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

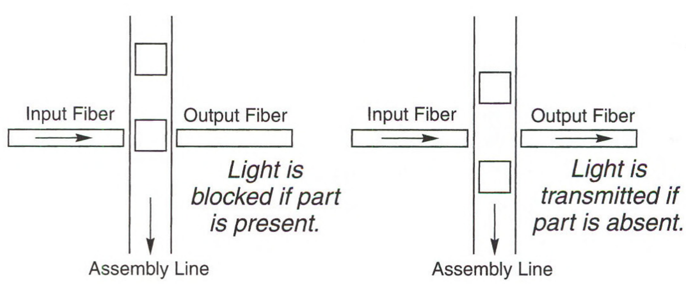
Fiber probes can detect objects when they block or reflect light.

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

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.

Fibers can collect light from other optical sensors.

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.

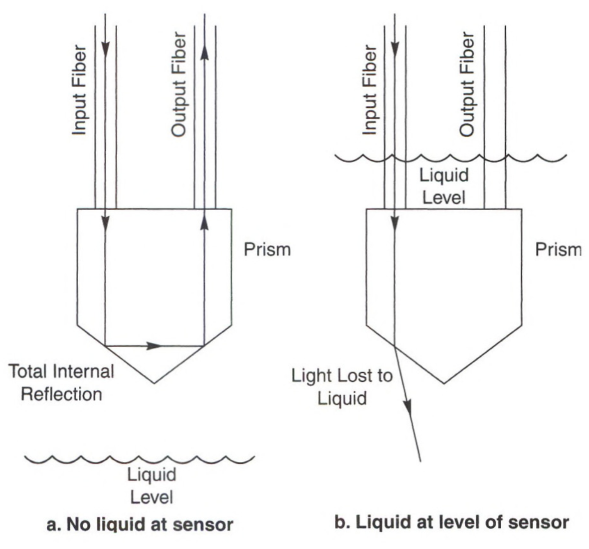


FIGURE 29.2
A liquid-level sensor.

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

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.

Some fiber sensors directly modulate transmitted light intensity.

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

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.

Some fiber sensors affect light polarization.

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.

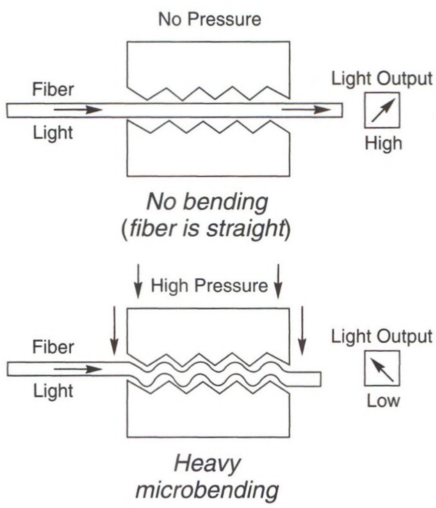


FIGURE 29.3
Increasing pressure on the plates causes microbending, reducing light transmission through the fiber.

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.

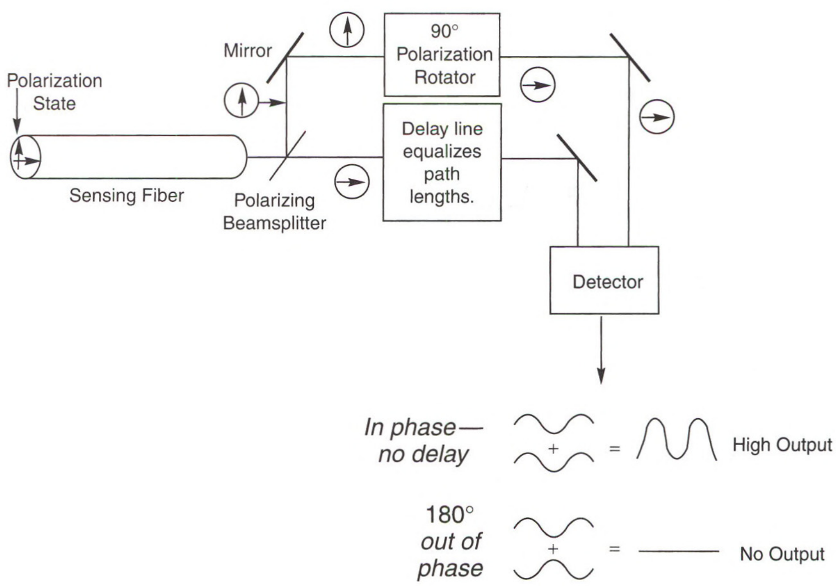
Sensors also can modulate the phase of light to cause interference effects that modulate light intensity. To understand how this works, let's continue with the example of the pressure sensor that changes the phase of polarized light. By changing the refractive indexes of different polarizations by different 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.

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

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.

