

FIBER AND INTEGRATED OPTICS SENSORS: FUNDAMENTALS AND APPLICATIONS

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The chapter summarizes the fundamentals of light propagation in fiber and integrated optics and explains the basic working principles of optical sensors making use of these waveguides. Outstanding applications where these sensors have been used are also presented.

1. Introduction

Optical techniques have always been used for a large number of metrological and sensing applications. The conventional methods based on free-space interferometry and spectroscopy, for example, are outstanding examples of optics capabilities. This kind of free-space monitoring, however, is effective only for line of sight and suffers from undesired misalignments and external perturbations. Guided-wave sensing adds to intrinsic advantages of optical techniques the possibility of guiding the light beam in a confined and inaccessible medium, thus allowing more versatile and less perturbed measurements.

Fiber- and integrated- optics technologies were primarily developed for telecommunication applications. However, the advances in the development of high quality and competitive price optoelectronic components and fibers have largely contributed to the expansion of guided wave technology for sensing as well. The main reasons which make guided wave optics attractive for sensing can be summarized as follows:

- Non-electrical method of operation, which is explosion-proof and offers intrinsic immunity to radio frequency and, more generally, to any kind of electromagnetic interference;
- Small size/weight and great flexibility, that allow access to otherwise restricted areas;
- Capability of resisting to chemically aggressive and ionizing environments;
- Easy interface with optical data communication systems and secure data transmission.

The guided wave sensors that have been proposed to solve problems in industrial, automotive, avionic, military, geophysical, environmental and biomedical applications are countless. This chapter aims at providing some fundamentals in this field. Sensors are presented in a relatively simple and straightforward way to give a tour through the subject by minimizing theoretical explanations and showing outstanding examples of what guided wave technology is able to offer for sensing. References to the extensive literature in this area are provided, where the interested reader can find more details. An increasing number of textbooks is also available.¹⁻⁴

2. Fiber and Integrated Optics: Fundamentals of Waveguiding

In accordance with the ray theory of light propagation, when light impinges at the interface between two transparent media, it is partially reflected and partially refracted. The Snell's law describes the refraction phenomena as (Fig. 1):

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1)$$

When $n_2 < n_1$, any ray impinging at the interface with an incident angle greater than θ_c is totally reflected inside the first medium.

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \quad (2)$$

An optical fiber consists of layered cylinders of glass or plastic, as shown in Fig. 2. Inner and outer cylinders, namely ‘core’ and ‘cladding’, have refractive indices n_1 and n_2 , respectively. Any ray impinging at the core-cladding interface with an incident angle greater than θ_c is undergoing multiple reflections within the core, in which it results trapped and propagates.

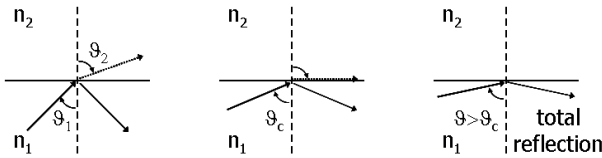


Figure 1. Reflection and refraction at the interface between two transparent media: the Snell law.

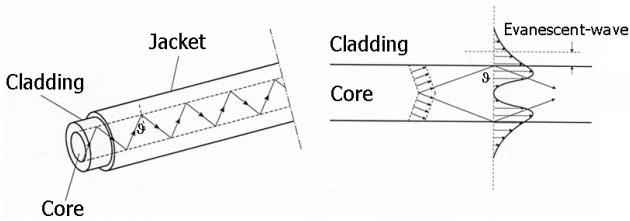


Figure 2. Ray propagation in the optical fiber.

An integrated optical waveguide, on the other hand, consists of a thin-film structure supported by a substrate. The simplest structure is shown in Fig. 3a, where the guiding layer (the core, with refractive index n_1) is deposited on a transparent substrate (having refractive index n_0) and is covered by another layer (the cladding, with refractive index n_2). If $n_2=n_0$ we have a symmetrical structure, analogous to an optical fiber; in fact, while the x-y cross sections of the fiber and the slab waveguide are different from each other, their x-z cross sections are identical and one can expect that their waveguiding properties are fundamentally the same ones. In most cases, however, the cladding is air ($n_2=1$), and we speak about a planar asymmetric waveguide. In this case light is confined only along the x direction, while the light energy can diffract in the y-z plane.

The confinement of light also along the y direction is obtained by a strip waveguide, as shown in Fig. 3b, where total reflections of light rays

occur also at side walls. For both fiber and slab waveguide the dependence of the refractive index on the x coordinate $n(x)$ is called the refractive index profile. In the simplest case, i.e. $n(x) = n_1 = \text{constant}$, we refer to step-index waveguides; otherwise, we speak about gradient-index waveguides, and sophisticated profiles may be produced as well, either by a multi-layer deposition technique or by a diffusion process.

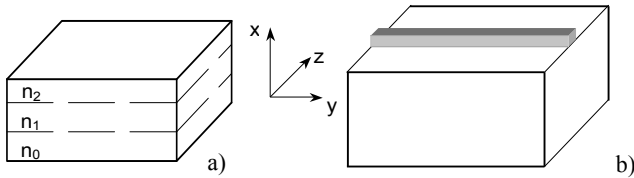


Figure 3. Slab waveguide (a), and strip waveguide (b).

Taking into account that light is an electromagnetic wave phenomenon, a more accurate description of light propagation within a waveguide is obtained by means of Maxwell's equations. When the geometric boundary conditions at media interfaces are introduced, only discrete solutions of the wave equations are permitted. This means that only discrete waves can propagate, namely 'modes', characterized by discrete amplitudes and discrete velocities.^{5,6} Waveguides can be single-mode or multimode according to whether a single or a multiplicity of modes can propagate. Once the materials constituting the waveguide are set for a given wavelength, the number of supported modes depends on waveguide dimension, namely on the fiber core radius or the planar waveguide thickness.

A characteristic of a guided mode which is particularly important for sensing devices is its spatial amplitude distribution. Often, in fact, the interaction between the propagating mode and the quantity to be measured (the measurand) occurs through the evanescent field of the mode itself, namely its exponentially-decreasing tail.

