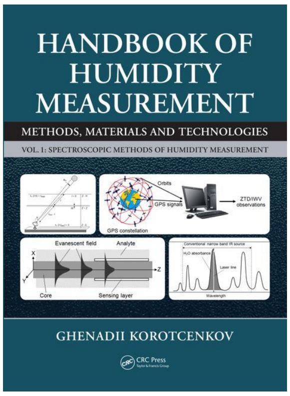

Handbook of Humidity Measurement Methods, Materials and Technologies: Spectroscopic Methods of Humidity Measurement

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Outlook—State of the Art and Future Prospects of Optical and Fiber-Optic Sensors

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24 Outlook—State of the Art and Future Prospects of Optical and Fiber-Optic Sensors

24.1 PROSPECTS OF OPTICAL AND FIBER-OPTIC SENSORS APPLICATION

Summarizing the consideration of optical and fiber-optic sensors (FOSs) one can state that the optical and fiber-optic technologies represent great opportunities for the development of a variety of devices capable of controlling the humidity. These devices can have a sufficiently high sensitivity and good operation speed necessary for *in situ* monitoring (Muto et al. 2003); and the sensing element may have a very small size. But at the same time, we must recognize that the fabrication of such sensors does not come to agreement with mass production. In addition, special sources and radiation detectors, and personal computer (PC) with special programs for signal processing are required for their functioning. This means that the detection systems and measuring systems may be complex, and their operation requires precise installation procedures and qualified professionals. This naturally substantially restricts the use of such facilities, since such sensors and devices, using them can be expensive. Therefore, it is difficult to expect that the optical and FOSs displace from the market of electronic and electrical humidity sensors, which, as well as optical and FOSs, do not possess the required selectivity, but considerably cheaper in production and in operation.

At the same time, optical and FOSs, which have a number of significant advantages, without a doubt can be used in the security systems and devices for special purposes, which are developed on different principles (Wolfbeis 1991, 1992; Burgess 1995; Cámara et al. 1995; Kersey 1996; Gansert et al. 2006; Consales et al. 2008; Korotcenkov et al. 2011). The main advantages of FOSs, including fiber-optic humidity sensors in comparison to their conventional electronic counterparts can be summarized as follows:

1. They allow *in situ* determination and real-time analyte monitoring.
2. They are excellent for applications where the measurement is to be made over a long period, with the major instrumental problems being window fouling and calibration.
3. They are easy to miniaturize because optical fibers have very small diameters. Therefore, FOSs can be used in the fields, where a measurement of humidity is needed but the accessibility is limited in space, and where an electronic sensor could be more difficult to locate.
4. They are fairly flexible: optical fibers can be bent within certain limits with no damage.
5. They can be used in hazardous places and locations of difficult access because of the ability of optical fibers to transmit optical signals over long distances (between 10 and 10,000 m). In addition, sensors have excellent corrosion resistance, and they are potentially resistant to ionizing radiation. Optical fiber humidity sensors have immune to radio frequency interference and electromagnetic interference. They are potentially resistant to ionizing radiation. In addition, sensors are nonmetallic and MRI compatible. The immunity to electric and magnetic fields suggests its applications in high-voltage installations, where it can be important to monitor humidity. For example, optic sensors do not use electricity and consequently they can be used for monitoring of inflammable liquids or gases because of the absence of sparks.
6. Fiber-optic chemical sensors are much safer in explosive environments compared with sensors involving electrical signals, where a spark may trigger a gas explosion.
7. Multielement analysis is possible when using various fibers and a single central unit.
8. They normally permit nondestructive analysis.
9. They perform a high-voltage insulation and absence of ground loops and hence one can avoid any necessity of isolation devices such as optocouplers.
10. Optical fibers can carry more information than electrical cables. Fiber-optic sensing is very versatile, because the intensity, wavelength, phase, and polarization of light can all be exploited as measurement parameters, and several wavelengths

