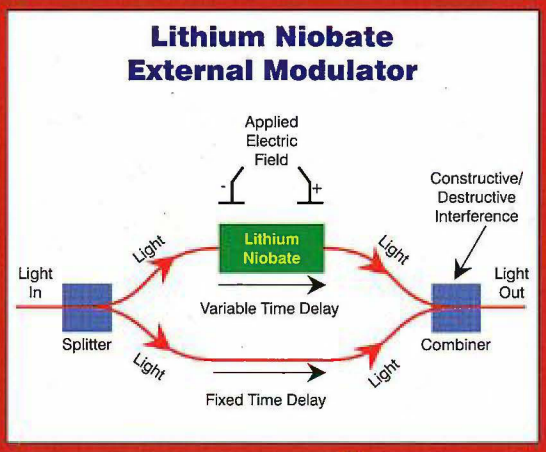
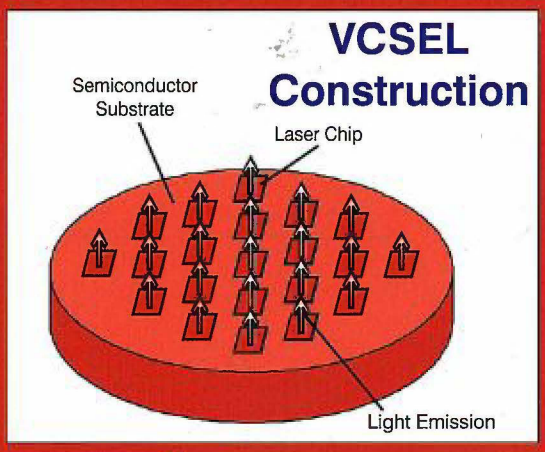
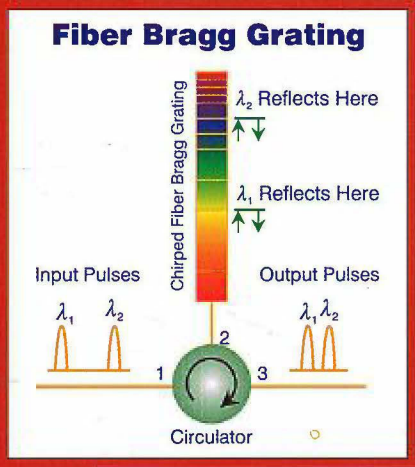
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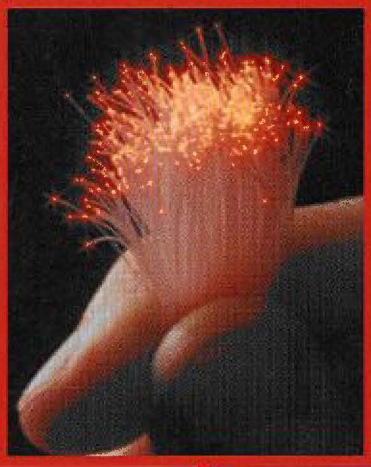
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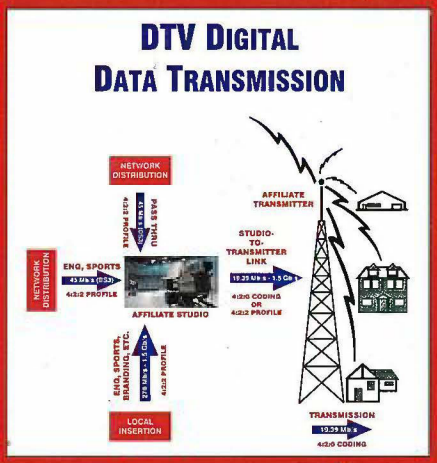
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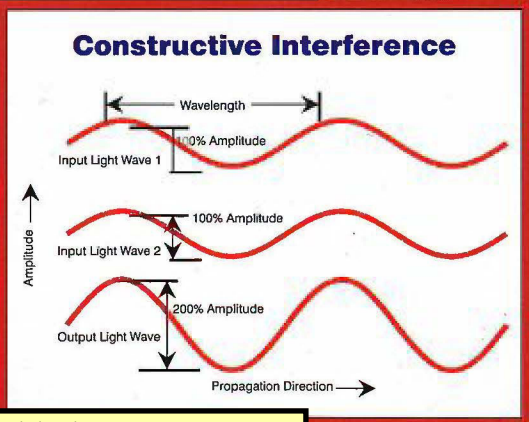


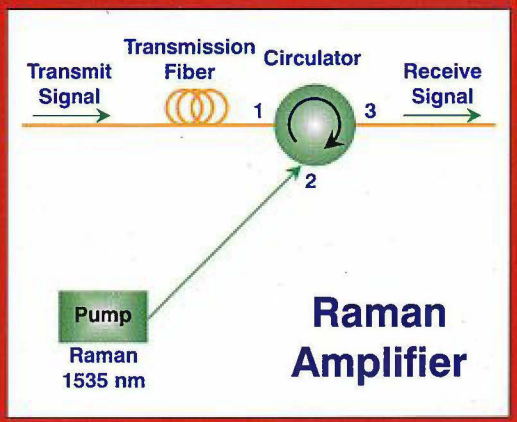












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CONTENTS

FOREWORD ix

ABOUT THIS BOOK vii
ACKNOWLEDGMENTS. viii

CHAPTER 1 A HISTORY OF FIBER OPTIC TECHNOLOGY 1

THE NINETEENTH CENTURY 1
Figure 1.1: John Tyndall's Experiment 1
THE TWENTIETH CENTURY 2
Figure 1.2: Optical Fiber with Cladding 2
Figure 1.3: 4 Wavelength Regions of Fiber . . . 4
Real World Applications 5
THE TWENTY-FIRST CENTURY AND BEYOND . . . 6
Figure 1.4: Internet Traffic Increases. 6
Figure 1.5: The Growth of Optical Fiber Transmission Capacity 6
Chapter Summary 7
Selected References and Additional Reading . . . 8

