CHAPTER

1

An Introduction to Fiber Optics

About This Chapter

This chapter is a starting point to look around and see where you're going before you dig into details. The goal is to put fiber optics and communications into context and show how they go together. I start with a personal commentary about the turbulent times of the past several years, then explain the plan for this book. A brief history of fiber optics follows, which introduces some important concepts. Then a brief history of communications explains the need for bandwidth and how fiber optics filled that need, perhaps too well. Finally, I explain some of the terminology of the field to help you in your looking about.

A Personal View: Ups and Downs

Fiber optics has come a long way in the nearly three decades I've been watching its development. For many years the field grew steadily, with new technology creating new applications, and new applications, in turn, supplying money to develop more new technology. The growth sped out of control in the late 1990s as the Internet fed a seemingly limitless thirst for bandwidth that only optical fibers could provide. The boom turned into a bubble, and the bubble into a bust as I watched in amazement.

Fiber revolutionized telecommunications by supplying tremendous bandwidth.

We knew the bubble was too good to be true, but none of us wanted it to end. We told ourselves that the communications industry was in better shape than the dot-coms because it had real hardware, not just web sites. Then the industry ran right off a cliff and landed with an ugly splat. We traded grim jokes, noting that we would have done better to invest in cases of beer and return the empties in a state with a bottle-deposit law. Employment dropped nearly as badly. The industry seemed a vast, smoking crater.

Fiber-optic technology remains healthy.

That depressing view is as much of an exaggeration as was the euphoric overenthusiasm of the bubble. We'll never see that manic growth again, and that's just as well. But fiber-optic technology remains healthy, with advances continuing at a more sober rate. Fiber optics has become the backbone of the global telecommunications network, giving us instant access to Web sites and telephones around the world. That network continues to reach toward homes and businesses. Cable television companies, telephone companies, Internet providers, and power companies have their own fiber-optic networks. When you use a cell phone, your calls usually go wireless only to the tower, where a fiber-optic cable runs to the backbone telephone network. The demand for bandwidth continues to rise, although there's a lot of surplus fiber in the ground right now.

Fiber revolutionized telecommunications in the twentieth century, just as the railroads revolutionized transportation in the nineteenth century. Overbuilding of railroads caused spectacular busts in the latter half of the nineteenth century, but railroads remained the backbone of the national transportation network until the spread of the interstate highway system in the 1950s and 1960s. Railroads still carry people and freight today—especially in Europe.

The fiber-optic gold rush is over, and the field has had a roller-coaster ride of dramatic ups and downs. We've gained some experience and a few gray hairs in the process, but we've survived. Fiber has carved itself a vital niche in the communications world and will play a growing role around the world as other countries expand their own communications networks. Fiber is here to stay.

The Roots of Fiber Optics

Fiber optics did not begin as a communications technology. Optical fibers evolved from devices developed to guide light for illumination or displays, and were first used to look inside the human body. Bundles of optical fibers are still used to examine the stomach and the colon because they can reach into otherwise inaccessible areas. It's worth looking at how this idea began—it will teach you the basic ideas of light guiding in a fiber.

Piping Light

Light normally goes in straight lines, but sometimes we want it to go around corners.

Think of optical fibers as pipes that carry light. Lenses can bend light and mirrors can deflect it, but otherwise light travels in straight lines. The working of optical devices, from our eyes to giant telescopes and sensitive microscopes, depends on light going in straight lines. Yet sometimes it is nice to be able to pipe light around corners and look into inaccessible places. The first steps in that direction were taken in the nineteenth century.

In 1880, William Wheeler, a young engineer from Concord, Massachusetts, filed for a patent on a way to pipe light through buildings. Thomas Edison had already made the first incandescent light bulbs but hadn't gotten all the bugs out. Wheeler wanted to distribute light from an electric arc, a light source that was better developed at the time, but was blindingly bright. He planned to put arc lamps in the basements of buildings and

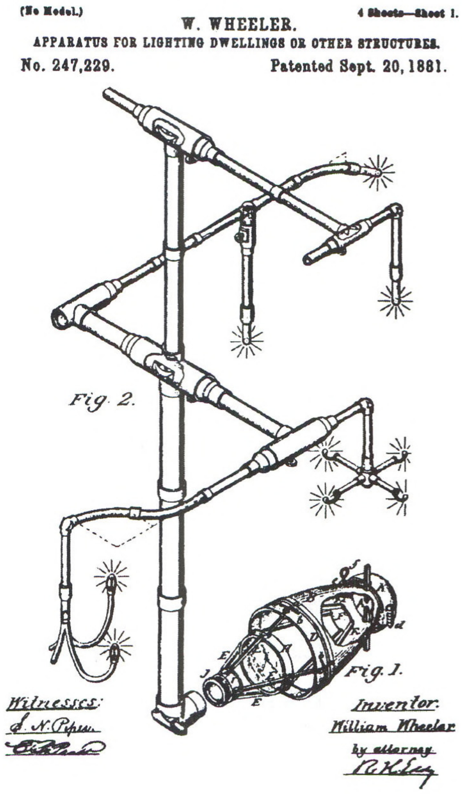


FIGURE 1.1
Wheeler's plan for piping light into rooms (U.S. Patent 247,229).

