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Introduction

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The optical telegraph, invented in 1791 by Claude Chappe, consisted of a network of stations that allowed the transmission of information at a speed of one symbol in two minutes between Paris and Lille (i.e. 230 km) [1]. Each station monitored, with the aid of a telescope, the character that was represented with a wooden semaphore in the previous station. This system was widely used for about 50 years because it was much faster than sending messages by letter, but it required direct vision between each couple of consecutive stations. Consequently, bad weather, or simply the night, prevented its utilization. These are the main reasons why with the invention of the electrical telegraph, a system based on a guided electrical signal, the utilization of the optical telegraph came soon to an end.

However, in parallel to the invention of the electrical telegraph, in 1841, the path towards optical guiding was started with an important discovery by two French researchers, Jean Daniel Colladon and Jacques Babinet, who independently demonstrated that it was possible to guide light in a curved waveguide [2]. Colladon proved this with light rays trapped in a water jet by total internal reflection, whereas Babinet did the same in a bent glass rod.

Another breakthrough occurred in 1966, when Charles Kao (he received the Nobel Prize in Physics in 2009) and George Hockham published a work demonstrating that the attenuation in optical fibres available at the time was caused by impurities, rather than fundamental physical effects such as scattering. They

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pointed out that fibres with low loss could be manufactured by using high-purity glass [3, 4]. This idea was proved in the North American company Corning in 1970, with the development of an optical fibre with losses lower than 20 dB/km. Soon afterwards, in 1977, losses were reduced to such a point that General Telephone and Electronics could carry live telephone traffic, 6 Mbit/s, in Long Beach, California, whereas the Bell System could transmit a 45 Mbit/s fibre link in the downtown Chicago phone system. Since that year optical fibre has become the most widely used guided medium in the twentieth century, mainly thanks to the huge bandwidth it presents compared with other guided communication media such as twisted pair and coaxial cable.

Optical communication is the main application of optical fibre. However, there is a second domain where this structure can be used: sensors. Despite the impact of optical fibre in the domain of sensors not being as big as in communications, their presence in the global market cannot be neglected. Indeed, it is the natural and ideal platform in terms of integrating the sensor in the communication system.

Optical fibre sensors (OFSs) can be classified in many different ways. The main classification concerns to the location where the light is modulated, existing in two groups: extrinsic and intrinsic OFSs. In both cases there is a parameter (physical, chemical, biological, etc.) that modulates light. However, the difference is that in an extrinsic OFSs light is guided to the interaction region, extrinsic to the optical fibre, where light is modulated, and after this modulation light is collected again in the optical waveguide, whereas in an intrinsic OFS light is always guided by the optical fibre. In Figure 1.1 the difference between an intrinsic and an extrinsic OFS

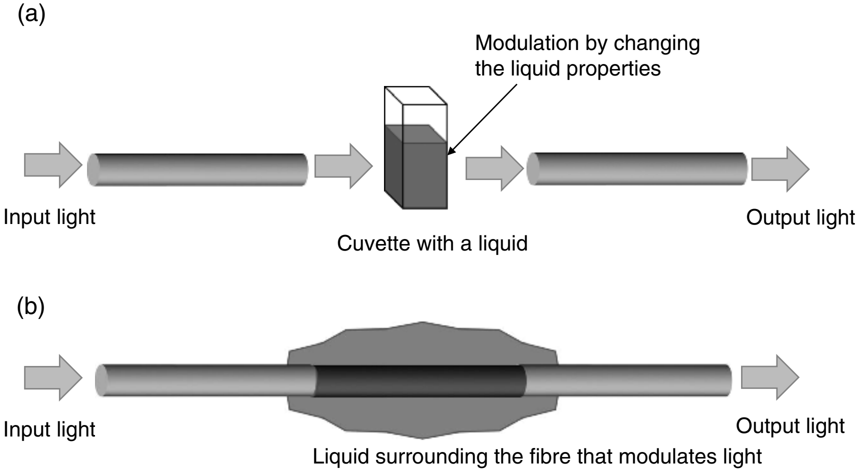


Figure 1.1 (a) Extrinsic sensor: light is modulated outside of the fibre. (b) Intrinsic sensor: light is modulated while it is transmitted through the fibre.

is shown. In the case of an extrinsic sensor, light is modulated outside of the fibre by a liquid (its properties may change as a function of temperature, for instance), whereas in the case of the intrinsic sensor, a fibre has been spliced to two other fibres (one input and one output fibre), which allows an enhanced interaction with the outer medium. In this case, a liquid modulates the light at the same time it is being transmitted through the fibre.

