Chapter 1
Introduction

1.1 Initial Concepts

By the 1970s, all telephone cables and microwave links on the planet were saturated. The solution came when Charles Kao and George Hockham of the British company Standard Telephones and Cables promoted the idea that the attenuation in the existing optical fibers could be reduced below 20 decibels per kilometer (dB/km), making fibers a practical communication medium. They proposed that the extremely high attenuation in fibers available at the time was caused by impurities that could be removed by chemical processes. They correctly and systematically theorized the light-loss properties for optical fiber, and they identified the right material for such fibers: silica glass with high purity. This discovery earned Kao the Nobel Prize in Physics in 2009.

The crucial attenuation limit of 20 dB/km was first achieved in 1970 by researchers at Corning Glass Works (an American glass maker, now Corning Incorporated). They demonstrated a fiber with 17-dB/km attenuation by doping silica glass with titanium. A few years later, they produced a fiber with only 4-dB/km attenuation using germanium dioxide as the core dopant. Such low attenuation allowed optical fiber to be used in telecom from the 1980s until now; current fibers have an attenuation of 0.25 dB/km at the telecom C-band.

Figure 1.1 shows the fiber optic attenuation spectrum with three telecom windows. The three lines represent the progress of optical fiber attenuation from the early 80s, late 80s, and the present. In the early 1980s, only the first window at 850 nm was known and used with multimode fibers. By the 1990s, the second window at 1300 nm was explored with specific lasers and a photodetector because the old silicon photodetector was useless at this wavelength. It was a promising window with a much lower attenuation. Finally, by the late 1990s, the third window at 1550 nm started being used with an attenuation that today is around 0.25 dB/km.

Although polymeric optical fibers (POFs) are much longer than silica fibers, only by the 1990s did they start to attract attention for local-area

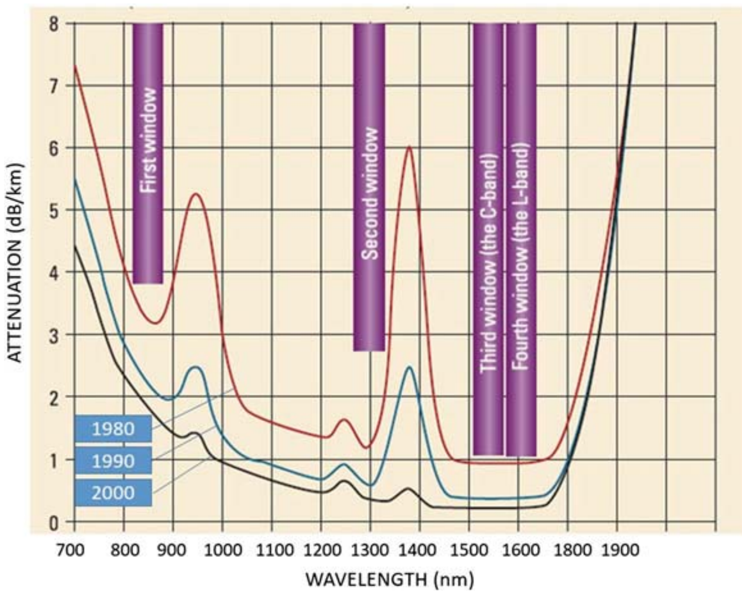

Figure 1.1 Fiber optic attenuation spectrum with the telecom windows.

networks (LANs) and small industrial networks, and their use for sensors emerged a few years later.

The first report of a poly-metil-meta-acrylate (PMMA) POF dates from 1968, when Du Pont presented a POF with an attenuation of 500 dB/km at the visible part of the spectrum. From then on, several laboratories keep trying to decrease the attenuation in order to apply a POF in long-haul telecom.

When comparing the attenuation of POFs and silica fibers, the latter are superior. However, when constructing a fiber sensor using a POF instead of silica, there are several additional advantages:

- Lower maintenance costs,
- More resistance to strain,
- Cheaper peripheral components,
- Easy handling, and
- No need for specialized skills for splicing and connectorization.

