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通信与信息科学教育丛书

Understanding Fiber Optics

Fourth Edition

光纤通信原理、系统与应用

[美] Jeff Hecht 著

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北京 • BEIJING

内 容 简 介

本书主要介绍了光纤通信的基本理论知识及其具体应用。其中包括光纤传输原理和传输特性、数字光纤通信和模拟光纤通信系统、光器件的特性、光纤测试等各方面的内容。本书内容丰富，条理性强。

本书可作为通信工程及其相关专业本科生及研究生的教材，也可作为相关专业人士的参考书。

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本套丛书可作为高等院校通信、计算机、电子信息等专业的高年级本科生、研究生的教材或教学参考书,也适合广大信息产业技术人员参考。

本套丛书所选取的均是国际上通信与信息科学领域具有代表性的经典著作,它们在全世界许多大学被用做教材或教学参考书。其主要特点是具有较强的先进性、实用性和权威性。丛书内容丰富,深入浅出,层次清楚,理论与应用并重,能够较好地引导读者将现代通信信息与信息科学的原理、技术与应用有机结合。我们希望本套丛书能够进一步推动国内高等院校教学与国际接轨,同时满足广大技术人员及时学习通信与信息科学领域中新知识的需求。

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Preface

Fiber optics has come a long way since I wrote the first edition of *Understanding Fiber Optics.* Optical-fiber communications was a radical new technology then, used mostly for high-capacity, long-distance transmission of telephone signals. As I finish the fourth edition, I can look out my office window and see a fiber cable that carries telephone, Internet, and cable-television signals down the street.

Over the years, I have been greatly impressed by the tremendous progress in developing practical fiber-optic equipment. The technology is interesting and elegant, as well as important. I find myself caught up in the advancing field, like a sports writer covering a team blazing its way to a championship. The thrill of technical achievement can be just as tangible to those of us involved with engineering or technology as the thrill of victory is to an athlete.

Although I wrote the first edition mainly for self-study, the book is now used in classroom settings. My goal is to explain principles rather than to detail procedures. When you finish this book you should indeed *understand* fiber optics. You should be able to pick up a trade journal such as *Lightwave* or *Fiberoptic Product News* and understand what you read, just as you should be able to understand the duties of a fiber engineer, a network planner, or a cable installer. You will not be able to do their jobs, but you will be literate in the field. Think of this as Fiber Optics 101, a foundation for your understanding of a growing technology.

To explain the fundamentals of fiber optics, I start with some ideas that may seem basic to some readers. When introducing a relatively new field, it is better to explain too much than too little.

To make concepts accessible, I include drawings to show how things work, limit the mathematics to simple algebra, and step through some sample calculations so you can see how they work. I compare fiber optics with other common technologies and highlight similarities and differences, and I have also organized the book to facilitate cross referencing and review of concepts.

The book is structured to introduce you to basic concepts first, then to dig deeper into fiber hardware and its applications. The chapters are organized as follows:

- The first three chapters present an overview, starting with a general introduction in Chapter 1. Chapter 2 introduces optics, light, and the concept of light guiding. Chapter 3 introduces communication systems and fiber-optic transmission. These chapters assume you have little background in the field, but they are worth reading even if you think your background is adequate.
- Chapters 4 through 8 cover optical fibers, their properties, and how they are assembled into cables. The material is divided into five chapters to make it easier to digest. Chapters 4 through 6 are essential to understanding the fiber concepts found in the rest of the book. Chapter 7 covers special-purpose fibers used in fiber amplifiers, fiber gratings, and a few odd applications such as architectural lighting. Chapter 8 is an overview of cabling.
- Chapters 9 through 12 cover laser and LED light sources, optical transmitters, optical detectors, receivers, optical amplifiers, and electro-optic regenerators. Chapter 12 compares and contrasts the operation of optical amplifiers and electro-optic regenerators.
- Chapters 13 through 16 cover a range of other components used in fiber-optic systems. Chapter 13 covers connectors and splices that join fibers. Chapter 14 covers optical couplers and other passive components used in simple fiber systems. Chapter 15 covers the optics used in wavelength-division multiplexing, which combine and separate signals at different wavelengths sent through the same fiber. Chapter 16 covers optical modulation and optical switching, key components for optical networking.
- Chapter 17 covers the fundamentals of optical and fiber-optic measurements, and describes how optical measurements differ from those of other quantities. Chapter 18 follows, covering fiber-optic test equipment and troubleshooting.
- Chapters 19 through 22 cover principles of fiber-optic communication. Chapter 19 describes the basic principles behind fiber-optic systems and optical networking. Chapter 20 covers major communication standards. Chapter 21 outlines the design of point-to-point single-wavelength systems, with sample calculations, so you can understand how these systems are put together. Chapter 22 extends design concepts, covering wavelength-division multiplexing and the emerging optical network.
- Chapters 23 through 27 cover various aspects of telecommunications, explaining how fiber optics fit into networks used for global and regional telephone and Internet transmission, cable television, and data networks. These chapters focus on different levels and aspects of the global network to keep concepts manageable. Chapter 28 covers special systems that don't fit elsewhere, such as fiber-optic cables for remote control of robotic vehicles, and networks in aircraft and automobiles.

