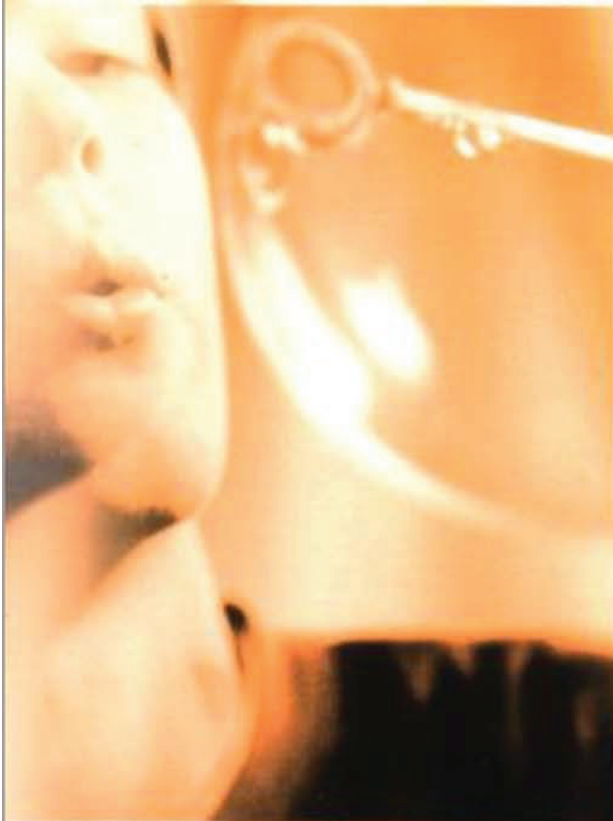




OPTICAL COMMUNICATIONS ESSENTIALS



- Clear, rapid introduction to any topic
- Optical fiber and components
- DWDM and CWDM
- Links design and performance fundamentals
- Network management, testing, and manufacturing
- Web access to interactive simulation tool

GERD KEISER

The McGraw-Hill Companies

Library of Congress Cataloging-in-Publication Data

Keiser, Gerd,

Optical communications essentials / Gerd Keiser.

p. cm.

Includes bibliographical references and index.

ISBN 0-07-141204-2 (alk. paper)

1. Optical communications. I. Title.

TK5103.59.K42 2003

621.3827—dc21

2003051171

Copyright © 2003 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 9 8 7 6 5 4 3

ISBN 0-07-141204-2

The sponsoring editor for this book was Stephen S. Chapman, the editing supervisor was David E. Fogarty, and the production supervisor was Sherri Souffrance. It was set in Century Schoolbook by Macmillan India Ltd. The art director for the cover was Handel Low.

Printed and bound by RR Donnelley.



This book was printed on recycled, acid-free paper containing a minimum of 50% recycled, de-inked fiber.

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, Professional Publishing, McGraw-Hill, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

Contents

Preface	xvii
Acknowledgments	xix

Chapter 1. Basic Concepts of Communication Systems	1
1.1. Definitions	2
1.2. Analog Signal Formats	4
1.3. Digital Signal Formats	6
1.4. Digitization of Analog Signals	7
1.5. Electromagnetic Spectrum	9
1.5.1. Telecommunication Spectral Band	9
1.5.2. Optical Communications Band	10
1.6. Transmission Channels	11
1.6.1. Carrier Waves	11
1.6.2. Baseband Signals	12
1.7. Signal Multiplexing	12
1.8. SONET/SDH Multiplexing Hierarchy	14
1.9. Decibels	15
1.10. Simulation Programs	18
1.11. Summary	19
Further Reading	20
Chapter 2. Optical Communication Systems Overview	21
2.1. Motivations for Using Optical Fiber Systems	21
2.2. Evolution of Optical Communications	22
2.3. Elements of an Optical Link	26
2.4. WDM Concept	28
2.5. Applications of Optical Fiber Links	29
2.6. Optical Networking and Switching	30
2.7. Standards for Optical Communications	31
2.8. Summary	32
Further Reading	33

Chapter 3. The Behavior of Light	35
3.1. The Dual Wave-Particle Nature of Light	35
3.2. The Speed of Light	36
3.3. Measuring Properties of Light	36
3.4. Refractive Index	37
3.5. Reflection and Refraction	38
3.6. Polarization	40
3.6.1. Unpolarized Light	40
3.6.2. Polarizers	42
3.6.3. Faraday Rotators	42
3.6.4. Double-Refractive Crystals	43
3.7. Summary	44
Further Reading	45
Chapter 4. Optical Fibers	47
4.1. Light Propagation in Fibers	47
4.2. Optical Fiber Modes	49
4.3. Variations of Fiber Types	50
4.4. Single-Mode Fibers	52
4.5. Optical Fiber Attenuation	52
4.6. Fiber Information Capacity	55
4.7. Optical Fiber Standards	58
4.8. Specialty Fibers	60
4.8.1. Erbium-Doped Fiber	60
4.9. Summary	63
Further Reading	64
Chapter 5. Optical Fiber Cables	67
5.1. Fiber-Related Design Issues	67
5.1.1. Fiber Strength	68
5.1.2. Dielectric Nature of Fibers	68
5.1.3. Small Size and Low Weight	68
5.2. Cable Materials and Structures	69
5.2.1. Tight-Buffered Fiber Cable	70
5.2.2. Loose-Tube Cable Configuration	71
5.2.3. Ribbon Cable	72
5.3. Indoor Cables	72
5.3.1. Indoor Cable Designs	72
5.3.2. Indoor Cable Applications	74
5.4. Outdoor Cables	75
5.4.1. Aerial Cable	75
5.4.2. Armored Cable	77
5.4.3. Underwater Cable	77
5.4.4. Military Cable	78
5.5. Fiber and Jacket Color Coding	78
5.6. Installation Methods	80
5.6.1. Direct-Burial Installations	80
5.6.2. Pulling into Ducts	82
5.6.3. Air-Assisted Installation	83

Contents	xi
5.6.4. Aerial Installation	84
5.6.5. Submarine Installation	85
5.7. Summary	85
Further Reading	86
Chapter 6. Light Sources and Transmitters	87
6.1. General Source Characteristics	87
6.1.1. Materials	87
6.1.2. Spectral Output Width	89
6.1.3. Modulation Speed	89
6.2. LEDs	90
6.2.1. Principles of Operation	90
6.2.2. Surface Emitters	91
6.2.3. Edge Emitters	92
6.3. Laser Diodes	93
6.3.1. Fabry-Perot Laser	96
6.3.2. Distributed-Feedback Laser	97
6.3.3. Tunable Lasers	98
6.3.4. Vertical Cavity Surface Emitting Laser	98
6.3.5. Pump Lasers	99
6.4. Optical Transmitters	99
6.4.1. LED Transmitters	99
6.4.2. Laser Transmitters	100
6.4.3. Transmitter Controllers	101
6.4.4. Transmitter Packages	101
6.5. External Modulators	102
6.6. Summary	104
Further Reading	105
Chapter 7. Photodiodes and Receivers	107
7.1. The <i>pin</i> Photodiode	107
7.1.1. Operation of a <i>pin</i> Photodiode	108
7.1.2. Photodetector Materials	109
7.1.3. Quantum Efficiency	110
7.1.4. Responsivity	110
7.1.5. Speed of Response	111
7.1.6. Bandwidth	112
7.2. Avalanche Photodiodes	113
7.3. Comparisons of Photodetectors	113
7.4. Optical Receiver	114
7.4.1. Photodetector Noise	114
7.4.2. Noise Sources	115
7.5. Summary	116
Further Reading	117
Chapter 8. Connectors and Splices	119
8.1. Source-to-Fiber Power Coupling	119
8.1.1. Source Output Pattern	120
8.1.2. Power Coupling Calculation	121
8.1.3. Lensed Fibers	122
8.1.4. End-Face Reflections	123

8.2. Mechanics of Fiber Joints	124
8.2.1. Mechanical Misalignments	124
8.2.2. Misalignment Effects	124
8.3. Fiber-Related Losses	126
8.4. End-Face Preparation	127
8.4.1. Grinding and Polishing	127
8.4.2. Controlled Fracture	128
8.4.3. End-Face Quality	128
8.5. Optical Connector Features	129
8.5.1. Design Requirements	130
8.5.2. Connector Components	130
8.6. Optical Connector Types	131
8.7. Optical Splices	137
8.7.1. Splicing Issues	138
8.7.2. Splicing Methods	139
8.8. Summary	140
Further Reading	141
 Chapter 9. Passive Optical Components	 143
9.1. Optical Couplers	144
9.1.1. Basic 2×2 Coupler	144
9.1.2. Coupler Performance	145
9.1.3. Tap Coupler	148
9.1.4. Star Coupler	148
9.1.5. Mach-Zehnder Interferometer	149
9.2. Isolators and Circulators	150
9.2.1. Optical Isolators	150
9.2.2. Optical Circulators	152
9.3. Dielectric Thin-Film Filters	153
9.4. Gratings	156
9.4.1. Grating Principle	156
9.4.2. Fiber Bragg Gratings	157
9.5. Summary	159
Further Reading	160
 Chapter 10. Active Optical Components	 161
10.1. Overview of Major Components	161
10.2. MEMS Technology	163
10.3. Variable Optical Attenuators	165
10.4. Tunable Optical Filters	166
10.5. Dynamic Gain Equalizers	168
10.6. Optical Add/Drop Multiplexers	169
10.7. Polarization Controllers	170
10.8. Chromatic Dispersion Compensators	171
10.9. Summary	172
Further Reading	173
 Chapter 11. Optical Amplifiers	 175
11.1. Basic Applications	176
11.2. Amplification Mechanism	177

11.3. Semiconductor Optical Amplifiers	178
11.3.1. SOA Construction	178
11.3.2. Basic SOA Parameters	179
11.4. Erbium-Doped Fiber Amplifier (EDFA)	182
11.4.1. Amplification Mechanism	182
11.4.2. EDFA Configurations	184
11.4.3. EDFA Pump Lasers	184
11.4.4. EDFA Noise	186
11.4.5. Operation in the L-Band	188
11.5. Raman Amplification	189
11.6. Wavelength Conversion	190
11.6.1. Optical-Gating Wavelength Converters	192
11.6.2. Wave-Mixing Wavelength Converters	193
11.7. Summary	194
Further Reading	195
 Chapter 12. Wavelength Division Multiplexing	 197
12.1. Operational Principles of WDM	198
12.1.1. WDM Operating Regions	199
12.1.2. WDM Standards	200
12.1.3. Generic WDM Link	202
12.2. Multiplexers for WDM	203
12.2.1. Thin-Film Filters	203
12.2.2. Fiber Bragg Gratings	204
12.2.3. Arrayed Waveguide Gratings	206
12.2.4. Diffraction Gratings	208
12.2.5. Interleavers	210
12.3. Wavelength Lockers	212
12.4. Summary	214
Further Reading	215
 Chapter 13. Constructing the WDM Network Puzzle	 217
13.1. Network Requirements	217
13.1.1. Wideband Long-Haul WDM Network	218
13.1.2. Narrowband Metro WDM Network	219
13.2. Component Performance in WDM Links	221
13.2.1. DWDM Optical Transmitters	221
13.2.2. CWDM Optical Transmitters	222
13.2.3. Wavelength Multiplexing Devices	223
13.2.4. Interleavers	224
13.2.5. Wideband Optical Amplifiers	225
13.2.6. Metro Optical Amplifiers	226
13.2.7. Optical Add/Drop Multiplexer	227
13.2.8. Chromatic Dispersion Compensation	227
13.2.9. Polarization Mode Dispersion Compensation	228
13.3. WDM Network Applications	228
13.3.1. DWDM Networks	228
13.3.2. CWDM Networks	229
13.4. Performance Monitoring Needs	230
13.5. Summary	231
Further Reading	231

Chapter 14. Performance Measures	233
14.1. Digital Link Performance	233
14.1.1. Bit Error Rate	234
14.1.2. Eye Diagrams	234
14.2. Optical Signal-to-Noise Ratio	237
14.3. Analog Link Performance	239
14.3.1. Carrier-to-Noise Ratio (CNR)	239
14.3.2. Limiting Conditions on CNR	241
14.4. Measuring Performance Parameters	243
14.5. Summary	244
Further Reading	244
Chapter 15. Performance Impairments	247
15.1. Impairment Effects	247
15.2. Chromatic Dispersion	248
15.3. Dispersion Compensation	250
15.3.1. Dispersion-Compensating Fiber	250
15.3.2. Bragg Grating Compensators	252
15.4. Polarization Mode Dispersion (PMD)	253
15.5. Nonlinear Effects	254
15.5.1. Effective Length and Area	255
15.5.2. Stimulated Raman Scattering	256
15.5.3. Stimulated Brillouin Scattering	257
15.5.4. Self-Phase Modulation and Cross-Phase Modulation	258
15.5.5. Four-Wave Mixing	259
15.6. Summary	260
Further Reading	261
Chapter 16. Optical Link Design	263
16.1. System Considerations	263
16.1.1. System Requirements	264
16.1.2. Link Margin	265
16.1.3. Power Penalties	265
16.2. Link Power Budget	266
16.2.1. Power Budgeting Process	267
16.2.2. Fast Ethernet LAN Example	268
16.2.3. SONET/SDH Link Example	269
16.2.4. DWDM Link Example	271
16.3. Rise-Time Budget	271
16.3.1. Basic Rise Times	272
16.3.2. Multimode LAN Link Rise Time	274
16.3.3. SONET Link Rise Time	275
16.4. Line Coding	275
16.4.1. NRZ and RZ Signal Formats	276
16.4.2. Block Codes	277
16.5. Forward Error Correction	277
16.6. Modeling and Simulation Tools	278
16.7. Summary	279
Further Reading	280

Chapter 17. Optical Networks	281
17.1. General Network Concepts	281
17.1.1. Types of Networks	282
17.1.2. Network Terminology	283
17.1.3. Network Layers	285
17.1.4. Optical Layer	287
17.2. SONET/SDH	287
17.2.1. SONET Transmission Formats	288
17.2.2. Optical Interfaces	290
17.2.3. SONET/SDH Rings	292
17.2.4. SONET/SDH Networks	296
17.3. Optical Ethernet	298
17.4. IP over WDM	298
17.5. Optical Transport Networks (OTNs)	299
17.5.1. Optical Network Services	300
17.5.2. OTN Standards	300
17.5.3. Wavelength Routing	300
17.6. FTTx	301
17.7. Summary	302
Further Reading	303
 Chapter 18. Network Management	 305
18.1. Management Architecture	306
18.2. Basic Management Functions	307
18.2.1. Performance Management	308
18.2.2. Configuration Management	308
18.2.3. Accounting Management	308
18.2.4. Fault Management	309
18.2.5. Security Management	310
18.3. Management Protocols	311
18.3.1. SNMP	311
18.3.2. RMON	311
18.4. Optical Layer Management	312
18.5. Element Management	315
18.5.1. Error Monitoring	315
18.5.2. Wavelength Management	316
18.5.3. Element Monitoring	316
18.6. Optical Service Channel	317
18.7. Summary	318
Further Reading	319
 Chapter 19. Test and Measurement	 321
19.1. Measurement Standards	322
19.2. Basic Test Equipment	324
19.3. Optical Power Measurements	325
19.3.1. Definition of Optical Power	325
19.3.2. Optical Power Meters	326
19.3.3. Optical Power Attenuators	327
19.4. Test-Support Lasers	328
19.5. Optical Spectrum Analyzer	329

xvi Contents

19.6. Optical Time-Domain Reflectometer	330
19.6.1. OTDR Trace	331
19.6.2. Fiber Fault Location	332
19.7. Multifunction Optical Test Systems	332
19.8. Summary	333
Further Reading	334
 Chapter 20. Manufacturing Issues	 335
20.1. Fiber Fabrication	335
20.1.1. Outside Vapor-Phase Oxidation	336
20.1.2. Vapor-Phase Axial Deposition	337
20.1.3. Modified Chemical Vapor Deposition	338
20.1.4. Plasma-Activated Chemical Vapor Deposition	338
20.2. Component Designs	338
20.2.1. Planar Lightwave Circuits	339
20.2.2. Athermal Designs	341
20.3. Integrated Automation	342
20.4. Packaging	344
20.4.1. Optical Connection	344
20.4.2. Thermal Management	344
20.4.3. Mechanical Concerns	345
20.4.4. Hermetic Sealing	346
20.5. Emerging Package Technology	347
20.6. Summary	347
Further Reading	348
 Appendix A. Units, Physical Constants, and Conversion Factors	 349
Appendix B. ITU-T Frequency and Wavelength Grid	351
Appendix C. Acronyms	355
 Index	 361

Basic Concepts of Communication Systems

Ever since ancient times, people continuously have devised new techniques and technologies for communicating their ideas, needs, and desires to others. Thus, many forms of increasingly complex communication systems have appeared over the years. The basic motivations behind each new one were to improve the transmission fidelity so that fewer errors occur in the received message, to increase the transmission capacity of a communication link so that more information could be sent, or to increase the transmission distance between relay stations so that messages can be sent farther without the need to restore the signal fidelity periodically along its path.

Prior to the nineteenth century, all communication systems operated at a very low information rate and involved only optical or acoustical means, such as signal lamps or horns. One of the earliest known optical transmission links, for example, was the use of a fire signal by the Greeks in the eighth century B.C. for sending alarms, calls for help, or announcements of certain events. Improvements of these systems were not pursued very actively because of technology limitations at the time. For example, the speed of sending information over the communication link was limited since the transmission rate depended on how fast the senders could move their hands, the receiver was the human eye, line-of-sight transmission paths were required, and atmospheric effects such as fog and rain made the transmission path unreliable. Thus it turned out to be faster, more efficient, and more dependable to send messages by a courier over the road network.

The invention of the telegraph by Samuel F. B. Morse in 1838 ushered in a new epoch in communications—the era of electrical communications. In the ensuing years increasingly sophisticated and more reliable electrical communication systems with progressively larger information capacities were developed and deployed. This activity led to the birth of free-space radio, television, microwave, and satellite links, and high-capacity terrestrial and undersea wire lines for sending voice and data (and advertisements!) to virtually anywhere in the world.

2 Chapter One

However, since the physical characteristics of both free-space and electric wire-based communication systems impose an upper bound on the transmission capacities, alternative transmission media were investigated. A natural extension was the use of optical links. After extensive research and development on the needed electrooptical components and the glass equivalent of a copper wire, optical fiber communication systems started to appear in the 1970s. It is this technology that this book addresses.

To exchange information between any two devices in a communication system, some type of electric or optical signal which carries this information has to be transmitted from one device to the other via a communication channel. This channel could consist of a wire, radio, microwave, satellite, infrared, or optical fiber link. Each of the media used for such communication channels has unique performance characteristics associated with it. Regardless of its type, the medium degrades the fidelity of the transmitted signal because of an imperfect response to the signal and because of the presence of electrical and/or optical noise and interference. This can lead to misinterpretations of the signal by the electronics at the receiving end. To understand the various factors that affect the physical transfer of information-bearing signals, this chapter gives a basic overview of fundamental data communication concepts. With that as a basis, the following chapters will describe how information is transferred using lightwave technology.

1.1. Definitions

We start by giving some concepts and definitions used in data communications and the possible formats of a signal. The signal format is an important factor in efficiently and reliably sending information across a network.

A basic item that appears throughout any communications book is the prefix used in metric units for designating parameters such as length, speed, power level, and information transfer rate. Although many of these are well known, a few may be new to some readers. As a handy reference, Table 1.1 lists standard prefixes, their symbols, and their magnitudes, which range in size from 10^{24} to 10^{-24} . As an example, a distance of 2×10^{-9} m (meters) = 2 nm (nanometers). The three highest and lowest designations are not especially common in communication systems (yet!), but are included in Table 1.1 for completeness.

Next let us define some terms and concepts that are used in communications.

- *Information* has to do with the content or interpretation of something such as spoken words, a still or moving image, the measurement of a physical characteristic, or values of bank accounts or stocks.
- A *message* may be considered as the physical manifestation of the information produced by the source. That is, it can range from a single number or symbol to a long string of sentences.
- The word *data* refers to facts, concepts, or instructions presented as some type of encoded entities that are used to convey the information. These can include

TABLE 1.1. Metric Prefixes, Their Symbols, and Their Magnitudes

Prefix	Symbol	Decimal	Magnitude	Multiple
yotta	Y			10^{24}
zetta	Z			10^{21}
exa	E			10^{18}
peta	P		Quadrillion	10^{15}
tera	T		Trillion	10^{12}
giga	G	1,000,000,000	Billion	10^9
mega	M	1,000,000	Million	10^6
kilo	k	1,000	Thousand	10^3
centi	c	0.01	Hundredth	10^{-2}
milli	m	0.001	Thousandth	10^{-3}
micro	μ	0.000001	Millionth	10^{-6}
nano	n	0.000000001	Billionth	10^{-9}
pico	p		Trillionth	10^{-12}
femto	f		Quadrillionth	10^{-15}
atto	a			10^{-18}
zepto	z			10^{-21}
yocto	y			10^{-24}

arrays of integers, lines of text, video frames, digital images, and so on. Although the words *data* and *message* each have a specific definition, these terms often are used interchangeably in the literature since they represent physical embodiments of information.

- *Signals* are electromagnetic waves (in encoded electrical or optical formats) used to transport the data over a physical medium.

A block diagram of an elementary communication link is shown in Fig. 1.1. The purpose of such a link is to transfer a message from an originating user, called a *source*, to another user, called the *destination*. In this case, let us assume the end users are two communicating computers attached to different local area networks (LANs). The output of the information source serves as the message input to a transmitter. The function of the *transmitter* is to couple the message onto a *transmission channel* in the form of a time-varying signal that matches the transfer properties of the channel. This process is known as *encoding*.

As the signal travels through the channel, various imperfect properties of the channel induce impairments to the signal. These include electrical or optical noise effects, signal distortions, and signal attenuation. The function of the *receiver* is to extract the weakened and distorted signal from the channel, amplify it, and restore it as closely as possible to its original encoded form before *decoding* it and passing it on to the message destination.

4 Chapter One

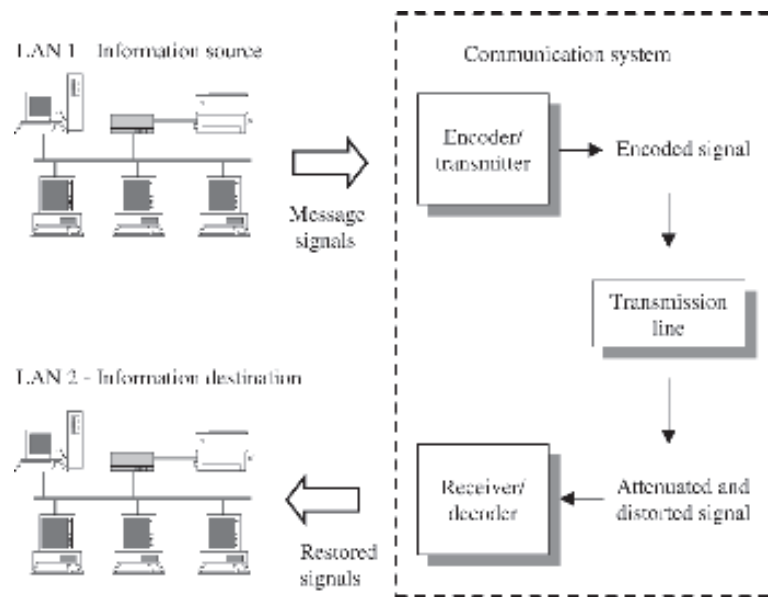


Figure 1.1. Block diagram of a typical communication link connecting separate LANs.

1.2. Analog Signal Formats

The signals emitted by information sources and the signals sent over a transmission channel can be classified into two distinct categories according to their physical characteristics. These two categories encompass analog and digital signals.

An *analog signal* conveys information through a *continuous and smooth variation in time* of a physical quantity such as optical, electrical, or acoustical intensities and frequencies. Well-known analog signals include audio (sound) and video messages. As examples,

- An optical signal can vary in color (which is given in terms of its wavelength or its frequency, as described in Chap. 3), and its intensity may change from dim to bright.
- An electric signal can vary in frequency (such as the kHz, MHz, GHz designations in radio communications), and its intensity can range from low to high voltages.
- The intensity of an acoustical signal can range from soft to loud, and its tone can vary from a low rumble to a very high pitch.

The most fundamental *analog signal* is the periodic *sine wave*, shown in Fig. 1.2. Its three main characteristics are its amplitude, period or frequency, and phase. The *amplitude* is the size or magnitude of the waveform. This is generally designated by the symbol A and is measured in *volts*, *amperes*, or *watts*, depending on the signal type. The *frequency* (designated by f) is the

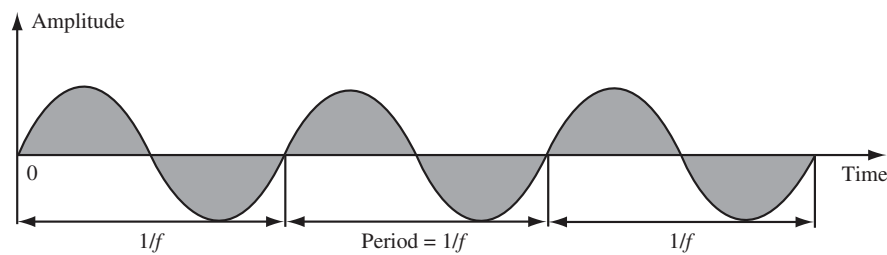


Figure 1.2. Characteristics of a basic sine wave.

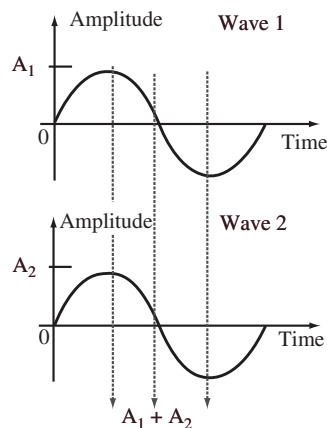


Figure 1.3. Two in-phase waves will add constructively.

number of cycles per second that the wave undergoes (i.e., the number of times it oscillates per second), which is expressed in units of *hertz* (Hz). A hertz refers to a complete cycle of the wave. The *period* (generally represented by the symbol T) is the inverse of the frequency, that is, period = $T = 1/f$. The term *phase* (designated by the symbol ϕ) describes the position of the waveform relative to time 0, as illustrated in Fig. 1.3. This is measured in *degrees* or *radians* (rad): $180^\circ = \pi$ rad.

If the crests and troughs of two identical waves occur at the same time, they are said to be *in phase*. Similarly, if two points on a wave are separated by whole measurements of time or of wavelength, they also are said to be in phase. For example, wave 1 and wave 2 in Fig. 1.3 are in phase. Let wave 1 have an amplitude A_1 and let wave 2 have an amplitude A_2 . If these two waves are added, the amplitude A of the resulting wave will be the sum: $A = A_1 + A_2$. This effect is known as *constructive interference*.

Figure 1.4 illustrates some *phase shifts* of a wave relative to time 0. When two waves differ slightly in their relative positions, they are said to be *out of phase*. As an illustration, the wave shown in Fig. 1.4c is 180° (π rad) out of phase with the wave shown in Fig. 1.4a. If these two waves are identical and have the same amplitudes, then when they are superimposed, they cancel each other out, which is known as *destructive interference*. These concepts are of

6 Chapter One

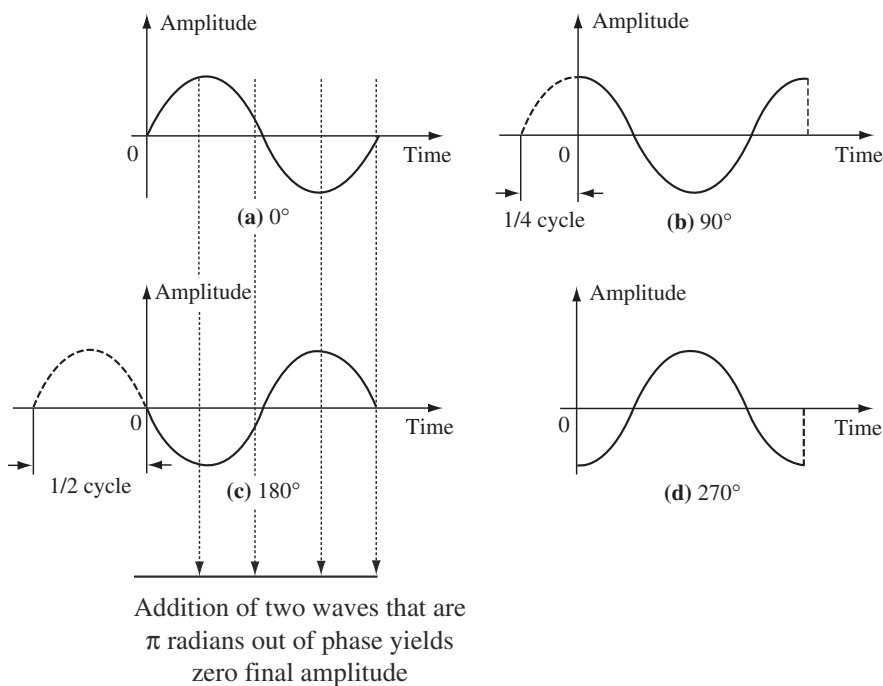


Figure 1.4. Examples of phase differences between two sine waves. Two waves that are 180° out of phase will add destructively.

importance when one is considering the operation of optical couplers, as described in Chap. 8.

