3. Optical Waveguide Sensors

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3.1 Introduction

3.1.1 History

Optical waveguide, by definition, is a central region called the core of certain refractive index, which is surrounded by either one medium of lower refractive index or two optical media, each of which has refractive index lower than that of the core. The former type is called a symmetric optical waveguide and the latter asymmetric optical waveguide. Due to the refractive index contrast, launched light into a waveguide could be confined within the core through total internal reflection. In its simplest form, a waveguide is planar in geometry. Optical fiber represents an optical waveguide in cylindrical geometry. These two variations are represented in Figure 3.1.

A planar waveguide is a 1D waveguide, in which refractive index is a function of only x, for example, and light is confined in one direction. On the other hand, 2D waveguides form the backbone of integrated optics, in which light is confined in two dimensions; few examples of 2D waveguides are shown in Figure 3.2.

A sensor typically converts a change in the magnitude of one physical parameter into a corresponding change in the magnitude of a more conveniently measurable second different parameter. For noncontact measurements and sensing, optical techniques have long played an important role in instrumentation and sensors. A substantial part of this

![Figure 3.1](image1.png)

**FIGURE 3.1** (a) The planar/slab waveguide geometry, here \( n_1 > n_c \); for a symmetric waveguide, \( n_c = n_s = n_2 \); (b) optical fiber waveguide geometry.

![Figure 3.2](image2.png)

**FIGURE 3.2** Examples of 2D optical waveguides: (a) embedded strip guide, (b) strip-loaded guide, (c) rib guide, and (d) immersed guide.
book addresses optical-fiber-based sensing with an emphasis on underlying principles, technologies, and applications, noting, however, that integrated optics platforms have also been extensively considered to perform the sensing functionality. In this chapter, we would essentially cover sensing principles and illustrative applications of fiber-optical waveguides, with details addressed in subsequent chapters.

In recent years, the scope of optical techniques in the area of instrumentation and sensors has made a quantum jump with the ready availability of low-loss optical fibers and associated optoelectronic components. The advantages and potentials offered by fiber-optical waveguides in sensing and instrumentation are many. Some of the key features of this new technology, which offer substantial benefits as compared to conventional electric sensors, are as follows: fiber being dielectric, sensed signal transported through it is immune to electromagnetic interference (EMI) and radio frequency interference, intrinsically safe in explosive environments, highly reliable and secure with no risk of fire/sparks, high-voltage insulation and absence of ground loops, and hence obviate any necessity of isolation devices like opto-couplers. Furthermore, a fiber has low volume and weight, for example, 1 km of 200 μm silica fiber would weigh only 70 g and occupies a volume of ~30 cm$^2$; as a point sensor, they can be used to sense normally inaccessible regions without perturbation of the transmitted signals. Fiber-optic sensors are potentially resistant to nuclear or ionizing radiations, and can be easily interfaced with low-loss telecom-grade optical fibers for remote sensing and measurements by locating the control electronics for LED/laser and detectors far away (could even be tens of kilometers away) from the sensor head. The inherent large bandwidth of a fiber offers the possibility of multiplexing a large number of individually addressed point sensors in a fiber network for distributed sensing that is, continuous sensing along the length of the sensing fiber at several localized points; these could be readily employed in chemical and process industries, health monitoring of civil structures, biomedical instrumentation, etc., due to their additional characteristics like small size, mechanical flexibility, and chemical inertness. These advantages were sufficient to attract intensive R&D effort around the world to develop fiber-optic sensors. This has eventually led to the emergence of a variety of fiber-optic sensors for accurate sensing and measurement of physical parameters and fields, for example, pressure, temperature, liquid level, liquid refractive index, liquid pH, antibodies, electric current, rotation, displacement, acceleration, acoustic, electric and magnetic fields, and so on. Initial developmental work had concentrated predominantly on military applications like fiber-optic hydrophones for submarine and undersea applications, and gyroscopes for applications in ships, missiles, and aircrafts. Gradually, a large number of civilian applications have also picked up. During the 1970s, the technology of optical fibers for telecommunication was evolving at a rapid pace after the reporting of the first low-loss (< 20 dB/km) high-silica optical fiber concomitantly with room temperature operation of semiconductor laser diodes for long hours without degradation as well as high-efficiency photodetectors (PDs). Researchers soon realized that the transmission characteristics of optical fibers exhibited strong sensitivity to certain external perturbation-like bends, microbends, and pressure. A great deal of effort was spent at that time to reduce the sensitivity of signal-carrying optical fibers to such external effects through suitable designs of fiber refractive index profiles and cabling geometries. An alternate school of thought took advantage of these observations and started to exploit this sensitivity of optical fibers to external effects, essentially representing a variety of
measurands to construct a large variety of sensors and instruments. This offshoot of optical fiber telecommunication soon saw a flurry of R&D activities around the world to use optical fibers for sensing.

### 3.1.2 Classification

Today, fiber-optic sensors play a major role in industrial, medical, aerospace, and consumer applications. Broadly, a fiber-optic sensor may be classified as either *intrinsic* or *extrinsic* (Culshaw 2006). In the intrinsic sensor, the physical parameter/effect to be sensed modulates the transmission properties of the sensing fiber, whereas in an extrinsic sensor, the modulation takes place outside the fiber, as shown in Figure 3.3. In the former, one or more of the physical properties of the guided light, for example, intensity, phase, polarization, and wavelength/color, are modulated by the measurands, while in the latter case, the fiber merely acts as a conduit to transport the light signal and from the sensor head to a PD/optical power meter for detection and quantitative measurement.

![Figure 3.3](Image)

**Figure 3.3** Examples of (a) intrinsic (b) extrinsic fiber sensors; in the intrinsic sensor, the measurands induce the modulation of one of the characteristics of the guided light, while in extrinsic sensors, the measurand-induced modulation takes place outside the fiber, for example, here in the gap between the two fibers. Measurand is debugged by the detector/power meter.

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Physical Mechanism</th>
<th>Detection Circuitry</th>
<th>Typical Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>Modulation of light by emission, absorption, or refractive index change</td>
<td>Analog/digital</td>
<td>Pressure, displacement, refractive index, temperature, liquid level</td>
</tr>
<tr>
<td>Phase</td>
<td>Interference between measurand-induced signal and reference in an interferometer</td>
<td>Fringe counting, intra-fringe detection</td>
<td>Hydrophone, gyroscope, magnetometer, pressure</td>
</tr>
<tr>
<td>Polarization</td>
<td>Changes in gyration optical tensor</td>
<td>Polarization analyzer and amplitude comparison</td>
<td>Magnetic field, large current measurement, e.g., in a busbar</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Spectral-dependent variation of absorption and emission</td>
<td>Amplitude comparison at two fixed wavelengths</td>
<td>Temperature measurement</td>
</tr>
</tbody>
</table>
Four of the most commonly employed fiber-optic sensing techniques are based on either intensity modulation or interferometry or fluorescence, or spectral modulation of the light used in the sensing process (see Table 3.1). However, out of these four, the intensity and phase-modulated ones offer the widest spectrum of optical fiber sensors.

The advantage of intensity-modulated sensors lies in their simplicity of construction and they being compatible to the multimode fiber technology. The phase-modulated fiber-optic sensors necessarily require an interferometric measurement setup with associated complexity in construction, although as we shall see later in the chapter that they theoretically offer orders of magnitude higher sensitivity as compared to intensity-modulated sensors.

The rest of the chapter would describe functional principles and samples of a variety of fiber-optic sensors as a versatile sensor technology platform. Several other chapters in this book discuss further details of this optical sensing approach with guidelines for future developments.

### 3.2 Intensity-Modulated Fiber Sensors

#### 3.2.1 General Features

Intensity-modulated fiber-optic sensors are the most widely studied fiber-optic sensors (Medlock 1987, Krohn 1988, Pal 1992a,b). The general configuration of an intensity-modulated sensor can be understood from Figure 3.4, in which the baseband signal (the measurand) modulates the intensity of the light propagating through the fiber that act as the sensor head. The resultant modulation envelope is reflected in the voltage output of the detector, which, upon calibration, can be used to retrieve measure of the measurand.

An alternative equivalent of the preceding Table 3.1 in an algebraic format is depicted in Figure 3.5. Intensity modulation can be achieved through a variety of schemes, for example, displacement of one fiber relative to the other, shutter type, that is, variable attenuation of light between two sets of aligned fibers, collection of modulated light reflected from a target exposed to the measurand, and loss modulation of light in the core or in the cladding through bending, microbending, or evanescent coupling to another fiber/medium.