- The final two chapters describe noncommunication applications. Chapter 29 explains the principles and operation of fiber-optic sensors. Chapter 30 covers imaging an illumination with fiber optics.

Most chapters include suggestions for further reading, and a list of resources appears at the back of the book. Links to Web sites are currently being added to my Web site, *http://www.fiberhome.com.* I would welcome any suggestions or comments you might have; please e-mail me at jeff@fiberhome.com or fiber@jeffhecht.com.

The glossary at the back of the book gives you quick translations of specialized terms and acronyms.

This edition also includes appendices that tabulate useful information, such as the values of important physical constants, conversion factors, standard data rates and wavelengths, and a few key formulas.

I have tried to make everything current, but the technology is advancing so fast that some details are bound to become obsolete. When you finish *Understanding Fiber Optics*, you should be prepared to follow the new advances, and perhaps contribute to them as well.

Acknowledgments

Over the years, many people in the fiber-optics industry have given generously of their time to patiently answer my questions. I owe special thanks to Kevin Able, Bill Chang, Erich Dzakler, Jim Hayes, Dennis Horwitz, Jim Masi, Nick Massa, Jim Refi, and Wayne Siddall for reviewing parts of this edition, clearly explaining complex concepts, and pointing me to useful resources. Prentice Hall reviewers Richard J. White, ITT Technical Institute; Stanley M. Krause, St. Philip's College; Kenneth E. Windham, Nash Community College; and Dr. Jalil Moghaddasi, City University of New York Bronx Community College also provided helpful feedback for this edition. David Charlton, Marc Duchesne, Robert Gallawa, Mike Pepper and John Schlager helped with earlier editions. I thank my editors at Prentice Hall, *Laser Focus World,* and *Integrated Communications Design* for patience with me above and beyond the call of duty. I also thank the companies, universities, and individuals who posted papers, application notes, tutorials, standards, and data sheets on the World Wide Web where I could find them when questions arose outside normal working hours. And very special thanks to anyone whose names and contributions may have slipped through my haphazard mental filing systems. Any errors that remain are my own.

This book is dedicated to the memory of Heather Williamson Messenger,
gifted editor, friend, and victim of domestic violence.

Jeff Hecht

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CHAPTER

1

Introduction to Fiber Optics

A Personal View

Light is an old friend that has fascinated me ever since I can remember. As a boy, I bought surplus lenses, prisms, and filters, and used them to play with light; I still have a box of optical toys. In college I studied physics and electronic engineering, but light drew me back, first to lasers and then to fiber optics.

The first optical fibers I saw were in decorative lamps. A bundle of fibers was clamped together at one end and splayed out in a fan at the other. A bulb illuminated the clamped end, and the fibers carried light to the loose ends, where it sparkled like tiny stars. The effect was pretty enough that I bought my sister one as a Christmas present, but useless enough that I wandered away to explore other things.

When I next saw fiber optics, they had improved so much that telephone companies were developing them for communications. Those were the days when phone companies were—with good reason—described as "traditionally conservative" in their use of technology. They probed and tested fiber optics almost as cautiously as a bomb squad investigates a suspicious package. Finally, in 1977, GTE, AT&T, and British Telecom each dared to run live telephone traffic through fiber-optic cables they had pulled through standard underground ducts.

Looking back, the technology they used looks primitive. It was daring then, and it worked. Not only that, it worked flawlessly. The small armies of engineers monitoring those test beds came to countless technical meetings afterward repeating the same monotonous but thrilling conclusion: "It works! Nothing has gone wrong!"

