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Instructor's Manual and PowerPoints
to accompany

Understanding Fiber Optics

Fifth Edition

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Preface:

About *Understanding Fiber Optics*, 5th ed

Understanding Fiber Optics began as a self-study text, but has been widely adopted for classroom use. It concentrates on fiber optics for communications, but also gives brief introductions to other uses of fiber optics in imaging, illumination, and sensing. It is written for the classroom rather than as a laboratory text; my goal is to explain principles rather than to detail procedures such as cable installation. Several chapters, including the first three introductory chapters, have been rewritten and reorganized. The entire book also has been updated to clarify concepts and to reflect new technology and business developments such as the start of deployment of fiber to the home systems. Many illustrations have been redrawn to make them clearer and to correct mistakes. The changes include more realistic descriptions of the actual use of fiber systems, and discussions of how the telecommunications bubble distorted reality. To help you keep up to date, I have included lists of written and organizational resources at the end of this manual, as well as notes on Web resources.

My goal is to explain fundamental concepts at an elementary level accessible to anyone with a minimal technical background. To that end, I have written in a casual tone, included many "cartoon" drawings showing how things work, taken pains to explain industry jargon before using it, and generally avoided math beyond basic algebra. I draw analogies and contrasts with common technologies, particularly electronics, both to help students understand how fiber optics work, and to illuminate important differences. I assume students taking a fiber optics course have had some exposure to electronics, but I don't assume an in-depth expertise in either electronics or communications.

I use metric units throughout, because they are standard for most dimensions in optics and fiber optics. I translate metric units into Imperial (English) units in only a few places. The communications industry is inconsistent in its usage; while fiber attenuation is universally measured in decibels per kilometer, cable runs are often given in miles or feet.

Each chapter includes a multiple-choice quiz for students to test themselves, and a set of open-ended "Questions to Think About" to push their horizons. The questions span a broad range, from asking "why" something works (or doesn't work) to word problems requiring calculations. The fifth edition for the first time includes short "things to think about" in many chapters, covering ideas from whether glass can flow at ordinary temperatures to digital rights management on the Internet.

This instructor's manual is intended to give you a quick overview of what each chapter contains, and to suggest teaching strategies and additional resources. The description of each chapter includes answers to the multiple choice quiz and to the open ended "Questions to Think About" included with each chapter in the text; to save you the trouble of looking back and forth, I repeat the Questions to Think About included in the text.

The CD-ROM that accompanies this instructor's manual includes art in PowerPoint form for your classroom use, based on short courses I have taught for the Optical Society of America and

SPIE, plus copies of illustrations from the book.

This edition is organized into several blocks of chapters.

The first three chapters are an introductory overview. Chapter 1 is a historical introduction to the field and to some fundamental concepts used throughout the book. Chapter 2 introduces basic concepts of optics and physics, then shows how they explain the basic principles of fiber optics and photonics. Chapter 3 introduces communications systems and concepts in general terms that cover both electronic and optical communications. Inevitably students have uneven preparation in basic optics and communications, and these chapters are designed to smooth over any holes in their backgrounds to prepare them for later chapters. How much class time you devote to these chapters depends on your students' preparations, but you should assign them as background reading.

Chapters 4 through 8 cover optical fibers and cables. To keep the information in manageable chunks, I divided the coverage of fibers into separate chapters on fiber types, properties, materials, and specialty fibers. Chapters 4 through 6 are essential to understanding the fiber concepts spread through the rest of the book. Chapter 7 covers fibers developed for purposes other than transmitting signals between points -- including fiber gratings, reduced-core fibers, polarization-maintaining fibers, and the rare-earth-doped fibers used in optical amplifiers. Chapter 8 explains the structure and function of cabling.

Chapters 9-12 cover optical sources, amplifiers, and receivers. Light sources are treated as components in Chapter 9, which covers their operating principles. Chapter 10 covers transmitters, including multiplexing and modulation as well as light sources. Chapter 11 covers both optical detectors and receivers. Chapter 12 covers repeaters, regenerators and optical amplifiers. These chapters give few circuit examples, but don't go into much detail because this is a book on optics rather than electronics.