Probably the first OFS was the fibrescope. In 1930 Heinrich Lamm, a German medical student, assembled a bundle of optical fibres to carry an image. His purpose was to use the device for obtaining images of inaccessible parts of the body. He tried to patent the device, but John Logie Baird and Clarence W. Hansell had patented a similar idea some years before. The quality of the images that Lamm obtained was not good, but he is the first researcher that experimentally achieved this breakthrough in the history of optical sensors. Afterwards, in 1954, the Englishman Harold H. Hopkins and the Indian Narinder S. Kapany presented results of better quality on the same principle [5].

Some years later, in 1967, the first effective demonstration of a fibre-optic sensor, the Fotonic sensor, was published [6]. The device was also based on a fibre bundle. However, this time the arrangement was different. Some of the fibres emitted light, and some others did not. The fibre bundle illuminated a surface in front of the fibre, and some part of light was coupled to the fibres that did not transmit light. The amount of light reflected back depended on the distance between the fibre bundle end and the surface. Consequently, the device could be used as a displacement sensor (Figure 1.2).

This type of sensor was the basis for the commercialization of the MTI Fotonic sensor. In the 1980s, the MTI 2000 version allowed monitoring vibration and displacement. Nowadays it is still sold under the version MTI 2100, which is the same concept but with improved characteristics such as the ability to operate in cryogenic, vacuum, high pressure, or in high magnetic field and harsh environments. The resolution has also been improved from 1 nm in the MTI 2000 to 0.25 nm with the MTI 2100 and frequency response from direct-coupled (dc) to 150 kHz in the MTI 2000 up to dc-500 kHz in the MTI 2100.

The concept used in the Fotonic sensor was also the basis for detection of intracranial pressure by using a surface that is a diaphragm that can be deformed by the action of pressure. Depending on the pressure, the surface is deformed, and in this way, the light coupled back to the receiving fibre is modulated. The commercialized device was called Camino ICP Monitor.

Interferometric fibre sensors emerged in the 1970s, the most successful one among them being the optical fibre gyroscope (OFG) (see Figure 1.3). The basic principle was very simple. Light from a laser is split by a beam splitter and enters the fibre on both ends. Both beams go out of the fibre and a photodetector receives them. Thanks to the Sagnac effect, both beams interfere constructively and