A generic classification of intensity-modulated fiber-optic sensors is schematically depicted in Figure 3.6. In this figure, an example is shown of a measurand-induced variable attenuation of transmitted light across an input fiber and a receive fiber, and also a generic example of light from a source, which undergoes measurand-induced modulation either through reflection from a diaphragm subjected to a variable pressure environment or through reflection/scattering from a chemical environment, which could be a turbid solution or a solution that fluoresces on excitation with light at a suitable wavelength.
One important care that needs to be addressed in all intensity-modulated sensors is to compensate for any variation/fluctuation in the intensity of the light source used in the measurements. This could be easily taken care of/accounted for by launching light through a tap fiber coupler so that tapped light intensity is continuously monitored by a PD/power meter as the reference; the ratio of measurand-induced variation in light intensity is always taken with respect to this reference intensity.
The principles and techniques associated with optical sensing based on intensity modulation are detailed in Chapter 4, while Chapter 13 further elaborates this sensing approach when supported by the optical fiber platform. In the following sections, some examples are presented illustrating the main characteristics of these sensors.

### 3.2.2 Intensity Modulation through Light Interruption between Two Multimode Fibers

Measurand-induced modulation of coupling of the light in a gap between two fibers can be exploited to detect threshold pressure, sound wave, threshold liquid level, etc. In its simplest form (see Figure 3.6, transmissive type), an interceptor in the form of a knife edge, for example, mounted on a diaphragm used as the lid of a pressure chamber could be used to detect/monitor if the pressure has exceeded a predetermined threshold value through suitable calibration. Optical fiber microswitches based on this basic principle are commercially offered to detect displacement (e.g., with pressure release valves) in hazardous environments (Pitt et al. 1985). Likewise, if the level of a liquid exceeds a predetermined threshold level/height, at which two fibers are kept perfectly aligned with a small air gap (approximately a few micrometers) in between from the wall of the liquid tank/container at a specific height, then an alarm signal could be triggered for taking corrective action as soon as the liquid level rises to that height. This configuration is particularly attractive if the liquid happens to be a potential source for fire hazard like gasoline, because there is no chance of electric spark in the measurement process. In an alternative version for detecting sound or displacement, one of these two fibers is mounted on an acoustically driven vibrating base/holder with a small length of the fiber extending from its holder as a cantilever and the other kept on a fixed base. Initially, without exposing to the measurand, the two fibers are kept perfectly aligned by maximizing the throughput power through the air gap in between. Then, as and when sound is switched on, the associated vibration would modulate the light transmitting through the gap between the two fibers, which could be detected and demodulated/processed to measure the frequency of the sound. The displacement between the fibers by one core diameter would result in approximately 100% light intensity modulation. Approximately, the first 20% of displacement yields a linear output (Krohn 1988). In the original experiment (Spillman and Mcmohan 1980), the device was found to detect deep-sea noise levels in the frequency range of 100 Hz to 1 kHz and transverse static displacements down to a few Angstroms. For higher accuracy measurements (Spillman and Gravel 1980, Pal 1992b), two opposed gratings were used in one such shutter mode actual device (as shown in Figure 3.7, in which acoustic waves were made to be incident on a flexible diaphragm made of rubber 1.5 mm thick and 2 cm diameter) to which one of the gratings was attached; the other was mounted on the rigid base plate of the housing. These gratings were made on two 9 × 3 × 0.7 mm³ cover strip glass substrates on which a 1.16 mm square grating pattern was produced from a 5 μm strip mask by means of photoresist lift-off technique through 1200 Å evaporation of chromium. An index matching liquid was inserted between the gratings, which were so aligned under a microscope that they were parallel and displaced relative to each other by one half strip width to ensure that the sensor works at the maximum and linear sensitivity region.
The overlap area of two glass slides was sealed with a soft epoxy like RTV, which enabled the displacement of one grating relative to the other and also provided an elastic restoring force. The fibers consisted of two 200 μm plastic core, plastic clad fibers. The output He–Ne laser light from the input fiber was collimated by means of a GRIN Selfoc lens bonded to it. This collimated beam after transmission through the grating assembly was defocused by means of a second GRIN lens onto the input end of the receiving fiber; this procedure led to the isolation of the input and output coupling optics from the gratings. Such a device was shown to be sensitive to acoustic pressure less than 60 dB (relative to 1 μPa) over the frequency range of 100 Hz to 3 kHz, and it could resolve relative displacements as small as few Angstroms with a dynamic range of 125 dB. Before testing, the interior of the sensor assembly was filled with distilled water through the pressure relief hole. Further, it was relatively insensitive to static pressure head and responded well to variation in ac pressure for use as a hydrophone.

### 3.2.3 Reflective Fiber-Optic Sensors

In reflective sensors, the measurand induces modulation of the light reflected from a reflecting surface. In its simplest form, a Y-coupler fiber-optic probe consisting of two multimode fibers cemented/fused along some portion of their length (two bundles of fibers may also be substituted in their place) to form a power divider constitutes a reflective fiber-optic sensor. As an example, if light is injected through port 1 of the Y-power divider on to a light-reflecting diaphragm and the picked-up back-reflected light exits through port 3, its intensity would depend on the distance of the reflecting target from the fiber probe (see Figure 3.8). A dynamic range of such sensors can be enhanced by the use of a lens intermediate between the fiber probe and the reflective target. Such sensors can be used to detect displacement, pressure, or even the position of a float in a variable area flowmeter (Medlock 1987). The use of such reflective fiber-optic sensors have been demonstrated in determination of surface texture (Uena 1973), flow of pulp suspension in a tube in the range ~1–10 m/s (Oki et al. 1975), pressure over a range of ~100 psi (Tallman et al. 1975), in medical catheters as inter-cardiac pressure transducer with a sensitivity ~1 mm of Hg and linearity in the range of 0–200 mm of Hg (Lindstroem 1970, Matsumoto et al. 1978), vibrations (Uena et al. 1977, Parmigiani 1978), and also as a fiber laser Doppler anemometer (fiber LDA) (Kyuma et al. 1981).
3.2.4 Fiber-Optic Liquid Level Sensing

Frustrated total internal reflection is exploited in a fiber-optic-based threshold liquid level sensor as shown in Figure 3.9. Light from a light source is coupled into a fiber, which is cemented with an optical adhesive at one end of the base of a 90° glass micro-prism, and a second fiber likewise is optimally fixed at the other end of the prism base to collect total internally reflected (TIR) light. As the liquid level rises and touches the prism, frustrated TIR takes place and the second fiber no longer receives any light and hence the power meter immediately detects a significant drop in the signal. This sensor configuration could be used as a threshold liquid level digital sensor, which could be used to stop, for example, an electric pump often used to fill an overhead water tank for

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**FIGURE 3.8** Schematic of a reflective sensor in which one fiber/a bundle of fibers transmits light from a source to a reflecting surface and another fiber/fiber bundle picks up the reflected light as a conduit for detection by a detector.

**FIGURE 3.9** Schematic of a liquid level sensor, whose working principle is based on frustrated total internal reflection as described in the text.
domestic use. The same configuration could also be used to trigger an alarm signal once a predetermined liquid level is reached to avoid spillage.

### 3.2.5 Fiber-Optic Microbend Sensor

Extrinsic perturbation, for example, introducing bend on a fiber’s lay leads to transmission loss. This effect needs to be accounted for while laying a fiber for use in a telecommunication link so that nowhere the fiber encounters a tight bend. A simple experiment that involves launching visible laser light like He–Ne laser into a fiber once when it is kept straight and once when the same fiber is bent into a circle (e.g. by looping a length of the same fiber around the experimenter’s finger) would immediately reveal that a fiber suffers radiation loss at a bend. Physically, it can be explained by appreciating that the fractional modal power that travels in the cladding along the periphery of a bent fiber would be required to travel at a rate faster than the local plane wave velocity of light in order to maintain equi-phase fronts across radial planes. This being physically disallowed that part of the modal field radiates away (Marcuse 1982). In contrast to bend-induced transmission loss due to a constant curvature, if the fiber lay goes through a succession of very small bends (see Figure 3.10), the fiber exhibits transmission loss due to what is referred as microbend-induced loss in a fiber.

Physically, microbending leads to redistribution of power among the modes of the fiber and also transfer of some power from some high-order guided modes to radiation modes and hence loss in throughput power. Through a theoretical coupled mode analysis, it could be shown that strong coupling between the $p$th and $q$th modes of a fiber would occur if $\Delta \beta = |\beta_p - \beta_q|$ matches the spatial wave number (=2\pi/\Lambda) of the microbending deformer. This phenomenon could be exploited to detect a variety of

![Diagram of Fiber-Optic Microbend Sensor](image)

**FIGURE 3.10** Schematic example of (a) macrobend and (b) microbend intensity-modulated fiber-optic sensor; $\Lambda$ represents spatial wavelength of a microbender.
fiber-optic sensors. Initially, these were used as hydrophones and displacement sensors (Fields and Cole 1980). Depending on the configuration of the microbender, same phenomenon could be exploited to construct a fiber-optic sensor, which could be used to determine several other environmental changes like temperature, acceleration, and electric and magnetic fields (Lagakos et al. 1987). For example, to function as a temperature sensor, the deformer should be made of a metal; for electric field, it should be a piezoelectric material and for magnetic field, it should be a magnetostrictive material. In Table 3.2, we tabulate minimum detectability of different environmental changes achievable in such fiber microbend sensors (Lagakos et al. 1987).