Chapters 13-16 cover various additional "nuts and bolts" of fiber-optic systems. Chapter 13 integrates connectors and splices to highlight their differences and similarities. Chapter 14 covers couplers and other passive components such as optical attenuators, optical isolators, and optical circulators. Chapter 15 is devoted to optics used for wavelength-division multiplexing. Chapter 16 covers active components including modulators, optical switches, and wavelength converters.

Test and measurements are the subjects of Chapters 17 and 18. Chapter 17 introduces the principles of optical measurements and important techniques. Chapter 18 covers test equipment and troubleshooting.

Note that Chapters 4-18 concentrate on *optical* components and measurements. They look at the building blocks of fiber-optic systems, rather than at the overall operation of communication systems. They also concentrate on the optical aspects of these devices, which are essential to understanding fiber optics. This grouping provides a logical break to review optical ideas and to run a question-and-answer session to help students fill gaps in their understanding. If you plan to cover *only* the component side of fiber optics, you may skip most of Chapters 19-28 which deal

with communication systems, and include Chapters 29 and 30, which cover non-communication uses of fibers. If systems are addressed in a different course which students have not yet taken, the material in Chapter 19-28 may be helpful as examples of how components are used.

Chapters 19-28 cover the principles and operation of fiber-optic systems and optical networking. These chapters are not intended as a comprehensive course in communications, but they do introduce important communication concepts needed to understand the applications of fiber optics in communications. Thus these chapters concentrate more on the transmission network where fiber-optics are used than on parts of the network where fibers have little role, such as home telephone instruments. The treatment assumes that students know little about communications systems, so students who have already had communications technology courses can skim the background material. The emphasis is on technology rather than on industry structure or regulations.

Chapter 19 introduces system and optical networking concepts, with particular emphasis on transmission. Chapter 20 covers the standards that impact fiber-optic networks. Chapter 21 explains the design of fiber-optic systems carrying only a single optical channel. Chapter 22 explains concepts of optical network design and wavelength-division multiplexed systems. Chapter 23 describes long-distance transmission on land and in submarine cables. Chapter 24 describes regional and metro telecommunications. Chapter 25 covers local telephone or "access" networks and fiber to the home or premises systems. Chapter 26 covers data transmission, local area networks, and the Internet. Chapter 27 covers video transmission with emphasis on cable television. Chapter 28 covers the use of fiber optics for remote control of robotic vehicles, and within vehicles ranging from battleships to automobiles.

The final two chapters can be skipped if your course covers only fiber-optic communications. However, sensing (Chapter 29) and image transmission and illumination (Chapter 30) are important applications for fiber optics.

Appendices A through D tabulate information that students may find useful during and after the course. Appendix A compiles important formulas and conversion factors mentioned in the text; they are gathered in one place to make life easier. Other appendices include tables of decibel equivalents, standard data rates, and standard optical channels. Appendix E gives a very basic introduction to laser and fiber safety. Appendix F lists resources valuable for further research.

The glossary defines important fiber-optic terms and acronyms used in the text.

Telecommunications is plagued by a bewildering variety of acronyms, which I try to avoid. One reason is philosophical -- acronyms are hard to assimilate, so I find it counterproductive to throw them at a beginning student entering a new field. Another reason is pragmatic -- few acronyms are standardized. Some appear only in specific articles or books; others are used only by a few technical journals, industry magazines, or corporate publications. The back of this instructor's guide includes a list of some extra acronyms that I don't use or that didn't appear in the glossary, but be aware that it is not comprehensive.

As a frequent user of reference books, I believe a good index is a vital part of textbooks like this, and have compiled one to make *Understanding Fiber Optics* valuable as a reference book during and after the course. Please urge your students to check the index if they have questions.

My home page for fiber optics is **<http://www.fiberhome.com>**. At this writing it is devoted to a brief description of this book, but I hope to add further material and links. You can find information on other books I have written at **<http://www.jeffhecht.com/books/html>**.

Although I do teach some short courses, my primary activity has long been writing about technology. You can find my articles in magazines including *Laser Focus World*, *New Scientist*, and *Optics & Photonics News*. I particularly recommend the articles in *Laser Focus World* and its companion magazine *Lightwave* as a way to update yourself on fiber optics.