3. Waveguide Sensors: Basic Working Principle

Although trapped within the dielectric medium of the optical waveguide, the radiation that propagates inside the waveguide can be perturbed by

the external environment, and this perturbation can be used to draw useful information for sensing purposes. In fact, the interaction of the parameter of interest, that is the measurand, with the waveguide produces a modulation in the propagation constants of the guided light beam. That modulation represents the sensitive function of the measurand of interest.

As shown in Fig. 4, the basic elements constituting a guided wave sensor are: an optical source, an optical interface for source-to-waveguide light coupling, the waveguide itself where the measurand-induced light modulation occurs, a photodetector and the electronics for amplification, signal processing and data display.

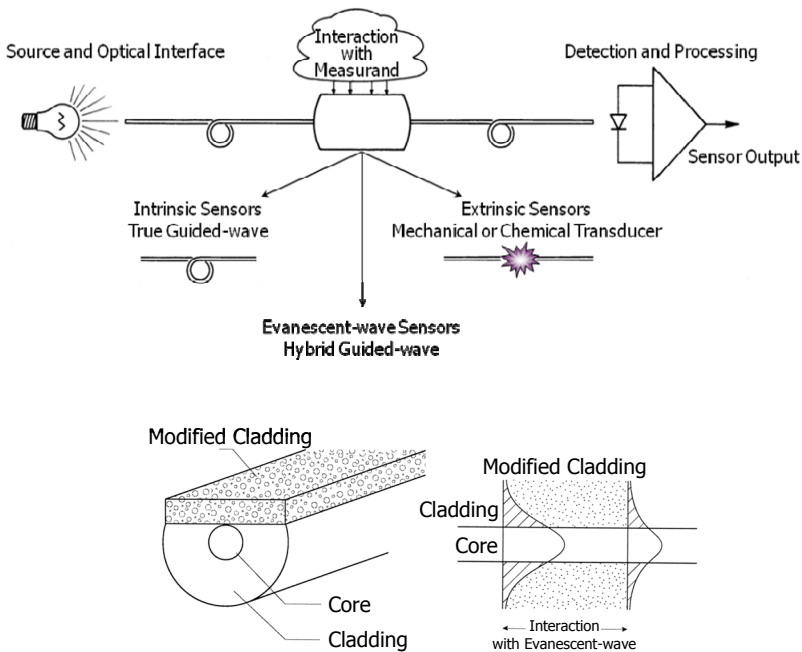


Figure 4. The waveguide sensor: general working principle.

In accordance to the optical parameter, which is modulated by the measurand, waveguide sensors can be divided into four basic categories:

- phase-modulated,

- polarisation-modulated,
- wavelength-modulated,
- intensity-modulated.

Waveguide sensors are further subdivided as intrinsic, extrinsic, or evanescent-wave sensors. Intrinsic sensors are true waveguide sensors in which the sensing element is the waveguide itself. Extrinsic sensors make use of an optical transducer coupled to waveguide, the optical constants of which are modulated by the measurand. Evanescent-wave sensors are hybrid intrinsic/extrinsic sensors, since measurand-induced modulation occurs in the waveguide itself, in most cases because of the presence of a measurand-sensitive cladding section.

The following section refers in particular to fiber optic sensors, but most considerations on the operation principle apply to integrated optical sensors as well.

4. Fiber Optic Sensors

Here, a brief overview of fiber optic sensors (FOSs) is given, according to their operational classification. An indication of their commercial availability is also provided.

4.1. Phase-Modulated Sensors

The action of measurand producing a variation of the waveguide length, ΔL , causes a phase shift of the guided lightwave, $\Delta\phi$, which is expressed as follows:

$$\Delta\phi = \frac{2\pi}{\lambda} \Delta L \quad (3)$$

where λ is the wavelength of light propagating in the waveguide. Being able to detect phase shifts as small as 10^{-7} rad, and assuming $\lambda \approx 1 \mu\text{m}$, a perturbation causing length differences as small as $\Delta L = 10^{-8} \mu\text{m}$ can be detected. Consequently, phase-modulated sensors are capable to offer extremely high sensitivity.

The previous expression given for $\Delta\phi$ takes into account length variations only. However, it should be noted that the wavelength is dependent on the waveguide refractive index, n_w , which, in turn, can be perturbed by a measurand. A more exact expression for the phase shift is the following:

$$\Delta\phi = \frac{2\pi}{\lambda_{\text{vacuum}}} (n_w \Delta L + L \Delta n_w) \quad (4)$$

Phase shifts are usually measured by means of interferometric schemes.⁷ Actually, phase-modulated waveguide sensors are classical interferometers, the legs of which are single-mode optical fibers or waveguide channels. Because many different measurands can perturb waveguide length and refractive index, cross sensitivity can occur. This is why most phase-modulated waveguide sensors have the sensing leg covered by means of an additional jacketing. The material of the jacketing is suitable to provide specific sensitivity to a certain measurand and also to amplify the length variation while desensitizing to refractive index, or vice versa.

The interferometric configurations most widely used by waveguide sensors are: the Mach-Zehnder, the Sagnac, and the Fabry-Perot, as shown in Fig. 5.

The Mach-Zehnder configuration is a two-beam interferometer. The light from a highly coherent laser is split by means of a beam splitter and injected into two optical fibers or waveguide channels which follow separate paths, one of which is exposed to the action of the measurand.

