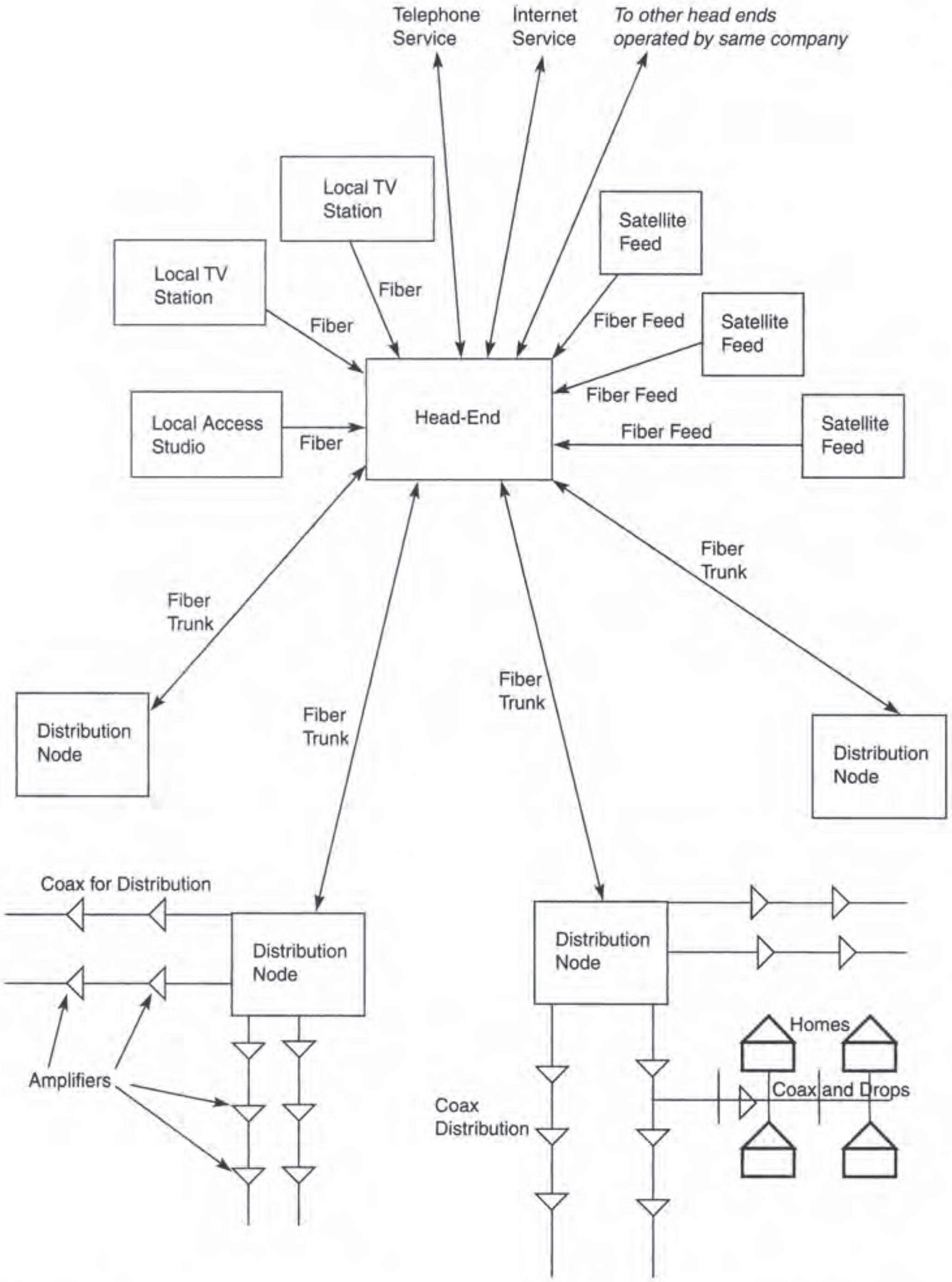


FIGURE 27.6
Hybrid fiber/coax.

same fiber. Typically signals would be transmitted downstream at 1550 nm and upstream at 1310 nm.

So far we've assumed that the same programs are broadcast to all subscribers. One trend in the cable industry is to direct some programs to specific subscribers, a practice called *narrowcasting*. Narrowcasting can be combined with broadcasting by transmitting the two sets of signals at different wavelengths, as shown in Figure 27.7.

Narrowcasting directs programs to specific subscribers.

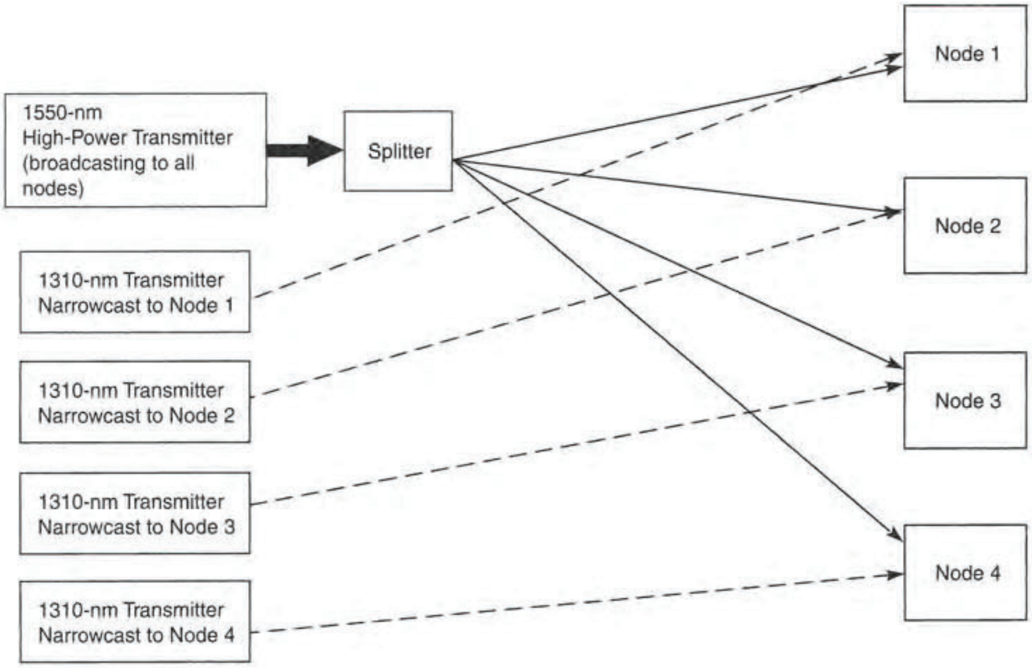


FIGURE 27.7 *Broadcasting and narrowcasting with hybrid fiber/coax.*

Identical signals can be broadcast to all nodes by splitting signals from one powerful transmitter at the head-end, shown emitting at 1550 nm in Figure 27.7. This can save money because one 100-mW transmitter generally costs less than 10 10-mW transmitters.

Other signals can be narrowcast by directing the output of one lower-power and lower-cost transmitter to a specific node. Figure 27.7 illustrates this process with four 1310-nm transmitters, each directing signals to a separate node. Narrowcasting is natural for services directed at individual customers, such as video-on-demand programs, telephone, or data transmission. It also allows cable companies to target specific advertising to certain groups of customers. For example, a cable company might direct an advertisement for a local Mercedes dealer to the affluent side of town, and an advertisement for a used-car dealer to a poor neighborhood.

Cable Modems and Telephone Service

A cable modem is a node on Ethernet distributed from a cable node.

Data channels delivered from the head-end provide downstream data for cable modems. Standard cable modems are really nodes on an Ethernet local-area network. You share that network capacity with your neighbors. The number of households connected depends on the system design and the number of people who subscribe to the service.

The distribution nodes receive downstream data and distribute those among one or more Ethernet networks on the cable. If the node serves 500 homes but only 2% have cable modems, it may deliver data to all 10 of you through one local-area network. If 60% of subscribers sign up for cable modems, the cable company typically would arrange its cables to split its 300 customers among 20 or 30 LANs.

Like other LANs, cable modems can carry data all the time without tying up a phone line. Although the network is shared, downloads can reach peak speeds in the megabit range as long as too many other users don't try to download at the same time. Access speeds also can be limited by traffic jams at other points on the Internet, not just by the cable modem's capacity.

Cable networks also can transmit telephone signals in digital form, with special hardware converting the digital signals to analog form so you can use standard telephones over the cable network. The signals are transmitted in the same way as cable modem signals.

Evolving Cable Networks and Bandwidth

Interactive services such as telephone, cable modems, and two-way video increase the demand on distribution nodes. Present nodes are very efficient at distributing identical signals to several hundred subscribers. They are less efficient in distributing different services to each of those subscribers. The more bandwidth each subscriber needs, the more serious the problem.

One way to enhance the bandwidth per subscriber is to split nodes so each one serves fewer households. Splitting nodes also can extend fiber farther into the community and closer to the home. Such extensions will be needed if cable networks are to compete with fiber-to-the-curb and fiber-to-the-home telephone networks for home users who want broadband net access.

Both cable and telephone networks are installing fiber closer to homes as they strive to offer voice, broadband data, and video services. Convergence won't make the two networks identical, but it will make them look more alike.

HDTV and Cable

The introduction of HDTV poses problems for cable systems, but it may also offer some opportunities.

Cable can transmit HDTV in standard 6-MHz channels.

The HDTV broadcast standard at least nominally solved the technical problem of fitting the broader-bandwidth high-definition signal into the same channel slot as NTSC analog signals. Broadcast HDTV squeezes 19.2 Mbit/s into a 6-MHz slot, so cable companies can simply transmit the signal in broadcast format. Cable carriers can provide the needed interfaces between digital signals and analog sets—and digital sets and analog signals—by installing new set-top boxes.

However, most cable companies don't have extra slots available for HDTV channels to use. They would have to turn off other channels to make room for them, and they don't have much incentive to do that as long as only a few people have HDTV. Another factor slowing the spread of HDTV has been a lack of available programs. The people who care most about video quality usually subscribe to cable or satellite services, so they face a choice of quality of images in HDTV versus quantity of programs on cable.

The cable industry won't have to replace its existing network because most of the changes are in the transmitter and receiver equipment. But it will have to pay for the new transmitters needed for HDTV signals, and for the new set-top boxes to convert the signals into the proper format for subscribers. The changeover will take time, and cable companies will lag behind broadcasters, who are much further along in the switch to HDTV.

The issues of restrictions on the copying of digital programs remain unsolved. The entertainment industry wants to ban copying, but the cable companies don't want to annoy customers who pay for premium services partly so they can record movies at odd hours and time-shift them to more convenient times.

Stay tuned for interesting times.

Other Video Applications

Small, light, and durable fiber cables are valuable for portable systems.

Cable television is the largest-volume video application for fiber optics, but there are many other cases where fiber is used for video transmission. Table 27.4 lists a sampling of important applications, with brief descriptions. Most involve point-to-point transmission.

Transmission requirements vary widely for these systems. Although many require high transmission quality, security video systems must be low in cost. Although metal cables can do some of these jobs, fibers offer benefits of lighter weight, smaller size, higher signal quality, longer transmission distances, immunity to electromagnetic interference, better durability, and avoidance of ground loops and potential differences.

Small, light, and flexible fiber cables offer important benefits where portability is important, such as in remote news gathering and when covering special events. Many systems use rugged cables and connectors developed to meet rigid military specifications for durability. Whenever cables are strung anywhere, they are vulnerable to damage. Wireless systems often cannot meet quality requirements, especially for broadcasting.

Fiber transmission also offers more subtle advantages, notably avoiding the need to adjust transmission equipment to account for differences in cable length. Television studio amplifiers are designed to drive coaxial cables with nominal impedance of 75 Ω. However, actual impedance of coaxial cables is a function of length. As cable length increases, so does its capacitance, degrading high-frequency response if the cable is longer than 15 to 30 m (50 to 100 ft). Boosting the high-frequency signal, a process called *equalization*, can compensate for this degradation, but proper equalization requires knowing the cable's length and attenuation characteristics. Compensation also becomes harder with cable lengths over 300 m (1000 ft) and is impractical for cables longer than about 900 m (3000 ft). There is no analogous effect in optical fibers, so operators need not worry about cable length.

Table 27.4 Other video-transmission applications for fiber optics

Application	Requirements	Special Notes
Electronic news gathering, special-event coverage	Light, durable cable to link mobile camera to fixed equipment	Wireless an alternative, but quality is lower
Security video	Vary; low cost important	Often low resolution
Studio and production transmission	High-quality link inside studio	1.5 Gbit/s for HDTV
Feeds to and from remote equipment (e.g., antennas)	High transmission quality	

What Have You Learned?

1. Video signals encode continuous changing pictures and sound. They are transmitted in standard formats and require considerably more capacity than voice or digital data.
2. Analog NTSC video displays 30 analog 525-line frames a second with interlaced scanning. Each NTSC channel requires 6 MHz of broadcast spectrum. PAL and SECAM are interlaced scanning systems that each second show 25 analog frames of 625 lines each. These formats are decades old.
3. Computer displays need progressive scanning to show text clearly, not the interlaced scanning of NTSC, PAL, or SECAM. Progressive scanning demands more bandwidth and faster electronics.
4. Digitized video signals can be compressed by a factor of 75 without seriously degrading quality.
5. Digital television standards cover both high-definition (HDTV) and standard-definition (SDTV) video. The HDTV formats have 720 or 1080 lines and a wide-screen format.
6. Digital television broadcasting is being phased in to replace analog broadcasts in the United States, but the change probably will take much longer than had been planned.
7. Video signals can be broadcast from a ground station to serve a local area. Microwave transmission from direct broadcast satellites can serve a much larger area; customers need satellite dishes and converters.
8. Modern cable television systems now carry dozens of analog NTSC video channels over fiber-optic and coaxial cables; the fiber runs from the head-end to distribution points or optical nodes. Coaxial cables run from those points to homes. Customers need set-top converters to access premium channels.
9. Hybrid fiber/coax systems transmit NTSC video to subscribers at 50 to 550 MHz. Digital services are transmitted to optical nodes at 550 to 750 MHz, and signals from subscribers return at 5 to 40 MHz. Each optical node serves about 500 homes.
10. Hybrid fiber/coax can deliver services including Internet connections, telephony, and subscription video services. Internet connections via cable modem work like local-area networks.
11. Hybrid fiber/coax can be upgraded by splitting optical nodes to serve fewer subscribers.
12. Video transmission generally is over single-mode fiber at 1300 or 1550 nm.
13. Small, lightweight fiber cables are valuable for portable news gathering and sports event coverage.
14. HDTV signals are compressed to a digital rate of 19.3 Mbit/s, which can be broadcast or transmitted through cable in a signal that fits into the same 6-MHz band used for analog channels.

15. Digital cable and DVDs are compatible with analog television sets; HDTV is not. Analog televisions will have to be discarded or equipped with adapters when television transmission is all-digital. The adapters can be installed in cable decoders.

What's Next?

In Chapter 28 you will learn about the role of fiber optics in vehicles and other mobile communications for civilian and military applications.

Further Reading

Analog television: *http://www.ntsc-tv.com/*

Walter Ciciora, James Farmer, and David Large, *Modern Cable Television Technology: Video, Voice and Data Communications* (Morgan Kaufmann, San Francisco, 1999)

Digitaltelevision.com: *http://www.digitaltelevision.com/*

Gary M. Miller, *Modern Electronic Communication*, 6th ed. (Prentice Hall, 1999). See Chapter 7 on television.

Ken Nist, *An HDTV Primer: http://www.hdtvprimer.com*

Questions to Think About

1. Analog-to-digital conversion generates lots of extra bits, so it isn't fair to say that a 25-megabit HDTV frame contains only 2.8 times more information than an NTSC frame digitized to give 9 megabits. It's fairer to compare the number of lines of resolution and the width of the screen. Using those guidelines, how much more information does a 1080-line HDTV image contain than a 525-line NTSC image? Remember that the HDTV image has a 16:9 aspect ratio, while the NTSC image is only 4:3. (*Hint:* calculate the number of picture elements or pixels.)
2. The highest resolution possible for digital television is 1080 lines by 1920 pixels, in 60 interlaced frames per second. The lowest is 480 lines by 640 pixels in 24 progressive scans per second (corresponding to a digitized movie). How do the numbers of pixels per second compare? (Note that multiple bits encode each pixel, so this is not the data rate.)
3. Digitizing voice and video both produce data streams with much higher numbers of bits per seconds than the bandwidth in hertz. Compare the ratios of bits per second per hertz for voice and video. What might cause the difference?
4. A broadcast transmitter in a hybrid fiber-coax system generates output power of 10 dBm (10 mW). Analog receivers require an input power of 5 μW (−23 dBm) for adequate signal-to-noise ratio. If the transmission loss between head-end and distribution node is 10 dB (not counting the splitter), and system margin is

10 dB, how many nodes can this transmitter support? How many could you serve by reducing the system margin by 3 dB?

5. You need narrowcast transmitters for the same system. What power level do they require if system margin, receiver sensitivity, and cable loss are the same?
6. You need to lease capacity on a metro network to transmit one channel of studio-quality HDTV from a studio to a television transmitter. The network operator has four types of transmitters available, which operate at rates to OC-3, OC-12, OC-48, and OC-192. Which one offers the capacity you need without too much excess?

Chapter Quiz

1. What is the analog bandwidth of one standard NTSC television channel?
    a. 56 kHz
    b. 1 MHz
    c. 6 MHz
    d. 25 MHz
2. How many lines per frame do standard analog European television stations show, and how many full frames are shown per second?
    a. 525 lines, 25 frames per second
    b. 625 lines, 25 frames per second
    c. 625 lines, 30 frames per second
    d. 1125 lines, 25 frames per second
3. The HDTV standard in the United States transmits 19.3 Mbit/s after digital compression. How much compression is used, and what would the data rate be without it?
    a. 4-to-1 compression, 80 MHz
    b. 10-to-1 compression, 200 Mbit/s
    c. 13-to-1 compression, 270 Mbit/s
    d. 75-to-1 compression, 1500 Mbit/s
    e. none of the above
4. What key development made the quality of analog fiber-optic transmission adequate for cable television trunks?
    a. highly linear distributed-feedback lasers
    b. inexpensive single-mode fiber
    c. dispersion-shifted fiber
    d. digital video compression
    e. optical amplifiers for 1550-nm systems

5. What is the most important advantage of fiber optics over coax for distributing cable television signals from head-ends to optical nodes?

  a. Fiber optics are hard to tap, so they reduce signal piracy.
  b. Fiber repeater spacing is much longer, avoiding noise and reliability problems with coax amplifiers.
  c. Fiber can be extended all the way to subscribers.
  d. Fiber cables are less likely to break.