Due to their larger diameter, it is very easy to work with POFs as compared with silica fibers. POFs are cheaper than their counterpart, including the peripheral components and devices, e.g., connectors, LEDs, and photodetectors. They also present more resistance to strain (larger modulus of elasticity), which means more reliable networks. Finally, many interfaces can be built in a laboratory, making the maintenance cost much lower than when dealing with silica fibers.

However, POFs have disadvantages, too. A POF only transmits in visible and near-infrared light, so the available telecommunication technology in the

1300-nm and 1550-nm telecom windows cannot be used. Additionally, a POF presents very high attenuation in the visible spectrum.

Temperature is another issue with POFs because plastic materials cannot withstand high temperatures as much as glasses. POFs can only operate up to 70–85°C. However, some special POFs have been developed mainly for harsh environments, such as in car networks. In these applications, POFs have to withstand temperatures as high as 150°C.

In this context, both POFs and silica fibers have found use in sensors and transducers in many industrial applications. Optical fiber sensors (OFSs) appeared just after the invention of the practical optical fiber by Corning. At the beginning of this era, optical devices (such as the laser, photodetectors, and optical fibers) were very expensive, affordable only by telecom companies to circumvent the saturated copper telephone network. Contrary to telecom companies that move a lot of money in the world, instrumentation companies have to produce cheap devices because the sensors market is full of solutions of any kind, and the one that does not produce competitive products will not survive.

However, with the great diffusion of optical fiber technology during the 1980s and on, opto-electronic devices became cheaper, favoring their use in OFSs. OFSs can be applied in many branches of the industry with applications that depend only on the imagination of scientists because everything depends on the interface between the real world (the measurand) and the light traveling inside the fiber.

In the electric-power industry, two factors can cause the collapse of an electronic sensor: the presence of high voltage and the presence of high electromagnetic interference. Therefore, depending on where a parameter is to be measured, it can be very difficult or even impossible to use a conventional sensor. The best option to circumvent this situation uses an OFS because the fiber is made of dielectric materials, and, therefore, it is possible to place them very close to or even in physical contact with a high-potential conductor; they do not necessarily need electric power at the sensor location.

Another problem with conventional sensors is that they all need electric energy to work. However, providing that energy at the sensor location is sometimes difficult if the device is located far from any appropriate power supply, e.g., in long, high-voltage transmission lines, at high voltage potentials, along pipelines, or in deep ocean. Because OFSs are passive sensors, they do not need electric energy to work.

Therefore, an OFS can be used to measure several parameters, including those that have electric-technology solutions. The following parameters have been measured in a laboratory by using an OFS:

- Strain ($\mu\varepsilon$),
- Vibration of structures and machines,
- Electric current (mA to kA),
- Voltage (mV to kV),

- Impedance (μΩ),
- Leakage current of insulators (μA to mA),
- Temperature (–40°C to 200°C),
- Pressure,
- Gas concentration (ppm),
- Distance between stationary and rotating or moving parts,
- Distance (μm to mm),
- Flow,
- Light intensity,
- X-ray radiation, and
- Bacteria (up to 10^6 CFU).

Some of these parameters, depending on where they are located, are very difficult or even impossible to be conventionally monitored because of the following well-known paradigm of the electric-power industry: an electric sensor cannot be close enough to a high potential to break the electric rigidity of the air, which is $\sim$1 kV/cm. This scenario would cause a short circuit when the current flows from a high voltage to the ground potential by the sensor's connecting wires. The best option to avoid this catastrophic effect is an OFS because the fiber is made of dielectric materials, and therefore it can be placed very close to or even touch a high-potential conductor, and they do not necessarily need electric power at the sensor's location.

An OFS can be built using several physical principles and materials. They have specific characteristics that are well exploited when applied to the electric-power industry or oil and gas, and in this case OFSs offer a large number of advantages over conventional sensors. The most important are

- High immunity to electromagnetic interference (EMI),
- Electrical insulation,
- No metallic parts,
- No need for local electric power,
- Chemically inert against corrosion,
- Long-distance functionality, and
- The ability to multiplex several sensors on the same fiber.