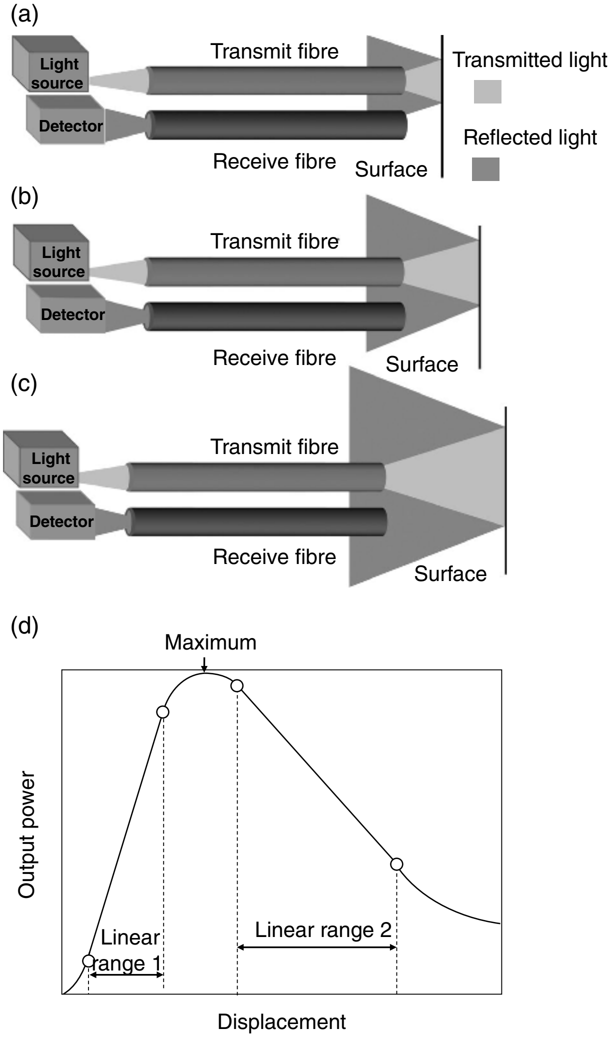


Figure 1.2 (a–c) Fotonic sensor setup with a fibre bundle composed of one transmitting and one receiving fibre: (a) with the surface too close and hence only a small part is coupled back to the receiving fibre; (b) with the surface at the optimal position for a highest coupling; and (c) with the surface too far and hence a great part of light is lost and not coupled to the receiving fibre. (d) MTI 2100 diagram showing the power detected as a function of the distance (the maximum is obtained when the distance is neither too big nor too small).

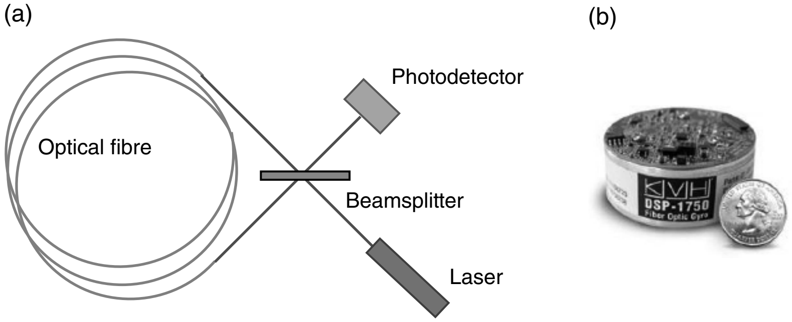


Figure 1.3 (a) Simplified setup: light from a laser is split by a beam splitter and enters the fibre on both ends. The two beams go out of the fibre and the photodetector receives them. Due to the Sagnac effect, both beams interfere constructively and destructively depending on the rotation speed of the device. (b) Commercial optical fibre gyro with a size comparable to a coin (from KVH website).

destructively depending on the rotation speed of the device. The first publication dates from the year 1976 [7]. Since that moment the device has been improved with additional elements such as polarization control, but the initial concept is still maintained. The true benefit of the OFG over traditional spinning-mass gyros is that it has no moving parts. As a result, OFGs are faster, tougher, more reliable and demand far less maintenance. That is why they have become an essential component in platform stabilizing systems, for example, for large satellite antennas, in missile guidance, in subsea navigation, and in aircraft stabilization and navigation, and a host of other applications [8]. It moves about 1000 million US$ per year according to MarketsandMarkets: Fibre Optics Gyroscope Market by Sensing Axis (1, 2, and 3), Device (Gyrocompass, Inertial Measurement Unit, Inertial Navigation System, and Attitude Heading Reference System), Application, and Geography – Global Forecast to 2022.

Based on the acousto-optic effect, it was possible also to develop hydrophones, OFSs that could detect acoustic waves when immersed in water. One of the first approaches was based on interferometry [9], by combining the signals transmitted by an optical fibre that was not immersed in water with the signal reflected at the end facet of another optical fibre immersed in water. By exciting an acoustic wave in front of the fibre immersed in water, it was possible to observe variations in the detected signal. Though it has not been a commercial success like OFG, this application still attracts interest, and the utilization of a Fabry–Pérot cavity (i.e. a coating on the end facet of the optical fibre immersed in water) allows avoiding the use of the reference fibre because in this way an interferometric pattern in the optical spectrum is generated. The setup is depicted in Figure 1.4, and a commercial device is available at the company Precision Acoustics. Its immunity from