6. How are analog video signals distributed to subscribers on present cable television systems?

  a. All subscribers receive the same signals, which require set-top decoders to show premium services.
  b. Signals from set-top controls are used to switch designed signals to the home.
  c. Equipment at the head-end switches selected services to each subscriber.
  d. One pair of optical fibers runs directly from head-end to home.

7. What must cable systems change to transmit HDTV signals instead of NTSC analog video signals?

  a. All coaxial cable must be replaced with fiber-optic cable reaching homes.
  b. Analog transmitters and set-top boxes must be replaced with digital versions.
  c. Only the transmitters at the head-end must be changed to HDTV format.
  d. Only the set-top boxes and the cable type must be changed to HDTV format.
  e. No changes are necessary because cable transmission has always been digital.

8. What frequencies are used for signals from the subscriber to the head-end in hybrid fiber-coax?

  a. 50 to 550 MHz
  b. 0 to 1 GHz
  c. 550 to 750 MHz
  d. 5 to 40 MHz
  e. none of the above

9. How do cable modems work on hybrid fiber/coax networks?

  a. They switch signals directly from the head-end to individual subscribers.
  b. They transmit signals in one direction only.
  c. They function like a local-area network, addressing high-speed signals to one of many subscriber terminals served by the same network.

d. They digitize video images for videoconferencing but cannot be used for other purposes.

e. They are incompatible with hybrid fiber/coax.

10. Which format is used for digital television displays?

a. 1080 lines, 1920 pixels, 60 interlaced frames per second

b. 1080 lines, 1920 pixels, 30 progressive scan frames per second

c. 720 lines, 1280 pixels, 60 progressive scan frames per second

d. 480 lines, 640 pixels, 60 interlaced frames per second

e. all of the above

11. How many analog video channels are required to transmit a full HDTV digital signal?

a. 1

b. 2

c. 4

d. 5

e. 6

12. A fundamental difference between cable-television and telephone networks is that

a. cable networks can't carry two-way telephone traffic.

b. only cable networks can carry high-speed data.

c. cable networks do not use circuit switching.

d. only cable networks use single-mode fiber.

e. there are no differences left.

CHAPTER

28

Mobile Fiber-Optic Communications

About This Chapter

The past few chapters have described the many applications of fiber optics in fixed telecommunication systems. Fibers also are used in a variety of mobile systems for civilian and military systems. Fiber cables can be used for remote control of robotic vehicles and guidance of tactical missiles. Fiber cables also are used inside vehicles ranging from battleships to private automobiles. This chapter briefly surveys these diverse applications, explaining how and why fibers are used.

Mobile Systems

Mobile systems differ in important ways from fixed systems, with the details depending on the application. This leads to some constraints on system design.

Some fiber-optic cables are used as tethers or connections for transmitting signals to and from moving objects. An example is a cable connected to a remotely operated vehicle that may venture into extreme environments where humans can't go. These cables have to survive whatever environment they pass through, so they are specially designed for that environment. The requirements can vary widely. Cables that tether a robotic mini-submarine to its human operators in a ship have to be strong and rugged. In contrast, the single fiber that connects to a fiber-guided missile during its brief flight must be light and flexible as well as strong, and is used only once.

Connections inside vehicles generally are short, with the exception of those in ships. Links inside a plane or car run no more than tens of meters, and often only meters, so plastic or graded-index fibers are often used, although single-mode fibers are used in some places. Often these are miniature dedicated local-area networks that interconnect

Connections in vehicles generally are short.

the growing variety of electronic systems in the vehicle. Copper cables often can carry data the required distances, but fiber cables are lighter and smaller. The immunity of fiber to electromagnetic interference is a big plus in vehicles where electrical, electronic, and mechanical systems are packed tightly together.

Vehicles are more hostile environments than offices.

Environmental requirements generally are much more stringent for equipment installed in a vehicle than in an office. Connections to your desktop computer don't have to withstand the constant vibration of a moving car or flying airplane. Some common fiber connectors that work perfectly well in an office building or telecommunications switching center can work loose in moving vehicles that are exposed to outdoor temperature extremes.

Military equipment must be rugged and repairable in the field.

Military equipment must meet special requirements for ruggedness and field repairability, and some must meet radiation-hardening specifications. Recent changes allow the use of some off-the-shelf commercial components that meet most military requirements.

Military systems share some other common features with civilian aircraft and automotive systems. They tend not to adapt cutting-edge optical and electronic technologies. Design cycles and production cycles are usually much longer than for telecommunications or computer equipment. Many systems are critical for safety and have to pass stringent testing requirements. You can survive a system error on your personal computer, but you might not survive if your car's computerized braking system froze when you stomped on the brakes in an emergency. The auto industry has different standards for entertainment systems and for safety-critical components. Military and civilian aircraft are designed to operate for a dozen years or more, so their control systems have to meet the same requirements. Automotive systems are supposed to last for many years, but also must be mass producible at low cost, which leads to long design lead times.

This chapter will give you a brief overview of these special fiber systems, emphasizing how they resemble and differ from other fiber communications equipment.

Remotely Controlled Robotic Vehicles

When we think of remotely controlled vehicles, most of us think first of radio-controlled toys that zip across the floor until the batteries run down. Radio controls are cheap and simple, but limited. You can command your radio-controlled car to go faster, slower, forward, backward, or turn right or left—but not much more.

Fiber-optic cables carry signals to control robotic vehicles.

Control of advanced robotic vehicles is a far more demanding job. The operator needs video transmission from a camera in the robot to see the local environment. Other environmental sensing information may also be needed, such as temperature and pressure readings. Signals must flow in the opposite direction so the operator can control the vehicle. Fiber-optic cables carry signals in both directions in a variety of remotely controlled vehicles, often sending two signals in opposite directions through a single fiber at different wavelengths. Although care must be taken to protect them, fiber-optic cables can work in places where radio signals cannot, including underwater and in electromagnetically noisy environments. Fiber cables can also be made quite rugged and special ruggedized connectors are made for military systems. Other fiber advantages include their ability to carry high-bandwidth signals over greater distances and their light weight.

Remotely controlled robots can go into places unsafe for humans. Robots can probe the radioactive parts of nuclear reactors to take measurements or make repairs, or to disassemble old reactors at the ends of their operating lifetimes. Robots can descend deep into the ocean or explore the surface of the moon or Mars. Robots can be scouts for armies, and they can even deliver weapons to their target (we call them guided missiles).

Fiber-Optic Guided Missiles

Guided missiles are essentially simple robots with deadly missions—to deliver bombs to their targets. One type of guided missile uses a ruggedized optical fiber to carry control signals to and from the launch site on the ground or a ship. The original version, called *FOG-M* for *fiber-optic guided missile,* was developed by the Pentagon, and gives a good idea how remote control through optical fibers works.

A fiber carries video images back to a soldier who guides the missile.

As shown in Figure 28.1, a video camera in the missile sends images to a soldier who guides the missile to its target by sending control signals in the opposite direction. The missile is preprogrammed to aim at the target, but the soldier provides fine guidance to make sure it hits the target. Images and control signals travel through a single bare ruggedized optical fiber that trails from the missile to the launcher. The soldier monitors the video image throughout the missile's flight to home the missile in on its target, following it all the way to impact. This system enables the soldier to stay hidden out of sight because it does not require a line of sight to the target, unlike laser-guided bombs that require that the soldier be able to see the target. The fiber-guided missile is similar to a wire-guided missile, but the fiber has much greater bandwidth, so it can carry video signals or span longer distances.

Up to 60 km of fiber can be deployed from the missile.

The components of the U.S. FOG-M system is shown in Figure 28.2. The missile contains a video camera, a fiber-optic video transmitter, a low-bandwidth receiver for control signals, and a special reel of fiber. One end of the fiber is fixed to the launcher, and remains behind when the missile is fired. As the missile flies toward its target, the fiber unwinds rapidly from the reel, forming a long arc over the battlefield. The reel is a critical component because it must deploy the fiber at the right rate so as not to tangle or break the fiber. The

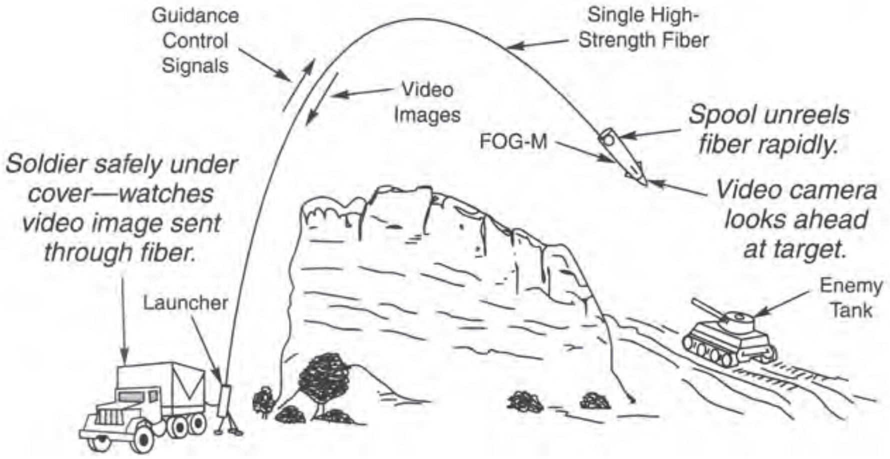
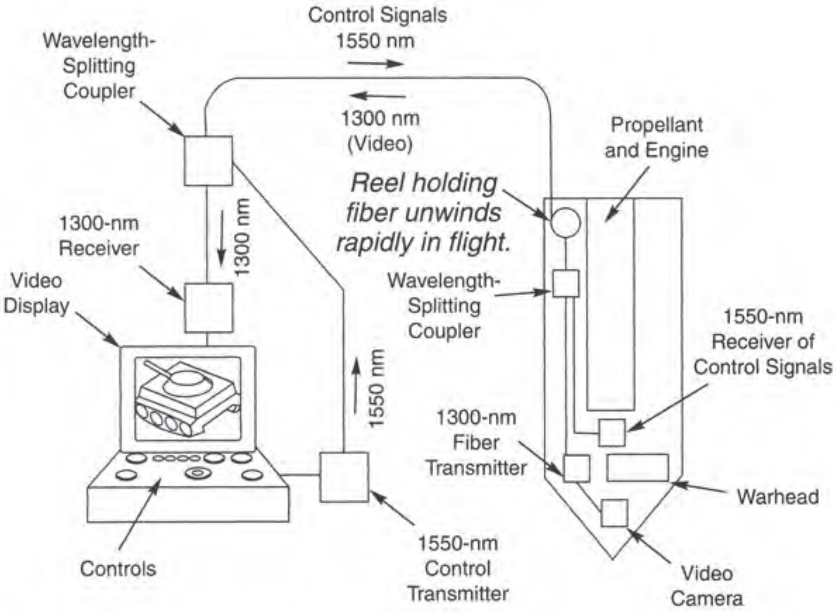


FIGURE 28.1

A concealed soldier guides a FOG-M missile to its target.

FIGURE 28.2
FOG-M components.



single fiber carries signals in both directions: a video signal from the missile at 1300 nm and a control signal to the missile at 1550 nm.

Raytheon developed an enhanced version of FOG-M with a range of 15 km, which could fly at altitudes to 300 meters. This design enabled it to hit the tops of armored vehicles, which are more vulnerable than the sides. Although test flights were successful, the Army cancelled the program in 2002.

In a parallel program, the governments of Germany, France, and Italy sponsored development of their own fiber-guided missile called *Polyphem.* Designed to be fired from ships or the ground, it has a range to 60 km and uses infrared cameras, which were optional on FOG-M. Data from the missile reportedly can be transmitted at rates above 200 Mbit/s.

Robotic Vehicles on Land

Fiber cables can control robotic land vehicles.

Fiber-optic cables also can guide robotic vehicles on land. Military agencies have done extensive testing of unmanned ground vehicles that are remotely controlled in various ways, including by fiber. Radio signals have the obvious advantage of not requiring a physical connection to the vehicle. Cables have to be ruggedized because the robots are likely to run over them. However, fiber cables are immune to electromagnetic interference, electromagnetic pulse effects, and jamming that could block radio communications. Fibers also offer high bandwidth, so operators can obtain detailed information from the vehicle.

The robots are intended for hazardous duty. For example, the Naval Sea Systems Command has developed the Remote Ordnance Neutralization System, which runs on pivoting tracks and has a robotic arm that can defuse explosives. A soldier can control the robot over a radio link or fiber cable, staying safely out of harm's reach in case anything goes wrong. Similar robots could be used to detect and remove land mines, which continue to take a heavy toll on civilians long after the wars are over. Other robots might fire weapons at dangerous targets.

The high bandwidth of fiber cables makes it possible to consider using virtual reality techniques to remotely operate robotic vehicles. Sensors on the vehicle would scan the area, serving as the operator's "eyes," while other sensors would listen for sounds and "feel" the terrain. The sights, sounds, and feel would be conveyed to the operator—far from the vehicle—using screens, speakers, and perhaps virtual-reality gloves. The goal would be to keep the operator safe while feeling as if he or she were driving the vehicle.

Remote-controlled robots could also serve many nonmilitary purposes in dangerous environments. Robots could inspect the "hot" interiors of nuclear power plants or perform needed repairs inside the reactor. The robots could be left inside the reactor permanently if they became contaminated. Specialized robots could be used to dismantle old reactors, without exposing people to the highly radioactive materials inside. Likewise, remotely controlled robots could clean up hazardous wastes. Scientists used a fiber-optic cable to control a multilegged robot as it climbed into a hazardous Antarctic volcano to collect data.

Remotely controlled robots could clean up hazardous wastes and dismantle old nuclear reactors.

Submersible Robots

Radio links can substitute for cables in many land applications, but most radio waves don't penetrate far into water. Cables or acoustic signaling are required to maintain contact with submerged vessels. Although crewed submersibles can operate without a continuous link to the surface, only cables can provide the transmission capacity needed to remotely operate a sophisticated submerged vessel. Fiber cables are preferred because of their high bandwidth and durability.

Hybrid fiber-electrical cables carry signals and power to remotely operated submersibles.

Hybrid fiber and electrical cables carry the signals and power needed to steer and accelerate submerged vessels, as well as bring video signals and telemetry to the surface, where shipboard operators can monitor them.

Fiber cables also allow operators aboard a submersible to control robotic vehicles that can be sent into small spaces or dangerous areas. The most famous example came when Robert Ballard's team from the Woods Hole Oceanographic Institution discovered the sunken wreck of the *Titanic* in 1985. The scientists discovered the wreck with *Alvin*, a submersible that carried three people. However, they did not dare to explore the inside of the deteriorating wreck. Instead, they used a 250-lb robot, tethered to *Alvin* with a fiber-optic cable that carried control signals. It was this fiber-controlled robot that photographed details of the dark interior of the wreck. Ballard remains enthusiastic about the use of fiber-controlled robot submarines.

Fibers in Aircraft

It was not too long ago that most aircraft were controlled by hydraulic systems. When the pilot moved a lever, it would cause hydraulic fluid to move a control surface (e.g., a wing flap), much as hydraulic brakes work in an automobile. Newer planes have fly-by-wire electronic controls that send electronic signals to motors that move control surfaces. Modern aircraft—particularly military planes—also use many electronic systems and sensors,

Fibers can serve as the control networks for aircraft.

adding to signal transmission requirements. These include radars, navigation and guidance systems, and—in military planes—weapons systems with automatic targeting capabilities and electronic countermeasure equipment.

Like many other users faced with increasing communications requirements, the aerospace industry and the Air Force began investigating fiber optics. Pentagon research programs date back to the 1970s. Aircraft performance depends on weight, and military engineers wanted to reduce the load of heavy, metal cables. They also wanted to protect their avionic systems from electromagnetic interference, electromagnetic pulse effects, and potential enemy countermeasures.

New tactical aircraft use fiber-optic links.

Fiber is used extensively in the latest generation of tactical aircraft, such as the U.S. Air Force F-22 Raptor and the Eurofighter. Multimode fibers transmit signals for radars, weapons control systems, and electronic warfare systems. The use of fiber greatly reduces vulnerability to enemy countermeasures.

Some older military aircraft have been retrofit with fiber for high-bandwidth applications. An example is the modernization of computer systems in the Air Force's AWACS (Airborne Warning and Communications System) fleet. Fiber systems transmitting 1 Gbit/s using the Fibre Channel standard are replacing communications equipment developed in the 1970s.

Another addition to existing airborne systems is the Fiber Optic Towed Decoy, which helps protect aircraft from enemy missiles. When instruments detect a potential threat, the aircraft releases the radar-emitting decoy and tows it behind the plane on a fiber-optic cable. The system identifies the type of threat, and commands the decoy to emit a radio signal designed to fool that particular enemy weapon system. The commands go through the fiber cable, which emits no radio waves, and the aircraft's radio emissions are limited, so the enemy weapon is fooled by the decoy's emissions and homes in on it. The decoy is part of a new countermeasure system being integrated into F-15 and F-18 fighter planes.

Fiber-optic aircraft links use multimode fiber.

Military systems have long development times, and most military aircraft use multimode fibers to transmit no more than a few hundred megabits per second over the short distances inside a plane. However, some new systems use advanced fiber technology. The towed decoy borrows techniques developed to transmit analog microwave signals in cable television and microwave antenna systems. High-speed detectors convert the analog signal from an externally modulated laser back to microwaves, which the decoy then emits. The special towing cable is built around single-mode fiber designed to be particularly insensitive to bending, which is hard to control in a cable hanging from a fast-moving jet.

Civilian airliners also use fibers in control systems. After testing "fly-by-light" controls in eight 757 jets, Boeing included a 100-Mbit/s fiber-optic local-area network in the control system of its 777 airliners. Boeing engineers calculated that they could have saved over 1300 kg if they used only fiber instead of copper wiring for the communication system in the plane, but they did not go that far. Airlines are looking to fiber for higher bandwidth as they upgrade in-flight entertainment systems.

Fiber-optic systems must meet some special requirements for aircraft use. Temperatures can vary widely, and planes suffer continual vibrations in flight. Many connectors that work fine in ground-based equipment, such as the FC, ST, and SC, are not recommended for aircraft use. However, suitable connectors are available, including some designed to meet military environmental requirements.