Example

- A sine wave has a frequency $f = 5 \text{ kHz}$. Its period is $T = 1/5000 \text{ s} = 0.20 \text{ ms}$.
- A sine wave has a period $T = 1 \text{ ns}$. Its frequency is $f = 1/(10^{-9} \text{ s}) = 1 \text{ GHz}$.
- A sine wave is offset by $1/4$ cycle with respect to time 0. Since 1 cycle is 360° , the phase shift is $\phi = 0.25 \times 360^\circ = 90^\circ = \pi/2 \text{ rad}$.

Two further common characteristics in communications are the frequency spectrum (or simply spectrum) and the bandwidth of a signal. The *spectrum* of a signal is the range of frequencies that it contains. That is, the spectrum of a signal is the combination of all the individual sine waves of different frequencies which make up that signal. The *bandwidth* (designated by B) refers to the width of this spectrum.

Example If the spectrum of a signal ranges from its lowest frequency $f_{\text{low}} = 2 \text{ kHz}$ to its highest frequency $f_{\text{high}} = 22 \text{ kHz}$, then the bandwidth $B = f_{\text{high}} - f_{\text{low}} = 20 \text{ kHz}$.

1.3. Digital Signal Formats

A *digital signal* is an ordered sequence of *discrete symbols* selected from a finite set of elements. Examples of digital signals include the letters of an alphabet,

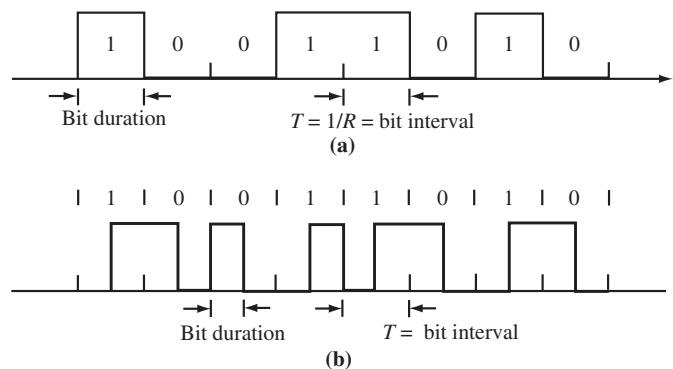


Figure 1.5. Examples of two binary waveforms showing their amplitude, period, and bit duration. (a) The bit fills the entire period for 1 bit only; (b) a 1 bit fills the first half and a 0 bit fills the second half of a period.

numbers, and other symbols such as @, #, or %. These discrete symbols are normally represented by unique patterns of pulses of electric voltages or optical intensity that can take on two or more levels.

A common digital signal configuration is the *binary* waveform shown in Fig. 1.5. A binary waveform is represented by a sequence of two types of pulses of known shape. The information contained in a digital signal is given by the particular sequence of the presence (a *binary one*, or simply either *one* or 1) and absence (a *binary zero*, or simply either *zero* or 0) of these pulses. These are known commonly as *bits* (this word was derived from binary digits). Since digital logic is used in the generation and processing of 1 and 0 bits, these bits often are referred to as a *logic one* (or *logic 1*) and a *logic zero* (or *logic 0*), respectively.

The time slot T in which a bit occurs is called the *bit interval*, *bit period*, or *bit time*. (Note that this T is different from the T used for designating the period of a waveform.) The bit intervals are regularly spaced and occur every $1/R$ seconds (s), or at a rate of R *bits per second* (abbreviated as bps in this book), where R is called the *bit rate* or the *data rate*. As an example, a data rate of 2×10^9 bits per second (bps) = 2 Gbps (gigabits per second). A bit can fill the entire bit interval or part of it, as shown in Fig. 1.5a and b, respectively.

A block of 8 bits often is used to represent an encoded symbol or word and is referred to as an *octet* or a *byte*.

1.4. Digitization of Analog Signals

An analog signal can be transformed to a digital signal through a process of periodic sampling and the assignment of quantized values to represent the intensity of the signal at regular intervals of time.

To convert an analog signal to a digital form, one starts by taking instantaneous measures of the height of the signal wave at regular intervals, which is called *sampling* the signal. One way to convert these analog samples to a

8 Chapter One

digital format is to simply divide the amplitude excursion of the analog signal into N equally spaced levels, designated by integers, and to assign a discrete binary word to each of these N integer values. Each analog sample is then assigned one of these integer values. This process is known as *quantization*. Since the signal varies continuously in time, this process generates a sequence of real numbers.

Example Figure 1.6 shows an example of digitization. Here the allowed voltage-amplitude excursion is divided into eight equally spaced levels ranging from 0 to V volts (V). In this figure, samples are taken every second, and the nearest discrete quantization level is chosen as the one to be transmitted, according to the 3-bit binary code listed next to the quantized levels shown in Fig. 1.6. At the receiver this digital signal is then demodulated. That is, the quantized levels are reassembled into a continuously varying analog waveform.

Nyquist Theorem Note that the equally spaced levels in Fig. 1.6 are the simplest quantization implementation, which is produced by a *uniform quantizer*. Frequently it is more advantageous to use a *nonuniform quantizer* where the quantization levels are roughly proportional to the signal level. The companders used in telephone systems are an example of this.

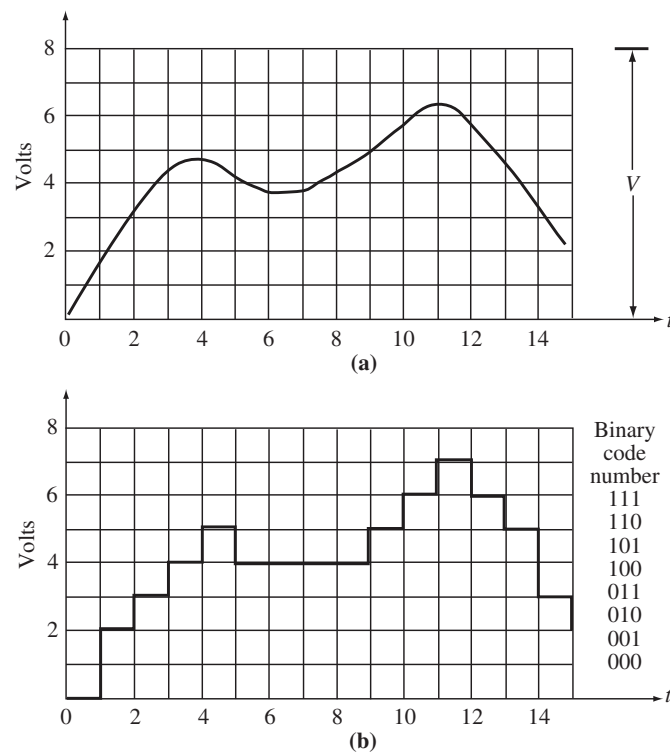


Figure 1.6. Digitization of analog waveforms. (a) Original signal varying between 0 and V volts; (b) quantized and sampled digital version.

Intuitively, one can see that if the digitization samples are taken frequently enough relative to the rate at which the signal varies, then to a good approximation the signal can be recovered from the samples by drawing a straight line between the sample points. The resemblance of the reproduced signal to the original signal depends on the fineness of the quantizing process and on the effect of noise and distortion added into the transmission system. According to the *Nyquist theorem*, if the sampling rate is at least 2 times the highest frequency, then the receiving device can faithfully reconstruct the analog signal. Thus, if a signal is limited to a bandwidth of B Hz, then the signal can be reproduced without distortion if it is sampled at a rate of $2B$ times per second. These data samples are represented by a binary code. As noted in Fig. 1.6, eight quantized levels having upper bounds $V_1, V_2, \dots, V$ can be described by 3 binary digits ($2^3 = 8$). More digits can be used to give finer sampling levels. That is, if n binary digits represent each sample, then one can have 2^n quantization levels.

1.5. Electromagnetic Spectrum

To understand the distinction between electrical and optical communication systems and what the advantages are of lightwave technology, let us examine the spectrum of electromagnetic (EM) radiation shown in Fig. 1.7.

1.5.1. Telecommunication spectral band

All telecommunication systems use some form of electromagnetic energy to transmit signals from one device to another. Electromagnetic energy is a combination of electrical and magnetic fields and includes power, radio waves, microwaves, infrared light, visible light, ultraviolet light, x rays, and gamma rays. Each of these makes up a portion (or band) of the electromagnetic spectrum. The fundamental nature of all radiation within this spectrum is the same in that it can be viewed as electromagnetic waves that travel at the speed of light, which is

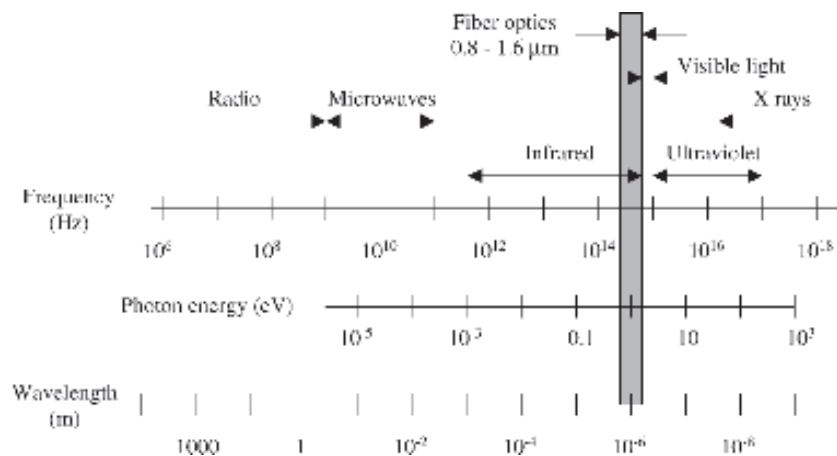


Figure 1.7. The spectrum of electromagnetic radiation.

10 Chapter One

about $c = 300,000$ kilometers per second (3×10^8 m/s) or 180,000 miles per second (1.8×10^5 mi/s) in a vacuum. Note that the speed of light in a material is less than c , as described in Chap. 3.

The physical property of the radiation in different parts of the spectrum can be measured in several interrelated ways. These are the length of one period of the wave, the energy contained in the wave, or the oscillating frequency of the wave. Whereas electric signal transmission tends to use frequency to designate the signal operating bands, optical communications generally use *wavelength* to designate the spectral operating region and *photon energy* or *optical power* when discussing topics such as signal strength or electrooptical component performance. We will look at the measurement units in greater detail in Chap. 3.

1.5.2. Optical communications band

The optical spectrum ranges from about 5 nm (ultraviolet) to 1 mm (far infrared), the visible region being the 400- to 700-nm band. Optical fiber communications use the spectral band ranging from 800 to 1675 nm.

The International Telecommunications Union (ITU) has designated six spectral bands for use in intermediate-range and long-distance optical fiber communications within the 1260- to 1675-nm region. As Chap. 4 describes, these band designations arose from the physical characteristics of optical fibers and the performance behavior of optical amplifiers. As shown in Fig. 1.8, the regions are known by the letters O, E, S, C, L, and U, which are defined as follows:

- Original band (O-band): 1260 to 1360 nm
- Extended band (E-band): 1360 to 1460 nm
- Short band (S-band): 1460 to 1530 nm
- Conventional band (C-band): 1530 to 1565 nm
- Long band (L-band): 1565 to 1625 nm
- Ultralong band (U-band): 1625 to 1675 nm

The operational performance characteristics and applications of optical fibers, electrooptic components, and other passive optical devices for use in these bands are described in later chapters.

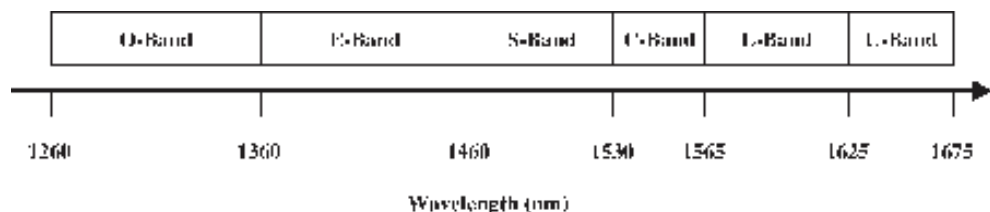


Figure 1.8. Definitions of spectral bands for use in optical fiber communications.

1.6. Transmission Channels

Depending on what portion of the electromagnetic spectrum is used, electromagnetic signals can travel through a vacuum, air, or other transmission media. For example, electricity travels well through copper wires but not through glass. Light, on the other hand, travels well through air, glass, and certain plastic materials but not through copper.

1.6.1. Carrier waves

As electrical communication systems became more sophisticated, an increasingly greater portion of the electromagnetic spectrum was utilized for conveying larger amounts of information faster from one place to another. The reason for this development trend is that in electrical systems the physical properties of various transmission media are such that each medium type has a different frequency band in which signals can be transported efficiently. To utilize this property, information usually is transferred over the communication channel by superimposing the data onto a sinusoidally varying electromagnetic wave, which has a frequency response that matches the transfer properties of the medium. This wave is known as the *carrier*. At the destination the information is removed from the carrier wave and processed as desired. Since the amount of information that can be transmitted is directly related to the frequency range over which the carrier operates, increasing the carrier frequency theoretically increases the available transmission bandwidth and, consequently, provides a larger information capacity.

To send digital information on a carrier wave, one or more of the characteristics of the wave such as its amplitude, frequency, or phase are varied. This kind of modification is called *modulation* or *shift keying*, and the digital information signal is called the *modulating signal*. Figure 1.9 shows an example of *amplitude shift keying* (ASK) or *on/off keying* (OOK) in which the strength (amplitude) of the carrier wave is varied to represent 1 or 0 pulses. Here a high amplitude represents a 1 and a low amplitude is a 0.

Thus the trend in electrical communication system developments was to employ progressively higher frequencies, which offer corresponding increases in bandwidth or information capacity. However, beyond a certain carrier frequency, electrical transmission systems become extremely difficult to design, build, and operate. These limitations, plus the inherent advantages of smaller sizes and lower weight of dielectric transmission materials

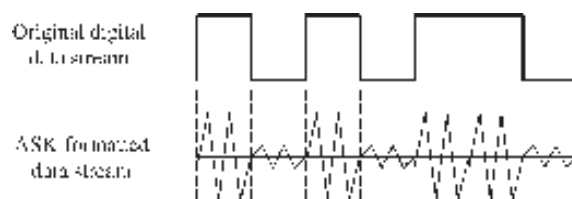


Figure 1.9. Concept of carrier waves.

12 Chapter One

such as glass, prompted researchers to consider optical fiber transmission technology.

1.6.2. Baseband signals

Baseband refers to the technology in which a signal is transmitted directly onto a channel without modulating a carrier. For example, this method is used on standard twisted-pair wire links running from an analog telephone to the nearest switching interface equipment.

The same baseband method is used in optical communications; that is, the optical output from a light source is turned on and off in response to the variations in voltage levels of an information-bearing electric signal. As is described in Chap. 6, for data rates less than about 2.5 Gbps, the light source itself can be turned on and off directly by the electric signal. For data rates higher than 2.5 Gbps, the optical output from a source such as a laser cannot respond fast enough. In this case an external device is used to modulate a steady optical output from a laser source.

1.7. Signal Multiplexing

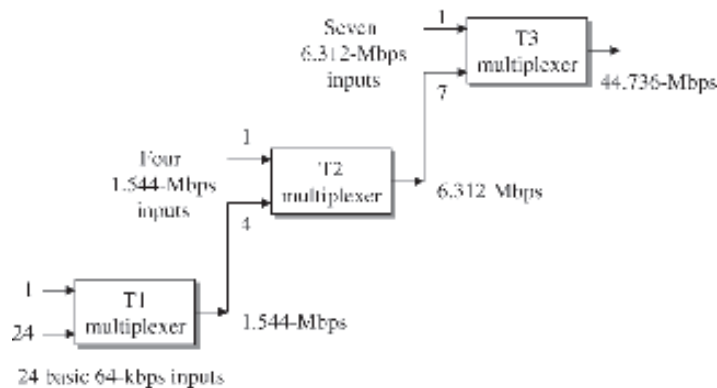
Starting in the 1990s, a burgeoning demand on communication network assets emerged for services such as database queries and updates, home shopping, video-on-demand, remote education, audio and video streaming, and video conferencing. This demand was fueled by the rapid proliferation of personal computers coupled with a phenomenal increase in their storage capacity and processing capabilities, the widespread availability of the Internet, and an extensive choice of remotely accessible programs and information databases. To handle the ever-increasing demand for high-bandwidth services from users ranging from home-based computers to large businesses and research organizations, telecommunication companies worldwide are implementing increasingly sophisticated digital multiplexing techniques that allow a larger number of independent information streams to share the same physical transmission channel. This section describes some common techniques. Chapter 2 describes more advanced methodologies used and proposed for optical fiber transport systems.

Table 1.2 gives examples of information rates for some typical voice, video, and data services. To send these services from one user to another, network providers combine the signals from many different users and send the aggregate signal over a single transmission line. This scheme is known as *time-division multiplexing* (TDM). Here N independent information streams, each running at a data rate of R bps (bits per second), are interleaved electrically into a single information stream operating at a higher rate of $N \times R$ bps. To get a detailed perspective of this, let us look at the multiplexing schemes used in telecommunications.

Early applications of fiber optic transmission links were mainly for large-capacity telephone lines. These digital links consisted of time-division multiplexed

TABLE 1.2. Examples of Information Rates for Some Typical Voice, Video, and Data Services

Type of service	Data rate
Video on demand/interactive TV	1.5 to 6 Mbps
Video games	1 to 2 Mbps
Remote education	1.5 to 3 Mbps
Electronic shopping	1.5 to 6 Mbps
Data transfer or telecommuting	1 to 3 Mbps
Video conferencing	0.384 to 2 Mbps
Voice (single channel)	64 kbps

**Figure 1.10.** Digital transmission hierarchy used in the North American telephone network.

64-kbps voice channels. The multiplexing was developed in the 1960s and is based on what is known as the *plesiochronous digital hierarchy* (PDH). Figure 1.10 shows the digital transmission hierarchy used in the North American telephone network. The fundamental building block is a 1.544-Mbps transmission rate known as a DS1 rate, where DS stands for *digital system*. It is formed by time-division multiplexing 24 voice channels, each digitized at a 64-kbps rate (which is referred to as DS0). *Framing bits*, which indicate where an information unit starts and ends, are added along with these voice channels to yield the 1.544-Mbps bit stream. At any level a signal at the designated input rate is multiplexed with other input signals at the same rate.

DSn versus Tn In describing telephone network data rates, one also sees the terms T1, T3, and so on. Often people use the terms Tn and DSn (for example, T1 and DS1 or T3 and DS3) interchangeably. However there is a subtle difference in their meaning. DS1, DS2, DS3, and so on refer to a *service type*; for example, a user who wants to send information at a 1.544-Mbps rate would subscribe to a DS1 service. T1, T2, T3, and so on refer to the technology used to deliver that service over a physical link. For example,

TABLE 1.3. Digital Multiplexing Levels Used in North America, Europe, and Japan

Digital multiplexing level	Number of 64-kbps channels	Bit rate, Mbps		
		North America	Europe	Japan
0	1	0.064	0.064	0.064
1	24	1.544		1.544
	30		2.048	
2	96	6.312		6.312
	120		8.448	
3	480		34.368	32.064
	672	44.736		
4	1920		139.264	
	4032	274.176		
	5760			397.200

the DS1 service is transported over a physical wire or optical fiber using electrical or optical pulses sent at a $T1 = 1.544$ -Mbps rate.

The system is not restricted to multiplexing voice signals. For example, at the DS1 level, any 64-kbps digital signal of the appropriate format could be transmitted as one of the 24 input channels shown in Fig. 1.10. As noted there and in Table 1.3, the main multiplexed rates for North American applications are designated as DS1 (1.544 Mbps), DS2 (6.312 Mbps), and DS3 (44.736 Mbps). Similar hierarchies using different bit rate levels are employed in Europe and Japan, as Table 1.3 shows. In Europe the multiplexing hierarchy is labeled E1, E2, E3, and so on.

1.8. SONET/SDH Multiplexing Hierarchy

With the advent of high-capacity fiber optic transmission lines in the 1980s, service providers established a standard signal format called *synchronous optical network* (SONET) in North America and *synchronous digital hierarchy* (SDH) in other parts of the world. These standards define a synchronous frame structure for sending multiplexed digital traffic over optical fiber trunk lines. The basic building block and the first level of the SONET signal hierarchy are called the *Synchronous Transport Signal—Level 1* (STS-1), which has a bit rate of 51.84 Mbps. Higher-rate SONET signals are obtained by byte-interleaving N of these STS-1 frames, which are then scrambled and converted to an *optical carrier—level N* (OC- N) signal. Thus the OC- N signal will have a line rate exactly N times that of an OC-1 signal. For SDH systems the fundamental building block is the 155.52-Mbps *Synchronous Transport Module—Level 1* (STM-1). Again, higher-rate information streams are generated by synchronously multiplexing N different STM-1 signals to form the STM- N signal. Table 1.4 shows commonly used SDH and SONET signal levels.

TABLE 1.4. Commonly Used SONET and SDH Transmission Rates

SONET level	Electrical level	SDH level	Line rate, Mbps	Common rate name
OC-1	STS-1	—	51.84	—
OC-3	STS-3	STM-1	155.52	155 Mbps
OC-12	STS-12	STM-4	622.08	622 Mbps
OC-48	STS-48	STM-16	2,488.32	2.5 Gbps
OC-192	STS-192	STM-64	9,953.28	10 Gbps
OC-768	STS-768	STM-256	39,813.12	40 Gbps

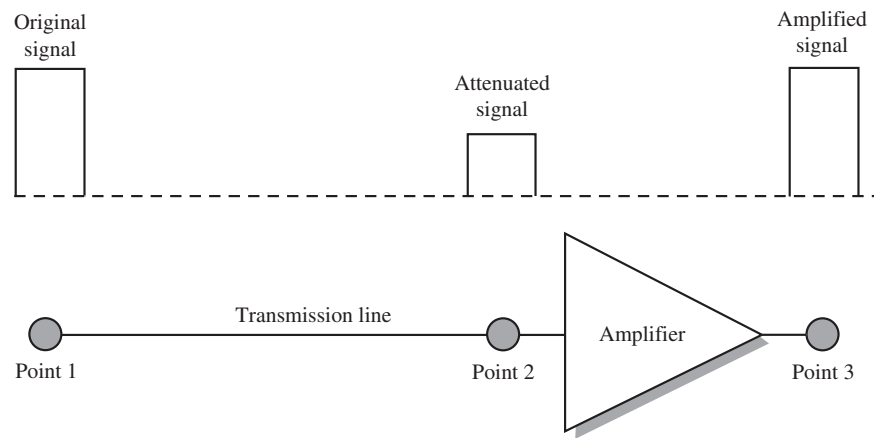


Figure 1.11. Amplifiers periodically compensate for energy losses along a channel.

1.9. Decibels

Attenuation (reduction) of the signal strength arises from various loss mechanisms in a transmission medium. For example, electric power is lost through heat generation as an electric signal flows along a wire, and optical power is attenuated through scattering and absorption processes in a glass fiber or in an atmospheric channel. To compensate for these energy losses, amplifiers are used periodically along a channel to boost the signal level, as shown in Fig. 1.11.

A convenient method for establishing a measure of attenuation is to reference the signal level to some absolute value or to a noise level. For guided media, the signal strength normally decays exponentially, so for convenience one can designate it in terms of a logarithmic power ratio measured in *decibels* (dB). In unguided (wireless) media, the attenuation is a more complex function of distance and the composition of the atmosphere. The dB unit is defined by

$$\text{Power ratio in dB} = 10 \log \frac{P_2}{P_1} \quad (1.1)$$

16 Chapter One

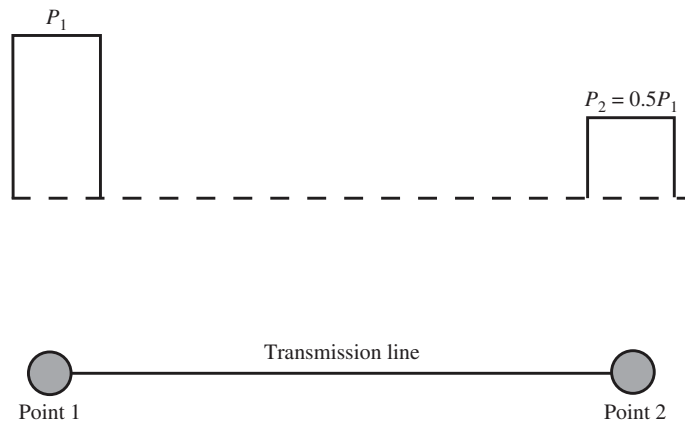


Figure 1.12. P_1 and P_2 are the electrical or optical power levels of a signal at points 1 and 2.

where P_1 and P_2 are the electrical or optical power levels of a signal at points 1 and 2 in Fig. 1.12, and $\log$ is the base-10 logarithm. The logarithmic nature of the decibel allows a large ratio to be expressed in a fairly simple manner. Power levels differing by many orders of magnitude can be compared easily when they are in decibel form. Another attractive feature of the decibel is that to measure changes in the strength of a signal, one merely adds or subtracts the decibel numbers between two different points.

Example Assume that after a signal travels a certain distance in some transmission medium, the power of the signal is reduced to one-half, that is, $P_2 = 0.5 P_1$ in Fig. 1.12. At this point, by using Eq. (1.1) the attenuation or loss of power is

$$10 \log \frac{P_2}{P_1} = 10 \log \frac{0.5 P_1}{P_1} = 10 \log 0.5 = 10(-0.3) = -3 \text{ dB}$$

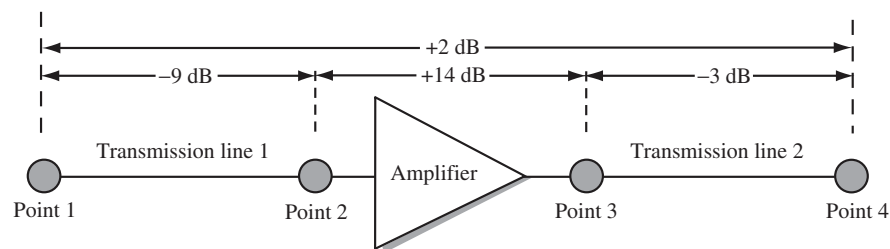
Thus, -3 dB (or a 3-dB attenuation or loss) means that the signal has lost one-half of its power. If an amplifier is inserted into the link at this point to boost the signal back to its original level, then that amplifier has a 3-dB gain. If the amplifier has a 6-dB gain, then it boosts the signal power level to twice the original value.

Table 1.5 shows some sample values of power loss given in decibels and the percentage of power remaining after this loss. These types of numbers are important when one is considering factors such as the effects of tapping off a small part of an optical signal for monitoring purposes, for examining the power loss through some optical element, or when calculating the signal attenuation in a specific length of optical fiber.

Example Consider the transmission path from point 1 to point 4 shown in Fig. 1.13. Here the signal is attenuated by 9 dB between points 1 and 2. After getting a 14-dB boost from an amplifier at point 3, it is again attenuated by 3 dB between points 3 and 4.

TABLE 1.5. Representative Values of Decibel Power Loss and the Remaining Percentages

Power loss, dB	Percentage of power left
0.1	98
0.5	89
1	79
2	63
3	50
6	25
10	10
20	1

**Figure 1.13.** Example of attenuation and amplification in a transmission path.

Relative to point 1, the signal level in decibels at point 4 is

$$\begin{aligned} \text{dB level at point 4} &= (\text{loss in line 1}) + (\text{amplifier gain}) + (\text{loss in line 2}) \\ &= (-9 \text{ dB}) + (14 \text{ dB}) + (-3 \text{ dB}) = +2 \text{ dB} \end{aligned}$$

Thus the signal has a 2-dB gain (a factor of $10^{0.2} = 1.58$) in power in going from point 1 to point 4.

Since the decibel is used to refer to ratios or relative units, it gives no indication of the absolute power level. However, a derived unit can be used for this. Such a unit that is particularly common in optical fiber communications is the *dBm*. This expresses the power level P as a logarithmic ratio of P referred to 1 mW. In this case, the power in dBm is an absolute value defined by

$$\text{Power level, dBm} = 10 \log \frac{P \text{ mW}}{1 \text{ mW}} \quad (1.2)$$

An important rule-of-thumb relationship to remember for optical fiber communications is $0 \text{ dBm} = 1 \text{ mW}$. Therefore, positive values of dBm are greater than 1 mW, and negative values are less than this. Table 1.6 lists some examples of optical power levels and their dBm equivalents.

TABLE 1.6. Some Examples of Optical Power Levels and Their dBm Equivalents

Power	dBm equivalent
200 mW	23
100 mW	20
10 mW	10
1 mW	0
100 μ W	-10
10 μ W	-20
1 μ W	-30
100 nW	-40
10 nW	-50
1 nW	-60
100 pW	-70
10 pW	-80
1 pW	-90

1.10. Simulation Programs

Computer-aided modeling and simulation software programs are essential tools to predict how an optical communication component, link, or network will function and perform. These programs are able to integrate component, link, and network functions, thereby making the design process more efficient, less expensive, and faster. The tools typically are based on graphical interfaces that include a library of icons containing the operational characteristics of devices such as optical fibers, couplers, light sources, optical amplifiers, and optical filters, plus the measurement characteristics of instruments such as optical spectrum analyzers, power meters, and bit error rate testers. To check the capacity of the network or the behavior of passive and active optical devices, network designers invoke different optical power levels, transmission distances, data rates, and possible performance impairments in the simulation programs.