CHAPTER 2 FIBER OPTIC FUNDAMENTALS 9

THE NATURE OF LIGHT 9
Interference 9
Figure 2.1: Constructive Interference 9
Figure 2.2: Destructive Interference 10
Polarization 10
Figure 2.3: Light Waves Showing E and B Vectors. 10
The Electromagnetic Spectrum 11
Figure 2.4: Electromagnetic Spectrum 11
APPLYING LIGHT. 11
FIBER OPTIC COMMUNICATIONS SYSTEM 13
Figure 2.5: Elements of a Fiber Optic Link . . 13
Figure 2.6: Basic WDM System. 13
Figure 2.7: Four Channel DWDM System . . 14
Figure 2.8: Modern DWDM Long-haul Communication System 14
Figure 2.9: Transmission Schemes 15
FIBER OPTIC COMPONENTS 15
Figure 2.10: Cross-section of a Fiber 16
Figure 2.11: Sources and Emission Patterns. 16
SOME USEFUL TERMINOLOGY 17
Chapter Summary 18
Selected References and Additional Reading. . 18

CHAPTER 3 OPTICAL FIBER 19

FIBER ERA's. 19
MANUFACTURE OF OPTICAL FIBER 20
Figure 3.1: Manufacturing Optical Fiber. . . . 20
Figure 3.2: Optical Fiber Draw Process. 20
PRINCIPLES OF OPERATION. 21
Figure 3.3: Total Internal Reflection 21
Figure 3.4: Snell's Law 21
Figure 3.5: Numerical Aperture. 22
Table 3.1: Refractive Indices and Propagation Times 23
Figure 3.6: Refractive Index of Fused Silica . . 24
MULTIMODE FIBER 24
Multimode Step-index Fiber. 24
Figure 3.7: Total Internal Reflection in Multimode Step-index Fiber 24
Multimode Graded-index Fiber 25
Figure 3.8: Multimode Graded-index Fiber. . 25
SINGLE-MODE FIBER 25
Figure 3.9: Single-mode Fiber. 25
Single-mode Fiber Types in the 1990's 26
Figure 3.10: Dispersion Behavior of Single-mode Fiber Types 26
Figure 3.11: Dispersion for Alternating 20 km Lengths of (+D) NZ-DSF and (-D) NZ-DSF Fiber 27
Polarization-maintaining Fiber 27
Figure 3.12: Cross-section of Polarization-maintaining Fiber 28
ATTENUATION 28
Figure 3.13: Scattering 29
Figure 3.14: Absorption 29
Figure 3.15: Bending 29
Figure 3.16: Optical Loss vs. Wavelength . . . 30
FIBER RIN 30
Figure 3.17: Fiber-induced RIN 30
MULTIMODE DISPERSION 31
CHROMATIC DISPERSION 31
Figure 3.18: Chromatic Dispersion 31
Figure 3.19: Single-mode Fiber Bandwidth. . 32
Material Dispersion 32
Figure 3.20: Material Dispersion. 33
Waveguide Dispersion 33
Profile Dispersion 33
POLARIZATION MODE DISPERSION 33
Figure 3.21: Pulse Broadening Due to PMD. 34
DISPERSION MANAGEMENT 34
Figure 3.22: DSC Using AWG's. 35

Figure 3.23: Accumulated Chromatic Dispersion Using DSC 35
Figure 3.24: Accumulated Chromatic Dispersion Without DSC 35
FIBER NONLINEARITIES 35
Figure 3.25: Refractive Index vs. Power 36
Stimulated Brillouin Scattering. 37
Figure 3.26: SBS Threshold Effects 37
Figure 3.27: SBS Threshold vs. Linewidth. . . 38
Figure 3.28: Optical Spectrum without Phase Modulation 38
Figure 3.29: Optical Spectrum with Phase Modulation 39
Stimulated Raman Scattering 39
Figure 3.30: Six Channel DWDM Transmitted Optical Spectrum. 39
Figure 3.31: SRS Effect on Six Channel DWDM Transmitted Optical Spectrum 40
Four Wave Mixing 40
Figure 3.32: FWM Products for a Three-wavelength System 41
Figure 3.33: FWM Products vs. Ch. Count. . 41
Figure 3.34: FWM Mixing Efficiency in Single-mode Fibers. 42
Self-phase Modulation 42
Figure 3.35: Effects of SPM on a Pulse. 42
Cross-phase Modulation. 42
Intermodulation (Mixing). 43
Summary of Fiber Nonlinearities 43
SELECTING FIBER TYPES. 44
Figure 3.36: Popular Fiber Sizes 44
Figure 3.37: Comparison of Fiber Types. . . . 45
Table 3.2: Typical Fiber Loss. 45
Table 3.3: Typical Fiber Bandwidth 46
Table 3.4: Miscellaneous Fiber Parameters . 46
Chapter Summary. 47
Selected References and Additional Reading. . 48

CHAPTER 4 FIBER OPTIC CABLES 49

FIBER OPTIC CABLE CONSTRUCTION 49
Figure 4.1: Fiber Optic Cable Construction . 49
Figure 4.2: Two Types of Cable Jackets. . . . 50
Table 4.1: Properties of Jacket Material 51
TYPES OF FIBER OPTIC CABLES 51
Figure 4.3: Simplex Cable Construction 51
Figure 4.4: Zipcord Cable Construction 52
Figure 4.5: Breakout Cable Construction. . . 52
FIBER OPTIC CABLE VS. COPPER COAX CABLE. 52
Figure 4.6: Hybrid Cable Construction. 53
Figure 4.7: Copper Coax vs. Optical Fiber . . 53
TENSILE STRENGTH 54
Figure 4.8: Mean Tensile Strength of Cable Materials 54
SPECIFYING FIBER OPTIC CABLES 55
Figure 4.9: Cable Environments 55
Figure 4.10: Aerial Cable Installation 56
Figure 4.11: Submarine Cable Construction. 57
Chapter Summary 58
Selected References and Additional Reading. . 58