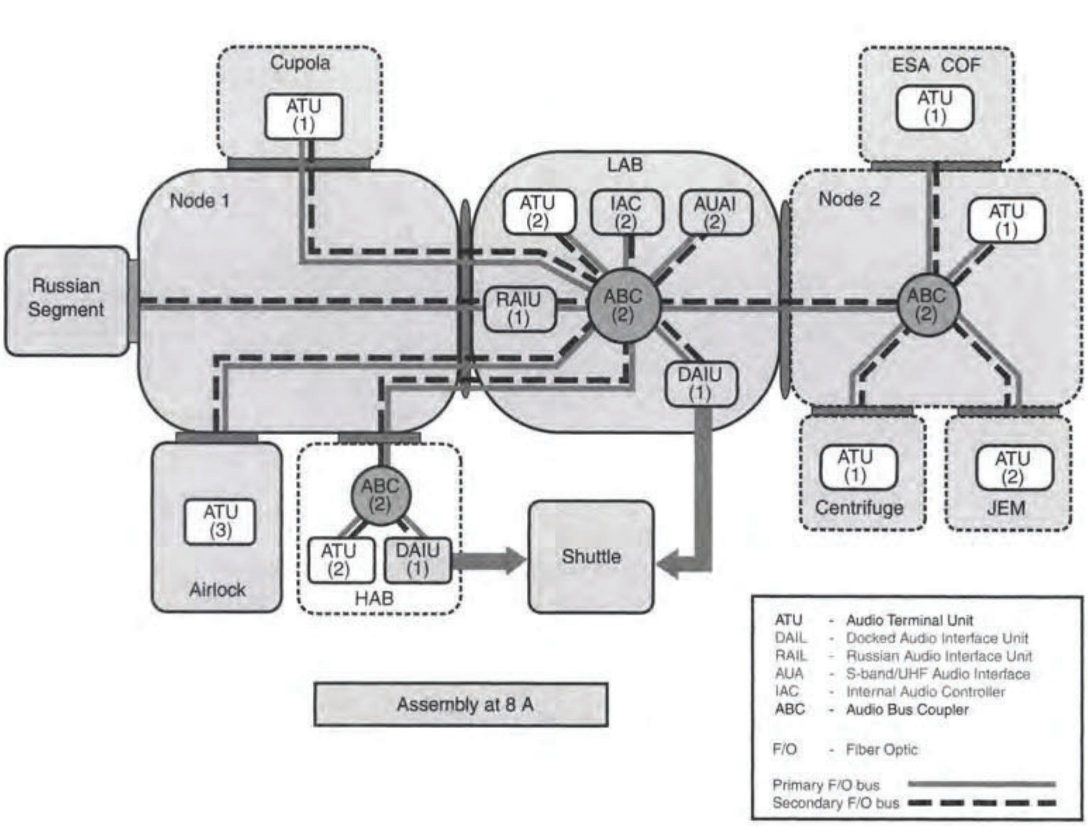


FIGURE 28.3

Fiber-optic audio network in the International Space Station. (From NASA "International Space Station Familiarization" government work not subject to copyright)

Light weight also tips the balance toward fiber in spacecraft, and the International Space Station includes fiber-optic networks for audio and video transmission. Figure 28.3 shows the layout of the station's fiber-optic audio network.

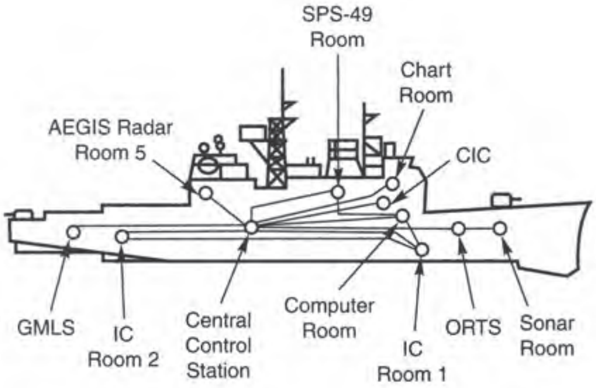
Shipboard Fiber-Optic Networks

Big ships have massive communication requirements.

The communication requirements of a big ship rival those of an office building. Ships have their own telephone networks to keep officers and crew in contact, as well as communication systems that link them to the outside world. Military ships carry a variety of weapon systems, as well as radars, sonar systems and other sensors. Modern military ships have computer rooms, both to control on-board weapon systems and to analyze incoming information. Computers have become so important to naval operations that many ships in the U.S. Navy are now equipped with fiber-optic local-area networks. Figure 28.4 shows one example of how fiber optics can interconnect shipboard systems.

Radars and other imaging and sensing systems often collect large volumes of data, requiring the high transmission capacity of fiber links. Weight is not as critical on ships as it is on aircraft, but scrapping metal cables can save valuable space. Fibers are immune to

FIGURE 28.4
Cabling in a large ship. (Courtesy of AT&T)



electromagnetic interference, which can be a problem when mechanical and electronic systems are packed tightly in the close quarters of ships.

Early naval systems used multimode fiber, but newer systems include some single-mode fibers for high-capacity systems. Recent developments include a standardized ship-to-shore cable for in-port connections, which includes eight multimode fibers and four single-mode fibers.

Automotive Fiber Optics

Automotive engineering, like military system design, involves an odd mix of conservative and advanced design. Some innovations appear surprisingly quickly in luxury cars, such as navigation systems based on the Global Positioning System. Yet fiber optics have appeared only recently, and only in a limited range of luxury cars.

Automotive design faces stringent requirements.

Automotive engineers are not hopelessly conservative about using fiber. They are cautious because car designers face very stringent requirements. Modern automotive equipment must survive hostile conditions ranging from freezing in Alaskan winters to baking in south Texas parking lots in mid-summer. Cars must be repairable by technicians with a wide range of skills and equipment, and able to withstand the efforts of amateur mechanics. Safety-critical systems such as steering, brakes, and wipers must withstand minor failures, so new technology for those applications requires very stringent testing. Planning cycles are long, with major changes often requiring five years to reach full-scale production. In addition, unit costs must be kept low so manufacturers can make profits.

Forward-looking automotive engineers realized more than two decades ago that fiber optics could reduce the weight and complexity of wiring harnesses and prevent electromagnetic interference from jamming electronic systems. However, other options looked better, so fiber optics stayed on the shelf for many years. A new generation of sophisticated electronics, such as video systems with back-seat screens, has now revived interest in fiber links in autos.

Plastic fibers are easy to connect and splice.

The new systems use step-index multimode plastic fiber with 1000-micrometer PMMA (polymethyl methacrylate) cores. Although its attenuation is high and bandwidth low by telecommunication standards, this fiber has plenty of capacity to deliver signals throughout even the biggest sport-utility vehicles. Plastic fibers also are easy to install and repair, critical concerns in both manufacture and repair. The big challenges are temperature and vibration, with the auto industry wanting robust connectors and fibers able to withstand

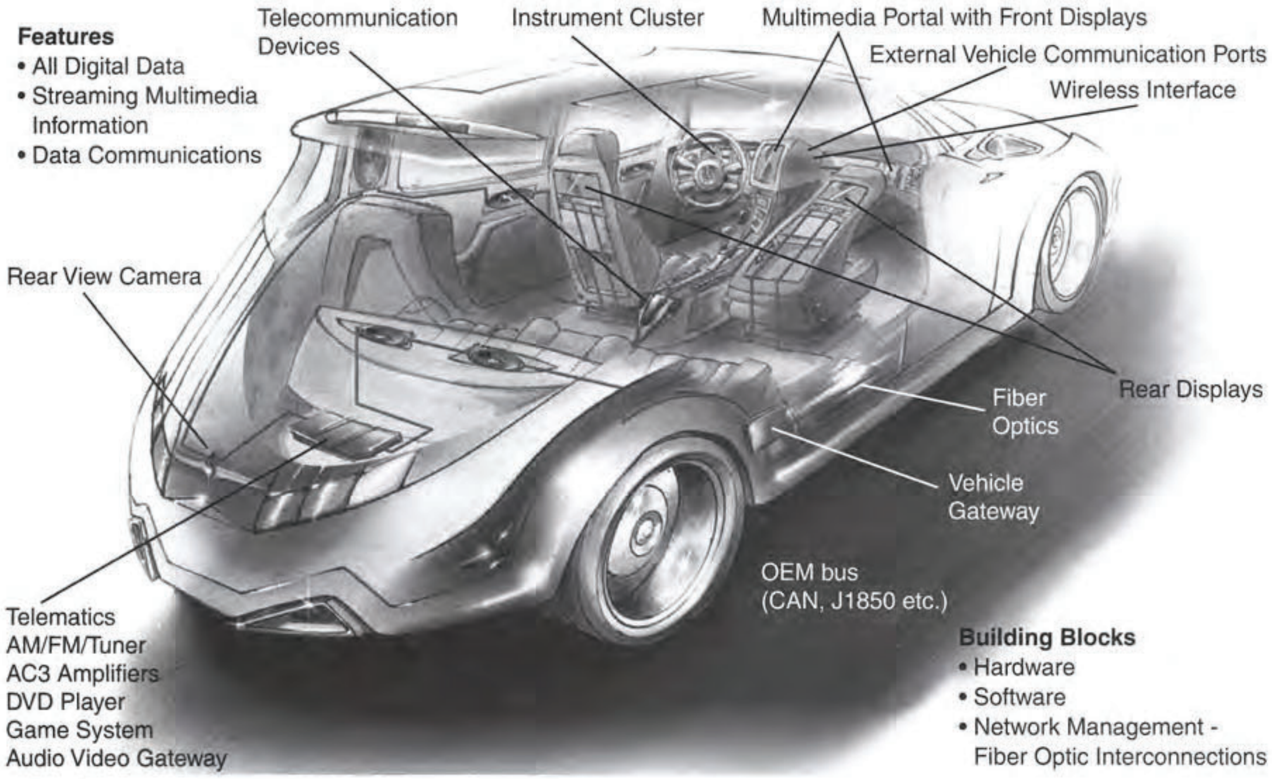


FIGURE 28.5

A MOST network links electronic equipment in a car. (Courtesy of MOST Cooperation)

temperatures as high as 85°C. Fiber networks are starting to appear as options on high-end luxury cars, where new automotive technology traditionally appears first. Separate networks have been developed for entertainment systems, where failures are annoying but not dangerous, and for systems critical to car safety.

Entertainment Networks

Networks carrying safety-critical data must be more reliable than entertainment networks.

The first generation of fiber systems installed in cars provide multimedia interfaces that carry audio, video, and digital data for entertainment equipment and amenities such as stereos, DVD players, and navigation systems. Driving a car without music, GPS navigation, and back-seat movies may not be pleasant, but it certainly poses no danger. So automotive engineers feel freer to experiment with these systems than with networks that control safety-critical equipment such as turn signals, windshield wipers, and brakes. Two major standards have been developed for fiber entertainment networks: MOST and an automotive version of FireWire.

MOST stands for *Media Oriented Systems Transport*, a network with a "plug and play" interface that can transmit data at up to 24.8 Mbit/s. It's targeted at automotive applications. Devices that follow the MOST standard can be used in any car network that complies with it. Figure 28.5 shows how the devices might be installed in a car.

A MOST network consists of point-to-point plastic-fiber links. The transmitters are 650-nm LEDs emitting 0.1 to 0.75 mW, which are directly modulated with an extinction ratio of at least 10 dB; the receivers are PIN photodiodes. Each device contains two ports, for input and output, and the links are arranged in a loop or ring. Each device converts the input optical signals to electronic form, then converts them back into optical form for retransmission to the next device. The loop can support up to 64 devices, including stereos, DVD players, video displays, speakers, mobile phones, computers, game centers, and navigation equipment.

MOST and FireWire are entertainment networks.

Devices automatically initialize when plugged into the network, and all analog signals are converted into digital format before transmission. A master clock synchronizes data transmission from all devices, which allows the use of simple transmitters and receivers and avoids the need for data buffering. A control channel carries 700 kbit/s, and the network can carry asynchronous data at up to 14.4 Mbit/s and synchronous data, like video, up to 24.8 Mbit/s. The MOST network is already used in some high-end luxury cars, including the Audi A-8, the BMW 7 Series, the Mercedes E class, the Porsche Cayenne, the Saab 9-3, and the Volvo XC-90. Developers have talked about extending network speed to as fast as 1 Gbit/s and about developing a version for use in home entertainment networks. Above 100 Mbit/s, hard-clad silica fibers and VCSEL transmitters would replace plastic fibers and red LEDs in MOST networks.

Like MOST, the automotive version of the FireWire standard developed by the 1394 Trade Association has point-to-point fiber links that connect plug-and-play devices. However, the links contain two fibers and do not have to form a complete ring. The standard does not specify transmission wavelength, but normally it uses 650-nm LEDs with plastic fiber. Alternatives include glass fibers and Category 5 twisted pairs. The original 1394 FireWire standard transmitted at 100, 200, or 400 Mbit/s, but an updated version adds 800 and 1200 Mbit/s. Current versions can link up to 63 devices. Although FireWire is common on computers, it is not yet widely used in cars.

Safety-Critical Networks

Byteflight carries 10 Mbit/s for safety-critical devices.

Different considerations apply to safety-critical networks, which shaped the Byteflight protocol developed by BMW and several electronics companies. Byteflight transmits at 10 Mbit/s through plastic fibers, picked for their immunity to electromagnetic interference. The network is arranged in an active star configuration, with fibers linking individual devices to the central active node, which regenerates input signals for transmission to other nodes. Transceivers consist of a red LED mounted on top of a photodiode, so both couple to the same fiber.

The transmission protocol is designed to meet safety needs, with transmission arranged in 250-microsecond blocks for sending urgent messages. The active node generates the clock signals. Byteflight was first used in BMW 7 Series cars to connect 13 electronic modules that controlled air bag deployment, transmission gear shifting, and other critical functions.

What Have You Learned?

1. Mobile systems must operate in different environments than fixed systems. Vehicle systems face more difficult conditions than those used in offices.
2. Vehicle communication systems generally span short distances.

3. Military equipment must meet special requirements for ruggedness and field repairability. New military systems can use some commercial equipment that meets their requirements.
4. Military systems have long design cycles. Military and aerospace systems typically have lifetimes of over a dozen years.
5. Optical fibers can carry signals to control robotic vehicles on land, in air, or in the water. Fibers' advantages are their small size, light weight, immunity to EMI, and high bandwidth. Ruggedization of cables is critical for vehicle applications.
6. A fiber can transmit images from a television camera in a missile back to a soldier guiding the missile to its target. Fiber unwinds from a special reel on the missile.
7. Remotely controlled robots could defuse bombs. In civilian applications, remotely controlled robots could clean up hazardous wastes and dismantle old nuclear reactors.
8. Fibers can be used for signal transmission in aircraft because of EMI immunity, small size, and light weight.
9. Fiber-optic communication networks are used on military ships, which have large communication needs.
10. Automotive fiber-optic links use plastic fiber to control production and repair costs.
11. MOST is a 25-Mbit/s network that carries entertainment and convenience signals in cars. A version of FireWire also has been developed for automotive entertainment; it operates at higher speeds.
12. Safety-critical automotive networks require different protocols than entertainment networks to reliably deliver signals such as those that trigger air-bag deployment.

What's Next?

Chapter 29 covers sensing applications of fiber optics.

Further Reading

Automotive Multimedia Interface Collaboration: *http://www.ami-c.org*

Byteflight: *http://www.byteflight.com*

Firewire/1394 Trade Association: *http://www.1394ta.com*

MOST Cooperation: *http://www.mostcooperation.com*

Questions to Think About

1. Military research agencies in Britain and the United States were among the first sponsors of fiber-optic development. Yet military equipment has lagged far behind civilian telecommunications in deploying fiber-optic systems. Why?

2. One of the first fiber-optic systems deployed by the military was a portable battlefield communications network. The lightweight fiber cables replaced thick copper cables, which had proved very vulnerable to damage in handling. Recently, wireless systems have replaced the fiber network. Why do you think fiber optics were deployed earlier in battlefield networks than in other systems?

3. Why can't radio-controlled vehicles be used underwater?

4. A Nimitz-class nuclear aircraft carrier is 1092 ft (333 m) long and requires a crew of 3300 people to sail. Could you run a gigabit Ethernet link the length of the ship with 62.5/125-μm graded-index fiber at 850 nm? If not, could you use other types of multimode fiber?

5. A new car is 20 ft (6 m) long. A step-index plastic fiber has bandwidth of 10 MHz/km. Can you use this fiber to run a 25-Mbit/s MOST link the length of the car?

6. How far can you transmit a 25-Mbit/s NRZ signal through the step-index fiber of Question 5, considering only bandwidth? If attenuation is 200 dB/km, and the link margin is 20 dB, what is the limit imposed by distance, neglecting connector and coupling losses?

Chapter Quiz

1. What kinds of remotely operated vehicles cannot be controlled by operators through fiber optics?

a. guided missiles
b. submersibles
c. munition-defusing robots
d. robots for nuclear waste cleanup
e. satellites

2. What signals are transmitted from fiber-guided missiles to the operator?

a. video images of the target
b. control commands
c. data on temperature and pressure
d. data on fiber attenuation

3. How are signals transmitted to and from a fiber-guided missile?

a. separately through two fibers in a single cable
b. bidirectionally through one fiber by time-division multiplexing
c. bidirectionally through one fiber by wavelength-division multiplexing
d. only one way
e. from the missile through the fiber; to the missile via radio

4. Which of the following attributes of fiber optics are important for remote control of land vehicles?

a. secure data transmission
b. lightweight, durable cable
c. EMI immunity
d. b and c
e. a, b, and c

5. Which of the following reasons do not influence the use of fibers for signal transmission in aircraft?

a. Optical fibers are immune to EMI.
b. Optical fibers are lighter than wires.
c. Aircraft lack adequate power supplies for wire-based communications.
d. Military aircraft must be hardened against enemy electronic countermeasures.
e. Fiber optics can help reduce aircraft visibility to radar.

6. What were the most serious problems in developing fiber-optic networks for automobiles?

a. reducing the attenuation of plastic fibers
b. temperature and vibration in vehicles
c. designing high-bandwidth transmitters for plastic fibers
d. developing glass fibers usable in automobiles
e. greater interest in designing tail fins than data links

7. Aircraft fly-by-light systems use optical fibers

a. to illuminate cockpit instruments.
b. in high-strength cables to pull mechanical actuators.
c. to carry control signals to motors that move mechanical parts.
d. only to transmit data from sensors to cockpit instruments.
e. to deliver bright flashes of light that ignite fuel in the engines.

8. Single-mode fibers are used

a. to transmit radio-frequency signals to radar decoys towed by aircraft.
b. in local-area networks on submarines.
c. in cables controlling mobile ground robots.
d. in data links on board aircraft.
e. in automotive systems.