An example of such programs is the suite of software-based modeling-tool modules from VPIsystems, Inc. These design and planning tools are intended for use across all levels of network analyses, performance evaluations, and technology comparisons ranging from components, to modules, to entire networks. They are used extensively by component and system manufacturers, system integrators, network operators, and access service providers for functions such as capacity planning, comparative assessments of various technologies, optimization of transport and service networks, syntheses and analyses of wavelength division multiplexing (WDM) system and link designs, and component designs.

One particular tool from the VPIsystems suite is VPItransmissionMaker, which is a design and simulation tool for optical devices, components, subsystems, and transmission systems. This has all the tools needed to explore, design, simulate, verify, and evaluate active and passive optical components, fiber amplifiers, dense WDM transmission systems, and broadband access networks. Familiar measurement instruments offer a wide range of settable options when displaying data from multiple runs, optimizations, and multidimensional parameter sweeps. Signal processing modules allow data to be manipulated to mimic any laboratory setup.

An abbreviated version of this simulation module is available for noncommercial educational use. This version is called VPIplayer and contains predefined component and link configurations that allow interactive concept demonstrations. Among the demonstration setups are optical amplifier structures, simple single-wavelength links, and WDM links. Although the configurations are fixed, the user has the ability to interactively change the operational parameter values of components such as optical fibers, light sources, optical filters, and optical amplifiers. This can be done very simply by using the mouse to move calibrated slider controls. Results are shown in a format similar to the displays presented by laboratory instruments and show, for example, link performance degradation or improvement when various component values change.

VPIplayer can be downloaded from www.VPIphotonics.com. In addition, at www.PhotonicsComm.com there are numerous examples of optical communication components and links related to topics in this book that the reader can download and simulate. As noted above, predefined component parameters in these examples may be modified very simply via calibrated slider controls.

1.11. Summary

This chapter provides some fundamental operational concepts and definitions of terminology related to wired telecommunication systems. This “wiring” encompasses copper wires and optical fibers. Some key concepts include the following:

- Section 1.1 gives basic definitions of metric prefixes, terms used in communications (e.g., information, message, and signal), waveform characteristics, and digital signal formats.
- Section 1.9 defines the concepts of decibels and the relative power unit dBm that is used extensively in optical communication systems.
- Although most signals occurring in nature are of an analog form, in general they can be sent more easily and with a higher fidelity when changed to a digital format.
- A common digital signal configuration is the binary waveform consisting of binary 0 and binary 1 pulses called bits.
- The SONET/SDH multiplexing hierarchy defines a standard synchronous frame structure for sending multiplexed digital traffic over optical fiber transmission lines.

The designations for SONET data rates range from OC-1 (51.84 Mbps) to OC-768 ($768 \times \text{OC-1} \approx 40 \text{ Gbps}$) and beyond.

The designations for SDH data rates range from STM-1 (155.52 Mbps) to STM-256 ($256 \times \text{STM-1} \approx 40 \text{ Gbps}$) and beyond.

- For optical communications the ITU-T has defined the following six spectral bands in the 1260- to 1675-nm range:

Original band (O-band): 1260 to 1360 nm

Extended band (E-band): 1360 to 1460 nm

Short band (S-band): 1460 to 1530 nm

Conventional band (C-band): 1530 to 1565 nm

Long band (L-band): 1565 to 1625 nm

Ultralong band (U-band): 1625 to 1675 nm

- Computer-aided modeling and simulation software programs are essential tools to predict how an optical communication component, link, or network will function and perform. These programs are able to integrate component, link, and network functions, thereby making the design process more efficient, less expensive, and faster. One particular tool from VPIsystems, Inc. is VPItransmissionMaker, which is a design and simulation tool for optical devices, components, subsystems, and transmission systems. An abbreviated version of this simulation module is available for noncommercial educational use. This version is called VPIplayer and contains predefined component and link configurations that allow interactive concept demonstrations. VPIplayer can be downloaded from www.VPIphotonics.com. In addition, at www.PhotonicsComm.com there are numerous examples of optical communication components and links related to topics in this book that the reader can download and simulate.

Further Reading

1. A. B. Carlson, *Communication Systems*, 4th ed., McGraw-Hill, Burr Ridge, Ill., 2002. This classic book gives senior-level discussions of electrical communication systems.
2. B. A. Forouzan, *Introduction to Data Communications and Networking*, 2d ed., McGraw-Hill, Burr Ridge, Ill., 2001. This book gives intermediate-level discussions of all aspects of communication systems.
3. W. Goralski, *Optical Networking and WDM*, McGraw-Hill, New York, 2001.
4. J. Hecht, *City of Light*, Oxford University Press, New York, 1999. This book gives an excellent account of the history behind the development of optical fiber communication systems.
5. G. Keiser, *Optical Fiber Communications*, 3d ed., McGraw-Hill, Burr Ridge, Ill., 2000. This book presents more advanced discussions and theoretical analyses of optical fiber component and system performance material.
6. G. Keiser, *Local Area Networks*, 2d ed., McGraw-Hill, Burr Ridge, Ill., 2002. This book presents topics related to all aspects of local-area communications.
7. R. Ramaswami and K. N. Sivarajan, *Optical Networks*, 2d ed., Morgan Kaufmann, San Francisco, 2002. This book presents more advanced discussions and theoretical analyses of optical networking material.
8. N. Thorsen, *Fiber Optics and the Telecommunications Explosion*, Prentice Hall, New York, 1998.

Optical Communication Systems Overview

Telecommunications network organizations started using optical fiber communication links just over 25 years ago. Since then, researchers have devised and developed a truly impressive collection of sophisticated passive and active optical components, transmission techniques that are unique to optical links, and software-based modeling tools for components, links, and networks. These developments enabled optical networks to deliver increasingly higher data rates over longer and longer distances for both terrestrial and transoceanic links.

The purpose of this chapter is to get an appreciation of this growth and to set the basis for understanding the material in the rest of the book. First we present the motivations for using optical communication, such as the physical differences and capacity advantages between electrical and optical signaling formats. Then we will review the evolution of optical fiber transmission systems, starting with the quest to create a viable optical fiber. This will lead us to present-day implementations. The chapter ends with an overview of the general concepts and issues of current transmission equipment, links, and networks. This includes the process of combining many independent wavelengths onto the same fiber, signal routing and switching, and standards for optical communications.

2.1. Motivations for Using Optical Fiber Systems

The motivation for developing optical fiber communication systems started with the invention of the laser in the early 1960s. The operational characteristics of this device encouraged researchers to examine the optical spectrum as an extension of the radio and microwave spectrum to provide transmission links with extremely high capacities. As research progressed, it became clear that many complex problems stood in the way of achieving such a super broadband communication system. However, it also was noted that other properties of optical fibers gave them a number of inherent cost and operational advantages over

copper wires and made them highly attractive for simple on/off keyed links. Included in these advantages are the following:

- *Long transmission distance.* Optical fibers have lower transmission losses compared to copper wires. This means that data can be sent over longer distances, thereby reducing the number of intermediate repeaters needed for these spans. This reduction in equipment and components decreases system cost and complexity.
- *Large information capacity.* Optical fibers have wider bandwidths than copper wires, which means that more information can be sent over a single physical line. This property results in a decrease in the number of physical lines needed for sending a certain amount of information.
- *Small size and low weight.* The low weight and the small dimensions of fibers offer a distinct advantage over heavy, bulky wire cables in crowded underground city ducts or in ceiling-mounted cable trays. This also is of importance in aircraft, satellites, and ships where small, lightweight cables are advantageous, and in tactical military applications where large amounts of cable must be unreeled and retrieved rapidly.
- *Immunity to electrical interference.* An especially important feature of optical fibers relates to the fact that they consist of dielectric materials, which means they do not conduct electricity. This makes optical fibers immune to the electromagnetic interference effects seen in copper wires, such as inductive pickup from other adjacent signal-carrying wires or coupling of electrical noise into the line from any type of nearby equipment.
- *Enhanced safety.* Optical fibers do not have the problems of ground loops, sparks, and potentially high voltages inherent in copper lines. However, precautions with respect to laser light emissions need to be observed to prevent possible eye damage.
- *Increased signal security.* An optical fiber offers a high degree of data security, since the optical signal is well confined within the fiber and any signal emissions are absorbed by an opaque coating around the fiber. This is in contrast to copper wires where electric signals often can be tapped off easily. This makes fibers attractive in applications where information security is important, such as in financial, legal, government, and military systems.

Now let us look at a very brief history of optical communications and how this led to present-day systems. For an interesting detailed account of the development of optical communications from ancient to modern times, the reader is referred to the book *City of Light* by Jeff Hecht.

2.2. Evolution of Optical Communications

A challenge in using an optical fiber for a communications channel is to have a flexible, low-loss medium that transfers a light signal over long distances without

significant attenuation and distortion. Glass is an obvious material for such applications. The earliest known glass was made around 2500 B.C., and glass already was drawn into fibers during the time of the Roman Empire. However, such glasses have very high losses and are not suitable for communication applications. One of the first known attempts of using optical fibers for communication purposes was a demonstration in 1930 by Heinrich Lamm of image transmission through a short bundle of optical fibers for potential medical imaging. However, no further work was done beyond the demonstration phase, since the technology for producing low-loss fibers with good light confinement was not yet mature.

Further work and experiments on using optical fibers for image transmission continued, and by 1960 glass-clad fibers had an attenuation of about 1 dB/m. This attenuation allowed fibers to be used for medical imaging, but it was still much too high for communications, since only 1 percent of the inserted optical power would emerge from the end of a 20-m-long fiber. Optical fibers attracted the attention of researchers at that time because they were analogous in theory to plastic dielectric waveguides used in certain microwave applications. In 1961 Elias Snitzer published a classic theoretical description of single-mode fibers with implications for information transmission use. However, to be applicable to communication systems, optical fibers would need to have a loss of no more than 10 or 20 dB/km (a power loss factor of 10 to 100).

In the early 1960s when Charles Kao was at the Standard Telecommunication Laboratories in England, he pursued the idea of using a clad glass fiber for an optical waveguide. After he and George Hockman painstakingly examined the transparency properties of various types of glass, Kao made a prediction in 1966 that losses of no more than 20 dB/km were possible in optical fibers. In July 1966, Kao and Hockman presented a detailed analysis for achieving such a loss level. Kao then went on to actively advocate and promote the prospects of fiber communications, which generated interest in laboratories around the world to reduce fiber loss. It took 4 years to reach Kao's predicted goal of 20 dB/km, and the final solution was different from what many had expected.

To understand the process of making a fiber, consider the schematic of a typical fiber structure, shown in Fig. 2.1. A fiber consists of a solid glass cylinder called the *core*. This is surrounded by a dielectric *cladding*, which has a different material property from that of the core in order to achieve light guiding in the fiber. Surrounding these two layers is a polymer buffer coating that protects the

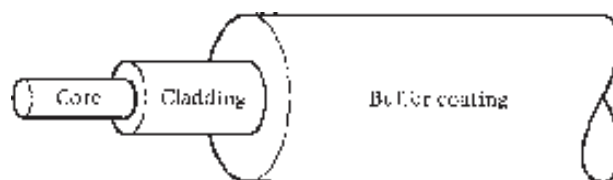


Figure 2.1. A typical fiber structure consists of a core, a cladding, and a buffer coating.

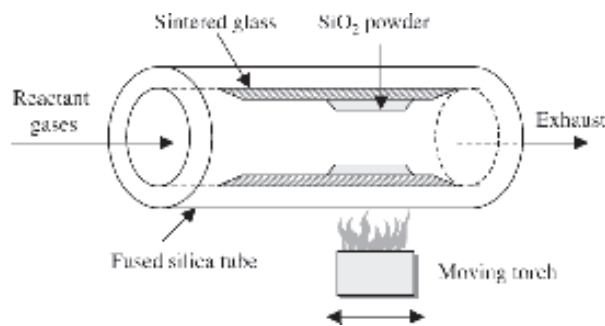


Figure 2.2. Illustration of the modified chemical vapor deposition (MCVD) process.

fiber from mechanical and environmental effects. (Chapter 4 gives the details of how a fiber guides light.)

The first step in making a fiber is to form a clear glass rod or tube called a *preform*. Currently a preform is made by one of several vapor-phase oxidation processes. In each of these processes, highly pure vapors of metal halides (e.g., SiCl_4 and GeCl_4) react with oxygen to form a white powder of SiO_2 particles. The particles are then collected on the surface of a bulk glass (such as the outside of a rod or the inside of a tube) and are *sintered* (transformed to a homogeneous glass mass by heating without melting) to form a clear glass rod or tube. Figure 2.2 shows one such process, which is known as the *modified chemical vapor deposition* (MCVD) process. Here as the SiO_2 particles are deposited, the tube is rotated and a torch travels back and forth along the tube to sinter the particles. Chapter 20 describes this and other fiber fabrication processes.

Depending on how long a fiber is desired, the preform might be a meter long and several centimeters in diameter. The preform has two distinct regions that correspond to the core and cladding of the eventual fiber. As illustrated in Fig. 2.3, fibers are made by precision feeding the preform into a circular furnace. This process softens the end of the preform to the point where it can be drawn into a long, very thin filament which becomes the optical fiber.

Prior to 1970 most researchers had tried to purify compound glasses used for standard optics, which are easy to melt and draw into fibers. A different approach was taken at the Corning Glass Works where Robert Maurer, Donald Keck, and Peter Schultz started with fused silica. This material can be made extremely pure, but has a high melting point. The Corning team made cylindrical preforms by depositing purified materials from the vapor phase. In September 1970, they announced the fabrication of single-mode fibers with an attenuation of 17 dB/km at the 633-nm helium-neon line (a loss factor of 50 over 1 km). This dramatic breakthrough was the first among the many developments that opened the door to fiber optic communications. The ensuing years saw further reductions in optical fiber attenuation. By the middle of 1972 Maurer, Keck, and Schultz had made multimode germania-doped fibers with a 4-dB/km loss and much greater strength than the earlier brittle titania-doped fibers.

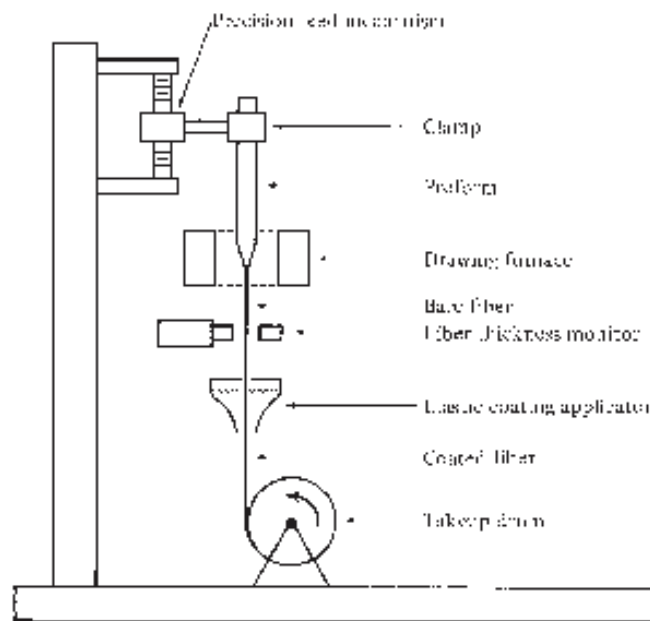


Figure 2.3. Illustration of a fiber-drawing process.

A problem with using single-mode fibers in the 1970s was that no light source existed which could couple a sufficient amount of optical power into the tiny fiber core (nominally $9\text{ }\mu\text{m}$ in diameter). Therefore, multimode fibers with larger core diameters ranging from 50 to $100\text{ }\mu\text{m}$ were used first. The main light sources were light-emitting diodes (LEDs) and laser diodes that emitted at 850 nm . The combination of early sources, multimode fibers, and operation at 850 nm limited the optical fiber links to rates of about 140 Mbps over distances of 10 km .

To overcome these limitations, around 1984 the next generation of optical systems started employing single-mode fibers and operated at 1310 nm where both the fiber attenuation and signal distortion effects are lower than at 850 nm . Figure 2.4 shows this attenuation difference in decibels per kilometer as a function of wavelength. The figure also shows that early optical fibers had three low-loss transmission windows defined by attenuation spikes due to absorption from water molecules. The *first window* ranges from 800 to 900 nm , the *second window* is centered at 1310 nm , and the *third window* ranges from 1480 to 1600 nm . In 1310-nm systems the transmission distance is limited primarily by fiber loss and not by other factors that might not allow a longer and faster transmission link. Therefore the next evolutionary step was to deploy links at 1550 nm where the attenuation was only one-half that at 1310 nm . This move started a flurry of activity in developing new fiber types, different light sources, new types of photodetectors, and a long shopping list of specialized optical components. This activity arose because transmitting in the 1550-nm region and pushing the data rate to higher and higher speeds brought about a whole series

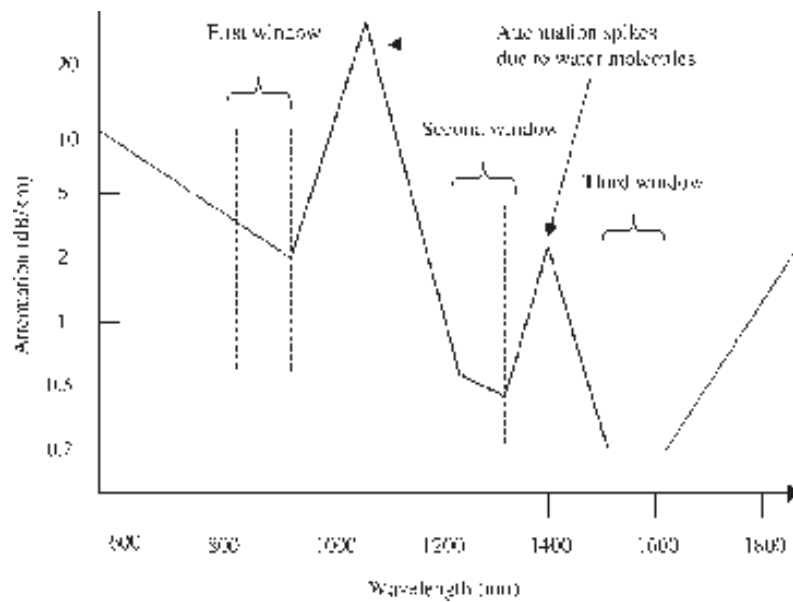


Figure 2.4. Attenuation of an optical fiber in decibels per kilometer as a function of wavelength.

of new challenging problems. The following sections give a taste of these challenges, and later chapters will elaborate on their solutions.

2.3. Elements of an Optical Link

From a simplistic point of view, the function of an optical fiber link is to transport a signal from some piece of electronic equipment (e.g., a computer, telephone, or video device) at one location to corresponding equipment at another location with a high degree of reliability and accuracy. Figure 2.5 shows the key sections of an optical fiber communications link, which are as follows:

- **Transmitter.** The transmitter consists of a light source and associated electronic circuitry. The source can be a light-emitting diode or a laser diode. The electronics are used for setting the source operating point, controlling the light output stability, and varying the optical output in proportion to an electrically formatted information input signal. Chapter 6 gives more details on sources and transmitters.
- **Optical fiber.** As Chap. 5 describes, the optical fiber is placed inside a cable that offers mechanical and environmental protection. A variety of fiber types exist, and there are many different cable configurations depending on whether the cable is to be installed inside a building, in underground pipes, outside on poles, or underwater.
- **Receiver.** Inside the receiver is a photodiode that detects the weakened and distorted optical signal emerging from the end of an optical fiber and converts

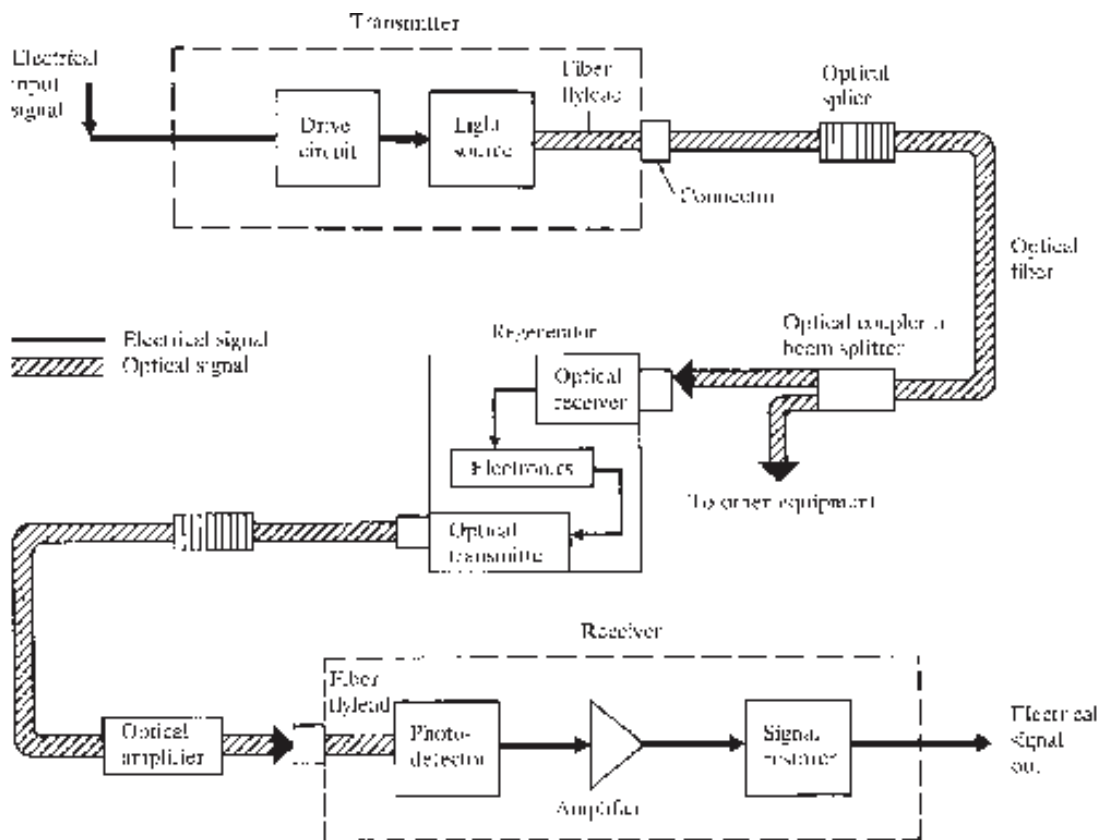


Figure 2.5. The key sections of an optical fiber communications link.

it to an electric signal. The receiver also contains amplification devices and circuitry to restore signal fidelity. Chapter 7 gives details on this topic.

- *Passive devices.* As Chap. 9 describes, passive devices are optical components that require no electronic control for their operation. Among these are optical connectors for connecting cables, splices for attaching one bare fiber to another, optical isolators that prevent unwanted light from flowing in a backward direction, optical filters that select only a narrow spectrum of desired light, and couplers used to tap off a certain percentage of light, usually for performance monitoring purposes.
- *Optical amplifiers.* After an optical signal has traveled a certain distance along a fiber, it becomes weakened due to power loss along the fiber. At that point the optical signal needs to get a power boost. Traditionally the optical signal was converted to an electric signal, amplified electrically, and then converted back to an optical signal. The invention of an optical amplifier that boosts the power level completely in the optical domain circumvented these transmission bottlenecks, as Chap. 11 describes.

- *Active components.* Lasers and optical amplifiers fall into the category of active devices, which require an electronic control for their operation. Not shown in Fig. 2.5 are a wide range of other active optical components. These include light signal modulators, tunable (wavelength-selectable) optical filters, variable optical attenuators, and optical switches. Chapter 10 gives the details of these devices.

2.4. WDM Concept

The use of *wavelength division multiplexing* (WDM) offers a further boost in fiber transmission capacity. As Fig. 2.6 illustrates, the basis of WDM is to use multiple light sources operating at slightly different wavelengths to transmit several independent information streams simultaneously over the same fiber. Although researchers started looking at WDM in the 1970s, during the ensuing years it generally turned out to be easier to implement higher-speed electronic and optical devices than to invoke the greater system complexity called for in WDM. However, a dramatic surge in its popularity started in the early 1990s as electronic devices neared their modulation limit and high-speed equipment became increasingly complex and expensive.

One implementation trend of WDM is the seemingly unending quest to pack more and more closely spaced wavelengths into a narrow spectral band. This has led to what is referred to as *dense WDM*, or DWDM. The wavelengths (or optical frequencies) in a DWDM link must be properly spaced to avoid having adjacent channels step on each other's toes, which would create signal distortion. In an optical system, interference between adjacent channels may arise from the fact that the center wavelength of laser diode sources and the spectral operating characteristics of other optical components in the link may drift with temperature and time. This may cause the signal pulses to drift or spread out spectrally. As Fig. 2.7 illustrates, if this drift or spreading is not controlled or if any guard band between wavelength channels is too small, the signal being produced at one wavelength will trespass into the spectral territory of another signal band and create interference.

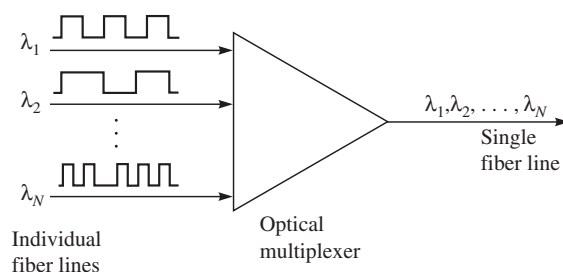


Figure 2.6. Basic concept of wavelength division multiplexing (WDM).

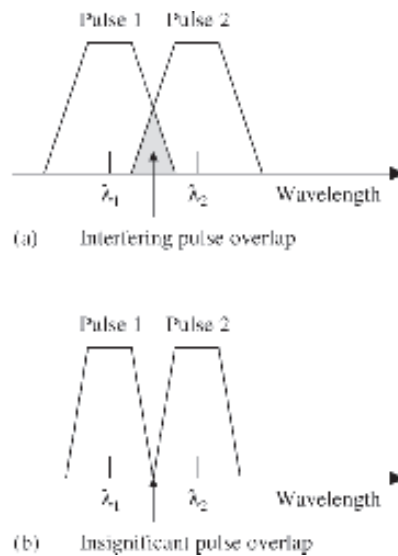


Figure 2.7. (a) Spectral interference between adjacent wavelength channels; (b) stable channels.

2.5. Applications of Optical Fiber Links

Optical fibers can be applied to interconnections ranging from localized links within an equipment rack to links that span continents or oceans. As Fig. 2.8 illustrates, networks are traditionally divided into the following three broad categories:

1. *Local-area networks* (LANs) interconnect users in a localized area such as a room, a department, a building, an office or factory complex, or a campus. Here the word *campus* refers to any group of buildings that are within reasonable walking distance of one another. For example, it could be the collocated buildings of a corporation, a large medical facility, or a university complex. LANs usually are owned, used, and operated by a single organization.

2. *Metropolitan-area networks* (MANs) span a larger area than LANs. This could be interconnections between buildings covering several blocks within a city or could encompass an entire city and the metropolitan area surrounding it. There is also some means of interconnecting the MAN resources with communication entities located in both LANs and wide-area networks. MANs are owned and operated by many organizations. When talking about MAN fiber optic applications, people tend to call them *metro applications*.

3. *Wide-area networks* (WANs) span a large geographic area. The links can range from connections between switching facilities in neighboring cities to long-haul terrestrial or undersea transmission lines running across a country or between countries. WANs invariably are owned and operated by many transmission service providers.

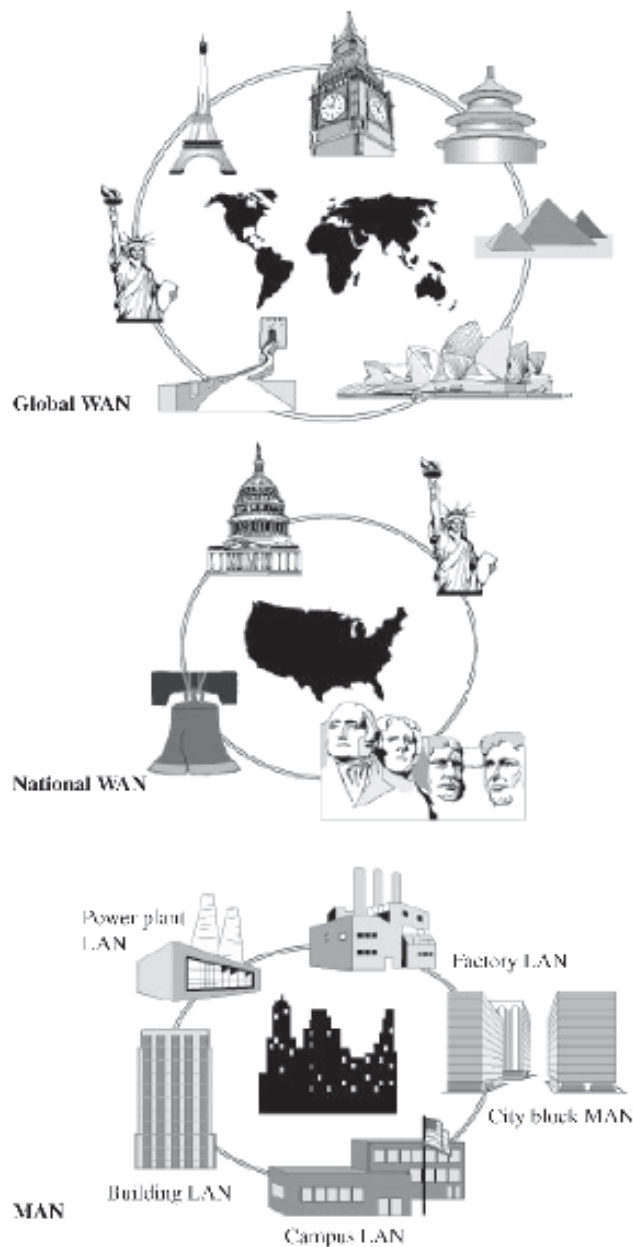


Figure 2.8. Examples of broad categories of networks.

