Contents

Author Biography xv
Preface xvii
Acknowledgments xxi
List of constants xxiii

SECTION 1

CHAPTER 1 Introduction 3
1.1 Why optical fiber 3
1.2 Evolution of fiber-optic communication technologies 6
1.3 Optical systems enabled by DSP 11
1.4 Basic units often used for fiber-optic system engineering 14

SECTION 2

CHAPTER 2 Optical fibers 19
Introduction 20
2.1 General properties of optical waves 21
2.2 Reflection and refraction 24
2.2.1 Fresnel reflection coefficients 25
2.2.2 Special cases of reflection angles 26
2.2.3 Optical field phase shift between the incident and the reflected beams 29
2.2.4 Brewster angle 29
2.3 Propagation modes in optical fibers 30
2.3.1 Geometric optics analysis 31
2.3.2 Mode analysis using electromagnetic field theory 34
2.3.3 Mode classification 39
2.3.4 Numerical aperture 39
2.3.5 Field distribution profile of SMF 43
2.4 Optical fiber attenuation 44
2.5 Group velocity and dispersion 48
2.5.1 Phase velocity and group velocity 48
2.5.2 Group velocity dispersion 50
2.5.3 Sources of chromatic dispersion 51
2.5.4 Modal dispersion 53
2.5.5 Polarization mode dispersion 53
2.5.6 Mode division multiplexing 55

2.6 Nonlinear effects in an optical fiber 56
2.6.1 Stimulated Brillouin scattering 56
2.6.2 Stimulated Raman scattering 57
2.6.3 Kerr effect nonlinearity and nonlinear Schrödinger equation 58
2.7 Different types of optical fibers 63
2.7.1 Standard optical fibers for transmission 63
2.7.2 Specialty optical fibers 66
2.8 Summary 69
Problems 71
References 75
Further reading 76

CHAPTER 3 Light sources for optical communications 77
Introduction 77
3.1 Properties of semiconductor materials for light sources 79
3.1.1 PN junction and energy diagram 79
3.1.2 Direct and indirect semiconductors 81
3.1.3 Spontaneous emission and stimulated emission 82
3.1.4 Carrier confinement 83
3.2 Light-emitting diodes 84
3.2.1 $P \sim I$ curve 85
3.2.2 Modulation dynamics 86
3.3 Laser diodes 88
3.3.1 Amplitude and phase conditions for self-sustained oscillation 88
3.3.2 Rate equations 91
3.3.3 Steady state solutions of rate equations 92
3.3.4 Side-mode suppression ratio 94
3.3.5 Modulation response 95
3.3.6 Laser noises 99
3.4 Single-frequency semiconductor lasers 104
3.4.1 DFB and DBR laser structures 105
3.4.2 External cavity LDs 108
3.5 VCSELs and arrays 111
3.6 LD biasing and packaging 115
3.7 Summary 119
Problems 121
References 124

CHAPTER 4 Photodetectors 125
Introduction 125
4.1 PN and PIN photodiodes 126
4.2 Responsivity and electric bandwidth 131

4.2.1 Quantum efficiency and responsivity 131
4.2.2 Speed of photodetection response 133
4.2.3 Electrical characteristics of a photodiode 135
4.3 Photodetector noise and SNR 137
4.3.1 Sources of photodetection noise 137
4.3.2 SNR of an optical receiver 139
4.3.3 Noise-equivalent power 140
4.4 Avalanche photodiodes 141
4.4.1 APD used as a linear detector 142
4.4.2 APD used as a single-photon detector 144
4.5 Other types of photodetectors 145
4.5.1 Photovoltaic 145
4.5.2 Charge-coupled devices 148
4.6 Summary 150
Problems 151
References 154
Further reading 154

CHAPTER 5 Optical amplifiers 155
Introduction 155
5.1 Optical gain, gain bandwidth, and saturation 157
5.2 Optical noise and noise figure 160
5.2.1 Optical noise power spectral density 160
5.2.2 Impact of ASE noise in the electrical domain 161
5.2.3 Noise figure 163
5.3 Semiconductor optical amplifiers 165
5.3.1 Steady-state analysis 165
5.3.2 Gain dynamics of SOA 169
5.3.3 All-optical signal processing based on the cross-gain and cross-phase modulation 172
5.3.4 Wavelength conversion based on four-wave mixing in an SOA 176
5.4 Erbium-doped fiber amplifiers 179
5.4.1 Absorption and emission cross sections 181
5.4.2 Rate equations 183
5.4.3 Numerical solutions of Rate equations 186
5.4.4 Additional considerations in EDFA design 190
5.5 Raman amplifiers 195
5.6 Summary 201
Problems 203
References 206
Further reading 207

CHAPTER 6 Passive optical components 209
Introduction 210
6.1 Fiber-optic directional couplers 211
6.1.1 Basic parameters of a fiber-optic directional coupler 213
6.1.2 Transfer matrix of a 2×2 optical coupler 217
6.2 Optical interferometer based on two-beam interference 219
6.3 Interferometers based on multi-pass interference 223
6.3.1 Fabry-Perot Interferometers 223
6.3.2 Optical ring resonators 230
6.4 Fiber Bragg gratings 234
6.5 WDM multiplexers and demultiplexers 239
6.5.1 Thin-film-based interference filters 239
6.5.2 Arrayed waveguide gratings 243
6.5.3 Acousto-optic filters 245
6.6 Optical isolators and circulators 249
6.6.1 Optical isolators 250
6.6.2 Optical circulators 252
6.7 PLCs and silicon photonics 255
6.7.1 Slab optical waveguides 256
6.7.2 Rectangle optical waveguides 263
6.7.3 Directional couplers 267
6.7.4 Silicon photonics 270
6.8 Optical switches 274
6.8.1 Types of optical switches 274
6.9 Summary 290
Problems 291
References 296
Further reading 297