9. What type of system uses plastic fibers for data transmission?

a. fiber-guided missiles
b. radar decoys towed by aircraft

   c. local-area networks on board ships
   d. data links on board aircraft
   e. automotive data links

10. The MOST standard for automotive data networks specifies what data rate?

   a. 25 Mbit/s
   b. 100 Mbit/s
   c. 155 Mbit/s
   d. 622 Mbit/s
   e. 1 Gbit/s

CHAPTER

29

Fiber-Optic Sensors

About This Chapter

So far, I have concentrated on how optical fibers are used for communications. However, fiber optics also have other important uses. This chapter will show how fibers are used as sensors. Fiber sensors work in a variety of ways, sometimes just using fibers to deliver light, other times monitoring changes induced in light transmission caused by external effects. Fiber sensors can measure pressure or temperature, serve as gyroscopes to measure direction and rotation, sense acoustic waves at the bottom of the sea, and do many other tasks.

Fiber-Sensing Concepts

The label *fiber sensors* covers a broad range of devices that work in many different ways. The simplest use optical fibers merely as a probe to detect changes in light outside the fiber. The fiber may collect light from a given point to see if an object (such as a part on an assembly line) is present or not. The fiber also may collect light from another type of optical sensor that responds to its environment in a way that changes the light reaching the fiber. For example, a prism in a tank of liquid may start reflecting light back into a fiber probe if the liquid level drops below the prism's reflective surface, exposing it to air so total internal reflection occurs.

Other fiber sensors detect changes in light passing through a fiber that is affected by changes in the outside world, such as the temperature or pressure. That may seem strange if you're used to communications fibers, which generally do not respond significantly to outside effects. However, you can design special fibers or special structures within fibers to respond more strongly to outside effects. You also can use optical effects such as interference to detect small effects that accumulate over long lengths of fiber. In these ways, fiber sensors can detect changes in quantities such as temperature, pressure, and rotation.

Fibers can serve as probes or as sensors themselves.

There is an amazing multitude of fiber sensors, most used only for a few special purposes. This chapter can't cover them all. Instead, I will concentrate on simple examples and important types of sensors. I will first survey simple fiber sensors, where the fiber merely probes the environment. Then I will describe sensing mechanisms and some important types of fiber sensors and their applications.

Fiber-Optic Probes

Fiber-optic probes collect light from remote points, often sampling light that was delivered there by fibers. They come in two broad families that perform different sensing functions. The simpler ones look to see if light is present or absent at the point they observe. Others collect light from remote optical sensors, bringing it back to a place where it can be analyzed.

Simple Probes

Fiber probes can detect objects when they block or reflect light.

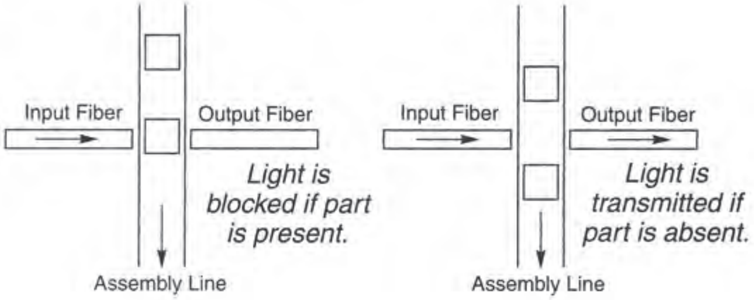
Figure 29.1 shows a simple fiber-optic probe checking for parts on an assembly line. One optical fiber delivers light from an external source, and a second fiber collects light emerging from the first, as long as nothing gets between the two. When a part passes between them on the assembly line, it blocks the light. Thus light off indicates that a part is on the assembly line, and light on indicates that no part is passing by.

This concept can be used in many ways and is not new. One early example was reading holes in the punched cards used to input data to early mainframe computers, although in this case a detector behind the card directly sensed the transmitted light without a light-collecting fiber. The card passed an array of fibers at a fixed speed, and detectors monitored light transmission as a function of time. When a hole passed the end of the fiber, light reached the detector. When there was no hole, the card blocked the light. The technique was simple and effective, but punched cards are now museum pieces.

More refined variations are possible, such as measuring the size of parts to make sure they meet tolerances. An array of fibers can be mounted beside the production line, so passing parts block the light to some of them. The parts pass inspection if all the fibers above the maximum height receive light and all those below the minimum height do not. Parts that are too small or too tall are rejected when light reaches fibers that are supposed to be dark or does not reach fibers that are supposed to be illuminated.

FIGURE 29.1

Fiber-optic probe checks for parts on an assembly line.



Optical Remote Sensing

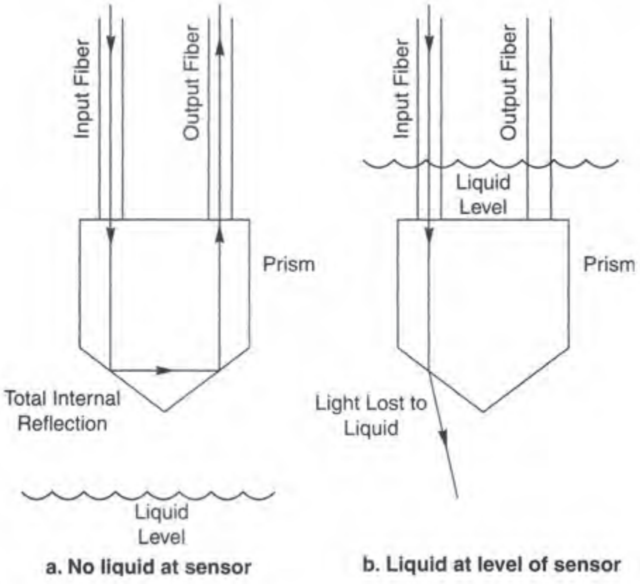
Fibers can collect light from other optical sensors.

Fiber probes can also collect light from other types of optical sensors. In this case, the fibers function like wires attached to an electronic sensor. The optical sensor (generally not a fiber) responds in some way to the environment, changing the light that reaches the fiber probe. The fiber carries that light to a detector, which senses the change.

One example is the liquid-level sensor shown in Figure 29.2, which senses when the gasoline in tank trucks reaches a certain level. Many tank trucks are filled from the bottom so vapor left in the tank can be collected to control pollution, and the liquid level must be sensed to prevent overfilling. One fiber delivers light to a prism mounted at the proper level. If there is no liquid in the tank, the light from the fiber experiences total internal reflection at the base of the prism and is directed back into the collecting fiber. If the bottom of the prism is covered with gasoline, total internal reflection cannot occur at the angle that light strikes the prism's bottom face, and no more light is reflected back into the fiber. When the light signal stops, the control system shuts off the gas pump.

Another example senses temperature changes by observing the response of a phosphor in a glass blob at the end of a fiber. Ultraviolet light transmitted by the fiber stimulates fluorescence from the phosphor at several wavelengths. The ratio of fluorescence at the different wavelengths changes with temperature. The fiber collects the fluorescent light and delivers it to an optical analyzer that compares intensities at different wavelengths and thus measures the temperature.

The same principle can be used with a bundle of fibers arranged so that each delivers light to a separate bio-sensing bead. The beads react to different chemical or biological agents, producing fluorescence when a particular material is present. The fiber bundle gathers the signals from the different sensing beads to quickly sample the materials present in the environment for security purposes or other applications.



a. No liquid at sensor

b. Liquid at level of sensor

FIGURE 29.2
A liquid-level sensor.

Fiber-Sensing Mechanisms

Some effects can change how fibers transmit light.

Outside influences can directly affect fiber transmission in a variety of ways, depending on the type of fiber and how the fiber is mounted. Communication fibers and cables are designed to be isolated from the environment. For sensing, you design fibers to respond as strongly as possible. For example, you may dope fibers with materials that change their refractive index as temperature or pressure change. Or you may mount fibers between grooved plates, so increasing pressure on the plates causes microbending.

Countless fiber sensors have been demonstrated in laboratories. Some are used for practical measurements, although only fiber gyroscopes and medical pressure sensors are in mass production. It's impossible to cover all the diverse types of fiber sensors here, but I will give you an overview of the basic principles of intrinsic fiber sensing, which depends on properties of the fiber.

The Idea of Sensing

Sensors convert something hard to measure into units easier to observe.

A sensor converts a physical effect you want to observe into a form you can measure. Let's start with a familiar sensor, a thermometer filled with liquid. As temperature changes, the liquid expands. Most liquid in the thermometer sits in the hollow bulb at the bottom; the hollow tube calibrated with temperatures has a much smaller volume. (It looks big because the glass or plastic cylinder magnifies the apparent width of the tube.) The engineers who design thermometers know how much the liquid expands per degree, so they can calculate how much liquid they need to expand to fill the extra tube.

Suppose, for example, a liquid expands 0.01% per degree Celsius. Then, if you start with a volume of 1 cm^3 of liquid, it grows 0.0001 cm^3 larger for each degree it is warmed. To make a thermometer, you can attach a bulb containing 1 cm^3 of liquid to a thin tube marked with lines that indicate 0.0001-cm^3 units of volume inside the tube. If the tube's cross-sectional area is 0.001 cm^2, each 0.1 cm—or 1 mm—represents a 1° temperature change. It isn't quite that simple, because a careful designer must consider thermal expansion of the tube itself, but that's the basic idea. The thermometer converts a hard-to-measure unit, temperature, into one that is easier to measure, the length of a column of colored liquid.

Fiber sensors work in the same way, but they measure properties like temperature by observing the light transmitted through the sensor. They make the property they are trying to measure modulate the light in some way.

Most fiber sensors work by modulating the light passing through them in one of four ways:

- Directly altering the intensity
- Affecting the polarization of the light
- Shifting the phase of the transmitted light
- Changing the wavelength of light transmitted

To actually measure that modulation, you have to convert those changes to variations in intensity.

Direct Intensity Modulation

Some fiber sensors directly modulate transmitted light intensity.

Sensors that directly change light intensity are conceptually simple. The simplest of all is a crack sensor based on a fiber embedded in a material. As long as the material is intact, the fiber transmits light without impediment. A crack breaks the fiber, reducing light intensity or cutting the light off altogether, depending on how large the crack is. You can think of it as a simple on-off sensor. If the light is on, you can drive a heavy truck across the bridge, but if the light stops coming through the fiber, you need to check the structure.

A more subtle type of intensity sensor depends on *microbending*. Figure 29.3 shows a pressure sensor based on a fiber passing between a pair of grooved plates. If there's no pressure on the plates, the fiber remains straight, and light passes through it. Pressure on the plates causes microbending—the more pressure, the more microbending—and microbending makes light leak from the fiber core. The more pressure, the less light is transmitted through the fiber.

Polarization Sensing

Some fiber sensors affect light polarization.

Other sensors affect the polarization of light in the fiber. There are a number of possible variations. One example is sensing of magnetic fields, using a process called *Faraday rotation*, which rotates the plane of polarized light by an angle proportional to the strength of the magnetic field. If you send vertically polarized light through a sensitive fiber, you can measure the magnetic field by measuring the angle the polarization is rotated.

In practice, you don't directly measure the angle of polarization, however. You actually measure the changes in the intensity of light transmitted by another polarizer. If the second polarizer is also vertical, the decrease in transmitted light intensity measures the degree of rotation. This converts a change in polarization to a change in intensity, which is easier to measure.

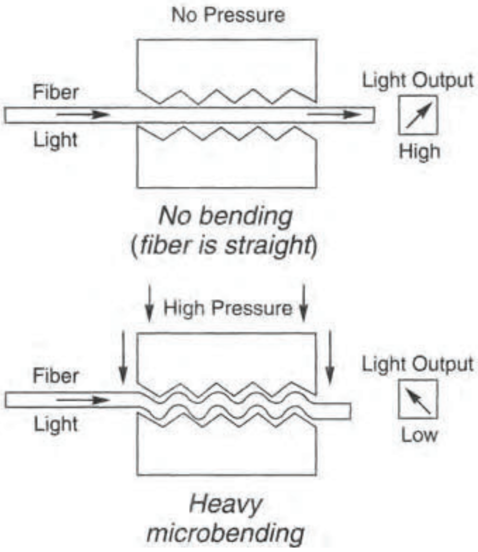


FIGURE 29.3

Increasing pressure on the plates causes microbending, reducing light transmission through the fiber.

Other fiber sensors produce effects that affect light of different polarizations differently. For example, pressure may change the refractive index for vertically polarized light differently than that for horizontally polarized light. This leads to a phase change in the intensities of the light in different polarizations, which requires another kind of measurement, as I describe next.

Phase or Interferometric Sensing

Interferometric sensors can detect very small changes.

Sensors also can modulate the phase of light to cause interference effects that modulate light intensity. To understand how this works, let's continue with the example of the pressure sensor that changes the phase of polarized light. By changing the refractive indexes of different polarizations by different amounts, the sensor effectively delays one polarization relative to the other. To measure this, you can separate the two polarizations at the output end, rotate one by 90°, equalize the path lengths, and then mix them together, as shown in Figure 29.4. If the two polarizations are in phase—that is, there is no delay between the two of them—the output is high; if one is 180° behind the other, the output is low.

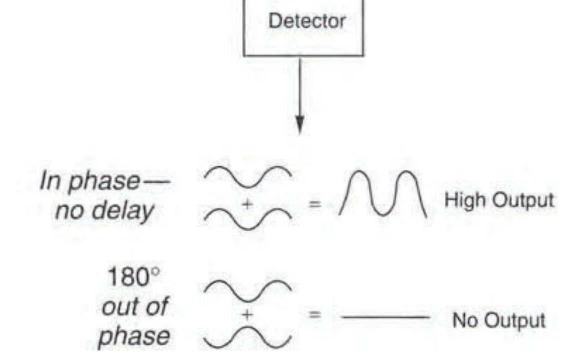
Interferometric sensors are very sensitive to small changes, but they have some limitations. One is that the light has to be coherent enough that interference occurs; thus, you need either laser sources or very carefully equalized path lengths. In addition, there is an inherent ambiguity because a 360° delay produces the same effect as no delay or a 720° delay. You have to keep track of how many cycles of shifting occur or just measure a small shift.

Note also that to convert the phase shift to a change in intensity for this sensor, you need to compare two signals. In the case of the polarization sensor, these signals are two polarizations of light affected differently by pressure-induced changes in refractive index.

Another approach is to compare the phases of light passing through two fibers, one isolated from the environment and the other exposed to it. If the effective length of the fiber

FIGURE 29.4

Polarization-delay fiber sensor.



exposed to the environment changes, the phase changes, which can be measured by mixing light from the two fibers in an interferometric detector.

A third approach is to make a sensor that is itself an interferometer, which changes its resonance wavelengths as pressure, temperature, or other conditions change. I'll describe an example of that type of sensor later.

Wavelength Sensing

Another approach to optical sensing is to change the wavelength of light transmitted. In principle this could be done by changing the light source, but in practice it is usually done by selecting the wavelength using an optical filter.

The fiber Bragg grating described in Chapter 7 is a fiber-optic filter, in which a series of regions along the fiber core with alternating high and low refractive indexes select the wavelength. The periodic variation of refractive index selectively reflects one wavelength back toward the light source while transmitting others. Stretching or compressing the fiber Bragg grating can change the selected wavelength. Measuring the wavelength directly, or measuring the change in light intensity at a particular wavelength selected by another optical filter, measures the amount of strain on the fiber grating.

Fiber Bragg gratings respond to strain by changing the reflected wavelength.

Constant versus Changing Measurements

One of the many subtleties of sensing is the difference between measuring long-term values and changing quantities. From a physical viewpoint, sound waves are really short-term variations in atmospheric pressure. However, you can't use the same instruments to measure the two. A microphone picks up sound waves but not atmospheric pressure. On the other hand, a barometer measures pressure but not sound waves.

The same is true for fiber sensors. Acoustic sensors work on different principles than pressure sensors. An interferometric fiber sensor on the seabed could pick up undersea sounds, but you'd need a different sensor to measure the pressure there.

Some Fiber Sensor Examples

Now that you've learned the basic principles of fiber sensing, let's look at a few examples. I will first cover a few general examples, then look at some promising specific cases.

Microbending Sensors

One attraction of microbending sensors is their simplicity. Microbending directly affects loss of a fiber; the more microbending, the higher the loss and the less light transmitted. Therefore, microbending sensors require only a simple measurement of light intensity, not a sophisticated interferometric setup to measure phase.

Pressure is the most straightforward quantity to measure with a microbending sensor, as shown in Figure 29.3. You can adapt microbending sensors to measure both static pressure and acoustic waves by designing and calibrating them differently. For total pressure—such as detecting whether a car seat is occupied—you could use a fairly small sensor that would not respond to a 10-lb briefcase but would respond to a small 80-lb person. On the other hand, you would use a longer length of more sensitive fiber to detect acoustic waves, monitoring output continuously to detect their variation in time.

Length and Refractive Index Changes

Changing length or refractive index causes a phase shift.

A large family of sensors depend on changes in the effective length of the sensor, which depends on both the refractive index and the physical length. Recall that the time, *t*, it takes light to travel through a length, *L*, of material with refractive index *n* is

$$t = \frac{nL}{c}$$

where *c* is the speed of light in a vacuum. You can think of *nL* as the "effective length" of the material. A change in temperature can affect both refractive index and physical length, giving

$$t = \frac{(n + \Delta n)(L + \Delta L)}{c} \approx \frac{nL + n\Delta L + L\Delta n}{c}$$

as long as the changes are small. The result is a change in transit time,

$$\Delta t = \frac{n\Delta L + L\Delta n}{c}$$

which is equivalent to a phase shift in the light emerging from the sensor.

Interferometric detection can sense this phase change. Note that the principles of operation are the same whether the sensor is detecting a temperature change that affects only physical length of the fiber, a pressure change that affects only its refractive index, or something that affects both.

Changes in Light Guiding

Refractive index change also can be measured if it affects light guiding in the fiber. Suppose, for example, the refractive indexes of core and cladding vary with temperature in different ways. At 0°C, the core index is 1.50 and the cladding index is 1.49. As temperature increases, the core index decreases by 0.0005 per degree, but the cladding index decreases by 0.0004 per degree. At 100°C, the two refractive indexes would both equal 1.45. At that point, the fiber would stop confining light to the core, so output light intensity would drop to near zero.

In practice, light intensity might decrease as the core and cladding indexes approach each other because at smaller index differences total internal reflection would trap an increasingly narrow range of light rays in a large-core fiber. However, the principle has been demonstrated in a sensor that can measure temperature within a few degrees.

A fiber Fabry-Perot interferometer detects a phase shift in a resonant cavity in the fiber.

