

Contents

1	Single-Carrier Advanced Modulation Formats	1
1.1	Summary of Modulation Formats	1
1.2	Optical Modulator	6
1.2.1	Phase Modulator	6
1.2.2	Mach-Zehnder Modulator (MZM)	8
1.2.3	IQ Modulator	9
1.2.4	Electro-absorption Modulator (EAM)	11
1.3	Single-Carrier High-Order Modulation	11
1.3.1	Implementation of QPSK	13
1.3.2	Implementation of 8PSK	13
1.3.3	Implementation of 8QAM	16
1.3.4	Implementation of 16QAM	17
1.3.5	High-Order QAM	18
1.3.6	Comparison of Multi-dimensional Multi-order Modulation Formats	22
1.4	Software-Defined Optical Transceiver	23
1.4.1	Software-Defined Multi-modulation Formats Transceiver (SPOT)	24
1.4.2	Software-Defined Polarization Conversion Transceiver	25
1.4.3	Software-Defined Transceiver of Adaptive Multiplexing PON	27
1.5	Conclusion	29
	References	29
2	Basic Digital Signal Processing for Single-Carrier Signals	31
2.1	Introduction	31
2.2	I/Q Imbalance Compensation and Orthogonal Normalization	34
2.2.1	Gram-Schmidt Orthogonalization Process (GSOP)	38
2.2.2	Löwdin Orthogonalization	39

2.3	Fiber Chromatic Dispersion Compensation	40
2.3.1	Dispersion Compensation Overview	41
2.3.2	Dispersion Compensation Basic Structure	43
2.3.3	Frequency-Domain Equalization Algorithm	45
2.3.4	Time-Domain Equalization Algorithm	49
2.4	Clock Recovery Algorithm	53
2.5	Channel Dynamic Equalization Algorithm and Polarization Demultiplexing	54
2.5.1	The Basic Principle of Bland Equalization	54
2.5.2	Classical CMA Algorithm	57
2.5.3	CMA Algorithm for Polarization Multiplexing Signals	60
2.5.4	CMMA Algorithm for High-Order Non-constant Mode Modulation	65
2.5.5	Modified Cascade Multi-modulus Algorithm (MCMMA)	69
2.5.6	Independent Component Analysis (ICA)	72
2.6	Carrier Recovery Algorithm	80
2.6.1	Frequency Offset Compensation Algorithm	81
2.6.2	V-V Based Frequency Offset Estimation Algorithm	82
2.6.3	Frequency Offset Estimation Algorithm Based on FFT	84
2.6.4	Frequency Offset Estimation Algorithm Based on Quartic Power Operation	87
2.7	Phase Compensation Algorithm	90
2.7.1	V-V Based Phase Compensation Algorithm	90
2.7.2	Feedforward Based Phase Rotation Algorithm	92
2.7.3	A Recovery Algorithm Based on the Combination of Modified V-V Phase Bias Algorithm and Maximum Likelihood	94
2.7.4	Algorithm Demonstration and Summary	100
	References	101
3	Quasi-linear Coherent Optical Transmission System and Digital Signal Processing	105
3.1	Introduction	105
3.2	Theoretical Model and Damage Mechanism of Coherent Optical Transmission System	106
3.3	Research on Time-Domain Digital Pre-equalization Technology with Band Limit Signal	108
3.3.1	Digital Time-Domain Pre-equilibrium Principle Based on Receiver-Side Adaptive Equalizer	109
3.3.2	Linear Digital Pre-equalization Implementation Method for Coherent Optical Communication System	112