The sections that follow briefly outline the goals of each chapter, give answers to questions, and suggest supplementary material. They explain answers to the open-ended "Questions to Think About", and include some worked-out numerical solutions to selected multiple-choice problems.

I welcome any suggestions and comments you might have for future editions. If you think you have found mistakes, or if anything seems unclear, please contact me. I am far from infallible, and continue searching for ways to improve my explanations. Please contact me by mail through Prentice-Hall, or e-mail me at jeff@fiberhome.com or jeff@jeffhecht.com.

-- Jeff Hecht, Auburndale, MA, March 2005

Chapter 1

Introduction to Fiber Optics

Chapter 1 is an introduction and overview, to give students a general background in fiber optics and its uses. Depending on the preparation of your students, you could use this material in an introductory lecture, or assign the chapter as outside reading.

Overview

The development of any technology can be a helpful blueprint to understanding its workings, so I have organized this explanation in historical sequence. Fiber optics began with the idea of using total internal reflection to guide light in jets of water, first demonstrated in lectures and later at the great Victorian exhibitions of the late 1800s. Later engineers expanded the idea of light guiding to groups of fibers bundled together to carry images, with the major applications in medicine and military imaging systems. Communications came only later, and required major improvements in glass transparency. (Note that many brief histories of early fiber optics include significant mistakes, starting with attributing the water jet experiment shown on page 4 of the book to John Tyndall.)

I find the history fascinating, but the real importance for the beginning student is to introduce the central concepts of total internal reflection, light guiding, the fiber cladding, bundles, imaging, and communications. It's also important for students to learn that ideas do not spring full-blown from the mind of a single inventor, but instead evolve over the years, as new ideas emerge in response to new technologies, capabilities, and new potential applications.

After describing the history, the chapter moves on to basic fiber-optic concepts. Later chapters cover these ideas in more detail, but my approach is to start with simple explanations for the least-prepared students. From there, the chapter moves to an introduction to the role of fiber optics in communications.

I also describe the business of telecommunications and the disruption caused by the Internet and the bubble. I think the booms and busts of the 19th century railroad industry are a good analogy for what happened to fiber optics. Like the railroads revolutionized ground transportation, fiber optics revolutionized telecommunications. Both technologies succeeded so well that investors poured tremendous sums of money into them, and their capacity was expanded far beyond any immediate needs, causing a bust. Essentially, the industry got running so fast that it ran right off a cliff, and like Wyle E. Coyote, didn't realize what had happened until it looked down.

Questions to Think About For Chapter 1

1. For a bundle of optical fibers to transmit an image, the fibers must be arranged in the same pattern on both ends of the bundle. What limits the size of the smallest details that can be seen?
Answer: The diameter of the fiber, because all light entering the fiber is mixed as it travels along

the fiber.

2. Devise an analogy to show how a bundle of fibers transmits an image using common implements found in a kitchen or cafeteria.

Answer: A bundle of drinking straws stacked parallel to each other.

3. Most of the light lost in going through a glass window is reflected at the surface. Ignoring this surface reflection loss, suppose that a one-millimeter window absorbs 1% of the light entering it and transmits 99%. Neglecting reflection, how much light would emerge from a one-meter thick window?

Answer: 99% passes through each millimeter, so you multiply 0.99 times itself 1000 times, calculating 0.99^{1000} . The answer is 0.000043, or 43×10^{-6} of the light entering the glass. For comparison, that's about the difference between the magnitude of the planet Venus at its brightest and the faintest star visible to the unaided eye on a dark night far from city lights.

4. If optical fibers transmit signals so much better than wires, why aren't they used everywhere?

Answer: Largely because telephone companies and others have installed billions of dollars worth of existing copper cables. In addition, input signals come in electronic form, and must be converted into optical form, which requires separate optical transmitters and receivers.

5. During the bubble years, many people in the industry thought Internet traffic was doubling every three months. In reality, it was doubling about every year. How much difference would this make over a period of five years?