### 3.2.6 Fiber-Optic Chemical Sensing

Fiber-optic chemical sensors have been reported in a variety of forms. An interesting application of microbend sensors to chemical sensing exploits an offshoot of telecom industry, namely, the equipment optical time-domain reflectometer (OTDR), which is extensively used for monitoring the health of an optical telecommunication network. OTDR in combination with a localized measurand-induced microbend loss in a fiber has been used to detect localized water ingress in a civil structure or localized oil spillage, etc., in a distributed manner (Maclean et al. 2003). The basic functional principle of an OTDR is that it captures a snapshot of the backscatter signal from a fiber when an optical light pulse is launched into its input end. The signature of the backscatter signal in terms of detected power level as a function of length of the fiber is picked up at the input end itself through a fiber coupler as shown in Figure 3.11. Local signal at a point

![FIGURE 3.11 Schematic of an OTDR-based microbend intensity-modulated fiber-optic sensor. (Courtesy of B. Culshaw, EEE Department, University of Strathclyde, Glasgow, U.K.)](image-url)
along the fiber’s lay is distinguishable on the OTDR trace itself because the $x$-axis of the OTDR trace is calibrated in terms of fiber length while the $y$-axis represents the power level of the captured signal. Any local loss along the fiber length would be reflected as a drop in signal level at that location on the OTDR trace.

Figure 3.12a represents a schematic of the fiber cable configuration. These cables are tailored cables meant for distributed microbend sensing. A specific polymer material in the form of a gel, which would swell due to ingress of water, for example, surrounds a central GRP rod; this combination is held along its length within the cable along with a multimode optical fiber by helical wrapping with a Kevlar rope.

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**FIGURE 3.12** (a) Schematic of the fiber cable configuration for microbent fiber-optic sensor; (b) portion of the microbent fiber cross section due to swelling of the polymer due to water or liquid chemical ingress, and the resultant OTDR trace from the fiber; (c) schematic of the OTDR trace from the sensing fiber cable under dry and wet conditions. (Courtesy of B. Culshaw, EEE Department, University of Strathclyde, Glasgow, U.K.)
around the polymer. Overall combination is held within a protective sheath having micropores. If there is a localized water spillage anywhere along the cable lay, water would penetrate the cable through these pores and the chemically active hydrogel would swell due to absorption of water. Accordingly, the swelled gel would induce localized microbending of the fiber within the cable (see Figure 3.12b) and hence introduce a local loss there, which could be instantly captured in the OTDR trace as shown in Figure 3.12c. The same principle could be employed to detect spillage of other liquids like gasoline, if the hydrogel is substituted by another gel, which would swell due to absorption of gasoline, that is, another custom-designed cable with specific gel needs to be assembled for this purpose. In this fashion, custom-designed sensor fiber cables for sensing spillage of liquids like petrol, kerosene, diesel, crude oil, etc., could be designed and fabricated.

Another example of fiber-optic chemical sensing is shown in Figure 3.13, a schematic depicting measurement through excitation and collection of fluorescence emission. Since fluorescence is characteristic of a material, its spectroscopic measurement could yield information about the presence and its concentration in a solution. Fiber-optic probes of various designs could be used in such measurements. These probes are also referred to in the literature as optrodes.

A generic schematic of an optrode-based optical sensing is shown in Figure 3.14a, and few possible examples of optrode cross-sections are shown in Figure 3.14b. Such optrode-based sensing finds application in biomedical optics in oncology, for example, for the detection of cancerous cells, and diagnostics and monitoring of anatomical sites, while in chemical industries, these could be useful in hazardous and aggressive environments, for example, acidic, nuclear, and inflammable chemicals.

Similar optrodes could also be used as reflective sensors mentioned in Section 3.2.3 by using the central fiber as carrying the probe light and by collecting the reflected light from the reflecting surface through the peripheral fibers. Likewise, these could

![FIGURE 3.13 Schematic example of a fiber-optic fluorescence sensor.](image-url)
be gainfully deployed to measure scattered light from a solution also, for example, in turbidity measurements. In a turbidity sensor configuration (see Figure 3.15) reported in Prerana et al. (2012), scattered light from a turbid solution is collected after reflection from a concave mirror. Turbidity of a specific solution can be estimated in terms of total interaction coefficient, which is defined as the sum of the absorption and scattering coefficients.

Extensive results of Monte Carlo simulation (see Figure 3.16a) on optrode-based collection of light with reference to the experimental setup (shown in Figure 3.15) from a turbid solution and corresponding experimental results (Figure 3.16b) could be found.
in Prerana et al. (2012). Turbidity is an important indicator for checking the quality of liquids like water and olive oil (Mignani et al. 2003).

### 3.2.7 Fiber-Optic Refractometer

Refractive index sensing is an important characteristic in many chemical industries. A multimode fiber-based refractometer reported in Kumar et al. (1984) is based on a
plastic clad silica core multimode fiber having a small tapered section. Figure 3.17 represents the geometry of such a tapered fiber.

The tapered portion can be thought of as interconnecting two fibers: #1 of core diameter $2a_{in}$ and #2 of core diameter $2a_o$ ($a_o < a_{in}$). Fibers #1, #2, and the tapered interconnecting zone, all have the same core and cladding refractive indices $n_1$ and $n_2$, respectively, except for the initial section of fiber #1, in which the cladding index is $n_{cl}$, that is, the plastic clad. A guided mode of effective index $n_{e1} (=n_1 \cos \theta_1, \theta_1$ being the characteristic mode propagation angle) in fiber #1 gets transformed to a corresponding characteristic mode effective index $n_{e2}$ in fiber #2 (Kumar et al. 1984) as

$$n_{e2} = \left[ n_{e1}^2 - R^2 \left( n_{e1}^2 - n_{cl}^2 \right) \right]^{1/2}$$  \hspace{1cm} (3.1)

where $R (=a_{in}/a_o)$ is the taper ratio. For a mode to be guided in fiber #2, one requires

$$n_{e1} \geq \left[ n_{e1}^2 - \frac{n_{e1}^2 - n_{cl}^2}{R^2} \right]^{1/2} \equiv n_{e1}^{\text{min}}$$  \hspace{1cm} (3.2)

If $P_o$ represents the total power injected into the guided modes of fiber #1, then the power in the modes with $n_{e1} > n_{e1}^{\text{min}}$ would be given by

$$P_b = P_o \frac{n_{e1}^2 - n_{e1}^{\text{min}}^2}{R^2 \left( n_{e1}^2 - n_{cl}^2 \right)}$$  \hspace{1cm} (3.3)

Thus it is evident from Equation 3.3 that power coupled to fiber #2 through the taper increases linearly with proportional decrease in $n_{e1}^2$. This result has been exploited to construct a fiber refractometer based on a plastic-clad silica core fiber, from a small portion of which plastic was removed and this bare portion of the fiber was then converted into a taper by heating and stretching in a flame burner. The tapered zone was immersed in a liquid of refractive index $n_L$ ($<n_1$). By immersing the taper subsequently in a number of other liquids while taking care to clean tapered zone each time appropriately, and monitoring the corresponding power reaching fiber #2, one can generate a calibration curve for a given
Thus, a measure of the output power exiting fiber #2 for a liquid of unknown refractive index would yield a refractive index of that liquid. Kumar and coworkers have shown a linear decrease in $P_b$ with $n^2_L$. In principle, the same technique could be exploited to construct a fiber-optic temperature sensor by encapsulating the taper with a metallic encapsulation filled with a thermo-optic liquid whose refractive index varies with temperature. In fact, plastic clad silica fibers provide an excellent platform to configure a range of intensity-modulated fiber-optic sensors. For example, a small bare section of such a fiber could be covered with a sol gel material to form a porous cladding, which could be used as a substrate to entrap a gas/liquid, which would form the local cladding there and hence would modulate the intensity of the propagating light in that region. Demodulation of this transmitted light could yield information about that gas/liquid.

### 3.2.8 Fiber-Optic Sensor Based on Side-Polished Fiber Half-Couplers

Side-polished single-mode fiber (SP-SMF) half-coupler offers a versatile sensor technology platform, in which phase resonant evanescent coupling of the SP-SMF with a multimode overlay waveguide (MMOW) could be exploited. A high-sensitive temperature sensor based on evanescent field coupling between a side-polished fiber half-coupler (SPFHC) and a thermo-optic MMOW was designed and realized in a paper by Nagaraju et al. (2008) (see Figure 3.18).

Such a structure essentially functions as an asymmetric directional coupler with a bandstop characteristic attributable to the wavelength-dependent resonant coupling between the mode of the SPFHC and one or more modes of the MMOW. The wavelength sensitivity of the device was ~5.3 nm/°C within the measurement range of 26°C–70°C; this sensitivity is more than five times higher compared to earlier reported temperature sensors of this kind. The SPFHC was fabricated by selective polishing of the cladding from one side of a bent telecommunication standard single-mode fiber, and the MMOW was formed on top of the SPFHC through spin coating. A seminumerical rigorous normal mode analysis was employed at the design stage by including the curvature effect of the fiber lay in the half-coupler block and the resultant $z$-dependent evanescent coupling mechanism. The agreement between theoretical and experimental results was excellent.