3.3.3	Analysis of Time-Domain Digital Pre-equalization Simulation Results for Coherent Optical Communication	113
3.3.4	Experimental Results	118
3.4	Conclusion	121
	References	123
4	Super-Nyquist Wavelength Division Multiplexing System	125
4.1	Introduction	125
4.2	Multi-modulus Blind Equalization Algorithms for Super-Nyquist Signals	127
4.2.1	Principle of Multi-modulus Blind Equalization Algorithm	127
4.2.2	Analysis of Simulation Results of Multi-modulus Blind Equalization Algorithm	131
4.2.3	Experimental Comparative Study of Multi-modulus Blind Equalization Algorithm	134
4.3	Four-Carrier Digital Super-Nyquist Signal Generation and 400 G Transmission	138
4.3.1	The Principle of Digital Super-Nyquist Signal Generation	138
4.3.2	Signal Generation and Transmission Experiment for 4×512 Gb/s 4-Carrier Super-Nyquist Channels	140
4.4	400 G Transmission Experiment of Single-Carrier 110-GBaud Super-Nyquist Filtered Signal	144
4.4.1	20×440 Gb/s Super-Nyquist WDM Long Distance Transmission Experiment	144
4.4.2	Experiment of Ten Channels Super-Nyquist WDM Signal Transmission over ROADM Link	147
4.4.3	Transmission Experiment of Single-Carrier 400 G Signal Based on 128.8 GBaud PDM-QPSK in the Terrestrial Fiber Link	150
4.5	Conclusions	155
	References	155
5	All-Optical Nyquist Signal	157
5.1	Introduction	157
5.2	The Generation and Signal Multiplexing Principle of All-Optical Nyquist Pulse	159
5.2.1	The Basic Theory of High-Quality Sinc-type Nyquist Pulse Generation	159

5.2.2	Principle of All-Optical Nyquist Signal Multiplexing and Coherent Detection	160
5.2.3	Principle of All-Optical Nyquist Pulse Generation Based on MZM and Bandpass Filter	162
5.3	Generation and Coherent Detection Experiment of Single-Polarized 125 GBaud All-Optical Nyquist QPSK Signal	164
5.4	Polarization-Multiplexed All-Optical Nyquist Signal Long-Distance Transmission Experiment	169
5.5	Summary	174
	References	175
6	Nonlinear Compensation in Optical Fiber	177
6.1	Introduction	177
6.2	Principle of DBP Fiber Nonlinear Compensation Algorithm	178
6.2.1	Nonlinear Compensation Experiment Based on 4×160.8 Gb/s Wavelength Division Multiplexing PDM-QPSK Signal	180
6.2.2	Improved Digital Nonlinear Compensation Algorithm Based on the Logarithmic Step Size	185
6.3	Experimental Setup and Results	194
6.4	Summary	198
	References	198
7	Probabilistic Shaping	201
7.1	Introduction	201
7.2	Principle of Probabilistic Shaping	202
7.3	Simulation of Probabilistic Shaping	206
7.3.1	Simulation Setup	206
7.3.2	Simulation Result and Discussion	207
7.4	Principle of PAS Scheme	210
7.5	Comparison of PS and Hybrid-QAM	211
7.6	Experiment of PS Transmission	213
7.6.1	Experimental Setup	213
7.6.2	Comparison of PS-64QAM and Hybrid-32/64QAM	215
7.7	Conclusion	220
	References	220
8	High Baud Signal Transmission	223
8.1	Introduction	223
8.2	110-GBaud Polarization-Multiplexed QPSK Signal for 3000 Km Transmission	226
8.2.1	Experimental Setup	226
8.2.2	Experiment Results and Analysis	228
8.2.3	Performance of the Multi-link System	229