Fiber Fabry-Perot Interferometer Sensors

The fiber Fabry-Perot interferometer is a sensor that detects a phase shift within a resonant cavity rather than by comparing the phase shifts of light taking two different paths. The

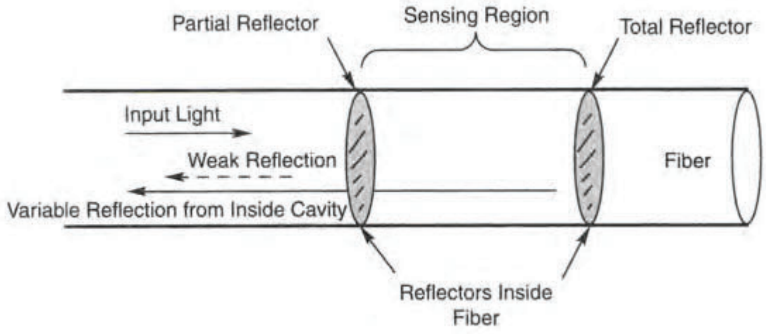


FIGURE 29.5
Fiber Fabry-Perot interferometer sensor.

sensing element is a section of fiber that has reflective layers on each end, as shown in Figure 29.5. Light passes through a partly reflecting layer and is reflected by a totally reflecting mirror some distance behind it. The layers can be made by splicing fiber segments together at those points.

These two mirrors form a Fabry-Perot interferometer, which has a series of resonances at characteristic wavelengths defined by the cavity length and refractive index. Recall that at a resonance the round-trip distance must equal an integral number of wavelengths in the material, with refractive index included to account for the difference between the vacuum wavelength, λ, and the wavelength in the material, λ/n.

$$N\lambda = 2Ln$$

If the wavelength stays fixed and the cavity is long compared to the wavelength, the intensity of the reflected light changes with variations in length or refractive index. In temperature sensors, the change in refractive index is about 20 times larger than the change in length, so it dominates the phase shift. The same approach can be used to sense pressure and strain.

Fiber Grating Sensors

Strain and temperature change peak reflectivity of a fiber grating.

The fiber Bragg gratings described in Chapter 7 also can be used as sensors when they are coupled to their environment in a way that affects the wavelength they select. As you learned in Chapter 7, the reflected wavelength $\lambda_{\text{reflected}}$ (measured in air) is

$$\lambda_{\text{reflected}} = 2nD$$

where n is the refractive index of the glass and D is the spacing of high-index zones in the grating.

Applying strain along the length of the fiber grating changes both the spacing of the grating and the refractive index of the fiber. The change in the wavelength is given in terms of change in grating spacing and refractive index by

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta D}{D} + \frac{\Delta n}{n}$$

Temperature also affects the grating spacing and refractive index. Measurements require an external light source that illuminates the grating and a detector that senses the change in peak reflectivity. Interferometric measurements can detect changes in the reflected wavelength, or a narrow-band filter can monitor changes in light intensity as the reflected wavelength changes.

Fiber gratings make sensitive sensors.

Fiber grating sensors are quite sensitive. At 1550 nm, a strain that changes fiber length one part in a million (or 1 microstrain) shifts wavelength by 1.2 picometers, and a 1°C temperature change shifts wavelength by 10 pm. Multiple gratings can be written on the same fiber, although care must be taken so that the channels do not overlap and interfere with each other.

Fiber gratings can be directly embedded into a variety of materials to monitor internal strain and the integrity of structures such as bridges and aircraft fuselages.

Fiber-Optic Gyroscopes

A fiber-optic gyroscope measures rotation interferometrically.

The *fiber-optic gyroscope* is probably the most successful fiber sensor so far. It relies on optical processes to sense rotation around the axis of a ring of fiber. Rotation sensing is vital for aircraft and missiles, which have traditionally used gimbaled mechanical gyroscopes as references. Fiber gyroscopes (and laser gyroscopes that serve a similar purpose but operate on different principles) offer a number of advantages, including no moving parts, greater reliability, and no need for a warm-up period to start the gyro.

Figure 29.6 shows the effect that is the basis of a fiber gyro. Light from a single source is split into two beams directed into opposite ends of a single-mode fiber. In actual sensors, the fiber is wound many times around a cylinder, but the drawing shows only one turn for clarity. Light takes a finite time to travel around a fiber loop, and in that time the loop can rotate a small amount. When the beams return to their starting point, that point has moved, and the two have traveled slightly different distances.

For simplicity, assume the loop is a circle with radius r and circumference $2\pi r$. During the interval that light travels around this loop, it rotates an angle θ, which is exaggerated in Figure 29.6b. To come back to the coupler where the beams combine, the counterclockwise beam must go an extra distance, Δ, from the point where it started, a total of $2\pi r + \Delta$. However, the clockwise beam goes a shorter distance, $2\pi r - \Delta$. The result is a phase shift of the two beams when they come to the coupler by an amount 2Δ. Figure 29.6c shows this as a total phase shift of 180°. This phase shift, called the *Sagnac effect*, can be detected with an interferometer for two beams passing in opposite directions through a suitable single-mode fiber.

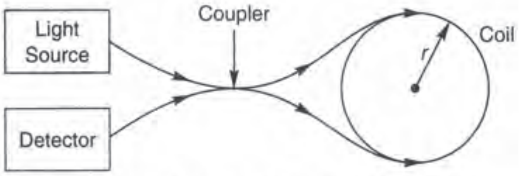
The distance Δ is a function of the rotation θ, given by

$$\Delta = \left(\frac{\theta}{360^\circ}\right) \times 2\pi r$$

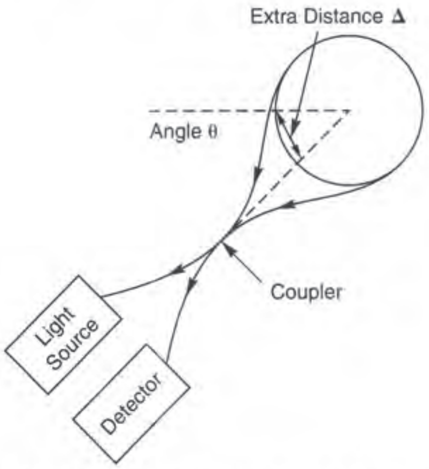
The actual phase shift is 2Δ or twice that value, which you have to remember when you calculate the rotation. In practice, the angle of rotation is calculated from the cumulative phase shift from the time the fiber gyro starts operating. If you start out heading north, and have a cumulative phase shift of 90° to the right, you wind up heading east.

Fiber gyros can be used as part of an inertial navigation system, which keeps track of a vehicle's position. Three separate fiber gyros keep track of the vehicle's angular direction on three perpendicular axes. To know its position, you also have to keep track of the time, so you know when the vehicle made a particular turn. You also need a separate accelerometer

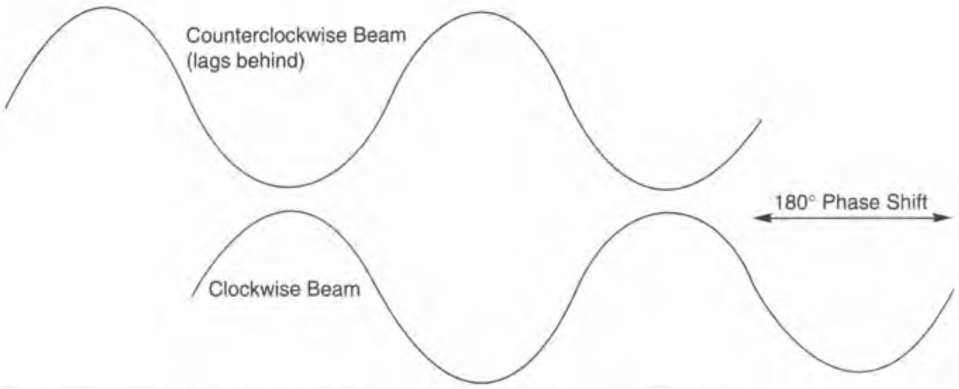
FIGURE 29.6
Fiber-optic gyroscope.



(a) Input light is split into two beams, which travel in opposite directions through coil.



(b) Rotation by angle θ moves loop so beams recombine after clockwise beam has gone shorter distance than counterclockwise beam.



(c) Rotation phase-shifts the clockwise beam ahead of the counterclockwise beam.

to measure acceleration and thus deduce how fast the vehicle is moving and—by keeping track of time—how far it has traveled. Current fiber gyros maintain direction accurately to around one degree per hour.

Fiber gyros are not as accurate as laser gyros, but they are less expensive and are entirely solid-state, unlike laser gyros that use gas lasers. Their low cost and durability make fiber gyros attractive for applications such as guiding missiles (which you don't want to load with lots of expensive equipment) and short-range aircraft. Without any moving parts, they are inherently more reliable than mechanical gyros. Fiber gyros were proposed for use in cars, but global positioning system (GPS) receivers are less expensive and have gained the lead in automobile navigation systems.

Smart Skins and Structures

Fiber sensors can be embedded in composites and other materials such as concrete to create *smart structures* or *smart skins.* The goal is to create a structural element (including the skins of aircraft) equipped to monitor internal conditions. The initial emphasis is on verifying that components meet initial structural requirements, but the fiber sensors could be used throughout the life of the component. Figure 29.7 shows how fibers can be embedded between layers of a composite material; in this case, they are encased in an epoxy layer.

Fiber sensors are embedded in composites to make smart structures and skins.

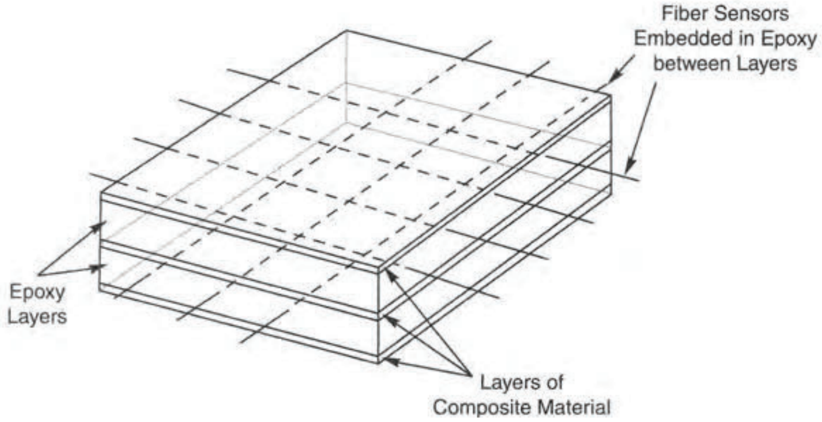
One use of embedded fiber sensors is to monitor fabrication and curing of the composite. The fiber sensors can monitor temperature to be sure curing conditions meet requirements. They can also monitor strain to verify that the component is not stressed excessively. Detection of cracked fibers indicates serious stress problems. Later, the fiber sensors can provide data on stresses and strains that occur after the composite component is mounted in its final position. Eventually this information may be used by operating engineers, but currently its main use is in studying properties of structures and aircraft.

Once a smart-skin or smart-structure system is in operation, engineers could use the fiber sensors for periodic checks of performance and structural integrity. For example, fibers embedded in aircraft wings could be plugged into monitoring equipment in the service bay to make sure they suffered no invisible internal cracks that could cause catastrophic failure. Dams and bridges likewise could be monitored by embedded fibers.

Some military planners think the ultimate step would be to plug the fiber sensors into a real-time control system designed to optimize performance. The performance limits of aircraft materials and structures are not known precisely, so engineers err on the side of safety and avoid pushing too far. Real-time fiber monitors could tell computers how well components were withstanding stresses in operation. Ultimately, perhaps, the computers could use the sensor data to apply corrections in real-time that would push the performance envelope further, without endangering pilots or aircraft.

FIGURE 29.7

Sensing fibers in a smart skin are embedded in an epoxy matrix between layers of a composite material.



What Have You Learned?

1. Fibers can serve as probes that collect light for sensing. Fibers can also function as sensors themselves.
2. Fiber probes can detect objects that block or reflect light. This lets them measure shapes, count parts, and do other simple tasks.
3. Fiber optics can collect light from remote optical sensors so it can be measured.
4. Sensors convert something hard to measure into units easier to observe.
5. Intrinsic fiber sensors detect changes in the way fibers transmit light. Unlike communication fibers, these fibers are designed to respond to changes in the environment.
6. Fiber sensors work by modulating light they transmit, either by changing light intensity, by affecting polarization, or by shifting the phase of the light.
7. Interferometric sensors measure phase changes; they can detect very small shifts.
8. Placing a fiber in a place where pressure can cause microbending allows the fiber to sense pressure; the more pressure, the more light lost from the fiber.
9. Temperature and pressure can change the refractive index of glass in a fiber, causing phase shifts and other effects.
10. A fiber Fabry-Perot interferometer detects a phase shift within a resonant cavity in a fiber.
11. Fiber grating sensors detect a shift in peak reflected wavelength when strain or temperature change the grating period and the refractive index of the fiber.
12. Loops of fiber can measure rotation by sensing differences in the time light takes to travel in opposite directions around the loop. Such fiber gyroscopes can be used in guidance systems.
13. Fiber sensors can be embedded in composite materials to make smart structures and smart skins.

What's Next?

In Chapter 30, I will look at other noncommunication applications of fiber optics.

Further Reading

David A. Krohn, *Fiber Optic Sensors: Fundamentals and Applications* (Instrumentation, Systems, and Automation Society Press, Research Triangle Park, NC, 2000)

Herve C. Lefevre, *Fiber-Optic Gyroscope* (Artech House, 1993)

Jose Miguel Lopez-Higuera, ed., *Handbook of Optical Fibre Sensing Technology* (Wiley, 2002)

A. Selvarajan, "Fiber Optic Sensors and Their Applications" *http://www.ntu.edu.sg/mpe/research/programmes/sensors/sensors/fos/foselva.html*

Eric Udd, ed., *Fiber Optic Sensors: An Introduction for Engineers and Scientists* (Wiley, 1991)

Questions to Think About

1. A crack sensor uses a step-index multimode fiber with 100-μm core to detect structural failure. It sets off an alarm when light intensity drops 10 dB. If a crack splits the block of material containing the fiber and causes one side to drop, estimate how far it must drop to set off the alarm. Ignore end reflection effects.
2. Temperature causes the refractive index of a fiber to increase by 0.001% per degree. Two arms of an interferometric fiber sensor each contain 1 cm of fiber. One arm is exposed to the environment, the other is kept at a constant temperature. If you use 1-μm light, how much temperature change is needed to produce a 180° phase shift?
3. There are two different ways you could increase the sensitivity of the interferometric sensor in Question 2 so the sensor measures a 1° temperature change with a 180° phase shift, without changing the glass used in the fiber. What are they?
4. A fiber-optic gyroscope includes a 1-m loop of fiber and a laser light source emitting at 1 μm. How much rotation does it take to cause a 180° phase shift between the two counter-propagating beams?
5. Recall that light travels roughly 3×10^8 m/s. What rotation rate does the 180° phase shift in Question 4 correspond to if it's detected over the time light takes to circle through the fiber once?

Chapter Quiz

1. How do fiber-optic probes work?
   a. They detect the presence or absence of light at a point.
   b. They detect the pressure of objects placed on top of them.
   c. Changes in temperature make them expand or contract.
   d. None of the above
2. Which of the following is an example of a fiber collecting light from a remote optical sensor?
   a. fiber-optic gyroscope
   b. liquid-level sensor based on total internal reflection from a prism
   c. acoustic sensor based on microbending

   d. fiber grating used as a pressure sensor
   e. smart skins

3. How can microbending effects be sensed?
   a. by observing tension along the length of the fiber
   b. by monitoring changes in light transmitted by the fiber
   c. by looking for changes in data rate of a signal transmitted through the fiber
   d. by measuring light emitted by the fiber

4. Which of the following can change the refractive index of a fiber?
   a. temperature changes
   b. pressure changes
   c. sound waves
   d. all of the above
   e. none of the above

5. Which sort of change in a fiber sensor can be measured by interferometry?
   a. changes in microbending
   b. changes in intensity of light
   c. changes in refractive index caused by pressure
   d. changes in optical absorption

6. An example of an interferometric sensor is a
   a. punched card reader.
   b. microbending sensor of acoustic waves.
   c. fiber-optic gyroscope.
   d. sensor that measures the height of parts on a production line.

7. How do fiber grating sensors work?
   a. Microbending causes increased attenuation.
   b. They alter wavelengths transmitted and reflected.
   c. They change polarization.
   d. They modulate light with a digital code.

8. A 1° increase in temperature reduces the refractive index of the glass in a sensing fiber by 0.000005 at a wavelength of 1 μm. Assuming the length of the fiber does not change significantly, how much does a 10° change in temperature shift the phase of 1-μm light passing through a 10-mm sensor?
   a. 1.8°
   b. 90°
   c. 180°
   d. 360°
   e. 1800°

9. How do fiber-optic gyroscopes detect rotation?

a. by measuring changes in the wavelength of light in the fiber
b. by interferometrically measuring differences in the paths of light going in opposite directions around a fiber loop
c. by detecting changes in polarization of light caused by inertial changes in the moving fiber loop
d. by measuring intensity changes caused by microbending
e. by detecting changes in the refractive index induced by acceleration

10. What can fiber sensors measure when embedded in a smart structure?

a. curing conditions of a composite material
b. internal strain in a composite material
c. structural integrity of a completed component
d. stresses on a component during use
e. all of the above

CHAPTER

30

Imaging and Illuminating Fiber Optics

About This Chapter

Communications and sensing were latecomers in the world of fiber optics. The early developers of fiber optics were interested in transmitting images through bundles of fibers. Fibers developed for imaging differ greatly from those designed for communications because different considerations affect performance. This chapter is about fiber-optic imaging and the related field of illumination. Some fiber-optic illumination uses *bundles* of fibers to deliver light, but much illumination is with single fibers. This chapter covers these diverse noncommunication applications of fiber-optic devices in medicine, industry, and military systems.

Basics of Fiber Bundles

As you read in Chapter 1, optical fibers were invented for imaging and were soon applied to illumination as well. Imaging requires a bundle of fibers, one to carry each point on the image. For imaging, the bundle must be *coherent*, which in this case means that the ends of the fibers must be arranged in the same way on both ends of the bundle. Project an image onto one end of a coherent bundle, and the same image appears on the other end.

To visualize how a coherent bundle works, start with a handful of drinking straws all the same length. With a little care, you can hold the straws so they are aligned parallel to each other. Look through the straws at a printed page, and you'll see the words through the array of little pipes. The smaller the straws, the smaller the bit of the page you see through each one. Individual fibers are like individual straws, but they are much thinner and far more flexible. Fibers guide light by total internal reflection, but straws only transmit light straight along their axes.