![FIGURE 3.18](image-url) (a) Schematic diagram of the sensing device; (b) shift in the resonance wavelength with temperature (solid curve is a linear fit through experimental data points).
The temperature range measurable by this sensor was limited by the thermo-optic overlay material used; other suitable MMOW material of appropriate thickness could be chosen to adapt such a device for the measurement of temperature in other ranges. Further refinement in such a fiber refractometer was recently reported by Prerana et al. (2010), in which the role of a tapered MMOW was investigated. Such an SPF-MMOW configuration was earlier exploited by Johnstone et al. (1992) as a refractometer, whose performance was theoretically explained in Raizada and Pal (1996).

3.3 Interferometric Fiber-Optic Sensors

3.3.1 General Features

Interferometric fiber-optic sensors are ultra-high-sensitive sensors, which are based on interferometric measurements of measurand-induced change in the phase of the light propagating in a fiber (Giallorenzi et al. 1982, Dandridge 1991, Culshaw 1992). These sensors offer huge potential in a variety of applications especially for high-sensitive measurements of low-magnitude measurands. At times, their ultrasensitive nature poses a problem to accurately measure a measurand due to sensitivity to ambient conditions, and hence, signal processing of the measured parameter is an important issue. The sensitivity of an interferometer to a measurand involves two basic criteria: the efficiency of the interface between the measurand and the optical delay in the fiber and the ability to reject the interfering measurands at the same time (Culshaw 1992). Phase sensitivities vary with measurands, for example, in the case of strain, about 10 rad per microstrain per meter, for temperature about 100 rad per degree per meter, and for pressure about 10 rad per bar per meter. In view of the relatively higher sensitivity to strain, pressure or magnetic fields are measured through corresponding transformation to strain as in a fiber-optic hydrophone and magnetometer (Culshaw 1992).

The principles and techniques associated with optical sensing based on interferometric modulation are introduced in the following sections and detailed further in Chapter 14. Although most of the material presented is associated with the optical fiber, it is quite general and equally applicable to other optical sensing platforms.

3.3.2 Fiber-Optic Mach–Zehnder Interferometer

A Mach–Zehnder interferometer (MZI) fiber-optic sensor is shown in Figure 3.19. It can be seen that two 3 dB fiber couplers are concatenated to form the interferometer.

![Figure 3.19](image-url)
If the amplitude of the light injected into port 1 is $E_{\text{in}}$, the corresponding intensity will be $I_{\text{in}} (=\text{Abs}[E_{\text{in}}]^2)$. If we consider the light from port 1 reaching port 2 via the upper and lower arms of the interferometer, its intensity detected by PD 1 would be

$$I_1 = E_1 \cdot E_1^* = \frac{1}{2} E_{\text{in}} \left( e^{i\phi_1} + e^{i(\pi + \phi_2)} \right) \cdot \frac{1}{2} E_{\text{in}} \left( e^{-i\phi_1} + e^{-i(\pi + \phi_2)} \right)$$

$$= \frac{I_{\text{in}}}{2} (1 - \cos \Delta \phi) = I_{\text{in}} \sin^2 \frac{\Delta \phi}{2} \quad (3.4)$$

where $\Delta \phi = \phi_1 - \phi_2$; $\phi_{1,2}$ correspond to respective phase accumulated along lengths of the upper and lower arms of the interferometer. In Equation 3.4, extra phase of $\pi/2$ accumulated by the coupled light at each of the two fiber couplers (Pal 2000) has been taken into account, which accounts for the additional phase of $\pi$ accumulated by light taking path via the lower arm of the interferometer to reach PD 1 after crossing over twice at the two couplers. Likewise, the intensity of light reaching PD 2 would be given by

$$I_2 = I_{\text{in}} \cos^2 \frac{\Delta \phi}{2} \quad (3.5)$$

Normalized $I_2$ versus $\Delta \phi$ is plotted in Figure 3.20. For $\Delta \phi = 0$, $I_2 = I_{\text{in}}$ while for $\Delta \phi = \pi$, $I_2 = 0$.

The corresponding plot of $I_1$ with $\Delta \phi$ would be complementary to it. In practice, measurand-induced $\Delta \phi$ is small, and hence, variation in $\phi$ would be very small around the maximum and minimum of $I_{1,2}$ as a function of $\Delta \phi$. The most sensitive point of operation would correspond to the quadrature point, where $\Delta \phi = (2m + 1) \pi/2$; $m = 0, 1, 2, \ldots \Rightarrow \Delta \phi$ is $\pi/2$, or $3\pi/2$, or $5\pi/2$, $\ldots$. Around this point, $I_{2,1}$ varies linearly with phase. This phase bias can be introduced through stretching the fiber, for example, by wrapping the portion of the reference fiber arm on a piezoelectric drum driven by a signal generator; any small deviation in $\Delta \phi$ around the quadrature bias point could be actively controlled through the piezo driver. Thus, if the measurand-induced phase change is $\delta \phi$ around the quadrature point, $\Delta \phi = \pi/2 + \delta \phi$ then

$$I_1 = I_{\text{in}} \sin^2 \left( \frac{\pi}{4} + \frac{\delta \phi}{2} \right) = \frac{I_{\text{in}}}{2} \left( 1 + \delta \phi \right) \quad (3.6)$$

![Figure 3.20](image-url)  
**Figure 3.20** Mach–Zehnder interferometer output intensity $I_2$ with variation in phase; the quadrature point at which $\Delta \phi$ is $\pi/2$ is marked as a dot on the figure for which normalized $I_2$ is 0.5.
It shows that $I_1 \propto \delta \phi$, that is, the phase difference is converted into intensity, which can be measured by a square-law detector. For a shot-noise-limited detection system, assuming SNR = 1, it can be shown that minimum detectable phase change over a detection frequency bandwidth ($\Delta \nu$) is given by (Ghatak and Thyagarajan 1998)

$$\delta \phi_{\text{min}} = 2\left( \frac{e\Delta \nu}{I_\text{in} \rho} \right)^{1/2} \tag{3.7}$$

where

- $\rho$ is the responsivity (A/W) of the detector
- $e$ is the electron charge = $1.6 \times 10^{-19}$ C

If $I_\text{in} = 1$ mW, $\Delta \nu = 1$ Hz, and $\rho = 0.5$ A/W, $\delta \phi_{\text{min}}$ from Equation 3.7 is $\approx 3.6 \times 10^{-8}$ rad, which is indeed very small. If this $\delta \phi_{\text{min}}$ indeed occurs at a wavelength of $\lambda_0 = 1550$ nm due to a change in fiber length ($\delta L$), then

$$\delta L = \frac{1}{2\pi \lambda_0 n_{\text{eff}}} \frac{\delta \phi}{\rho} = \frac{3.6 \times 10^{-8} \times 1.55 \times 10^{-6}}{2\pi \times 1.449} \approx 6 \times 10^{-13} \text{ m} \tag{3.8}$$

Thus, if a variation in fiber length induces earlier-mentioned phase change of $\delta \phi_{\text{min}}$, and if that is measurable, then $\delta L$ given earlier would amount to a miniscule change in the fiber length of approximately 100 fm (~$10^{-13}$ m)! This is indeed extremely small. However, since a detector is usually not shot-noise-limited, measurable $\delta \phi_{\text{min}}$ is about one to two orders of magnitude larger and hence $\delta L$ correspondingly would be about a picometer.

If the phase of the propagating light in a fiber of length $L$ varies due to a temperature change $\Delta T$, then

$$\Delta \phi = k_0 \left( L \cdot \Delta T \frac{dn_{\text{eff}}}{dT} + n_{\text{eff}} \cdot \Delta L \right) \tag{3.9}$$

where $dn_{\text{eff}}/dT$ represents the thermo-optic coefficient. Thus,

$$\frac{\Delta \phi}{L \Delta T} = k_0 \left( \frac{dn_{\text{eff}}}{dT} + n_{\text{eff}} \frac{\Delta L}{L \Delta T} \right) \tag{3.10}$$

In fibers, thermo-optic coefficient dominates over the linear expansion term; thus, the first term within the bracket in Equation 3.10 is the dominating term for determining the phase change per unit length of a silica fiber due to variation in temperature. It is apparent from the earlier text that the signal would vary from a maximum ($= I_\text{in}$) to a minimum ($=0$) depending on $\Delta \phi$. However, in practice, this complete modulation is not observed, and one can associate fringe visibility $V$ defined as

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \tag{3.11}$$
In the early days of fiber-optic MZI development, detection of acoustic waves, which led to the development of fiber-optic hydrophones (see Figure 3.21) by scientists at Naval Research Laboratory in Washington, the United States, was the most widely pursued sensing scheme based on fiber-optic MZI (Cole et al. 2004).