CHAPTER 5 LIGHT EMITTERS 59

THEORY OF OPERATION 59
Table 5.1: Bandgap Energy & Wavelengths of Various Semiconductors. 60
LIGHT EMITTER PERFORMANCE CHARACTERISTICS. 60
SPECTRAL CHARACTERISTICS. 61
Figure 5.1: LED Optical Spectra 61
Figure 5.2: Laser Optical Spectra 61
LIGHT-EMITTING DIODES 62
Figure 5.3: Typical Packaged LED's 62
Figure 5.4: Surface-emitting LED 62
Figure 5.5: Edge-emitting LED. 62
Figure 5.6: LED Behavior vs. Temperature . . 63
LED Driver Circuits. 63
Figure 5.7: Optical Output vs. Current in an InGaAsP Light-emitting Diode 64
Figure 5.8: LED Driver Circuits 64
Figure 5.9: Response of an LED to a Digital Modulation Signal 65
LASER DIODES 66
Figure 5.10: Laser Construction 66
VCSEL's. 67
Figure 5.11: Basic VCSEL Structure. 67
Figure 5.12: VCSEL Wafer. 68
CHIRP 68
Figure 5.13: Laser Chirp: DFB. 69
Figure 5.14: Wideband FM Modulator. 69
BACKREFLECTION 69
Figure 5.15: Faraday Rotator Isolator 70
Figure 5.16: Laser Optical Output With No Backreflection. 70
Figure 5.17: Frequency versus Amplitude Response of a Laser 71
Figure 5.18: Laser Optical Output With Backreflection. 71
TEMPERATURE EFFECTS ON LASERS. 72
Figure 5.19: Laser Optical Power Output versus Forward Current. 72
PELTIER COOLERS 73
Figure 5.20: Cross-section of a Single-stage, Multi-element Peltier Cooler. 73
Figure 5.21: A Peltier Cooler Mounted in a 14-pin Laser Package. 74
HIGH POWER AND CW LASERS. 74
DWDM LASERS. 74

Table 5.2: ITU DWDM Wavelengths. 75
MICROELECTROMECHANICAL SYSTEMS. 75
Figure 5.22: MEMS Device 76
TUNABLE LASERS 76
Figure 5.23: Tunable VCSEL's. 76
Figure 5.24: Tunable Laser 77
DFB LASERS 77
LASER SAFETY. 77
Table 5.3: Laser Safety Classes 78
Figure 5.25: Typical Laser Warning Labels . . 78
COMPARISON OF LED'S AND LASER DIODES . 78
Table 5.4: Comparison of Light Emitters . . . 79
LIGHT EMITTERS AS DETECTORS. 79
Figure 5.26: Ping-pong LED Operation 79
Chapter Summary 79
Selected References and Additional Reading. . 80

CHAPTER 6 LIGHT DETECTORS 81

IMPORTANT DETECTOR PARAMETERS 81
Responsivity. 81
Figure 6.1: Spectral Response of Various Detector Materials 81
Quantum Efficiency. 82
Capacitance. 82
Figure 6.2: Capacitance vs. Reverse Voltage 82
RESPONSE TIME. 83
Dark Current 83
Edge Effect 83
Figure 6.3: Edge Effect. 84
Linearity & Backreflection. 84
Figure 6.4: Low Backreflection Detector Alignment 84
Noise. 84
PIN PHOTODIODE. 85
Figure 6.5: Low Backreflection Photodiodes 85
Figure 6.6: Cross-section and Operation of a PIN Photodiode 86
IDP DETECTORS. 86
Transimpedance Amplifier. 86
Table 6.1: TIA Characteristics 86
AVALANCHE PHOTODIODE. 86
APD-TIA DETECTORS. 87
DETECTOR ENHANCEMENT TECHNIQUES . . . 87
PIN PHOTODIODES VS. APD'S 87
Table 6.2: PIN Photodiodes vs. APD's 87
Chapter Summary 88
Selected References and Additional Reading. . 88

CHAPTER 7 OTHER ACTIVE DEVICES 89

SEMICONDUCTOR OPTICAL AMPLIFIERS 89
Figure 7.1: SOA 89
ERBIUM-DOPED FIBER AMPLIFIERS. 89
Figure 7.2: Two-stage EDFA with Mid-stage Access 90
Figure 7.3: Typical Packaged EDFA. 91
Power Amplifier/Booster 91
Figure 7.4: 3 Applications for an EDFA. 91
In-line Amplifier 91
Preamplifier 91
Loss Compensation in Optical Networks. 91
Figure 7.5: Loss Compensation in Optical Networks 92
Wideband EDFA's 92
Figure 7.6: Optical Gain Spectrum of a Hybrid Optical Amplifier. 92
Figure 7.7: Wideband EDFA/Raman Amplifiers Achieved by 1998. 93
Figure 7.8: Gain of EDFA plus Raman Optical Amplifier Showing 67 nm Bandwidth. . . 93
RAMAN AMPLIFIERS 93
Figure 7.9: Sample DWDM Transmit Spectrum, Six Wavelengths 94
Figure 7.10: Received Spectrum After SRS in a Long Fiber. 94
Figure 7.11: Raman Amplifier 95
Figure 7.12: Raman Amplifier Example — Transmitted Spectrum 95
Figure 7.13: Raman Amplifier Example — Received Spectrum 96
EXTERNAL MODULATORS 96
Lithium Niobate Amplitude and Phase Modulators. 96
Figure 7.14: Basic Lithium Niobate ($LiNbO_3$) Optical Modulator 97
Figure 7.15: Simple Phase Modulator. 98
Figure 7.16: Single Output Intensity Modulator 98
Figure 7.17: Dual Output Intensity Modulator 98
Figure 7.18: Dual Output External Modulator Response 99
Digital Operation. 99
Analog Operation 99
WAVELENGTH CONVERTERS. 99
Figure 7.19: Wavelength Converter 99
Wavelength Conversion Technologies. 100
WAVELENGTH LOCKER 100
Tunable Filters 100
Figure 7.20: Packaged Tunable Filter 100
Figure 7.21: Tunable Filter Airy Function . . 101
Chapter Summary 101
Selected References and Additional Reading . 102