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

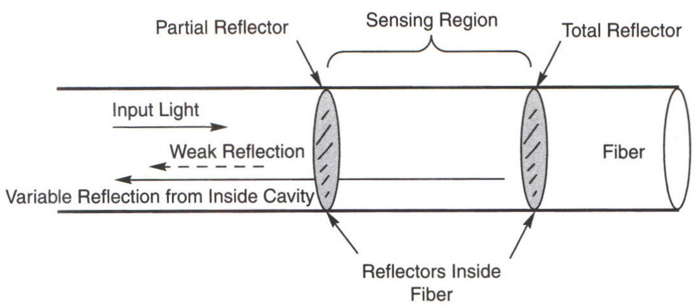


FIGURE 29.5
Fiber Fabry-Perot interferometer sensor.

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

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

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

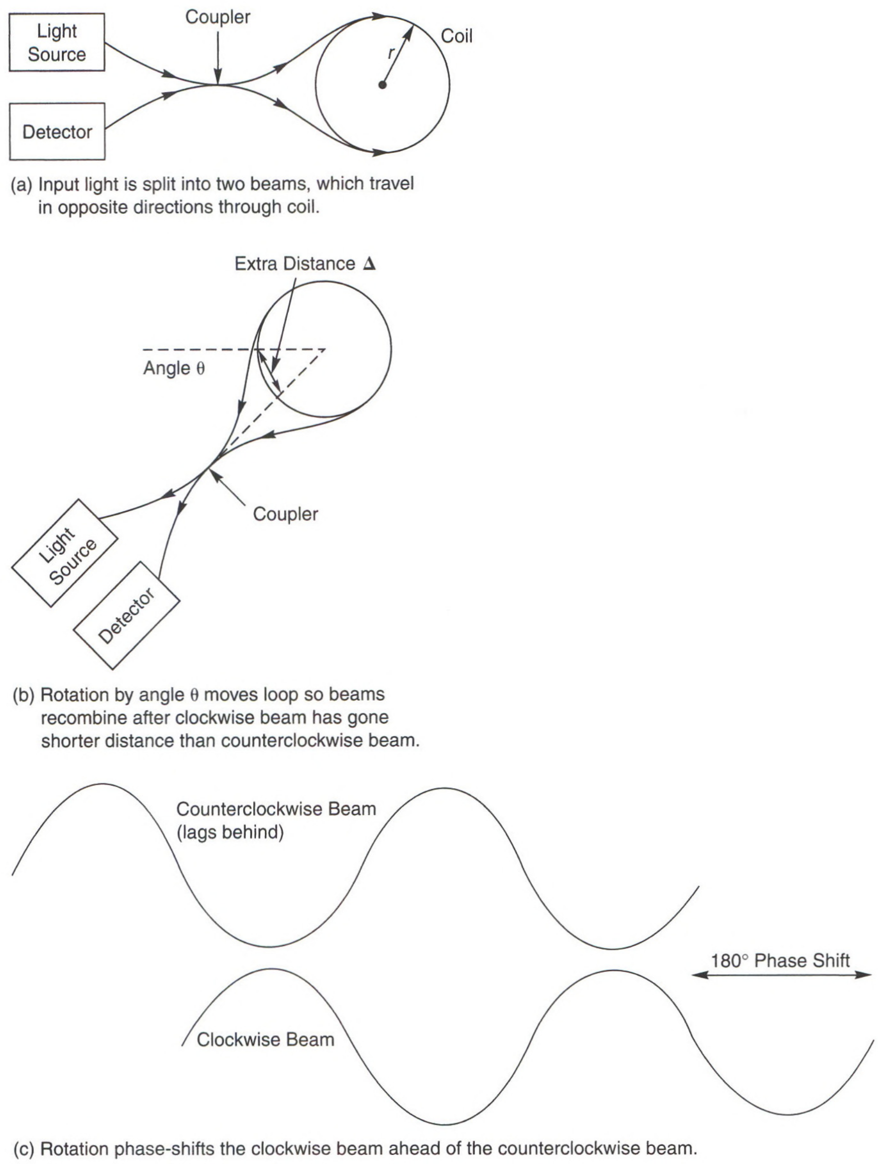


FIGURE 29.6
Fiber-optic gyroscope.

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.

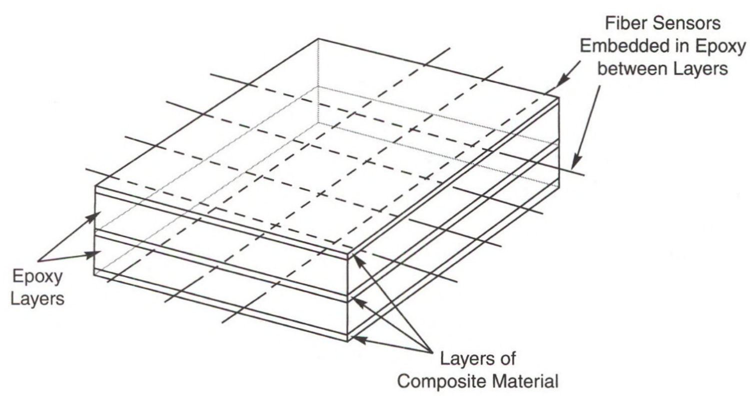
Fiber sensors are embedded in composites to make smart structures and skins.

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