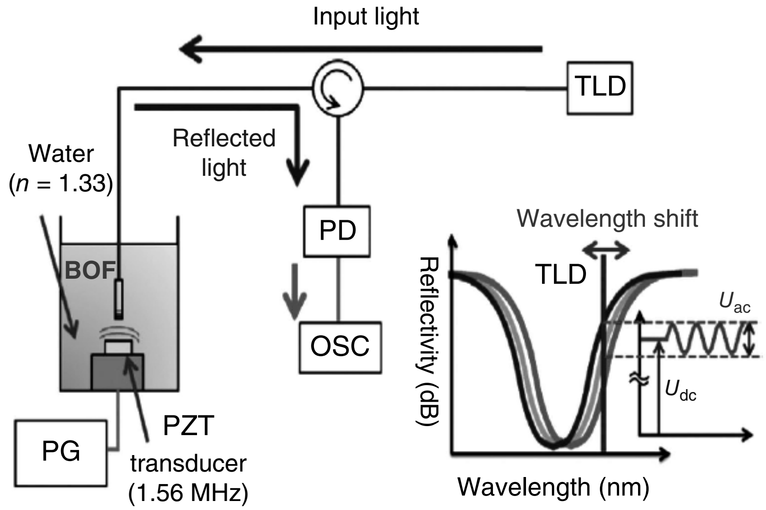


Figure 1.4 Optical setup for a Fabry–Pérot hydrophone [10]. OSC is oscilloscope, PD photodiode, PG pulse generator, PZT piezoelectric transducer, and TLD tunable laser diode. *Source*: Reproduced with permission of Elsevier.

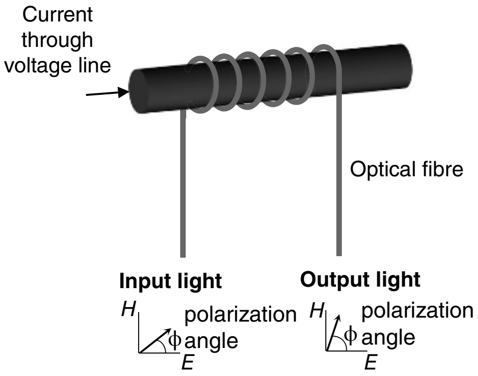
electromagnetic radiation makes it particularly suited for high-frequency measurements in hostile fields.

As we can see, this property was also included in the Fotonic sensor and is one of the key advantages of optical fibres in general. However, in order to make a fibre optical sensor the first option of an end user, more advantages are required compared with the rest of sensors in the market. In the case of the OFG, the key property was that it was not necessary to use moving parts, which means long duration and fast response.

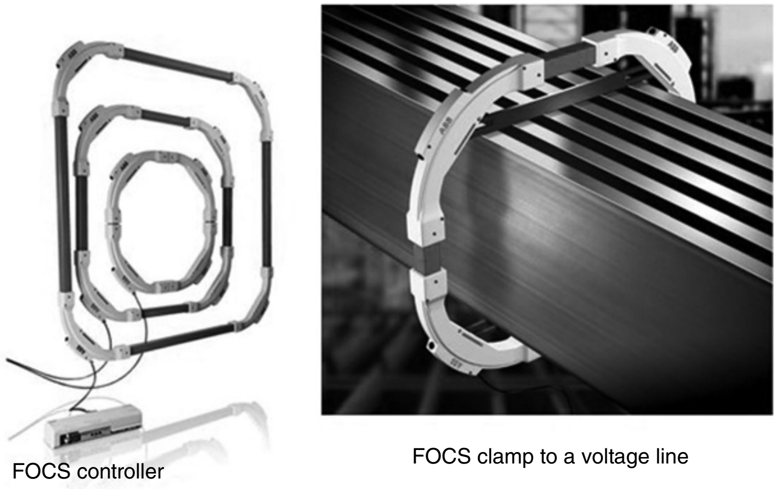
A second OFS success was the measurement of current and voltage with the aid of the Faraday effect [11, 12]. As an example, ABB has developed a commercial device called fibre-optic current sensor (FOCS), which can be used instead of magnetic systems due to its exceptional accuracy and reliability. It can measure uni- or bidirectional DC currents of up to 600 kA with an accuracy of ±0.1% of the measured value (Figure 1.5).

Strain gauges are another well-known application where optical fibres can be used. The first work was published in 1978 [13]. SOFO, from the company Smartec, is a commercial example that can be used for surface mounting or embedding in concrete and mortars. It is ideal for long-term structural deformation monitoring and presents a 20-year track record in field applications.

(a) **Faraday effect principle**



(b) **ABB fibre optic current sensor**



FOCS controller

FOCS clamp to a voltage line

Figure 1.5 (a) Basic principle of optical fibre sensors: the polarization of the input light in and optical fibre is rotated by the action of the magnetic field generated around a line transmitting current. (b) Commercial ABB FOCS sensor.