2.6. Optical Networking and Switching

Another step toward realizing the full potential of optical fiber transmission capacity is the concept of an intelligent WDM network. In these networks the wavelength routing is done in the optical domain without going through the usual time-consuming sequence that involves an optical-to-electric signal conversion, an electric signal switching process, and then another conversion from

an electrical back to an optical format. The motivation behind this concept is to extend the versatility of communication networks beyond architectures such as those provided by high-bandwidth point-to-point SONET light pipes. So far most of these types of *all-optical networks* are only concepts, since the technology still needs to mature. In particular, as described in Chap. 17, an optical cross-connect switch is one of the key elements needed to deploy agile optical networks. Developing such a component is a major challenge since it needs to switch optical signals at line rates (e.g., at 10-Gbps OC-192 or 40-Gbps OC-768 rates) without optical-to-electrical conversion, thereby providing lower switching costs and higher capacities than the currently used electrical cross-connects.

2.7. Standards for Optical Communications

When people travel from one country to another, they need to bring along an electrical adapter that will match up the voltage and plug configurations of their personal appliances to those of the other country. Even when you do this, sometimes you are greeted by sparks and black smoke as you plug something into a foreign electric socket. If the hotel personnel or clerks in stores do not speak the same language as you do, there is another interface problem. To avoid similar situations when trying to interface equipment from different manufacturers, engineers have devised many different types of standards so that diverse equipment will interface properly. However, since many people like to do things their own way, sometimes the standards in one country do not quite match those of another. Nevertheless, international standards for a wide range of component and system-level considerations have made life a lot easier.

There are three basic classes of standards for fiber optics: primary standards, component testing standards, and system standards.

Primary standards refer to measuring and characterizing fundamental physical parameters such as attenuation, bandwidth, operational characteristics of fibers, and optical power levels and spectral widths. In the United States the main organization involved in primary standards is the National Institute of Standards and Technology (NIST). This organization carries out fiber optic and laser standardization work, and it sponsors an annual conference on optical fiber measurements. Other national organizations include the National Physical Laboratory (NPL) in the United Kingdom and the Physikalisch-Technische Bundesanstalt (PTB) in Germany.

Component testing standards define relevant tests for fiber optic component performance, and they establish equipment calibration procedures. Several different organizations are involved in formulating testing standards, some very active ones being the Telecommunication Industries Association (TIA) in association with the Electronic Industries Association (EIA), the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T), and the International Electrotechnical Commission (IEC). The TIA has a list of over 120 fiber optic test standards and specifications under the general designation TIA/EIA-455-XX-YY, where XX refers to a specific measurement technique

TABLE 2.1. A Sampling of ITU-T Recommendations for Optical Links and Networks

Rec. no.	Title
G.650 to G.655	Definitions, test methods, and characteristics of various types of multimode and single-mode fibers
G.662	Generic Characteristics of Optical Amplifier Devices and Subsystems
G.671	Transmission Characteristics of Optical Components and Subsystems
G.709	Interfaces for the Optical Transport Network (OTN)
G.872	Architecture of Optical Transport Networks
G.874	Management Aspects of the Optical Transport Network Element
G.959.1	Optical Transport Network Physical Layer Interfaces
G.694.1	Spectral Grids for WDM Applications: DWDM Frequency Grid
G.694.2	Spectral Grids for WDM Applications: CWDM Wavelength Grid
G.975	Forward Error Correction for Submarine Systems

and YY refers to the publication year. These standards are also called *Fiber Optic Test Procedures* (FOTPs), so that TIA/EIA-455-XX becomes FOTP-XX. These include a wide variety of recommended methods for testing the response of fibers, cables, passive devices, and electrooptic components to environmental factors and operational conditions. For example, TIA/EIA-455-60-1997, or FOTP-60, is a method published in 1997 for measuring fiber or cable length.

System standards refer to measurement methods for links and networks. The major organizations are the American National Standards Institute (ANSI), the Institute for Electrical and Electronic Engineers (IEEE), and the ITU-T. Of particular interest for fiber optics systems are test standards and recommendations from the ITU-T. Within the G series (in the number range G.650 and higher) there are at least 44 recommendations that relate to fiber cables, optical amplifiers, wavelength multiplexing, optical transport networks (OTNs), system reliability and availability, and management and control for passive optical networks (PONs). In addition, within the same number range there are many recommendations referring to SONET and SDH. Table 2.1 lists a sampling of these ITU-T recommendations, which aim at all aspects of optical networking.

2.8. Summary

The dielectric properties of optical fibers give them a number of inherent cost and operational advantages over copper wires. Among these are lower weight, smaller size, greater information capacity, and immunity to signal interference. On the other hand, this comes with some increased complexity with respect to handling and connecting the hair-thin fibers.

Optical fiber communications has rapidly become a mature technology and now is ubiquitous in the telecommunications infrastructure. As is the case with

any other technology, the challenges to improve performance are never-ending. Researchers are working to pack more and more wavelengths closer together in a given spectral band, to increase the data rates per wavelength, and to go longer distances by developing new types of optical amplifiers.

As a further step toward realizing the full potential of optical fiber transmission capacity, researchers are considering the concept of an intelligent WDM network. The major activity in this area is the development of an optical cross-connect (OXC) that will switch optical signals at line rates (e.g., at 10-Gbps OC-192 or 40-Gbps OC-768 rates) without optical-to-electrical conversion. The eventual creation of such a component will provide lower switching costs and higher capacities than the currently used electrical cross-connects.

A key ingredient for the widespread implementation of optical fiber technology is an extensive body of test, interface, and system design standards. For example, the TIA has published over 120 fiber optic test standards and specifications for testing the response of fibers, cables, passive devices, and electrooptic components to environmental factors and operational conditions. Furthermore, within the ITU-T G series there are at least 44 recommendations that relate to performance specifications for fiber cables, optical amplifiers, wavelength multiplexing, optical transport networks, system reliability and availability, and management and control for passive optical networks. In addition, within this G series there are many recommendations referring to SONET and SDH. Table 2.1 lists a sampling of ITU-T recommendations, which aim at all aspects of optical networking.

Further Reading

1. J. Hecht, *City of Light*, Oxford University Press, New York, 1999.
2. K. C. Kao and G. A. Hockman, "Dielectric-fibre surface waveguides for optical frequencies," *Proceedings IEE*, vol. 113, pp. 1151–1158, July 1966.
3. E. Snitzer, "Cylindrical dielectric waveguide modes," *J. Opt. Soc. Amer.*, vol. 51, pp. 491–498, May 1961.
4. G. Keiser, "A review of WDM technology and applications," *Opt. Fiber Technol.*, vol. 5, no. 1, pp. 3–39, 1999.
5. National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO 80303 (<http://www.nist.gov>).
6. National Physical Laboratory (NPL), Teddington, Middlesex, United Kingdom (<http://www.npl.co.uk>).
7. Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany (<http://www.ptb.de>).
8. Telecommunication Industries Association (TIA) (<http://www.tiaonline.org>).
9. Electronic Industries Association (EIA), 2001 Eye Street, Washington, D.C. 20006.
10. Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T), Geneva, Switzerland (<http://www.itu.int>).
11. International Electrotechnical Commission (IEC), Geneva, Switzerland (<http://www.iec.ch>).
12. American National Standards Institute (ANSI), New York (<http://www.ansi.org>).
13. Institute of Electrical and Electronic Engineers (IEEE), New York (<http://www.ieee.org>).
14. A. McGuire and P. A. Bonenfant, "Standards: The blueprints for optical networks," *IEEE Commun. Mag.*, vol. 36, pp. 68–78, February 1998.

The Behavior of Light

The concepts of how light travels along an optical fiber and how it interacts with matter are essential to understanding why certain components are needed and what their functions are in an optical fiber communication system. In this chapter discussions on the properties of light cover the dual wave-particle nature of light, the speed of light in different materials, reflection, refraction, and polarization. These concepts relate to optical phenomena that we see every day, such as light traveling through a solid (e.g., glass), reflection, and refraction. Obviously these factors also play a major role in optical fiber communications. So, let's get "enlightened" with the following discussions.

3.1. The Dual Wave-Particle Nature of Light

The fundamental behavior of light is somewhat mysterious since some phenomena can be explained by using a wave theory whereas in other cases light behaves as though it is composed of miniature particles. This results in a *dual wave-particle nature of light*. The wave nature is necessary to explain how light travels through an optical fiber, but the particle theory is needed to explain how optical sources generate signals and how photodetectors change these optical signals to electric signals.

Light particles are known as *photons*, which have a certain energy associated with them. As described in Sec. 3.3, the most common measure of photon energy is the *electron volt* (eV), which is the energy a photon gains when moving through a 1-V electric field. Photons travel in straight lines called *rays* and are used to explain certain light phenomena using the so-called *ray theory* or *geometric optics* approach. This approach is valid when the object with which the light interacts is much larger than the wavelength of the light. This theory explains large-scale optical effects such as reflection and refraction (which are described in Sec. 3.4) and describes how devices such as light sources, photodetectors, and optical amplifiers function.

As noted in Chap. 1, all types of waves including light waves can interfere with one another. Thus if two light waves line up with each other (or are in phase), they produce a bright spot. However, when two light waves are 180° out of phase, then the peaks of one wave are aligned with the troughs of the other wave. In this case the two waves will interfere destructively, thereby canceling each other out. To explain effects such as these, we need to turn to the *electromagnetic wave theory* or *physical optics* viewpoint of light. The concepts involved here are important when we examine the behavior of devices such as wavelength-sensitive optical couplers.

Whereas the geometric optics approach deals with light rays, the physical optics viewpoint uses the concept of electromagnetic field distributions called *modes*. We will examine the concept of modes in greater detail in Chap. 4 when discussing optical fibers. Basically the discussion in Chap. 4 shows that modes are certain allowable distributions of light power in an optical fiber. Later chapters describe other specific physical aspects of the wave theory as they relate to optical components.

3.2. The Speed of Light

One of the earliest recorded discussions of the speed of light is that by Aristotle (384 to 347 B.C.), when he quoted Empedocles of Acragas (495 to 435 B.C.) as saying the light from the sun must take some time to reach the earth. However, Aristotle himself disagreed with the concept that light has a finite speed and thought that it traveled instantaneously. Galileo disagreed with Aristotle and tried to measure the speed of light with a shuttered lantern experiment, but was unsuccessful. Finally, about 600 years later in the 1670s, the Danish astronomer Ole Roemer measured the speed of light while making detailed observations of the movements of Jupiter's moon Io.

In free space a light wave travels at a speed $c = 3 \times 10^8 \text{ m/s}$ (300,000,000 m/s), which is known as the *speed of light*. Actually this is a convenient and fairly accurate estimate. To be exact, $c = 299,792,458 \text{ m/s}$ in a vacuum, which is equivalent to 186,287.490 mi/s, if you prefer those units. The speed of light is related to the wavelength λ (Greek lambda) and the wave frequency ν (Greek nu) through the equation $c = \lambda\nu$.

3.3. Measuring Properties of Light

The physical property of the radiation in different parts of the spectrum can be measured in several interrelated ways (see the "Measurements in the EM Spectrum" discussion below). These are the length of one period of the wave, the energy of a photon, or the oscillating frequency of the wave. Whereas electric signal transmission tends to use frequency to designate the signal operating bands, optical communications generally uses *wavelength* to designate the spectral operating region and *photon energy* or *optical power* when discussing topics such as signal strength or electrooptical component performance.

Measurements in the EM Spectrum As can be seen from Fig. 1.7, there are three different ways to measure various regions in the EM spectrum. These measurement units are related by some simple equations. First, the speed of light c is equal to the wavelength λ times the frequency ν , so that $c = \lambda\nu$. Rearranging this equation gives the relationship between wavelength and frequency. For example, if the frequency is known and we want to find the wavelength, then we use

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8 \text{ m/s}}{\nu} \quad (3.1)$$

where the frequency ν is measured in cycles per second or *hertz* (Hz). Conversely, if the wavelength is known and we want to find the frequency, then we use the relationship $\nu = c/\lambda$.

The relationship between the energy of a photon and its frequency (or wavelength) is determined by the equation known as *Planck's law*

$$E = h\nu \quad (3.2)$$

where the parameter $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s} = 4.14 \text{ eV}\cdot\text{s}$ is called *Planck's constant*. The unit J means joules, and the unit eV stands for *electron volts*. In terms of wavelength (measured in units of micrometers), the energy in electron volts is given by

$$E \text{ eV} = \frac{1.2406}{\lambda \text{ } \mu\text{m}} \quad (3.3)$$

3.4. Refractive Index

A fundamental optical parameter of a material relates to how fast light travels in it. Upon entering a dielectric or nonconducting medium, a light wave slows down and now travels at a speed s , which is characteristic of the material and is less than c . The ratio of the speed of light in a vacuum to that in matter is known as the *refractive index* or *index of refraction* n of the material and is given by

$$n = \frac{c}{s} \quad (3.4)$$

Typical values of n to two decimal places are 1.00 for air, 1.33 for water, 1.45 for silica glass, and 2.42 for diamond. Note that if we have two different materials, then the one with the larger value of n is said to be *optically denser* than the material with the lower value of n . For example, glass is optically denser than air.

Number Accuracy People who design optical test and measurement equipment often must know the precise value of the refractive index for air, and they need to take into account its variation with wavelength, temperature, pressure, and gas composition. The wavelength dependence of the index of refraction n_{air} of standard dry air at

38 Chapter Three

a pressure of 760 torr and 15°C is

$$n_{\text{air}} = 1 + 10^{-8} \left(8342.13 + \frac{2,406,030}{130 - 1/\lambda^2} + \frac{15,997}{38.9 - 1/\lambda^2} \right) \quad (3.5)$$

where the wavelength λ of the light is measured in micrometers (10^{-6} m). Using this equation, we find that for a wavelength of 1550 nm = 1.550 μm used in fiber optic communications, the refractive index for air is $n_{\text{air}} = 1.00027325$, which yields a speed of light $c_{\text{air}} = 299,710,562$ m/s.

3.5. Reflection and Refraction

The concepts of reflection and refraction can be understood most easily by using light rays. When a light ray encounters a boundary separating two materials that have different refractive indices, part of the ray is reflected to the first medium and the remainder is bent (or *refracted*) as it enters the second material. This is shown in Fig. 3.1 where $n_1 > n_2$. The bending or refraction of the light ray at the interface is a result of the difference in the speed of light in two materials with different refractive indices.

Snell's Law The relationship describing refraction at the interface between two different light-transmitting materials is known as *Snell's law* and is given by

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \quad (3.6)$$

or equivalently as

$$n_1 \cos \theta_1 = n_2 \cos \theta_2 \quad (3.7)$$

where the angles are defined in Fig. 3.1. The angle ϕ_1 between the incident ray and the normal to the surface is known as the *angle of incidence*.

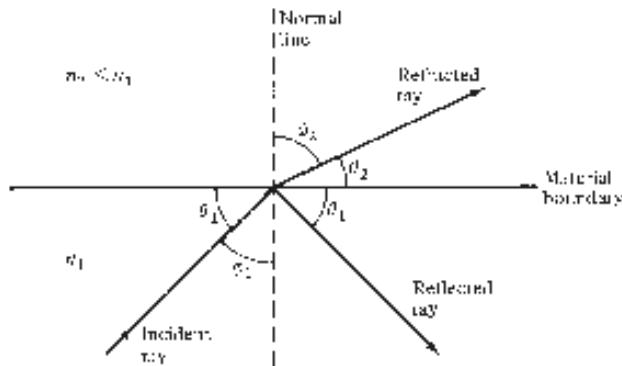


Figure 3.1. Refraction and reflection of a light ray at a material boundary.

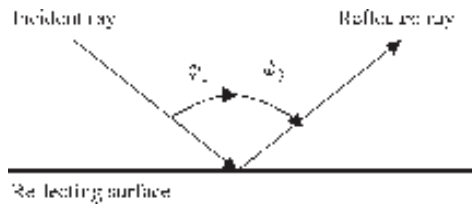


Figure 3.2. Illustration of the law of reflection.

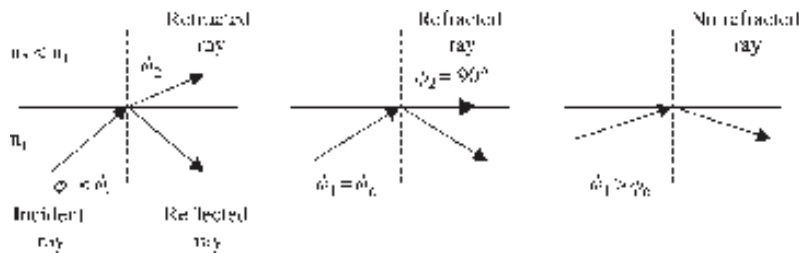


Figure 3.3. Representation of the critical angle and total internal reflection at a glass-air interface.

According to the law of reflection, as illustrated in Fig. 3.2, the angle ϕ_1 at which the incident ray strikes the interface is exactly equal to the angle ϕ_3 that the reflected ray makes with the same interface. In addition, the incident ray, the normal to the interface, and the reflected ray all lie in the same plane, which is perpendicular to the interface plane between the two materials. This is called the *plane of incidence*.

When light traveling in a certain medium is reflected off an optically denser material (one with a higher refractive index), the process is referred to as *external reflection*. Conversely, the reflection of light off a less optically dense material (such as light traveling in glass being reflected at a glass-to-air interface) is called *internal reflection*.

As the angle of incidence ϕ_1 in an optically denser material becomes larger, the refracted angle ϕ_2 approaches $\pi/2$. Beyond this point no refraction into the adjoining material is possible, and the light rays become *totally internally reflected*. The conditions required for total internal reflection can be determined by using Snell's law [see Eq. (3.6)]. Consider Fig. 3.3, which shows a glass surface in air. A light ray gets bent toward the glass surface as it leaves the glass in accordance with Snell's law. If the angle of incidence ϕ_1 is increased, a point will eventually be reached where the light ray in air is parallel to the glass surface. This point is known as the *critical angle of incidence* ϕ_c . When ϕ_1 is greater than ϕ_c , the condition for total internal reflection is satisfied; that is, the light is totally reflected back into the glass with no light escaping from the glass surface.

Example If we look at the glass-air interface in Fig. 3.3, when the refracted light ray is parallel to the glass surface, then $\phi_2 = 90^\circ$ so that $\sin \phi_2 = 1$. Thus $\sin \phi_c = n_2/n_1$.

40 Chapter Three

Using $n_1 = 1.48$ for glass and $n_2 = 1.00$ for air, we get $\phi_c = 42^\circ$. This means that any light in the glass incident on the interface at an angle ϕ_1 greater than 42° is totally reflected back into the glass.

3.6. Polarization

Light is composed of one or more *transverse electromagnetic waves* that have both an electric field (called an E field) and a magnetic field (called an H field) component. As shown in Fig. 3.4, in a transverse wave the directions of the vibrating electric and magnetic fields are perpendicular to each other and are at right angles to the direction of propagation (denoted by the vector $\mathbf{k}$) of the wave. The wave shown in Fig. 3.4 is *plane-polarized*. This means that the vibrations in the electric field are parallel to one another at all points in the wave, so that the electric field forms a plane called the *plane of vibration*. Likewise all points in the magnetic field component of the wave lie in a plane that is at right angles to the electric field plane.

3.6.1. Unpolarized light

An ordinary light wave is made up of many transverse waves that vibrate in a variety of directions (i.e., in more than one plane) and is referred to as *unpolarized light*. However, any arbitrary direction of vibration can be represented as a combination of a parallel vibration and a perpendicular vibration, as shown in Fig. 3.5. Therefore, unpolarized light can be viewed as consisting of two orthogonal plane polarization components, one that lies in the plane of incidence (the plane containing the incident and reflected rays) and the other that lies in a plane perpendicular to the plane of incidence. These are denoted as the *parallel polarization* and the *perpendicular polarization* components,

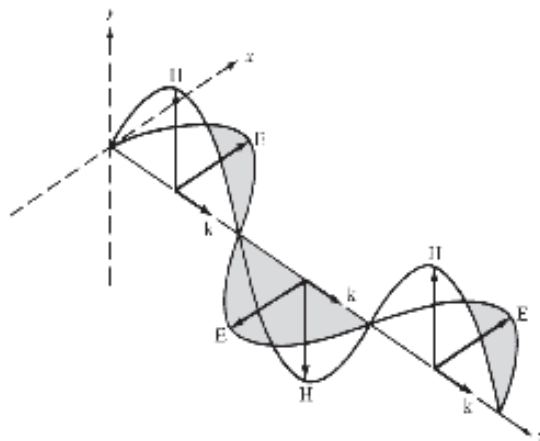


Figure 3.4. Electric and magnetic field distributions in a train of plane electromagnetic waves at a given instant in time.

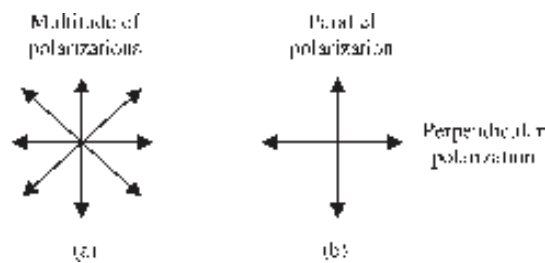


Figure 3.5. Polarization represented as a combination of a parallel vibration and a perpendicular vibration.

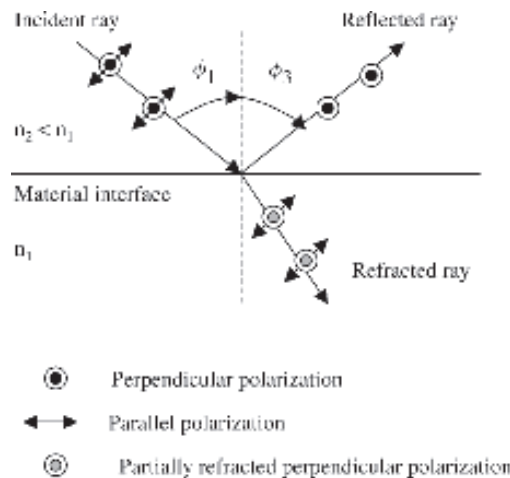


Figure 3.6. Behavior of an unpolarized light beam at the interface between air and a non-metallic surface.

respectively. In the case when all the electric field planes of the different transverse waves are aligned parallel to one another, then the light wave is *linearly polarized*. This is the simplest type of polarization.

Unpolarized light can be split into separate polarization components either by reflection off a nonmetallic surface or by refraction when the light passes from one material to another. As noted earlier in Fig. 3.1, when an unpolarized light beam traveling in air impinges on a nonmetallic surface such as glass, part of the beam is reflected and part is refracted into the glass. A circled dot and an arrow designate the parallel and perpendicular polarization components, respectively, in Fig. 3.6. The reflected beam is partially polarized and at a specific angle (known as *Brewster's angle*) is completely perpendicularly polarized. A familiar example of this is the use of polarizing sunglasses to reduce the glare of partially polarized sunlight reflections from road or water surfaces. The parallel component of the refracted beam is entirely transmitted into the glass, whereas the perpendicular component is only partially refracted. How much of

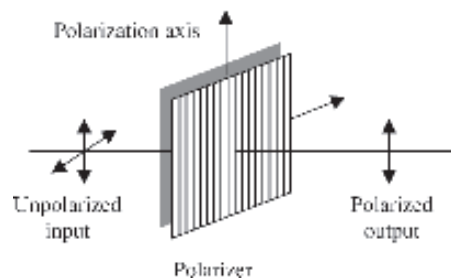


Figure 3.7. Only the vertical polarization component passes through this polarizer.

the refracted light is polarized depends on the angle at which the light approaches the surface and on the material itself.

These polarization characteristics of light are important when we examine the behavior of components such as optical isolators and light filters, which are described in Chap. 9. Here we look at three polarization-sensitive materials or devices that are used in such components. These are polarizers, Faraday rotators, and birefringent crystals.

3.6.2. Polarizers

A *polarizer* is a material or device that transmits only one polarization component and blocks the other. For example, when unpolarized light enters a polarizer that has a vertical transmission axis as shown in Fig. 3.7, only the vertical polarization component passes through the device. As noted earlier, a familiar application is the use of polarizing sunglasses. To see the polarization property of the sunglasses you are wearing, tilt your head sideways. A number of glare spots will then appear. The sunglasses block out the polarized light from these spots when you hold your head normally.

3.6.3. Faraday rotators

A *Faraday rotator* is a device that rotates the *state of polarization* (SOP) of light passing through it by a specific amount. For example, a popular device rotates the SOP clockwise by 45° or one-quarter wavelength, as shown in Fig. 3.8. This rotation is independent of the SOP of input light, but the rotation angle is different depending on the direction in which the light passes through the device. That is, the rotation is not reciprocal. In addition, the SOP of the input light is maintained after the rotation; for example, if the input light to a 45° Faraday rotator is linearly polarized in a vertical direction, then the rotated light exiting the crystal also is linearly polarized at a 45° angle. The material is usually some type of asymmetric crystal such as yttrium iron garnet (YIG), and the degree of angular rotation is proportional to the thickness of the device.

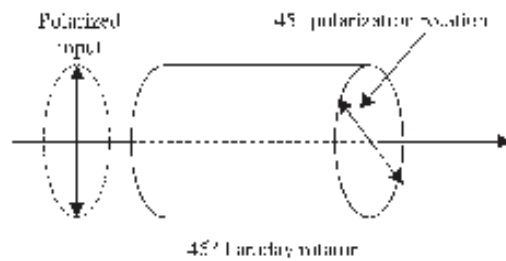


Figure 3.8. A Faraday rotator is a device that rotates the state of polarization clockwise by 45° or one-quarter wavelength.

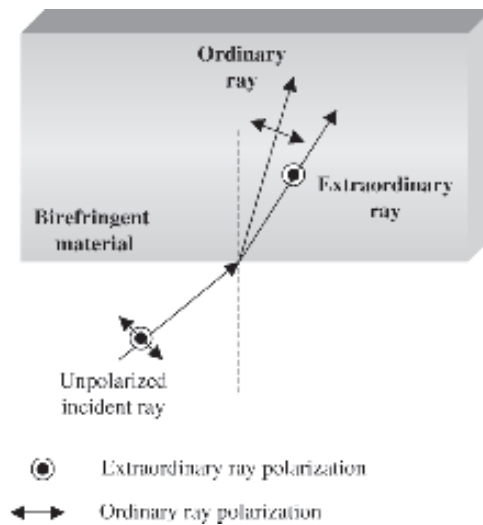


Figure 3.9. A birefringent crystal splits the light signal entering it into two perpendicularly polarized beams.

3.6.4. Double-refractive crystals

Certain crystalline materials have a property called *double refraction* or *birefringence*. This means that the indices of refraction are slightly different along two perpendicular axes of the crystal, as shown in Fig. 3.9. A device made from such materials is known as a *spatial walk-off polarizer* (SWP). The SWP splits the light signal entering it into two orthogonally (perpendicularly) polarized beams. One of the beams is called an *ordinary ray* or *o ray*, since it obeys Snell's law of refraction at the crystal surface. The second beam is called the *extraordinary ray* or *e ray*, since it refracts at an angle that deviates from the prediction of the standard form of Snell's law. Each of the two orthogonal polarization components thus is refracted at a different angle, as shown in Fig. 3.9. For example, if the incident unpolarized light arrives at a perpendicular angle to the surface of the device, the *o ray* can pass straight through the device whereas

TABLE 3.1. Some Common Birefringent Crystals and Their Ordinary and Extraordinary Indices of Refraction

Crystal name	Symbol	n_o	n_e
Calcite	CaCO_3	1.658	1.486
Lithium niobate	LiNbO_3	2.286	2.200
Rutile	TiO_2	2.616	2.903
Yttrium vanadate	YVO_4	1.945	2.149

the e ray component is deflected at a slight angle so it follows a different path through the material.

Table 3.1 lists the ordinary index n_o and the extraordinary index n_e of some common birefringent crystals that are used in optical communication components. As will be described in later chapters, they have the following applications:

- Calcite is used for polarization control and in beam splitters.
- Lithium niobate is used for light signal modulation.
- Rutile is used in optical isolators and circulators.
- Yttrium vanadate is used in optical isolators, circulators, and beam displacers.

3.7. Summary

Some optical phenomena can be explained using a wave theory whereas in other cases light behaves as though it is composed of miniature particles called *photons*. The wave nature explains how light travels through an optical fiber and how it can be coupled between two adjacent fibers, but the particle theory is needed to explain how optical sources generate light and how photodetectors change an optical signal to an electric signal.