In addition, fiber-optic MZI has been extensively used to detect temperature, linear strain, axial load, electric field, magnetic field, seismic signals, and vibration (Dandridge 1991). In several cases, the mechanical design of the sensing element is an extremely important issue such as the nature of the fiber coating. In more recent times, a pair of long-period gratings (LPGs) within a fiber was shown to effectively function as an MZI as illustrated in Figure 3.22 (Maier et al. 2007, Kim et al. 2008).

Since \( n_{\text{eff}} \) in the cladding is smaller than that at the core, the two different paths taken by the two distinct beams, namely, one as a core mode and the other as a core–cladding–core mode, lead to an optical path difference and hence form a two-beam interference pattern similar to that in an MZI described earlier. Such LPG pair-based MZI were shown to detect refractive index changes as low as \( \sim 1.8 \times 10^{-6} \) for hydrogen detection (Kim et al. 2008, Lee et al. 2012). Hydrogen sensing/leak detection has become extremely important in the context of wide interest on fuel cells in recent times. Several other techniques have been reported for forming in-fiber MZIs including the use of photonic crystal fibers (Lee et al. 2012).

FIGURE 3.21 Photograph of a Virginia class fiber-optic hydrophone developed at the Naval Research Laboratory, Washington, DC. (Adapted from Cole, J.H. et al., Wash. Acad. Sci. J., 90, 40, 2004. With the permission of the Washington Academy of Sciences.)
3.3.3 Fiber-Optic Michelson Interferometer

Fiber-optic Michelson interferometers (MIs) are another platform for two-beam interferometric sensors similar to MZI with the difference that it involves only one 3 dB fiber coupler to split one beam into two, both of which are reflected back by two mirrors placed at their ends as shown in Figure 3.23a.

The light from the source splits into two beams shown in the figure as full thick arrows at the 3 dB coupler. The reflected beams (full and dashed—both thin arrows for the two reflected beams from the mirrors M1 and M2 via arms a and b) reach the PD at port 4, where they interfere. These beams destructively interfere at port 1 as part of the reflected beams reaching back the source via arms a and b reach there with a phase difference of $\pi$. An algebraic analysis for the transmittance of an MZI presented in the

FIGURE 3.22 Schematic of an MZI formed with a pair of LPGs separated by a certain distance. LPG1 induces partial coupling of power from the core mode to a cladding mode, which after propagating as a cladding mode recouples back to the core mode after interacting with the second LPG. These two sets of beams taking different paths, when recombined after the second LPG, form an interference pattern that is characteristic of an MZI.

FIGURE 3.23 (a) A fiber-optic Michelson interferometer, in which one of the arms functions as a reference arm. The other arm as the signal arm is exposed to a measurand, which induces a change in the optical path length, and hence, the relative phase between the two light paths varies. As a result, an interference pattern is formed at the photodetector (PD), which varies with the measurand; (b) an alternative version of a fiber-optic Michelson interferometer for sensing in which an LPG is used to split and recombine reflected core and cladding mode lights to form interference and the same is captured on an OSA; a circulator is used in place of a fiber coupler. (After Swart, P.L., Long period grating Michelson refractometric sensor, *Meas. Sci. Technol.*, 15, 1576–1580, Copyright 2004 IOP.)
previous section could be extended to analyze transmittance of an MI, and it can be
shown that at the port containing PD (Jones 1992),

\[ I_4 = \frac{I_{in}}{2} \left(1 + V \cos(\Delta \phi)\right) \quad (3.13) \]

where \( \Delta \phi = \phi_a - \phi_b \). Essentially, an MI is half of an MZI. Thus, all discussions made ear-
ier for MZI would be valid here also. The fiber coupler, in principle, could be replaced
with a circulator as shown in Figure 3.23b. An interesting compact version of a single
fiber-based MI without involving a fused fiber coupler was proposed in the literature
(Swart 2004, Kim et al. 2005), the basic concept of which is shown in Figure 3.23b. An
LPG of about 50% coupling strength divides the propagating light in the core into two
paths—one along the core via the LPG and the other along the cladding as a cladding
mode—both of which are reflected by a common mirror fabricated directly at the end of
the fiber. These two reflected beams form the two arms of the MI and form the interfer-
ence fringes after being mixed through the same LPG at the input side, which is cap-
tured through a circulator on an optical spectrum analyzer. Such an MI has been used
as a refractometer. Cross-sensitivity to temperature could be reduced in these measure-
ments by using two types of fibers (Brakel and Swart 2005) or a photonic crystal fiber
(Park et al. 2010).

### 3.3.4 Fiber-Optic Sagnac Interferometer

Rotation sensing is of significant interest in several areas, for example, in inertial naviga-
tion in aircraft/spaceships, surveying where accurate determination of geodesic latitude
and azimuth is required, in determination of torsional oscillations in earth due to earth-
quakes, in determination of astronomical latitude, and in monitoring polar motion due
to various geophysical effects (Ezekiel and Arditty 1982). Traditionally, rotation sensors
have been mechanical gyroscopes based on spinning wheels and have relied on the con-
servation of angular momentum. However, fiber-based optical gyroscopes (FOGs) have
attracted a much stronger interest in recent times due to the absence of moving parts,
absence of warm-up time, and sensitivity to gravity (Ezekiel and Arditty 1982). FOGs
have emerged as an offshoot of ring laser gyroscopes (RLGs), first reported by Rosenthal
(1962). RLGs are now routinely used for inertial navigation in many passenger aircraft
(Lee et al. 2006) whose navigational controls depend critically on accurate rotation sensors.
Typical precision requirement in aircraft navigation lies in the range of 0.001–0.01°/h.
In terms of rotation rate of earth \( \Omega_E = 15\°/h \), this amounts to \( 10^{-5} \sim 10^{-3} \) times \( \Omega_E \). The
first proposal for implementing an FOG in the form of a Sagnac interferometer was
made in 1976 (Vali and Shorthill 1976). These sensors are produced commercially to
support high-end automobile navigation systems, for the pointing and tracking of sat-
teilite antennas, inertial navigation for aircraft and missiles, and as backup guidance
system for commercial aircraft such as Boeing 777 (Udd 2002). Other areas where fiber
gyros find applications are mining, tunneling, radio-controlled attitude control of heli-
copters, guidance for unmanned trucks, and so on. The Sagnac interferometer in its
classical form uses a beam splitter to split a light beam, which is directed to follow a
square or triangular trajectory in opposite directions toward the input end, where these
are recombined to interfere. In an FOG, two oppositely directed light beams are divided into two counterpropagating beams through a few hundreds of meters long single-mode fiber coil/loop—one in clockwise (cw) and the other in counterclockwise (ccw) direction as shown in Figure 3.24.

These two counterpropagating cw and ccw beams exiting from the fiber loop are recombined to form the interference pattern at the PD for further signal processing. Two couplers FC1 and FC2 are required to make the cw and ccw propagating beams experience identical paths because an additional fixed phase retardation of $\pi/2$ (in the absence of measurand) is introduced by the coupler to the coupled beam. In order to understand the working principle, we outline below the simple analysis given in Ezekiel and Arditty (1982), which ignores relativistic mechanics. Let us consider a disk of radius $R$ that is rotating clockwise with an angular velocity $\Omega$ about an axis perpendicular to the plane of the disk as shown in Figure 3.25.

If we assume that two identical photons are sent cw and ccw along the circumference starting at an arbitrary location 1, then, by the time cw propagating photon returns to its starting point, the disk would have rotated to location 2. Thus, this photon would be required to travel an extra linear distance (as compared to the case when the disk remains stationary, that is, for $\Omega = 0$, in which case physical path length $L = 2\pi R$ [i.e., the perimeter of the disk]) of

$$L_{cw} = 2\pi R + R\Omega t_{cw} = c_{cw}t_{cw}$$

(3.14)
and likewise the \( ccw \) propagating photon would take a shorter path length given by

\[
L_{ccw} = 2\pi R - R\Omega t_{ccw} \equiv c_{ccw} t_{ccw}
\]  
(3.15)

where

\[ R\Omega (=\Delta S) \]

\[ t_{cw,ccw} \]

represent the times taken to cover the distances

\[ L_{cw,ccw} \]

and \( c_{cw,ccw} \) correspond to the velocity of light

Thus, the net time difference between the two counterpropagating beams to cover \( L_{cw,ccw} \) would be

\[
\Delta t = \frac{2\pi R}{c_{cw} - R\Omega} - \frac{2\pi R}{c_{cw} + R\Omega} \equiv \frac{4\pi R^2}{c^2} \Omega = \frac{4A}{c} \Omega
\]

(3.16)

where we have assumed that in vacuum light velocity, \( c_{cw} = c_{ccw} = c \) and the product \( R^2\Omega^2 \) is negligible relative to \( c^2 \). Equivalently, this time difference amounts to a path length difference of

\[
\Delta L = c\Delta t = \frac{4A}{c} \Omega
\]  
(3.17)