Coherent bundles have the fibers in the same places on both ends.

There are two basic families of fiber bundles, each developed for distinct applications. Long, thin flexible bundles of loose fibers are used to examine or deliver light to otherwise inaccessible places. Important examples are the flexible endoscope threaded down a patient's throat to examine the stomach, and the flexible colonoscope used to examine the colon. Industrial counterparts are used to inspect the interiors of engines. Imaging requires coherent bundles, but illumination normally is done with bundles in which the fibers are randomly aligned. For most imaging and illumination applications, flexibility is important.

A second family is rigid fiber bundles in which the fibers have been fused together to make a solid block. Processing retains the light-guiding structure of the individual fibers that are aligned end to end in the bundle. Usually they are shorter and fatter than flexible bundles. These fused bundles can be used as optical devices for transmitting or magnifying images piece by piece, as well as for some types of inspection and for some other optical applications.

Both types of fiber bundles are based on step-index multimode fibers with thick cores and thin claddings. This structure means that light reaching the input face of the bundle is most likely to fall on a core, so it is transmitted to the other end of the bundle. Individual fibers may be drawn quite thin, but the ratio of core to cladding thickness remains unchanged. The difference between core and cladding index is larger than in communication fibers, so the cores can be drawn finer and still transmit multiple modes of light. Single-mode transmission is not desirable in imaging or illumination fibers because it limits how much light they can collect at the face of the bundle.

Making Fiber Bundles

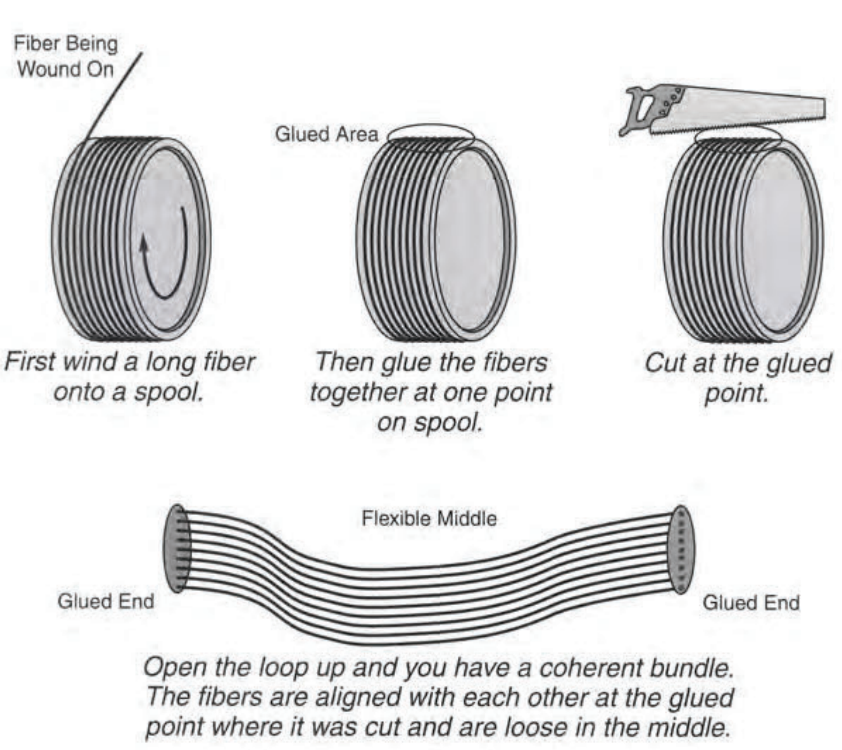
Long, thin flexible bundles are made by winding a fiber around a spool and cutting through a glued region.

Figure 30.1 shows one way to make coherent fiber bundles. Start by looping a single long, thin fiber many times around a spool, glue the fibers together in one spot and remove them from the spool. Then cut through the glued region. This gives a flexible bundle, with fibers loose in the middle and fixed on both ends. Because the two ends were originally adjacent to each other, the fibers are all in the same positions.

This approach is simple in concept and dates back to the mid-1950s, when it was used to make the first flexible fiber bundle. However, it is a demanding process and is difficult when using very thin fibers, which are likely to break.

Fused imaging bundles are drawn jointly into solid rods.

An alternative approach is to draw many fibers simultaneously to finer and finer diameters in a series of stages. The first step is to draw a step-index fiber with a diameter about 2.5 mm. These fibers are easy to handle, and a group of them—typically 37 to 169—are grouped together, heated until they soften, and stretched out into a rigid *multifiber* about 2 mm in diameter, as shown in Figure 30.2. Then a number of multifibers (typically 61 to 271) are packed together, heated, and drawn again to produce a rigid fiber bundle, containing many thousands of fibers. Each fiber in the final bundle is about 3 to 20 μm in diameter. The number of fibers drawn together in each step is chosen to make patterns that pack together well.



First wind a long fiber onto a spool.

Then glue the fibers together at one point on spool.

Cut at the glued point.

Open the loop up and you have a coherent bundle. The fibers are aligned with each other at the glued point where it was cut and are loose in the middle.

FIGURE 30.1
Flexible bundle made by winding fiber around a spool.

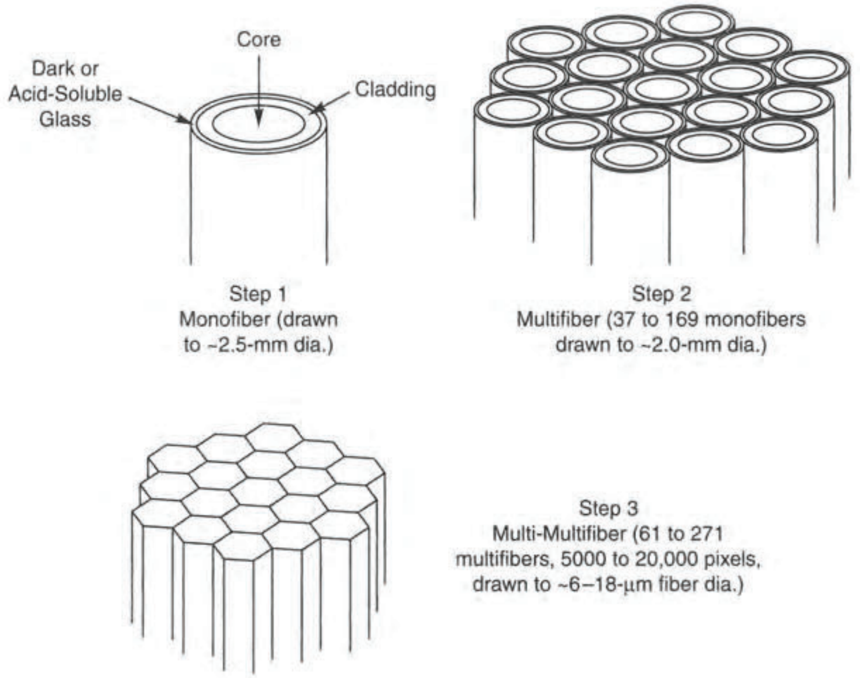
The *fused fiber* bundle process can be used to make flexible bundles, with a few important changes. Look carefully at Figure 30.2, and you will note that the large core is surrounded by two rings of cladding. One is the conventional low-index cladding that confines light to the core in all fibers. The composition of the other depends on the type of bundle being made.

For rigid bundles, that outer layer is a dark absorptive glass that keeps light from leaking between the cores in the bundle. A certain amount of light always leaks into the fiber cladding. Usually this stays in the inner part of the cladding, but for imaging bundles the cladding is quite thin. If the claddings were all fused together—as they would be without the dark glass—the light could freely disperse through the whole bundle within the fused cladding glass. Then it could leak back into the cores and degrade the image.

For flexible bundles, that outer layer is a glass that is soluble in acid. Manufacturers cover the ends of the rigid rod and then dip the whole fused bundle into an acid that dissolves away that leachable layer in the middle of the rod, leaving a flexible bundle of many thin fibers, which are arranged so their ends are aligned for imaging.

Individual fibers in a flexible coherent bundle can be small, but not quite as small as in a fused bundle. Some performance limits of flexible bundles are comparable to those of rigid bundles. When flexible bundles are used, an added concern is breakage of individual fibers, which does not occur in fused bundles. Each fiber break prevents light transmission from one spot on the input face. The loss of a single fiber is not critical, but as more fibers break, the transmitted light level drops and resolution can decline as well. Eventually breakage reaches a point where the image-transmitting bundle is no longer usable. Plastic fibers can reduce the breakage problem, but have other limitations.

FIGURE 30.2
Stages in making a fiber bundle. (Courtesy of Schott Fiberoptics)



Randomly aligned bundles serve as "light pipes."

Randomly aligned bundles are made by collecting many fibers into a bundle, much like collecting strands of spaghetti. This would be very difficult if the fibers were as thin as those in imaging bundles, but such fine fibers are not needed because the resolution does not matter; random bundles serve purely as "light pipes." Typically, random bundles are made of fibers with diameters in the 100-μm range, which are flexible enough to bend freely with minimum fiber breakage.

Imaging and Resolution

Resolution is a crucial issue in an imaging fiber bundle. Figure 30.3 shows how an image is carried from one end of the bundle to the other. Each fiber core carries its own segment of the image to the other end, maintaining its alignment.

Bundle resolution depends on the core sizes of the fibers it contains.

To visualize what happens, imagine that each fiber core captures a chunk of the image and delivers it to the other end of the bundle. This process averages out any details that fall within a single core. For example, if the input to a single core is half black and half white, the output will be gray. Thus, the fiber cores must be small to see much detail. For a stationary fiber bundle, the resolution is about half a line pair per fiber core, meaning two fiber core widths are needed to measure a line pair. Numerically, that means 10 μm fiber cores could resolve 50 line pairs per millimeter (1 line pair per 20 μm). Imaging bundles have fiber cores as small as 3 μm. Resolution is significantly higher—about 0.8 line pair per fiber core diameter—if the fiber bundle is moving with respect to the object.

Before you wonder too much about the quality of fiber-bundle images, you should realize that fiber cores typically are about 10 μm. If that was the case, the letter A in Figure 30.3 would be only 60 μm high, less than $\frac{1}{16}$ mm tall. That's many times smaller than the finest

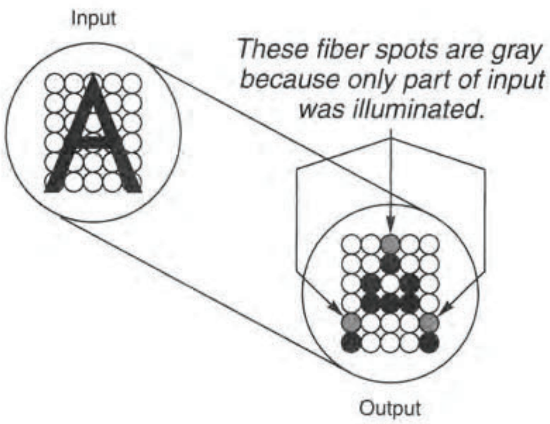


FIGURE 30.3
Image transmission through a fiber bundle.

of fine prints used in legal documents. You have to look very hard, and may need a strong magnifying lens to see the individual fiber spots on a good imaging bundle.

Cladding Effects

Light that falls into fiber claddings in bundles is lost, but typically 90% falls onto fiber cores.

The cores conduct light in fiber bundles, but they are surrounded by cladding layers. Bundles are made with thin cladding layers, but some light must fall onto the cladding rather than the core. The fate of that light depends on the bundle design. Fibers in rigid bundles have a dark outer cladding layer that absorbs light so that little can pass between fiber cores. Light that leaks out of the cores of individual fibers in flexible bundles cannot easily enter other fibers. However, neither type can completely prevent light from leaking between fibers.

Most light entering the cladding is lost, which can limit transmission efficiency. This makes the fraction of the surface made up by fiber cores an important factor in a bundle's light-collection efficiency. That is, the collection efficiency depends (in part) on the *packing fraction*, defined as

$$\text{Packing fraction} = \frac{\text{total core area}}{\text{total surface area}}$$

A typical value is around 90%.

Transmission Characteristics

Typical attenuation of bundled fiber is around 1 dB/m.

Fiber bundles need to carry light only a few meters, so they do not have as low attenuation as communication fibers. Typical attenuation of bundled fiber is around 1 dB/m, thousands of times higher than that of communication fibers at 1550 nm.

Likewise, operating wavelengths differ. Visible light is needed for imaging and illumination, and even for other applications the short distances make it unnecessary to operate at wavelengths where fibers are most transparent. Glass fiber bundles are typically usable at wavelengths of 400 to 2200 nm, and special types made from glass with good ultraviolet transmission are usable at somewhat shorter wavelengths. Plastic fibers are usable at visible wavelengths, 400 to 700 nm. Some special-purpose bundles are made of other materials, but they are not widely used.

Bundled fibers are step-index multimode types with large NA.

Bundled fibers generally have higher numerical apertures than communication fibers, because light-collection efficiency is critical and pulse dispersion is irrelevant. The relatively large difference between core and cladding index gives bundled fibers typical NAs of 0.35 to 1.1. The same holds true for large-core single fibers used in illumination; larger NAs are better because they boost light-collection efficiency.

Optics of Bundled Fibers

Some simplifications valid for communications are not valid for bundled fibers.

The underlying principles of fiber optics are the same if fibers are separate or bundled. However, earlier descriptions of communication fibers relied on some simplifications of optical principles. These simplifications don't always work for bundles or other noncommunication fibers. It's time to go back and face some complications that don't affect communications through single fibers.

Light Rays in Optical Fibers

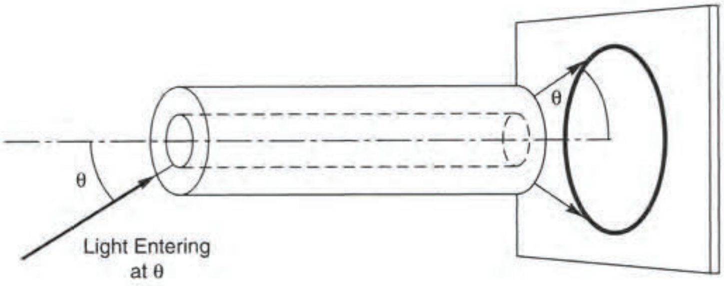
Light rays are an important concept in understanding how optical devices affect light. Earlier you learned how lenses worked, and saw a simple explanation of how total internal reflection of light rays guides light down a fiber. Those explanations are true as far as they go, but the behavior of light rays in a fiber is a bit more complicated.

As shown in Figure 30.4, a light ray that enters the fiber at an angle θ to the fiber axis will later emerge at roughly the same angle to the fiber axis, as long as the ray is within the fiber's acceptance angle. However, the ray may not emerge in the same direction; it will be part of a ring of light at roughly the original angle to the fiber axis. *Roughly* is the operative word, because imperfections in the fiber and other factors cause the light to emerge in a ring of angles centered on θ.

This does not conflict with what you learned about communication fibers. There the light ray was only an example of the path light could follow. In looking at multimode fibers, we considered the light rays and the modes collectively, never worrying about individual mode patterns. Generally there's no reason to worry about individual modes in multimode fibers.

FIGURE 30.4

Light rays emerge from a fiber in a diverging ring.



One other thing should be pointed out: step-index fibers with constant diameter cores do not focus light. (As you will see later, both tapered and graded-index fibers can focus light passing along their lengths.) All light emerges from a step-index multimode fiber at roughly the same angle that it entered, not at a changed angle, as would happen if it did focus light. As long as the fiber's sides and ends are straight and perpendicular to each other, a single step-index multimode fiber or a bundle of them—like a flat window pane—cannot focus light.

Step-index fibers with constant size cores do not focus light.

This has one important practical consequence that you'll discover the first time you look through an imaging bundle. You have to put the distant end up very close to what you want to see, or the image will become blurred. You see the image on the near end of the bundle because light travels straight through each fiber. For the light from the object to enter the right collecting fibers, it must either be focused onto the collecting end or the collecting end must be very close to the object, so light can't slip into other fibers.

If the fiber's output end is cut at an angle not perpendicular to its axis, light entering at an angle θ still emerges in a cone, but the center of the cone is at an angle to the fiber axis. If the slant angle (from the perpendicular) is a small value ϕ, the angle β by which the rays are offset is approximately

$$\beta = \phi(n - 1)$$

where n is the refractive index of the fiber core.

Tapered Fibers

I assumed earlier that fiber cores are straight and uniform, but they could also be tapered (although not over long distances). Figure 30.5 shows what happens to a light ray entering a tapered fiber at an angle θ_1. If the ray meets criteria for total internal reflection, it is confined in the core. However, it meets the core-cladding boundary at different angles on each bounce so each total internal reflection is at different angles from the axis. The result is that it emerges from the fiber at a different angle, θ_2. If input core diameter is d_1 and output core diameter is d_2, the relationship between input and output angles is

$$d_1 \sin \theta_1 = d_2 \sin \theta_2$$

Tapered fibers magnify or demagnify objects seen through them. Tapered fibers are used in bundles.

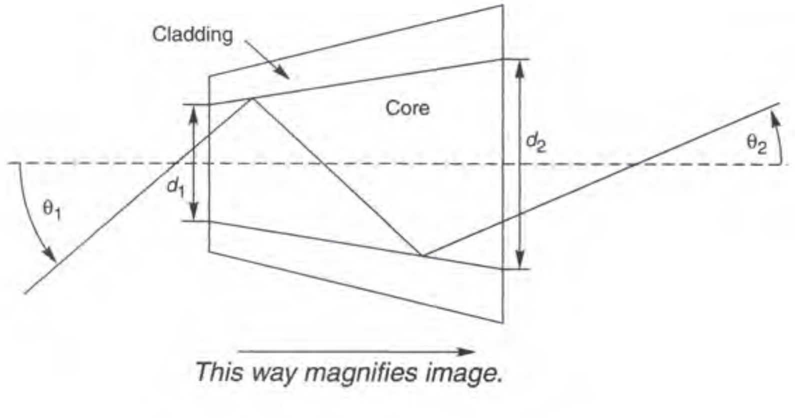


FIGURE 30.5
Light passing from the narrow to the broad end of a tapered fiber.

The same relationship holds for the fiber's outer diameter as long as core and outer diameter change by the same factor, d_2/d_1.

As a numerical example, suppose the input angle is 30° and the taper expands diameter by a factor of 2. The sine of the output angle θ_2 would be

$$\sin\theta_2 = \frac{d_1}{d_2}\sin\theta_1 = \frac{1}{2}(\sin 30^\circ) = 0.25$$

Thus θ_2 would be about 14.5° and light exiting the broad end of a taper would emerge at a smaller angle to the fiber axis than it entered. Conversely, light going from the broad end to the narrow end would emerge at a broader angle.