In free space a light wave travels at a speed $c = 3 \times 10^8$ m/s, but it slows down by a factor $n > 1$ when entering a material, where the parameter n is the index of refraction (or refractive index) of the material. Values of the refractive index for materials related to optical communications are 1.00 for air and between 1.45 and 1.50 for various glass compounds. Thus light travels at about 2×10^8 m/s in a glass optical fiber.

When a light ray encounters a boundary separating two media that have different refractive indices, part of the ray is reflected back into the first medium and the remainder is bent (or *refracted*) as it enters the second material. As will be discussed in later chapters, these concepts play a major role in describing the amount of optical power that can be injected into a fiber and how light waves travel along a fiber.

The polarization characteristics of light waves are important in examining the behavior of components such as optical isolators and filters. Polarization-sensitive devices include light signal modulators, polarization filters, Faraday

rotators, beam splitters, and beam displacers. Birefringent crystals such as calcite, lithium niobate, rutile, and yttrium vanadate are polarization-sensitive materials used in such components.

Further Reading

1. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, Wiley, New York, 1991. This book presents an advanced encyclopedic treatment of all aspects of the fundamentals of photonics.
2. E. Hecht, *Optics*, 4th ed., Addison-Wesley, Reading, Mass., 2002. A classical undergraduate-level university textbook on optics.
3. J. L. Miller and E. Friedman, *Photonics Rules of Thumb: Optics, Electro-Optics, Fiber Optics, and Lasers*, McGraw-Hill, New York, 1996.

Optical Fibers

The optical fiber is a key part of a lightwave communication system. An optical fiber is nominally a cylindrical dielectric waveguide that confines and guides light waves along its axis. Except for certain specialty fibers, basically all fibers used for telecommunication purposes have the same physical structure. The variations in the material and the size of this structure dictate how a light signal is transmitted along different types of fiber and also influence how the fiber responds to environmental perturbations, such as stress, bending, and temperature variations. This chapter describes various fiber structures, physical characteristics, operational properties, and applications.

4.1. Light Propagation in Fibers

Figure 4.1 shows the end-face cross section and a longitudinal cross section of a standard optical fiber, which consists of a cylindrical glass core surrounded by a glass cladding. The *core* has a refractive index n_1 , and the *cladding* has a refractive index n_2 . Surrounding these two layers is a polymer *buffer coating* that protects the fiber from mechanical and environmental effects. Traditionally the core radius is designated by the letter a . In almost all cases, for telecommunication fibers the core and cladding are made of silica glass (SiO_2).

The refractive index of pure silica varies with wavelength, ranging from 1.453 at 850 nm to 1.445 at 1550 nm. By adding certain impurities such as germanium or boron to the silica during the fiber manufacturing process, the index can be changed slightly, usually as an increase in the core index. This is done so that the refractive index n_2 of the cladding is slightly smaller than the index of the core (that is, $n_2 < n_1$), which is the condition required for light traveling in the core to be totally internally reflected at the boundary with the cladding. The difference in the core and cladding indices also determines how light signals behave as they travel along a fiber. Typically the index differences range from 0.2 to 3.0 percent depending on the desired behavior of the resulting fiber.

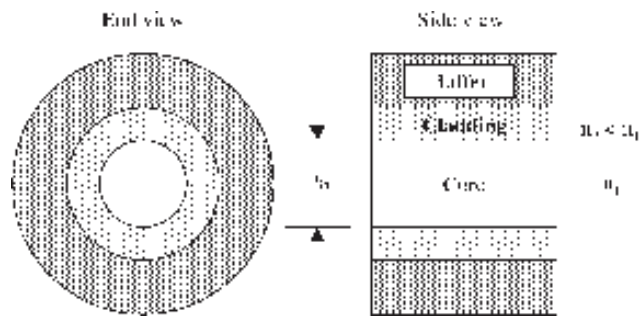


Figure 4.1. End-face cross section and a longitudinal cross section of a standard optical fiber.

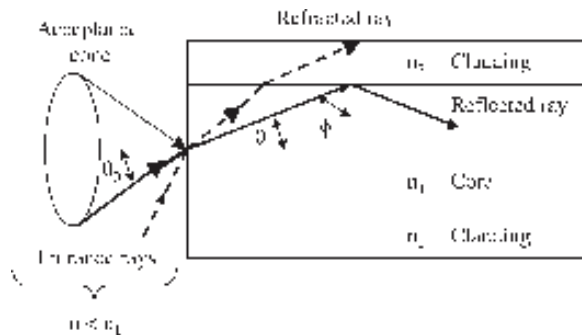


Figure 4.2. Ray optics representation of the propagation mechanism in an ideal step-index optical waveguide.

To get an understanding of how light travels along a fiber, let us first examine the case when the core diameter is much larger than the wavelength of the light. As discussed in Chap. 3, for such a case we can consider a simple geometric optics approach using the concept of light rays. Figure 4.2 shows a light ray entering the fiber core from a medium of refractive index n , which is less than the index n_1 of the core. The ray meets the core end face at an angle θ_0 with respect to the fiber axis and is refracted into the core. Inside the core the ray strikes the core-cladding interface at a normal angle ϕ . If the light ray strikes this interface at such an angle that it is totally internally reflected, then the ray follows a zigzag path along the fiber core.

Now suppose that the angle θ_0 is the largest entrance angle for which total internal reflection can occur at the core-cladding interface. Then rays outside of the acceptance cone shown in Fig. 4.2, such as the ray given by the dashed line, will refract out of the core and be lost in the cladding. This condition defines a *critical angle* ϕ_c , which is the smallest angle ϕ that supports total internal reflection at the core-cladding interface.

Critical Angle Referring to Fig. 4.2, from Snell's law the minimum angle $\phi = \phi_{\min}$ that supports total internal reflection is given by $\phi_c = \phi_{\min} = \arcsin(n_2/n_1)$. Rays striking the core-cladding interface at angles less than $\phi_{\min}$ will refract out of the core

and be lost in the cladding. Now suppose the medium outside of the fiber is air for which $n = 1.00$. By applying Snell's law to the air-fiber interface boundary, the condition for the critical angle can be related to the maximum entrance angle $\theta_{0,\max}$ through the relationship

$$\sin \theta_{0,\max} = n_1 \sin \theta_c = (n_1^2 - n_2^2)^{1/2}$$

where $\theta_c = \pi/2 - \phi_c$. Thus those rays having entrance angles θ_0 less than $\theta_{0,\max}$ will be totally internally reflected at the core-cladding interface.

Example

1. Suppose the core index $n_1 = 1.480$ and the cladding index $n_2 = 1.465$. Then the critical angle is $\phi_c = \arcsin(1.465/1.480) = 82^\circ$, so that $\theta_c = \pi/2 - \phi_c = 8^\circ$.
2. With this critical angle, the maximum entrance angle is

$$\theta_{0,\max} = \arcsin(n_1 \sin \theta_c) = \arcsin(1.480 \sin 8^\circ) = 11.9^\circ$$

4.2. Optical Fiber Modes

Although it is not directly obvious from the ray picture shown in Fig. 4.2, only a finite set of rays at certain discrete angles greater than or equal to the critical angle ϕ_c is capable of propagating along a fiber. These angles are related to a set of electromagnetic wave patterns or field distributions called *modes* that can propagate along a fiber. When the fiber core diameter is on the order of 8 to 10 μm , which is only a few times the value of the wavelength, then only the one single *fundamental ray* that travels straight along the axis is allowed to propagate in a fiber. Such a fiber is referred to as a *single-mode fiber*. The operational characteristics of single-mode fibers cannot be explained by a ray picture, but instead need to be analyzed in terms of the *fundamental mode* by using the electromagnetic wave theory. Fibers with larger core diameters (e.g., greater than or equal to 50 μm) support many propagating rays or modes and are known as *multimode fibers*. A number of performance characteristics of multimode fibers can be explained by ray theory whereas other attributes (such as the optical coupling concept presented in Chap. 8) need to be described by wave theory.

Figure 4.3 shows the field patterns of the three lowest-order *transverse electric* (TE) modes as seen in a cross-sectional view of an optical fiber. They are the TE_0 , TE_1 , and TE_2 modes and illustrate three of many possible power distribution patterns in the fiber core. The subscript refers to the *order* of the mode, which is equal to the number of zero crossings within the guide. In single-mode fibers only the lowest-order or *fundamental mode* (TE_0) will be guided along the fiber core. Its $1/e^2$ width is called the *mode field diameter*.

As the plots in Fig. 4.3 show, the power distributions are not confined completely to the core, but instead extend partially into the cladding. The fields vary harmonically within the core guiding region of index n_1 and decay exponentially outside of this region (in the cladding). For low-order modes the

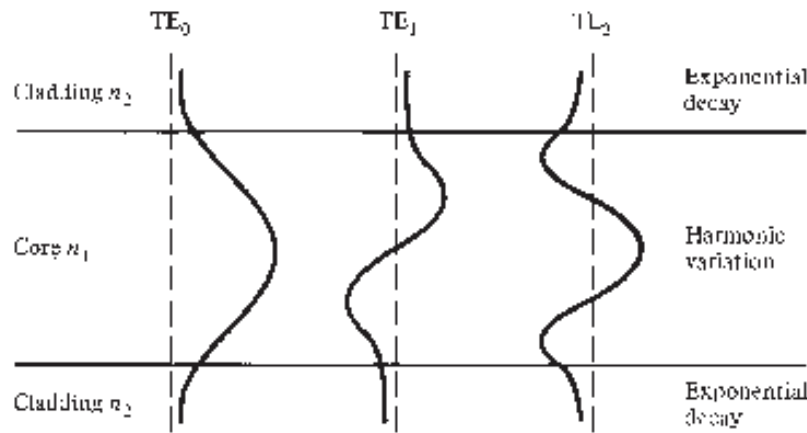


Figure 4.3. Electric field patterns of the three lowest-order guided modes as seen in a cross-sectional view of an optical fiber.

fields are concentrated tightly near the axis of the fiber with little penetration into the cladding. On the other hand, for higher-order modes the fields are distributed more toward the edges of the core and penetrate farther into the cladding region. The importance of the characteristic that the power of a mode extends partially into the cladding will be seen in later chapters which discuss applications such as coupling of power from one fiber to another.

4.3. Variations of Fiber Types

Variations in the material composition of the core and the cladding give rise to the two basic fiber types shown in Fig. 4.4a. In the first case, the refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary. This is called a *step-index fiber*. In the second case, the core refractive index varies as a function of the radial distance from the center of the fiber. This defines a *graded-index fiber*. Section 4.6 describes the advantages of graded-index fibers over step-index fibers for high-speed data transfer when using multimode fibers. More complex structures of the cladding index profile allow fiber designers to tailor the signal dispersion characteristics of the fiber (see Sec. 4.6). Figure 4.4b shows two of many different possible configurations.

Table 4.1 lists typical core, cladding, and buffer coating sizes of optical fibers for use in telecommunications, in a metropolitan-area network (MAN), or in a local-area network (LAN). The outer diameter of the buffer coating can be either 250 or 500 μm . Single-mode fibers are used for long-distance communication and for transmissions at very high data rates. The larger-core multimode fibers typically are used for local-area network applications in a campus environment, particularly for gigabit or 10-Gbit rate Ethernet links, which are known popularly as GigE and 10GigE, respectively. Here the word *campus* refers to any group of buildings that are within reasonable walking distance of one another (see Sec. 2.5).

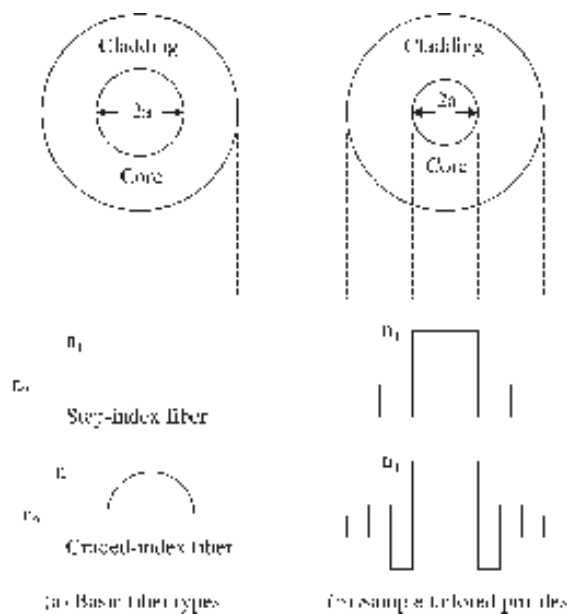


Figure 4.4. Variations in the material composition of the core and cladding yield different fiber types. (a) Simple profiles define step- and graded-index fibers; (b) complex cladding-index profiles tailor the signal dispersion characteristics of a fiber.

TABLE 4.1. Typical Core, Cladding, and Buffer Coating Sizes of Optical Fibers

Fiber type	Core diameter, μm	Cladding outer diameter, μm	Buffer outer diameter, μm	Application
Single-mode	7–10	125	250 or 500	Telecommunications
Multimode	50.0	125	250 or 500	LAN or MAN
Multimode	62.5	125	250 or 500	LAN
Multimode	85	125	250 or 500	Older LAN fiber
Multimode	100	140	250 or 500	Older fiber type

The critical angle also defines a parameter called the *numerical aperture* (NA), which is used to describe the light acceptance or gathering capability of fibers that have a core size much larger than a wavelength. This parameter defines the size of the acceptance cone shown in Fig. 4.2. The numerical aperture is a dimensionless quantity which is less than unity, with values ranging from 0.14 to 0.50.

Numerical Aperture The critical angle condition on the entrance angle defines the *numerical aperture* (NA) of a step-index fiber. This is given by

$$\text{NA} = n \sin \theta_{0,\max} = n_1 \sin \theta_c = (n_1^2 - n_2^2)^{1/2} \approx n_1 \sqrt{2\Delta}$$

52 Chapter Four

where the parameter Δ is called the *core-cladding index difference* or simply the *index difference*. It is defined through the equation $n_2 = n_1(1 - \Delta)$. Typical values of Δ range from 1 to 3 percent for multimode fibers and from 0.2 to 1.0 percent for single-mode fibers. Thus, since Δ is much less than 1, the approximation on the right-hand side of the above equation is valid.

Since the numerical aperture is related to the maximum acceptance angle, it is used commonly to describe the light acceptance or gathering capability of a multimode fiber and to calculate the source-to-fiber optical power coupling efficiencies.

Example A multimode step-index fiber has a core index $n_1 = 1.480$ and an index difference $\Delta = 0.01$. The numerical aperture for this fiber is $\text{NA} = 1.480 \sqrt{0.02} = 0.21$.

4.4. Single-Mode Fibers

An important parameter for single-mode fibers is the *cutoff wavelength*. This is designated by λ_{cutoff} and specifies the smallest wavelength for which all fiber modes except the fundamental mode are cut off; that is, the fiber transmits light in a single mode only for those wavelengths that are greater than λ_{cutoff} . The fiber can support more than one mode if the wavelength of the light is less than the cutoff. Thus if a fiber is single-mode at 1310 nm, it is also single-mode at 1550 nm, but not necessarily at 850 nm.

When a fiber is fabricated for single-mode use, the cutoff wavelength usually is chosen to be much less than the desired operating wavelength. For example, a fiber for single-mode use at 1310 nm may have a cutoff wavelength of 1275 nm.

Cutoff Wavelength For a fiber to start supporting only a single mode at a wavelength λ_{cutoff} , the following condition (derived from solutions to Maxwell's equations for a circular waveguide) needs to be satisfied:

$$\lambda_{\text{cutoff}} = \frac{2\pi a}{2.405} (n_1^2 - n_2^2)^{1/2}$$

where a is the radius of the fiber core, n_1 is the core index, and n_2 is the cladding index.

Example Suppose we have a fiber with $a = 4.2 \mu\text{m}$, $n_1 = 1.480$, and $n_2 = n_1(1 - 0.0034) = 1.475$. Its cutoff wavelength then is

$$\lambda_{\text{cutoff}} = \frac{2\pi(4.2 \mu\text{m})}{2.405} [(1.480)^2 - (1.475)^2]^{1/2} = 1334 \text{ nm}$$

4.5. Optical Fiber Attenuation

Light traveling in a fiber loses power over distance, mainly because of absorption and scattering mechanisms in the fiber. The fiber loss is referred to as *signal attenuation* or simply *attenuation*. Attenuation is an important property of an optical fiber because, together with signal distortion mechanisms, it determines

the maximum transmission distance possible between a transmitter and a receiver (or an amplifier) before the signal power needs to be boosted to an appropriate level above the signal noise for high-fidelity reception. The degree of the attenuation depends on the wavelength of the light and on the fiber material.

Figure 4.5 shows a typical attenuation versus wavelength curve for a silica fiber. The loss of power is measured in decibels (see Chap. 1), and the loss within a cable is described in terms of decibels per kilometer (dB/km).

Example Suppose a fiber has an attenuation of 0.4 dB/km at a wavelength of 1310 nm. Then after it travels 50 km, the optical power loss in the fiber is 20 dB (a factor of 100).

Figure 4.5 also shows that early optical fibers had a large attenuation spike between 900 and 1200 nm due to the fourth-order absorption peak from water molecules. Another spike from the third-order water absorption occurs between 1350 and 1480 nm for commonly fabricated fibers. Because of such absorption peaks, three transmission windows were defined initially. The *first window* ranges from 800 to 900 nm, the *second window* is centered at 1310 nm, and the *third window* ranges from 1480 to 1600 nm. Since the attenuation of low-water-peak fibers makes the designation of these windows obsolete, the concept of operational spectral bands arose for the 1260- to 1675-nm region, as described in Chap. 1. Figure 4.6 shows the attenuation as a function of wavelength for a low-water-peak fiber in the region covered by the six operational bands.

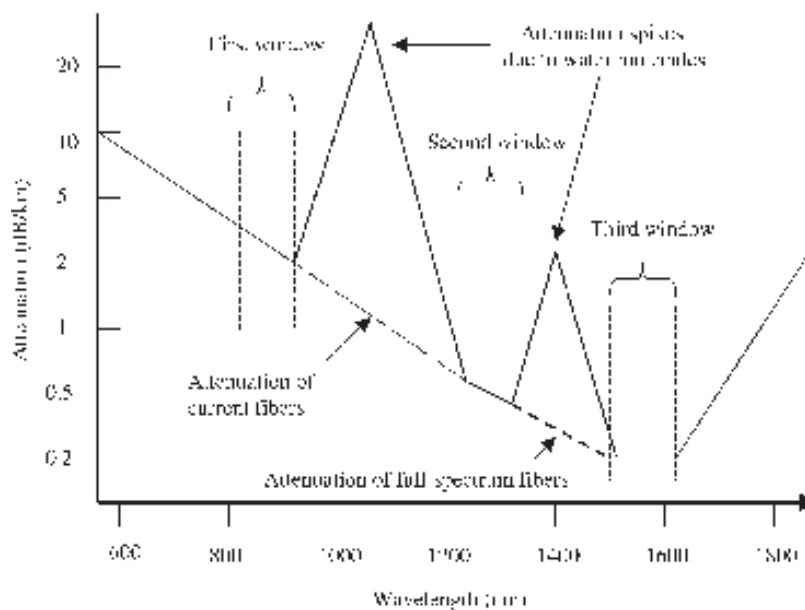


Figure 4.5. A typical attenuation versus wavelength curve for a silica fiber. Early fibers had a high loss spike around 1100 nm. Full-spectrum (low-water-content) fibers allow transmission in all spectral bands.

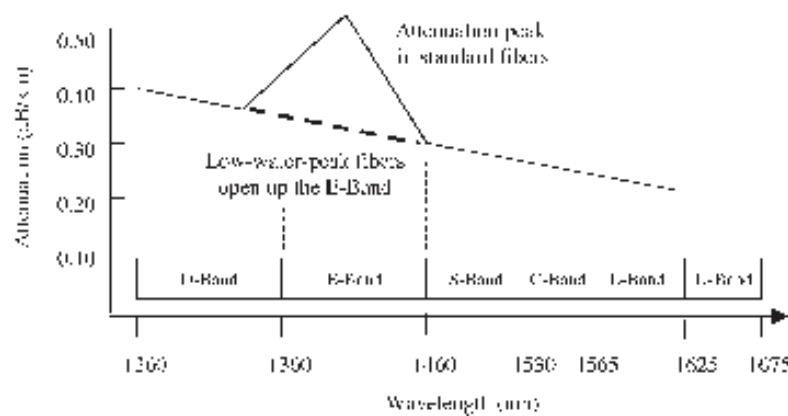


Figure 4.6. Attenuation versus wavelength for a low-water-peak fiber in the six operational spectral bands.

TABLE 4.2. Typical Losses in Standard 9- μm Fiber for Three Fiber Turns on a Specific Mandrel

Mandrel radius	Loss at 1310 nm	Loss at 1550 nm
1.15 cm	2.6 dB	23.6 dB
1.80 cm	0.1 dB	2.6 dB

In addition to the intrinsic absorption and scattering loss mechanisms in a fiber, light power can be lost as a result of fiber bending. Fibers can be subject to two types of bends: (1) *macroscopic bends* that have radii which are large compared with the fiber diameter, for example, those that occur when a fiber cable turns a corner, and (2) random *microscopic bends* of the fiber axis that can arise when fibers are incorporated into cables. Since the microscopic bending loss is determined in the manufacturing process, the user has little control over the degree of loss resulting from them. In general cable fabrication processes keep these values to a very low value, which is included in published cable loss specifications.

For slight bends, the excess optical power loss due to macroscopic bending is extremely small and is essentially unobservable. As the radius of curvature decreases, the loss increases exponentially until at a certain critical bend radius the curvature loss becomes observable. If the bend radius is made a bit smaller once this threshold has been reached, the losses suddenly become extremely large. Bending losses depend on wavelength and are measured by winding several loops of fiber on a rod of a specific diameter. Table 4.2 gives typical bending loss values when three loops of a standard 9- μm core-diameter single-mode fiber are wound on rods with radii of 1.15 and 1.80 cm. Note the large difference in losses between operation at 1310 and 1550 nm. As a rule of thumb, it is best not to make the bend radius of such a fiber be less than 2.5 cm.

Since often fibers need to be bent into very tight loops within component packages, special fibers that are immune to bending losses have been developed for such applications. This class of specialty fibers is described in Sec. 4.7.

4.6. Fiber Information Capacity

The information-carrying capacity of the fiber is limited by various distortion mechanisms in the fiber, such as signal dispersion factors and nonlinear effects. The three main dispersion categories are modal, chromatic, and polarization mode dispersions. These distortion mechanisms cause optical signal pulses to broaden as they travel along a fiber. As Fig. 4.7 shows, if optical pulses travel sufficiently far in a fiber, they will eventually overlap with neighboring pulses, thereby creating errors in the output since they become indistinguishable to the receiver. Nonlinear effects occur when there are high power densities (optical power per cross-sectional area) in a fiber. Their impact on signal fidelity includes shifting of power between wavelength channels, appearances of spurious signals at other wavelengths, and decreases in signal strength. Chapter 15 discusses these nonlinear-induced degradations in greater detail.

Modal dispersion arises from the different path lengths associated with various modes (as represented by light rays at different angles). It appears only in multimode fibers, since in a single-mode fiber there is only one mode. By looking at Fig. 4.8 it can be deduced that rays bouncing off the core-cladding interface follow a longer path compared to the fundamental ray that travels straight down the fiber axis. For example, since ray 2 makes a steeper angle than ray 1,

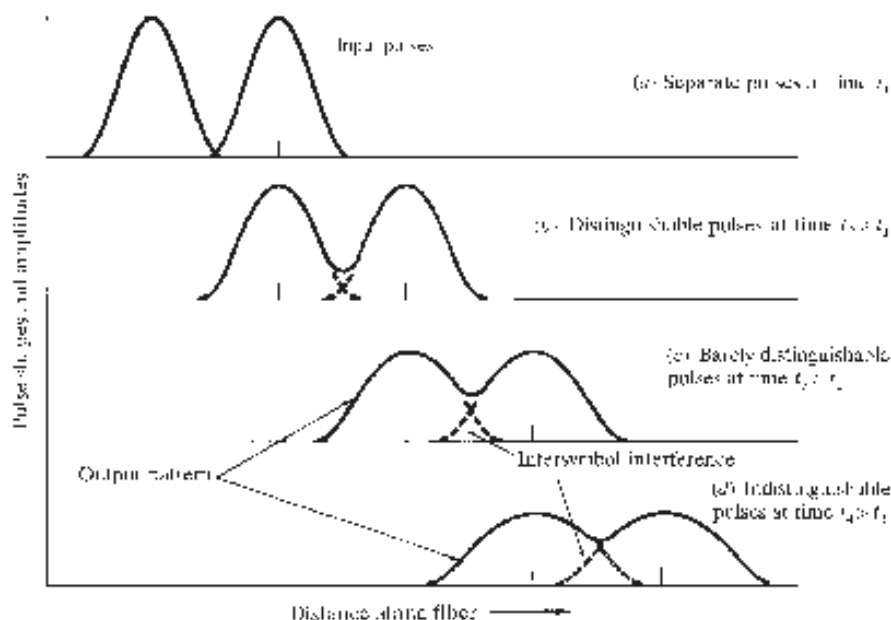


Figure 4.7. Broadening and attenuation of two adjacent pulses as they travel along a fiber.

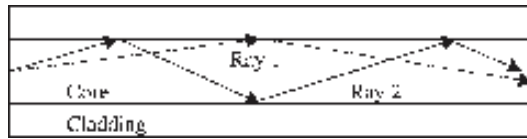


Figure 4.8. Rays that have steeper angles have longer path lengths.

ray 2 has a longer path length from the beginning to the end of a fiber. If all the rays are launched into a fiber at the same time in a given light pulse, then they will arrive at the fiber end at slightly different times. This causes the pulse to spread out and is the basis of modal dispersion.

In a graded-index fiber, the index of refraction is lower near the core-cladding interface than at the center of the core. Therefore, in such a fiber the rays that strike this interface at a steeper angle will travel slightly faster as they approach the cladding than those rays arriving at a smaller angle. For example, this means that the light power in ray 2 shown in Fig. 4.8 will travel faster than that in ray 1. Thereby the various rays tend to keep up with one another to some degree. Consequently the graded-index fiber exhibits less pulse spreading than a step-index fiber where all rays travel at the same speed.

The index of refraction of silica varies with wavelength; for example, it ranges from 1.453 at 850 nm to 1.445 at 1550 nm. In addition, as described in Chap. 6, a light pulse from an optical source contains a certain slice of wavelength spectrum. For example, a laser diode source may emit pulses that have a 1-nm spectral width. Consequently, different wavelengths within an optical pulse travel at slightly different speeds through the fiber (recall from Chap. 3 that $s = c/n$). Therefore each wavelength will arrive at the fiber end at a slightly different time, which leads to pulse spreading. This factor is called *chromatic dispersion*, which often is referred to simply as *dispersion*. It is a fixed quantity at a specific wavelength and is measured in units of picoseconds per kilometer of fiber per nanometer of optical source spectral width, abbreviated as ps/(km·nm). For example, a single-mode fiber might have a chromatic dispersion value of $D_{CD} = 2$ ps/(km·nm) at 1550 nm. Figure 4.9 shows the chromatic dispersion as a function of wavelength for several different fiber types, which are described in Sec. 4.8.

Polarization mode dispersion (PMD) results from the fact that light-signal energy at a given wavelength in a single-mode fiber actually occupies two orthogonal polarization states or modes. Figure 4.10 shows this condition. At the start of the fiber the two polarization states are aligned. However, fiber material is not perfectly uniform throughout its length. In particular, the refractive index is not perfectly uniform across any given cross-sectional area. This condition is known as the *birefringence* of the material. Consequently, each polarization mode will encounter a slightly different refractive index, so that each will travel at a slightly different velocity and the polarization orientation will rotate with distance. The resulting difference in propagation times between the two orthogonal polarization modes will result in pulse spreading. This is the basis of polarization mode dispersion. PMD is not a fixed quantity but fluctuates

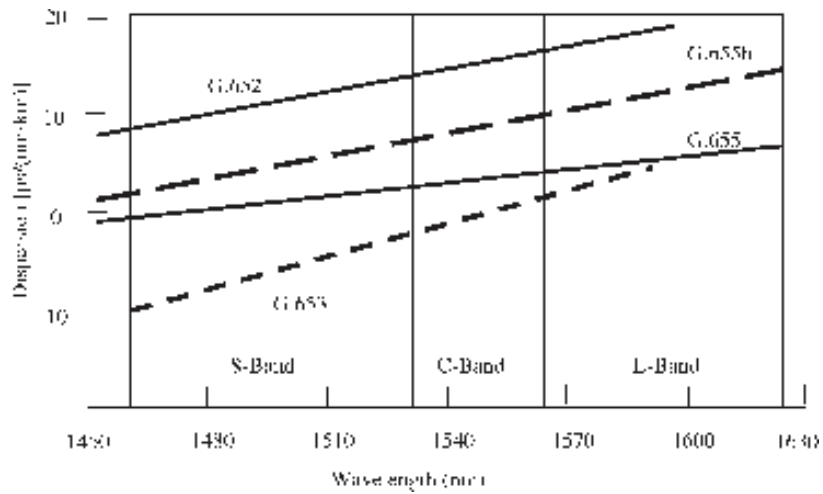


Figure 4.9. Chromatic dispersion as a function of wavelength in various spectral bands for several different fiber types.