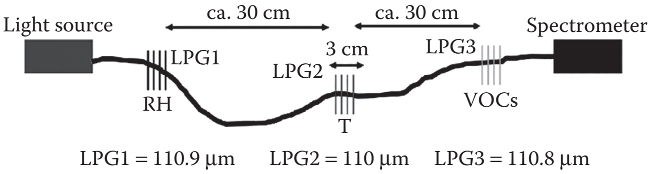

FIGURE 24.1 Schematic illustration of the LPG sensor array for multiparameter measurements; the individual LPGs were used to measure: LPG1 relative humidity (RH); LPG2 temperature; and LPG3 volatile organic compounds (VOCs). Each LPG sensor was designed with optimized response to a particular measurand. The first sensor was with no surface modification. The second one was modified by a mesoporous coating of silica nanoparticles (SiO_2 NPs), and the third one was modified with a coating of SiO_2 NPs infused with a functional material, p-sulphanatocalix[8]arene (CA[8]). The LPGs were fabricated with periods such that they operated at or near the phase matching turning point. (Reprinted from *Sens. Actuators B*, 244, Hromadka, J. et al., Multi-parameter measurements using optical fibre long period gratings for indoor air quality monitoring, 217–225, Copyright 2017, with permission from Elsevier.)

launched in the same fiber in either direction form independent signals. This gives the possibility of monitoring several chemicals with the same fiber sensor or even simultaneously monitoring unwanted environment parameters variations, which could drastically affect the chemical concentration measurements, such as the temperature or disturbance of the fiber. For example, FOSs can also provide simultaneous monitoring of parameters such as temperature and humidity inside microwave ovens. Hromadka et al. (2017) have shown that an array of three long-period gratings (LPGs) fabricated in a single optical fiber and multiplexed in the wavelength domain can be used to measure simultaneously temperature, relative humidity (RH), and volatile organic compounds (VOCs), which are key indoor air quality (IAQ) indicators (Figure 24.1).

11. Probes are often easy and inexpensive to build.
12. The sensor element can be a long length of fiber providing an extended sensing element: this can be used to enhance sensitivity by wrapping the fiber in a compact form to create the transducer head, or it can be used to provide spatial averaging of the measurand of interest.
13. Another option is the ability to spatially discriminate the measurand at different locations along a fiber length (Figure 24.2). This leads to the capability to perform distributed sensing in addition to local measurement. Such ability is a powerful sensing tool, which is not generally possible in using conventional sensor technologies. If the fiber is not sensitive along its entire length, but is locally sensitized at various points, the system becomes a *quasi-distributed* sensor system (Kersey 1996). In addition, the optical

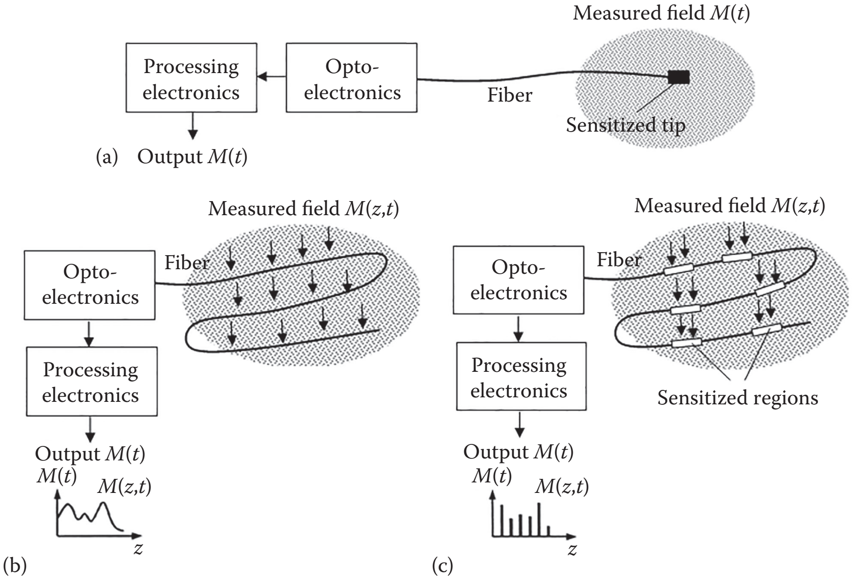

FIGURE 24.2 (a) Point, (b) distributed, and (c) quasi-distributed sensing.

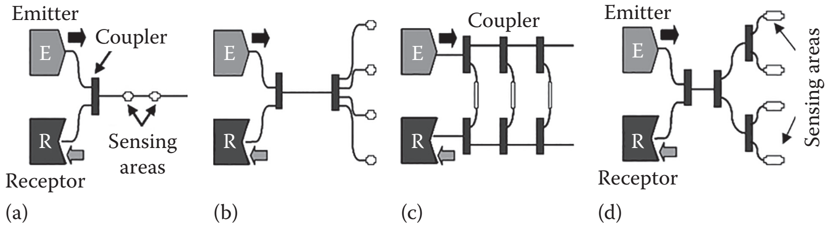

FIGURE 24.3 Examples of optical fiber sensor networks: (a) line, (b) star, (c) ladder, and (d) tree. (From Elosua, C. et al., *Sensors*, 6, 1440, 2006. Published by MDPI as open access.)

fiber sensors permit coupling of the interrogating and the response signal in the same fiber, which simplifies the sensor system and also makes possible the implementation of a multipoint sensor network (Figure 24.3). These properties are all very attractive when is important to control gas concentrations in large spaces or in pollutant control applications (Elosua et al. 2006).