distribute the light to distant rooms through a set of pipes coated with a reflective layer inside, as shown in Figure 1.1. Diffusers at the ends of the pipes would spread the light out inside each room.

Wheeler was a solid engineer who became an expert in designing water works. He later founded a successful company that made reflectors for street lamps. His design was logical at the time since air seemed to be a much clearer medium than any known solid. But his light pipes never caught on, and Edison's incandescent bulbs eventually worked much better than arc lamps.

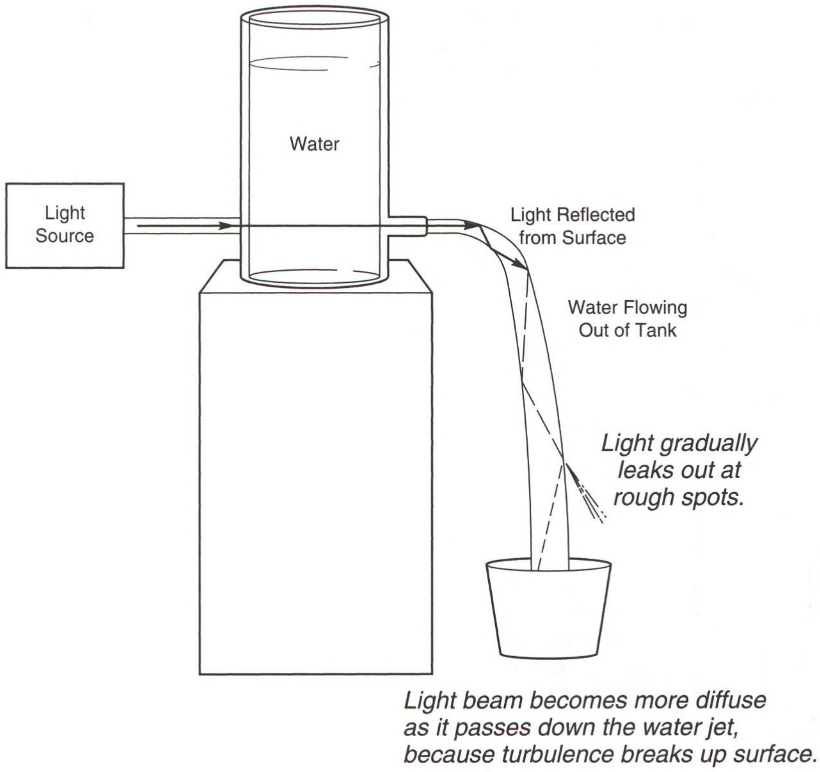
Total Internal Reflection

Even before Wheeler's time, scientists knew how to trap light inside a solid. A phenomenon called *total internal reflection*, described in Chapter 2, can confine light inside glass or other transparent materials. This phenomenon involves sending light through the material in such a way that it strikes the surface exposed to air at a glancing angle. Then the light is reflected back into the solid. You can see the effect in diamond or cut glass, in which one surface acts like a mirror to reflect light to your eye.

Total internal reflection can guide light along a glass rod or water jet.

Glassblowers may have been the first to realize this effect could guide light along a bent glass rod, but it wasn't widely recognized until 1841 when a Swiss physicist, Daniel Colladon,

FIGURE 1.2
Light guided down a water jet.



adapted the trick for a jet of flowing water in his popular science lectures. Figure 1.2 shows how he directed a bright light down a horizontal pipe leading out of a tank of water. When he opened the spout, water flowed out in a jet and the pull of gravity bent the water jet into a parabolic arc. Total internal reflection trapped the light inside the water jet. The light beam bounced off the top surface, then off the lower surface, until turbulence in the flowing water broke up the beam.

Others borrowed the idea for their own demonstrations. The Paris Opera used it on stage in 1853. The great Victorian exhibitions of the 1880s adapted the idea to make illuminated fountains that fascinated fairgoers who hadn't seen bright artificial lights. But the water jet remained essentially a parlor trick of little practical use.

Glass Light Guides and Imaging

An optical fiber guides light like a very thin glass rod.