8.3	128 GBaud Polarization Multiplexing QPSK Signal Transmission Over 10,000 Km	235
8.3.1	Experimental Setup	235
8.3.2	Experimental Result and Analysis	236
8.4	Long-Distance Transmission of 128-GBaud Polarization-Multiplexed 16QAM Signal	239
8.4.1	Experimental Setup	239
8.4.2	Experimental Results and Analysis	240
8.5	Conclusion	241
	References	242
9	Advanced Modulation Code Optical Signal Transmission Technology	245
9.1	Introduction	245
9.2	Trade-Offs Between Coding Overhead and Bandwidth Limitations	246
9.3	Single-Carrier 400 G PM-256QAM Signal Transmission Experiment	248
9.4	Conclusion	251
	References	252
10	Carrierless Amplitude and Phase Modulation	253
10.1	Introduction	253
10.2	Modulation and Demodulation Principles of CAP	254
10.2.1	Modulation and Demodulation Principles of Single-Band CAP	254
10.2.2	Modulation and Demodulation Principles of Multi-band CAP	256
10.3	Multi-band Multi-level CAP for WDM-PON Access Network	258
10.4	Application of CAP-64QAM in Wireless Access Network	262
10.5	DML-Based 60 Gb/s CAP-64QAM Transmission Experiment	265
10.6	100 G CAP Long-Distance Transmission with Dispersion Compensation	269
10.6.1	Digital Signal Processing of CAP	270
10.6.2	Generation of SSB Signal	271
10.6.3	Experimental Setup and Results	272
10.6.4	Comparison Between Pre-CD and DCF with DDMZM	273
10.6.5	Comparison Between Pre-CD and SSB with DDMZM	274

10.6.6 Comparison Between DDMZM and IQ Modulator	275
10.6.7 Conclusion	276
10.7 Summary	277
References	278
11 PAM4 Signal Modulation and Digital Signal Processing-Based Detection Technology	281
11.1 Introduction	281
11.2 Principle and Related Algorithms of PAM4 Modulation	282
11.2.1 Principle of PAM4 Modulation	282
11.2.2 DD-LMS Algorithm	283
11.2.3 Principle of Dispersion Pre-compensation	284
11.2.4 Lookup Table Algorithm	285
11.3 PAM4 High-Speed Transmission System	286
11.3.1 4-Lane IM/DD 112.5 Gbit/s PAM4 Transmission System	286
11.3.2 50 Gbit/s and 64 Gbit/s PAM4 PON Downlink Transmission System	289
11.3.3 4-Lane IM/DD 112 Gbit/s PAM4 Dispersion Pre-compensation Transmission System	291
11.3.4 400 Gbit/s PDM-PAM4 Signal Generation and Coherent Detection	294
11.4 Summary	299
References	300
12 Optical OFDM	303
12.1 Introduction	303
12.2 Basic Structure of Direct Detection Optical OFDM System	306
12.3 Structure and Basic Principles of Coherent Detection Optical OFDM Systems	307
12.4 Summary	331
References	331
13 Direct Detection OFDM	335
13.1 Introduction	335
13.1.1 System Principle	339
13.2 Study on Elimination of SSMI in DDO-OFDM Based on Half-Cycled Technique	343
13.2.1 Experimental Setup and Results	343
13.2.2 Summary	347
13.3 Research on High Order QAM-OFDM Signal Modulation Transmission by Direct-Detect	347
13.3.1 Experimental Setup	347
13.3.2 Experimental Results and Analysis	349
13.3.3 Summary	355

13.4	Short Distance Transmission of Large Capacity DDO-OFDM Based on DFT-Spread	355
13.4.1	Optimization of Training Sequences in Large Capacity DDO-OFDM Systems Based on DFT-Spread	355
13.4.2	Comparison of Pre-equalization and DFT-Spread Techniques in High-Capacity DDO-OFDM	362
13.4.3	Summary	369
	References	370
14	Intensity Modulation Direct Detection High-Speed Fiber Access System	373
14.1	Introduction	373
14.2	High Spectral Efficiency Modulation Technique	375
14.2.1	Nyquist Modulation Technique	376
14.2.2	Faster Than Nyquist Modulation Technique	383
14.3	Nonlinear Compensation Technique	388
14.3.1	Nonlinear Compensation Technology Based on Volterra Series	389
14.3.2	Nonlinear Compensation Technique Based on Quasi-balanced Coding and Detection	391
14.4	Single Sideband Modulation System	396
14.5	High-Speed Wavelength Division Multiplexing System	403
14.6	Conclusions	405
	References	406
15	High-Speed Fiber Access System Based on Direct Detection of I/Q Modulation	407
15.1	Introduction	407
15.2	Independent Sideband Modulation Direct Detection System Based on I/Q Modulator	408
15.3	Image Elimination Algorithm Based on Training Sequence	411
15.3.1	Principle of Image Elimination Algorithm Based on Training Sequence	411
15.3.2	Experimental Setup	413
15.3.3	Experimental Result	415
15.4	Image Elimination Algorithm Based on Adaptive Blind Equalization	421
15.4.1	Principle of Image Elimination Algorithm Based on Adaptive Blind Equalization	421
15.4.2	Experimental Setup and Results	423
15.5	Summary	425
	References	426

