Structural Health Monitoring of Composite Structures Using Fiber Optic Methods

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Introduction to Optical Fiber Sensors

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3 Introduction to Optical Fiber Sensors

Dipankar Sengupta and Ginu Rajan

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3.1 INTRODUCTION

Sensing has become a key enabling technology in many areas, from entertainment technology to health, transport, and many industrial technologies. In many such advanced applications, where miniaturization, sensitivity, and remote measurement are vital, optical fiber–based sensing techniques can provide novel solutions. As a result of this, optical fiber sensing (OFS) technology has been developed as a powerful and rich technology that is currently being implemented in a wide variety of applications [1,2].

Research work on OFS began in the 1960s, but it is the development of modern low-loss optical fibers that has enabled the transition from the experimental stage to practical applications. Some of the first sensing experiments using low-loss
optical fibers [3–6] were demonstrated during the early 1970s. The field of OFS has continued to progress and has developed enormously since that time. For instance, distributed fiber-optic sensors have now been installed in bridges and dams to monitor the performance of and structural damage to these facilities. Optical fiber sensors are used to monitor the conditions within oil wells and pipelines, railways, wings of airplanes, and wind turbines. Decades of research has led to the development of accurate optical fiber measuring instruments, including gyroscopes, hydrophones, temperature probes, and chemical monitors. As the OFS field is complementary to optical communication, it has benefited from advances in optical fibers and optoelectronic instrumentation. With the rapid development of optical communication networks, the cost of fiber sensors has significantly reduced because of the commercially available key components, such as light sources and photodetectors.

It is anticipated that research on OFS technology will continue to grow and the technology will become widespread. Several new types of fiber sensors are progressively emerging, and some of the fiber sensing technologies are in a mature state and have been commercially produced and used in different applications. As lightwave technology is becoming the new enabling technology behind many advanced high-end applications, optical fiber sensors can play an integral part in those developments.

The aims of this chapter are to introduce the basic principles of OFS, to provide a brief overview of some of the different types of fiber sensors developed over the years, and to form the basis for the rest of the chapters in this book.

### 3.2 OPTICAL FIBER SENSORS: CONCEPT

For a given process or operation, a system needs to perform a given function, which requires the condition of one or multiple parameters to be qualified and/or quantified. Therefore, these parameters must be measured and processed so that the system can carry out its function. To facilitate the process, a sensor can be used, which is a device that provides this information by measuring any physical/chemical/biological measurand of interest (pressure, temperature, stress, pH, etc.) and converting it into an alternative form of energy (e.g., an electrical or optical signal) that can be subsequently processed, transmitted, and correlated with the measurand of interest.

The optical fiber alternative to traditional sensors, *optical fiber sensors*, can be defined as a means through which a physical, chemical, or biological measurand interacts with light guided through an optical fiber, or guided to an interaction region by an optical fiber, to produce a modulated optical signal with information related to the measurement parameter. The basic concept of a fiber-optic sensing system is demonstrated in Figure 3.1, where the fiber (guided light) interacts with an external parameter and carries the modulated light signal from the source to the detector. The input measurand information can be extracted from this modulated optical signal. Depending on the type of fiber sensor and its operating principle, the sensor system can operate either in transmission mode or in reflection mode, which is elaborated in later sections of this chapter.
3.3 MEASUREMENT CAPABILITIES AND ADVANTAGES OF OPTICAL FIBER SENSORS

One of the biggest advantages of fiber sensors is that they have the capability to measure a wide range of parameters based on the end user requirement, once a proper fiber sensor type is used. Some (not an exhaustive list) of the measurement capabilities of fiber sensors are

- Strain, pressure, force
- Rotation, acceleration
- Electric and magnetic fields
- Acoustics and vibration
- Temperature, humidity
- Liquid level
- pH and viscosity
- Bio-sensing: single molecules, chemicals, and biological elements such as DNA, single viruses, and bacteria

Given the advancement in the development of optical fibers and instrumentation, the development and measurement capability of optical fiber sensors have also increased, and they are currently being employed in many structural health monitoring and biomedical applications [7–9]. Optical fiber sensors share all the benefits of optical fibers and are excellent candidates for monitoring environmental/external changes. Some of the advantages of fiber sensors over conventional electronic sensors are

- Light weight
- Passive/low power
- Resistance to electromagnetic interference
- High sensitivity and bandwidth
- Environmental ruggedness
• Complementarity to telecom/optoelectronics
• Multiplexing capability
• Multifunctional sensing possibility
• Easy integration into a wide variety of structures
• Robustness, greater resistance to harsh environments

Though optical fiber sensors have many advantages compared with their electrical counterparts, there are also some concerns over this technology. Major drawbacks include cost, long-term stability, less efficient transduction mechanism, and complexity in its interrogation systems. Another disadvantage of the fiber sensing system is the unfamiliarity of the end user in dealing with the system. As more research, commercialization, and standardization efforts are ongoing, it is expected that some of the current disadvantages may become extinct in the near future.

3.3.1 Types of Optical Fiber Sensors

3.3.1.1 Intrinsic and Extrinsic Sensors

As the optical fiber sensors operate by modifying one or more properties of light passing through the fiber, they can be broadly classified as extrinsic or intrinsic. In the extrinsic sensor types, the optical fiber is used as a means to carry light to an external sensing system, while in the intrinsic type, the light does not have to leave the optical fiber to perform the sensing function, as shown in Figure 3.2a. The intrinsic fiber sensor types are more attractive and widely researched, as this scheme has many advantages compared with the extrinsic type, such as their in-fiber nature and the flexibility in the design of the fiber sensor head (Figure 3.2b).