Inventors soon adapted the idea of guiding light to more practical purposes. By the early 1900s, they had patented a scheme for guiding light through a bent glass rod to illuminate the inside of the mouth for dentistry. This technique was much better than sticking a gas lamp into a patient's mouth, but it was far from perfect. Illuminated tongue depressors followed.

A fine glass fiber is actually a very thin, flexible rod, so it can guide light in the same way. Assemble glass fibers into a *bundle*, and they can carry 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, was the first to take this logical step and patented the idea in the late 1920s. Hansell thought the bundles could be used for inspecting out-of-the-way places, for medical applications, or even for a facsimile machine.

Heinrich Lamm, a German medical student, made the first image-transmitting bundle in 1930 and was able to photograph the bright filament of a lamp. He combed the fibers to align them, but the bundle didn't work well because it consisted of bare fibers, in which total internal reflection was at the surface exposed to the air. Light can easily leak through that surface if anything touches or scratches it, and the fibers inevitably touched and scratched each other in Lamm's bundle. Light even leaked out at places where fingerprint oil was smudged on the surface.

Neither Hansell nor Lamm got very far. The same problems bedeviled other men who independently invented fiber bundles for imaging in the early 1950s. These men were a Danish inventor, Holger Møller Hansen, two eminent optics professors, Abraham van Heel and Harold H. Hopkins, and Hopkins' student, Narinder Kapany.

Solving the problem required a fresh look at the requirements for total internal reflection. We normally think of it as occurring where light is unable to enter the air, but what really matters is a quantity called the *refractive index*, which you'll learn about in Chapter 2. Total internal reflection can happen when light travelling in one medium tries to enter another medium with a lower refractive index. Air has a much lower refractive index than glass, but the difference does not have to be large. Oils, beeswax, and many plastics have refractive indexes that are higher than air but lower than glass. Coat the glass fiber with one of those materials, and total internal reflection can still occur, but the surface is protected from scratches, fingerprints, and leakage of light into other glass fibers, as shown in Figure 1.3.

Clad fibers were the key development in making fiber-optic imaging practical.

Møller Hansen tried coating a fiber with margarine, but the results were impractically messy. Brian O'Brien, a noted American optical physicist, suggested the idea to van Heel, who coated his fibers with plastic and beeswax, which were more practical. In December 1956, Larry Curtiss, an undergraduate student at the University of Michigan, slipped a rod of glass with high refractive index into a tube of glass with lower index and made the first glass-clad fiber.

The technology has been refined considerably since then, but glass-clad fiber remains the most common type. Fiber bundles were the key to making flexible endoscopes, gastroscopes, and colonoscopes to examine the throat, stomach, and colon. Other imaging applications soon emerged, as described in Chapter 30. Fiber bundles are also used for illumination; however, this technology has been largely eclipsed by fiber-optic communications.

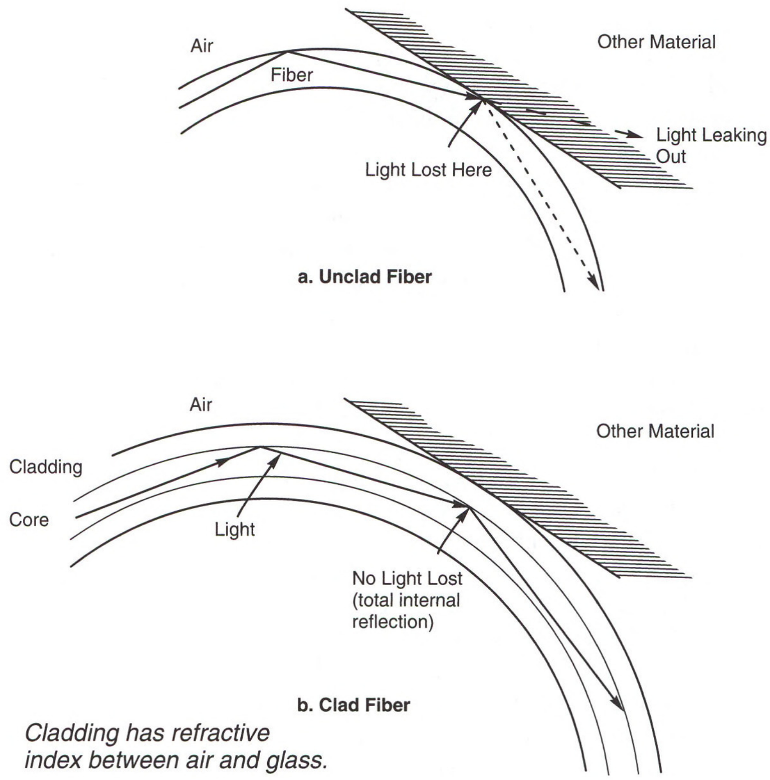
The first practical application of fiber optics was gastroscopy.