Answer: If traffic doubled every year, it would be 32 times higher after 5 years. If traffic doubled every 3 months, it would be more than one million times higher (there are 20 three-month periods in five years, and $2^{20}=1,048,576$). The estimate that traffic was doubling every month came from WorldCom, which time has proved was not the most reliable source.

6. Why didn't anybody wonder how long Internet traffic could continue doubling every three months?

Answer: A few people did, and it was Andrew Odlyzko, now at the University of Minnesota, who first showed data to contradict those claims, but most people either were carried away by the mania of the bubble, or didn't have data to question it.

Answers to Quiz for Chapter 1

1. c
2. d
3. a
4. d
5. b
6. a
7. d
8. d

- 9. c
- 10. a

Supplemental Materials and Suggestions:

A sample of fiber (preferably flexible thick plastic fiber for safe and easy handling) to pass around the classroom. Fiber-optic Christmas ornaments are cheap and should be readily available. Handling fibers is a good way to understand how they work, and plastic fibers are much safer than glass to pass around.

The water-jet experiment is not as simple as it looks, so don't expect to recreate it easily.

For more on the history of fiber optics and the bubble, see Jeff Hecht, *City of Light: The Story of Fiber Optics* (Oxford University Press, 1999, 2nd edition 2004).

A good example of how bad the collapse of the bubble hit telecommunication stocks is a comparison of a couple of rather different investments. If you'd invested \$1000 in Nortel stock about September 2000, you would have had \$72 a year later. If you'd invested \$1000 at the same time in Budweiser -- the beer, not the stock -- and lived in a state with a bottle deposit law, you would have had \$76 worth of empties.

Chapter 2

Fundamentals of Fiber-Optic Components

This chapter explains the basic principles of optics, optical fibers, and fiber-optic components that are essential to understanding later chapters. This is the starting point for your "meaty" lectures. You should open with the basics of refraction, and show how those principles lead to total internal reflection. Then you should cover light guiding in fibers (using the total internal reflection model), and other properties of fibers and optical components.

Overview

The starting point is basic optics, because students must understand light and its properties before they consider fiber optics. Much of this information may not be new to students who have had a good introductory physics course, but you can't count on that. This review focuses upon the parts of optics relevant for fiber optics.

I start with the ideas of the electromagnetic spectrum, wavelength, frequency, and photons. Then I introduce refraction and refractive index, which leads to total internal reflection, and how it can explain light guiding in a multimode step-index optical fiber. That explanation of light guiding takes the traditional optical perspective of tracing the paths of light rays, rather than the more accurate treatment of an optical fiber as a waveguide, because the ray model is more intuitive for students. The waveguide model is introduced in Chapter 4, which also introduces the graded-index and single-mode fibers.

This chapter also introduces fiber properties, including attenuation coupling losses, pulse dispersion and transmission bandwidth. These are fundamental concepts that appear throughout the book, and are described in more detail in later chapters. They are introduced here to give students a working background for later chapters. You can refer students who want more details to the index. A brief final section introduces optical transmitters, receivers, amplifiers, and repeaters.

Students should finish this chapter with a general knowledge of fiber optic components, adequate to explain the subject to the proverbial man on the street, and to comprehend more detailed descriptions.

Questions to Think About for Chapter 2

1. Interference seems to be a strange effect. The total light intensity from two bulbs is the sum of the two intensities. Yet the light intensity is really the square of the amplitudes, and if the two waves are in phase, you double the amplitude, which when squared means the intensity should be four times the intensity of one bulb. Don't these views contradict each other?

Answer: Not really because interference varies from place to place. If the bulbs emitted identical light waves, they would interfere constructively in some spots but destructively in others.

Averaged over space, they're halfway between completely in phase (where intensity would be

four times that of one bulb) and completely out of phase (where intensity would be zero), so intensity would average to that of two bulbs. If you scanned over the whole volume with a detector small enough to see the variations on the scale of a wavelength, you would see intensity varying continually between total darkness and peak light.

2. One photon is a wave packet that doesn't last very long. A continuous light source emits a steady or continuous wave. How is the continuous light source emitting photons?

Answer: In a steady stream. If the light source emits a steady amount of energy per second, it emits a constant number of photons each second.