3.3.1.2 Point Sensor and Distributed Sensor

Another classification of fiber optic sensors is based on whether they allow measurements of the physical parameter of interest locally, in which case they are called point sensors, or provide the value of the physical parameter over a distance and as a function of position along the fiber-distributed sensors. Point transducers have a finite length and therefore provide the value of the physical parameter averaged over a given volume of space corresponding to the length of the point transducer. If multiple point measurements are required, a number of point sensors need to be used, which in many cases requires installing multiple lead-in/lead-out fibers,
arrays of detectors, and so on. The number of point sensors, which defines the spatial resolution of the system, is limited by the cost, and therefore becomes insufficient for many practical applications, as shown in Figure 3.3a.

The distributed fiber-optic sensing approach has no real equivalent among other types of sensors and has become an important differentiator of fiber-optic sensing. Distributed sensors are most often intrinsic, and the sensing principles and practical implementation are significantly different from those used for point sensing. Since only one fiber needs to be installed to sense the physical parameter of interest at many points, as shown in Figure 3.3b, it is possible to share the optical source and detector and often eliminate the other equipment required for multipoint sensing using point sensors. This results in much lower cost per point measurement and also much higher weight and space efficiency of the distributed sensing, making this technique the most powerful monitoring option in many applications, especially for structural monitoring of civil and aerospace structures.

### 3.3.2 Modulation Schemes

Furthermore, depending on the light property that is modified, optical fiber sensors can be mainly classified into four main categories:

- Intensity-modulated sensors
- Phase-modulated (interferometric) sensors
- Polarization-modulated (polarimetric) sensors
- Wavelength-modulated (spectrometric) sensors

Optical fiber sensors can also be further classified based on their spatial positioning as well as on their measurement capabilities. A summary of different classifications of OFS is shown in Table 3.1.

#### 3.3.2.1 Intensity-Modulated Sensors

Intensity-modulated sensors are one of the earliest types and perhaps the simplest type of optical fiber sensor. In the intensity modulation scheme, optical signal is transmitted through optical fibers, and then its intensity is modulated by various
means, such as by fiber bending, reflectance, or changing the medium through which the light is transmitted. The main advantages of intensity-modulated sensors are ease of fabrication, simple detection system and signal processing requirements, and low price-performance. A simple example of a reflection-type intensity-modulated fiber optic sensor using a single fiber that can be used to measure distance, pressure, and so on is shown in Figure 3.4.

Compared with the single-fiber type, two-fiber-type reflection sensors are often used as proximity sensors in a variety of applications. In this case, one fiber is used as the input fiber, and a second fiber is used to collect the reflected light from a reflecting surface. The schematic of a two-fiber configuration and its typical intensity response is shown in Figure 3.5. The modulation function of a two-fiber reflection-type sensor is given as [10]

\[
M_s = \frac{\Phi_{RS}}{\Phi_E} = \frac{S_R \cos^4 \theta}{\pi (2hNA)^2}
\]  

(3.1)

where:

- \(\Phi_E\) is the radiant flux from the emitting fiber
- \(\Phi_{RS}\) is the radiant flux intercepted by the end face of the receiving fiber

### TABLE 3.1
**Different Classifications of Optical Fiber Sensors**

<table>
<thead>
<tr>
<th>Classification Based on the Working Principle</th>
<th>Classification Based on the Spatial Positioning</th>
<th>Classification Based on the Measurement Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity-modulated sensors</strong></td>
<td><strong>Point sensors</strong></td>
<td><strong>Physical sensors</strong></td>
</tr>
<tr>
<td>Detection through light power</td>
<td>Discrete points, different channels for each sensor/measurand</td>
<td>Temperature, strain, pressure, and so on</td>
</tr>
<tr>
<td><strong>Phase-modulated (interferometric) sensors</strong></td>
<td><strong>Distributed</strong></td>
<td><strong>Chemical sensors</strong></td>
</tr>
<tr>
<td>Detection using the phase of the light beam</td>
<td>Measurand can be determined along a path, surface, or volume</td>
<td>pH content, gas sensors, spectroscopic study, and so on</td>
</tr>
<tr>
<td><strong>Polarimetric sensors</strong></td>
<td><strong>Quasi-distributed</strong></td>
<td><strong>Bio-sensors</strong></td>
</tr>
<tr>
<td>Detection of changes in the state of polarization of the light</td>
<td>Variable measured at discrete points along an optical link</td>
<td>DNA, blood flow, glucose sensor, and so on</td>
</tr>
<tr>
<td><strong>Spectrometric sensors</strong></td>
<td><strong>Integrated</strong></td>
<td></td>
</tr>
<tr>
<td>Detection of changes in the wavelength change of the light</td>
<td>Measurand is integrated along an optical link giving a single-value output</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 3.4**  Simple extrinsic intensity-modulated sensor.
Introduction to Optical Fiber Sensors

\[ S_R \] is the area of the end face of the receiving fiber
\[ \theta \] is the angle between the axis of the receiving fiber and the line connecting the centers of the receiving fiber and the emitting fiber (virtual image)
\[ NA \] is the numerical aperture of the fiber

In contrast to other sensing principles, intensity modulation can be obtained by using a simple arrangement; however, optical fiber bending, coupling misalignments, source power fluctuation, and so on can cause signal attenuation and signal intensity instability, which leads to a less reliable sensor system. One solution to this problem is intensity referencing, in which a fraction of the input light (obtained using a fiber splitter) is used for monitoring the input power fluctuation. An example of such a configuration is shown in Figure 3.6 [11], where the power ratio of the modulated signal and reference signal is used.

Other types of intensity-modulated fiber-optic sensors include evanescent wave sensors, microbend, and macrobend sensors.