When they are recombined by means of another beam splitter, interference fringes appear. The phase of these fringes is proportional to measurand-induced optical path difference between co-propagating beams within the legs of the interferometer. The Mach-Zehnder scheme is the basic principle of most fiber optic hydrophones, also arranged in very dense arrays,⁸⁻¹³ as well as current and magnetic field sensors.¹⁴⁻¹⁶

The Sagnac configuration is a two-beam interferometer the primary application of which is in rotation sensing.¹⁷⁻¹⁹ The light beam is split by means of a beam splitter and injected as two counter-propagating beams into the same optical fiber arranged in a coil. When the coil is held stationary, clockwise and counter-clockwise beams return on the detector

in phase after having travelled along the same path in opposite direction. If a rotation rate is applied to the fiber coil, the co-rotating beam reaches the starting point having travelled a longer path with respect to the counter-rotating beam, and the path length difference results in a phase difference. Several gyroscopes for military and civil applications are now commercially available.²⁰⁻²³

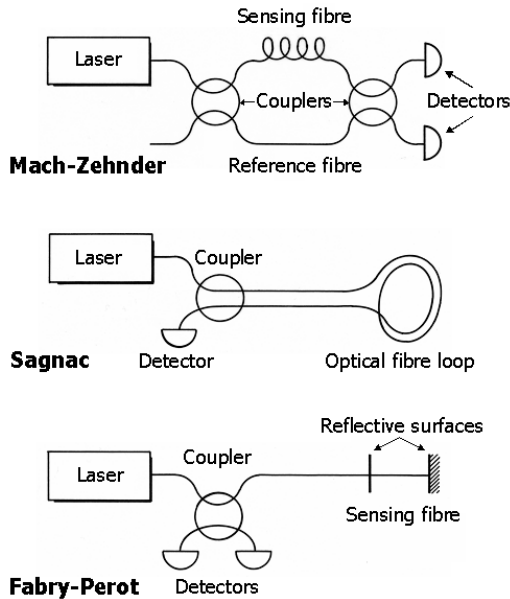


Figure 5. Interferometric arrangements for waveguide sensors.

The Fabry-Perot interferometer is a multiple-beam interferometer that does not make use of a reference fiber, since the interference results from multiple reflections of the light beam inside a single optical fiber.²⁴ The laser light is coupled to a single-mode optical fiber by means of a beam splitter. A resonant cavity is created by splicing a mirrored fiber section to the fiber end. The light beam is partially reflected and partially transmitted inside the cavity, which is exposed to the measurand action. Because of the reflectivity of the distal fiber section, the light beam impinging the cavity undergoes multiple reflections, the measurand

acting on the light at every pass, thus magnifying the phase difference.^{25,26} A measurand can act on the Fabry-Perot cavity at fiber end by changing its length and/or refractive index. This type of device is particularly suitable for temperature and pressure sensing, and these sensors are also commercially available.²⁷

In addition to intrinsic Fabry-Perot sensors, also extrinsic sensors have been implemented, which make use of an etalon or a MEMS as resonant cavity at fiber end. Also these sensors are commercially available for pressure, strain, acceleration, temperature and vibration monitoring.²⁸⁻³⁰

The previously discussed interferometers do not produce absolute data, unless extra complexity is added to the sensor system. The generation of fringes is dependent on the two beams being able to interfere at the detector. This requires that the beams have the same polarization, the same wavelength and a path length difference less than the coherence length of the source.

Unfortunately, all real sources possess finite bandwidth and size. In addition, single-mode optical fibers are actually two-mode fibers, having the two modes different polarization states. All these factors affect fringe visibility thus impairing interferometer performance. To overcome the mentioned problems, a smart interrogation technique was setup, namely white-light interferometry.^{31,32} A low-coherence optical source is used to illuminate two cascaded interferometers, one of which responds to the measurand, while the other is a reference interferometer. The reference interferometer is used as processing interferometer, having a known optical path difference which can be scanned by means of a piezoelectric system over a known range. The maximum of the intensity on the detector will appear when the optical path differences of the two interferometers are equal (zero-order fringe). Consequently, the optical path difference of the sensing interferometer can be measured by the known optical path difference of the processing interferometer, thus achieving absolute measurements.

The most modern fiber optic interferometers are based on white-light interferometry, which is particularly suitable for processing Fabry-Perot and Michelson interferometers.^{33,34}

4.2. Polarization-Modulated Sensors

Because of slightly noncircular core and asymmetric thermal stress distributions, single-mode fibers are in reality dual-mode fibers, with the fundamental mode split into two orthogonally polarized states.³⁵ The modes propagate with slightly different propagation constants, and the fiber is said to have a modal birefringence. Highly birefringent fibers are particularly suitable for current and magnetic field measurements.³⁶⁻³⁹

The monitoring of electromagnetic phenomena is critical for power utilities, and optical sensors are particularly attractive, being able to offer high electrical insulation and total immunity to electromagnetic interferences. For this reason, many devices are now commercially available.^{29,40-42}

4.3. Wavelength-Modulated Sensors

Truly wavelength-modulated sensors are those making use of gratings inscribed inside the optical fiber. The following paragraph 5 describes the operating principle and applications of sensors making use of optical fiber long-period gratings, while we refer the reader to Chapter 2 for details on the sensors that use optical fiber Bragg gratings.

Other wavelength-modulated sensors are of the extrinsic type, and make use of optical or chemical transducers joint at fiber end.

A typical example of an optical transducer is a section of sapphire fiber joint to a conventional silica fiber. Sapphire acts as a black-body cavity emitting a broad band radiation which is wavelength modulated by temperature conditions. This radiation is remotely transmitted to the detector unit by means of the silica fiber, in order to perform a remote pyrometry.⁴³ Sensors of this type are commercially available since many years; their wide sensing range (up to 2000 °C) and good sensitivity (0.1 °C) are particularly attractive for many industrial applications.^{44,45}

Wavelength-modulated guided wave sensors making use of a chemical transducer are also called *optrodes*, by the combination of the two terms 'optical' and 'electrode'. Interaction of the measurand with the chemistry changes the spectral properties of the chemistry itself, the measurement of which makes it possible to monitor measurand status. A

variety of guided wave sensors have been implemented, based on this type of indirect chemically-mediated spectroscopy.^{46,47} Absorption- or fluorescence-based optrodes have been experimented for the monitoring of physical, chemical (pH, for instance, is one of the most considered ones) and environmental parameters.⁴⁸⁻⁴⁹ The measurement of pH is frequently carried out by means of optrodes based on chromophores or fluorophores usually bond on polymeric or sol-gel supports.⁵⁰ The sensitive chemistry can be butt-coupled to the fiber-end for single-point measurements, or can constitute the fiber cladding for distributed monitoring by means of evanescent-wave sensing.⁵¹ Oxygen is another parameter widely measured by means of optrodes, usually making use of a ruthenium complex as sensitive transducer.^{52,53} A good selection of commercial products is available since many years, thanks to the reliability and good sensitivity of the probes. These products are offered for a wide range of sectors, including environmental, medical and food applications.⁵⁴⁻⁵⁶

4.4. Intensity-Modulated Sensors

Since it is relatively easy to perturb the intensity of the light guided by an optical fiber, intensity-modulated sensors represent the most experimented fiber sensors. They can use multimode fibers and simple optoelectronic devices, making thus possible the implementation of low-cost sensing devices.