3. The sun emits an energy of about 3.8×10^{33} ergs per second. A photon with wavelength of 1.3 micrometers has an energy of about 1.6×10^{-12} erg. If you assume the sun emits all its energy at 1.3 μm , How much attenuation in decibels do you need to reduce the sun's entire output to a single 1.3- μm photon per second?

Answer: The ratio is 2.375×10^{45} , which corresponds to 454 dB.

4. If an entire galaxy contains a billion stars, each one as luminous as the sun, how much attenuation does it take to reduce its entire output to a single 1.3- μm photon per second.

Answer: The ratio is 2.375×10^{54} or 544 dB.

5. Suppose window glass has attenuation of 10 dB/meter at 1.3 micrometers (not an actual value). How thick a block of glass would you need to reduce the sun's entire output to a single photon as in problem 3?

Answer: Divide 454 dB by 10 dB/m to get 45.4 meters.

6. Medical imaging fiber has attenuation of 1 dB/meter at optical wavelengths. If the attenuation is the same at 1.3 μm , and you don't have to worry about the sun's energy melting the fiber, how long a fiber would reduce the sun's output in problem 3?

Answer: Divide 454 dB by 1 dB/m, giving 454 meters.

7. Atoms and molecules in the atmosphere scatter light in the same way that atoms in glass scatter light in an optical fiber. The shorter the wavelength in the visible spectrum, the stronger the scattering. Where do you think the sky gets its blue color from and why?

Answer: Blue and violet light have the shortest wavelengths in the visible spectrum, but the eye isn't very sensitive to violet. The blue light is scattered much more than longer wavelengths. The blue light you see is scattered sunlight.

8. Diamond has a refractive index of 2.4. What is its critical angle in air and what does that have to do with its sparkle.

Answer: The critical angle is 28° , so it reflects light by total internal reflection over a wider range of angles than glass. Diamonds are cut so the facets at the back of the stone will reflect light back to your eye.

Worked Quiz Problems

Problem 7:

The problem implicitly assumes the zircon is in air. The critical angle is

$$\theta_{crit} = \arcsin\left(\frac{n_{air}}{n_{zircon}}\right) = \arcsin\left(\frac{1}{2.1}\right) = 31.6^\circ$$

Problem 9:

First calculate total loss in decibels:

$$Loss = 0.3db/km \times 100km = 30dB$$

Then convert that loss back to a percentage:

$$Ratio = 10^{\left(\frac{loss\ in\ dB}{-10}\right)} = 10^{\left(\frac{30}{-10}\right)} = 10^{-3} = 0.1\%$$

Answers to Quiz for Chapter 2

1. e
2. e
3. c
4. b
5. c
6. d
7. c
8. c
9. a
10. d
11. a
12. b

Supplemental Material and Suggestions

Illustrations showing light refraction and the operation of lenses, if available.

Shine a laser pointer through a cloud of chalk dust to show how light travels in straight lines. (Cigar smoke also works well.)

Chart of the optical spectrum to illustrate wavelengths and colors. Point out that most fiber-optic transmission is at 850, 1300 and 1550 nm.

Plot of fiber loss to show fiber transmission windows; see Figure. 5.2.

David Falk, Dieter Brill, and David Stork's *Seeing the Light: Optics in Nature, Photography, Color, Vision, and Holography* (Wiley, 1986) is a wonderful nonmathematical treatment of optics.

J. Warren Blaker and Peter Schaeffer, *Optics: An Introduction for Technicians and Technologists* (Prentice Hall, 2000) is a short primer on optics for technicians, with some math, which goes into more detail on optical components other than fibers.

Chapter 3

Fundamentals of Communications

This chapter is an introductory overview of communications systems and services, intended to provide the background needed to understand fiber-optic components and systems and how they are used. It covers basic concepts and applications, then turns to fiber optics. Although software is important in communications, my emphasis is on hardware because fiber optics fall in that category. If your students have had an introductory communications course, this chapter can serve as a review, and you may not need to go through it in class. The chapter introduces terms used in the rest of the text, which can be important because communications terminology is far from universal.