### 3.3.2.1.1 Evanescent Field-Based Fiber Sensor

The evanescent field–based fiber sensor is one of the most useful and commonly used intensity-modulated fiber-optic sensors. When light propagates along the optical fiber with an incidence angle at the core/cladding interface greater than the critical angle, the beam is totally reflected back into core of the fiber (Figure 3.7).
Interesting enough, light is not instantaneously reflected when it reaches the interface. Rather, the superposition of the incident and reflected beams results in the formation of a standing electromagnetic wave. The maximum of the electric field amplitude of the standing wave is located at the interface, but the field decays exponentially in the direction of an outward normal to the interface. The decaying field is called an *evanescent field*. The electric field amplitude, $E$, at a distance $x$ along the normal is given by

$$E = E_0 \exp \left( -\frac{x}{d_p} \right)$$  \hspace{1cm} (3.2)

where:

- $E_0$ is the electric field at the interface
- $d_p$ is the penetration depth

The magnitude of the penetration depth is given by

$$d_p = \frac{\lambda}{2\pi n_1 \sqrt{\sin^2 \theta - \left( \frac{n_2}{n_1} \right)^2}}$$  \hspace{1cm} (3.3)

where:

- $\lambda$ is the wavelength of the light source
- $\theta$ is the angle of incidence of the light at the core/cladding interface
- $n_1$ and $n_2$ are the refractive indices (RI) of the core and cladding, respectively
Figure 3.7 is a cross-sectional view of a fiber cut at the long axis, and provides a graphical representation of the penetration depth of the evanescent field, the angle of incidence, and a hypothetical ray of light propagating along the fiber. The magnitude of the evanescent field depends on the cladding thickness. The increase in evanescent field forms the basis for increased sensitivity toward the surrounding medium. Evanescent wave absorption sensors are typically used to monitor the concentration of an absorbing fluid, humidity, chemical sensing, and so on [11].

In single-mode (SM) and multimode (MM) fibers, the effects associated with bending found their application in two early type of intensity-modulated point sensors popularly known as microbend and macrobend fiber sensors. The terms micro and macro in this context refer to the scale of the fiber bends rather than to the scale of the volume within which the parameter of interest is measured. The concepts of micro- and macrobending of fiber have certain similarities as well as differences.

3.3.2.1.2 Microbending

Microbending can be achieved by mechanical perturbation of the fiber and causes a redistribution of light power among the many modes in the fiber. When fiber is bent, consequently the guided mode of SM fiber couples to cladding modes, and the highest guided mode of MM fiber couples to the first radiated mode due to the deformations of the refractive index (RI) distribution or the geometry of the fiber. Coupling to cladding modes or radiated modes causes power to be lost from the guided core mode, and the power traveling in the cladding modes will be rapidly dissipated because of the high losses in these modes. The loss of power also depends on the period of the tooth spacing Λ on the moving plate (Figure 3.8).

For the step index fibers, this expression can be approximated as

$$\Lambda = \frac{\pi a}{\sqrt{\Delta}}$$

(3.4)

where:

- $a$ is the fiber core radius
- $\Delta$ is the normalized index difference between core and clad
The step index fiber exhibits a threshold response and the graded index fiber a resonant response. For a graded index fiber, it is shown that to achieve maximum microbend sensitivity, the spatial period of the deformer must match the expression $\Lambda = \sqrt{2\pi a/\Delta}$. Typically, the spatial period is within the range of 0.2–2 mm. Although not as sensitive as interferometric sensors, microbenders have good sensitivity to small displacements in the order $10^{-10}$ m/√Hz and a very large dynamic range, which is one of the major advantages of these sensors [12].

### 3.3.2.1.3 Macrobend Sensors

Macrobend sensors are another type of intensity-modulated, intrinsic fiber-optic sensors, for which a single-mode fiber (SMF) is usually used, and it is bent at relatively large diameters; typically, the bend radius is in the order of a few centimeters. Power loss in the core of an SMF due to a uniform bend consists of two components: a pure bend loss and a transition loss. The pure bend loss results from the loss of guidance at the outer portion of the evanescent field of the fundamental mode [13]. This loss of guidance is due to the phase velocity of the outer part of the evanescent field becoming equal to the speed of light in the cladding. The smaller the bend radius, the greater the fraction of the evanescent field affected, and hence, the greater the percentage of light lost at the bend. The transition loss arises from the coupling of light from the fundamental mode to leaky core modes whenever there is a change in curvature of the fiber axis, for example, from straight to curved or vice versa. Based on macrobending loss, physical parameters such as temperature and displacement can be measured. Figure 3.9 shows a displacement sensor using high–bend loss fiber.

### 3.3.2.2 Phase-Modulated Fiber-Optic Sensors

Phase-modulated sensors, also known as interferometric sensors, are based on the phase difference of coherent light traveling along two different paths, either in
the same fiber or in different fibers. These sensors are often considered as high-sensitivity sensors due to their capability to respond to small changes in the external measurands. The common interferometric fiber sensors include fiber-optic Mach–Zehnder, Michelson, Fabry–Perot, and Sagnac interferometers.

The fiber-optic Mach–Zehnder interferometric sensor (MZI) has two independent arms, the reference arm and the sensing arm, as illustrated in Figure 3.10. Incident light is split into two arms by a fiber coupler and then recombined by another fiber coupler.

The recombined light has an interference component according to the optical path difference (OPD) between the two arms. For sensing applications, the reference arm is kept isolated from external variation, and only the sensing arm is exposed to the variation. Then, the variation in the sensing arm induced by factors such as temperature, strain, and RI changes the OPD of the MZI, which can be easily detected by analyzing the variation in the interference signal. With the advent of the long-period fiber grating (LPFG), this scheme has been rapidly replaced by the scheme of the in-line waveguide interferometer (Figure 3.11).

