

Specially designed fibers can measure directly changes in temperature, pressure, and light polarization, as well as physical integrity of composite materials.

The term fiberoptic sensors covers a broad range of devices. This article focuses on those in which the fiber itself serves as the sensor because light passing through it is affected by its environment. Such fiber sensors depend on mechanisms such as microbending, physical stress, and phase shifts caused by changes in the fiber itself. They are used to measure quantities such as temperature, pressure, and rotation and to verify the physical integrity of materials.

Another broad group of devices often referred to as fiber sensors are more properly fiber *probes*, because the fiber merely collects light from an external sensor or a point in space. One example is a fiber placed next to an assembly line of moving parts that block light as they go by; the fiber merely serves to deliver light to a detector that senses the presence or absence of light. Another example is a fiber that collects light from a remote optical sensor that is reacting to the environment; again, the fiber does not act upon the light, but instead merely serves as a light pipe. This article, however, does not discuss fiber probes.

The idea of sensing

The function of sensing is to convert a physical effect you want to observe into a form you can measure easily. With fiber sensors, the external environment must affect light transmission in a way that can be detected at the other end. This is a goal quite different from communications, where ideally the external environment does not affect transmitted light at all. Fiber sensors thus are designed quite differently from communication cables. One approach is to make the fibers particularly sensitive to some environmental parameter, such as using glasses with refractive indexes that vary strongly with temperature. Another is to mount the fibers in ways that amplify environmental stresses that affect light transmission, instead of isolating the fibers as in communication cables. A third is to use long fibers so that weak interactions build up over a long transmission distance. In practice, individual sensors may take advantage of two or more of these approaches.

Fiber sensors capture environmental changes

Jeff Hecht, Contributing Editor

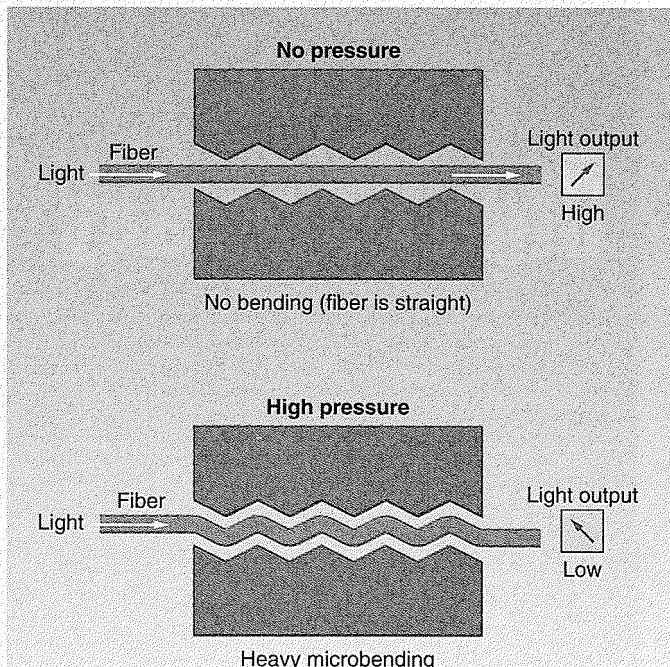


FIGURE 1. Fiber pressure sensor depends on microbending in a fiber mounted between two grooved plates. Increasing the pressure increases microbending losses, so pressure can be inferred from measurements of transmitted optical power.



Most fiber sensors work when the environment modulates light passing through them in one of three ways: directly altering its intensity, affecting its polarization, or shifting its phase. To actually measure polarization and phase modulation, you must convert those changes to variations in intensity. Note that it is important for the sensor to react strongly to variations in one parameter but weakly in variations in others. A pressure sensor is not very good if it also responds strongly to temperature changes.

Direct intensity modulation

Sensors that directly modulate light intensity are conceptually simple. The simplest is a fiber embedded in a material as a crack sensor. 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. Such a sensor can mea-

sure structural integrity of a building, bridge, or airframe.

More-subtle intensity sensors rely on effects such as microbending, which causes light to leak out of the fiber core. In a pressure sensor, for example, mounting a fiber between a pair of grooved plates greatly enhances its sen-

sitivity to microbending (see Fig. 1). If there's no pressure on the plates, the fiber remains straight, and light passes through it with little attenuation. As pressure increases, microbending causes increasing attenuation proportional to the pressure.

Another type of intensity-modulation

sensor depends on changes in light guiding within the fiber, which can arise when external conditions affect properties of the fiber material. Refractive index is a good example because both temperature and pressure affect it. 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 the temperature increases, the core index decreases by 0.0005 per degree, while the cladding index decreases by 0.0004 per degree. At 100°C, the two refractive indexes would both equal 1.45. At this point, the fiber stops confining light to the core and output light intensity drops to near zero. In practice, losses typically increase gradually with temperature, so power would drop gradually, not cut off abruptly. The principle has been demonstrated in a sensor that can measure temperature within a few degrees.