In addition, the invention of optical fibre Bragg gratings (FBGs) in 1978 [14] widened even more the possibilities of OFSs in terms of detection of strain, because the path was open to include multiple Bragg gratings in the same optical fibre, each one operating at a different wavelength, and to use a multiplexing technology (developed in parallel back in 1980 [15]), to analyse each signal separately. This can be used to monitor strain at multiple points in aircrafts, tunnels, etc., in what is typically called structural health monitoring [16]. The first commercial Bragg grating sensors were available in 1995, and since that moment many companies have commercialized their own FBGs.

However, despite it being possible, unlike electronic gauges, to include multiple strain OFSs in the same wire and despite strain OFSs being less sensitive to vibration or heat and far more reliable than electronic gauges, they have not achieved a commercial success comparable with the OFG. Here we can see a good example of the problem that faces OFSs: there is an electronic competitor, the metallic strain gauge, that nowadays is more widespread than optical fibre gauges because engineers are more familiarized with electronic technology. Like OFSs, electronic sensors have also become popular thanks to another technology, electronics, and to the vast utilization of copper wire for communications. Moreover, the computer, the basic unit in the information technology era, is also based on electronics. All this has made it possible for electronic sensors to nearly monopolize the domain of sensors. Therefore, it is necessary to find applications where optical fibre makes a difference compared with the electronic counterpart.

In this sense, it is important to consider the advantages and disadvantages of optical fibre. The main good points of optical fibre are [17, 18]:

- Small size (its diameter is typically around 100 μm, which allows embedding in many structures) and lightweight.
- Low losses, which allow remote sensing.
- Anti-electromagnetic interference and anti-radio-frequency interference.
- No electrical biasing is required to guide light, so the resulting sensors are passive, which is very relevant in environments with an explosion risk.
- High bandwidth, which allows multiplexing and multi-parameter sensing,
- Distributed sensing in optical fibre communication lines: it is possible to develop modulation techniques that allow physical quantities to be measured along the fibre itself.

However, there are also important concerns [18], which are being progressively solved as the technology matures:

- Cost
- Complexity in interrogation systems
- Unfamiliarity of the end user with the technology

By taking a look at these properties, it is easy to understand why the most successful type of OFS, in terms of covering the sensors market, is distributed sensing. First, it is possible with optical fibre to make distributed measurements over distances up to several tens of kilometres, an ability that is unique to fibre optics. A second advantage of those mentioned above is the small diameter of optical fibre, which allows embedding it in tunnels, bridges, or concrete constructions [19, 20], and, once installed, the initial cost is compensated with a continuous monitoring of variables such as strain, temperature, or vibration, an operation that may last years and that does not affect the optical fibre it is embedded in. This explains its success in the following domains:

- Civil engineering: leakage of dams and river embankments, monitoring of cracks in bridges and other concrete structures; structural health monitoring of large civil projects; and fire monitoring and safety alarms for roads, subways, tunnels, etc. [21].
- Petrochemical: detection of oil and natural gas transmission pipelines or storage tank leaks; temperature monitoring of oil depots, oil pipes, and oil tanks; and detection of fault points.
- Power cable: detection and monitoring of surface temperature of power cable and location of accident points; temperature monitoring of power plants and substations; and detection of fault points and fire alarms.
- Aerospace: monitoring of aircraft pressure, temperature, fuel level, and landing gear status; temperature and strain monitoring of composite skins; and measurement of stress and temperature of aircraft jet turbine engine systems [22].

Distributed sensing technology can be classified in two groups: quasi-distributed (multiplexing FBGs like in Figure 1.6 are a good example) and distributed sensing [24]. A comparison between both technologies is presented in Figure 1.7. With quasi-distributed sensing, discrete points can be monitored, whereas with distributed sensing changes in any point in the optical fibre path length can be detected. Effective gauge lengths of the order of 1 m are common, and there are some that go to even shorter discrimination lengths [8]. Regarding purely distributed sensing, the first works date from the 1980s [25, 26], and since that moment up to now, the utilization of Rayleigh, Brillouin, and Raman scattering for remotely detecting changes in a parameter at a specific point has been widely explored [22, 27, 28].