This in-line type of MZI has the same physical length in both the reference arm and the sensing arm, but has different optical path lengths due to the modal dispersion; the cladding mode beam has a lower effective index than the core mode beam. The reported RI sensitivity achieved is $1.8 \times 10^{-6}$ [14]. Fiber tapering has been applied to the separated region between two LPFGs to improve the sensitivity [15]. Various effective in-line MZI configurations have also been developed using a lateral offset between the fibers [16], different core sizes [17], tapering a fiber at two points along the fiber [18], using a double-cladding fiber [19], micro-cavities [20], and a twin-core fiber [21].

Fiber-optic sensors based on Michelson interferometers (MIs) are quite similar to MZIs. However, each beam is reflected by the mirror at the end of each arm in MI configuration (Figure 3.12a).

MI sensors are operated under reflection modes and are compact and handy in practical uses and installation. Multiplexing capability with parallel connection of

![FIGURE 3.10 Mach–Zehnder sensor configuration.](image)

![FIGURE 3.11 Inline MZI configuration using LPFG.](image)
several sensors is another beneficial point of MIs. However, it is essential to adjust the fiber length difference between the reference arm and the sensing arm of an MI within the coherence length of the light source [22,23]. An in-line configuration of MI is also possible, as shown in Figure 3.12b. In this configuration, a part of the core mode beam is coupled to the cladding mode(s), which is reflected along with the uncoupled core mode beam by the common reflector at the end of the fiber. MI-based sensors are especially useful for measurements of the temperature and RI of liquid specimens.

Fiber-optic Fabry–Perot interferometers (FPIs) offer the advantages of high resolution, compact structure, and immunity to electromagnetic interference. They play important roles in a large number of sensing applications, such as RI, strain, temperature, and pressure. In FPIs, sensor interference occurs due to the multiple superpositions of both reflected and transmitted beams at two parallel surfaces, sometimes called etalon [24]. The basic configuration is different from MZI and MI. Fiber-optic FPI can be simply formed by intentionally building up reflectors either inside or outside the fibers, and based on this, they are classified into two categories, extrinsic and intrinsic FPI, as shown in Figure 3.13a and b, respectively. Extrinsic FPI is useful for obtaining a high-finesse interference signal, is easy to fabricate, and does not need any high-cost equipment. However, the low coupling efficiency and need for careful alignment and packaging are drawbacks compared with intrinsic FPI.

On the other hand, the intrinsic FPI fiber sensors have reflecting components within the fiber itself, for example, when the reflectors are formed within a fiber by any means, as in Figure 3.13b. The local cavity of the intrinsic FPI can be formed by a range of methods, such as micromachining [25], fiber Bragg gratings (FBGs) [26], chemical etching [27], and thin film deposition [28]. However, they still have the problem of using high-cost fabrication equipment for the cavity formation.
The reflection or transmission spectrum of an FPI can be described as the wavelength-dependent intensity modulation of the input light spectrum, which is mainly caused by the optical phase difference between two reflected or transmitted beams. The phase difference of the FPI is simply given as

$$\delta_{\text{FPI}} = \frac{2\pi}{\lambda} n 2L \quad (3.5)$$

where:
- $\lambda$ is the wavelength of incident light
- $n$ is the RI of the cavity material or cavity mode
- $L$ is the physical length of the cavity

When perturbation is introduced to the sensor, the phase difference is influenced by the variation in the OPD of the interferometer. For example, longitudinal strain applied to the FPI sensor changes the physical length of the cavity and/or the RI of the cavity material, which results in phase variation. By measuring the shift of the wavelength spectrum of an FPI, the strain applied on it can be quantitatively obtained.

### 3.3.2.2.1 Fiber-Optic Sagnac Interferometric (SI) Sensors

Fiber-optic Sagnac interferometric (SI) sensors are simple in structure, easy to fabricate, and environmentally robust. An SI consists of an optical fiber loop, in which the input light is split into two directions by a 3 dB fiber coupler, and the two counterpropagating beams are combined again at the same coupler (Figure 3.14). Unlike other fiber-optic interferometers, the OPD is determined by the polarization-dependent propagating speed of the mode guided along the loop. To maximize the polarization-dependent feature of SIs, birefringent fibers are typically used in sensing parts. The polarizations are adjusted by a polarization controller (PC) attached at the beginning of the sensing fiber. The signal at the output port of the fiber coupler is governed by the interference between the beams polarized along the slow axis and the fast axis. The phase of the interference is simply given as
\[ \delta \frac{2\pi B L}{\lambda} B + \left| n_f \right| \mathcal{L} \]

where:
- \( B \) is the birefringent coefficient of the sensing fiber
- \( L \) is the length of the sensing fiber
- \( n_f \) and \( n_s \) are the effective indices of the fast and slow modes, respectively

In general, high birefringent fibers (HBFs) or polarization-maintaining fibers (PMFs) are chosen as the sensing fibers to acquire a high phase sensitivity. The SI has been principally used to measure rotation and is a replacement for ring laser gyros and mechanical gyros [29]. It may also be employed to measure time-varying effects, such as acoustics and vibration, and slowly varying phenomena, such as strain.

### 3.3.2.3 Wavelength-Modulated Sensors

Wavelength-modulated fiber sensors exhibit a change in the propagating optical wavelength (spectral modulation) when interacted with by an external perturbation. Some common wavelength-based fiber sensors include Bragg grating sensors, fluorescence sensors, and black body sensors.