Overview

The first part of the chapter introduces the concept of telecommunications, and describes the historical evolution of communications technology. This puts fiber optics into the context of the growing need for bandwidth. I also introduce important terms the student is likely to encounter, giving fuller descriptions than is possible in a glossary, and revealing my prejudices about the most meaningless buzzwords. This section also introduces the concept of multiplexing, and defines frequency-division, wavelength-division, and time-division multiplexing. Note that I use the term "optical channel" to mean a signal carried by one wavelength in any kind of optical system, but it generally applies to wavelength-division multiplexing.

The next section covers signal formats, explaining carriers and modulation. I give examples of carriers and modulation. The section on analog and digital communications is important in explaining the difference, and in showing how an analog signal can be converted to digital form. It also introduces the difference between optical signals, as a number of photons, and electronic signals, as a voltage or current.

The next section describes the types of connectivity offered by fiber-optic systems, divided loosely into broadcast systems, switched systems, and networked systems. It also introduces switching technologies.

The following section covers communication services in general, emphasizing the telephone network, cable television, and the Internet. It also introduces the concept of convergence, which will be important in the systems section of the book.

The final section outlines the business side of telecommunications, listing a number of different types of carriers and other elements of the industry, and introduces the importance of regulations in telecommunications. The treatment throughout is elementary, but the concepts are critical to further understanding.

Questions to Think About for Chapter 3

1. How does using a higher-frequency carrier affect the amount of information that can be transmitted?

Answer: It increases bandwidth.

2. Why does multiplex transmission of a combined signal cost less than separate transmission of each signal?

Answer: Each multiplex transmitter generally costs more than a single-channel transmitter, but you need fewer of them. Likewise, the transmission medium often costs more, but the cost is not multiplied by as large a number as the capacity.

3. Computer networks, mobile telephones and broadcast systems all distribute signals to many terminals. How do these systems differ?

Answer: Computer terminals and mobile telephones ignore signals that are not addressed to them. Broadcast signals are picked up and decoded by all terminals within range.

4. Why is frequency-division multiplexing equivalent to wavelength-division multiplexing?

Answer: Wavelength and frequency are two different ways of measuring the same property of an electromagnetic wave. Radio engineers usually speak of frequency, while optical engineers usually talk of wavelength. Interestingly, the standard spacing for wavelength-division multiplexing channels is specified in frequency units.

5. The bandwidth of digitized signals measured in bits per second is much higher than the bandwidth of the original analog signal measured in hertz. For example, the analog bandwidth of a phone line is 4000 Hz, but the digitized signal is 64,000 bits per second. Why are these two bandwidths usually equivalent in practice?

Answer: Analog signals must be reproduced much more accurately than digital signals, so an analog transmission line has to carry some higher-frequency harmonics. A digital system doesn't need to reproduce frequencies higher than the bit rate.

6. Why was telephone service considered a natural monopoly?

Answer: It was considered impractical to build multiple telephone networks to serve the same community.

7. Data transmission rates to personal computers have increased from 1200 bits per second with dial-up modems in 1985 to about 400,000 bits per second with a cable modem or DSL in 2000. If bandwidth keeps increasing at the present rate, how fast will transmission be in 2015?

Answer: A linear extrapolation is 133 megabits per second.

Answers to Quiz for Chapter 3

1. b
2. e
3. e

- 4. d
- 5. a
- 6. d
- 7. c
- 8. a
- 9. a
- 10. c
- 11. d
- 12. d

Supplemental Material

Illustrations or maps of communication systems. A good source is **<http://www.cybergeography.org>**

Examples of voice, video, and data communications.

Demonstrate analog-to-digital and digital-to-analog conversion. A blow-up showing the discrete levels in a digital signal would help.

Mention any fiber networks in your facility or nearby that students might know.

Ask students what uses of fiber optics they have seen, both in communications and in other fields. (Note that some endoscopes uses fibers to deliver light which is picked up by a tiny video camera on the end of the device inside the body.)

Chapter 4:

Types of Optical Fibers

This chapter describes how different types of fibers work and how they are used, introducing transmission modes. These topics are among the most important topics for you to cover in lectures. Types of fibers specified by ITU standards are now identified by the standard number as well as by their common descriptions.

