Contents

Preface xi
About the Author xv
Constants xvii

1 Fundamentals of Optical Devices 1

1.0 Introduction 2
1.1 Laser Diodes and LEDs 4
1.1.1 Pn Junction and Energy Diagram 5
1.1.2 Direct and Indirect Semiconductors 6
1.1.3 Carrier Confinement 7
1.1.4 Spontaneous Emission and Stimulated Emission 8
1.1.5 Light-Emitting Diodes (LEDs) 9
1.1.6 Laser Diodes (LDs) 13
1.1.7 Single-Frequency Semiconductor Lasers 26
1.2 Photodetectors 32
1.2.1 Pn-Junction Photodiodes 32
1.2.2 Responsivity and Bandwidth 34
1.2.3 Electrical Characteristics of a Photodiode 36
1.2.4 Photodetector Noise and SNR 37
1.2.5 Avalanche Photodiodes (APDs) 41
1.3 Optical Fibers 44
1.3.1 Reflection and Refraction 44
1.3.2 Propagation Modes in Optical Fibers 49
1.3.3 Optical Fiber Attenuation 62
1.3.4 Group Velocity and Dispersion 67
1.3.5 Nonlinear Effects in an Optical Fiber 77
1.4 Optical Amplifiers 85
1.4.1 Optical Gain, Gain Bandwidth, and Saturation 86
1.4.2 Semiconductor Optical Amplifiers 89
1.4.3 Erbium-Doped Fiber Amplifiers (EDFAs) 100
1.5 External Electro-Optic Modulator 115
1.5.1 Basic Operation Principle of Electro-Optic Modulators 116

1.5.2 Frequency Doubling and Duo-Binary Modulation 121
1.5.3 Optical Single-Side Modulation 123
1.5.4 Optical Modulators Using Electro-Absorption Effect 125

2 Basic Instrumentation for Optical Measurement 129

2.0 Introduction 130
2.1 Grating-Based Optical Spectrum Analyzers 131
2.1.1 General Specifications 131
2.1.2 Fundamentals of Diffraction Gratings 134
2.1.3 Basic OSA Configurations 138
2.2 Scanning FP Interferometer 146
2.2.1 Basic FPI Configuration and Transfer Function 146
2.2.2 Scanning FPI Spectrum Analyzer 153
2.2.3 Scanning FPI Basic Optical Configurations 157
2.2.4 Optical Spectrum Analyzer Using the Combination of Grating and FPI 159
2.3 Mach-Zehnder Interferometers 160
2.3.1 Transfer Matrix of a 2 × 2 Optical Coupler 161
2.3.2 Transfer Function of an MZI 162
2.3.3 MZI Used as an Optical Filter 164
2.4 Michelson Interferometers 168
2.4.1 Operating Principle of a Michelson Interferometer 169
2.4.2 Measurement and Characterization of Michelson Interferometers 172
2.4.3 Techniques to Increase Frequency Selectivity 174
2.5 Optical Wavelength Meter 179
2.5.1 Operating Principle of a Wavelength Meter Based on Michelson Interferometer 180
2.5.2 Wavelength Coverage and Spectral Resolution 183
2.5.3 Wavelength Calibration 185
2.5.4 Wavelength Meter Based on Fizeau Wedge Interferometer 186
2.6 Optical Polarimeter 188
2.6.1 General Description of Lightwave Polarization 188
2.6.2 The Stokes Parameters and the Poincare Sphere 190
2.6.3 Optical Polarimeters 193
2.7 Measurement Based on Coherent Optical Detection 196
2.7.1 Operating Principle 196
2.7.2 Receiver SNR Calculation of Coherent Detection 199

2.7.3 Balanced Coherent Detection and Polarization Diversity 202
2.7.4 Phase Diversity in Coherent Homodyne Detection 204
2.7.5 Coherent OSA Based on Swept Frequency Laser 207
2.8 Waveform Measurement 211
2.8.1 Oscilloscope Operating Principle 212
2.8.2 Digital Sampling Oscilloscopes 216
2.8.3 High-Speed Sampling of Optical Signal 219
2.8.4 High-Speed Electric ADC Using Optical Techniques 223
2.8.5 Short Optical Pulse Measurement Using an Autocorrelator 224
2.9 Optical Low-Coherent Interferometry 232
2.9.1 Optical Low-Coherence Reflectometry 232
2.9.2 Fourier-Domain Reflectometry 240
2.10 Optical Network Analyzer 246
2.10.1 S-Parameters and RF Network Analyzer 246
2.10.2 Optical Network Analyzers 249

3 Characterization of Optical Devices 259

3.0 Introduction 260
3.1 Characterization of RIN and Linewidth of Semiconductor Lasers 260
3.1.1 Measurement of Relative Intensity Noise (RIN) 261
3.1.2 Measurement of Laser Phase Noise and Linewidth 266
3.2 Measurement of Electro-Optic Modulation Response 276
3.2.1 Characterization of Intensity Modulation Response 277
3.2.2 Measurement of Frequency Chirp 282
3.2.3 Time-Domain Measurement of Modulation-Induced Chirp 292
3.3 Wideband Characterization of an Optical Receiver 296
3.3.1 Characterization of Photodetector Responsivity and Linearity 297
3.3.2 Frequency Domain Characterization of Photodetector Response 299
3.3.3 Photodetector Bandwidth Characterization Using Source Spontaneous-Spontaneous Beat Noise 301
3.3.4 Photodetector Characterization Using Short Optical Pulses 304