Arguably, one of the most widely used wavelength-based sensors is the Bragg grating sensor. Originating with the discovery of the photosensitivity of germanium-doped silica, FBG sensing technology has attracted widespread attention and has been the subject of continuous and rapid development since FBGs were used for the first time for sensing purposes in 1989. An elementary FBG comprises a short section of an SMF in which the core RI is modulated periodically using an intense optical interference pattern, typically at UV wavelengths. The change in the core RI is between \( 10^{-5} \) and \( 10^{-3} \), and the length of a Bragg grating is usually around 10 mm. A schematic of an FBG is shown in Figure 3.15. The periodic index modulated structure enables the light to be coupled from the forward-propagating core mode into a backward-propagating core mode, generating a reflection response.
Introduction to Optical Fiber Sensors

The light reflected by the periodic variations of the RI has a central wavelength [30]

\[ \lambda_B = 2n_{eff} \Lambda \]  

(3.7)

where:

- \( \Lambda \) is the grating periodicity
- \( n_{eff} \) is the effective RI of the waveguide mode

The basic principle of operation of any FBG-based sensor is that any local strain or temperature change alters the effective index of core refraction and the grating period, followed by changes in wavelength of the reflected light. The corresponding Bragg wavelength shifts are typically of the order of 1 pm/\( \mu \)e and 10 pm/°C.

Monitoring of the changes in the reflected wavelength can be achieved by employing edge filters, tunable narrowband filters, tunable lasers, or charge-coupled device (CCD) spectrometers. In comparison with other fiber-optic sensors, FBGs have a unique advantage in that they encode the wavelength, which is an absolute parameter and which does not suffer from disturbances in the light path and optical source power fluctuations.

This wavelength-encoding nature of FBGs facilitates wavelength-division multiplexing (WDM) of multiple sensors; FBG sensors can be particularly useful when gratings with different periods are arranged along an optical fiber. Each of the reflected signals will have a unique wavelength and can be easily monitored, thus achieving multiplexing of the outputs of multiple sensors using a single fiber. Thus,
strain, temperature, or pressure can be measured at many locations, making FBGs a kind of typical quasi-distributed sensor (Figure 3.16). FBG sensors are preferred in many civil engineering applications and have been successfully employed in many full-scale structures requiring multiple-point sensing distributed over a long range.

Most of the research on FBG sensors has focused on the use of these devices to provide quasi-distributed point sensing of strain or temperature. FBGs have also been used as point sensors to measure pressure, magnetic field, high voltage, liquid level, RI of liquid, and acoustic emission levels, and to monitor the curing process of composites. One disadvantage of the FBG technology in real engineering applications is associated with its cross-sensitivity effect, which causes simultaneous sensitivity of Bragg wavelength shift to both strain and temperature. Therefore, some methods to discriminate both measurements are usually needed.

Another type of grating, LPFG, couples light from a guided mode into forward-propagating cladding modes, where it is lost due to absorption and scattering. The coupling from the guided mode to cladding modes is wavelength dependent, so we can obtain a spectrally selective loss. It is an optical fiber structure with the properties periodically varying along the fiber, such that the conditions for the interaction of several co-propagating modes are satisfied (Figure 3.17).

The period of such a structure is of the order of a fraction of a millimeter. In contrast to the fiber Bragg gratings, LPFGs couple co-propagating modes with close propagation constants; therefore, the period of such a grating can considerably exceed the wavelength of radiation propagating in the fiber. Because the period of an LPFG is much larger than the wavelength, LPFGs are relatively simple to manufacture. Since LPFGs couple co-propagating modes, their resonances can only be observed in transmission spectra. The transmission spectrum has dips at the wavelengths corresponding to resonances with various cladding modes (in an SMF). Depending on

![FIGURE 3.17](a) Structure of LPFG; (b) schematic experimental setup for LPFG.)
the symmetry of the perturbation that is used to write the LPFG, modes of different symmetries may be coupled. For instance, cylindrically symmetric gratings couple symmetric LP$_{0m}$ modes of the fiber. Microbend gratings, which are antisymmetric with respect to the fiber axis, create a resonance between the core mode and the asymmetric LP$_{1m}$ modes of the core and the cladding.

LPFGs with periods ranging from several hundred microns to several millimeters couple incident light guided by a fundamental mode in the core to different forward-propagating cladding modes of high diffraction order, $m$, in an optical fiber, which decay rapidly because of the radiation from scattering losses. The coupling of the light into the cladding region generates a set of resonant bands centered at wavelength $\lambda_m$ in the transmission spectrum of the fiber. The resonance wavelengths, $\lambda_m$, of an attenuation band are solutions of the phase-matched conditions

$$\lambda_m = \left[ n_{co}^{\text{eff}} - n_{cl,m}^{\text{eff}} \right] \Lambda = \delta n_{\text{eff}} \Lambda$$

where:

- $\Lambda$ is the period of the grating
- $n_{co}^{\text{eff}}$ is the effective RI of the fundamental core mode at the wavelength of $\lambda_m$, which also depends on the core RI and cladding RI

In addition, $n_{cl,m}^{\text{eff}}$ is the effective RI of the $m$th radial cladding mode ($m = 2, 3, 4, \ldots$) at the wavelength $\lambda_m$, which is also a function of cladding RI and in particular the RI of the surrounding medium, $n_s$. It is noted that both indices depend on the temperature and the strain experienced by the fiber. The spectral properties of individual cladding modes are determined by the fiber structure and may be observed through their associated attenuation bands. When the RI of the surrounding medium changes, $n_{cl,m}^{\text{eff}}$ also changes, and a wavelength shift can be obtained in the transmission spectrum. An LPFG can be very sensitive to changes in temperature and deformations due to fiber imperfections, loading, and bending, which also produce a noticeable wavelength shift in loss peaks. Therefore, to precisely measure variations in RI changes, temperature changes and deformations must be compensated or avoided.

