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Optical Fibre Sensors

Fundamentals for Development of Optimized Devices

Ignacio Del Villar | Ignacio R. Matias

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Ignacio Del Villar, PhD, is an Associate Professor in the Electrical, Electronic and Communications Engineering Department at the Public University of Navarra, Spain, where he teaches on electronics and industrial communications. He is a member of the IEEE and an Associate Editor of different journals. In addition, he has participated in multiple research projects and co-authored more than 150 papers, conferences, and book chapters related to fibre-optic sensors.

Ignacio R. Matias, PhD, is the Scientific Director of the Institute of Smart Cities and Professor of the Electrical, Electronic and Communications Department at the Public University of Navarra, Spain. He was one of the Associate Editors who founded the *IEEE Sensors Journal*, promoting fibre-optic sensors since then through conferences, special issues, awards, books, etc. He has co-authored more than 500 book chapters, journal and conference papers related to optical fibre sensors. He is currently member-at-large at the IEEE Sensors Council AdCom.

1

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

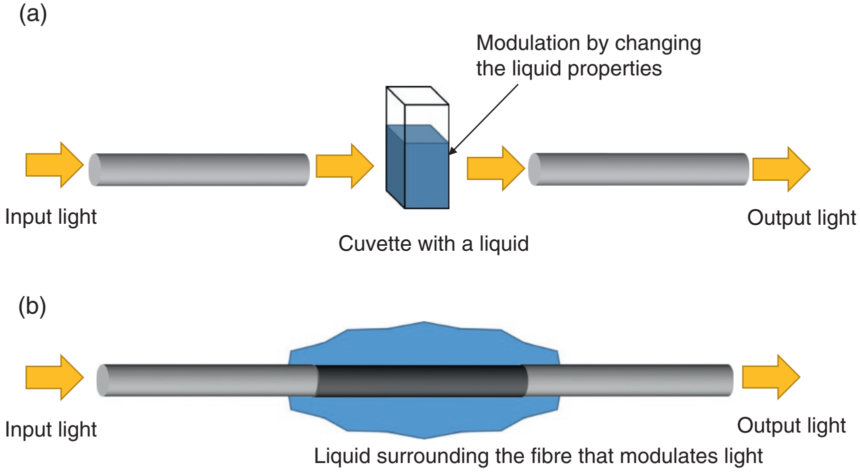

Figure 1.1 (a) Extrinsic sensor: light is modulated outside of the fibre. (b) Intrinsic sensor: light is modulated while it is transmitted through the fibre.

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

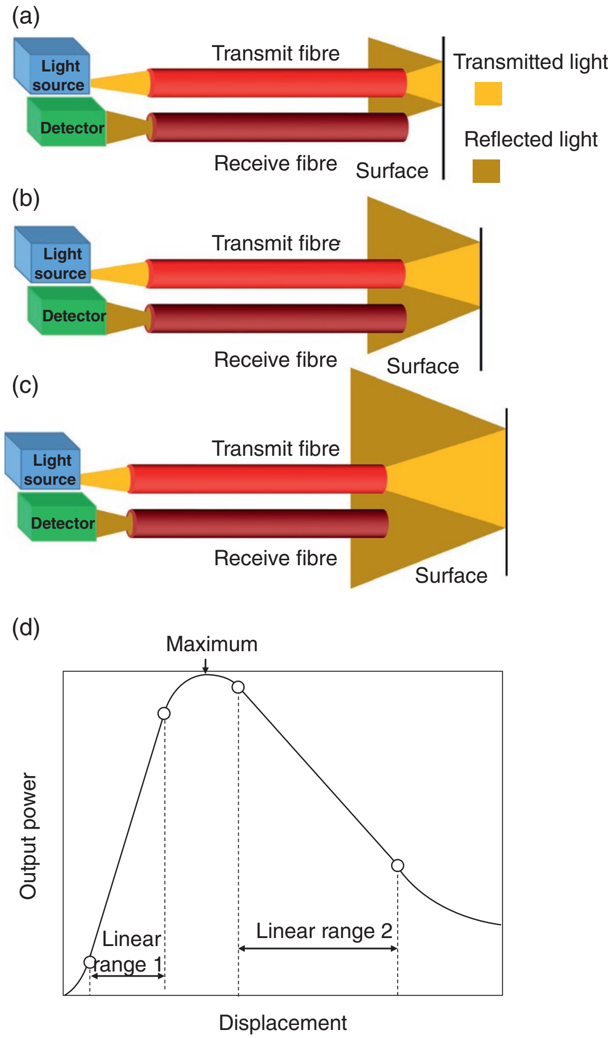

Figure 1.2 (a–c) Fotonic sensor setup with a fibre bundle composed of one transmitting and one receiving fibre: (a) with the surface too close and hence only a small part is coupled back to the receiving fibre; (b) with the surface at the optimal position for a highest coupling; and (c) with the surface 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).

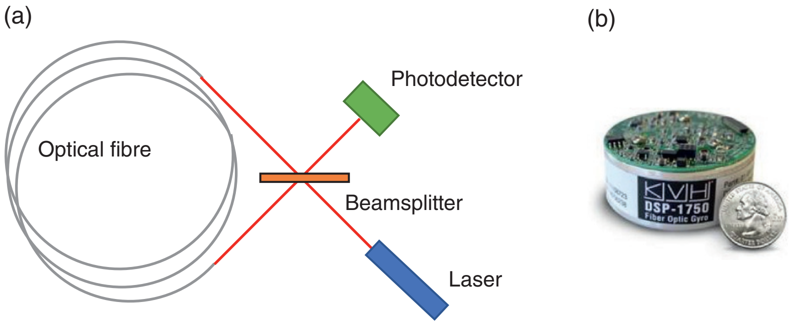

Figure 1.3 (a) Simplified setup: light from a laser is split by a beam splitter and enters the fibre on both ends. The two beams go out of the fibre and the photodetector receives them. Due to the Sagnac effect, both beams interfere constructively and destructively depending on the rotation speed of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

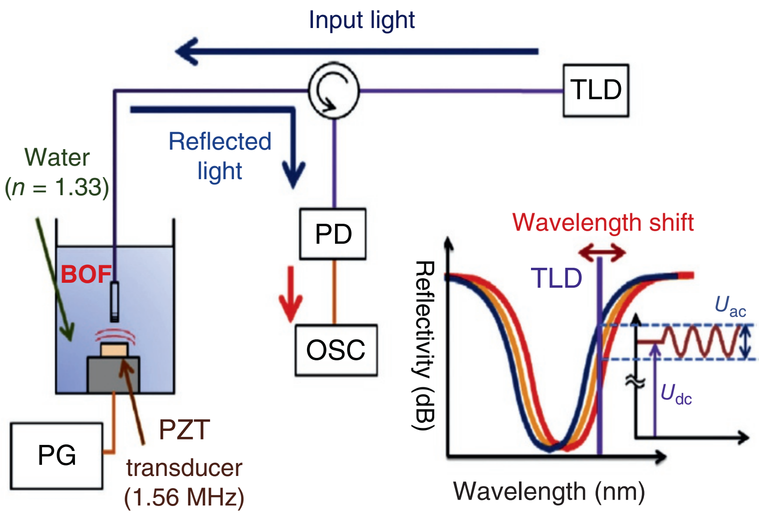

Figure 1.4 Optical setup for a Fabry–Pérot hydrophone [10]. OSC is oscilloscope, PD photodiode, PG pulse generator, PZT piezoelectric transducer, and TLD tunable laser diode. *Source*: Reproduced with permission of Elsevier.

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.