Intensity-modulated sensors can be sub-divided into two main classes: extrinsic sensors making use of mechanical transducers positioned in front or in-between an optical fiber strand (Fig. 6), and intrinsic sensors, which measure the loss produced by the measurand on the fiber itself (Fig. 7).

Extrinsic-type sensors are photocells and intrusion detectors, which are widely commercially available,⁵⁷⁻⁶¹ and position, pressure or vibration sensors implemented for medical or industrial applications.⁶²⁻⁶⁶

Intrinsic-type sensors make use of an optical fiber squeezed between a periodic structure, or a plastic spiral wrapped around the optical fiber. Impact, edge, anti-squeeze and weight-in-motion sensors are based on

this simple concept and are commercially available. They are often realized by embedding the fiber in a mat or ribbon.^{67,68}

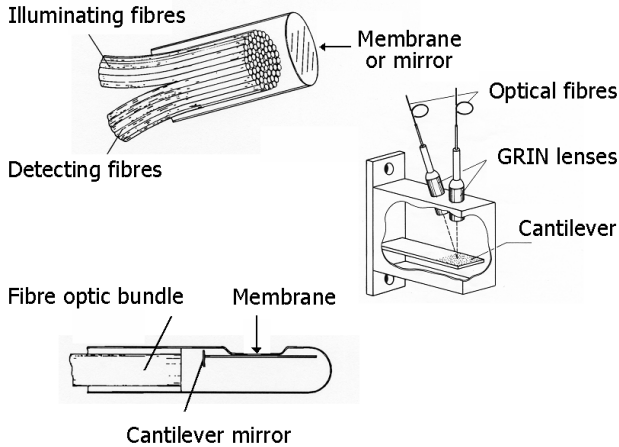


Figure 6. Examples of fiber optic pressure or vibration sensors based on a mechanical transducer.

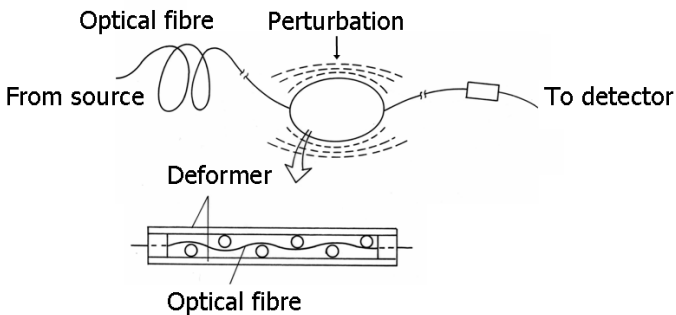


Figure 7. Fiber optic pressure or vibration sensor based on a microbending effect.

4.5. Fiberized Sensors

The geometrical versatility of optical fibers, together with their capability of guiding light with very low attenuation, make them ideal tools to

replace free space architectures in conventional optical instrumentation. Indeed, many optical sensors have been *fiberized* by using fiber optic strands for illuminating and detecting means. It is worth mentioning that vibrometer and other Laser Doppler-based instruments have been *fiberized* to easily achieve localized measurements without complex bulk-optics architectures. A number of them is now commercially available.^{69,70}

Optical fibers have been advantageously exploited also for dynamic and static light scattering measurements. Especially for dynamic light scattering measurements, single-mode fiber-based instrumentation not only offers measurement flexibility, but is also able to provide improved performance than that achieved by conventional bulk-optics systems.⁷¹

The early warning of cataract on-set is an outstanding example of what optical fibers are able to offer to dynamic light scattering measurements.^{72,73} As far as static light scattering measurements are concerned, countless are the applications in which optical fibers have played an essential role, ranging from the monitoring of smokes, steams and aerosols, to the characterization of water-suspended sediments.⁷⁴⁻⁷⁶

Most commercially available spectrophotometers and spectrofluorimeters are now equipped with fiber optic probes for localized measurements without sample drawing. This is particularly useful in many industrial process control in which avoiding sample handling represents a cost effective approach. Also, the availability of miniaturized spectrometers and bright LEDs makes it possible the implementation of compact spectrophotometers which can be used for monitoring parameters in a wide arrange of industrial and biomedical applications. Custom probes are now commercially available to face both the most common or simple measurement requirements.⁷⁷⁻⁷⁹

5. Long-Period Optical Fiber Grating Sensors

An optical fiber grating consists on a periodic modulation of the properties of an optical fiber (usually the refraction index of the core).

These structures have been actively studied since several years,⁸⁰⁻⁸¹ but now have a considerable impact on the development of fiber optic communication systems, laser sources, instrumentation for the detection

and the measurement of various physical, chemical, biological and environmental quantities.

Depending on the period of the grating, fiber gratings are categorized into two types: Short Period Fiber gratings (or Fiber Bragg Grating-FBG), which have a sub-micron period, and Long Period Fiber Gratings (LPG), which have typically a period in the range 100-1000 micron. The FBGs act as narrow-band reflection filters (or narrow-band rejection filters if used in transmission). Sensors making use of FBGs are examined in detail in Chapter 2. In the following, a short review of LPG sensors is presented.

An LPG is an optical fiber structure in which the energy typically couples from the fundamental core propagation mode to forward propagating cladding modes. As the cladding modes undergo a rapid attenuation due to scattering, bends of the fiber and absorption by the fiber jacketing, the transmission spectrum of the LPG is characterized by a number of attenuation bands centered at discrete wavelengths.⁸²⁻⁸⁴ Each of these attenuation bands corresponds to a coupling of the energy of the core mode to a distinct cladding mode (Fig. 8).