3.4 Characterization of Optical Amplifiers 306
3.4.1 Measurement of Amplifier Optical Gain 306
3.4.2 Measurement of Static and Dynamic Gain Tilt 311
3.4.3 Optical Amplifier Noise 314
3.4.4 Optical Domain Characterization of ASE Noise 316
3.4.5 Impact of ASE Noise in Electrical Domain 318
3.4.6 Noise Figure Definition and Its Measurement 323
3.4.7 Time-Domain Characteristics of EDFA 327
3.5 Characterization of Passive Optical Components 329
3.5.1 Fiber-Optic Couplers 330
3.5.2 Fiber Bragg Grating Filters 335
3.5.3 WDM Multiplexers and Demultiplexers 340
3.5.4 Characterization of Optical Filter Transfer Functions 345
3.5.5 Optical Isolators and Circulators 353

4 Optical Fiber Measurement 365

4.0 Introduction 366
4.1 Classification of Fiber Types 367
4.1.1 Standard Optical Fibers for Transmission 367
4.1.2 Specialty Optical Fibers 370
4.2 Measurement of Fiber Mode-Field Distribution 374
4.2.1 Near-Field, Far-Field, and Mode-Field Diameter 375
4.2.2 Far-Field Measurement Techniques 378
4.2.3 Near-Field Measurement Techniques 380
4.3 Fiber Attenuation Measurement and OTDR 382
4.3.1 Cutback Technique 382
4.3.2 Optical Time-Domain Reflectometers 384
4.3.3 Improvement Considerations of OTDR 391
4.4 Fiber Dispersion Measurements 394
4.4.1 Intermodal Dispersion and Its Measurement 395
4.4.2 Chromatic Dispersion and Its Measurement 400
4.5 Polarization Mode Dispersion (PMD) Measurement 409
4.5.1 Representation of Fiber Birefringence and PMD Parameter 409
4.5.2 Pulse Delay Method 413
4.5.3 The Interferometric Method 415
4.5.4 Poincare Arc Method 418
4.5.5 Fixed Analyzer Method 420
4.5.6 The Jones Matrix Method 424
4.5.7 The Muellèr Matrix Method 431

4.6 Determination of Polarization-Dependent Loss 438
4.7 PMD Sources and Emulators 442
4.8 Measurement of Fiber Nonlinearity 446
4.8.1 Measurement of Stimulated Brillouin Scattering Coefficient 447
4.8.2 Measurement of the Stimulated Raman Scattering Coefficient 453
4.8.3 Measurement of Kerr effect nonlinearity 459

5 Optical System Performance Measurements 481

5.0 Introduction 482
5.1 Overview of Fiber-Optic Transmission Systems 483
5.1.1 Optical System Performance Considerations 484
5.1.2 Receiver *BER* and *Q* 486
5.1.3 System *Q* Estimation Based on Eye Diagram Parameterization 494
5.1.4 Bit Error Rate Testing 499
5.2 Receiver Sensitivity Measurement and OSNR Tolerance 508
5.2.1 Receiver Sensitivity and Power Margin 509
5.2.2 OSNR Margin and Required OSNR (R-OSNR) 514
5.2.3 BER vs. Decision Threshold Measurement 521
5.3 Waveform Distortion Measurements 524
5.4 Jitter Measurement 527
5.4.1 Basic Jitter Parameters and Definitions 527
5.4.2 Jitter Detection Techniques 532
5.5 In-situ Monitoring of Linear Propagation Impairments 537
5.5.1 *In Situ* Monitoring of Chromatic Dispersion 537
5.5.2 *In Situ* PMD Monitoring 541
5.5.3 *In Situ* PDL Monitoring 551
5.6 Measurement of Nonlinear Crosstalk in Multi-Span WDM systems 556
5.6.1 XPM-Induced Intensity Modulation in IMDD Optical Systems 556
5.6.2 XPM-induced Phase Modulation 572
5.6.3 FWM-Induced Crosstalk in IMDD Optical Systems 575
5.6.4 Characterization of Raman Crosstalk with Wide Channel Separation 581

5.7 Modulation Instability and Its Impact in WDM Optical Systems 590
5.7.1 Modulation-instability and Transfer Matrix Formulation 590
5.7.2 Impact of Modulation Instability in Amplified Multispan Fiber Systems 600
5.7.3 Characterization of Modulation Instability in Fiber-Optic Systems 601
5.8 Optical System Performance Evaluation Based On Required OSNR 606
5.8.1 Measurement of R-SNR Due to Chromatic Dispersion 607
5.8.2 Measurement of R-SNR Due to Fiber Nonlinearity 610
5.8.3 Measurement of R-OSNR Due to Optical Filter Misalignment 615
5.9 Fiber-Optic Recirculating Loop 616
5.9.1 Operation Principle of a Recirculating Loop 617
5.9.2 Measurement Procedure and Time Control 618
5.9.3 Optical Gain Adjustment in the Loop 622

Index **631**