Optical Communications

Optical fibers aren't necessary for optical communications. People have communicated using light since ancient times. The ancient Greeks lit signal fires on hilltops to relay news of the fall of Troy. 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."

An optical telegraph was invented in the 1790s in France.

FIGURE 1.3
Light cannot leak out of clad fibers if they touch another surface.



After inventing the telephone, Alexander Graham Bell turned to sending voices through the air on beams of light, demonstrating his "photophone" in 1880. Bell was elated and considered it his greatest invention. The photophone, however, never proved practical, and radio waves eventually provided the means for wireless communications. Other attempts at optical communications followed, but few people took them seriously until Theodore Maiman made the first laser in 1960.

Invention of the laser stimulated interest in optical communications.

The laser generates a tight beam of coherent light at a single pure wavelength. It's the optical equivalent of the pure carrier frequency that is modulated with a radio or television signal. Its coherence made it very attractive for optical communications, and within a few months Bell Laboratories had made their own laser and used it to send light pulses between two towers 25 miles apart. However, other experiments soon showed that fog, rain, snow, and haze could block signals. Bell Labs tried sending laser beams through hollow light pipes, but they didn't work well either.

Optical fibers were available at this time, but they couldn't send light very far. The clearest fibers used for medical endoscopes lost half of the light they carried after three meters (10 feet). Go 30 meters (100 feet) and just 0.1% of the light remains. That loss was acceptable for examining the stomach through several feet of fiber, but it made optical fiber useless for communications.

Charles Kao and George Hockham proposed fiber-optic communications.

Two young engineers at Standard Telecommunications Laboratories in England, Charles K. Kao and George Hockham, took a different approach. Instead of asking how clear was the best fiber, Kao asked what was the fundamental lower limit on the loss of glass. He and Hockham found that most of the loss in the glass was caused by impurities, not by the glass itself. In 1966, they predicted that a fiber made of highly purified glass would be so clear that 10% of the light entering it would remain after 500 meters (1600 feet). This level of purity sounded unattainable, but a few laboratories around the world tackled the problem.

Kao and Hockham turned out to be too conservative and Robert Maurer, Donald Keck, and Peter Schultz of the Corning Glass Works beat their prediction in 1970. Two years later they had fibers in which 10% of the light remained after 2.5 kilometers (8000 feet). Better fibers followed and in today's best optical fibers 10% of the light remains after passing through 50 kilometers (30 miles) of fiber. That exceptionally low loss lets fibers carry signals much further than copper wires.

Other Fiber Properties

Long-distance transmission isn't the only thing that matters in communications. It's also important to be able to carry a lot of information, which in the communications world is called *bandwidth*. The more bandwidth, the more information a signal can carry. For reasons we'll explore later, optical signals inherently have a very high bandwidth, which is why the laser first interested communications engineers. Equally important, optical fibers can transmit those signals without seriously limiting their bandwidth. That's not true for copper wires. Electronic devices can generate signals at high frequencies, carrying lots of information, but copper cables tend to attenuate those essential high frequencies, so the signals can't go far.

Optical fibers have very high bandwidth.

Telecommunications fibers are made of glass, but they're not as fragile as they sound. Glass is inherently a strong material as long as it's not cracked, but it is brittle in bulk. Communication fibers, however, are flexible because they're relatively thin. Optical fibers are often compared to a human hair. The sizes are close, but fibers are stiffer. On a microscopic scale, a well-made optical fiber is also much smoother than a human hair.

Glass fibers are inherently strong, allowing their use in outdoor cables.

The cross-section of a typical communications fiber is shown in Figure 1.4. The glass fiber itself is 125 micrometers (0.005 inch) thick, with the light-guiding core a central

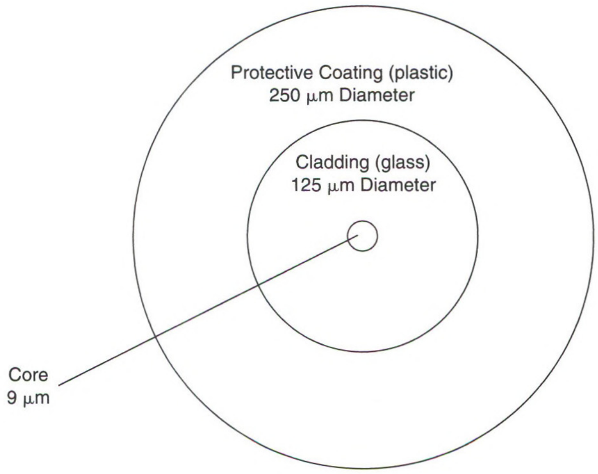


FIGURE 1.4 *Cross-section of a typical communications fiber.*

region about 9 μm in diameter. A plastic *coating* covers the entire fiber, bringing its overall size to 250 μm, or 0.25 mm (about 0.01 inch). These dimensions, like those of other fiber-optic components, are usually given in metric units. The plastic layer protects the fiber surface from scratches and microcracks that could cause it to break. The result is a fiber that's much stronger than you would expect. It's very hard to snap a fiber with your hands, although you can break one if you trip on it while wearing heavy shoes. Communications fiber works perfectly well in cables used in harsh outdoor environments.