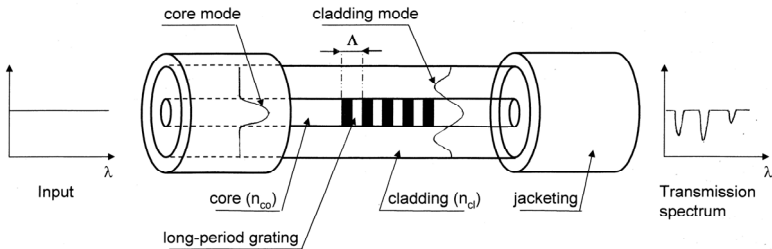


Figure 8. Schematic of a long-period fiber grating.

With the help of the coupled-modes theory⁸⁵ the central wavelength λ_m at which this coupling occurs can be expressed with:⁸⁶ $\lambda_m = (n_{co} - n_{cl}^m) \Lambda$, where λ_m = mth resonance wavelength, n_{co} = effective refractive index of the core mode, n_{cl}^m = effective refractive index of the mth cladding mode, Λ is the grating period.

Any modulation in the grating period Λ or in the effective refractive index of the core (n_{co}) and cladding (n_{cl}) modes induces changes in the

distribution of the light between the core and the cladding modes and, as a consequence, gives rise to changes in the spectral response of a long-period fiber grating. As these changes in the spectral response can be measured, this behavior of the LPFGs can be utilized for sensing purpose.⁸⁷ Bend, strain, temperature, refractive index of the surrounding medium are some of the typical parameters that a LPFG can measure.

As to the fabrication method, LPFGs can be produced in various types of fibers, from standard telecommunication fibers to microstructured ones. So far, many techniques have been developed, such as point-by-point exposure to UV radiation,⁸⁴ CO₂ laser pulses,⁸⁸ infrared femtosecond laser pulses⁸⁹ or electric arc discharges.⁹⁰

5.1. Bending Measurements

Two main effects occur in LPFGs subject to bend, which can be utilized to detect the bend itself: a) the attenuation bands in the spectral response, which are present when the LPFG is straight, shift in wavelength and change in depth as LPFG is bent (*wavelength shift detection*); b) each attenuation band can split into two peaks when the LPFG is curved and the resulting two peaks tend to separate as the bend increases (*resonance splitting detection*).

An LPFG bend sensor using the *wavelength shift detection* method has been proposed for shape sensing in smart structures.⁹¹ The sensing of curvatures up to 4.4 m⁻¹ has been demonstrated, and detection of curvature changes as small as 2×10⁻³ m⁻¹ seems to be possible. A significantly higher sensitivity has been obtained by other authors using bend sensors based on the *resonance splitting detection*.^{92,93} Over 80 nm mode splitting was measured under a bend curvature of 5.6 m⁻¹, giving a bend sensitivity of 14.5 nm/m⁻¹, which is nearly four times higher than the value demonstrated by the wavelength shift detection method.

The exact physical interpretation of the resonance mode splitting in an LPFG under bending is quite complex, and several works related to this matter have been published.^{6,7,94,95}

Using two LPFG bonded to either side of a bent structure, it is possible to determine magnitude and sign of curvature. One grating is utilized for negative, and the other for positive curvature measurement.⁹⁶

5.2. Temperature Measurements

The temperature sensitivity of LPFGs arises from two contributions: a) changes in the differential refractive index of the core and the cladding due to thermo-optic effects, b) changes in the LPFG's period with the temperature. The first contribution depends on the composition of the fiber and is also strongly dependent on the order of the cladding mode, the second one is generally very small, due the low thermal expansion of the silica, and its contribution to the overall temperature sensitivity is generally insignificant.

In an LPFG-based temperature sensor,⁹⁷ a reflector is applied to one cleaved end of a fiber embedding a conventional long-period grating, so that a light beam passing through the long period grating is reflected back. Then the system behaves as a pair of cascaded identical long period gratings. The reflected light beam crossing twice the long period grating gives rise to a self-interference effect; as a consequence, a fine interference fringe pattern is obtained within each attenuation band of the conventional LPFG resonant spectrum. As this pattern is temperature sensitive, fine temperature variations can be monitored by measuring the temperature-induced wavelength shifts of the fringes. The measured temperature-induced fringe-shift results to be 0.055 nm/°C, within a dynamic range of 75-145 °C.

A method for enhancing the temperature sensitivity of a long period grating fabricated in standard optical fiber takes advantage of a material (oil) with high thermo-optic coefficient set around the grating. Temperature-induced refractive index changes of the surrounding material then induce changes in the transmission spectrum of the LPFG which, over a limited temperature range, results in enhanced temperature sensitivity. A temperature sensitivity as high as 19 nm/°C (over a temperature range of 1.1 °C) has been obtained.⁹⁸

5.3. Strain Measurements

Strain induces significant variations in the core and cladding indices of refraction of an optical fiber and, unlike the temperature, it also induces significant changes in the dimensions of an optical fiber. In an LPFG the

deviation of these parameters from the unperturbed state gives rise to different coupling of the light between the propagating modes and, as consequence, to variations in the transmission spectrum. These variations can be detected and related to the strain intensity.