Overview

This chapter covers major fiber types largely in the historical order of their development. This largely follows the level of increasing conceptual complexity. I start by describing light guiding in step-index multimode fibers using the traditional model of total internal reflection of optical rays. Then I introduce waveguides and modes, and explain how that model is a more complete description of light guiding than the simpler view of total internal reflection.

The description of modes is targeted at the introductory level, and includes only algebraic equations. I avoid derivations except the few that can be done clearly with simple algebra, an approach I take throughout the book with very few exceptions. This approach gives students what they need to know, without discouraging them with complex equations. I introduce modes to describe single-mode fibers, and move from that to graded-index fibers.

The balance of the chapter covers various types of single-mode fibers, starting with the simplest case, standard step-index single-mode fiber. Then I introduce the concept of chromatic dispersion, and describe the concept of dispersion shifting. That leads into descriptions of the different types of dispersion-shifted fibers. I show a sampling of refractive-index profiles, but do not explain the design of dispersion-shifted fibers, which requires too much math for this level. The final brief section explains polarization in single-mode fibers.

The dispersion problem has shaped fiber design in many ways, so I have interwoven descriptions of dispersion with those of fiber types. The importance of modal dispersion was recognized very early, and the first proposals for fiber-optic communications

envisioned using single-mode fiber. Step-index multimode fiber was never considered useful for communications over any significant distance because of its high modal dispersion. Graded-index multimode fiber was developed to reduce modal dispersion while retaining the advantage of large core diameter; it was used in a few early telephone systems, but now is used mostly in local-area and campus networks spanning no more than a few kilometers. New graded-index fibers allow much higher bandwidth than previously, but remain limited to relatively short distances.

Single-mode fiber is used in most telecommunications networks, including fiber to the premises or home. The most widely used design is "standard" step-index single-mode fiber, specified by the ITU G.652 standard. Dispersion-shifted fibers normally are used only in long systems where dispersion management is required.

Questions to Think About for Chapter 4

1. A step-index multimode fiber has modal dispersion of about 30 ns/km. Using the formula for maximum data rate for a given dispersion, about how far could it transmit a signal at 1 Gbit/s?

Answer: The formula specifies Data Rate = $0.7 / (\text{dispersion})$, a formula for No-Return-to Zero signals. Dispersion in this formula is the characteristic dispersion (per unit length) times the length. Thus

$$\text{Data rate} = \frac{0.7}{(30 \text{ ns/km}) \times \text{Length(km)}}$$

Inverted to calculate the maximum transmission length, this becomes

$$\text{Length(km)} = \frac{0.7}{(30 \times 10^{-9} \text{ s/km}) \times 10^9 \text{ bits/s}} = 0.023$$

Or 23 meters. Thus step-index multimode fiber is like twisted pair copper wires -- it can carry high-speed signals, but not very far.

2. Why doesn't dispersion affect imaging or illumination fibers?

Answer: It doesn't matter because the transmitted signals are not varying with time.

3. Graded-index fiber typically is more expensive than step-index single-mode fiber. Yet it is used to carry Gigabit

Ethernet signals several hundred meters. What advantage does it offer?

Answer: The larger core diameter makes it easier to get light into graded-index fiber, reducing the cost of transmitters and connectors.

4. What are the tradeoffs between effective area and dispersion slope?

Answer: Normally reduced dispersion slope fibers have small effective areas. Reducing dispersion slope reduces the variation of dispersion with wavelength, and makes dispersion easier to compensate for. However, small effective area fibers are more vulnerable to crosstalk because the light is concentrated in a smaller volume, increasing nonlinear effects.

5. Your system has to transmit wavelength-division multiplexed signals at the 1530 to 1620 nm band of erbium-doped fiber amplifiers. What type of fiber is best?

Answer: Non-zero dispersion-shifted fiber. Depending on the details, you can use reduced-dispersion-slope or large-effective area fiber with the same properties.

6. Your cheapskate purchasing department just got a great deal on zero dispersion-shifted fiber. Why can't you use it in the erbium-amplifier system in Question 5?

Answer: Zero dispersion-shifted fiber suffers from strong nonlinear effects at 1550 nm which causes four-wave-mixing crosstalk between channels.