LPFGs have a wide variety of applications, including band-rejection filters, gain-flattening filters, and sensors. Various gratings with complex structures have been designed: gratings combining several LPFGs, LPFGs with superstructures, chirped gratings, and gratings with apodization. Various LPFG-based devices have been developed: filters, sensors, fiber dispersion compensators, and so on [31].

### 3.3.2.4 Fluorescent-Based Fiber Sensors

Fluorescent-based fiber sensors are widely used for physical and chemical sensing for measurands such as temperature, humidity, and viscosity. Among the different configurations used, two of the most common are the end tip sensor and the blackbody cavity types [32]. In the case of a blackbody sensor, a blackbody cavity is placed at the end of an optical fiber [33], and as the temperature of the cavity rises, it starts to glow and act as a light source. Using suitable detectors and narrow band filters, the profile of the blackbody curve can be determined, which provides the measurand
information. Due to the capability to measure temperature to within a few degrees centigrade under intense RF fields, sensors of this type have been developed as optical fiber thermometers and have been successfully commercialized.

3.3.2.5 Polarimetric Fiber Sensors

Polarimetric fiber sensors are quite well known. As the light wave propagates along the optical fiber, its state of polarization changes because of the difference in the phase velocity of the two polarization components in a birefringent fiber. The polarization properties of light propagating though an optical fiber can be affected by stress, strain, pressure, and temperature acting on it, and in a fiber polarimetric sensor, the change in state of polarization is measured and is used to retrieve the sensing parameter [34]. A symmetric deformation effect or temperature variation in an SMF influences the propagation constant ($\beta$) for every mode because of the changes in the fiber length ($L$) and the RIs of the core and the cladding. Under the influence of longitudinal strain ($\varepsilon$) or temperature ($T$), for SMF polarimetric sensors, the change in the phase difference can be written as [35]

$$\frac{\delta(\Delta\Phi)}{\delta X} = \Delta\beta \frac{\partial L}{\partial X} + L \frac{\partial (\Delta\beta)}{\partial X}$$

(3.9)

where $X$ stands for temperature, pressure, or strain.

A fiber-optic polarimetric sensor that operates in intensity domain using a polarizer–analyzer arrangement is shown in Figure 3.18. In a typical polarimetric sensor, linearly polarized light is launched at 45° to the principal axes of a birefringent fiber such that both the polarization modes can be equally excited. The polarization state at the output is converted to intensity by using a polarizer analyzer oriented at 90° to the input polarization state. For such polarimetric sensors, the change in the output intensity at a wavelength $\lambda$ due to externally applied perturbation can be described by the formula

$$I_s(\lambda) = \frac{I_0}{2} \left[1 + \cos(\Delta\Phi)\right]$$

(3.10)

Therefore, a change in polarization can be observed as a change in intensity, and by correlating the output change in intensity with the measurand, a polarimetric fiber sensor can be effectively used as a sensor for a variety of applications. The phase difference between the two orthogonal polarizations can also be extracted.
using an experimental setup consisting of a tunable laser source and a polarimeter/polarization control system.

For polarimetric fiber sensors, typically high birefringent optical fibers are used, such as panda fiber, bow-tie fiber, elliptical core, or polarization-maintaining photonic crystal fibers. Due to the high sensitivity of polarimetric fiber sensors to external parameters such as strain and temperature, cross-sensitivity is often a major problem with these types of sensor. The capability of polarimetric fiber sensors to measure strain, temperature, and pressure is demonstrated in a variety of applications, such as in structural health monitoring [35–38]. Fiber polarimetric sensors are also used for current and voltage measurements, in which a range of polarization-based effects (optical activity, Faraday Effect, electro-optic effect) are used. A detailed description of polarimetric fiber sensors and their applications can be found in Chapter 11.

3.3.3 Fiber-Optic Scattering-Based Distributed Fiber Sensors

Distributed fiber-optic sensors are capable of providing a continuous measurand profile over the length of the optical fiber and thus are most suitable for large structural applications such as bridges, buildings, and pipelines. Three main physical effects are used for distributed sensing: Rayleigh scattering, Raman scattering, and Brillouin scattering [39]. When a monochromatic light of frequency $f_0$ at $\lambda_0 \sim 1550$ nm propagates through an optical fiber, there is always Rayleigh, Brillouin, and Raman scattering within the fiber. The spectrum of these scatterings is shown in Figure 3.19.

The components whose frequency is beyond $f_0$ correspond to anti-Stokes, while those below $f_0$ correspond to Stokes.

The Rayleigh scattering effect can be used for both strain and temperature monitoring. It is based on the shifts in the local Rayleigh backscatter pattern, which is dependent on the strain and the temperature. Thus, the strain measurements must be compensated for temperature. The main characteristics of this system are high resolution of measured parameters and good spatial resolution (typically a few meters),

![FIGURE 3.19 Schematic spectrum of Rayleigh, Brillouin, and Raman scattering in optical fibers.](image-url)
but the maximal length of the sensor is limited to a relatively short distance (70 m). This is due to the low-level signal arising as a result of low nonlinear coefficients for the silica that constitutes the fiber, resulting in quite a long system response time, resulting from the necessity to integrate small signals received over many pulses. Thus, this system is suitable for monitoring localized strain changes.