As a drawback, LPFG strain sensors suffer from cross-sensitivity to temperature variations. The two effects, however, can be separated by an appropriate choice of grating period and fiber composition. In fact the different contributions generated by strain and temperature can show opposite polarities thus making possible to counter-balance the different effects and producing temperature-insensitive grating sensors or strain-insensitive temperature sensors.⁹⁹ These gratings can result useful everywhere a decoupling of temperature and strain responses is necessary. For example, temperature-insensitive long-period gratings can be used to measure strain in situations where the surrounding temperature is varying, while strain-insensitive gratings can be employed as temperature sensors where the thermal-expansion-induced strain of the host material can be a limitation.¹⁰⁰

A proposed method to measure strain and temperature simultaneously makes use of two in-series long-period gratings with controlled temperature and strain sensitivities. The two gratings are fabricated with positive and negative temperature sensitivities, respectively, while they have similar strain sensitivity. Then, considering the total transmission spectrum of the dual-LPFG, and conveniently choosing two attenuation peaks each one relative to a different grating, it is possible to note that such peaks undergo a separation with a temperature change, while they undergo a shift with a strain change. This allows simultaneous and unambiguous measurement of temperature and strain. The reported displacement of the peak with the temperature change is $0.69 \text{ nm}/^\circ\text{C}$, and with the strain is $0.46 \text{ nm}/\mu\text{strain}$.^{101,102}

A further application of long-period gratings concerns the fabrication of fiber-optic load sensors. These devices are based on the measurement of the birefringence induced by transverse strain in long-period fiber gratings produced in conventional or high birefringence fibers.^{103,104} The spectral response of a long-period grating subject to loading shows a splitting in two peaks of each original single resonant attenuation band. The two peaks correspond to the two orthogonal polarization states. As

the birefringence increases with increasing loading, the related spectral peaks separation provides a measurement of the transverse loading.

Corrugated long-period gratings can be used to form tensile stress sensors and torsion sensors.^{105,106} A corrugated LPFG consists of a periodicity of etched and non etched regions along the fiber. When a conventional LPGF is twisted, the induced refractive index perturbation is small because the fiber structure is uniform. On the contrary the application of axial load, torsion and bending to a corrugated LPFG, owing to the photoelastic effect, causes a periodic modulation of the refractive index of the fiber and results in mode coupling between the fundamental core mode and the forward-propagating cladding modes with the effect of changing the central wavelength of the LPFG attenuation bands. Therefore, corrugated LPFG are sensitive to the external stresses and can act as strain and torsion sensor.

5.4. Sensors Based on the Response to External Refractive Index

The attenuation spectrum of an LPFG is highly sensitive to the ambient refractive index. This sensitivity results from the dependence of the attenuation bands wavelength on the effective refractive index of the cladding modes, which are dependent upon the difference between the refractive index of the cladding and that of the medium surrounding it.

Several chemical sensors based on the response of LPFGs to the changes on the refractive index of the external medium have been proposed. For instance, LPFGs have been used to determine the concentration of antifreeze in water,^{107,108} or for online concentration measurements of aqueous solutions with sodium chloride, calcium chloride and ethylene glycol.¹⁰⁹ As optical fiber sensors can be safely used in inflammable environments, LPFG sensors can be used to monitor organic aromatic compounds in the petrochemical industry. For such applications they offer the possibility of continuous in situ control measurements and can therefore be an attractive alternative to the current monitoring techniques, such as high performance liquid chromatograph (HPLC) and UV spectroscopy.^{110,111}

The sensitivity to the ambient refractive index of an LPFG can be improved by coating the fiber grating with a thin film of material with

higher refractive index than that of the fiber cladding.^{112,113} As an example, an opto-chemical sensor employing LPFGs coated with polymeric sensitive overlays (syndiotactic polystyrene (SPS) in the nanoporous crystalline δ form) has been proposed.¹¹⁴ A monolayer of colloidal gold nano-particles has also been proposed for improving the spectral sensitivity and detection limit of long-period gratings.^{115,116}

This kind of sensors have been demonstrated to be able to measure refractive indices in the range of 1.34 to 1.39 with resolution of 10^{-3} to 10^{-4} , suggesting that these devices may be suitable for use with aqueous solutions in applications such as medical diagnostics, biochemical sensing, and environmental monitoring.¹¹⁷

6. Micro-structured Fiber Sensors

Photonic Crystal Fibers (PCFs) constitute a class of optical fibers that has a large potential for sensing applications. Their novel structure, with a lattice of air holes running along the length of the fiber, offers extraordinary control over the waveguiding properties in a way that is not possible with conventional fibers.

PCFs are commonly classified by the light-guidance mechanism in two categories, namely index guiding and photonic band gap (PBG) fibers (Fig. 9). In the two types, the microstructured cladding surrounds a solid and a hollow core, respectively.

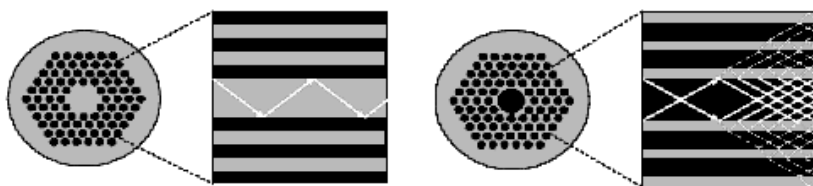


Figure 9. Structure of index guiding (*left*) and photonic band-gap (*right*) fibers.

In the index guiding fibers, the refractive index of the core is higher than the effective refractive index of the cladding and a modified form of total internal reflection guides the light; in the second type photonic band

gap effect provides guidance, allowing for novel features such as light confinement to a low-index core.¹¹⁸

The PCFs design suggests a variety of strategies for optical sensing of different physical parameters (temperature, hydrostatic pressure, elongation, force, bending, etc.). The most studied approach involves the interaction with an evanescent field of PCF modes for the detection and analysis of liquid and gas phases species infiltrated in air holes of the cladding in index-guiding PCF^{119,120} or with a guided field in hollow core of the PBG fibers.¹²¹ Even if the majority of sensors reported in literature is based on index guiding fibers, because first introduced into the market, for sensing applications there are considerable advantages also in band-gap fibers: one of them is the possibility of guiding light in hollow cores filled with liquid or gas solutions of molecules.

In a well designed photonic band gap fiber, the largest part of the mode field (< 90%) is guided in the sample volume, thus providing a strong interaction between molecules and light over several tens of centimetres using few microliters of sample.¹²² For acetylene detection with high sensitivity, Ritari et al.¹²³ investigated the feasibility of using PBG fibers. A significant interaction between light and molecules in the air holes of the cladding can take place also in index guiding PCFs, but the effect is smaller because it concerns only the evanescent field. For evanescent-wave sensing of biomolecules, such as DNA or proteins,¹²⁴ this effect can be enhanced using index guiding PCFs based on polymers.