CHAPTER 8 INTERCONNECTION DEVICES 103

Table 8.1: Connector Evolution 103
OPTICAL CONNECTOR BASICS 103
Figure 8.1: Parts of a Connector. 104

TYPES OF FIBER OPTIC CONNECTORS 104
Table 8.2: Connector Types 106
INSTALLING FIBER OPTIC CONNECTORS 108
Figure 8.2: Fiber End Face Defects 108
Cleaving 109
Figure 8.3: A Well-cleaved MM Fiber 109
Polishing 109
Figure 8.4: Fiber Polishing Technique. 110
Figure 8.5: Alignment Sleeve 110
CARE OF FIBER OPTIC CONNECTORS 110
Cleaning Technique 111
Handling 111
SPLICING 111
Fusion Splices 112
Figure 8.6: Typical Fusion Splicer 112
Mechanical Splices 112
Figure 8.7: Capillary Splice 112
INTERCONNECTION LOSSES. 113
Other Concerns 113
CONNECTOR SELECTION GUIDE 113
Table 8.3: Connector Selection Guide 113
Chapter Summary 114
Selected References and Additional Reading. 114

CHAPTER 9 OTHER PASSIVE DEVICES 115

FIBER OPTIC COUPLERS. 115
Figure 9.1: Star and Tee Couplers 115
Table 9.1: Typical Insertion Losses for Modern Single-mode Optical Fibers 116
Figure 9.2: Tee Network Configurations . . 117
WDM 117
Figure 9.3: Bidirectional WDM Application. 117
Figure 9.4: Bulk Optics WDM 118
CWDM 118
Figure 9.5: CWDM Passband Characteristics for an 8 Channel Device 118
DWDM 119
Figure 9.6: 0.4 nm Channel Spacing DWDM FBG's 119
Red and Blue Bands 120
ARRAYED WAVEGUIDE GRATING (AWG) 120
Figure 9.7: Cross-section of a PLC 120
Figure 9.8: Operation of an AWG 120
FUSED FIBER COUPLERS 121
Figure 9.9: Fused Fiber Coupler 121
Figure 9.10: Optical Characteristics of a Fused Fiber WDM. 121
FIBER OPTIC SWITCHES 122
Figure 9.11: Typical Switch Configurations 122
Opto-mechanical Switches 122
Figure 9.12: FDDI Optical Switch. 122
Thermo-optic Switches 122
Electro-optic Switches 123
CIRCULATORS 123
Figure 9.13: Circulator 123
BRAGG GRATINGS 123
Figure 9.14: Bragg Gratings 123
Figure 9.15: Fiber Bragg Grating Used to Compensate for Chromatic Dispersion 124
Figure 9.16: High-performance DWDM System Using Fiber Bragg Gratings 125
ETALON 125
Figure 9.17: FP Etalon in a Laser Cavity . . . 125
Chapter Summary 126
Selected References and Additional Reading. 126

CHAPTER 10 SYSTEM DESIGN CONSIDERATIONS 127

SYSTEM DESIGN FACTORS. 127
Table 10.1: Evaluating System Design 127
OPTICAL LINK LOSS BUDGET. 127
Figure 10.1: Optical Link Loss Budget 128
Table 10.2: Decibel to Power Conversion. . 129
Table 10.3: Typical dBm Values 130
RISE-TIME BUDGET 130
Table 10.4: Rise-time Analysis 131
SENSITIVITY ANALYSIS 131
Figure 10.2: Eye Diagrams 132
SIGNAL-TO-NOISE RATIO 132
Figure 10.3: BER Dependence on SNR. . . . 133
MODULATION SCHEMES 133
Figure 10.4: Modulation Schemes 133
Amplitude Modulation (AM) 134
Figure 10.5: Typical AM System 134
Frequency Modulation (FM) 135
Figure 10.6: Typical FM System Response . 135
Pulse-Code Modulation (PCM) 136
Table 10.5: Digital System Operation. 136
ANALOG VERSUS DIGITAL. 136
Digital Basics 136
Figure 10.7: Analog and Digital Signals . . . 137
Figure 10.8: Typical Pulse Train. 137
Figure 10.9: Parts of a Pulse 137
DISPERSION 138
Dispersion Power Penalty 138
Figure 10.10: MLM Laser Spectral Width . . 138
Figure 10.11: SLM Laser Spectral Width . . . 139
Figure 10.12: Dispersion with a Normal DFB Laser. 140
Figure 10.13: Dispersion with a Narrow DFB Laser. 140
Figure 10.14: Dispersion with an FP Laser . 141
OPTICAL SIGNAL-TO-NOISE RATIO 141
Figure 10.15: OSNR Through a Long Chain of EDFA's and Fiber Lengths 141

Q-Factor 142
Figure 10.16: Determining Q-Factor 142
OPTICAL REGENERATORS 142
Figure 10.17: Optical Regenerators 143
COST/PERFORMANCE CONSIDERATIONS. . . . 143
Chapter Summary 143
Selected References and Additional Reading . 144