Fibers designed for other purposes have different properties, as you will learn in Chapters 4 through 7.

The Very Basics of Communications

The basic idea of communications is very simple: to transmit information from one point to another. Both the technology and the business of communications are much more complicated, and you should understand a bit about both before you dig deeper into this book. Chapter 3 will give you a more formal introduction to communications, but here you will get some idea of how communications in general, and fiber communications in particular, really work.

Communications Technology

Telecommunications means communications over a distance.

The word "communications" is used in many different ways. We say we are trying to "communicate" with someone when we convey a message in words. Colleges have "communications" departments that focus on writing and broadcasting, not engineering. Here we're talking about *telecommunications*, which means communications over a distance by means of radio waves, electrical signals, or optical signals.

Today's telecommunications are based on electronic technology. Electronic devices generate and process signals. When you talk on the telephone, circuits in the phone convert your voice to electrical signals. If you're talking on a corded phone, those electrical signals pass along wires into the phone company's network. If you're talking on a cell phone, the phone converts its electrical signals into radio signals and transmits them to a tower, which sends them to the telephone network through wires, optical fibers, or radio links. The Internet and cable television systems work similarly. The networks are vast and complex. You'll learn more about basic concepts in Chapter 3 and learn some details in Chapters 23 through 27.

The optics in a fiber-optic network have to talk with the electronics. The basic idea is shown in Figure 1.5. The input signal drives a light source, modulating its intensity. If the input signal is a series of bits, it turns the light source off and on. In practice, the light source is part of an optical transmitter. The optical transmitter contains electronic circuits that process the signal so it drives the light source properly, but we won't worry about those details now. The light then leaves the source and enters an optical fiber, which carries it to a receiver. The receiver converts the light back to electronic form to drive devices on the other end. We'll cover the details later. This simple example shows transmission between a pair of points. A system that performs that job is often called a *link* between the points. A link that carries digital data is called a *data link*.

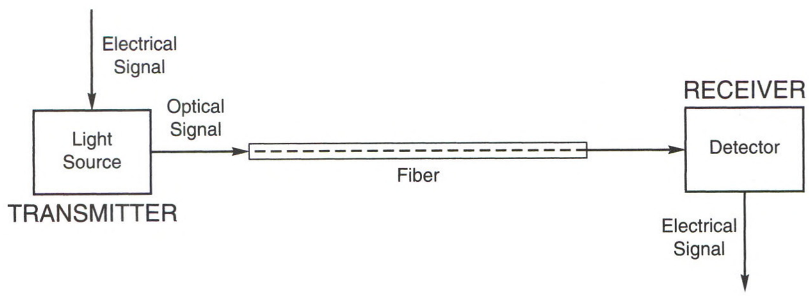


FIGURE 1.5
Elements of a simple fiber-optic system.

The telecommunications network is considerably more complex and uses different technologies at different levels. Like a network of roads or streams, the telecommunications network starts out small and packs more traffic onto main arteries. Fiber optics are the backbone of these networks, the superhighways that carry the heaviest traffic along the busiest routes. Today, fiber-optic links reach into virtually every community in the United States, although they carry different amounts of traffic. Wireless transmission over radio or microwaves is used for some links, largely for mobile phones and broadcasting from ground antennas or satellites. Plain copper wires and coaxial cables are used for other links. Both copper and wireless usually carry less traffic than fibers.

The basic functions of the telecommunications network are to transmit and distribute information. Think of these two functions as being performed by pipes and switches, as shown in Figure 1.6. The pipes carry information from its source to its destination. The switches direct the information through the proper pipes. The principles are the same whatever the network is, and in some cases, such as broadcast television, there isn't much

The telecommunications network distributes and transmits information.