An improvement of this sensing technique is represented by new geometries of cladding holes and, very recently, by the development of defected solid core.¹²⁵

When the evanescent field sensing method may be impractical or inconvenient, an improvement is achieved by tapering the fiber.¹²⁶ There are two possibilities during the tapering: the holes structure may be preserved or may collapse. In both cases the guided mode of the PBG fiber spreads out, and the tapered PBG fiber results highly sensitive to external environment. The mechanism is very similar to what happens in tapered conventional fibers.¹²⁷ The collapse of the holes makes the core mode to couple to multiple modes of the solid taper waist, which is a solid multimode fiber. Several interference peaks appear from the beating of the multiple modes of the collapsed region, and they shift as

external index changes.¹²⁸ The tapering technique has been successfully employed with fibers formed by a Germanium doped core surrounded by large air holes in the cladding,¹²⁹ demonstrating to be of particular interest also for biophotonic sensing.

The optical properties of PCFs are strongly controlled by the geometry of the holey region, and in sensing application this tunability is widely employed. One of the most promising advantages of PCF is the possibility of fabrication of multi-core fibers. A two-core index guiding fiber¹³⁰ bends in the plane containing the two cores, each of them supports a single guided mode. Because of the bending, the outer and the inner cores undergo an increase and a reduction in length, respectively. The PCF with these two cores acts as a two arms Mach-Zehnder interferometer in which the phase difference is a function of curvature in the plane containing the two cores fiber, demonstrating a resolution of about $170 \mu\text{rad}/\text{rad}$.¹³²

A particular advantage of PCF based sensors is the possibility of writing additional periodic structures on fibers such as Bragg and Long Period Gratings (LPGs). Standard grating fabrication techniques applied to PCFs have enabled the fabrication of gratings with original properties, mainly due to the complex index profile and dispersion properties of PCFs. From the point of view of fabrication, LPGs are generally easily fabricated, and can also generate well-isolated resonance, by proper selection of cladding mode for coupling, that can be highly sensitive to different measurands such as temperature, bending, strain and external refractive index. In particular for DNA sensing, this kind of gratings can be employed to detect the average thickness of a biomolecules layer within a few nm with sensitivity of approximately $1.4 \text{ nm} / 1 \text{ nm}$ in terms of shift in resonance wavelength per thickness of DNA layer.¹³¹

The control of the dispersion properties of core and cladding can be used, in principle, to increase the sensitivity to one measurand and to make the device insensitive to another. Recently it has been reported that LPGs inscribed in a dopant free endlessly single mode (ESM) PCF and in a large mode area PCF by electric arc discharges eliminate the cross-sensitivity^{132,133} to temperature perturbations.

Another sensing technique makes use of birefringence in PCFs, which can indeed be made highly birefringent: the large index contrast

facilitates high form birefringence, allowing the development of a new generation of polarimetric fiber sensors which use polarization (phase) modulation induced by external perturbations. Different methods have been developed to introduce birefringence into PCFs, such as using elliptical air holes^{134,135} and/or asymmetric core or asymmetric distribution of holes.^{136,137}

Important engineering areas can be influenced by future advances of polarimetric PCF based sensors, in particular thanks to their direct sensitivity to strain. The best example is the measurement of axial strain for structural monitoring. The essential mechanisms for strain and pressure sensing are almost the same: physical changes in fiber dimensions and the elasto-optic effect. Taking advantage of these two effects, one can implement distributed sensing elements to assess length changes, internal stresses or pressure in civil engineering structures. Based on elasto-optical measurements of the polarization state of the fiber output, it is possible to determine the fiber birefringence (beat length) for different wavelengths and compare it with numerical simulations. A new and quite important application of highly birefringent PCF is in dynamic pressure sensing for tsunami detection,¹³⁸ making use of standard polarimetric technique.

7. Integrated Optic Sensors

While the basic principles on which integrated optic sensors (IOSs) are based are the same as for fiber optic sensors, the two fields have developed at different paces and with slight different targets.

Fibers have the unique capability of operating over extended gauge lengths (even km!) in either point sensing or distributed sensing format. In the former case, the FOS is configured in such a way that monitoring of the measurand occurs at a specified location along the fiber (generally at its distal end); in the latter case, the values of the measurand (e.g. temperature or strain) are probed as a function of the position along the fiber. Remote measurements are made possible by the low attenuation characteristic of an optical fiber. Integrated optics (IO), on the other hand, has been developed with the aim of implementing multi-functional miniaturized circuits, possibly of size of a few cm, if not mm.

High-quality fibers, for both telecommunications and sensing, are mostly made of a silica core (even if, of course, there are alternative materials, including polymers). IO waveguides can be fabricated in a variety of materials, from dielectrics to polymers, from liquid crystals to semiconductors, and none of them has so far emerged as the key material. The lack of a unique solution for IO in terms of material and fabrication technology, however, is at the same time its major limit and its greater advantage: it permits, in fact, very great flexibility both in design and manufacture. Thus, an IOS may fully exploit the combination of thin films technology with other planar technologies, such as surface acousto-optic interaction, laser writing, silicon micromachining, micro-electro-mechanical systems (MEMS), optoelectronics integration on a semiconductor substrate, etc. Since two papers on IOSs, a temperature and a displacement sensor, respectively, were first published in 1982,^{139,140} many other integrated optical devices for sensing have been proposed and demonstrated.¹⁴¹⁻¹⁴⁷ In the following, some examples of IOSs will briefly presented and discussed.