Even if the Sagnac effect is considered in a medium of refractive index \( n \), for which the relativistic addition of the light velocity in that medium with the tangential velocity \( R\Omega \) is required, \( \Delta t \) and \( \Delta L \) would still be given by Equations 3.16 and 3.17, respectively (Ezekiel and Arditty 1982). If that medium is a single-mode fiber wound \( N \) number of turns in the form of a coil (see Figure 3.24), then

\[
\Delta t = \frac{4AN}{c^2} \Omega \Rightarrow \Delta L = c\Delta t = \frac{4AN}{c} \Omega
\]  
(3.18)

If we consider phase difference \( \Delta \phi \) between the \( cw \) and \( ccw \) propagating beams as they cover the total fiber length, \( \Delta \phi \) would be given by

\[
\Delta \phi = k_0 c\Delta t = \frac{8\pi AN}{\lambda_0 c} \Omega \Rightarrow \Delta L = \frac{\Delta \phi}{k_0} = \frac{4AN}{c} \Omega = \frac{LD}{c} \Omega
\]  
(3.19)

where

\[ D \]

is diameter of the fiber

\[ N = L/(\pi D) \]
The output intensity from a Sagnac interferometer due to interference between the \( cw \) and \( ccw \) propagating beams can be shown by following the analysis identical to the one described earlier for MZI to be given by

\[
I = \frac{I_{in}}{2}(1 + \cos \Delta \phi)
\]

(3.20)

where \( \Delta \phi = \phi_{cw} - \phi_{ccw} \). Following the same arguments as in the case of MZI before, the interferometer may be biased through the use of a PZT phase modulator at the quadrature point (\( \Rightarrow \Delta \phi = \pi/2 + \delta \)) so that Equation 3.20 becomes

\[
I_{out} = \frac{I_{in}}{2}(1 - \sin \delta) \approx \frac{I_{in}}{2}(1 - \delta)
\]

(3.21)

since \( \delta \) in general would be small. If we assume shot-noise-limited detector as in the case of MZI described earlier (see Equation 3.7), then minimum measurable \( \Omega \) would be given by \([\text{Ghatak and Thyagarajan (1998)}]\)

\[
\Omega_{\min} = \left( \frac{c \Delta v}{\lambda_0 4\pi AN \rho I_{in}} \right)^{1/2}
\]

(3.22)

If we assume a fiber length to be 500 m spooled in a loop of 3.2 cm radius, \( \rho = 0.5 \) A/W, \( I_{in} = 1 \) mW, \( \lambda_0 = 1.3 \) \( \mu \)m, and \( \Delta v = 1 \) Hz, then \( \Omega_{\min} \sim 30 \times 10^{-8} \) rad/s. Several companies market application-specific FOGs, for example, for missile guidance systems, commercial aircraft’s navigation systems, military helicopter as well as marine and submarine navigation systems, gas pipe mapping, compasses for tunnel construction, rockets, and even for automotive navigation systems (Lee et al. 2006). Birefringent fibers (including birefringent microstructured fibers) have been also used in fiber-optic Sagnac interferometers for the measurement of pressure (Fu et al. 2008), temperature (Moon et al. 2007), strain, and temperature (Frazao et al. 2006, Sun et al. 2007, Kim et al. 2009a,b), multiple-beam Sagnac topology (Baptista et al. 2000), twist sensor (Zu et al. 2011), cladding-mode resonance-based Sagnac interferometer (Dong et al. 2011), and curvature (Frazao et al. 2008).

### 3.3.5 Fiber-Optic Fabry–Perot Interferometer

In any of the sensors given earlier, the interaction of the measurand with the guided light in a fiber is most important and the same needs to be maximized for maximum sensitivity of the sensor. In order to enhance this interaction and hence the sensitivity of the sensor, one could design the sensor in such a way that the light is made to pass through the same length of the signal fiber several times, which could be possible through the use of multiple-beam interferometry like that in a Fabry–Perot interferometer (FPI). In general, FPI, also often referred to as FP etalon, is composed of two parallel reflecting surfaces with a small separation between them as shown in Figure 3.26a.

In intrinsic fiber form (referred to as FFPI in the literature), the reflecting mirrors are formed either within the fiber itself (see Figure 3.26b) through formation of Bragg gratings (Wan and Taylor 2002, Wang et al. 2007) or through micromachining (Ran et al. 2008, 2009) or by some other means like chemical etching (Machavaram et al. 2007) or...
by end cleaving followed by coating with titanium dioxide and re-splicing with a second piece of identical fiber (Udd 2002). On the other hand, the extrinsic version (referred to as EFPI) is shown in Figure 3.26c, in which one mirrored end of each fiber forms the two reflectors with an air gap in between; portions of the two mirrored fiber ends are kept inside a capillary for stability. In both cases, $R_1$ and $R_2$ together with a separation in between form a cavity of length $L$; light entering the cavity through partially reflecting $R_1$ is partially reflected and partially transmitted through $R_2$. The reflected wave from $R_2$ undergoes further partial reflections at $R_1$ and $R_2$. Those wavelengths, for which $L$ is an integral multiple of half the wavelength within the cavity (resulting one round-trip through the cavity is an integral multiple of the wavelength), would add in phase on transmission through $R_2$. Any perturbation to the cavity in terms of its length or refractive index by a measurand through either of the mirrors would affect the optical path length of the cavity. In principle, the cavity could be extremely small mimicking a point sensor. It may be noted that a fiber-optic FPI sensor is less complex than fiber-optic MZI and MI sensors described earlier as the FPI sensor does not require any couplers; the earliest form of fiber-optic FPI sensors involved well-cleaved fiber end faces (Kersey et al. 1983) or dielectric mirrors as the mirrors (Petuchowski et al. 1981, Yoshino et al. 1982). If we neglect any potential loss due to scattering and absorption in the mirrors, classical expressions for transmittance, defined as the ratio of transmitted power to incident power and likewise for reflectance of the mirrors in a FPI are (Lee and Taylor 1995)

$$T_{FP} = \frac{T_1T_2}{1+R_1R_2+2\sqrt{R_1R_2}\cos\phi}$$  (3.23)

$$R_{FP} = \frac{R_1+R_2+2\sqrt{R_1R_2}\cos\phi}{1+R_1R_2+2\sqrt{R_1R_2}\cos\phi}$$  (3.24)
where $\phi$, the round-trip propagation phase shift, through the cavity having a refractive index $n$ and length $L$, is given by

$$\phi = \frac{4\pi n L}{\lambda_0}$$

(3.25)

Naturally, $T_{FP}$ is maximum for $\phi = (2p + 1)\pi$ with $p = \text{an integer}$. Equations 3.23 and 3.24 are valid for fiber-optic FPIs also. In particular, for FFPI having low reflectance and assuming $R_1 = R_2 = R \ll 1$, these equations simplify to (Taylor 2002)

$$T_{FFP} \equiv 1 - 2R (1 + \cos \phi)$$

(3.26)

$$R_{FFP} \equiv 2R (1 + \cos \phi)$$

(3.27)

Equations 3.24 and 3.27 are plotted in Figure 3.27 as a function of round-trip phase $\phi$. In order to test the validity of the approximate expression Equation 3.27 for low mirror reflectivity, $R$ as a function of $\phi$ is shown in the same figure as a full curve.

The FFPI sensors could provide high sensitivity, large dynamic range, and fast response for the measurement of pressure, temperature, strain, displacement, magnetic field, flow rate, etc., and could be used also as embedded sensors in materials (Taylor 2002, Lee et al. 2012). The detection of acoustic noise burst produced by breaking a pencil lead on the surface of an aluminum sample by an EFPI has also been demonstrated as a pressure sensor (Tran et al. 1991). Other FFPI sensors have been reported for the measurement of humidity (Mitschke 1989), displacement (Li et al. 1995, Barrett et al. 1999), and magnetic field (Oh et al. 1997). FFPI sensors are suitable for implementing multiplexed sensing like space division multiplexing (Rao and Jackson 1995, Sadkowski et al. 1995), time division multiplexing (Lee and Taylor 1988), frequency division multiplexing (Farahi et al. 1988), and coherence multiplexing (Davis et al. 1988).

![Figure 3.27](image-url)
3.4 Fiber Grating–Based Sensors

In-fiber gratings are extensively used in dense wavelength division multiplexed optical communication links, in which fiber amplifiers are inevitably used. In-fiber gratings are also attractive for use as strain and temperature sensors in particular. One important attribute of in-fiber grating sensors over typical fiber-optic intensity-modulated sensors is that the measurand information is wavelength encoded, which makes the sensor self-referencing independent of fluctuations in source intensity during a measurement (Orthonos and Kalli 1999, Measures 2001).

Within the types of fiber gratings, Bragg gratings are particularly attractive. Their operation, sensing characteristics, and applications as sensors are described in detail in Chapter 17. In this section, highlights of their functional properties and relevance as sensing elements are presented.

A schematic of a fiber Bragg grating (FBG) of spatial period $\Lambda$, which is formed/written through interference between two oblique UV beams made incident (through the silica cladding from one side) inside the photosensitive core made of Germania doped silica, is shown in Figure 3.28a. Due to photosensitivity of the core material, the interference pattern leads to a periodic variation in refractive index in the core region exposed to the interference pattern.