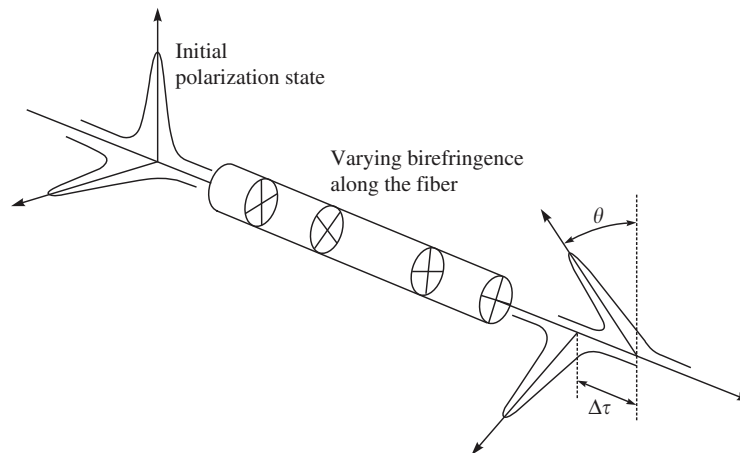


Figure 4.10. Variation in the polarization states of an optical pulse as it passes through a fiber that has varying birefringence along its length.

with time due to factors such as temperature variations and stress changes on the fiber. It varies as the square root of distance and thus is specified as a mean value in units of $\text{ps}/\sqrt{\text{km}}$. A typical value is $D_{\text{PMD}} = 0.05 \text{ ps}/\sqrt{\text{km}}$.

Dispersion Calculation If t_{mod} , t_{CD} , and t_{PMD} are the modal, chromatic, and polarization mode dispersion times, respectively, then the total dispersion t_T can be calculated by the relationship

$$t_T = \sqrt{(t_{\text{mod}})^2 + (t_{\text{CD}})^2 + (t_{\text{PMD}})^2}$$

Note that $t_{\text{mod}} = 0$ for single-mode fibers. As a rule of thumb, the information-carrying capacity over a certain length of fiber then is determined by specifying that the pulse spreading not be more than 10 percent of the pulse width at a designated data rate.

Example Consider a single-mode fiber for which $D_{CD} = 2 \text{ ps}/(\text{km} \cdot \text{nm})$ and $D_{PMD} = 0.1 \text{ ps}/\sqrt{\text{km}}$. If a transmission link has a length $L = 500 \text{ km}$ and uses a laser source with a spectral emission width of $\Delta\lambda = 0.01 \text{ nm}$ (we will see more details about what this means in Chap. 6), then we have $t_{\text{mod}} = 0$, $t_{CD} = D_{CD} \times L \times \Delta\lambda = 10 \text{ ps}$, and $t_{PMD} = D_{PMD} \times \sqrt{L} = 2.24 \text{ ps}$. Thus

$$t_T = \sqrt{(10 \text{ ps})^2 + (2.24 \text{ ps})^2} = 10.2 \text{ ps}$$

If t_T can be no more than 10 percent of a pulse width, then the maximum data rate R_{max} that can be sent over this 500-km link is $R_{\text{max}} = 0.1/t_T = 9.8 \text{ Gbps}$ (gigabits per second).

4.7. Optical Fiber Standards

The International Telecommunications Union (ITU-T) and the Telecommunications Industry Association (TIA/EIA) are the main organizations that have published standards for both multimode and single-mode optical fibers used in telecommunications. The recommended bounds on fiber parameters (e.g., attenuation, cutoff wavelength, and chromatic dispersion) designated in these standards ensure the users of product capability and consistency. In addition, the standards allow fiber manufacturers to have a reasonable degree of flexibility to improve products and develop new ones.

Multimode fibers are used widely in LAN environments, storage area networks, and central-office connections, where the distance between buildings is typically 2 km or less. The two principal multimode fiber types for these applications have either 50- or 62.5- μm core diameters, and both have 125- μm cladding diameters. To meet the demands for short-reach low-cost transmission of high-speed Ethernet signals, a 50- μm multimode fiber is available for 10-Gbps operation at 850 nm over distances up to 300 m. Table 4.3 shows the operating ranges of various multimode fibers for applications up to 10GigE. The standards document TIA/EIA-568 lists the specifications for 10GigE fiber. The ITU-T recommendation G.651 describes other multimode fiber specifications for LAN applications using 850-nm optical sources.

The ITU-T has published a series of recommendations for single-mode fibers. The characteristics of these fibers are given in the following listing. They are summarized in Table 4.4.

TABLE 4.3. Operating Ranges of Various Multimode Fibers for Applications up to 10GigE

Parameter	62.5- μm fiber		50- μm fiber			Unit
Bandwidth	160	200	400	500	2000	MHz-km
Range	26	33	66	82	300	m
Attenuation	2.5	2.5	2.5	2.5	2.5	dB/km

TABLE 4.4. ITU-T Recommendations for Single-Mode Fibers

ITU-T recommendation no.	Description
G.651	Multimode fiber for use at 850 nm in a LAN
G.652	Standard single-mode fiber (1310-nm optimized)
G.652.C	Low-water-peak fiber for CWDM applications
G.653	Dispersion-shifted fiber (made obsolete by NZDSF)
G.654	Submarine applications (1500-nm cutoff wavelength)
G.655	Nonzero dispersion-shifted fiber (NZDSF)
G.655b	Advanced nonzero dispersion-shifted fiber (A-NZDSF)

ITU-T G.652. This recommendation deals with the single-mode fiber that was installed widely in telecommunication networks in the 1990s. It has a Ge-doped silica core which has a diameter between 5 and 8 μm . Since early applications used 1310-nm laser sources, this fiber was optimized to have a zero-dispersion value at 1310 nm. Thus it is referred to as a *1310-nm optimized fiber*. With the trend toward operation in the lower-loss 1550-nm spectral region, the installation of this fiber has decreased dramatically. However, the huge base of G.652 fiber that is installed worldwide will still be in service for many years. If network operators want to use installed G.652 fiber at 1550 nm, complex dispersion compensation techniques are needed, as described in Chap. 15.

ITU-T G.652.C. *Low-water-peak fiber* for CWDM applications is created by reducing the water ion concentration in order to eliminate the attenuation spike in the 1360- to 1460-nm E-band. The fibers have core diameters ranging from 8.6 to 9.5 μm and an attenuation of less than 0.4 dB/km. The main use of this fiber is for low-cost short-reach CWDM (coarse WDM) applications in the E-band. In CWDM the wavelength channels are sufficiently spaced that minimum wavelength stability control is needed for the optical sources, as described in Chap. 13.

ITU-T G.653. *Dispersion-shifted fiber* (DSF) was developed for use with 1550-nm lasers. In this fiber type the zero-dispersion point is shifted to 1550 nm where the fiber attenuation is about one-half that at 1310 nm. Although this fiber allows a high-speed data stream of a single-wavelength channel to maintain its fidelity over long distances, it presents dispersion-related problems in DWDM applications where many wavelengths are packed into one or more of the operational bands. As a result, this fiber type became obsolete with the introduction of G.655 NZDSF.

ITU-T G.654. This specification deals with *cutoff-wavelength-shifted fiber* that is designed for long-distance high-power signal transmission. Since it has a high cutoff wavelength of 1500 nm, this fiber is restricted to operation at 1550 nm. It typically is used only in submarine applications.

ITU-T G.655. *Nonzero dispersion-shifted fiber* (NZDSF) was introduced in the mid-1990s for WDM applications. Its principal characteristic is that it has

a nonzero dispersion value over the entire C-band, which is the spectral operating region for erbium-doped optical fiber amplifiers (see Chap. 11). This is in contrast to G.653 fibers in which the dispersion varies from negative values through zero to positive values in this spectral range.

ITU-T G.655b. Advanced nonzero dispersion-shifted fiber (A-NZDSF) was introduced in October 2000 to extend WDM applications into the S-band. Its principal characteristic is that it has a nonzero dispersion value over the entire S-band and the C-band. This is in contrast to G.655 fibers in which the dispersion varies from negative values through zero to positive values in the S-band.

4.8. Specialty Fibers

Whereas telecommunication fibers, such as those described above, are designed to transmit light over long distances with minimal change in the signal, *specialty fibers* are used to manipulate the light signal. Specialty fibers interact with light and are custom-designed for specific applications such as optical signal amplification, wavelength selection, wavelength conversion, and sensing of physical parameters.

A number of both passive and active optical devices use specialty fibers to direct, modify, or strengthen an optical signal as it travels through the device. Among these optical devices are light transmitters, optical signal modulators, optical receivers, wavelength multiplexers, couplers, splitters, optical amplifiers, optical switches, wavelength add/drop modules, and light attenuators. Table 4.5 gives a summary of some specialty fibers and their applications. Later chapters describe the applications of each of these devices in greater detail.

4.8.1. Erbium-doped fiber

Erbium-doped optical fibers have small amounts of erbium ions added to the silica material and are used as a basic building block for optical fiber amplifiers. As described in Chap. 11, a length of Er-doped fiber ranging from 10 to 30 m is used as a gain medium for amplifying optical signals in the C-band (1530 to 1560 nm). There are many variations on the doping level, cutoff wavelength,

TABLE 4.5. Summary of Some Specialty Fibers and Their Applications

Specialty fiber type	Application
Erbium-doped fiber	Gain medium for optical fiber amplifiers
Photosensitive fibers	Fabrication of fiber Bragg gratings
Bend-insensitive fibers	Tightly looped connections in device packages
High-loss attenuating fiber	Termination of open optical fiber ends
Polarization-preserving fibers	Pump lasers, polarization-sensitive devices, sensors
High-index fibers	Fused couplers, short- λ sources, DWDM devices
Holey (photonic crystal) fibers	Switches; dispersion compensation

TABLE 4.6. Generic Parameter Values of an Erbium-Doped Fiber for Use in the C-Band

Parameter	Specification
Peak absorption at 1530 nm	5 to 10 dB/m
Effective numerical aperture	0.14 to 0.31
Cutoff wavelength	900 ± 50 nm; or 1300 nm
Mode field diameter at 1550 nm	5.0 to 7.3
Cladding diameter	125 μ m standard; 80 μ m for tight coils
Coating material	UV-cured acrylic

mode field diameter, numerical aperture, and cladding diameter for these fibers. Higher erbium concentrations allow the use of shorter fiber lengths, smaller claddings are useful for compact packages, and a higher numerical aperture allows for the fiber to be coiled tighter in small packages. Table 4.6 lists some generic parameter values of an erbium-doped fiber for use in the C-band.

Photosensitive fiber. A photosensitive fiber is designed so that its refractive index changes when it is exposed to ultraviolet light. This sensitivity may be provided by doping the fiber material with germanium and boron ions. The main application is to create a fiber Bragg grating, which is a periodic variation of the refractive index along the fiber axis (Chap. 9 has details on this). Applications of fiber Bragg gratings include light-coupling mechanisms for pump lasers used in optical amplifiers, wavelength add/drop modules, optical filters, and chromatic dispersion compensation modules.

Bend-insensitive fiber. A bend-insensitive fiber has a moderately higher numerical aperture (NA) than that in a standard single-mode telecommunication fiber. The numerical aperture can be varied to adjust the mode field diameter. Increasing the NA reduces the sensitivity of the fiber to bending loss by confining optical power more tightly within the core than in conventional single-mode fibers. Bend-insensitive fibers are available commercially in a range of core diameters to provide optimum performance at specific operating wavelengths, such as 820, 1310, or 1550 nm. These fibers are offered with either an 80- μ m or a 125- μ m cladding diameter as standard products. The 80- μ m *reduced-cladding fiber* results in a much smaller volume compared with a 125- μ m cladding diameter when a fiber length is coiled up within a device package. Whereas Table 4.2 shows there is a high bending loss for tightly wound conventional single-mode fibers, the induced attenuation at the specified operating wavelength due to 100 turns of bend-insensitive fiber on a 10-mm-radius mandrel is less than 0.5 dB.

Attenuating fiber. These fibers have a uniform attenuation in the 1250- to 1620-nm band. This makes an attenuating fiber useful for WDM applications to lower the power level at the input of receivers or at the output of an EDFA. The fibers are offered commercially with attenuation levels available from 0.4 dB/cm to

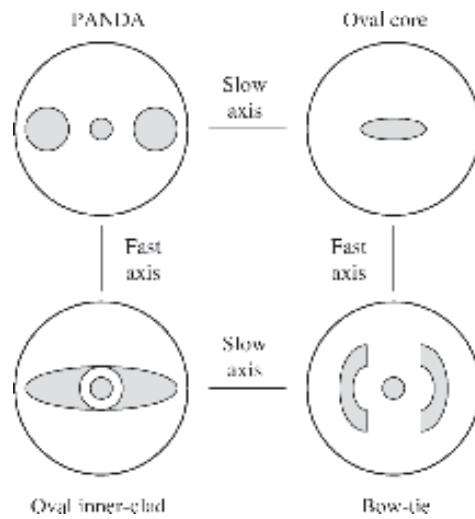


Figure 4.11. Cross-sectional geometry of four different polarization-maintaining fibers.

greater than 15 dB/cm. Fibers with an attenuation of 15 dB/cm (a loss factor of 32 within 1 cm) may be used to terminate the end of a fiber optic link so that there are no return reflections, or as a high-level plug-type attenuator.

Polarization-preserving fiber. In contrast to standard optical fibers in which the state of polarization fluctuates as a light signal propagates through the fiber, polarization-preserving fibers have a special core design that maintains the polarization. Applications of these fibers include light signal modulators fabricated from lithium niobate, optical amplifiers for polarization multiplexing, light-coupling fibers for pump lasers, and polarization-mode dispersion compensators. Figure 4.11 illustrates the cross-sectional geometry of four different polarization-maintaining fibers. The light circles represent the cladding, and the dark areas are the core configurations. The goal in each design is to introduce a deliberate birefringence into the core so that the two polarization modes become decoupled within a very short distance, which leads to preservation of the individual polarization states.

High-index fiber. These fiber types have a higher core refractive index, which results in a larger numerical aperture. Consequently, since a higher NA enables optical power to be coupled more efficiently into a core, a short (nominally 1-m) length of such a fiber may be attached directly to an optical source. Such a fiber section is referred to as a *pigtail* or a *flylead*. The fibers can be designed specifically for short-wavelength or long-wavelength optical sources (see Chap. 6). In addition, they have applications in fused-fiber couplers (Chap. 8) and in wavelength division multiplexing (Chaps. 12 and 13).

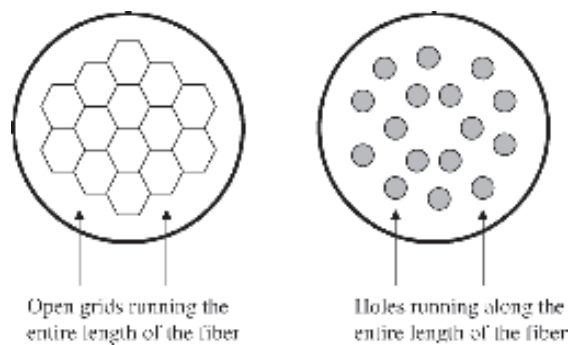


Figure 4.12. End-face patterns of two possible holey fiber structures.

Holey fiber. A holey or photonic crystal fiber typically consists of a silica material which contains numerous air-filled microscopic holes. Figure 4.12 shows the end-face patterns of two possible holey fiber structures. The tubular holes run along the entire length of the fiber parallel to the fiber axis. The size, position, and number of holes provide the fiber with specific waveguide properties. This technology is under development. Potential applications of holey fibers in telecommunications include dispersion compensation, wavelength conversion, optical switching, and high-power optical amplification.

4.9. Summary

An optical fiber is nominally a cylindrical dielectric waveguide that confines and guides light waves along its axis. Basically all fibers used for telecommunication purposes have the same physical structure, which consists of a cylindrical glass core surrounded by a glass cladding. The difference in the core and cladding indices determines how light signals travel along a fiber.

An important physical concept is that only a finite set of light rays that impinge on the core walls at specific angles may propagate along a fiber. These angles are related to a set of electromagnetic wave patterns called *modes*. For a *single-mode fiber*, the core diameter is around 8 to 10 μm (several wavelengths), and only the *fundamental ray* is allowed to propagate. *Multimode fibers* have larger core diameters (e.g., around 50 μm) and support many modes. The ray theory can explain a number of fiber performance characteristics, but other attributes require the wave theory. The power distribution of modes is not confined completely to the core, but extends partially into the cladding. This concept is important when we examine concepts such as optical power coupling.

Light traveling in a fiber loses power over distance, mainly because of absorption and scattering mechanisms in the fiber. This attenuation is an important property of an optical fiber because, together with signal distortion mechanisms, it determines the maximum transmission distance possible. The degree

of the attenuation depends on the wavelength of the light and on the fiber material. The loss of power is measured in decibels, and the loss within a cable is described in terms of decibels per kilometer.

The information-carrying capacity of the fiber is limited by various distortion mechanisms in the fiber, such as signal dispersion factors and nonlinear effects. The three main dispersion categories are modal, chromatic, and polarization mode dispersions. These distortion mechanisms cause optical signal pulses to broaden as they travel along a fiber.

The ITU-T and the TIA/EIA have published standards for both multimode and single-mode optical fibers used in telecommunications. The recommended bounds on fiber parameters (e.g., attenuation, cutoff wavelength, and chromatic dispersion) designated in these standards ensure the users of product capability and consistency. Multimode fibers are used in LAN environments, storage area networks, and central-office connections, where the distance between buildings is typically 2 km or less. The two principal multimode fiber types have either 50- or 62.5- μm core diameters, and both have 125- μm cladding diameters. For short-reach, low-cost transmission of high-speed Ethernet signals, a 50- μm multimode fiber is available for 10-Gbps operation at 850 nm over distances up to 300 m.

The ITU-T also has published a series of recommendations for single-mode fibers. Of these, two key ones for DWDM use are the ITU-T G.655 (nonzero dispersion-shifted fiber, or NZDSF) and the ITU-T G.655b (advanced nonzero dispersion-shifted fiber, or A-NZDSF). The G.655 fibers are designed for the C-band, and the G.655b fibers allow DWDM operation over the entire S-band and the C-band. In addition, the G.652.C recommendation describes fibers for CWDM applications.

Whereas telecommunication fibers, such as those described above, are designed to transmit light over long distances with minimal change in the signal, *specialty fibers* are used to manipulate the light signal. Specialty fibers interact with light and are custom-designed for specific applications such as optical signal amplification, wavelength selection, wavelength conversion, and sensing of physical parameters.

Further Reading

1. B. Comycz, *Fiber Optic Installer's Field Manual*, McGraw-Hill, New York, 2000.
2. G. Keiser, *Optical Fiber Communications*, 3d ed., McGraw-Hill, Burr Ridge, Ill., 2000.
3. T. R. Jordal, "How to test laser-based premises networks," *Lightwave*, vol. 18, pp. 126, 128, 156, February 2001 (www.lightwaveonline.com).
4. R. E. Kristiansen, "Holey fibers," *SPIE OE Magazine*, vol. 2, pp. 25–27, June 2002 (www.oemagazine.com).
5. TIA/EIA-568-B.3, *Optical Fiber Cabling Components Standard*, April 2000.
6. ITU-T Recommendation G.651, *Characteristics of a 50/125- μm Multimode Graded-Index Optical Fiber Cable*, February 1998.
7. ITU-T Recommendation G.652, *Characteristics of a Single-Mode Optical Fiber Cable*, October 2000.
8. ITU-T Recommendation G.653, *Characteristics of a Dispersion-Shifted Optical Fiber Cable*, October 2000.

9. ITU-T Recommendation G.654, *Characteristics of a Cutoff-Shifted Single-Mode Optical Fiber Cable*, October 2000.
10. ITU-T Recommendation G.655, *Characteristics of a Nonzero Dispersion-Shifted Single-Mode Optical Fiber Cable*, October 2000.
11. J. Ryan, "Next-generation NZ-DSF fibers will balance performance characteristics," *Lightwave*, vol. 18, pp. 146–152, March 2000 (www.light-wave.com).
12. F. Aranda, "Asymmetry maintains polarization," *Laser Focus World*, vol. 38, pp. 187–190, May 2002.

Performance Impairments

The information-carrying capacity of a fiber is limited by various internal distortion mechanisms, such as signal dispersion factors and nonlinear effects. The two main distortion categories for high-performance single-mode fibers are chromatic and polarization mode dispersions, which cause optical signal pulses to broaden as they travel along a fiber. Nonlinear effects occur when there are high power densities (optical power per cross-sectional area) in a fiber. Their impact on signal fidelity includes shifting of power between wavelength channels, appearances of spurious signals at other wavelengths, and decreases in signal strength. These nonlinear effects can be especially troublesome in high-rate WDM links. Important challenges in designing such multiple-channel optical networks include

- Transmission of the different wavelength channels at the highest possible bit rate
- Transmission over the longest possible distance with the smallest number of optical amplifiers
- Network architectures that allow simple and efficient network operation, control, and management

15.1. Impairment Effects

The design of a WDM network requires the use of proven design practices when one is selecting optical fibers, specifying component types and the values of their operating parameters, and laying out networks to mitigate performance degradation processes. Signal impairment effects that are inherent in optical fiber transmission links and which can seriously degrade network performance include these:

- *Dispersion*, which refers to any effect that causes different components of a transmitted signal to travel at different velocities in an optical fiber. The

result is that a pulse spreads out progressively as it travels along a link. This spreading leads to interference between adjacent pulses (called *intersymbol interference*) and may limit the distance a pulse can travel. The three main types of dispersion are modal dispersion, chromatic dispersion, and polarization mode dispersion.

Modal dispersion occurs only in multimode fibers in which each mode travels at a different velocity. Multimode fibers are used mainly for short-distance communications (such as local-area networks) since modal dispersion limits the link length. See Chap. 4 for more details on this effect.

Chromatic dispersion originates from the fact that each wavelength travels at a slightly different velocity in a fiber. Two factors contribute to chromatic dispersion, as Sec. 15.2 describes. Whether one implements high-speed single-wavelength or WDM networks, this effect can be mitigated by the use of various dispersion compensation schemes.

Polarization mode dispersion (PMD) arises in single-mode fibers because the two fundamental orthogonal polarization modes in a fiber travel at slightly different speeds owing to fiber birefringence. This effect cannot be mitigated easily and can be a very serious impediment for links operating at 10 Gbps and higher.

- *Nonlinear effects*, which arise at high power levels because both the attenuation and the refractive index depend on the optical power in a fiber. The nonlinear processes can be classified into the following two categories:
 - Nonlinear inelastic scattering processes*, which are interactions between optical signals and molecular or acoustic vibrations in a fiber
 - Nonlinear variations of the refractive index* in a silica fiber that occur because the refractive index is dependent on intensity changes in the signal
- *Nonuniform gain* across the desired wavelength range of optical amplifiers in WDM links. This characteristic can be equalized over the desired wavelength range by techniques such as the use of grating filters or variable optical attenuators (VOAs), as described in Chap. 10.
- *Reflections* from splices and connectors that can cause instabilities in laser sources. These can be eliminated by the use of optical isolators.

When any of these dispersion or nonlinear effects contribute to signal impairment, there is a reduction in the signal-to-noise ratio (SNR) of the system from the ideal case. This reduction in SNR is known as the *power penalty* for that effect, which generally is expressed in decibels.

15.2. Chromatic Dispersion

The index of refraction of silica varies with wavelength; for example, it ranges from 1.453 at 850 nm to 1.445 at 1550 nm. Furthermore, as described in Chap. 6, a light pulse from an optical source contains a certain slice of wavelength spectrum. For example, a modulated laser diode source may emit pulses that

have an 0.1-nm spectral width. Consequently each wavelength within an optical pulse will see a slightly different refractive index and therefore will travel at a slightly different speed through the fiber (recall from Chap. 3 that light speed $s = c/n$). Therefore the range of arrival times at the fiber end of the spectrum of wavelengths will lead to pulse spreading. This effect is known as *material dispersion*.

Another dispersion factor is *waveguide dispersion*. This occurs because the various frequency components of a pulse travel with slightly different group velocities in a fiber, and thus arrive at different times at the fiber end.

The combination of these two factors is called *chromatic dispersion*. This often is referred to simply as *dispersion*, since it has a strong impact on the design of single-mode fiber transmission links. Chromatic dispersion is a fixed quantity at a specific wavelength and is measured in units of picoseconds per kilometer of fiber per nanometer of optical source spectral width, that is, it is measured in $\text{ps}/(\text{km} \cdot \text{nm})$. For example, a single-mode fiber might have a chromatic dispersion value of $D_{\text{CD}} = 2 \text{ ps}/(\text{km} \cdot \text{nm})$ at 1550 nm. Figure 15.1 shows the chromatic dispersion as a function of wavelength for several different fiber types, which are described in Sec. 4.8.

The accumulated dispersion increases with distance along a link. Therefore, either a transmission system has to be designed to tolerate the total dispersion, or some type of dispersion compensation method has to be employed. Although the exact calculation of the effect of dispersion is quite complex, a basic estimate of what limitation dispersion imposes on link performance can be made by specifying that the accumulated dispersion should be less than a fraction of the bit period. For example, the Bellcore/Telcordia standard GR-253-CORE specifies that for a 1-dB performance penalty the accumulated dispersion should be less

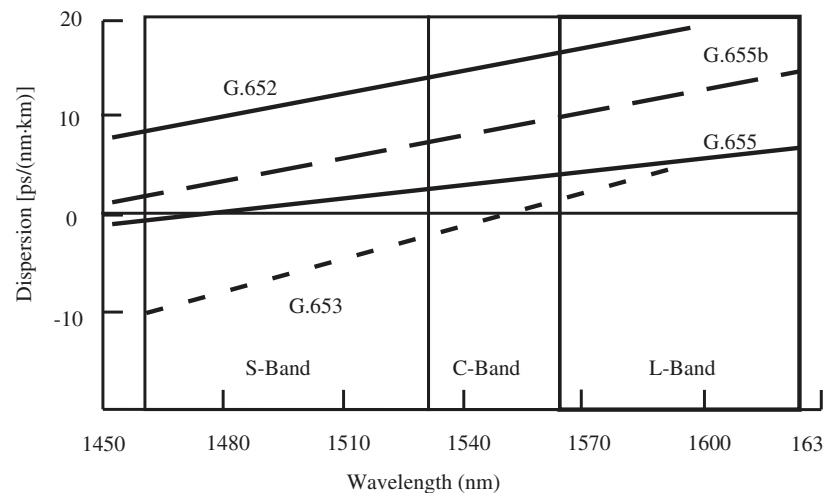


Figure 15.1. Chromatic dispersion as a function of wavelength in various spectral bands for several different fiber types.

than 0.306 of a bit period. If B is the bit rate and $\Delta\lambda$ is the spectral width of the light source, then for a link of length L this limitation can be expressed as

$$|D_{\text{CD}}| LB \Delta\lambda < 0.306 \quad (15.1)$$

As an example, if $D_{\text{CD}} = 2 \text{ ps}/(\text{km} \cdot \text{nm})$, $B = 2.5 \text{ Gbps}$, and $\Delta\lambda = 0.1 \text{ nm}$, then the maximum allowed link length is $L = 612 \text{ km}$.

An important factor to remember when you are designing a WDM system is that in order to mitigate some of the nonlinear effects described in Sec. 15.5, the dispersion must be a positive value (or a negative value) across the entire spectral band of the WDM system. As described in Sec. 4.8, this was the motivation for designing the G.655 and G.655b optical fibers.

15.3. Dispersion Compensation

A large base of G.653 dispersion-shifted fiber has been installed throughout the world for use in single-wavelength transmission systems. As described in Sec. 15.5, a nonlinear effect called four-wave mixing (FWM) can be a significant problem for these links when one attempts to upgrade them with high-speed dense WDM technology in which the channel spacings are less than 100 GHz and the bit rates are in excess of 2.5 Gbps. One approach to reducing the effect of FWM is to use *dispersion compensation* techniques that negate the accumulated dispersion of the transmission fiber. Two possible methods are the insertion of a dispersion-compensating fiber into the link or the use of a chirped Bragg grating.

15.3.1. Dispersion-compensating fiber

A *dispersion-compensating fiber* (DCF) has a dispersion characteristic that is opposite that of the transmission fiber. Dispersion compensation is achieved by inserting a loop of DCF into the transmission path. The total dispersion in the DCF loop needs to be equal and opposite to the accumulated dispersion in the transmission fiber. If the transmission fiber has a low positive dispersion [say, $2.3 \text{ ps}/(\text{nm} \cdot \text{km})$], then the DCF will have a large negative dispersion [say, $-90 \text{ ps}/(\text{nm} \cdot \text{km})$]. With this technique, the total accumulated dispersion is zero after some distance, but the absolute dispersion per length is nonzero at all points along the fiber. The nonzero absolute dispersion value causes a phase mismatch between wavelength channels, thereby destroying the possibility of effective FWM production.

Figure 15.2 shows that the DCF can be inserted at either the beginning or the end of an installed fiber span between two optical amplifiers. A third option is to have a DCF at both ends. In *precompensation* schemes the DCF is located right after the optical amplifier and thus just before the transmission fiber. Conversely, in *postcompensation* schemes the DCF is placed right after the transmission fiber and just before the optical amplifier. Figure 15.2 also shows plots of the accumulated dispersion and the power level as functions of distance along the fiber. These plots are called *dispersion maps* and *power maps*, respectively.