Brillouin scattering is the result of the interaction between optical and sound waves in optical fibers. Thermally excited acoustic waves produce a periodic modulation of the RI. Brillouin scattering occurs when light propagating in the fiber is diffracted backward by the moving grating, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift. This process is called spontaneous Brillouin scattering. A schematic experimental setup for sensing is shown in Figure 3.20. The main challenge in using spontaneous Brillouin scattering for sensing applications resides in the extremely low level of the detected signal. This requires sophisticated signal processing and relatively long integration times.

Acoustic waves can also be generated by injecting into the fiber two counterpropagating waves with a frequency difference equal to the Brillouin shift. Through electrostriction, these two waves will give rise to a traveling acoustic wave that reinforces the phonon population. This process is called stimulated Brillouin amplification. Systems based on the stimulated Brillouin amplification have the advantage of working with a relatively stronger signal but face another challenge. To produce a meaningful signal, the two counterpropagating waves must maintain an extremely stable frequency difference. This usually requires the synchronization of two laser sources, which must inject the two signals at the opposite ends of the fiber under test.

Brillouin scattering sensor systems are able to measure strain or temperature variations of fiber with length up to 50 km, with spatial resolution down in the meter range. For temperature measurements, the Brillouin sensor is a strong competitor to systems based on Raman scattering, while for strain measurements, it has practically no rivals.

Raman scattering is the result of a nonlinear interaction within the light traveling in silica fiber. When an intense light signal is launched into the fiber, two frequency-shifted components called Raman Stokes and Raman anti-Stokes will appear in the backscattered spectrum. The relative intensity of these two components depends only on the local temperature of the fiber. If the light signal is pulsed, and the backscattered intensity is recorded as a function of the round trip time, it becomes possible...
to obtain a temperature profile along the fiber. The insensitivity of this parameter to strain is an advantage compared with Rayleigh and Brillouin-based temperature monitoring, since no particular packaging of the sensor is needed to keep the sensing fiber strain free. Systems based on Raman scattering have been commercialized by SMARTech (Switzerland), Sensornet, and Sensa (UK). Typically, a temperature resolution of the order of 0.1°C and a spatial resolution of 1 m over a measurement range up to 8 km are obtained for MMFs. Since the leakage of pipelines, dams, and so on often changes the thermal properties of surrounding soil, besides the temperature monitoring, Raman-based systems are used for leakage monitoring of large structures.

Distributed fiber sensors are often categorized based on the interrogation method and the physical effect underpinning the operating principle: (1) optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR), both based on Rayleigh scattering; (2) Raman OTDR (ROTDR) and Raman OFDR (ROFDR), both based on Raman scattering; and (3) Brillouin OTDR (BOTDR) and Brillouin OFDR (BOFDR), both based on Brillouin scattering.

### 3.3.4 Surface Plasmon Resonance Sensors

Surface plasmon resonance (SPR) refers to the excitation of surface plasmon polaritons (SPPs), which are electromagnetic waves coupled with free electron density oscillations on the surface between a metal and a dielectric medium (or air). SPPs or surface plasmon waves (SPWs) propagate along the interface of the metal and the dielectric material. For nanoscaled metallic structures such as metallic nanoparticles, or nanorods, a light of the appropriate wavelength can be used to excite the localized oscillation of charges, a process that is referred to as localized SPR.

When the energy as well as the momentum of both the incident light and the SPW match, a resonance occurs that results in a sharp dip in the reflected light intensity. The resonance condition depends on the angle of incidence, the wavelength of the light beam, and the dielectric function of both the metal and the dielectric. In an SPR-based fiber-optic sensor, all the guided rays are launched, and hence, the angle of incidence is not varied. In this case, the coupling of the evanescent field with surface plasmons strongly depends on wavelength, fiber parameters, probe geometry, and the metal layer properties.

The SPR-based fiber-optic sensor has a large number of applications for quantitative detection of chemical and biological species. These include food quality, medical diagnostics, and environmental monitoring. The sensing principle is based on detecting the change in RI of the medium around the metallic coating [40].

### 3.3.5 Photonic Crystal Fiber Sensors

Since the first demonstration of microstructured fiber (MOF) in 1996 (photonic crystal fiber), it has caused enormous attention and excitement in the photonics community. The unique features of the fiber, such as light guidance, dispersion properties, endlessly single-mode nature, higher birefringence, and enhanced nonlinear effects, have led to MOFs being applied in many fields, such as in optical communications,
nonlinear optics, and sensing. Unlike conventional fibers, MOFs can be optimized for a large range of applications by tailoring the size, number, and geometry of the air holes that form the confining microstructure around the core region (Figure 3.21a and b). This led to great interest among researchers in exploiting the advantages and using MOF-based sensors in a variety of applications. In a short span of time since the first introduction of the MOF, a variety of microstructured fibers have been reported, ranging from silica to polymer, for applications ranging from environmental sciences to medicine, industry, and astronomy [41]. The fascinating physics and applications of MOFs are still of great interest among researchers.

3.3.6 **Optical Microfiber Sensors**

Another rapidly growing fiber sensor type is the optical microfiber-based sensor. Optical microfibers exhibit many desirable characteristics, such as large evanescent field, strong optical confinement, bend insensitivity, configurability, compactness, robustness, and feasibility of extremely high-Q resonators [42,43]. The resulting sensors have numerous advantages over their standard optical fiber counterparts, including high responsivity, fast response, selectiveness, nonintrusiveness, and small size. With sensing areas spanning acceleration, acoustic, bend/curvature, current, displacement, electric/magnetic field, roughness, rotation, and temperature, the future of optical microfiber technology looks exceptionally promising (Figure 3.22).