CHAPTER 11 FIBER OPTIC APPLICATIONS 145

BROADCAST. 145
Digital Video 145
Figure 11.1: Serial Digital Component Video Fiber Optic Links. 145
BROADBAND CATV TRANSPORT. 146
Figure 11.2: CATV Video Distribution. 146
TELECOMMUNICATIONS 146
Fiber-to-the-home and Fiber-to-the-curb . . . 147
Figure 11.3: Fiber-to-the-curb and Fiber-to-the-home System. 147
HIGH-RESOLUTION IMAGING. 148
Table 11.1: RGB Bandwidth and Screen Resolution 148
DISTANCE LEARNING (TELE-CLASSROOMS) . . 148
Figure 11.4: Distance Learning and Teleconferencing 148
TELECONFERENCING 148
DATA COMMUNICATIONS 149
Computers 149
Local Area Networks 149
Network Automatic Protection Switching . . . 149
Figure 11.5: SONET Protection Strategy. . . 150
CONTROL SYSTEMS AND INSTRUMENTATION 151
Control Systems. 151
Instrumentation. 151
MILITARY. 151
Figure 11.6: HAWK Missile Fiber Optic Converter Set 152
SECURITY AND SURVEILLANCE 152
Figure 11.7: Typical Video/2-Way Data Link for Security and Surveillance Applications . 152
Chapter Summary 153
Selected References and Additional Reading . 154

CHAPTER 12 VIDEO OVER FIBER 155

METHODS OF ENCODING VIDEO SIGNALS. . 155
Table 12.1: Comparison of AM, FM and Digital Encoding 155
VIDEO QUALITY PARAMETERS 156
ADVANTAGES OF FM 156
DISADVANTAGES OF FM. 157
Figure 12.1: FM Video Link. 157
FM VIDEO LINK PERFORMANCE 158
Figure 12.2: SNR versus Fiber Length. 158
Figure 12.3: FM Video vs. AM Video 158
DIGITAL VIDEO. 159
Figure 12.4: Optical Tx Multiplexing & Sending 16 Video Signals 159
Figure 12.5: Optical Rx Receiving & Demultiplexing 16 Video Signals 159
Table 12.2: Digital Video Formats. 160
SERIAL DATA TRANSMISSION FORMATS AND STANDARDS 160
Table 12.3: Signal Levels and Specifications for SMPTE 259M, 292M and 310M 161
CATV TRANSMISSION. 161
Figure 12.6: CATV Headend Diagram 161
Chapter Summary 162
Selected References and Additional Reading . 162

CHAPTER 13 DATA OVER FIBER 163

DIGITAL DATA TRANSMISSION 163
DATA CODING. 164
Table 13.1: 3B6B Coding Scheme 164
DATA INTERFACE CHARACTERISTICS. 164
Table 13.2: Data Interface Characteristics . 164
KEY DATA LINK ATTRIBUTES. 165
Table 13.3: Relationship Between $SNR_{Optical}$ and BER. 165
Figure 13.1: Typical Eye Diagram 166
Figure 13.2: BER Contours of a Typical Eye Diagram 166
Table 13.4: Conversion for Root Mean Square Jitter to Peak-to- Peak Jitter 167
Figure 13.3: Jitter Buildup. 167
DISTORTION IN FIBER OPTIC DATA LINKS 167
Figure 13.4: Fiber Optic Receiver — Noise to Jitter Conversion. 168
Figure 13.5: Jitter vs. Optical Loss 168
Figure 13.6: Frequency Spectrum of a Pseudorandom NRZ Data Stream. 169
COMMON TRANSMISSION STANDARDS. 169
Figure 13.7: Communication Standards . . . 169
HIGH-SPEED DATA TRANSMISSION. 170
Figure 13.8: Ethernet Applications for LAN, WAN and SAN 170
Figure 13.9: Multi-protocol High-speed Data Link. 171
FDDI 172
Figure 13.10: FDDI Dual Ring Topology . . . 172
FIBRE CHANNEL. 172
OC-192. 173
OC-768/OC-3072. 173
CONVERGENCE. 173
Figure 13.11: Convergence of 10 Gb/s Data Transmission Over Time . 173
Chapter Summary 173
Selected References and Additional Reading . 174

CHAPTER 14 PUSHING FIBER TO THE LIMITS 175

TRENDS 175
Figure 14.1: Potential System Capacity . . . 175
LIMITS TO FIBER'S GROWTH 176
SPECTRAL EFFICIENCY 176
FORWARD ERROR CORRECTION. 176
The Hamming Code 177
Figure 14.2: Effect of an FEC Algorithm on System BER 178
1R/2R/3R REGENERATION 179
Figure 14.3: 1R/2R/3R Regeneration 179
SOLITONS, RZ, AND NRZ TRANSMISSION 180
Figure 14.4: Typical Soliton Pulse 180
Figure 14.5: NRZ Data Format for 8-Bit Data Sequence (10011101) starting at time "1" and ending at time "9" 181
Figure 14.6: RZ Data Format for 8-Bit Data Sequence (10011101) starting at time "1" and ending at time "9" 181
Dispersion Managed Soliton Transmission . . 182
PMD COMPENSATION 182
Figure 14.7: PMD-limited Distance of OC-48, OC-192 and OC-768. 182
Figure 14.8: Overcoming Chromatic Dispersion and PMD 183
ULTRA LONG-HAUL TELECOMMUNICATIONS 183
Figure 14.9: TDM versus DWDM Fiber Transmission Capacity 183
Long-Haul, OC-192, Multichannel DWDM Transmission 184
THE RECIRCULATING LOOP 184
Figure 14.10: Recirculating Loop Setup . . . 184
Chapter Summary 185
Selected References and Additional Reading. 186

CHAPTER 15 TESTING & MEASUREMENT TECHNIQUES 187

FIBER OPTIC TEST EQUIPMENT 187
Figure 15.1: OTDR 188
Table 15.1: OTDR Settings. 188
Figure 15.2: Fiber Optic Attenuator. 188
COMPONENT MEASUREMENT TECHNIQUES 189
Fiber Measurements 189
Figure 15.3: EMD — Excitation of Graded-index Fiber 189
Figure 15.4: Cable Testing 189
Light Source Measurements 189
Light Detector Measurements 190
Interconnection Loss Measurements 191
Figure 15.5: NA Mismatch Loss 192
Figure 15.6: Core-diameter Mismatch Loss 192
Figure 15.7: Concentricity and Ellipticity . . 192
Figure 15.8: Fiber End Face Finishes 193
Systems Measurements. 194
Chapter Summary 194
Selected References and Additional Reading. 194