Tapered bundles of fused fibers can be used as magnifiers if the narrow end is placed on a page and you look at the top side. Each fiber expands or shrinks the spot of the image it transmits by the same amount. The eye sees this as each spot being spread over a larger area at the large end of the taper. This increases the size of the image, but not the clarity, because the transmitted image has only as many picture elements as the narrow end of the bundle.

Focusing with Graded-Index Fibers

Graded-index fibers can focus light in certain cases.

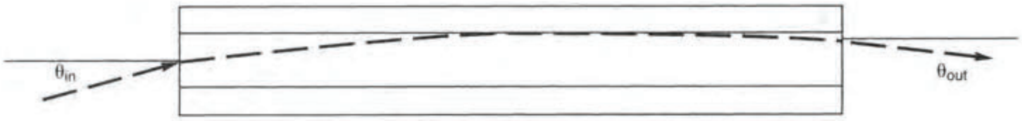
Unlike step-index fibers, graded-index fibers can focus light in certain cases. This does not make graded-index fibers useful for image transmission or other fiber-bundle applications, but short segments of graded-index fibers can function as focusing components in some optical systems.

In Chapter 4, you saw that light follows a sinusoidal path through graded-index fiber. When you looked at how a cone of light was transmitted through a long fiber, you saw output as a cone of the same angle. Now look instead at the path of an individual ray through a short segment of graded-index fiber, shown in Figure 30.6, and compare that with the path of a light ray in step-index fiber.

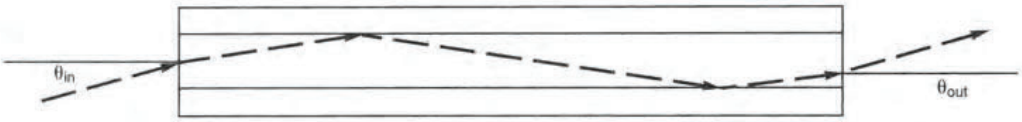
There is an important but subtle difference. Total internal reflection from a step-index boundary keeps light rays at the same angle to the fiber axis all along the fiber. However, graded-index fibers refract light rays, so the angle of the ray to the axis is constantly changing as the ray follows a sinusoidal path. If you cut the fiber after the light ray has gone

FIGURE 30.6

Rays in graded-index and step-index fibers.



a. Graded-index fiber: θ_{in} does not equal θ_{out} except at multiples of 180° pitch.



b. Step-index fiber: Input and output angles are always equal.

through 180° or 360° of the sinusoid, the light emerges at the same angle to the axis that it entered. However, if the distance the light ray travels is not an integral multiple of 180° of the sinusoid, it emerges at a different angle. This property allows segments of graded-index fiber to focus light.

In the design of *graded-index fiber lenses* (usually sold under the trade name *Selfoc*), the key parameter is the fraction of a full sinusoidal cycle that light goes through before emerging. That fraction is called the *pitch*. A 0.23-pitch lens, for instance, has gone through 0.23 of a cycle, or $0.23 \times 360° = 82.8°$. The value of the pitch depends on various factors including refractive-index gradient, index of the fiber, core diameter, and wavelength of light.

Pitch is a critical parameter of graded-index lenses.

Although the lenses are segments of fiber, they are short by fiber-optic standards, just a few millimeters long. Thus, they can be considered as rod lenses as well as fiber lenses.

These tiny fiber lenses are used in a variety of applications. Some are used in fiber-optic transmitters to focus light from an LED or diode laser so that it can be coupled efficiently into a fiber. Others are used in optical systems such as fax machines and scanners. A linear array of fiber-optic microlenses can focus light reflected from a small area of a page onto a linear array of sensors that detect the light. Ideally each sensor collects light focused by one microlens.

Imaging Applications

Imaging covers a broad range of fiber-bundle applications. Most imaging systems use lenses and conventional optics, but fiber bundles do a better job in certain cases. Imaging bundles often are better for reaching into inaccessible places, from the inside of the human body to the interior of machines. Let's look briefly at these applications.

Medical Endoscopes

The most important use of imaging fiber bundles is to allow physicians to look inside the body without surgery. This is done with special-purpose coherent fiber bundles called *endoscopes*, which are up to a couple of meters long. Versions called *gastroscopes* are threaded down the throat to examine the stomach. *Colonoscopes* are versions designed to examine the colon. Short rigid bundles are used for some medical examinations because of their high resolution, but flexible types are preferred for most purposes because they are easier to insert and manipulate through body orifices.

Endoscopes allow physicians to look inside body cavities.

Traditional fiber-optic endoscopes use one set of fibers to transmit light inside the body and a separate set to collect and view the reflected light. Lenses on the end of the instrument focus light onto the fiber bundle, so it does not have to be pressed against tissue. Endoscopes may include surgical tools to treat lesions in the stomach or colon. Some newer endoscopes use fibers to transmit light into the body, but collect light with a miniature CCD (charge-coupled device) imaging camera that is inserted into the body.

Some endoscopes include fibers capable of transmitting high laser powers as well as illuminating light, so physicians can perform laser surgery. For example, a surgeon performing microsurgery on the knee could make an incision to insert an endoscope. After viewing the area to be treated, the surgeon could look through the viewing fibers to align the instrument, look away, then fire laser pulses to treat the lesion. (Surgeons avoid watching during laser pulses to protect their eyes.) After each set of laser pulses, the surgeon looks back to check progress.

Industrial Inspection Instruments

Fiber-optic imaging instruments also are used in industry to inspect dangerous or otherwise inaccessible areas. Lenses on the end of the instrument focus light onto the end of the bundle. Flexible fiber bundles could be used in this way to examine the inside of a storage tank that has only one small opening. Fiberscopes also could examine the interiors of machinery.

Faceplates

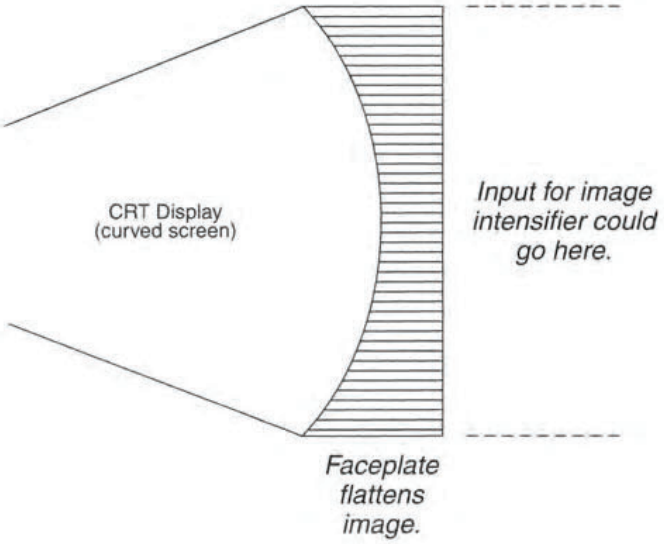
Image transmission does not have to be over a long distance. Another common application of fiber-optic image transmission is the fiber-optic *faceplate*, a thin slice of a coherent bundle in which individual fibers are only a fraction of an inch long. Faceplates are cut from longer, fused coherent bundles like slices of salami, although generally one or both surfaces are not flat.

Fiber-optic faceplates transfer light between surfaces of different shapes.

The job of a faceplate is to transmit an image between two stages of an imaging system that must amplify weak input light to generate a clearly visible image. It is typically used in military systems where faint light is amplified so soldiers can see an image of the scene. Image amplifiers may go through multiple stages, each amplifying the input light by a certain factor. Infrared light is used to generate a visible image. The output stages often are strongly curved screens that can't be focused onto flat input devices without distortion. A faceplate can convert the curved output screen to a flat surface, as shown in Figure 30.7. If the input of the next stage works best with a curved screen, the other side of the faceplate can be curved to match.

The big advantage of the faceplate is that it transfers light very efficiently between two surfaces that otherwise can't be butted face to face. Suppose, for example, you're trying to

FIGURE 30.7
A fiber-optic faceplate transfers light from a curved display tube.



detect some very weak light from a scene illuminated only by starlight. A single-stage image-intensifier camera makes the image brighter, but not bright enough to see clearly. You want to add a second stage, but the output of the first stage is on a curved screen. Put a fiber faceplate between that output and the input of the second-stage tube and you lose very little light. An imaging lens would lose much more light. The first fiber-optic faceplates were developed for such military imaging tubes, and they remain in use for newer equipment.

Faceplates also can help flatten the curved image generated by some display screens, correct for distortion, and make the display appear brighter by concentrating light toward the viewer.

Image Manipulation, Splitting, and Combining

Coherent fiber bundles can do more than just transmit images; they can also manipulate them. Twisting a coherent bundle by 180° inverts the image. You can do the same with lenses, but a fiber-optic image inverter does not require as long a working distance, which is of critical importance in some military systems. (Some image inverters are less than 1 in. long.)

Coherent fiber bundles can manipulate images.

Another type of image manipulation possible with fused fiber optics is the image combiner and splitter shown in Figure 30.8. This is made by laying down a series of fiber-optic ribbons, alternating them as if shuffling a deck of cards. One ribbon goes from the single input to output 1, the next from the input to output 2, the next to output 1, and so on. Put a single image into the input, and you get two identical (but fainter) output images. Put separate images into the two outputs, and you get one combined image.

Similar ideas could be used in other image manipulators or in devices to perform operations on optical signals. However, before you rush out for a patent application on your

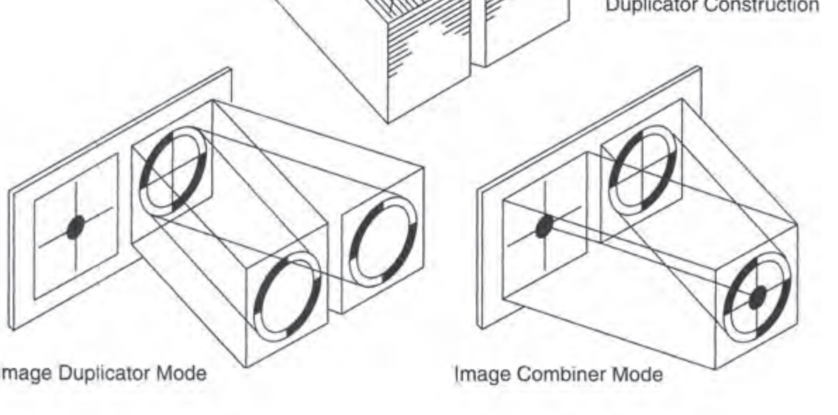


FIGURE 30.8
A fiber-optic image combiner and duplicator. (Courtesy of Galileo Electro-Optics Corp.)

own bright idea, you must face the ugly reality of cost. Manufacture of the fiber-optic image combiner in Figure 30.8 requires time and exacting precision, making it too expensive for most uses. Image inverters are used in some systems, but only where less costly lens systems won't do the job.

Light Piping and Illumination

Light piping delivers light through optical fibers.

Illumination and light piping are the simplest applications of optical fibers. *Light piping* is simply the transfer of light from one place to another by guiding it through one or more optical fibers. It doesn't matter how the fibers are arranged, as long as they deliver the light to the desired place. Thus fibers need not be arranged in the same way at both ends of an illuminating bundle. A single fiber may suffice for many applications.

Light piping for illumination is merely the delivery of light to a desired location. Why bother with optical fibers to do a lightbulb's job? A flexible bundle of optical fibers can efficiently concentrate light in a small area, or deliver light around corners to places it otherwise could not reach, such as inside machinery. A fiber bundle also can deliver light without the heat generated by incandescent bulbs, and without bringing electric current near the illuminated spot. This can be important in locations where bulbs and current can't be used because of explosive vapors or heat-sensitive materials. Fiber bundles also can be divided to deliver light from one bulb to many separate places. Light-piping fibers also can serve as indicators, to verify that an important bulb is operating.

Another important application of light piping is *optical power delivery*, transmitting laser beams for medical treatment or industrial material working. Conventional laser systems use lenses or mirrors to focus beams onto the desired spots. These systems use large optics, making them bulky, which is cumbersome for fine tasks such as delicate surgery. Optical-fiber beam delivery systems are much easier to manipulate. Some are designed for surgeons to use with their hands; others are built for robotic control in factories.

Single large-core fibers can deliver powerful laser beams.

Single large-core step-index fibers are best for many power delivery applications as long as the input light can be concentrated into a single core. Low-loss, large-core silica fibers have surprisingly high power transmission capabilities, and can easily carry tens of watts over a few meters. Illuminating bundles transmitting lower powers can use smaller-core, step-index fibers of glass or plastic, as long as light intensities and heat levels are low.

If all fibers in an illuminating bundle go to the same place, they illuminate a single area. If they are directed to different places, they can form a patterned image, such as the fiber-optic sign shown in Figure 30.9. All the fibers collect input light from one bulb, then are splayed out to show the desired pattern. Diffusing lenses at the fiber ends can spread light to make large, easily visible spots. (The WALK sign makes a good example, but it's not widely used.)

A bundle of fibers spreading out from a single illuminating bulb can make a sparkling display, like the one that introduced me to fiber optics 30 years ago. Then they were a rarity, but today they're commonplace. At Christmas, you can buy little fiber splays to attach to Christmas tree lights, and at a recent trade show one company was handing out little plastic flashlights with a splay of plastic fibers that sparkled with colors at their tips. I couldn't resist and picked one up.

FIGURE 30.9
A fiber-optic sign.

What Have You Learned?

1. Rigid or flexible bundles of optical fibers can transmit images if the fibers that make them up are properly aligned at the ends (coherent). Rigid bundles are made of fibers fused together; flexible bundles contain separate fibers bonded at the ends. Resolution is limited by the size of the fiber cores, typically around 10 μm.
2. Bundles of fibers in which the ends are not aligned with one another serve as "light pipes" to illuminate hard-to-reach places. The bundle can be broken up on one end to form an image or display (e.g., a WALK sign).
3. Light that falls into fiber claddings in bundles is lost, but typically 90% falls onto fiber cores.
4. Imaging and other short-distance fibers generally have much higher attenuation than communication fibers. Bundled fibers are step-index multimode types with large NA.
5. Step-index multimode fibers do not focus light, but segments of graded-index fiber do focus light and can serve as lenses. Tapered fibers magnify or demagnify objects seen through them; they are used in bundles.
6. Thin fiber-optic faceplates are used to concentrate light from certain displays in a particular direction. They are used with certain high-performance imaging tubes, but not for ordinary cathode-ray tubes.

7. Coherent fiber bundles can invert, split, and combine images.
8. Endoscopy is the use of coherent fiber bundles to view inside the body without surgery.
9. Large-core fibers can deliver laser power for medicine or materials-working.

Further Reading

Schott Fiberoptics, "Introduction to Fiber Optic Imaging," *http://www.schottfiberoptics.com/introfiber.html*

Walter Siegmund, "Fiber Optics," Chapter 13 in Walter G. Driscoll, ed., *Handbook of Optics* (McGraw-Hill, 1978)

Questions to Think About

1. Many laser printers have resolution of 600 dots per inch. Could you spot those dots with a bundle of 10-μm fibers? (Assume that resolution in line pairs is equivalent to dots per inch.)
2. Using the criterion that the finest possible resolution corresponds to half a line pair per fiber core diameter, what is the largest core fiber that could resolve 300 line pairs per inch?
3. A typical packing fraction for bundled fiber is 90%. Assuming that the fiber cores are 10 μm and you can neglect space between fibers (not a good assumption, but it makes the math manageable), what is the outer diameter of each fiber and how thick is the cladding?
4. Given the same assumption about neglecting the spacing between fibers, what would be the packing fraction for a bundle assembled from 100/140 step-index multimode fibers?
5. You are trying to deliver a 50-W laser beam through a 3-m length of fiber with attenuation of 10 dB/km. How much power is lost in the fiber?
6. If you put a fiber-optic image inverter flat on a printed sheet of paper, you can read the inverted letters through the taper. You're seeing reflected light. How did it reach the paper?

Chapter Quiz

1. Which of the following statements is false?
    a. Coherent fiber bundles can transmit images.
    b. Coherent fiber bundles can focus light.

c. Graded-index fiber segments can focus light.
d. Imaging fiber bundles contain step-index multimode fibers.

2. A graded-index fiber lens has a pitch of 0.45. How much of a sinusoidal oscillation cycle do light rays experience in passing through it?

a. 27°
b. 45°
c. 81°
d. 162°
e. 180°

3. What does it mean to say that a fiber bundle has a packing fraction of 90%?

a. 90% of the fibers are intact.
b. 90% of the input surface is made up of optical fibers.
c. 90% of the input surface is made up of fiber core.
d. 90% of the input surface is made up of fiber cladding.
e. The bundle transmits 90% of the incident light through its entire length.

4. You want to resolve an image with 8 line pairs per millimeter. In theory, what is the largest fiber core size that you could use in a stationary coherent bundle?

a. 8 μm
b. 50 μm
c. 62.5 μm
d. 100 μm
e. 125 μm

5. Endoscopes used in medicine to view inside the body

a. usually are flexible fiber bundles.
b. sometimes transmit laser beams to treat disease.
c. can examine the stomach or colon.
d. all of the above
e. none of the above

6. Fiber-optic faceplates are

a. specialized sensors that detect temperature variations across a surface.
b. thin, rigid fiber bundles used to transfer light efficiently in image intensifiers.
c. assemblies of graded-index fiber lenses that focus light in photocopiers.
d. used on most television sets.

7. Average attenuation of bundled fibers is

a. 0.5 dB/km.
b. 1 to 5 dB/km.

   c. 10 to 100 dB/km.
   d. around 1 dB/m.