The high immunity to EMI is a strong requirement for sensing in electromagnetically contaminated environments, e.g., RF fields and highly electric and magnetic fields present in power lines.

Insulation is another special requirement: because these sensors are inherently electrically insulated (dielectric) and do not require external power, there is no electric path from the power line to the ground, which means high personnel security.

The ability to work with no local electric power makes these sensors adequate to measure parameters in explosive environments because the fiber does not carry light power capable of producing sparks or heat.

Optical fibers can be used as sensors by modifying a fiber so that the measurand interferes on the guided light by modulating light parameters such as intensity, phase, polarization, or wavelength. OFSs can be divided into four basic categories: hybrid, extrinsic, intrinsic, and evanescent-field-based.

Hybrid fiber optic sensors use an optical fiber (usually multimode) to transmit modulated light from either a non-fiber-optic sensor or an electronic sensor connected to an optical transmitter. In this case, the optical fiber is used only to transmit light as a transportive media to and from the sensor. It is called a hybrid sensor because it encloses different technologies, such as optics and electronics.

Extrinsic fiber optic sensors use a multimode optical fiber to guide the light to the sensor and back to a receiver. At the sensor extremity, the light leaves the fiber, is modulated by the measurands, and is injected back into the fiber. These sensors are normally amplitude modulated (in a pressure sensor, for instance) or color modulated (e.g., in a pH sensor).

In intrinsic sensors, the light does not leave the fiber, and the light modulation takes place inside the fiber. This kind of sensor has the major benefit of being able to reach otherwise inaccessible places without needing electric energy at the sensing location. An example of this kind of sensor is a macro-bend sensor, wherein the measurand forces several small bends on the fiber to cause controlled light attenuation.

The fourth category is the evanescent-field-based sensor. Due to the total internal reflection (TIR) phenomenon that occurs in the core–cladding interface of the fiber, the light propagating in the fiber has two components: an oscillatory field in the core and an exponentially decaying field in the cladding. The latter field, referred to as the evanescent field, is the key to sensing that is based on the modulation of the light amplitude in the core of the fiber by the optical properties of the surrounding medium.

At the beginning of the fiber optic era, the great majority of OFSs were of the amplitude-modulated kind. This kind of sensor is accomplished by making the measurand modulate the light amplitude (i.e., the power). However, amplitude-modulated sensors suffer from several foreign interferences, such as losses due connectors; modal drifts; macro bends; LED, laser, and photodetector aging; or temperature drifts. A lot of effort was made in the last 40 years to compensate for these factors.

Although these sensors were very common at the beginning of the OFS era, they were gradually replaced by wavelength-based sensors, which are more stable and self-calibrated because the wavelength does not depend on the foreign interferences as amplitude-modulated sensors do.

Among the wavelength-based sensors, fiber Bragg grating (FBG) sensors have become dominant due to their simplicity. FBGs are formed by a periodic modulation of the refractive index of the fiber core along the longitudinal direction and can be produced by various techniques. The term "fiber Bragg grating" was borrowed from the Bragg law and applied to the periodic structures inscribed inside the core of a conventional Ge- or B-doped telecom fiber, as shown in Fig. 1.2.

Figure 1.2 shows the basic operation of a FBG; note that it acts as a tuned mirror in which only a small fraction of the input spectrum returns (the rest is transmitted through the FBG). The center wavelength of the reflected spectrum is known as the Bragg wavelength. Chapter 2 describes this effect in detail.