CHAPTER 16 FUTURE TRENDS 195

INCREASED FIBER TRANSPARENCY 195
Figure 16.1: 5 Windows in Fiber. 196
ALL-OPTICAL NETWORKS. 196
MULTI-TERABIT TRANSMISSION. 196
COMPETING TECHNOLOGIES 196
EXPANSION INTO MASS MARKETS 197
DWDM and the Internet Demand 197
Figure 16.2: Capacity of Fiber Over Time . . 197
HDTV and Digital Video 198
Figure 16.3: Studio-to-Transmitter Link . . . 198
Smart Highways 198
Figure 16.4: Variable Message Sign Typical in Smart Highway Systems. 199
State-of-the-Art Telecommunication Networks 199
COST REDUCTION. 200
MINIATURIZATION. 200
Figure 16.5: Miniaturization in Data Links . 200
NEW MATERIALS 201
TECHNOLOGY REFINEMENTS. 201
NEW TECHNOLOGY 201
Figure 16.6: Coherent Transmission. 202
Chapter Summary 203
Selected References and Additional Reading. 204

APPENDIX A GENERAL REFERENCE MATERIAL 207

CONCERNING NUMBERS 207
Table A.1: Names and Symbols for Metric Prefixes 207
CONSTANTS. 207
CONVERSION FACTORS 208
Table A.2: Conversion Factors 208

APPENDIX B GLOSSARY OF TERMS 209

APPENDIX C FIBER OPTIC SYMBOLS 239

NATIONAL CABLE TELEVISION ASSOCIATION SYMBOLS. 239
MILITARY SYMBOLS 240

APPENDIX D INDUSTRIAL, TELCORDIA & ITU STANDARDS 241

INDUSTRIAL STANDARDS. 241
TELCORDIA STANDARDS 245
ITU STANDARDS. 248

APPENDIX E SOCIETIES, CONFERENCE SPONSORS & TRADE MAGAZINES 249

SOCIETIES & CONFERENCE SPONSORS 249
FIBER OPTIC & RELATED TRADE MAGAZINES. 251

INDEX 253

LIGHT-EMITTING DIODES

LED's are made of several layers of p-type and n-type semiconductors. A p-n junction generates the photons, and several p-p and n-n junctions direct the photons to create a focused emission of light. The p-p and n-n junctions direct the light by providing energy barriers and changes in the index of refraction. There are two main types of LED's currently being used, surface-emitters and edge-emitters.

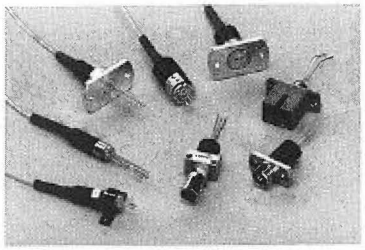


Figure 5.3: Typical Packaged LED's

(Photo courtesy of PD-LD, Inc.)

Surface-emitters are made of layers of semiconducting material that emit light in a 180° arc. They are relatively inexpensive and very reliable, but the emission pattern limits the coupling efficiency with the fiber, and therefore, the power that can be transmitted. Surface-emitters are the most economical of the two types of LED's, but they have low output power and are generally slower devices.

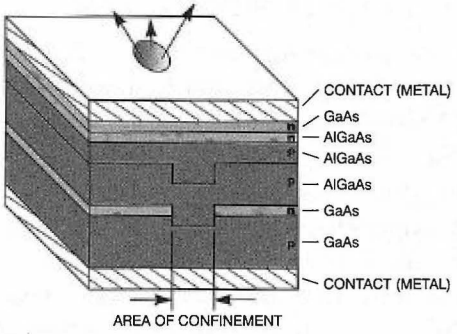


Figure 5.4: Surface-emitting LED

Edge-emitters are designed to confine the light to a narrow path directed out the side of the emitter. This focusing of the light means more power is emitted, and more power can be coupled to the fiber because the path is comparable to the size of the optical fiber core. Edge-emitters can provide high optical power levels (even into smaller core fibers) and are generally faster devices than surface-emitting LED's.

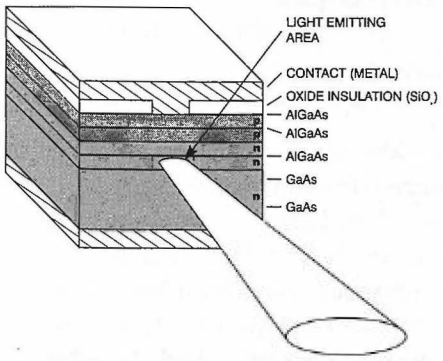


Figure 5.5: Edge-emitting LED

LED's can survive and operate in extreme temperature ranges (up to full military specifications, -55°C to +125°C), although their optical output power can drift considerably as temperature varies. In general, shorter wavelength LED's are less prone to drift over temperature. Also, surface-emitting LED's are almost always more stable over temperature than edge-emitting types. An 850 nm LED may only drift -0.03 dB/°C, while a 1310 nm LED may drift three to five times as much. Always, the LED's optical power drops as the temperature increases.

Temperature also affects the peak emission wavelength. Most LED's exhibit a 0.3 nm/°C to 0.6 nm/°C drift in the peak emission wavelength as temperature varies. This can be important in multi-wavelength systems where there is a possibility of crosstalk, the interference of one channel on another, if the LED wavelength drifts.