The optical time-domain reflectometer (OTDR) is the typical commercial device, though there are many types of detectors such as the example presented in Figure 1.7c for sensing an acoustic field. The basic principle of this type of device is the injection of a series of optical pulses into the fibre and the further detection of light that is scattered or reflected back from points along the fibre. These points may be splices, failures, or even changes introduced by variables such as temperature (in this last case the system can be used to detect a fire), strain, or vibration. Since that moment many companies have focused on distributed sensing, such as Omnisens, Sensornet, Silixa, Fotec, Luna, OptaSense, or Future Fibre Technologies, just to mention a few.

In 2017 their market was more than 1 billion US dollars, and it is expected to grow at a 10.4% annual growth rate through 2026. The main application is

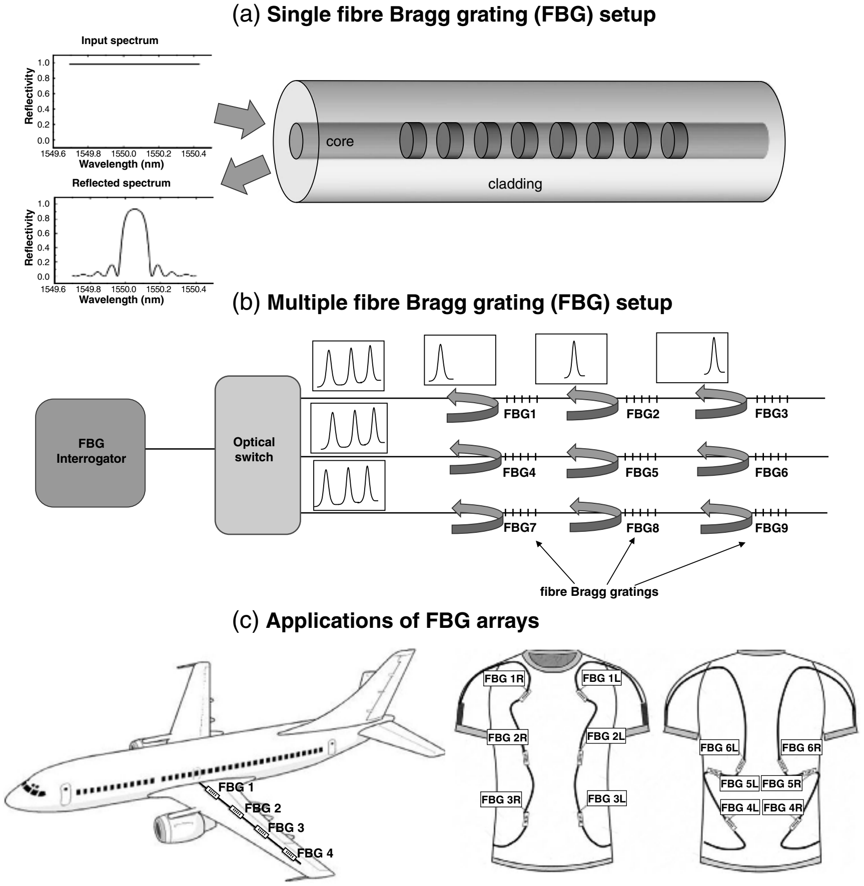


Figure 1.6 (a) Single fibre Bragg grating. (b) Multiple fibre Bragg gratings in a multiplexed system monitored with an interrogator. (c) Applications of FBG arrays for monitoring strain in different points of an aircraft and for developing a smart textile [23].

the oil and gas vertical segment, which occupied a 60.9% share of the global distributed fibre-optic sensor market in 2015. But also pipelines, intrusion detection and security, transport, and infrastructures are other important domains where this technology is used.

Consequently, it can be concluded that optical fibre distributed sensors, along with the gyro, are the two most successful OFSs and both cases can serve as an example to follow towards new commercial opportunities.