Polarization sensing

A number of mechanisms can affect light polarization in a fiber for sensing applications. For example, magnetic fields cause Faraday rotation of the plane of polarized light by an angle proportional to the strength of the magnetic field. If linearly polarized light enters a fiber, the angle of rotation of the polarization is a measure of the magnetic field strength. In practice, the angle of rotation is not measured directly, but is instead converted into easier-to-measure intensity variations by passing the light through an external polarizer.

Other fiber sensors produce effects that affect light of different polarizations differently, taking advantage of birefringence, the difference in refractive index for light with different polarizations. For example, raising pressure may increase the refractive index for horizontally polarized light more than the refractive index for vertically polarized light. The effect is to retard horizontally polarized light, so its phase falls behind that of vertically polarized light in the fiber. Measuring these changes requires interferometric techniques.

Phase or interferometric sensing

Measuring phase shifts in sensing fibers is a particularly sensitive approach

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requiring complex optics. To understand how this works, let's continue with the example of the pressure sensor that shifts the phases of orthogonally polarized light in a fiber. By changing the refractive indexes of different polarizations by different amounts, the sensor effectively delays one polarization relative to the other. This can be measured by separating the two polarizations at the output end, rotating one by 90°, equalizing the path lengths, then mixing them together (see Fig. 2). If the two polarizations are in phase—that is,

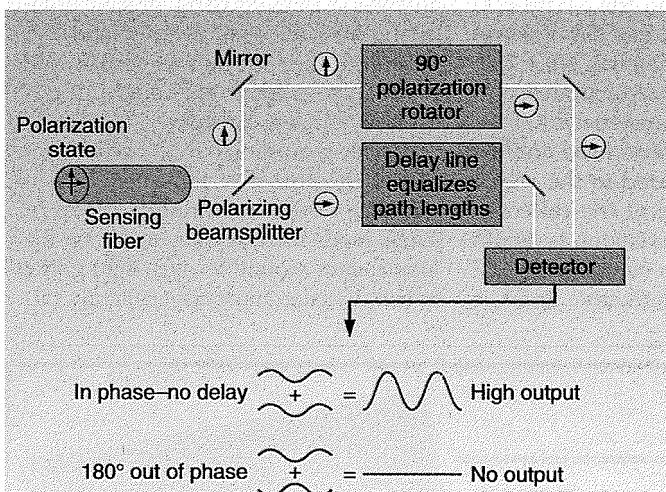


FIGURE 2. Interferometric polarization sensor converts a phase shift between two orthogonal polarizations in a fiber sensor to an intensity change by rotating the polarization of one beam and combining the two in an interferometer.

there was no delay between the two of them—the output is high. If one was 180° behind the other, the output is low.

Interferometric sensors are very sensitive to small changes, but they have a few important limitations. One is that the light must be coherent enough that interference occurs. In addition, there is an inherent ambiguity because a 360° delay produces the same effect as no delay or a 720° delay. This requires keeping track of how many cycles of shifting occur except when measuring small shifts.

Note that the only way to measure a phase shift is by comparing the phase-shifted signal with a second signal not subjected to the same effect. In the polarization sensor, these signals are two polarizations of light affected differently by pressure-induced changes

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

Length and refractive-index changes

Many interferometric sensors are based on phase shifts arising from changes in the transit time of light through the sensor. These arise from changes in the sensor's effective length, the product of its refractive index times its physical length, both of which can be affected by the environment.

Suppose that the refractive index n and the sensor length L both change by small amounts (Δn and ΔL). Then the transit time of light through the sensor becomes

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

(where c is the speed of light) for small changes. The corresponding change in transit time is

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

This causes a phase shift that can be detected interferometrically by comparing light passing through the sensor with light that followed a different path. Length times refractive-index sensing works well for measuring changes in both temperature and pressure.

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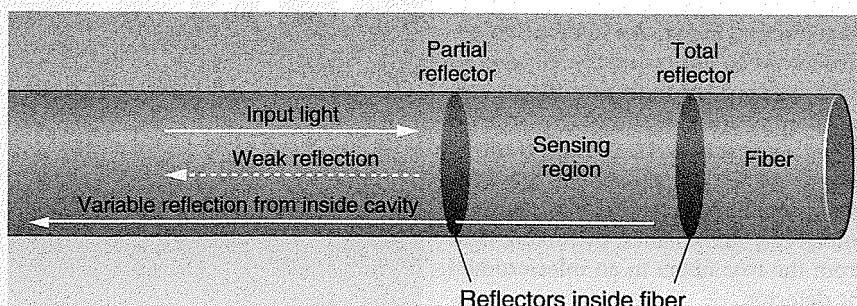


FIGURE 3. Fiber Fabry-Perot interferometer sensor is a segment of fiber defined by one partly reflective layer and one total reflector, which together form a resonant cavity.

resonant cavity rather than by comparing the phase shifts of light taking two different paths (see Fig. 3). Light passing through a partly reflective layer in the fiber is reflected by a total reflector 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 wavelengths where the

round-trip distance in the cavity ($2L$) equals an integral number (N) of wavelengths in the fiber material, $N\lambda = 2Ln$, where the vacuum wavelength λ and the wavelength in the material is λ/n .