3.4 **Optical Fiber Sensor Instrumentation**

Though sensor heads based on optical fibers are relatively cheap, the optical and electronic instrumentation required to interrogate the sensor is often expensive and complicated. Based on the type of fiber sensor used, the instrumentation requirements for interrogating the sensor will vary. The basic characteristics of any fiber-optic sensing instrumentation are its suitability for the type of fiber sensor and sufficient sensitivity and resolution with an adequate measurement range.

The simplest instrumentation requirement is for the intensity-based systems, where a simple light source (light-emitting diode [LED], semiconductor laser, etc.)
and an optical receiver with or without an amplifier would be sufficient in most applications. However, based on the stability and accuracy required, further modifications might be necessary, such as ratiometric measurement (Figure 3.6). For spectrometric fiber sensors, devices that can measure the spectral change are required, such as an optical spectrum analyzer or an optical spectrometer. One of the most common types of widely used spectrometric fiber sensor are FBG sensors, and for their interrogation, FBG interrogation systems are widely used. The operating principles of these interrogation units vary, and a range of techniques that can be used to interrogate an FBG are reported.

For polarimetric fiber-based sensing systems, a polarimeter, a polarization controller, and so on are most often used to improve the accuracy and reliability of the system.

In general, optical fiber sensor instrumentation plays a vital part in the overall development of the fiber sensing area, and over the years we have seen a tremendous increase in new developments in the instrumentation area, supported by the growth of the optical fiber networks area, which shares a common interest when it comes to instrumentation requirements. It should also be noted that the instrumentation requirements for different fiber sensor types are sometimes unique to these sensor types, and as a result, overall system development is required to realize a complete fiber sensing unit. Some examples of OFS instrumentation are shown in Figure 3.23 [44,45].

### 3.5 OPTICAL FIBER SENSORS: INDUSTRY APPLICATIONS AND MARKET

Over the years, optical fiber sensors have grown rapidly in quality and functionality and have found widespread use in many areas, such as defense, aerospace, automotive, manufacturing, biomedical, and various other industries. Rapid development of sensor devices and instrumentation over the years has made OFS an attractive alternative to conventional sensors for measuring a range of parameters, such as pressure, temperature, strain, vibration, acceleration, rotation, magnetic field, electric field,
viscosity, and a wide range of other measurands. Improvements in performance and standardization, together with decrease in price, have helped OFS to make an impact on the industry.

Among the different types of optical fiber sensors, FBGs, fiber gyroscopes, and distributed fiber sensors are the most widely used and popular. High-speed and reliable interrogation systems for data acquisition, processing and interpretation have also been developed for these devices. They also meet application-specific demands that are not efficiently satisfied by conventional electronic sensors. Examples of such applications include the use of fiber-optic sensors for pressure and high-temperature monitoring in the oil and gas exploration industry, which is a major market for distributed fiber sensors.

Fiber-optic sensors can contribute to improving safety by providing an early warning of failure in critical structures and components, for example in the

**FIGURE 3.23** (a) An OEM interrogation system for a fiber temperature sensor. (From Rajan et al., *Sensors and Actuators A: Physical*, 163, 88–95, 2010.) (b) A portable FBG interrogator. (From [http://www.smartfibres.com/FBG-interrogators](http://www.smartfibres.com/FBG-interrogators).)
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Aeronautical and civil engineering sectors. Therefore, structural health monitoring (SHM) is emerging as a promising market for optical fiber sensors. As the growth of production of composite parts has increased, the composite/aerospace industry has increasingly focused on damage/failure-free composite structures and non-destructive techniques for SHM over their lifetime. Compared with conventional nondestructive sensing techniques, optical fiber sensors have achieved wide acceptance due to their attractive properties, such as small size and capability to be embedded within the host structure. Optical fiber sensors embedded in various structures are very useful for strain and temperature monitoring applications in extreme environmental conditions. For example, issues such as bend loading, and icing on wind turbine and helicopter blades, can be monitored and avoided by implementing smart composite structures with embedded optical fiber sensors. Such smart structures can enhance the safety of advanced machines, structures, and devices.

The medical and biomedical industry also provides many challenging instrumentation requirements for which optical fiber sensing can provide novel and reliable solutions. One such challenge is the need to monitor within radioactive medical environments and in magnetic resonance imaging (MRI) systems, where electrical sensors cannot operate. Another is the need for in vivo sensing during keyhole surgical procedures and catheter procedures, where space is a premium and where a miniature fiber sensor is the largest intrusion that can be tolerated. Recent success with fiber sensors on the biomedical front includes commercial use of fiber-based catheters and miniature fiber temperature and pressure transducers for medical applications.

The acceptance of optical fiber sensors among different industries/applications is expected to experience rapid growth during the coming years due to a number of initiatives being taken by market participants [46]. Another driving force behind the growth of OFS is that a number of research initiatives and efforts to achieve standardization are also ongoing and being promoted by various research groups and industry leaders. However, more initiatives are required, such as ensuring the reliability, longevity, and accuracy of fiber sensor products to achieve a wider acceptance of the technology across various industrial sectors. According to analysis by a market research firm (BCC Research), [47] the global fiber-optic sensor market reached almost a billion dollars in 2010, and is expected to reach 2.2 billion dollars by 2018 [47].

3.6 CONCLUSION

This chapter provided a brief summary of the basic broad principles of different types of optical fiber sensors. Descriptions of fiber sensors based on different classifications, such as modulation methods, spatial positionings, and measurement parameters, were also discussed. Some of the emerging optical fiber sensors were also introduced, and finally, the fiber-optic instrumentation and market trends were discussed. With the emergence of a variety of new types of fibers and new configurations, OFS and instrumentation is still growing and is expected to further widen the scope of its applications in the near future.
REFERENCES