I was at the first fiber-optic trade show in the late 1970s, and have watched the excitement spread since then. Each year the meetings have grown larger. In the early years, breakthroughs were almost routine. The first generation of systems was barely in the ground before a second generation was ready. A third generation followed quickly and, starting in the mid-1980s, became the backbone of the long-distance telephone network. That technology is fading away, and today we're seeing a new revolution in optical networking. State-of-the-art fiber systems can carry billions of bits per second at each of dozens of different wavelengths. Optical devices now switch signals as well as carry them from point to point. The rate of change has varied over the years, but the accomplishments are far beyond what anyone dared dream 20 years ago.

Looking back, it's been an incredible ride. It's a thrill to watch a new technology spring from the laboratory into the real world. Once I heard about fiber optics from research scientists; now I hear about fiber optics from telephone technicians working on the poles down the street. But the fun isn't over yet. The fiber-optics revolution will continue until fiber comes to every home. Today fiber-optic cables run mainly to businesses that need high-speed telecommunications. Fiber goes to only a relative handful of homes today, and it will take time to spread. Yet when it does come, fiber will bring a wealth of new information services, and make today's cable modems and digital subscriber line (DSL) look like yesterday's 1200-bit/second modems. The visionaries who foresaw a wired city were wrong—we will have a fibered society instead. We can all watch it happen.

But that's enough of this visionary stuff. Let's get down to the nuts and bolts—and fiber.

About This Chapter

The idea of communication by light was around long before fiber optics, as were fibers of glass. It took many years for the ideas behind fiber optics to evolve from conventional optics. Even then, people were thinking more of making special optical devices than of optical communications. In this chapter you will see how fiber-optic technology evolved and how it can solve a wide variety of problems in communications.

The Roots of Fiber Optics

Light normally travels in straight lines, but sometimes it is useful to make it go around corners.

Left alone, light will travel in straight lines. Even though lenses can bend light and mirrors can deflect it, light still travels in a straight line between optical devices. This is fine for most purposes. Cameras, binoculars, telescopes, and microscopes wouldn't form images properly if light didn't travel in straight lines.

However, there also are times when people want to look around corners or probe inside places that are not in a straight line from their eyes. Or they may just need to pipe light from place to place, for communicating, viewing, illuminating, or other purposes. That's when they need fiber optics.

Piping Light

The problem arose long before the solution was recognized. In 1881, a Concord, Massachusetts, engineer named William Wheeler patented a scheme for piping light through buildings. Evidently not believing that Thomas Edison's then new incandescent bulb would prove practical, Wheeler planned to use light from a blindingly bright electric arc in the basement to illuminate distant rooms. He devised a set of pipes with reflective linings and diffusing optics to carry light through a building, then diffuse it into other rooms, a concept shown in one of his patent drawings in Figure 1.1.

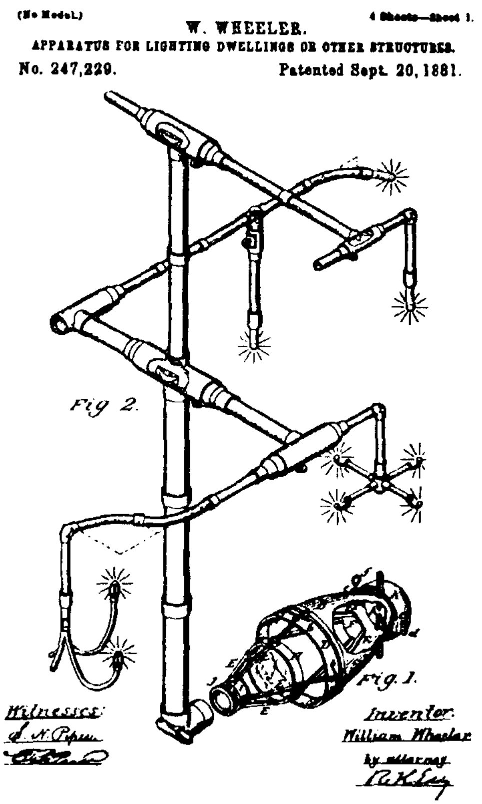


FIGURE 1.1
Wheeler's vision of piping light (U.S. Patent 247,229).