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 sense pressure and strain.

Fiber gyroscopes

The fiberoptic gyroscope is the most widely used fiber sensor to date. Its ability to sense rotation around the axis of a ring of fiber allows its use as a reference in navigation systems, where tracking orientation is vital. Fiber gyros have some important advantages over older mechanical gyros, including the absence of moving parts, greater reliability, and no need for a warm-up. Although they are not as accurate as laser gyros, fiber gyros are good, durable, and less expensive.

A fiber gyro senses rotation by comparing the phases of light traveling in opposite directions through a loop of single-mode fiber (see Fig. 4). When the loop rotates around its axis, light going in one direction must travel slightly far-

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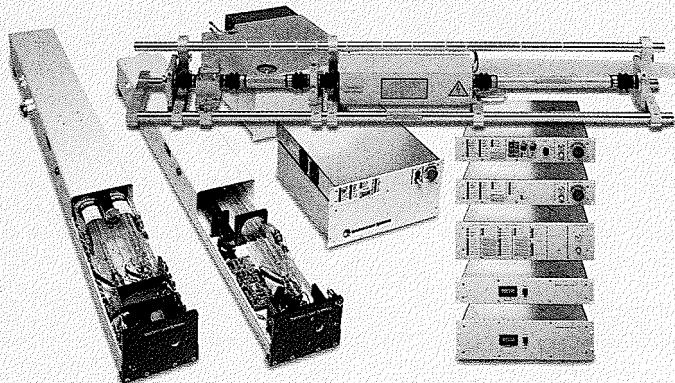
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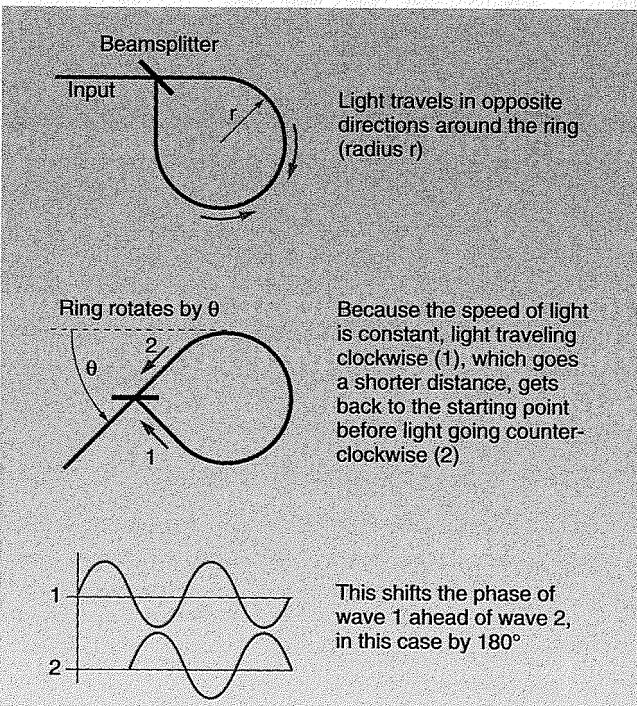


FIGURE 4. A fiber gyro tracks orientation by comparing phases of light traveling in opposite directions through a loop of single-mode fiber.

ther than light going in the other, causing a phase shift when the two beams combine at the interferometer. This is called the Sagnac effect.

Smart skins and structures

Fiber sensors can be embedded in composites, concrete, and other materials to create "smart skins" or "smart structures." The goal is to create structural elements for uses from airplanes to bridges that are equipped to monitor internal conditions. Much early work has focused on verifying that composite materials meet initial requirements, such as curing at the proper temperature. However, longer-term goals include monitoring stress and structural integrity throughout the component's lifetime. Thus the sensors could verify the safety of airframes and bridge supports.

Military planners have suggested that smart skins could be incorporated into real-time control systems to help optimize aircraft performance. The limitations of present materials and structures are not well known, so engineers err on the side of safety. Real-time monitors could tell computers how well components are withstanding operating stresses, and perhaps ultimately the computers could apply real-time corrections to push the performance envelope. □

Next month's Back to Basics will discuss fiberoptic beam delivery.

ACKNOWLEDGMENT

This article is adapted from Jeff Hecht, *Understanding Fiber Optics*, 3rd ed., Prentice Hall, Upper Saddle River, NJ, 1999.