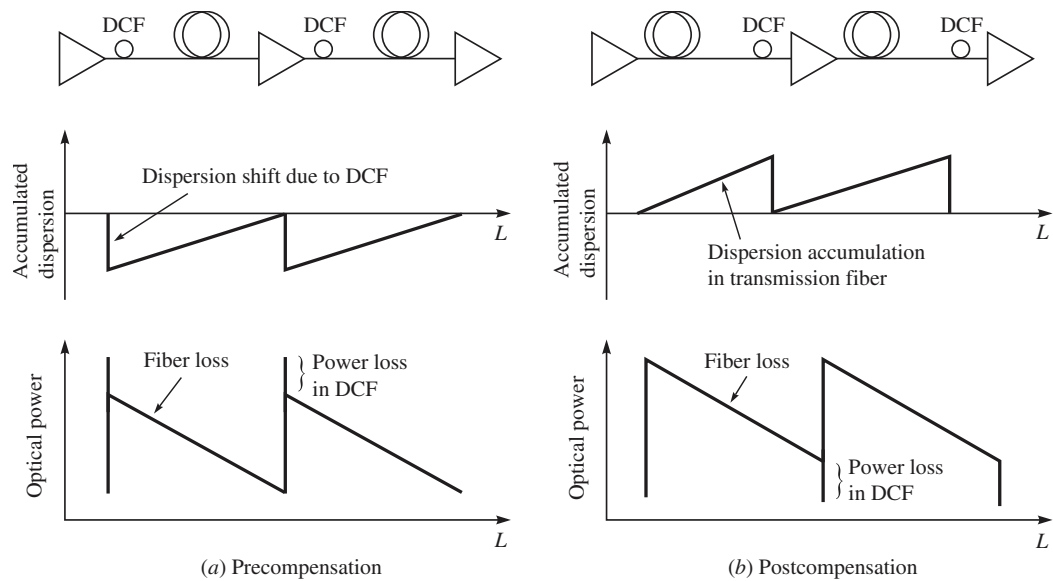


Figure 15.2. Dispersion maps and power maps using a DCF for (a) precompensation and (b) postcompensation methods.

As Fig. 15.2a illustrates, in precompensation the DCF causes the dispersion to drop quickly to a low negative level from which it slowly rises towards zero (at the next optical amplifier) with increasing distance along the trunk fiber. This process repeats itself following amplification. The power map shows that the optical amplifier first boosts the power level to a high value. Since the DCF is a loop of fiber, there is a drop in power level before the signal enters the actual transmission path, in which it decays exponentially before being amplified once more.

Similar processes occur in postcompensation, as shown in Fig. 15.2b. In either case the accumulated dispersion is near zero after some distance to minimize the effects of pulse spreading, but the absolute dispersion per length is nonzero at all points, thereby causing a phase mismatch between different wavelengths, which mitigates FWM effects.

In actual systems, both experiments and simulations have shown that a *combination* of postcompensation and precompensation provides the best solution for dispersion compensation. When one is implementing such a compensation technique, the length of the DCF should be as short as possible since the special fiber used has a higher loss than the transmission fiber. The loss is around 0.5 dB/km at 1550 nm compared to 0.21 dB/km for G.655 fiber. Since around 1 km of DCF is needed for every 10 to 12 km of operational fiber, the additional DCF loss needs to be taken into account when one is designing a link. The required length L_{DCF} of the DCF fiber can be calculated by using the expression

$$L_{\text{DCF}} = |D_{\text{TX}}/D_{\text{DCF}}| \times L \quad (15.2)$$

Here L is the length of the operational fiber, D_{TX} is the dispersion of the operational fiber, and D_{DCF} is the dispersion of the DCF.

15.3.2. Bragg grating compensators

Another way of viewing dispersion is to consider the propagation speed of the different wavelength constituents of an optical pulse. When an optical pulse travels along a fiber in the anomalous-dispersion region (where $D_{TX} > 0$), the shorter-wavelength (higher-frequency) components of the pulse travel faster than the longer-wavelength (shorter-frequency) components. This is a dispersive effect which broadens the pulse.

To compensate for the difference in arrival times of the various frequency components resulting from anomalous dispersion, one can use a chirped fiber Bragg grating that provides normal dispersion. As shown in Fig. 15.3, in such a dispersion compensator the grating spacing varies linearly over the length of the grating. This results in a range of wavelengths (or frequencies) that satisfy the Bragg condition for reflection. In the configuration shown, the spacings decrease along the fiber which means that the Bragg wavelength decreases with distance along the grating length. Consequently the shorter-wavelength components of a pulse travel farther into the fiber before being reflected. Thereby they experience greater delay in going through the grating than the longer-wavelength components. The relative delays induced by the grating on the different frequency components of the pulse are the opposite of the delays caused by the fiber. This results in dispersion compensation, since it compresses the pulse.

Prior to the year 2000, manufacturing difficulties limited gratings to lengths of about 10 cm. Since the round-trip time T_R inside the grating of length L_G is given by $T_R = 2n_G L_G / c$, where n_G is the refractive index of the grating fiber, the maximum round-trip delay time of light through a 10-cm-long grating is 100 ns. The delay per unit length is 500 ps/nm, which corresponds to the product of the dispersion D_G of the grating and the spectral width $\Delta\lambda$ of the light being delayed, that is,

$$\frac{T_R}{L_G} = D_G \Delta\lambda \quad (15.3)$$

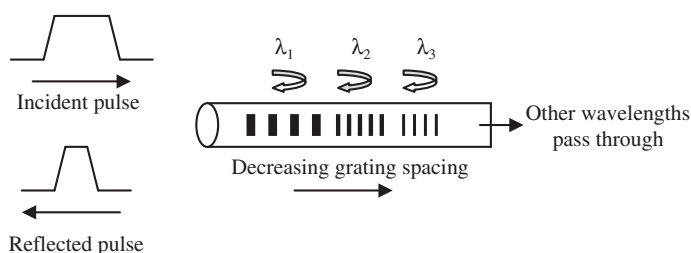


Figure 15.3. Chromatic dispersion compensation can be accomplished through the use of a chirped fiber Bragg grating.

Now one can make some application tradeoffs. Suppose one selects a compensation value of 500 ps/nm. Then, for example, since for G.655 fiber the total dispersion that arises over a 100-km length is about 500 ps/nm, in order to use a 10-cm chirped Bragg grating to compensate for this dispersion, the gratings must be used over a very narrow bandwidth of less than 1 nm. That means the short gratings made prior to 2000 only could be used to compensate for individual wavelengths in a WDM system.

In 2001, 3M Corporation developed a manufacturing technique that can make fiber gratings several meters long. For example, now it is possible to fabricate a chirped fiber Bragg grating that is about 2 m long, has a bandwidth of over 30 nm, an insertion loss of about 1 dB, and a delay slope of -1.1 ps/nm^2 . These types of chirped Bragg gratings are multichannel components that are capable of compensating for chromatic dispersion across the entire C-band or L-band in individual fibers.

15.4. Polarization Mode Dispersion (PMD)

Polarization mode dispersion (PMD) results from the fact that light signal energy at a given wavelength in a single-mode fiber actually occupies two orthogonal polarization states or modes. Figure 4.10 shows this condition. At the start of the fiber the two polarization states are aligned. However, fiber material is not perfectly uniform throughout its length. In particular, the refractive index is not perfectly uniform across any given cross-sectional area, which is known as the *birefringence* of the material. Consequently each polarization mode will encounter a slightly different refractive index, so that each will travel at a slightly different velocity, and the polarization orientation will rotate with distance. The resulting difference in propagation times between the two orthogonal polarization modes will result in pulse spreading. This is the basis of polarization mode dispersion. PMD is not a fixed quantity but fluctuates with time due to factors such as temperature variations and stress changes on the fiber. Since these external stresses vary slowly with time, the resulting PMD also fluctuates slowly. It varies as the square root of distance and thus is specified as a maximum anticipated value in units of ps/ $\sqrt{\text{km}}$.

A typical PMD value for a fiber is $D_{\text{PMD}} = 0.05 \text{ ps}/\sqrt{\text{km}}$, but the cabling process can increase this value. The PMD value does not fluctuate widely for cables that are enclosed in underground ducts or in buildings. However it can increase periodically to over $1 \text{ ps}/\sqrt{\text{km}}$ for outside cables that are suspended on poles, since such cables are subject to wide variations in temperature, wind-induced stresses, and elongations caused by ice loading.

Pulse spreading Δt_{PMD} resulting from polarization mode dispersion is given by

$$\Delta t_{\text{PMD}} = D_{\text{PMD}} \times \sqrt{\text{fiber length}} \quad (15.4)$$

As an example, consider a 100-km-long fiber for which $D_{\text{PMD}} = 0.5 \text{ ps}/\sqrt{\text{km}}$. Then the pulse spread over this distance is $\Delta t_{\text{PMD}} = 5.0 \text{ ps}$. Suppose one wants

to send an NRZ-encoded signal over this distance and the power-penalty requirement is that the pulse spread can be no more than 10 percent of a pulse width T . In this case the maximum possible data rate is

$$\text{Maximum data rate} = \frac{0.1}{\Delta t_{\text{PMD}}} = 20 \text{ Gbps}$$

Whereas several methods exist for mitigating the effects of chromatic dispersion, it is more difficult to compensate for polarization mode dispersion. This is so because PMD varies with wavelength and slowly drifts with time in a random fashion. Since this factor requires any compensation technique to adapt dynamically to polarization state changes while the system is running, no practical PMD compensation method has been implemented as yet (for further details see the paper by Sunnerud et al.).

15.5. Nonlinear Effects

This section addresses the origins of the two nonlinear categories and shows the limitations they place on system performance. The first category encompasses the nonlinear inelastic scattering processes. These are *stimulated Raman scattering* (SRS) and *stimulated Brillouin scattering* (SBS). The second category of nonlinear effects arises from intensity-dependent variations in the refractive index in a silica fiber. This produces effects such as *self-phase modulation* (SPM), *cross-phase modulation* (XPM), and *four-wave mixing* (FWM). In the literature, FWM is also referred to as *four-photon mixing* (FPM), and XPM is sometimes designated by CPM. Table 15.1 gives a summary of these effects.

The SBS, SRS, and FWM processes result in gains or losses in a wavelength channel that are dependent on the optical signal intensity. These nonlinear processes provide gains to some channels while depleting power from others, thereby producing crosstalk between the wavelength channels. In analog video systems, SBS significantly degrades the carrier-to-noise ratio when the scattered power is equivalent to the signal power in the fiber. Both SPM and XPM affect only the phase of signals, which causes chirping in digital pulses. This can worsen pulse broadening due to dispersion, particularly in very high-rate systems (>10 Gbps).

Viewing these nonlinear processes in a little greater detail, Sec. 15.5.1 first shows how to define the distances over which the processes are important. Sections 15.5.2 and 15.5.3 then qualitatively describe the different ways in which the stimulated scattering mechanisms physically affect a lightwave

TABLE 15.1. Summary of Nonlinear Effects in Optical Fibers

Origin	Single-channel	Multiple-channel
Index-related	Self-phase modulation	Cross-phase modulation Four-wave mixing
Scattering-related	Stimulated Brillouin scattering	Stimulated Raman scattering

system. Section 15.5.4 presents the origins of SPM and XPM and shows their degradation effect on system performance. The mechanisms giving rise to FWM and the resultant physical effects on link operation are outlined in Sec. 15.5.5. As noted in Sec. 15.3, FWM can be suppressed through clever arrangements of fibers having different dispersion characteristics.

15.5.1. Effective length and area

Modeling the nonlinear processes can be quite complicated, since they depend on the transmission length, the cross-sectional area of the fiber, and the optical power level in the fiber. The difficulty arises from the fact that the impact of the nonlinearity on signal fidelity increases with distance. However, this is offset by the continuous decrease in signal power along the fiber due to attenuation. In practice, one can use a simple but sufficiently accurate model that assumes the power is constant over a certain fiber length, which is less than or equal to the actual fiber length. This *effective length* L_{eff} , which takes into account power absorption along the length of the fiber (i.e., the optical power decays exponentially with length), is given by

$$L_{\text{eff}} = \frac{1 - e^{-\alpha L}}{\alpha} \quad (15.5)$$

Given a typical attenuation of $\alpha = 0.22 \text{ dB/km}$ (or, equivalently, $\alpha = 5.07 \times 10^{-2} \text{ km}^{-1}$) at 1550 nm, this yields an effective length of about 20 km when $L_{\text{eff}} \gg 1/\alpha$. When there are optical amplifiers in a link, the signal impairments owing to the nonlinearities do not change as the signal passes through the amplifier. In this case, the effective length is the sum of the effective lengths of the individual spans between optical amplifiers. If the total amplified link length is L_A and the span length between amplifiers is L , the effective length is approximately

$$L_{\text{eff}} = \frac{1 - e^{-\alpha L}}{\alpha} \frac{L_A}{L} \quad (15.6)$$

Figure 15.4 illustrates the effective length as a function of the actual system length. The two curves shown are for a nonamplified link with $\alpha = 0.22 \text{ dB/km}$ and an amplified link with a 75-km spacing between amplifiers. As indicated by Eq. (15.6), the total effective length decreases as the amplifier span increases.

The effects of nonlinearities increase with the light intensity in a fiber. For a given optical power, this intensity is inversely proportional to the cross-sectional area of the fiber core. Since the power is not distributed uniformly over the fiber-core cross section, for convenience one can use an *effective cross-sectional area* A_{eff} . Although this can be calculated accurately from mode-overlap integrals, in general the effective area is close to the actual core area. As a rule of thumb, standard nondispersion-shifted single-mode fibers have effective areas of $80 \mu\text{m}^2$, dispersion-shifted fibers have effective areas of $55 \mu\text{m}^2$, and dispersion-compensated fibers have effective areas on the order of $20 \mu\text{m}^2$.

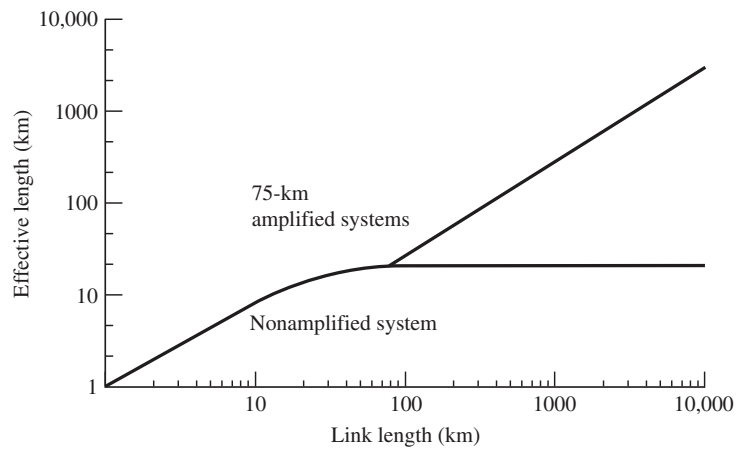


Figure 15.4. Effective length as a function of the actual link length for a link without amplifiers and a link with optical amplifiers spaced 75 km apart.

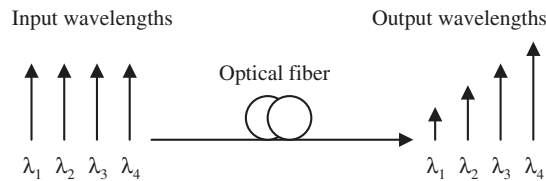


Figure 15.5. SRS generates scattered light at a longer wavelength, thereby decreasing the power in the pump wavelength signal.

15.5.2. Stimulated Raman scattering

Stimulated Raman scattering is an interaction between light waves and the vibrational modes of silica molecules. If a photon with energy $h\nu_1$ is incident on a molecule having a vibrational frequency ν_m , the molecule can absorb some energy from the photon. In this interaction the photon is scattered, thereby attaining a lower frequency ν_2 and a corresponding lower energy $h\nu_2$. The modified photon is called a *Stokes photon*. Because the optical signal wave that is injected into a fiber is the source of the interacting photons, it is often called the *pump wave*, since it supplies power for the newly generated wave.

This process generates scattered light at a wavelength longer than that of the incident light. If another signal is present at this longer wavelength, the SRS light will amplify it and the pump wavelength signal will decrease in power. Figure 15.5 illustrates this effect. Consequently, SRS could limit the performance of a multichannel optical communication system by transferring energy from short-wavelength channels to neighboring higher-wavelength channels. This is a broadband effect that can occur in both directions. Powers in channels separated by up to 16 THz (125 nm) can be coupled through the SRS effect, thereby producing crosstalk between wavelength channels.

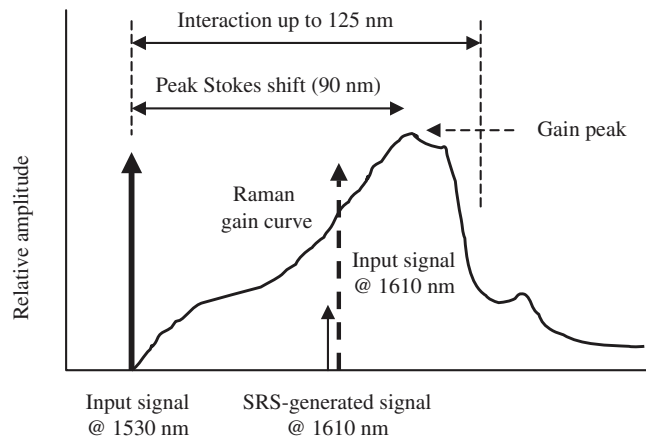


Figure 15.6. As a result of SRS, the signal at 1530 nm acts as a pump for the signal at 1610 nm.

In general, if the optical power per channel is not excessively high (e.g., less than 1 mW each), then the effects of SRS do not contribute significantly to the eye closure penalty as a function of transmission distance. Furthermore, since the generated wavelength is around 90 nm away from the signal wavelength, crosstalk from SRS is not a significant problem unless the system operates over a wide spectral range. As an example, consider a WDM system that operates over both the C-band and the L-band (from 1530 to 1620 nm). As shown in Fig. 15.6 for two specific wavelengths in this range, as a result of SRS the signal at 1530 nm acts as a pump for the signal at 1610 nm.

15.5.3. Stimulated Brillouin scattering

Stimulated Brillouin scattering arises when light waves scatter from acoustic waves. The resultant scattered wave propagates principally in the backward direction in single-mode fibers. This backscattered light experiences gain from the forward-propagating signals, which leads to depletion of the signal power. The frequency of the scattered light experiences a Doppler shift given by

$$\nu_B = \frac{2nV_s}{\lambda} \quad (15.7)$$

where n is the index of refraction and V_s is the velocity of sound in the material. In silica this interaction occurs over a very narrow *Brillouin linewidth* of $\Delta\nu_B = 20$ MHz at 1550 nm. For $V_s = 5760$ m/s in fused silica, the frequency of the backward-propagating light at 1550 nm is downshifted by 11 GHz (0.09 nm) from the original signal. This shows that the SBS effect is confined within a single wavelength channel in a WDM system. Thus, the effects of SBS accumulate individually for each channel, and consequently they occur at the same power level in each channel as occurs in a single-channel system.

System impairment starts when the amplitude of the scattered wave is comparable to the signal power. For typical fibers the threshold power for this process is around 10 mW for single-fiber spans. In a long fiber chain containing optical amplifiers, there are normally optical isolators to prevent backscattered signals from entering the amplifier. Consequently, the impairment due to SBS is limited to the degradation occurring in a single amplifier-to-amplifier span.

15.5.4. Self-phase modulation and cross-phase modulation

The refractive index n of many optical materials has a weak dependence on optical intensity I (equal to the optical power per effective area in the fiber) given by

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{\text{eff}}} \quad (15.8)$$

where n_0 is the ordinary refractive index of the material and n_2 is the *nonlinear index* coefficient. In silica, the factor n_2 varies from 2.2 to $3.4 \times 10^{-8} \mu\text{m}^2/\text{W}$. The nonlinearity in the refractive index is known as the *Kerr nonlinearity*. This nonlinearity produces a carrier-induced phase modulation of the propagating signal, which is called the *Kerr effect*. In single-wavelength links, this gives rise to *self-phase modulation* (SPM), which converts optical power fluctuations in a propagating light wave to spurious phase fluctuations in the same wave.

To see the effect of SPM, consider what happens to the optical pulse shown in Fig. 15.7 as it propagates in a fiber. Here the time axis is normalized to the parameter t_0 , which is the pulse half-width at the $1/e$ intensity point. The edges of the pulse represent a time-varying intensity, which rises rapidly from zero to a maximum value and then returns to zero. In a medium that has an intensity-dependent refractive index, a time-varying signal intensity will produce a time-varying refractive index. Thus the index at the peak of the pulse will be slightly different from the value in the wings of the pulse. The leading edge will see a positively changing index change (represented by $+dn/dt$), whereas the trailing edge will see a negative change (represented by $-dn/dt$).

This temporally varying index change results in a temporally varying phase change, shown by $d\phi/dt$ in Fig. 15.7. The consequence is that the instantaneous optical frequency differs from its initial value across the pulse. That is, since the phase fluctuations are intensity-dependent, different parts of the pulse undergo different phase shifts. This leads to what is known as *frequency chirping*, in that the rising edge of the pulse experiences a shift toward higher frequencies whereas the trailing edge of the pulse experiences a shift toward lower frequencies. Since the degree of chirping depends on the transmitted power, SPM effects are more pronounced for higher-intensity pulses.

For some types of fibers, the time-varying phase may result in a power penalty owing to a spectral broadening of the pulse as it travels along the fiber. In the wavelength region where chromatic dispersion is negative, the leading edge of the pulse travels faster and thus moves away from the center of the pulse. The

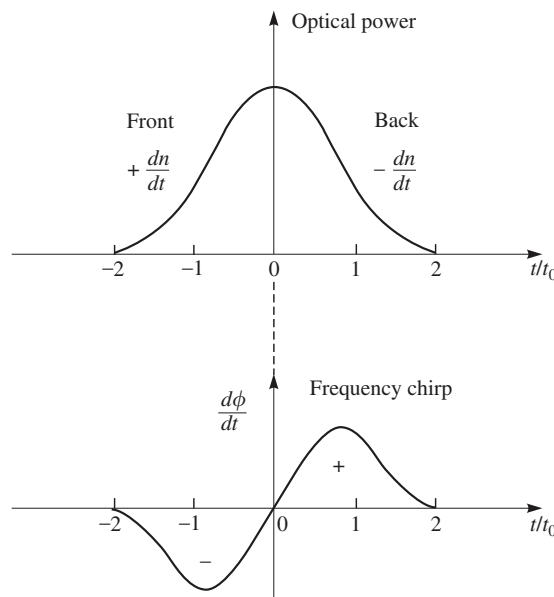


Figure 15.7. Phenomenological description of spectral broadening of a pulse due to self-phase modulation.

trailing edge travels more slowly and thus also moves away from the center of the pulse, but in the opposite direction from the leading edge. Therefore in this case chirping worsens the effects of pulse broadening. On the other hand, in the wavelength region where chromatic dispersion is positive, the leading edge of the pulse travels more slowly and thus moves toward the center of the pulse. Similarly, the trailing edge travels faster and thus also moves toward the center of the pulse from the other direction. In this case, SPM causes the pulse to narrow, thereby partly compensating for chromatic dispersion.

In WDM systems, the refractive index nonlinearity gives rise to *cross-phase modulation* (XPM), which converts power fluctuations in a particular wavelength channel to phase fluctuations in other copropagating channels. This can be mitigated greatly in WDM systems operating over standard non-dispersion-shifted single-mode fiber, but can be a significant problem in WDM links operating at 10 Gbps and higher over dispersion-shifted fiber. When combined with fiber dispersion, the spectral broadening from SPM and XPM can be a significant limitation in very long transmission links, such as cross-country or under-sea systems.

15.5.5. Four-wave mixing

Four-wave mixing is a third-order nonlinearity in silica fibers that is analogous to intermodulation distortion in electrical systems. When wavelength channels

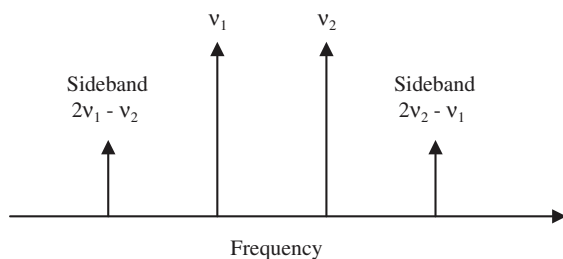


Figure 15.8. Two optical waves at frequencies ν_1 and ν_2 mix to generate two third-order sidebands.

are located near the zero-dispersion point, three optical frequencies (ν_i, ν_j, ν_k) will mix to produce a fourth intermodulation product ν_{ijk} given by

$$\nu_{ijk} = \nu_i + \nu_j - \nu_k \quad \text{with } i, j \neq k \quad (15.9)$$

When this new frequency falls in the transmission window of the original frequencies, it can cause severe crosstalk.

Figure 15.8 shows a simple example for two waves at frequencies ν_1 and ν_2 . As these waves copropagate along a fiber, they mix and generate sidebands at $2\nu_1 - \nu_2$ and $2\nu_2 - \nu_1$. Similarly, three copropagating waves will create nine new optical sideband waves at frequencies given by Eq. (15.9). These sidebands will travel along with the original waves and will grow at the expense of signal strength depletion. In general, for N wavelengths launched into a fiber, the number of generated mixing products M is

$$M = \frac{N^2}{2} (N - 1) \quad (15.10)$$

If the channels are equally spaced, a number of the new waves will have the same frequencies as the injected signals. Thus, the resultant crosstalk interference plus the depletion of the original signal waves can severely degrade multi-channel system performance unless steps are taken to diminish it.

The efficiency of four-wave mixing depends on fiber dispersion and the channel spacings. Since the dispersion varies with wavelength, the signal waves and the generated waves have different group velocities. This destroys the phase matching of the interacting waves and lowers the efficiency at which power is transferred to newly generated frequencies. The higher the group velocity mismatches and the wider the channel spacings, the lower the four-wave mixing. The G.655 and G.655b fibers were developed specifically to address the FWM issues.

15.6. Summary

Signal dispersion factors and nonlinear effects in fibers limit the information carrying capacity in optical links. For high-performance single-mode fibers,

chromatic and polarization mode dispersions cause optical signal pulses to broaden as they travel along a fiber. Nonlinear effects occur when there are high power densities (optical power per cross-sectional area) in a fiber. Their impact on signal fidelity includes shifting of power between wavelength channels, appearances of spurious signals at other wavelengths, and decreases in signal strength. These nonlinear effects can be especially troublesome in high-rate WDM links.

When any of these dispersion or nonlinear effects contribute to signal impairment, there is a reduction in the signal-to-noise ratio (SNR) of the system from the ideal case. This reduction in SNR is known as the *power penalty* for that effect, which generally is expressed in decibels.

Chromatic dispersion originates from the fact that each wavelength travels at a slightly different velocity in a fiber. Whether one implements high-speed single-wavelength or WDM networks, this effect can be mitigated by the use of dispersion-compensating fiber or a chirped Bragg grating. *Polarization mode dispersion* (PMD) arises in single-mode fibers because the two fundamental orthogonal polarization modes in a fiber travel at slightly different speeds owing to fiber birefringence. This effect cannot be mitigated easily and can be a very serious impediment for links operating at 10 Gbps and higher.

Two categories of nonlinear effects can place limitations on system performance. The first category encompasses the nonlinear inelastic scattering processes. These are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The second category of nonlinear effects arises from intensity-dependent variations in the refractive index in a silica fiber. This produces effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Table 15.1 gives a summary of these effects.

Further Reading

1. Telcordia, *SONET Transport Systems, Common Generic Criteria*, GR-253-CORE, Piscataway, N.J., September 2000.
2. L. Grüner-Nielsen, S. N. Knudsen, B. Edvold, T. Veng, D. Magnussen, C. C. Larsen, and H. Damsgaard, "Dispersion compensating fibers," *Optical Fiber Technology*, vol. 6, pp. 164–180, 2000.
3. M. Karlsson, J. Brentel, and P. A. Andrekson, "Long-term measurement of PMD and polarization drift in installed fibers," *J. Lightwave Technology*, vol. 18, pp. 941–951, July 2000.
4. H. Sunnerud, C. Xie, M. Karlsson, R. Samuelsson, and P. A. Andrekson, "A comparison between different PMD compensation techniques," *J. Lightwave Technology*, vol. 20, pp. 368–378, March 2002.
5. F. Forghieri, R. W. Tkach, and A. R. Chraplyvy, "Fiber nonlinearities and their impact on transmission systems," Chap. 8, pp. 196–264, in I. P. Kaminow and T. L. Koch, eds., *Optical Fiber Telecommunications—III*, vol. A, Academic, New York, 1997.

Manufacturing Issues

A key issue in the successful widespread application of any emerging technology is the implementation of cost-efficient component production. Whereas it is acceptable to use highly expensive custom-made devices for proving that the technology works, the cost of components must be reduced significantly when bringing systems into the field. This is especially challenging in optical communications where new concepts have been appearing rapidly and standards are not fully mature in many areas. Ways of achieving this include adapting semiconductor manufacturing techniques, setting up automation processes, and devising reliable optoelectronic packaging methods.

This chapter looks at a few of the many issues associated with optical fiber and component production. First, Sec. 20.1 describes methods for producing optical fibers. Next, Sec. 20.2 discusses some component design issues, such as integration of various functions on planar lightwave circuits and athermal package designs. An important step in manufacturing is the connector and component polishing process, which is critical for high light coupling efficiency and low optical return loss. Section 20.3 describes some factory automation equipment to achieve this. Finally, Sec. 20.4 addresses various component packaging issues such as package designs, bonding of metallized fibers, and hermetic sealing.