Although he was in his twenties when he received his patent, Wheeler had already helped found a Japanese engineering school. He later founded a successful company that made street lamps, and went on to become a widely known hydraulic engineer. Nevertheless, light piping was not one of his successes. Incandescent bulbs proved so practical that they're still in use today. Even if they hadn't, Wheeler's light pipes probably wouldn't have reflected enough light to do the job. However, the idea of light piping reappeared again and again until it finally coalesced into the optical fiber.

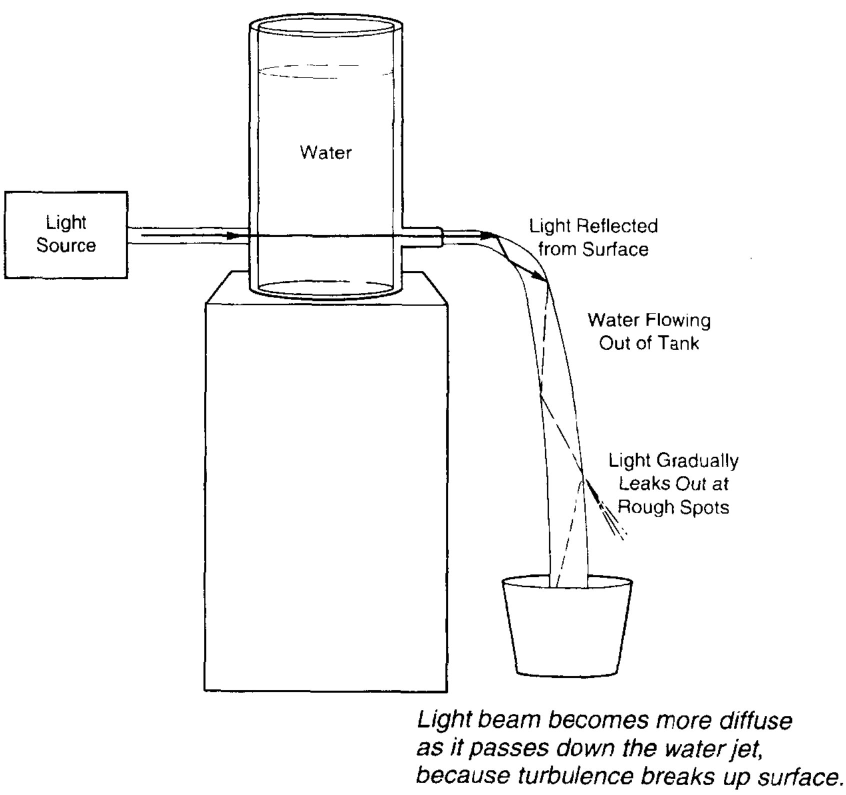
Total Internal Reflection

Ironically, the fundamental concept underlying the optical fiber was known well before Wheeler's time. A phenomenon called *total internal reflection*, described in more detail in Chapter 2, can confine light inside glass or other transparent materials denser than air. If the light in the glass strikes the inside surface at a glancing angle, it cannot pass out of the material and is instead reflected back inside it. Glassblowers probably saw this effect long ago in bent glass rods, but it wasn't widely recognized until 1841, when Swiss physicist Daniel Colladon used it in his popular lectures on science.

Colladon's trick, shown in Figure 1.2, worked like this. He shone a bright light down a horizontal pipe leading out of a tank of water. When he turned the water on, the liquid flowed out, with the pull of gravity forming a parabolic arc. The light was trapped within the water by total internal reflection, first bouncing off the top surface of the jet, then off the lower surface, until the turbulence in the water broke up the beam.

The Paris Opera used Colladon's light jet as a special effect in 1853 during performances of a ballet and of Gounod's opera *Faust*. The great Victorian exhibitions of the 1880s borrowed the idea to make illuminated fountains that fascinated fair-goers. But curving water jets had few practical uses. Light inevitably leaked out as the surface of the flowing water grew rough.

FIGURE 1.2
Light guided down a water jet.



Glass Light Guides and Imaging

Clear glass rods could also guide light. By the early 1900s, they were being used to illuminate microscope slides. Inventors patented schemes for guiding light through bent glass rods to illuminate the inside of the mouth for dentistry. It was better than sticking a gas lamp in the patient's mouth, but it was far from perfect, and was never widely used.