In addition to this, OFS research during the last years has focused on two important fields: the fabrication of specialty fibres, where the main breakthrough took place in 1996 with the first microstructured optical fibres [29], and the

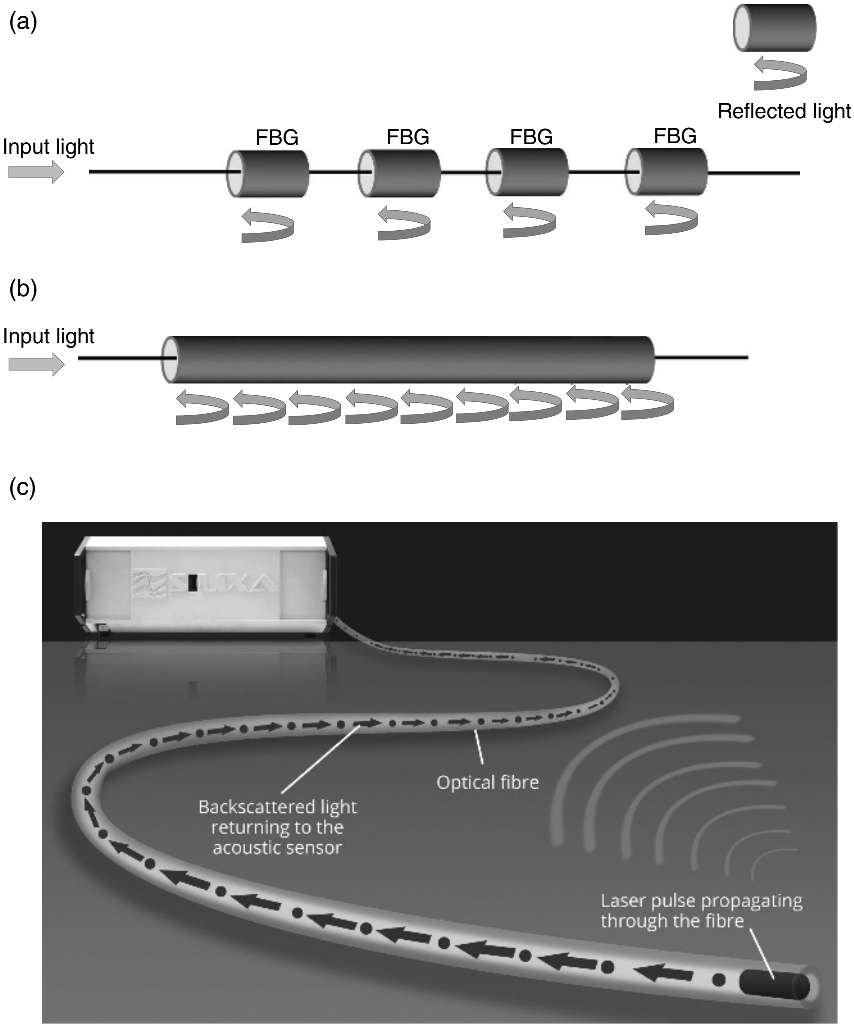


Figure 1.7 (a) Quasi-distributed sensing (with FBGs). (b) Distributed sensing. (c) Commercial distributed sensor for detection of an acoustic field from Silixa.

improvement of nanodeposition techniques [30, 31], which has permitted OFSs to be used in the domain of gas, chemical, and biological sensors [32–37]. The explanation is simple. The optical fibre transmits light, and light can be modulated by parameters that affect the guidance of light through the optical fibre such as strain, temperature, or surrounding medium refractive index. Consequently, if the deposition of a material on the optical fibre modulates the transmission of light