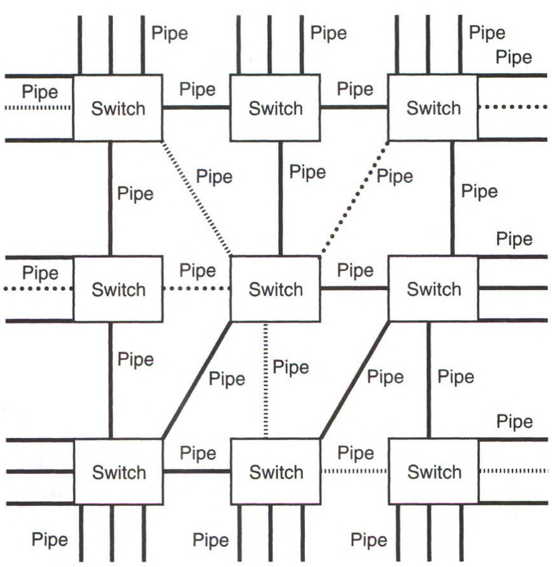


FIGURE 1.6
A communications system consists of pipes that transmit signals and switches that direct them to their destinations.

switching involved. The same signals go through one big pipe—radio waves transmitted through the air—to everybody.

The pipes are called *transmission media* and include optical fibers, copper wires, satellites, and broadcasts through the atmosphere. The switches direct the signals through particular pipes. As you'll learn later, different networks use different types of switches (often special-purpose computers). Most switches are electronic, but some optical switches have been developed. This book is about fiber optics, so it concentrates mainly on optical systems, although it does describe some electronics.

The Business of Telecommunications

Telecommunications is a big business with billions of dollars at stake. It used to be a quiet, orderly business run by government agencies or private monopolies that had to comply with detailed sets of rules and regulations. The rules divided their turf. The telephone monopoly couldn't carry video signals, and the cable television monopoly couldn't carry telephone signals. Then governments began to change the rules, new technology arrived on the scene, new competitors appeared, and the picture became very complicated.

Major costs are capital expense and operating expense.

Most telecommunications systems today are operated by businesses that make money from charging customers for their services. Their expenses fall into the usual business categories such as providing service, sales, marketing, and overhead. The most important costs in running a network are *operating expense* or "opex" and *capital expense* or "capex." Operating expense covers day-to-day operations, the salaries of equipment operators, technicians and managers, maintenance, and repairs. Some work is done on company sites; other work is done elsewhere and requires sending a technician to a remote site (a "truck roll" in industry jargon). Capital expense is buying and installing new equipment. Network operators can trade one expense off against the other, investing capital expense in an expensive new automated system that automatically performs functions to reduce operating expenses. Government agencies that provide communications services to the public handle their expenses in a similar manner, but they aren't expected to make a profit.

Communications companies decide what equipment to use by estimating how much it will cost and what new revenue it will bring in, and balancing these considerations against other budgetary priorities. The decision process can get quite complex, and installation costs can play a big role. Companies have to pay for rights of way, and construction in downtown urban areas can be extremely expensive. Some of the earliest fiber-optic systems were installed because the small cables fit much better into crowded underground ducts in big cities than did thicker copper cables. The fiber-optic equipment cost more, but the overall project cost less because it didn't require new construction.

Wavelength-division multiplexing sends signals at different wavelengths through one fiber.

The major advantage of fiber has always been its ability to transmit signals at higher speeds and over longer distances than other transmission media. The demand for bandwidth has increased with the steady growth in telephone and video traffic, and the explosive growth in data traffic over the Internet. Engineers steadily increased the volume of data that fiber systems could transmit. The most explosive growth came in the past decade, as a new technique called *wavelength-division multiplexing (WDM)* made it possible to transmit separate signals through the same fiber at many wavelengths. WDM multiplies the capacity of individual fibers. The idea is similar to transmitting signals through the air at many separate radio frequencies, which allows many radio and television stations to transmit simultaneously to homes. Developers also began talking about *optical networking*, in which signals would be routed around the country optically without being converted into electronic form.

Eventually investment in fiber optics got out of hand, creating an economic "perfect storm," which survivors call "the bubble."

Understanding the Bubble

The rapid growth of the Internet and the proliferation of dot-com companies started pumping up the bubble in the late 1990s. A number of factors magnified its impact on the telecommunications industry.

For decades, the conventional wisdom of telecommunications engineers had been that you can't have enough bandwidth. Networks are designed around the assumption that everyone is not on the phone at the same time. The long-distance network can't handle all the country's phone lines at once, which is why you sometimes can't get a long-distance line on Mother's Day. As Internet demand started rising, telecommunications carriers installed more fiber to handle the demand. Extra fibers are cheap compared to construction projects, so the carriers added lots of fibers to make sure they had extra capacity in the future. They also planned on using wavelength-division multiplexing to multiply the capacity of every fiber. Nobody thought that they could ever have too much bandwidth.

Bandwidth was traditionally scarce in telecommunications.