A fine glass fiber is really a very thin rod, so it can guide light in the same way. Glass fibers also are flexible. Assemble a bundle of them, and they can transmit an image from one end to the other, as you will learn in Chapter 30. Clarence W. Hansell, an American electrical engineer and prolific inventor, patented the concept in the late 1920s. Heinrich Lamm, a German medical student, made the first image-transmitting bundle in 1930. However, the images were faint and hazy.

The key development in making optical fibers usable was perfecting a cladding to keep the light from leaking out.

Lamm had to comb the fibers to align them, but he didn't recognize a more important problem. When many bare fibers are bundled together, their surfaces touch, so light can leak from one into the other. The fibers also can scratch each other, and light leaks out at the scratches. Light even leaks out where fingerprint oils cling to the glass. The same problem plagued three men who independently reinvented imaging bundles in the early 1950s: a Danish engineer and inventor, Holger Møller Hansen, and two eminent professors of optics, Abraham van Heel in the Netherlands and Harold H. Hopkins in England.

The solution to that problem seems painfully obvious with 20/20 hindsight. Everyone started by looking at total internal reflection at the boundary between glass and air. However, total internal reflection can occur at any surface where light tries to go from a material with a high refractive index to one with a lower refractive index. Air is convenient, and its refractive index of 1.000293 is much lower than that of ordinary glass, which is 1.5. But total internal reflection occurs as long as the material covering the glass has a refractive index smaller than the glass, as shown in Figure 1.3. Møller Hansen produced total internal reflection by coating glass fibers with margarine, but the results were impractically messy.

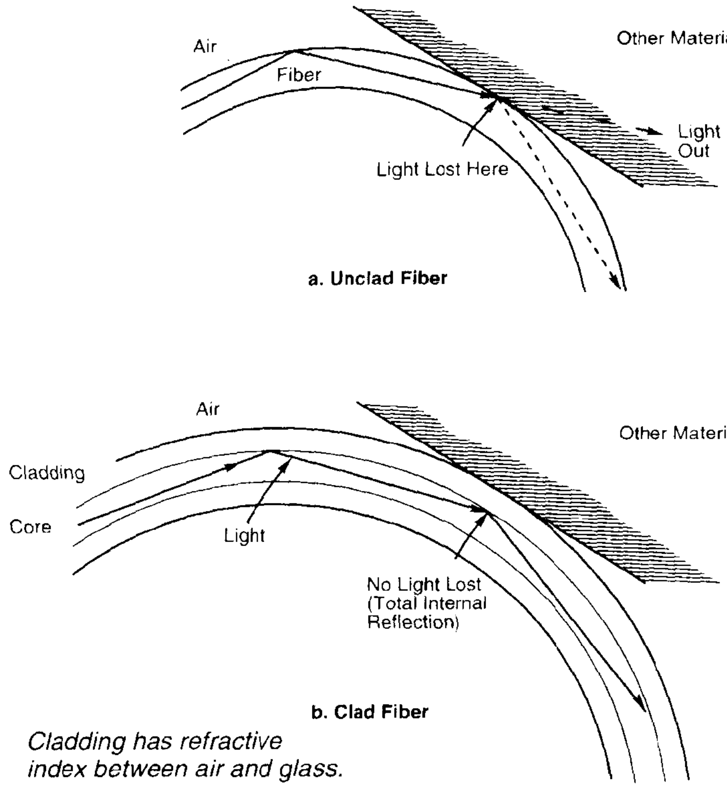
Brian O'Brien, a noted American optical physicist, separately suggested the cladding to van Heel in 1951. Van Heel used beeswax and plastic, which were more practical than margarine. In December 1956, Larry Curtiss, an undergraduate student at the University of Michigan, made the first good glass-clad fibers by melting a tube of low-index glass onto a rod of high-index glass. Glass cladding soon became standard, although a few fibers continue to be plastic-clad, and plastic is used to *coat* fibers to protect them mechanically.

Glass-clad fibers were the key to making flexible fiber-optic *endoscopes* or *gastroscopes* to look down the throat into the stomach. The fibers are glued in place on each end, but left loose in the middle, forming a flexible bundle that can be bent to follow the natural curves of the throat. Flexible fibers bundles are inserted in the opposite end of the body to examine the colon. The fiber-optic endoscope has become an important medical tool, although some instruments now combine fibers with miniature electronic cameras.

