration Approach	642
14.3	High-speed Signal Processing in Silicon	651
14.3.1	Silicon Optical Modulators	652
14.3.2	Hybrid Silicon Modulators	654
14.4	Summary	657
	References	658
About the Authors		665
Index		677