8. What types of fibers are used in imaging bundles?
   a. step-index multimode
   b. graded-index multimode
   c. step-index single-mode
   d. all of the above

9. The practical use of fiber-optic bundles to manipulate images is limited by what?
   a. poor resolution
   b. high attenuation
   c. fragility
   d. high cost

10. Which of the following is the most important advantage of random fiber bundles over coherent bundles for illumination?
   a. flexibility
   b. low cost
   c. size
   d. durability

APPENDIX A

Important Constants, Units, Conversion Factors, and Equations

Table A.1 Metric unit prefixes and their meanings

Prefix	Symbol	Multiple
peta-	P	10^{15} (quadrillion)
tera-	T	10^{12} (trillion)
giga-	G	10^{9} (billion)
mega-	M	10^{6} (million)
kilo-	k	10^{3} (thousand)
hecto-	h	10^{2} (hundred)
deca-	da	10^{1} (ten)
deci-	d	10^{-1} (tenth)
centi-	c	10^{-2} (hundredth)
milli-	m	10^{-3} (thousandth)
micro-	μ	10^{-6} (millionth)
nano-	n	10^{-9} (billionth)
pico-	p	10^{-12} (trillionth)
femto-	f	10^{-15} (quadrillionth)
atto-	a	10^{-18} (quintillionth)

Table A.2 Standard symbols in optics and physics

Quantity	Symbol
Angle	θ (Greek theta) or φ (Greek phi)
Boltzmann constant	k
Change	Δ (Greek delta)
Decibels	dB
Decibels relative to 1 mW	dBm
Decibels relative to 1 μW	dBμ
Energy	E (sometimes Q)
Frequency	ν (Greek nu)
Intensity	I
Planck's constant	h
Power	P
Pulse spreading	Δt
Refractive index	n
Speed of light	c
Time	t
Wavelength	λ (Greek lambda)

Table A.3 Important physical constants

Boltzmann constant *(k)*	2.380658×10^{-23} J/K
Charge of electron *(e)*	1.602177×10^{-19} coulomb
Planck's constant *(h)*	4.14×10^{-15} eV/sec
Planck's constant *(h)*	$6.6260755 \times 10^{-34}$ J/sec
Speed of light *(c)*	299,792.458 km/sec

Table A.4 Important conversion factors

From	To	Multiply by
Ångstroms (Å)	nm	0.1
electron volts (eV)	joules (J)	1.602177×10^{-19}
ergs	joules (J)	10^{-7}
inch	mm	25.4

continues

Table A.4 (continued)

joules (J)	ergs	10^7
km	miles (statute)	0.6214
lb	kg	0.453592
miles (statute)	km	1.6093
mils (0.001 inch)	μm	25.4
mm	inch	0.03937

Table A.5 Other useful data and formulas

Attenuation in decibels: $\mathrm{dB} = -10 \log_{10} \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}$

Bandwidth (MHz) $= \frac{350}{\Delta t\,(\mathrm{ns})}$

Critical angle: $\theta_c = \arcsin\left(\frac{n_{\mathrm{clad}}}{n_{\mathrm{core}}}\right)$

Cutoff wavelength (single-mode): $\lambda_c = \frac{\pi D \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2}}{2.4}$

Data rate: Maximum NRZ in bits per second $= \frac{0.7}{\Delta t\,(\mathrm{total})}$

Data rate: Maximum RZ in bits per second $= \frac{0.35}{\Delta t\,(\mathrm{total})}$

Dispersion: $\Delta t_{\mathrm{total}} = \sqrt{(\Delta t_{\mathrm{modal}})^2 + (\Delta t_{\mathrm{chromatic}})^2 + (\Delta t_{\mathrm{PMD}})^2}$

Frequency in terms of wavelength and speed of light: $v = c/\lambda$

Numerical aperture: $\mathrm{NA} = \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2}$ (sine of half-acceptance angle)

Photon energy in terms of frequency: $E = hv$

Photon energy in terms of electron volts: $E = \nu \times (4.14 \times 10^{-15}\ \mathrm{eV/sec})$

Photon energy in terms of joules: $E = \nu \times 6.6260755 \times 10^{-34}\ \mathrm{J/sec}$

Photon energy in terms of wavelength: $E = hc/\lambda$

Power output when input and loss are known: $P_{\mathrm{out}} = P_{\mathrm{in}} \times 10^{(-\mathrm{dB}/10)}$

Refractive index of material: $n = \frac{c_{\mathrm{vacuum}}}{c_{\mathrm{material}}}$

Resonances of laser cavity (length L): $N\lambda = 2nL$

Snell's law of refraction: $n_i \sin I = n_r \sin R$

continues

Table A.5 Other useful data and formulas (continued)

Speed of light in terms of frequency and wavelength: $c = \lambda v$

Wavelength in terms of frequency and speed of light: $\lambda = c/v$

Wavelength of 1 eV photon = 1.2399 μm

Wavelength of photon with energy E: $\lambda = hc/E$

Table A.6 ITU wavelength bands

Name	Meaning	Wavelengths (nm)
O-band	Original	1260–1360
E-band	Extended	1360–1460
S-band	Short	1460–1530
C-band	Conventional	1530–1565
L-band	Long	1565–1625
U-band	Ultra-long	1625–1675

Table A.7 CWDM channels (ITU G.964.2)

O-band	1270 nm
	1290 nm
	1310 nm
	1330 nm
	1350 nm
E-band	1370 nm
	1390 nm
	1410 nm
	1430 nm
	1450 nm
S-band	1470 nm
	1490 nm
	1510 nm
C-band	1530 nm
	1550 nm
L-band	1570 nm
	1590 nm
	1610 nm

APPENDIX B

Decibels and Equivalents

Decibels and equivalent power ratios

Loss in Decibels	Power Ratio
0.1	0.9772
0.2	0.9550
0.3	0.9333
0.4	0.9120
0.5	0.8913
0.6	0.8710
0.7	0.8511
0.8	0.8318
0.9	0.8128
1	0.7943
2	0.6310
3	0.5012
4	0.3981
5	0.3162
6	0.2512
7	0.1995
8	0.1585
9	0.1259
10	0.1
20	0.01

continues

Decibels and equivalent power ratios (continued)

Loss in Decibels	Power Ratio
30	0.001
40	0.0001
50	0.00001
60	0.000001
70	0.0000001
80	0.00000001
90	10^{-09}
100	10^{-10}
200	10^{-20}
300	10^{-30}
400	10^{-40}
500	10^{-50}
600	10^{-60}
700	10^{-70}
800	10^{-80}
900	10^{-90}
1000	10^{-100}

APPENDIX C

Standard Time-Division Multiplexing Rates

North American Digital Telephone Hierarchy (Plesiochronous Digital Hierarchy)

Rate Name	Data Rate	Nominal Voice Circuits
Single circuit	64,000 bit/s	1
T1 or DS1	1.544 Mbit/s	24
T2 or DS2	6.312 Mbit/s	96
T3 or DS3	44.736 Mbit/s	672
*T3C or DS3C	90 Mbit/s	1,344
*T4 or DS4	274 Mbit/s	4,032

*Obsolete (not used in new equipment)

ITU/European Digital Telephone Hierarchy

Rate Name	Data Rate	Nominal Voice Circuits
Single circuit	64,000 bit/s	1
Level 1	2.048 Mbit/s	30
Level 2	8.448 Mbit/s	120
Level 3	34.3 Mbit/s	480
Level 4	139 Mbit/s	1920
*Level 5	565 Mbit/s	7680

*Obsolete (not used in new systems)

SONET/Synchronous Digital Hierarchy (SDH)

SONET Rate Name	SDH Rate Name	Data Rate	Nominal Equivalent
OC-1/STS-1	—	51.84 Mbit/s	672 voice 1 T3
OC-3/STS-3	STM-1	155.52 Mbit/s	2016 voice 1 Level 4
OC-12/STS-12	STM-4	622.08 Mbit/s	8064 voice
OC-48/STS-48	STM-16	2.488 Gbit/s	32,256 voice
OC-192/STS-192	STM-64	9.953 Gbit/s (10 Gbit/s)	129,024 voice
OS-768/STS-768	STM-256	40 Gbit/s	516,096 voice

APPENDIX D

ITU Frequencies and Wavelengths for L- and C-bands, 100-GHz Spacing, 100 Channels

Frequency (THz)	Wavelength (nm)
186.00	1611.79
186.10	1610.92
186.20	1610.06
186.30	1609.19
186.40	1608.33
186.50	1607.47
186.60	1606.60
186.70	1605.74
186.80	1604.88
186.90	1604.03
187.00	1603.17
187.10	1602.31
187.20	1601.46
187.30	1600.60
187.40	1599.75
187.50	1598.89
187.60	1598.04
187.70	1597.19
187.80	1596.34
187.90	1595.49
188.00	1594.64
188.10	1593.79
188.20	1592.95
188.30	1592.10
188.40	1591.26
188.50	1590.41
188.60	1589.57
188.70	1588.73
188.80	1587.88
188.90	1587.04

continues

ITU Frequencies and Wavelengths (continued)

Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
189.00	1586.20	192.50	1557.36
189.10	1585.36	192.60	1556.55
189.20	1584.53	192.70	1555.75
189.30	1583.69	192.80	1554.94
189.40	1582.85	192.90	1554.13
189.50	1582.02	193.00	1553.33
189.60	1581.18	193.10	1552.52
189.70	1580.35	193.20	1551.72
189.80	1579.52	193.30	1550.92
189.90	1578.69	193.40	1550.12
190.00	1577.86	193.50	1549.32
190.10	1577.03	193.60	1548.51
190.20	1576.20	193.70	1547.72
190.30	1575.37	193.80	1546.92
190.40	1574.54	193.90	1546.12
190.50	1573.71	194.00	1545.32
190.60	1572.89	194.10	1544.53
190.70	1572.06	194.20	1543.73
190.80	1571.24	194.30	1542.94
190.90	1570.42	194.40	1542.14
191.00	1569.59	194.50	1541.35
191.10	1568.77	194.60	1540.56
191.20	1567.95	194.70	1539.77
191.30	1567.13	194.80	1538.98
191.40	1566.31	194.90	1538.19
191.50	1565.50	195.00	1537.40
191.60	1564.68	195.10	1536.61
191.70	1563.86	195.20	1535.82
191.80	1563.05	195.30	1535.04
191.90	1562.23	195.40	1534.25
192.00	1561.42	195.50	1533.47
192.10	1560.61	195.60	1532.68
192.20	1559.79	195.70	1531.90
192.30	1558.98	195.80	1531.12
192.40	1558.17	195.90	1530.33

APPENDIX E

Laser and Fiber Safety

With the exercise of reasonable common sense, fiber-optic systems are reasonably safe. As in any workplace, you should always be careful of chemicals, electrical voltages, and flying fragments that might endanger the eyes. Two potential hazards are specific to fiber-optic systems: sharp fiber fragments and laser light.

Fiber fragments are sharp, very small, and extremely hard to see. They can do serious damage in the wrong place, especially in your eye. They are very light, so they can easily fly into the air when cut, making good safety goggles particularly important when fibers are to be cut. Fragments are hard to see on many surfaces, so you should keep careful track of them. The best procedure is to grasp them with tweezers and dispose of them immediately in a sealed container. (Fiber labs and workshops should have special containers for that purpose.) If you have to lay a fiber fragment down, put it on a flat (nonreflecting) black surface, where it is easiest to see. If a fiber splinter jabs you, pull it out carefully with tweezers if it's accessible. If it gets in your eye, call for medical help.

You may find laser light warnings posted in many labs and attached to a variety of equipment. The levels of laser light you will encounter in fiber optics are not deadly. The most powerful lasers used in fiber optics are not going to burn holes through you. However, they could cause serious eye damage. Because the beams in fiber-optic systems are invisible to the human eye, they give you no warning that they are turned on, or that they are entering the air in front of you. You have to rely on safety equipment and labels. You should always know what you're working with.

The hazard of laser light comes from the fact that the eye focuses the parallel light rays in a laser beam onto a tiny spot on the retina, the light-sensitive layer at the back of the eyeball. This concentrates the beam from even a milliwatt laser so much that the light intensities on that tiny spot are comparable to that produced from looking directly at the sun. Just as with the sun, a momentary glance into a milliwatt laser beam will not blind you instantly, but you should not intentionally look into it.

Nature is fairly kind in some ways. The eye is full of water, which absorbs light at wavelengths longer than about 1400 nm, blocking it from the retina—the most sensitive part of the eye. Thus, low powers in the erbium-fiber band are less hazardous than those at shorter wavelengths. Light emerging from optical fibers also spreads out much faster than the familiar beams from red laser pointers, so you don't have to worry much about being zapped by beams from loose fiber ends on the other side of the room. However, erbium-fiber amplifiers can generate hundreds of milliwatts, which are not powers you should trifle with.

The most dangerous lasers you are likely to find in modern fiber-optic systems are 980-nm pump lasers for erbium-doped fiber amplifiers, and high-power transmitters in the 1300-nm band for cable television systems. Both can generate hundreds of milliwatts, are invisible to the eye, and can penetrate to the retina.

The eye hazards presented by different lasers vary widely, so pay close attention to what types are being used where you are working.

FURTHER READING

Roy Henderson and Karl Schulmeiester, *Laser Safety* (Institute of Physics Publishing, 2004)

APPENDIX F

Fiber-Optic Resources

No single book can tell you everything about fiber optics. This list covers sources that may be helpful to readers at various levels. It is far from comprehensive, but should give you a starting point.

Plenty of additional online resources are available, but unfortunately they tend to move about as Web sites are reorganized, so any printed list would be obsolete before the ink was dry. Your best bet is to do Web searches for relevant terms. For example, a search for 10-Gigabit Ethernet standards should quickly lead to the Web site of the 10-Gigabit Ethernet Alliance, the organization that promotes them.

Books

FIBER OPTICS

Vivek Alwayn, *Optical Network Design and Implementation* (Cisco Press, 2004) (telecommunication systems using fibers)

Michael Bass, ed., *Handbook of Optics: Vol. 4 Fiber Optics & Nonlinear Optics* (McGraw-Hill, 2001) (massive, comprehensive handbook)

John A. Buck, *Fundamentals of Optical Fibers* (Wiley InterScience, New York, 1995) (textbook on fibers and their properties)

C. David Chaffee, *Building the Global Fiber Optics Superhighway* (Kluwer Academic, 2001) (recent history of global telecommunications)

Bob Chomycz, *Fiber Optic Installer's Field Manual* (McGraw-Hill, New York, 2000) (for the practicing technician)

Dennis Derickson, *Fiber Optic Test and Measurement* (Prentice Hall, Upper Saddle River, NJ, 1998) (excellent coverage)

David R. Goff, *Fiber Optic Reference Guide: A Practical Guide to the Technology*, 2nd ed. (Focal Press, 1999) (concise reference guide)

Jim Hayes, *Fiber Optics Technician's Manual* (Delmar Publishers, Albany, 1996) (for the practicing technician)

Jeff Hecht, *City of Light: The Story of Fiber Optics* (Oxford University Press, New York, 1999) (history, easy reading)

Gerd Keiser, 3rd ed., *Optical Fiber Communications* (McGraw-Hill, New York, 2000) (recommended if you want more details)

Rajiv Ramaswami and Kumar N. Sivarajan, *Optical Networks, A Practical Perspective* (Morgan Kaufmann, 2002) (fiber-optic telecommunications systems)

TELECOMMUNICATIONS IN GENERAL

John C. Bellamy, *Digital Telephony*, 3rd ed., (Wiley, 2000)

Walter Ciciora, James Farmer, and David Large, *Modern Cable Television Technology: Video, Voice, and Data Communications* (Morgan Kaufmann, San Francisco, 1999) (very comprehensive)

Alan Freedman, *The Computer Glossary* (American Management Association, New York, 2001) (includes many telecommunications terms)

Roger L. Freeman, *Fundamentals of Telecommunications* (Wiley InterScience, New York, 1999 (oriented toward systems, at the engineering level)

Gary M. Miller, *Modern Electronic Communications,* 6th ed. (Prentice Hall, Upper Saddle River, NJ, 1999) (good nuts and bolts introduction)

Laszlo Solymar, *Getting the Message: A History of Communications* (Oxford University Press, 1999) (an entertaining and enjoyable history)

OPTICS, PHOTONICS, AND LASERS

Govind P. Agrawal, ed., *Semiconductor Lasers: Past, Present, and Future* (AIP Press, Woodbury, NY, 1995) (good overview)

Michael Bass, ed., *Handbook of Optics: Vol. 1: Fundamentals, Techniques & Design* and *Vol. 2: Devices, Measurements and Properties* (McGraw-Hill, 1995) (massive, comprehensive handbooks)

J. Warren Blaker and Peter Schaeffer, *Optics: An Introduction for Technicians and Technologists* (Prentice Hall, 2000) (good concise introduction to basic optics)

Emmanuel Desurvire et al., eds., *Erbium-Doped Fiber Amplifiers: Principles and Applications* (Wiley InterScience, 2002) (comprehensive introduction)

Eugene Hecht, *Optics,* 2nd ed. (Addison Wesley, Reading, MA, 1987) (the standard upper-level undergraduate text; no relation)

Jeff Hecht, *Understanding Lasers* (IEEE Press, Piscataway, NJ 1994) (introductory level, but a bit dated on semiconductor lasers)

Francis A. Jenkins and Harvey E. White, *Fundamentals of Optics*, 4th ed. (McGraw-Hill, New York, 1976) (very old, but a good introduction to classical optics)

B. A. E. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley InterScience, New York, 1991) (wide-ranging upper-level textbook)

Amnon Yariv, *Optical Electronics in Modern Communications*, 5th ed. (Oxford University Press, New York, 1997) (widely used but very advanced textbook)

Periodicals

INDUSTRY MAGAZINES

Fiberoptic Product News (technology): *www.fpnmag.com*

Laser Focus World (for laser and optoelectronics engineers): *lfw.pennnet.com/home.cfm*

Lightwave (fiber-optic communications and business): *lw.pennnet.com*

OE Magazine (SPIE monthly)

Optics & Photonics News (Optical Society monthly)

Photonics Spectra (optics and photonics): *www.photonics.com*

Telephony (telephone industry and technology): *www.telephonyonline.com*

SCHOLARLY JOURNALS

Bell Labs Technical Journal (free online access at *www.lucent.com/minds/techjournal/*)

Electronics Letters (published by Institution of Electrical Engineers; many cutting-edge fiber-optic papers)

IEEE Communications Magazine (excellent review articles)

IEEE Journal on Selected Areas in Communications (reviews of selected areas)

IEEE Photonics Technology Letters

Journal of Lightwave Technology (published by IEEE and Optical Society of America)

ONLINE ONLY PUBLICATIONS

Fiberoptics Online (*www.fiberopticsonline.com*)

Fibers.org (*www.fibers.org*)

Light Reading (*www.lightreading.com*)

Other Resources

PROFESSIONAL SOCIETIES

The Fiber Optic Association (*www.thefoa.org*)

Institute of Electrical and Electronics Engineers (*www.ieee.org*)

- IEEE Lasers and ElectroOptics Society
- IEEE Communications Society

Optical Society of America (*www.osa.org*)

SPIE-The International Society for Optical Engineering (*www.spie.org*)

MAJOR FIBER OPTICS CONFERENCES

European Conference on Optical Communications (annual, see *www.ecoc-exhibition.com/*)

Optical Fiber Communications Conference (annual in United States, March, see *www.ofcconference.com*)