If light from a broadband source is launched into this fiber having an FBG in its core, a particular wavelength $\lambda_B$ contained within the broadband source that satisfies the following phase matching Bragg condition

$$\lambda_B = 2n_{\text{eff}}\Lambda$$

would undergo strong reflection while the rest of the spectrum would get transmitted; here $n_{\text{eff}}$ represents the fiber mode effective index. These features of an FBG are shown in Figure 3.28b.

**FIGURE 3.28** (a) Schematic of a fiber Bragg grating (FBG) inside the core, which is wavelength encoded with a specific Bragg wavelength $\lambda_B$, which gets reflected out of a broadband light launched into the fiber, and rest of the spectrum is transmitted; (b) typical reflection and transmission spectra of an FBG. (Courtesy of Parama Pal.)
in Figure 3.28b. Due to this wavelength-encoded response (for the reflected light), several fiber gratings of different spatial periods could be formed at different locations on the same fiber in a distributed manner in a network, which enable distributed measurements of strain and temperature. This feature is very attractive for local damage detection in civil structures like bridges, buildings (Kersey et al. 1997), and also aircraft (Cusano et al. 2006, Ben-Simon et al. 2007), as well as for internal strain mapping with high spatial resolution (Orthonos and Kalli 1999). The characteristic optical path length \( \eta \) in a fiber grating is given by the product of \( n_{\text{eff}} \) with spatial wavelength (\( \Lambda \)) of the grating. The parameter \( \eta \) would depend on both stress (\( \sigma \)) and temperature (\( T \)), and hence, a change \( \Delta \eta \) in \( \eta \) with respect to a reference value would be given by (Pal 2003)

\[
\Delta \eta (\Delta \sigma, \Delta T) = \eta (\sigma, T) - \eta (\sigma_r, T_r) = \left[ \frac{\partial n}{\partial \sigma} \right]_T \Delta \sigma + \left[ \frac{\partial n}{\partial T} \right]_\sigma \Delta T
\]  

(3.29)

where

The subscript \( r \) refers to the reference value

\( \Delta \sigma \) and \( \Delta T \) represent incremental changes in the local stress and temperature from their reference values.

For an FBG, it is known that peak reflection, which occurs at the Bragg wavelength (\( \lambda_B \)), is given by (Pal 2000)

\[
R_{\text{peak}} = \tanh^2(\kappa L)
\]  

(3.30)

Thus, Equation 3.29 could be rewritten as

\[
\frac{\Delta \lambda_B}{\lambda_B} = \left[ \frac{\varepsilon}{\partial \sigma} + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \varepsilon} \right] \Delta \sigma + \left[ \frac{\varepsilon}{\partial T} + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right] \Delta T
\]  

(3.31)

where \( \varepsilon \), which means strain, is given by

\[
\varepsilon = \pm \frac{\partial \Lambda}{\Lambda}
\]  

(3.32)

The signs ± represent tensile and compressive stresses, respectively. In terms of Young’s modulus (\( Y_F \)) and thermal expansion coefficient (\( \alpha_F \)), Equation 3.31 could be rewritten as

\[
\frac{\Delta \lambda_B}{\lambda_B} = \frac{1}{Y_F} \left[ 1 + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \varepsilon} \right] \Delta \sigma + \left[ \alpha_F + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right] \Delta T
\]

\[
= \left[ 1 - \frac{n_{\text{eff}}^2}{2} p_e \right] \varepsilon_z + \left[ \alpha_F + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right] \Delta T = S_e \cdot \Delta \sigma + S_T \cdot \Delta T
\]  

(3.33)

where

\( \varepsilon_z \) is the strain along fiber axis

\( p_e \) represents an effective strain-optic or photo-elastic coefficient defined through
Optical Waveguide Sensors

\[ p_e = \left[ p_{12} - \nu (p_{11} + p_{12}) \right] \]

(3.34)

Here

- \( p_{11} \) and \( p_{12} \) are Pockel’s (piezo) coefficients, that is, components of the strain optic tensor.
- \( \nu \) is Poisson’s ratio.
- \( S_e \) and \( S_T \) represent strain and temperature sensitivities, respectively.

For a typical germano-silicate fiber, values of \( p_{11}, p_{12}, \) and \( \nu \) are 0.113, 0.252, and 0.16, respectively. With \( n_{\text{eff}} \) as 1.482 at 1550 nm, strain sensitivity at this wavelength region is 1.2 pm/\( \mu \varepsilon \) (Lee et al. 2006) and shift in Bragg wavelength is typically almost linear with strain (\( \varepsilon \)).

The mirror characteristic of FBGs opens new possibilities for interferometric sensing. As an example, a fiber-optic MI based on a fiber coupler, in which an FBG is placed in one of its arms, as shown in Figure 3.29, could be used to measure strain-induced shift in Bragg wavelength and hence strain.

Figure 3.30 depicts sample results from measurements of small strain through a corresponding shift in Bragg wavelength carried out with in-house fabricated FBG by the Fiber Optics Group at the Central Glass and Research Institute (CGCRI, Kolkata, India); achieved strain sensitivity was 1.2 pm/\( \mu \varepsilon \) (Gangopadhyay et al. 2009a, Gangopadhyay 2012).

Results reported on fiber grating sensors indicate their capability to measure dynamic strain from DC to over 10 MHz with a strain resolution of 0.02 \( \mu \varepsilon \) (DC to 10 KHz) to 25 \( \mu \varepsilon \) (10 MHz). Many bridges around the world are now retro-fitted with FBGs as strain gauge for distributed measurements of strain. FBGs in general yield better and more reliable results than their electric counterpart due to smaller size and ruggedness and hence are suitable for embedding in civil structures, aircraft, ships, etc.; in fact, a large array of FBG strain sensors, each of which is uniquely wavelength encoded in terms of individual \( \lambda_B \), could be sequentially interrogated by a broadband source (see Figure 3.31). Different topologies for the multiplexing of fiber-optic sensors have been discussed in detail in Bløtekjær (1992).

FBGs can be used to detect ultrasound propagating in structures and also for monitoring both static and dynamic strain fields (Culshaw 2004). Experiments (Perez et al. 2001) have indicated that dynamic strains up to \( 10^{-2} \mu \varepsilon \) or smaller and frequencies \( \sim 1 \) MHz...
FIGURE 3.30 (a) Optical spectrum analyzer trace of reflected light from a fiber Bragg grating showing shift of the reflection spectrum due to strain and corresponding shift in the Bragg wavelength; (b) measured shift in Bragg wavelength as a function of strain (με). These measurements were carried out in the Fiber Optics Laboratory at CGCRI (Kolkata, India). (Courtesy of T.K. Gangopadhyay, CGCRI, Kolkata, India.)

FIGURE 3.31 Distributed strain measurement with an array of FBGs of different pitch attached/embedded in, for example, a civil structure or an aircraft or a ship for monitoring its health. (Courtesy of Parama Pal.)
are detectable by FBGs. When cracks develop in a civil structure due to fatigue and loading, bursts of ultrasonic waves are generated that propagate through the structure. Detection of this acoustic emission (AE) could be exploited as alarm signal for structural failure. AE is due to transient elastic waves within a material, caused by the release of local stress energy, which implies the generation of sound waves when a material undergoes internal stress due to an external force.

If we consider temperature sensitivity $S_T$ (Equation 3.33), the first term $\alpha_F$ representing thermal expansion coefficient of the fiber, which for silica is $\sim 0.55 \times 10^{-6}/^\circ C$, whereas the second term, namely, the thermo-optic coefficient term is $\sim 8.6 \times 10^{-6}/^\circ C$, which is naturally the more dominating term. At $\lambda_B = 1550$ nm, change $\Delta \lambda_B \sim 0.013$ nm/$^\circ C$. Temperature change strongly impacts FBG signals, and hence, it is important to realize that precise strain measurements require proper temperature compensation. Since fractional change in $\lambda_B$ depends on both strain and temperature, it is important to note that for absolute measurements of either of these parameters, one needs to de-convolve the second effect. An additional FBG could be deployed in parallel, which is isolated from the measurand, and through appropriate calculation, measurand signal could be corrected. Readers may find in Chapter 19 detailed information on strain sensing with FBGs (the white paper on strain measurements with fiber grating sensors from the company HBM by Kreuzer (2007)—http://www.hbm.com, optical—is also useful for further details). Figure 3.32 depicts sample results on temperature measurements with in-house fabricated FBG carried out by the Fiber Optics Group at CGCRI (Kolkata, India); $\lambda_B$ at room temperature of this FBG was 1545 nm. CGCRI group in collaboration with SINTEF (Trondheim, Norway) had successfully installed FBGs to monitor real-time local temperature directly in real-world 400 kV electric power transmission lines of Power Grid Corporation (India) at a location near Kolkata (Gangopadhyay et al. 2009a,b); Figure 3.32b is a depiction of the experimental layout used for these measurements at that site (Gangopadhyay et al. 2009b, Gangopadhyay 2012).