CHAPTER 7 External electro-optic modulators 299
Introduction 299
7.1 Basic operation principle of electro-optic modulators 301
7.1.1 EO coefficient and phase modulator 301
7.1.2 Electro-optic intensity modulator 307
7.1.3 Optical intensity modulation vs. field modulation 310
7.1.4 Frequency doubling and high-order harmonic generation 311
7.2 Optical single-sideband modulation 312
7.3 Optical I/Q modulator 316
7.4 Electro-optic modulator based on ring-resonators 317
7.5 Optical modulators using electro-absorption effect 324
7.6 Summary 329

Problems 330
References 334
Further reading 335

CHAPTER 8 Optical transmission system design 337
Introduction 337
8.1 BER vs. *Q*-value for binary modulated systems 339
8.1.1 Overview of IMDD optical systems 339
8.1.2 Receiver *BER* and *Q* 342
8.2 Impacts of noise and waveform distortion on system *Q*-value 347
8.2.1 *Q*-calculation for optical signals without waveform distortion 347
8.2.2 *Q*-estimation based on eye diagram parameterization 348
8.3 Receiver sensitivity and required OSNR 352
8.3.1 Receiver sensitivity 352
8.3.2 Required OSNR 356
8.4 Concept of wavelength division multiplexing 358
8.5 Sources of optical system performance degradation 361
8.5.1 Performance degradation due to linear sources 361
8.5.2 Performance degradation due to fiber nonlinearities 372
8.5.3 Semi-analytical approaches to evaluate nonlinear crosstalks in fiber-optic systems 376
8.6 Conclusion 408
Problems 409
References 414
Further reading 416

CHAPTER 9 Coherent optical communication systems 417
Introduction 417
9.1 Basic principles of coherent detection 418
9.2 Receiver signal-to-noise ratio calculation of coherent detection 421
9.2.1 Heterodyne and homodyne detection 421
9.2.2 Signal-to-noise-ratio in coherent detection receivers 422
9.3 Balanced coherent detection and polarization diversity 427
9.3.1 Balanced coherent detection 428
9.3.2 Polarization diversity 429
9.4 Phase diversity and I/Q detection 430
9.5 Conclusion 435
Problems 436
References 438
Further reading 438

CHAPTER 10 Modulation formats for optical communications 439
Introduction 439
10.1 Binary NRZ vs. RZ modulation formats 440
10.2 Generation of PRBS patterns and clock recovery 445
10.3 Polybinary, duobinary, and carrier-suppressed RZ modulation 449
10.3.1 M-ary and Polybinary coding 450
10.3.2 Duo-binary optical modulation 453
10.3.3 Carrier-suppressed return-to-zero (CSRZ) 456
10.4 BPSK and DPSK optical systems 460
10.5 High-level PSK and QAM modulation 466
10.6 Analog optical systems and radio over fiber 472
10.6.1 Analog subcarrier multiplexing and optical single-sideband modulation 473
10.6.2 Carrier-to-signal ratio, inter-modulation distortion and clipping 478
10.6.3 Impact of relative intensity noise 481
10.6.4 Radio-over-fiber technology 483
10.7 Optical system link budgeting 486
10.7.1 Power budgeting 486
10.7.2 OSNR budgeting 487
10.8 Summary 489
10.9 Problems 490
References 494
Further reading 495

CHAPTER 11 Application of high-speed DSP in optical communications 497
Introduction 497
11.1 Enabling technologies for DSP-based optical transmission 498
11.2 Electronic-domain compensation of transmission impairments 499
11.2.1 Dispersion compensation 500
11.2.2 PMD compensation and polarization de-multiplexing 505
11.2.3 Carrier phase recovery in a coherent detection receiver 507
11.3 Digital subcarrier multiplexing: OFDM and Nyquist frequency-division multiplexing 511
11.3.1 Orthogonal frequency-division multiplexing 512
11.3.2 Nyquist pulse modulation and frequency-division multiplexing 523
11.3.3 Optical system considerations for DSCM 527
11.4 Summary 549
Problems 549
References 553

CHAPTER 12 Optical networking 555
Introduction 555
12.1 Layers of communication networks and optical network topologies 556
12.1.1 Layers of an optical network 557
12.1.2 Optical network topologies 559
12.1.3 SONET, SDH, and IP 567
12.2 Optical network architectures and survivability 573
12.2.1 Categories of optical networks 573
12.2.2 Optical network protection and survivability 574
12.3 Passive optic networks and fiber to the home 579
12.3.1 TDM-PON 580
12.3.2 WDM-PON 584
12.4 Optical interconnects and datacenter optical networks 586
12.4.1 Optical interconnection 586
12.4.2 Datacenter optical networks 588
12.5 Optical switching and cross connection 596
12.5.1 Reconfigurable optical add/drop multiplexing 596
12.5.2 Optical cross-connect circuit switching 599
12.5.3 Elastic optical networks 602
12.5.4 Optical packet switching 604
12.6 Electronic circuit switching based on digital subcarrier multiplexing 606
12.7 Summary 612
Problems 613
References 618
Further reading 619

Index 621