20.1. Fiber Fabrication

Modern optical fibers are made of highly pure *silica* (SiO_2) to which certain impurities, such as germanium or boron, have been added to induce slight changes in the value of the refractive index. These fibers are produced principally by what is called a *vapor-phase oxidation* process. In this method, highly pure vapors of metal halides (e.g., SiCl_4 and GeCl_4) react with oxygen in a high-temperature environment to form a white powder of SiO_2 particles called *soot*. These particles then are collected on the surface of a bulk glass by one of three different commonly used processes. During or immediately after the collection

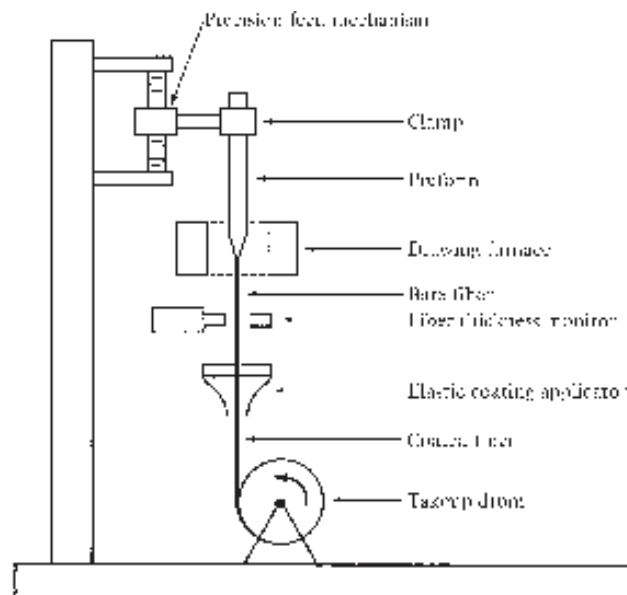


Figure 20.1. Illustration of an optical fiber-drawing process.

process, the particles are *sintered* (transformed to a homogeneous glass mass by heating without melting) by one of a variety of techniques to form a clear glass rod or tube (depending on the fabrication process). The chlorine gas produced in this process is evacuated from the system.

The glass rod or tube is called a *preform*. It is typically around 10 to 25 mm in diameter and 60 to 120 cm long. Fibers are made from the preform by using the *draw tower* equipment shown in Fig. 20.1. The preform is precision-fed into a circular heater called the *drawing furnace*. Here the preform end is softened to the point where it can be drawn into a very thin filament, which becomes the optical fiber. The turning speed of the takeup drum at the bottom of the draw tower determines how fast the fiber is drawn. This in turn will determine the thickness of the fiber, so that a precise rotation rate must be maintained. An optical fiber thickness monitor is used in a feedback loop for this speed regulation. To protect the bare glass fiber from external contaminants, such as dust and water vapor, an elastic coating is applied immediately after the fiber is drawn.

20.1.1. Outside vapor-phase oxidation

Figure 20.2 shows the *outside vapor-phase oxidation* (OVPO) process. Here a layer of SiO_2 particles is deposited from a burner onto a rotating graphite or ceramic rod called a *mandrel*. The glass soot adheres to this bait rod, and layer by layer, a porous cylindrical glass preform is built up. By properly controlling the constituents of the metal halide vapor stream during the deposition process, the glass composition and dimensions desired for the core and cladding can be incorporated into the preform.

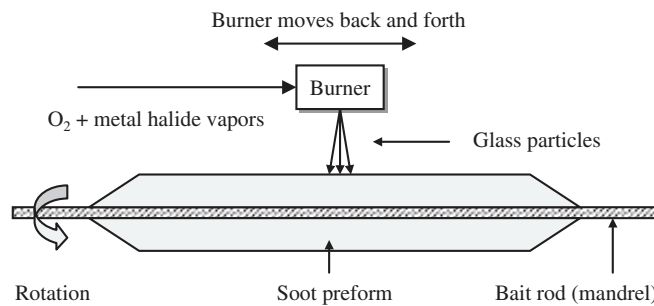


Figure 20.2. Illustration of the outside vapor-phase oxidation (OVPO) process.

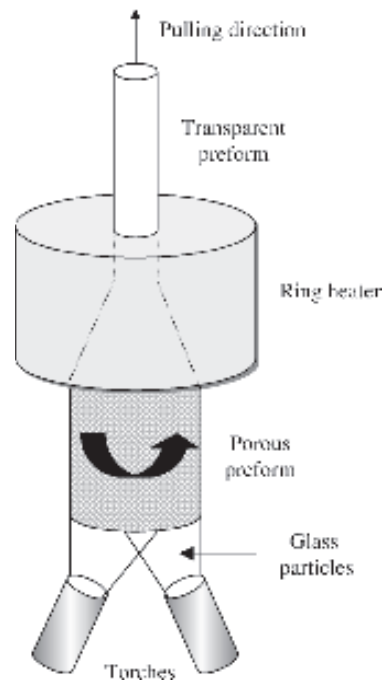


Figure 20.3. Illustration of the vapor-phase axial deposition (VAD) method.

When the deposition process is complete, the mandrel is removed and the porous tube is vitrified to a clear glass preform. The central hole in the tube preform collapses during the fiber drawing process.

20.1.2. Vapor-phase axial deposition

In the *vapor-phase axial deposition* (VAD) method, shown in Fig. 20.3, the soot particles are formed in the same way as in the OVPO process. However, in this case the particles are deposited on the end of a silica glass rod, which acts as a seed. A porous glass preform is grown in the axial direction by moving the rod

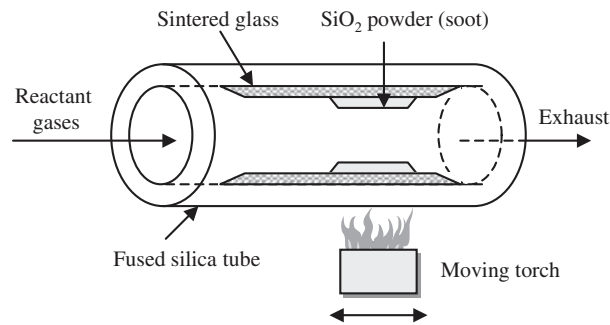


Figure 20.4. Illustration of the modified chemical vapor deposition (MCVD) process.

upward and rotating it continuously to maintain a cylindrical symmetry of the particle deposition. As the porous preform moves upward, it is transformed into a solid transparent glass rod preform by a ring heater.

20.1.3. Modified chemical vapor deposition

The *modified chemical vapor deposition* (MCVD) process shown in Fig. 20.4 was pioneered at Bell Laboratories and has been adopted widely elsewhere. In this technique, metal halide gases and oxygen flow through the inside of a revolving silica tube. As the SiO_2 particles are deposited, they are sintered to a clear glass layer by an oxyhydrogen torch which travels back and forth along the tube. When the desired thickness of glass has been deposited, the vapor flow is shut off and the tube is strongly heated to cause it to collapse into a solid rod preform. The fiber that is drawn from this preform rod will have a core that consists of the vapor-deposited material and a cladding that consists of the original silica tube.

20.1.4. Plasma-activated chemical vapor deposition

The *plasma-activated chemical vapor deposition* (PCVD) process is similar to the MCVD method in that deposition occurs within a silica tube. However, a moving microwave plasma operating at low pressure initiates the chemical reaction within the tube. This process deposits clear glass material directly on the tube wall without going through a soot deposition step. Thus, no extra sintering step is required. Just as in the MCVD case, when the desired thickness of glass has been deposited, the vapor flow is shut off and the tube is strongly heated to cause it to collapse into a solid rod preform.

20.2. Component Designs

Significant cost reductions and enhanced performance are two key factors for component design related to the growing use of dense WDM systems. These are great challenges, since performance improvement often leads to more expensive

devices. However, this is being addressed through developments in areas such as planar lightwave circuits and inexpensive passive athermal designs for thermal wavelength stability. This section addresses those two issues. Other cost reduction techniques are the use of manufacturing automation, as described in Sec. 20.3, and improved packaging methods, which is the topic of Sec. 20.4.

20.2.1. Planar lightwave circuits

A significant saving in manufacturing cost may be realized by integrating the functions of several optical functions (such as filtering, amplification, coupling, and attenuation) on a single substrate. This substrate then can be placed in a single package, thereby reducing the size required on a circuit card. This is the aim of *planar lightwave circuit* (PLC) technology, which also is known as *integrated optics* technology. Since PLC technology increases the density and functionality of photonic devices per square centimeter, it leads to optical transmission equipment designs that are simpler, cost less, and are not as expensive to operate since they consume less electric power.

The manufacture of PLC devices is achieved by using tools and techniques from the semiconductor industry, which allow high-performance components to be made in high volume at low cost. At the core of this technology are traditional silicon-wafer processes and silica-on-silicon photonic circuit designs. These processes are extremely flexible and allow a modular design approach. Circuit configuration modifications within established design rules may be implemented rapidly through mask changes. In addition to using waveguides for passive optical functions, active control of light signals can be achieved through the incorporation of thermo-optic elements. Naturally, similar to the fabrication of electronic components, extremely precise control must be exercised in every manufacturing step.

Components that may be integrated include variable optical attenuators (VOAs), optical switches, optical power splitters, optical couplers, arrayed waveguide gratings (AWGs), and rare earth-doped waveguides. As one example, suppose an engineer wants to construct an eight-channel wavelength multiplexer that has a variable output control on each channel. By using separately packaged components, this can be done with an AWG and eight VOAs plus some control circuitry, as shown in Fig. 20.5. Here the discrete packages need to be interconnected by short fiber jumpers. Integrating the AWG and VOA functions into a single PLC device greatly reduces the size and cost of the final module. In addition, the PLC design eliminates the external optical connections that normally are needed to interconnect the AWG and the VOAs, which results in a much lower optical power insertion loss.

As another example, consider the replacement of the erbium-doped fiber in a conventional EDFA with an integrated erbium-doped waveguide. The resultant *erbium-doped waveguide amplifier* (EDWA) is significantly smaller than its EDFA counterpart. In the example from NKT Integration shown in Fig. 20.6, eight EDWA devices are integrated on a single substrate. Each amplifier has

340 Chapter Twenty

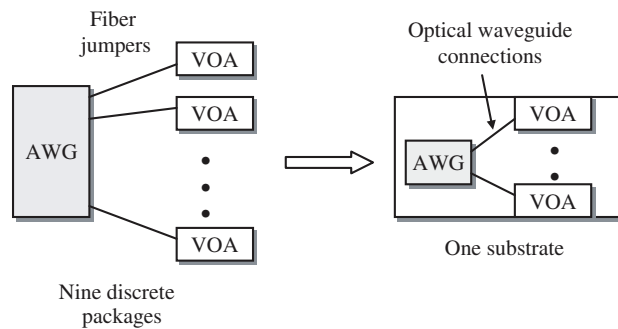


Figure 20.5. Example of planar lightwave circuit (PLC) technology. Here an AWG and eight VOAs are combined into a single PLC device.

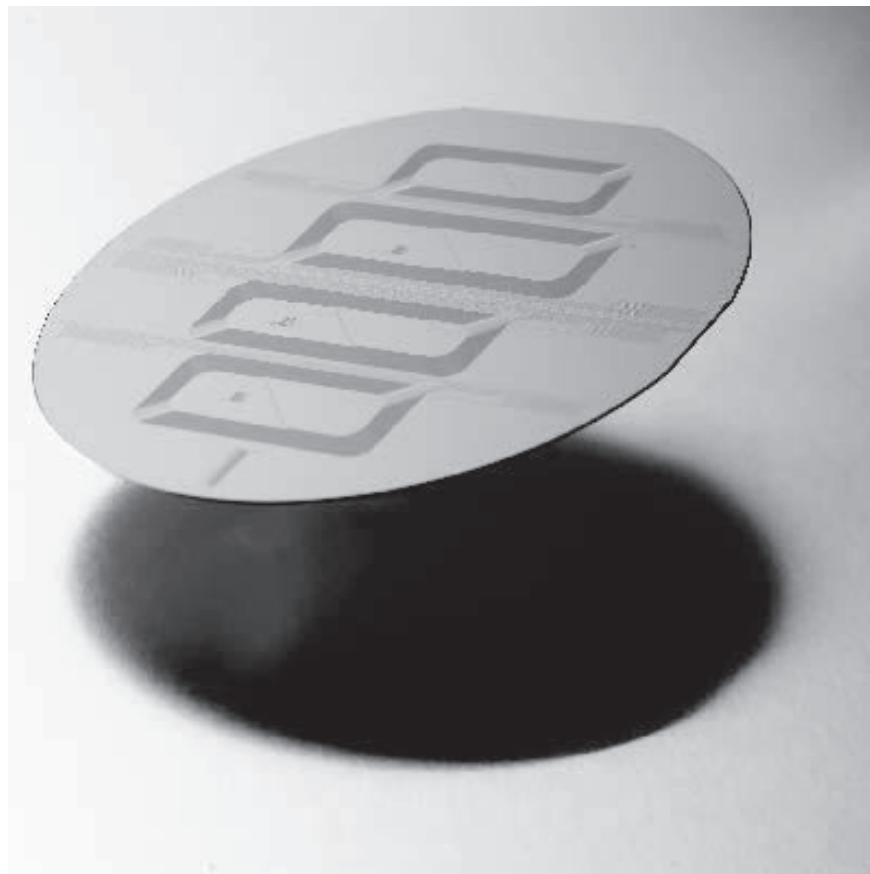


Figure 20.6. Example of PLC technology showing the integration of eight EDWA devices plus associated signal and pump multiplexers on a single substrate. (Photo courtesy of NKT Integration; www.nktintegration.com.)

TABLE 20.1. Representative Specifications of an EDWA (Specification from NKT Integration; www.nktintegration.com)

Parameter	Specification
Wavelength range	1528–1562 nm
Pump wavelength	980 nm
Small-signal gain	>20 dB @ 100-mW pump power
Output power	>10 dBm @ 100-mW pump power and 0-dBm input signal
Noise figure	<5.0 dB @ –20-dBm input power
PDL (PDG)	<0.3 dB
PMD	<0.3 ps
Size of bare chip	25 × 55 × 1 mm

individual on-chip multiplexers for C-band and 980-nm pump wavelengths on both the input and the output for either codirectional or counterdirectional pumping. Table 20.1 gives some specifications of such an amplifier. Here the acronyms *PDL* and *PDG* refer to polarization-dependent loss and gain, respectively. This module may be used in metro applications where a few channels are added or dropped from a high-capacity DWDM trunk line.

20.2.2. Athermal designs

The performance of a passive optical component may change significantly with temperature. Of particular concern is wavelength drift in a DWDM application. Among thermally sensitive components are standard arrayed waveguide gratings, fiber Bragg gratings, and bulk-grating-based optical products. To maintain reliable performance of a DWDM communication link, it is essential that the wavelength characteristics of such system components be as invariant as possible.

Conventional AWGs consist of lightwave circuits made of quartz glass waveguides. Since the index of refraction of quartz glass changes with temperature, the wavelengths of light transmitted through such an AWG also change. Thus a conventional AWG typically will have a thermoelectric cooler-based temperature controller built into the package to maintain wavelength stability. However, by using different materials for the waveguides, an AWG can be fabricated without the need for a temperature control device and, consequently, without the need for a source of electric power. For example, an athermal AWG made by NTT Electronics uses a special silicon resin in part of the lightwave circuit that has a different temperature coefficient from that of quartz glass. This design cuts the temperature dependence of the wavelengths of transmitted light to less than one-tenth of its original value, which makes using a temperature control device unnecessary.

A different approach based on a passive temperature compensation method can be taken for a fiber Bragg grating (FBG). In this case the FBG is attached

to a platform consisting of a material which has the opposite thermal expansion property from that of the FBG. With this method a wavelength stability of better than $0.5 \text{ pm}/^\circ\text{C}$ can be achieved together with a temperature-dependent loss below $0.01 \text{ dB}/^\circ\text{C}$ over an operating range of 0 to 70°C .

Likewise, bulk-grating-based optical products may be designed to be passively athermal, so that no active temperature control is required. In contrast to components that require active temperature control, for devices with passive athermal compensation there is no need for electric power, alarms, and monitoring circuitry.

20.3. Integrated Automation

Sometimes what appears to be the simplest step in a fabrication process can take a long time if individual pieces are processed manually. Among these are connector attachment, preparation of optical fiber pigtails for use in devices, and polishing of optical components. This section examines integrated-automation machines from two different vendors for these functions.

First consider the connector preparation system from Sagitta, which is shown in Fig. 20.7. This system has the integrated capabilities of batch polishing,



Figure 20.7. Example of an automated connector preparation system. (Photo courtesy of Sagitta; www.sagitta.com.)

cleaning, and optical-surface inspection of various types of fiber optic connectors and cable assemblies. These include the SC, FC, ST, LC, MU, MT-RJ, and MPO connectors described in Chap. 8. Connector properties, such as surface quality, end-face curvature, fiber height, and apex offset, can be controlled through a servo-control polishing head. The system includes an integrated microscope and CCD camera for image capture and the manual or automatic inspection of optical surfaces for scratches, pits, and material defects. The areas to be examined may be defined by regions in the core, cladding, or ferrule. Imaging software enables automatic surface-defect recognition, and a pass/fail sorting criterion can be set. The images can be seen on a display screen that is connected to the equipment. The machine allows a throughput of 100 to 300 connectors per hour, depending on the connector style.

As another example, consider the system shown in Fig. 20.8 from kSaria which fully automates the processes of fiber pigtail fabrication. When done manually, the fiber pigtail preparation process normally requires five processes and takes up to 10 min to complete. With this system a fiber preparation module automatically pays out a predetermined length of fiber (ranging from 0.75 to 3 m) and prepares the end. First, the spooling/pay-out tool dispenses a pre-programmed length of fiber, coils it, and inserts it into a holding tray with the two ends secured for further processing. The spooled trays then are transported to the strip, clean, and cleave tools. When the fiber preparation process is



Figure 20.8. Example of a system that fully automates the processes of fiber pigtail fabrication. (Photo courtesy of kSaria; www.ksaria.com.)

complete, a ferrule is loaded automatically and attached to the prepared fiber. Before attachment, a metered amount of thermally curable epoxy is dispensed into the ferrule. The fiber is inserted into the ferrule, and the assembly is heated to cure the epoxy. After the ferrule attachment process is complete, pig-tails are unloaded into an empty cassette as a fiber pigtail. The entire process is controlled by a personal computer. The system software provides all operator controls, including multilevel user access, error logging, process statistics, and diagnostics. The throughput capability is 120 fibers per hour.

20.4. Packaging

The term *packaging* refers to the encapsulation of a device in a form that takes into account optical power coupling, thermal management, mechanical support, and hermetic sealing for environmental protection. In addition there are the standard concerns related to electrical connections. These concerns are the same as for ordinary microelectronics packages and are relevant only for active devices, since passive components do not have electrical connections.

20.4.1. Optical connection

The optical connection is the most critical aspect of a photonics package. Since light must be coupled efficiently into very small fiber cores, the optical connections require extremely precise alignment. They are especially sensitive to axial misalignments, as noted in Sec. 8.3. In some cases alignments need to be held to a fraction of a micrometer in order to have an acceptable component. To make matters more complicated, passive devices often have multiple couplings, all of which need to be precision-aligned simultaneously.

Micropositioning machines are available commercially that allow six-axis alignments to a resolution precision of 0.1 nm. Such systems usually can be software-controlled to allow their use for both development techniques and manufacturing procedures. Typically included with such machines is a video magnification system with illumination.

20.4.2. Thermal management

Management of *thermal effects* is an important factor for both active and passive devices. Thermal gradients within or across a device can lead to misalignments of components within a device package, which may cause a reduction in optical power coupling efficiency. In addition, heat generated within active components needs to be dissipated in order to avoid degradation of the device. In most cases this is done by means of a thermoelectric (TE) cooler. Typically the TE cooler is soldered to the package base, which later will be mounted on an external heat sink.

A TE cooler (which also is known as a *Peltier cooler*, since its function is based on the Peltier effect) is a semiconductor-based electronic component that functions as a small heat pump. When a low voltage is applied to a TE module, heat

moves from one side of the module to the other in proportion to the applied voltage. Thus, one module face will be cooled while the other is heated simultaneously. As noted in Chap. 6, with appropriate control circuitry TE coolers can stabilize temperatures to $\pm 0.02^\circ\text{C}$.

In packaging devices such as laser diodes, careful design procedures must be followed to ensure that the heat generated by the laser chip during operation will flow away from the laser out of the package. Creating the interface between a laser chip and the carrier it is mounted on is a standard procedure known as *eutectic die attachment*. This bonding traditionally is done by means of a gold/tin solder (80% Au/ 20% Sn), which can be done in a fairly straightforward manner in an automated assembly environment.

20.4.3. Mechanical concerns

The mechanical structure that houses active components usually is the industry-standard hermetically sealed 14-pin *butterfly package* or some variation thereof, as illustrated in Fig. 20.9. The housing is made of either Kovar (a low-expansion iron-nickel-cobalt alloy) or Kovar and a copper-tungsten (Cu-W) alloy. Once the components are placed inside and are bonded and interconnected properly, the package may be heated to reduce or even eliminate any moisture and other contaminants (see Sec. 20.4.4). Next the package is sealed, evacuated, and then backfilled with helium to a very low pressure.

To mount the optoelectronic components within the package, manufacturers use a metallic subassembly or platform that fits inside the butterfly package, as illustrated in Fig. 20.10. Included on the subassembly may be bonding pads for attaching wires, an alignment block for precise component placement, miniature circuit boards, and special inserts for mounting items such as fiber alignment

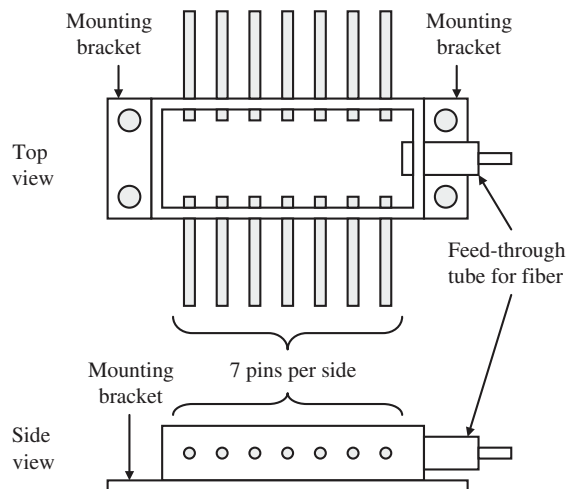


Figure 20.9. Schematic of an industry-standard hermetically sealed 14-pin butterfly package.

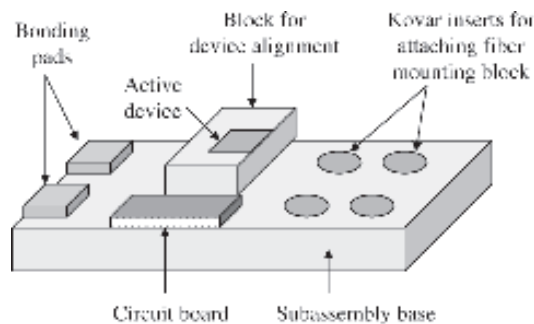


Figure 20.10. Subassembly or platform and some of its associated parts for mounting optoelectronic components within a butterfly package.

blocks. The basic properties of these complex metallic subassemblies include a heat dissipation ability, a thermal expansion match with the internal devices, and an ability to weld or bond items such as metallized fibers, semiconductor die carriers, and high-speed electronic circuitry. The basic platform structure nominally consists of a Cu-W alloy and also may include other metals or metallic alloys such as copper, nickel, a copper-molybdenum alloy, and Kovar.

Manufacturers of these butterfly packages often supply the housings with a TE cooler already attached inside.

20.4.4. Hermetic sealing

The purpose of *hermetic sealing* is to prevent contaminants from entering a device package. The items inside a package that require such protection include electronics, electrodes, microelectromechanical system (MEMS) devices, epoxy and die bonds, laser chips, and component surfaces. A key culprit is moisture, which over time can corrode electrodes, cause mechanical shifts in items bonded with water-sensitive epoxy, and damage the surfaces of fiber ends, mirrors, optical filters, or MEMS devices.

Hermetic packaging designs basically use the same packaging principles that have proved very successful in the microelectronics and microwave industries. The additional challenge in optical fiber components lies in how to create a hermetic seal at the point where the optical fiber passes through the package wall. When a fiber is inside a cable, the plastic buffer coating surrounding the cladding is sufficient to protect the fiber from typical environmental effects and mechanical disturbances that it may encounter. However, this coating is not adequate to provide a tight moisture seal when the fiber traverses a package wall.

To provide such a seal, the elastic coating is stripped off the fiber down to the cladding, and then a thin metal film is bonded to the bare fiber. The metal film nominally consists of two layers. First the fiber is coated with a layer of nickel to provide a strong adhesion to the glass and a stable soldering base. Then the fiber is plated with an overcoat layer of gold to provide resistance to oxidization. This creates a strong metal coating that is capable of withstanding the rigors of

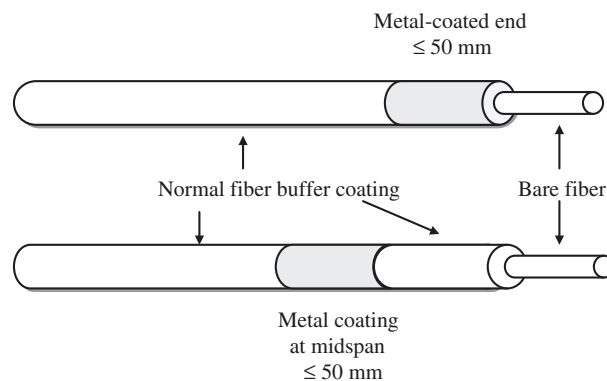


Figure 20.11. Two possible locations for creating a metal coating on a fiber to allow hermetic sealing to device packages.

soldering and hermetic sealing. A typical coating length ranges up to 50 mm, and the thickness is less than $2\mu\text{m}$. Metallic coatings can be put on either single fibers or ribbon fibers.

As shown in Fig. 20.11, the metal coating can be at any location on the fiber. For metallic coatings on the end, the metal can go completely to the fiber end, or a short final length of fiber can remain bare so that it may be terminated with ceramic ferrules, fusion-spliced to another fiber, or connected directly to a device inside a package. In the *midspan metallization* only a short section near the end of the fiber is metallized. When such a fiber passes through a package, it can be soldered to the package at the midspan point, thereby leaving a short pigtail within the package for connecting to a device inside.

20.5. Emerging Package Technology

Although most devices for optical fiber communications are enclosed in hermetically sealed metallic packages, there is a trend to produce both hermetic and non-hermetic ceramic packages. This development is being driven by the need to reduce manufacturing costs and to produce packaged devices in very high volumes. The mechanical structure that houses active components usually is the industry-standard hermetically sealed 14-pin butterfly package or some variation thereof.

20.6. Summary

The successful application of any emerging technology lies in the implementation of cost-efficient component production. This is especially challenging in optical communications where new concepts have been appearing rapidly and standards are not fully mature in many areas. Ways of achieving this include adapting semiconductor manufacturing techniques, setting up automation processes, and devising reliable optoelectronic packaging methods.

Significant cost reductions and enhanced performance are two key factors for component design related to the growing use of dense WDM systems. These are great challenges, since performance improvement often leads to more expensive devices. This is being addressed through developments in areas such as planar lightwave circuits (PLCs) and inexpensive passive athermal designs for thermal wavelength stability. Since PLC technology increases the density and functionality of photonic devices per square centimeter, it leads to optical transmission equipment designs that are simpler, cost less, and are not as expensive to operate since they consume less electric power.

Sometimes what appears to be the simplest step in a fabrication process can take a long time if individual pieces are processed manually. Among these are connector attachment, preparation of optical fiber pigtailed for use in devices, and polishing of optical components. Several companies are offering integrated-automation machines for such functions.

Packaging of devices for optical fiber communications must take into account issues such as optical power coupling, thermal management, mechanical support, and hermetic sealing for environmental protection. Hermetic packaging designs have the challenge of creating a hermetic seal at the point where the optical fiber passes through the package wall. This can be achieved by stripping the fiber down to the cladding and then bonding a thin metal layer to the glass. This creates a strong metal coating that allows the fiber to be soldered to the package at the point where it passes through the enclosure wall, thereby providing a hermetic sealing.

Further Reading

1. J. G. Bornstein, "Semiconductor techniques enhance production of planar lightwave circuits," *Optical Manufacturing*, vol. 1, no. 1, pp. 25–29, March 2002.
2. R. Cisneros and G. Shechter, "Integrated automation promises improved planar lightwave circuits," *Optical Manufacturing*, vol. 1, no. 1, pp. 31–34, March 2002.
3. J. Sepulveda and L. Valenzuela, "Integrated subassemblies improve optoelectronic package performance," *Optical Manufacturing*, vol. 1, no. 2, pp. 27–29, May 2002.
4. B. Benton, "Automating optical and IC module assembly and thermal management," *Optical Manufacturing*, vol. 1, no. 2, pp. 23–25, May 2002.
5. G. Ogura, "Hermetic packaging," *Lightwave*, vol. 18, pp. 28–30, October 15, 2001 (www.lightwave.com).
6. S. J. Horowitz and D. I. Amey, "Ceramics meet next-generation fiber optic packaging requirements," *Photonics Spectra*, pp. 123–126, November 2001 (www.photonics.com).