FBG technology is one of the most popular choices for optical fiber sensors, particularly for strain or temperature measurements due to their simple manufacture, the relatively strong reflected signal, and the fact that the wavelength, its measuring parameter, is something absolute in the universe. Theoretically, a photon produced 15 billion light years away reaches earth at exactly the same wavelength it had when it was created. Therefore, when using a FBG as a sensor, its measuring parameter, the Bragg wavelength, does not change with time, with temperature, or even with any kind of fiber losses,

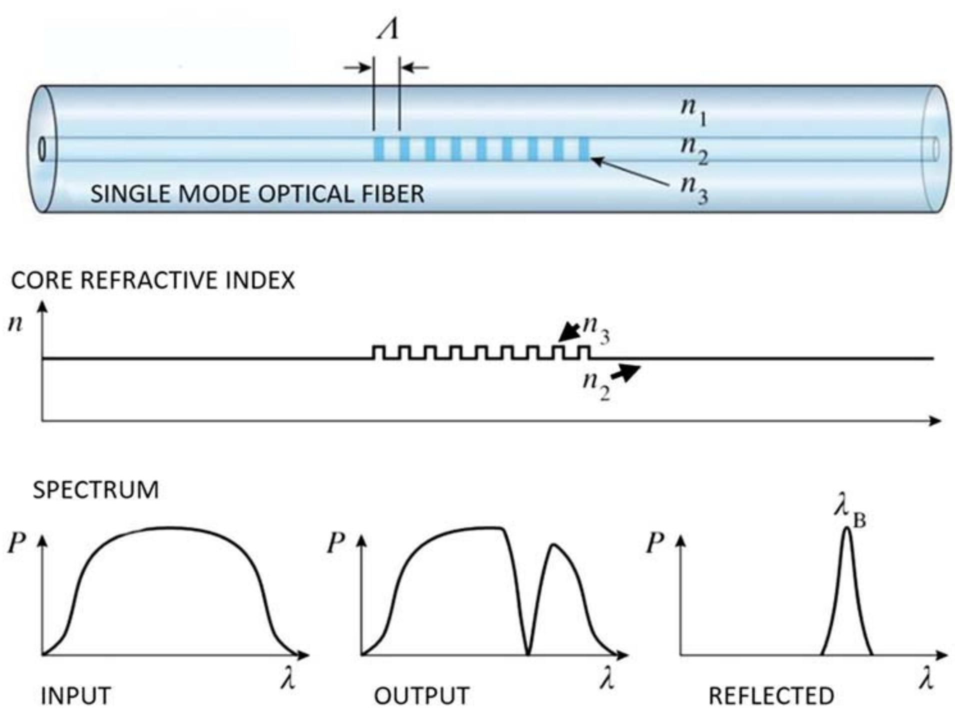

Figure 1.2 Basic operation of a FBG. The top image shows an optical fiber with a FBG inscribed in its core. The center image depicts the refractive index of the core modified into a periodic modulation. The bottom image, from left to right, represent the input light spectrum, the resultant transmitted spectrum, and the spectrum reflected by the FBG.

such as micro- or macro-bending losses, attenuation, light source or photodetector aging, or temperature drifts of any kind.

FBGs were originally employed in telecommunication systems as bandpass filters in add/drop and wavelength division multiplexing (WDM) passive systems; when the FBGs are made with a variable pitch, they can be used to compensate for fiber optic chromatic dispersion.

When scientists realized that the Bragg wavelength displaces with temperature and strain, FBGs started being used in the sensing world for measuring and monitoring several parameters, such as strain, temperature, pressure, displacement, voltage, electric current, or chemical substances in a number of applications and environments. In addition, due to their inherent advantages, they can be used to replace conventional measurement techniques and devices.

These transducers represent enhancements and benefits to power-system operators and users because they enable the development of practical and lightweight devices. In addition, the general safety of the measurement system can be improved due to the insulating characteristics of optical fibers, while the integration with the emerging smart-grid technology can be easily achieved.

Thus, FBGs are considered key devices and important alternatives when compared with conventional technologies such as strain gauges or solid-state sensing. Many other uses of FBGs exist, such as biosensors for bacteria or chemical sensors for measuring H_2S. This book focuses on FBG theory, fabrication, and applications as sensors.