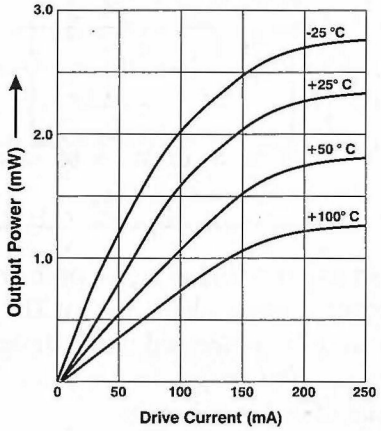


Figure 5.6: Typical LED Behavior versus Temperature

Of the two light source types, LED's are the most widely used for short system fiber optic applications. In general, LED's tend to cost less than laser diodes, although the cost advantage has diminished some, so they find wider application. A common trait of all LED types is that they turn on much faster than they turn off. This is due to the long carrier recombination lifetimes in LED's. Often, this carrier recombination will be in the tens of nanoseconds range. Most LED driver circuits employ special tricks to overcome this, such as applying quick reverse bias to the LED at turn-off to sweep the carriers out of the active region. Even with these circuit tricks, LED's are limited to lower speed applications than laser diodes. Most commercial LED's have a top-end bandwidth of 100-200 MHz. A few specialty LED's are available with bandwidths as high as 600 MHz, according to manufacturer's claims, but still, LED's are only widely used for data rates below 270 Mb/s. Part of the reason is that the wider spectral bandwidth of LED's causes more dispersion in the optical fiber. This increased dispersion severely limits optical signal's maximum transmission distance.

The availability of low-cost CD and DVD lasers has also limited the use of LED's in high data rate applications. These lasers are manufactured in very high volumes (over one million a month) making them very economical. While these lasers were not specifically developed for data applications, they often do very well at data rates of one gigabit per second or more.

LED Driver Circuits

LED optical output is approximately proportional to drive current. Other factors, such as temperature, also affect the optical output. Figure 5.7 shows the typical behavior of an LED. Two curves are shown. The top curve represents a 0.1% duty cycle with the peak

current as shown on the horizontal axis. The bottom curve shows the output with 100% duty cycle. The drop is primarily due to the heating of the LED chip. Most LED's have light versus current curves that droop or fall below a linear curve. A few, such as super-radiant LED's (near lasers) can have curves that bow upward rather than downward.

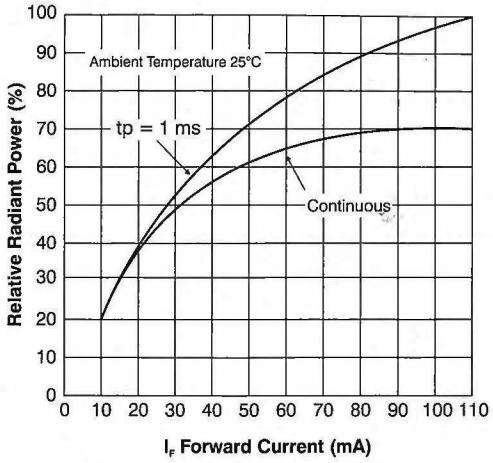
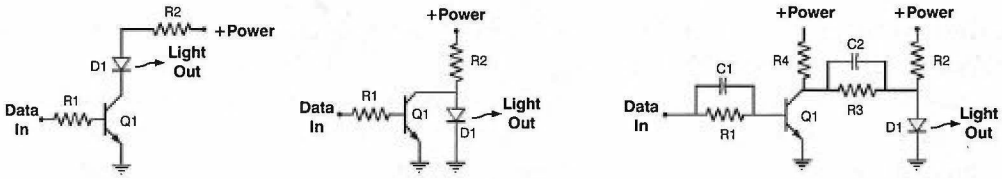


Figure 5.7: Optical Output versus Current in an InGaAsP Light-emitting Diode

LED's are usually driven with either a digital signal or an analog signal. When the drive signal is digital, there is no concern about LED linearity. The LED is either on or off. There are special problems that need to be addressed when designing an LED driver. The key concern is driving the LED so that the maximum speed is achieved. Figures 5.8a, 5.8b and 5.8c show three popular digital LED driver circuits.



(a) Series (b) Shunt (c) Faster

Figure 5.8: LED Driver Circuits

The first circuit, shown in Figure 5.8a, is a simple series driver circuit. The input voltage is applied to the base of transistor Q1 through resistor R1. The transistor will either be off or on. With Q1 in the off condition, no current will flow through the LED, and no light will be emitted. When transistor Q1 is on, the cathode (bottom) of the LED will be pulled low. Transistor Q1 will pull its collector down to about 0.25 Volts. The current is equal to the voltage across resistor R2 divided by the resistance of R2. The voltage across R2 is equal to the power supply voltage less the LED forward voltage drop and the saturation voltage of the drive transistor. This circuit offers the key advantage of a low average power supply current. If one defines the peak LED drive current as I_{LEDmax} and assumes that the LED duty cycle is 50%, then the average power supply current is only $I_{LEDmax}/2$. Further, the power dissipated is $(I_{LEDmax}/2) \bullet V_{SUPPLY}$ where V_{SUPPLY} is the power supply voltage. The power dissipated by the individual components, the LED, transistor and resistor R1, is equal to the voltage drop across each component multiplied by $(I_{LEDmax}/2)$. The key disadvantage of the circuit shown in Figure 5.8a is low speed. This type of driver circuit is rarely used at data rates above 30-50 Mb/s. In general, there are two ways to design an LED drive

circuit for low power dissipation. The first is to use a high-efficiency LED and reduce I_{LEDmax} to the lowest possible value. The second is to reduce the duty cycle of the LED to a low value. Usually larger gains can be made with the second method.