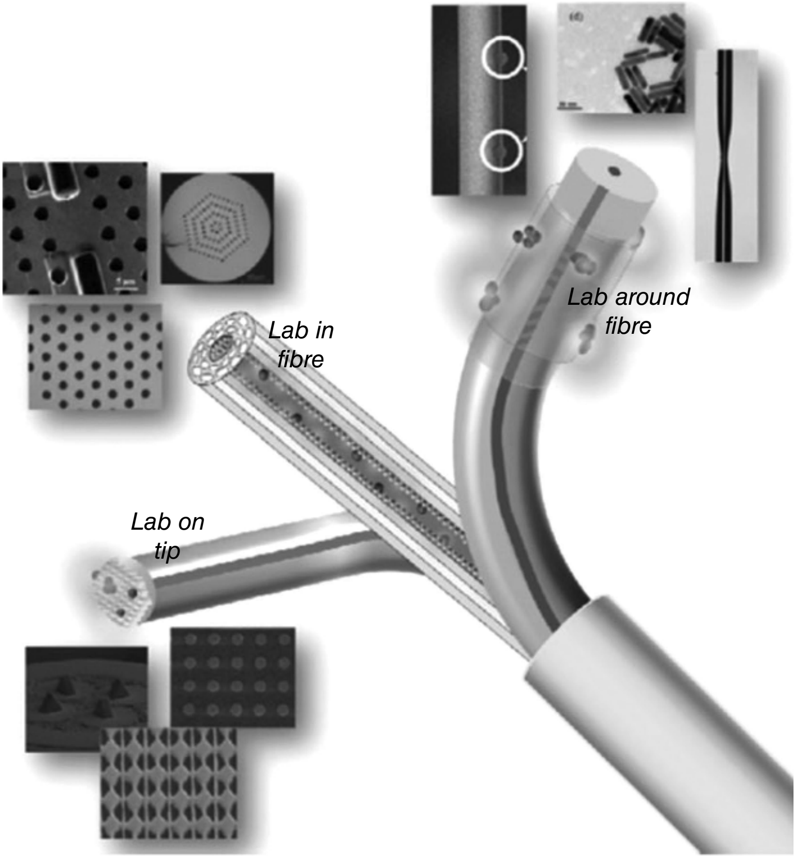


Figure 1.8 Combination of nanotechnology with optical fibre. Deposition of nanostructures: around the fibre, inside the fibre (in the holes of holey fibre), and on the tip of optical fibre (in a probe in reflection configuration). *Source*: With permission from [40] © Wiley.

through the fibre, sensitive materials will modulate the transmission of light through the optical fibre as a function of almost any parameter (i.e. any environmental variables, chemical or biological species, etc.). Moreover, nanotechnology is evolving so much that a lab on fibre can be developed with optimized sensitivity to one or several parameters [38] (Figure 1.8). This positions OFSs in the strategic field of nanophotonics. Even an array of nanoantennas has been deposited on the tip of an optical fibre to enhance the Raman scattering detection [39].

Other important fields are human structural health monitoring, also called biomechanics [41–43], or the development of optical fibre composed of new materials. In this sense, it is well known that the use of plastic optical fibre (also called polymer optical fibre) is an economic alternative to silica fibre in optical communications. Though it has disadvantages, such as higher losses, this technology can be transferred also to optical fibre sensing for the same purpose: low-cost solutions. In addition, the polymer itself presents some different mechanical and thermal properties, which allows new possibilities for the development of multi-parameter sensors, new modulation schemes, and embedded systems for several target applications (e.g. textiles, composite and concrete integration) [44]. The success of plastic optic fibre suggests the exploration of other materials that can be used for harsh environment applications, as it will be shown in one of the chapters of the book. Moreover, OFS technology has evolved so much that even a spider silk optical sensor has been developed for detection of chemical vapours [45]. So the question arises as to why not even metamaterials could be used in OFSs [46].

Considering the current research lines of OFS technology and the commercial devices that are already available, this book will aim for providing the reader with the key concepts towards transforming research into final products. The success of distributed OFSs and the gyro must be followed by others along the twenty-first century, and to this purpose we will combine basic concepts, such as the elements that compose an OFS setup and how light propagates through optical fibre, along with the latest progress of OFSs in multiple important domains of the modern society.

To this purpose, the book will be divided into these sections:

Chapter 2 offers the basics for understanding light propagation in optical fibre: single-mode and multimode fibres under both a geometric optics and wave theory perspective. As a special and challenging case, the propagation through microstructured optical fibre will also be discussed. Finally, some ideas on propagation of light through specialty optical fibres optimized for sensing will be presented.

Chapter 3 describes the key elements that are necessary for an OFS setup (i.e. the optical source, the detector, light coupling, splices, etc.).

Chapters 4 and 5 present different detection techniques: intensity modulation, polarimetric sensors, phase modulation (interferometers), wavelength modulation, and detection based on Rayleigh, Raman, and Brillouin scattering.

Chapters 5–7 focus on applications of distributed sensing: structural health monitoring, biomechanical sensing, and the gas and oil industry (this group is the most successful domain of application of OFSs).

Chapters 8–11 present other important domains such the application of nanotechnology towards improving the performance of OFSs, gas and volatile organic compound sensors, chemical sensors, and biosensors.

Finally, Chapter 12 addresses the important topic of interaction of light with matter with a biomedical perspective. Chapter 13 shows detection in harsh environments, one of the domains where optical fibre can more successfully compete with other technologies. Chapter 14 concludes the book with a thorough analysis of the future trends of OFSs.

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