Many optical fibers can be bundled together to transmit images.

Other imaging applications soon emerged for bundles of optical fibers. Fibers can be melted together and drawn to be extremely fine light guides in rigid bundles. Flexible fiber bundles can "pipe" light for illumination into hard-to-reach spots. A whole industry grew

FIGURE 1.3
Light cannot leak out of clad fibers.



around fiber-optic imaging and light-piping in the 1960s. The technology remains in use, and is covered in Chapter 30, but has largely been eclipsed by fiber-optic communications.

Fibers in Communications

An optical telegraph was invented in France in the 1790s but made obsolete by the electric telegraph.

The idea of communicating by light probably goes back to signal fires on prehistoric hilltops. The ancient Greeks relayed news of the fall of Troy by signal fires; Native Americans used smoke signals. Even the first "telegraph" was an optical one, invented by French engineer Claude Chappe in the 1790s. Operators relayed signals from one hilltop telegraph tower to the next by moving semaphore arms. Samuel Morse's electric telegraph put the optical telegraph out of business, but it left behind countless Telegraph Hills.

In 1880, a young scientist who had already earned an international reputation used beams of light to transmit voices in the first wireless telephone. Alexander Graham Bell had invented the telephone four years earlier, but he considered the photophone his greatest invention. It reproduced voices by detecting variations in the amount of sunlight or artificial light focused through the open air onto a receiver. Bell was elated to hear beams of light laugh and sing, but the Photophone never proved practical in cities, where too many things could get in the way of the light. Wires and radio waves proved more practical for communications.

A few people kept experimenting with optical communications. In the 1930s, an engineer named Norman R. French—who worked for the American Telephone & Telegraph Corp. built around Bell's telephone—patented the idea of communicating by sending light through pipes. But few people took optical communications seriously until Theodore Maiman demonstrated the first laser in 1960.

Invention of the laser stimulated interest in optical communications and led to efforts to reduce light loss in fibers, which was essential for communications.

The laser generates a tightly focused beam of coherent light at a single pure wavelength. It's the optical equivalent of the pure carrier-frequency signal used by a radio or television station. That made it look very promising for communications, and many laboratories started experimenting. They first tried sending laser beams through air, but like Bell soon found that open air was not a very good transmission medium because fog, rain, snow, and haze could block signals. They tried sending light through more modern versions of Wheeler's light pipes and found other troubles.

Optical fibers were available, but they didn't look very promising. The fibers used in endoscopes are much clearer than window glass, but half the light that enters them is lost after 3 meters (10 feet). That's fine for examining the stomach, but not for communications. Go through a mere 20 meters (66 feet) of such fiber, and only 1% of the light remains. Go another 20 meters, and only 1% of that light remains—0.01% of the input. Convinced that transparent solids inevitably absorbed too much light for optical communications, most engineers either gave up or tried to develop new versions of hollow light pipes or better ways to send light through the air.

Two young engineers at Standard Telecommunication Laboratories in England, Charles K. Kao and George Hockham, took a different approach. Instead of asking how clear the best fiber was, Kao asked what the fundamental limit on loss in glass was. He and Hockham concluded that the loss was caused mostly by impurities, not by the glass itself. In 1966, they predicted that highly purified glass should be so clear that 10% of the light would remain after passing through at least 500 meters (1600 feet) of fiber. Their prediction sounded fantastic to many people then, but it proved too conservative.

Publication of Kao and Hockham's paper set off a worldwide race to make better fibers. The first to beat the theoretical prediction were Robert Maurer, Donald Keck, and Peter Schultz at the Corning Glass Works (now Corning Inc.) in 1970. Others soon followed, and losses were pushed down to even lower levels. In today's best optical fibers, 10% of the entering light remains after the light has passed through more than 50 kilometers (30 miles) of fiber. Losses are not quite that low in practical telecommunication systems, but as you will see in Chapter 5, impressive progress has been made. Because of that progress, fiber optics have become the backbones of long-distance telephone networks around the world.

Basic Fiber Concepts

The rest of this book will teach you the details of how fiber optics work and how they are used, particularly in communications. The rest of this chapter is a starting point, to give you a quick snapshot of what's involved in fiber-optic technology. Chapters 2 and 3 go into a bit more depth to lay the foundation for the rest of the book. Their goal is