LPGs (Vengsarkar et al. 1996) could also be used as fiber-optic sensor. Bhatia and Vengsarkar (1996) demonstrated LPG-based sensors written on standard telecommunication fibers with temperature, strain, and refractive index resolutions of 0.65°C, 65.8 με, and $7.7 \times 10^{-5}$, respectively. The characteristic period $\Lambda_LPG$ of such in-fiber gratings are typically few hundreds of micrometers in contrast to submicrometer period in FBGs. The transmission spectrum of the LPG exhibits a bandstop kind of filter characteristics as the LPG induces coupling of power from the core mode $LP_{01}$ to cladding modes. In contrast to Equation 3.28, the corresponding phase-matching equation for an LPG leads to

$$\lambda_c = \Lambda \cdot \left(n_{e1} - n_{e2}\right)$$  \hspace{1cm} (3.35)

where $\lambda_c$ is the center wavelength at which the power coupling takes place, while $n_{e1,e2}$ represent mode effective indices of the core mode and the cladding mode involved in this power coupling process at this wavelength. Essentially, the LPG acts like a filter (Ghatak and Thyagarajan 1998, Pal 2000). The cladding modes interact with the surrounding environment as they are formed through total internal reflection at the cladding–air interface (see Figure 3.33), and hence any change in the ambient properties of the surrounding medium could be detected in terms of the transmittance of the LPG and measured.
FIGURE 3.32 (a) Measured Bragg wavelength as a function of temperature of an FBG having Bragg wavelength of 1545 nm at room temperature; (b) schematic layout of the field experiment carried out for real-time monitoring of temperature with a pair of FBGs in a real-world 400 kV electric power transmission lines between power transmission towers. (Courtesy of T.K. Gangopadhyay, CGCRI, Kolkata, India.)

FIGURE 3.33 Schematic of a long-period grating (LPG) that induces power coupling from the core to the cladding modes at the phase matching wavelength $\lambda_c$ given by Equation 4.8; core and cladding modes are represented schematically through ray diagrams showing core and cladding modes as being formed respectively through total internal reflections at the core–cladding interface and at the cladding–air interface.
A broadband light source, due to coupling of power from a guided to several of the cladding modes having little difference in their propagations constants, leaves a series of loss bands or resonance dips in the transmission spectrum of an LPG. Measurand-induced shift in these loss bands caused by the modified cladding mode spectrum could be exploited to get a measure of the measurand. Readers may find more details about use of in-fiber LPG as sensors in Bhatia (1999).

### 3.5 Fiber-Optic Current Sensor

Electric current measurement in electric power generation stations is a critical requirement because a sudden accidental surge in current needs to be detected, which should trigger isolation of the failed section from the power system network to minimize damage and system failure time for reliability and stability of the system. Current transformers (CTs) are most often used as current sensors in power protection relay systems (Sanders et al. 2002). In a CT, an iron core and suitable wire windings are used as secondary transformer to step down the high current flowing in the primary to a much lower current (typically 1–5 A). Unfortunately, these devices are subject to EMIs and could suffer distortions due to saturation and residual field in the magnetic cores besides chances of insulation failure due to large current in the system (approximately kiloamperes) (Lee et al. 2006). Due to these factors, optical sensors for large electric currents have assumed considerable importance in recent years (Sanders et al. 2002). With typical transmission voltages hovering around 400 kV requiring control and switching of currents approximately a few kiloamperes, dielectric optical fibers naturally are very attractive for use in communication and sensing in a power industry (Rogers 1992). The basic concept behind the optical detection of electrical current relies on the classical Faraday effect (Rogers 1988, 1992). The Faraday effect states that if a transparent solid or liquid is placed in a uniform magnetic field, and a beam of plane polarized light is passed through it in the direction parallel to the magnetic lines of force (e.g., through holes in the pole shoes of a strong electromagnet), its plane of polarization gets rotated (though remains plane polarized) by an angle proportional to the magnetic field intensity. The modes of light propagating in glass in the presence of a longitudinal magnetic field are right and left circularly polarized light waves, each of which propagates with different velocities. An optical fiber being made of silica exhibits Faraday effect. If a loop of one turn of a single-mode fiber encloses a current carrying conductor, for example, a busbar, the generated magnetic field around it due to the current influences the state of polarization (SOP) of the light propagating through the fiber through Faraday effect. The Faraday rotation of the SOP is given by

\[ \theta = V \int \mathbf{H} \cdot d\mathbf{l} \quad (3.36) \]

where
- \( \mathbf{H} \) is the applied magnetic field intensity
- \( d\mathbf{l} \) is the length of the medium
- \( V \) is the Verdet constant of silica
The Verdet constant for silica is \( \cong 2.64 \times 10^{-4} \text{°}/\text{A} = 4.6 \times 10^{-6} \text{rad}/\text{A} \). If there are \( N \) turns of fiber in the loop that surround the current-carrying conductor, then by Ampere’s law,

\[
\oint \vec{H} \cdot d\vec{l} = NI
\]  

(3.37)

By combining Equations 3.36 and 3.37, we get

\[
\theta = V \cdot N \cdot I
\]  

(3.38)

where \( I \) is the current enclosed by a single fiber turn in the loop. Faraday rotation depends only on the magnitude of the electric current regardless of the shape or size of the loop and position of the conductor within the loop (Lee et al. 2006). A schematic of the Faraday effect-based fiber-optic electric current sensor is shown in Figure 3.34.

Light from a polarized laser after passing through a half-wave plate is focused onto a single-mode fiber (which is single-moded at the laser wavelength, e.g., on a lab-scale experiment, the laser could be a He–Ne laser, for which the fiber should be single-moded). The fiber is used in the form of a loop that surrounds the current-carrying conductor. Output light from the fiber is picked up by a microscope objective and passed through a Wollaston prism or a polarization beam splitter, which divides the Faraday rotated light into two mutually orthogonal linearly polarized components, which are picked up by two independent photodetectors PD 1 and PD 2. The difference between the two PD output intensities, \( I_{1,2} \), is normalized with respect to their sum, which is proportional to \( \theta \) (Lee et al. 2006), that is, for small \( \theta \), the ratio \( R \) is

\[
R = \frac{I_1 - I_2}{I_1 + I_2} = \sin \theta \approx 2\theta
\]  

(3.39)

This procedure also makes the output independent of any laser power fluctuation during the measurement or laser drift. In real-world systems, some random birefringence could also be present; besides, bend-induced linear birefringence could also be present.

**FIGURE 3.34** Schematic of fiber-optic Faraday sensor for the measurement of large electric current (MO stands for microscope objective; functional principle is described in the text).
in the fiber loop especially in case of small loop radii. In the presence of linear as well as circular birefringence, \( R \) is given by (Ghatak and Thyagarajan 1998)

\[
R = 2\theta \left( \frac{\sin \Delta}{\Delta} \right)
\]  

(3.40)

where

\[
\Delta^2 = 4\theta^2 + \delta^2; \quad \delta = k_0 \Delta n_{\text{eff}} 2\pi R_1 N
\]

(3.41)

with \( \theta \) in rad, \( \Delta n_{\text{eff}} \) is the linear birefringence, and \( R_1 \) is the fiber loop radius. Linear birefringence \( \Delta n_{\text{eff}} \) is inversely proportional to the square of \( R_1 \) and directly proportional to the square of fiber cladding radius. For the case in which circular birefringence due to Faraday effect dominates over linear birefringence, \( R \) is given by Equation 3.40, whereas if linear birefringence dominates over circular birefringence, then

\[
R \approx 2\theta \frac{\sin \delta}{\delta}
\]

(3.42)

In the latter case, sensitivity is rather low (Ghatak and Thyagarajan 1998). Linear birefringence can be significantly reduced or compensated by the introduction of additional circular birefringence through twist in the fiber (Ulrich and Simon 1979). Fiber-optic Faraday current sensors have been successfully used to measure large currents, approximately a few kiloamperes. Faraday rotation could be also measured through fiber-optic Sagnac interferometer (Briffod et al. 2002).

### 3.6 Conclusions

In this chapter, we have attempted a unified description of the basic functional principles and applications of a variety of optical waveguide sensor platforms based on intensity, phase, polarization, and wavelength modulation of light, mostly supported by optical fibers. Wherever appropriated, applications of these sensors were also described and a large number of relevant references introduced. The chapter should be useful as an introduction to basics, technology, and applications of these types of sensors, further details are available in subsequent chapters of the book.

### Acknowledgment

I wish to thank the editors of the book for their kind invite to write this chapter. I am particularly grateful to Professor Santos for his enormous patience, encouragement, and also for his concern about my recent health issues including my hospitalization for a surgery that I had to undergo, which resulted in long delay in the submission of my chapter. My graduate students Somnath Ghosh and Ajanta Barh are thanked for their help in the drawing of a few figures. My secretary Shashi is thanked for typing some portions of the manuscript. My daughter Parama and wife Subrata are thanked for their help in editing the manuscript and also for their encouragement. Parama is also thanked for pointing out technical corrections here and there and also helping me draw certain figures.
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