But nobody fully grasped how fast the Internet was growing. For a brief period around 1996, Internet traffic seemed to be doubling every three months. Worldcom kept quoting that number for years until it became an Internet myth, widely believed although its origins were dubious. Telecommunications carriers looked at that tremendous growth rate and decided they'd need more fibers to handle the projected traffic. They didn't know that in reality Internet traffic was doubling only once every year, a fact hard to ascertain because the traffic was divided among many different carriers.

A gold rush started in technology stocks, focusing on the Internet, as new companies reported fast growth in sales. In reality, many of the numbers were fudged, and others looked deceptively large because they were starting from zero. Market analysts made wild projections of fantastic growth. A few people made fortunes selling promising new companies. Even when the first dot-coms began to fail, telecommunications looked good compared to selling dog food on the Internet, as I heard leading market analyst John Ryan say at a conference.

Venture capitalists kept pumping money into the optical industry. New companies popped up from nowhere. Some had solid ideas, but others seemed to have little more than fancy trade-show booths and a pitch to investors. Yet their valuations kept rising with the growth of the bubble. It was tempting to believe that this growth was real and everyone would get rich.

It wasn't. No one had realized how much market projections or corporate profits had been inflated by wishful thinking and fraud. When the collapse came, it was disastrous. Companies either folded or shrank to shadows of their former selves. Many fibers installed

The bubble badly hurt telecommunications and fiber optics.

THINGS TO THINK ABOUT

The Problem of the Bubble

The bubble created a tremendous amount of paper wealth that largely evaporated in its aftermath and left the telecommunications industry in shambles. Fortunes were made by a few people who sold stock near the peak; many more saw their holdings shrink.

The development of new technology requires investment, and the bubble distorted the entire pattern of investment. Cumulative losses are estimated to be in the hundreds of billions of dollars. Allegations of fraud abound, going far beyond the handful of criminal charges filed and regulatory actions taken. Both crooks and fools played roles, but we may never know which was more important, nor how we can avoid future bubbles.

The historical parallels with the rise of the railroads during the nineteenth century are striking. You might find it illuminating to read some of the excellent books that chronicle the age of robber barons and the lives of railroad tycoons such as Cornelius Vanderbilt, James J. Hill, Jay Gould, and Jim Fisk.

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during the bubble remain unused. The industry is still nursing a massive hangover. Troubling questions remain about how telecommunications carriers can make a profit when the price of bandwidth keeps dropping.

Yet telecommunications remains a viable product, and the demand continues to grow. Fiber-optic technology is needed to meet that demand, and to help reduce costs so carriers can make a profit. Unused fibers are likely to be lit in the future as the demand for bandwidth continues to increase. That's why it's important to learn about fiber optics.

Fiber Terms: Terminology and Units

The appendixes include a glossary, tables listing important units, and other useful data. Many terms are standardized or widely accepted, but others are not. The communications industry is notorious for its many cryptic acronyms and sometimes puzzling buzzwords. I have tried to avoid unclear terms and all but the most widely accepted acronyms. I do use some designations set by international standards organizations, such as types of optical fiber specified by the International Telecommunications Union (ITU), because these labels have specific meanings and are widely used in the industry. Terms are explained the first time they appear. The terminology will continue to evolve as the field grows and changes.

I try to avoid proprietary terms. Many companies develop their own terminology, and different companies often have different names for the same technology. I do use a few trade names or trademarked terms that are widely used or are descriptive; they are capitalized as proper names to reflect their status.

Every writer has their own terminological preferences. I particularly despise meaningless market-speak, such as calling a product or system a "solution," because it tells nothing about what the thing is. I also prefer to spell out whole words rather than resort to acronyms. The latter conviction comes from reading too many specialized magazines that don't communicate clearly to readers who are not experts in the field. The acronyms I do use are well accepted.

In this introductory chapter, I have used both metric and Imperial units to help you get started. In the rest of the book I give virtually all measurements only in the metric units that are used throughout the telecommunications industry. You should get used to those units. Standard dimensions for most devices—starting with the fiber itself—are quoted in metric units. The American fiber industry uses Imperial units in only a few cases, usually for the lengths of cable runs. Appendix A lists the common metric prefixes for units.

Fiber-optic measurements are metric.

Because this book is published in the United States, it uses standard American spelling such as "meter" and "fiber" with few exceptions. The only important exception is in the "Fibre channel" set of standards for data transmission.

What Have You Learned?