16	Forward Error Correction	427
16.1	Introduction	427
16.2	Block Code	428
16.2.1	Linear Block Code	429
16.2.2	Cyclic Code	431
16.2.3	BCH Code	434
16.2.4	Rs Code	437
16.2.5	Parity-Check Code	438
16.3	Turbo Code	440
16.3.1	Decoding of Turbo Code	440
16.3.2	Iteration Decoding of Turbo Code	442
16.3.3	MAP Decoding	443
16.3.4	MAP Equalization Technology	444
16.3.5	Turbo Iterative Equalization of OFDM Signal	445
16.3.6	MIMO-CMA Equalization Algorithm	447
16.4	LDPC Code	454
16.4.1	Principle of LDPC Code	454
16.4.2	Principle of LDPC-TCM OFDM Optical Millimeter-Wave Signal Transmission System at 60 GHz	456
16.4.3	Experimental Results and Discussion	459
16.4.4	Experimental Conclusion	460
16.5	Concatenated Coding	461
16.6	Summary	463
	References	463
17	High Spectral Efficiency Optical Four-Dimensional Modulation	467
17.1	Introduction	467
17.2	Constellation Point Distribution and Performance Analysis of Two-Dimensional and Three-Dimensional Constant Modulus Modulation	469
17.3	Principle and Implementation of Four-Dimensional Multi-level Modulation	472
17.3.1	Basic Principles of Four-Dimensional Multi-order Modulation	472
17.3.2	Implementation of Four-Dimensional Multi-order Modulation	474
17.4	Design Basis for Multi-dimensional Multi-order Modulation Constellation	482
17.4.1	“Cluster” Problem	483
17.4.2	“Ball” Problem	485

17.5 Typical Multi-dimensional Multi-order Constellation Performance Analysis	485
17.5.1 N = 2	486
17.5.2 N = 4	488
17.6 Experimental Demonstration Based on Geometric Shaped Signal	494
17.6.1 A Constellation-Designed Method for 32QAM with Geometric and Probabilistic Shaping (G/PS 32QAM)	494
17.6.2 Experimental Demonstration Based on PS-Star-16QAM	497
17.6.3 CAP-PS-9QAM Gray Mapping Scheme in IM/DD System	499
17.7 Summary and Outlook	500
References	501
18 Machine Learning Algorithm in the Optical Communication System	503
18.1 Introduction	503
18.2 Support Vector Machines	505
18.2.1 Margin and Support Vector	506
18.2.2 Dual Problem	507
18.2.3 Kernel Function	508
18.2.4 SVM-Based Modulation Format Recognition	509
18.3 BP Neural Network	509
18.3.1 BP Neuron	510
18.3.2 BP Network	512
18.3.3 OSNR Estimator Based on BP Neural Network	513
18.4 Clustering Algorithm	514
18.4.1 Principle of K-Means Clustering Algorithm	514
18.4.2 Algorithm Flow	515
18.4.3 Algorithm Display and Analysis	516
18.5 Application of Clustering Algorithm in Nonlinearity	518
18.5.1 Application Principle	518
18.5.2 Result Analysis	520
References	521
19 Kramers-Kronig Receiver in Direct Detection Systems	523
19.1 Introduction	523
19.2 Principle of KK Receiver	525
19.3 Simulation Setup and Results	527
19.3.1 Simulation Setup	527
19.3.2 Simulation Results and Discussions	528

19.4 Experimental Setup and Results	531
19.4.1 Experimental Setup	531
19.4.2 Experimental Results and Discussions	533
19.5 Conclusions	539
References	540