The second LED driver circuit, shown in Figure 5.8b, offers much higher speed capability. It uses transistor Q1 to quickly discharge the LED to turn it off. This circuit, known as a shunt drive circuit, will drive the LED several times faster than the series drive circuit shown in Figure 5.8a. The shunt drive circuit gives greater drive symmetry. In the shunt driver circuit in Figure 5.8b, resistor R2 provides a positive current to turn on the LED. Typically, R2 would be in the 40 Ohm range. This makes the turn-on current about 100 mA peak. Transistor Q1 provides the turn-off current. When saturated, transistor Q1 will have an impedance of a few Ohms. This provides a much larger discharging current allowing the LED to turn off quickly. Power dissipation typically more than doubles in a shunt driver circuit compared to the series driver. In fact, the circuit draws more current and power when the LED is off than when the LED is on! The exact power dissipation can be computed by first analyzing the off and on state currents and then combining the two values using information about the operating duty cycle.

Figure 5.8c shows a variation on the shunt driver shown in Figure 5.8b. Two additional resistors and two capacitors have been added to the basic circuit. These additional components further improve the operating speed. Capacitor C1 improves the turn-on and turn-off characteristics of transistor Q1 itself. Care should be taken to keep the value of C1 down to prevent the transistor base from being overdriven and damaged. The additional components, resistors R3 and R4, and capacitor C2 provide overdrive when the LED is turned on and underdrive when the transistor is turned off. The overdrive and underdrive accelerates the LED transitions. Typically, the RC time constant of R3 and C2 approximately equals the rise or fall time of the LED itself when driven with a square wave. All of these tricks together can increase the operating speed of the LED and driver circuit to about 270 Mb/s. There have been numerous laboratory tests and prototype circuits that have achieved rates to 500-1000 Mb/s, but none of these have made it into mass production. Typically, these levels of performance require a great deal of custom tweaking on each part to achieve the high data rates.

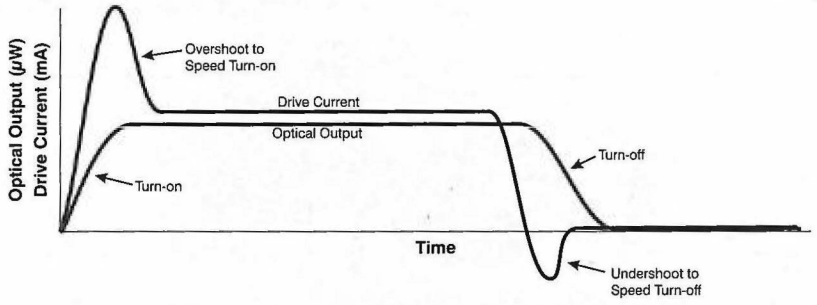


Figure 5.9: Response of an LED to a Digital Modulation Signal

Figure 5.9 shows the response of an LED to a digital modulation signal. The electrical signal shown is the type generated by more sophisticated LED driver circuits such as that shown in Figure 5.8c. Starting at time zero, we first see the digital signal go to a logic level *1*. The most remarkable part of this event is the strong overshoot seen on the electrical drive signal. This overshoot may be two times the steady state logic *1* drive current, and it accelerates the turn-on time or rise time of the LED. Even so, we see that the optical output lags behind the electrical signal.

Typical values for very high-performance LED's and driver circuits would be 0.7 ns rise time of the electrical signal and 1.5 ns optical rise time. Later, when the digital signal goes back to a logic *0*, we see the same process repeated. The electrical signal has a strong undershoot component which acts to accelerate the turn-off of the LED. The undershoot serves to reverse bias the LED, sweeping out the carriers. Even so, the turn-off time of most LED's is always slower than the turn-on time. Typical values for turn-off times are 0.7 ns for the electrical signal and 2.5 ns for the optical signal. Note that while in a logic *0* state, the drive current does not quite go to zero. It is common to provide a small amount of pre-bias current, typically a few percent of the peak drive current, to keep the LED forward biased and improve dynamic response.

LASER DIODES

There are two main types of laser diode structures, Fabry-Perot (FP) and distributed feedback (DFB). DFB lasers offer the highest performance levels and also the highest cost of the two types. They emit nearly monochromatic light (i.e. they emit a very pure single color of light) while FP lasers emit light at a number of discrete wavelengths. DFB lasers tend to be used for the highest speed digital applications and for most analog applications because of their faster speed, lower noise, and superior linearity.

Fabry-Perot lasers further break down into buried hetero (BH) and multi-quantum well (MQW) types. BH and related styles ruled for many years, but now MQW types dominate. MQW lasers offer significant advantages over all former types of Fabry-Perot lasers. They offer lower threshold current, higher slope efficiency, lower noise, better linearity, and much greater stability over temperature. As a bonus, the performance margins of MQW lasers are so great, laser manufacturers get better yields, so laser cost is reduced. One disadvantage of MQW lasers is their tendency to be more susceptible to backreflections. MQW lasers also perform poorly as detectors, making them ill-suited for ping-pong applications (described at the end of this chapter).

Most laser diodes used for fiber optic communications incorporate a rear facet photodiode to provide a real-time means of monitoring the output of the laser. This is necessary because the threshold current of the laser changes with temperature as does slope efficiency. (Figure 5.19, later in this chapter, shows these effects.) Vertical cavity surface-emitting lasers (VCSEL's), discussed later, are one of the exceptions. They have very stable characteristics over time and often omit monitor photodiodes.

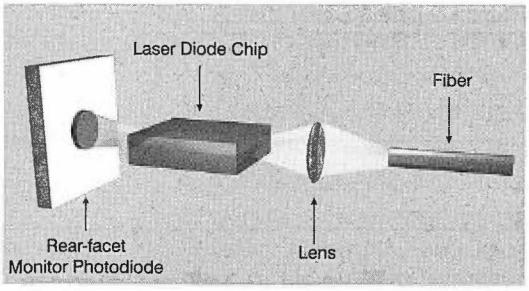


Figure 5.10: Laser Construction

Figure 5.10 shows the typical optical construction of a laser diode. The laser diode chip emits light in two directions. The light from one end of the laser chip is focused onto the fiber and provides the useful output. The light from the other end falls on a large area photodiode. Usually, this photodiode is mounted some distance from the laser chip and is angled to reduce backreflections into the laser cavity.