7.1. Integrated Optical Interferometers

Mach-Zehnder Interferometers (MZI) are easily fabricated in integrated optics, by means of standard photolithographic processes, and are one of the most common structures exploited for the detection of the phase shift induced by a measurand. While the free-space configuration requires several optical components and a tight alignment, a single IO circuit a few mm long represents a very stable and efficient solution. The schematic structure of an integrated optical MZI is shown in Fig. 10a, while the field distribution in the waveguide (and the interacting evanescent field) is sketched in Fig. 10b. MZI IO sensors have been fabricated in various materials, from glass to lithium niobate, from silicon-oxynitride on silicon to silicon-on-insulator. Several sensing devices have been demonstrated, e.g. for the detection of displacement, for refractometry and for bio-sensing.¹⁴⁸⁻¹⁵⁶ Some sensors of this type, especially for biomedical applications, are also commercially available.¹⁵⁷

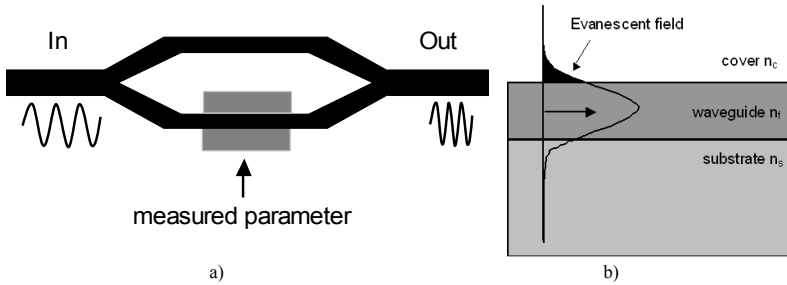


Figure 10. a) Top-view of an IO MZI structure. b) Behavior of the modal field distribution in the waveguide structure.

7.2. Grating-Coupler Sensors

Light coupling into an optical fiber usually occurs only by transverse coupling method (also called “end-fire” coupling), namely by focusing the beam from the laser source onto the fiber facet. In integrated optics, the light may be injected into the thin-film waveguide also by prism coupling, grating coupling, or fiber-to-waveguide butt-coupling.¹⁵⁸ While prism-coupling is the most common technique in the laboratory, grating couplers, which can be fabricated directly on top or inside the waveguide itself, offer a more robust mechanism for practical application.

Grating couplers, however, are not simply another way of performing the access function to/from an optical waveguide. As their operation depends critically on the refractive indices of the guiding film and of surrounding media (once the wavelength is fixed), the precise measurement of the in-coupling angle constitutes a sensitive tool to detect changes in refractive index and/or wavelength induced by a measurand.¹⁵⁹⁻¹⁶¹

Commercial grating coupler sensor chips are available. A producer, for instance, makes them available in either a single-layer version (namely a sol-gel guiding layer, in which the grating is fabricated, on top of a glass substrate) or a two-layer version (where a cladding layer has been added).¹⁶² This cladding layer modifies the optical, chemical or biochemical properties of the surface of the chip; the producer offers a wide choice of coatings, from thin films of SiO_2 , TiO_2 ,

TaO₂, ITO (Indium Tin Oxide), ZrO₂, to thick films of PTFE, silicone etc., to functionalization by means of silanization with APTS. Suggested biosensing applications include adsorption of protein at surface, immunosensing, drug screening, analysis of association and dissociation kinetics, and many more. Typical size of the chip is 48 mm (length) × 16 mm (width) × 0.55 mm (thickness), and the guiding sol-gel layer has thickness in the range 170 to 220 nm; grating area is 2 mm (L) × 16 mm (W), its depth (the grating is a surface relief structure) is about 20 nm, and its pitch is ≈ 0.4 μm.

7.3. Evanescent-Wave and Surface Plasmon Resonance Sensors

The field of chemical and biochemical sensors is very likely the one where IO can find its largest market in the next years, at least in terms of number of manufactured devices. Other markets, like that of IO gyro sensors, may however retain larger economical importance, due to the much higher cost per item.

Most of the chemical and biochemical sensors rely on the penetration of the propagating evanescent wave into the cladding layer (Fig. 4 and Fig. 10b) for detection of the measurand to occur: the change in a chemical or physical parameter of the clad (usually constituted by a fluid or an ultra-thin transducer film) is converted into an optically measurable quantity by means of a change in absorption of the guided wave or in its effective index. Alternatively, the evanescent tail of the propagating modal field can excite the fluorescence of the cladding material; this may be either natural fluorescence of the species or fluorescence of a label which will react only with the species of interest.

A recently proposed sensing structure is based on a strip-loaded waveguide in which the strip consists of a several nanometers thick sensitive material. An attractive option is to realize this strip as a monomolecular antibody layer making the sensor capable to monitor chemical concentrations. This sensing structure relies on measurand induced changes of the field profile of the probing guided mode; this is in contrast to the big majority of the refractive IO-sensors in which the changes of the effective refractive index n_{eff} are exploited.¹⁶³

The technique which is becoming a key tool for characterizing biomolecular interaction is that based on surface plasmon resonance (SPR).¹⁶⁴ The optical excitation of surface plasmons by the method of attenuated total reflection (ATR) was demonstrated in the late Sixties, and very soon it was applied for characterization of metal thin films.¹⁶⁵ In early Eighties the use of SPR for gas sensing and biosensing was demonstrated^{166,167} and since then SPR sensor technology has continued to grow up¹⁶⁸⁻¹⁷² and it is now commercialized.¹⁷³

An example of low-cost SPR sensor is represented by polymer-based chips, exploiting replication fabrication processes, which include a prism, microchannels and a chamber at microscale dimensions.¹⁷⁴

The reader is also referred to Chapter 5 for a more detailed discussion on SPR-based sensors and biosensors.

8. Conclusions

Optical waveguide sensors have certain advantages that include immunity to electromagnetic interference, lightweight, small size, high sensitivity, large bandwidth, and ease in implementing multiplexed or distributed sensors.

Strain, temperature and pressure are the most widely studied measurands for optical fiber sensors, but biomedical applications are becoming the most interesting area for both fiber and integrated optic sensors. Nowadays, some success has been gained in the commercialization of optical waveguide sensors, even if in various fields they still suffer from competition with other mature sensor technologies.

New ideas, materials and structures, however, are being continuously developed and tested not only for the traditional measurands but also for new applications. As an example, we can conceive that further advances in the fabrication and understanding of microstructured fibers and photonic crystal structures will provide a platform for new sensors, aiming at being alternatives for standard sensing technologies.

Brilliant perspectives also exist for new "smart" optical sensors which mix nanoelectronics and micro/nano optical devices on the same silicon chip. These fully integrated optosensors would have the same, or better,

characteristics of current sensors, while being much smaller, lighter and lower power than the existing systems.

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