1. Fiber optics has revolutionized telecommunications by supplying tremendous bandwidth, which previously was in short supply.
2. Fiber-optic technology remains healthy, but the business has suffered problems.
3. Light normally goes in straight lines, but optical fibers can guide it around corners.
4. Total internal reflection can guide light along a glass rod or water jet. An optical fiber guides light in a manner similar to a very thin glass rod.
5. Clad fibers were crucial in making fiber-optic imaging practical for examining the stomach and colon. The first practical application of fiber optics was gastroscopy.
6. An optical telegraph was invented in the 1790s in France. It was replaced by the electrical telegraph.
7. Optical fibers have very high bandwidth and can transmit signals farther than copper wires.
8. Glass fibers are inherently strong, allowing their use in outdoor cables.
9. Telecommunications means communications over a distance.
10. The telecommunications network is made of "pipes" and "switches" that distribute and transmit information.
11. Wavelength-division multiplexing transmits multiple signals through one fiber at different wavelengths.
12. The telecommunications bubble seriously disrupted the fiber-optics industry.
13. Fiber-optic measurements are made in metric units, although American companies often measure cable lengths in Imperial units (feet or miles).

What's Next?

In Chapter 2, you'll learn basic principles of physics and optics needed to understand fiber optics. Then you'll learn basic fiber-optic concepts.

Further Reading

On the evolution of fiber optics:

Jeff Hecht, *City of Light: The Story of Fiber Optics* (Oxford University Press, 1999 and 2004)

On the Internet bubble:

K. G. Coffin and A. M. Odlyzko, "Growth of the Internet," in I. P. Kaminow and T. Li, eds., *Optical Fiber Telecommunications IV B: Systems and Impairments* (Academic Press, 2002), pp. 17–56; available online at *http://www.dtc.umn.edu/~odlyzko/doc/oft.internet.growth.pdf*

On the development of communications in general:

Arthur C. Clarke, *How the World Was One: Beyond the Global Village* (Bantam, 1992)

Anton A. Huurdeman, *The Worldwide History of Telecommunications* (Wiley InterScience, 2003)

Irwin Lebow, *Information Highways & Byways: From the Telegraph to the 21st Century* (IEEE Press, 1995)

Laszlo Solymar, *Getting the Message: A History of Communications* (Oxford University Press, 1999)

Questions to Think About

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?
2. Devise an analogy using common implements found in a kitchen or cafeteria to show how a bundle of fibers transmits an image.
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-thick window absorbs 1% of the light entering it and transmits 99%. Neglecting reflection, how much light would emerge from a one-meter-thick window?
4. If optical fibers transmit signals so much better than wires, why aren't they used everywhere?
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 in growth of Internet traffic would this make over a period of five years?
6. Why didn't anybody wonder how long Internet traffic could continue doubling every three months?

Chapter Quiz

1. Light can be guided around corners best in
  a. reflective pipes.
  b. hollow pipes with gas lenses.
  c. clad optical fibers.
  d. bare glass fibers.

2. The first practical use of optical fibers was
  a. in communications via optical telegraph.
  b. in Alexander Graham Bell's photophone.
  c. to illuminate flowing jets of water.
  d. in bundles to examine the inside of the stomach.

3. What is the principal requirement for a cladding on an optical fiber?
  a. It must have a refractive index lower than the core to produce total internal reflection.
  b. It must be opaque so light doesn't leak out.
  c. It must be made of plastic to keep the fiber flexible.
  d. It must have a refractive index lower than that of air.

4. Flexible bundles of optical fibers can be used to
  a. examine the inside of the stomach without surgery.
  b. examine the inside of the colon without surgery.
  c. illuminate hard-to-reach machinery.
  d. all of the above
  e. none of the above

5. A new automated control system costs $1 million. How much will it have to reduce annual operating expenses if company policy says the payback time has to be no more than four years? (Neglect interest rates.)
  a. $100,000
  b. $250,000
  c. $400,000
  d. $500,000
  e. $1 million

6. The elements of a fiber-optic data link must include
  a. light source, receiver, and fiber.
  b. light source and cable.
  c. fiber and receiver.

d. fiber only.

e. cable only.

7. You need to install a new cable to handle four years of growth on a transmission route. The traffic now fills one fiber, and traffic is doubling every three months. How many fibers will you need in four years?

a. 4

b. 16

c. 128

d. 65,536

e. over 1 million

8. As in Problem 7, you need to install a new cable to handle four years of growth on a transmission route where traffic is doubling every three months. All the traffic now fits in a signal that requires one wavelength in a fiber that can handle 32 wavelengths with wavelength-division multiplexing. How many fibers will you need to carry that traffic if you fill each one with 32 wavelengths?

a. 4

b. 16

c. 128

d. 2048

e. 65,536

9. Reality has set in, and you realize that traffic is doubling every year. How many fibers would you need if each fiber carried only one signal and the first fiber was already full?

a. 1

b. 4

c. 16

d. 128

e. 2048

10. How many fibers would you need to handle the transmission load in Problem 9 if each fiber could transmit signals at 32 wavelengths?

a. 1

b. 2

c. 4

d. 16

e. can't tell from data given