However, the optical and fiber-optic humidity sensors have found their area on the sensor market; further research is needed, aimed at optimizing the manufacturing technology, increasing the life time of sensors, and increasing the reproducibility of the parameters.

24.2 WHAT CONSTRAINS THE USE OF OPTICAL AND FIBER-OPTIC SENSORS?

As it was noted by Cámara et al. (1995), fiber-optic sensors, including humidity sensors, have the following disadvantages:

1. In a similar way to their electronic counterparts, optical and fiber-optic humidity sensors are secondary devices.
2. The number of reversible reactions is very limited, so in many cases probes have to be regenerated after use.
3. The area of interaction between the chemical and the material is very small, that is, 8–10 μm in diameter, in the case of single-mode fiber and 50–200 μm in diameter, which directly affects the sensitivity achieved from this type of sensors.
4. Ambient light may distort the measurement and some of the reagents immobilized at the sensor surface, mainly dyes, are unstable and can be bleached by ultraviolet (UV) radiation or washed out by solvents.
5. The properties of the indicator may vary. Besides they usually have lower dynamic ranges than electrodes. There are other shortcomings of the fiber-optic-based humidity sensors, which should be resolved, such as the presence of hysteresis, long response time and relatively low accuracy, and so on.
6. In some cases, the concentration of the immobilized indicator is unknown and two optodes prepared similarly can have different analytical characteristics.
7. Some limitations arise from the somewhat restrictive spectral windows that can be effectively accessed using available low-cost fibers. Frequently, an analyte will not have an intrinsic spectral feature within a usable window or will simply be too weak an absorber in any optical path length that could reasonably be accommodated in the remote cell.
8. Stability and durability are also an important issue for polymer-based humidity sensors. Many papers and reviews dealing with the development of FOSs have been published in the literature but only a few have reported applications to environmental monitoring. It was also established that some polymers undergo degradation or an irreversible swelling process when exposed to certain environments (Pejcic et al. 2007). Polymer degradation is a change in the properties—tensile strength, color, shape, conductivity, and so on—of a polymer or polymer-based product under the influence of one or more environmental factors such as heat, light, and chemicals (Carraher 2008). For example, Jiang et al. (2005) reported that the sensitivity of polypyrrole (PPy)/polyvinyl alcohol (PVA) composite sensor was only maintained for two weeks, while the sensitivity of pure PPy sensor was maintained more than one month. Of course, this lifetime is too short. Irreversible changes in polymers under influence of UV radiation and oxidizers such as ozone and NO_2 also

limit appreciably of the application of polymers for designing sensors aimed at environment control. Experiment has shown that the reaction of ozone with the polymer is irreversible and the average useful lifetime is found to range from 20 to 3000 ppb hours only. It has been reported that ozone and other oxidizing components in the polluted atmospheres of industrial centers could either initiate or accelerate the photochemical destruction of polymers (Razumovskii and Zaikov 1982). As a result, in the case of an ozone-containing atmosphere, the lifetime of polymer-based sensors was considerably shorter (Muller et al. 2011). Polymer sensors used for environmental control also have a significant disadvantage in terms of their sensitivity to UV radiation. Moreover, it was found that polymer degradation was almost always faster in the presence of oxygen (air) and moisture. However, that longtime instability, which is accompanied by the temporal drift and degradation of sensor performance, is a big drawback of all types of sensors-based on polymers (Kumar and Sharma 1998; Kondratowicz et al. 2001; Bai and Shi 2007). It is clear that environment stability of sensors depends on the type of polymer material and therefore, this feature of the polymers should be taking into account during selection of polymers for humidity sensor design (Carraher 2008). On account of the low stability, even ultrasensitive sensors are unsuitable for real application in industry and environment monitoring.

9. The big problem of modern developments in the field of optical and FOSs is also poor reproducibility of parameters. Unfortunately, the methods used for the deposition of humidity indicators on the surface of optical fibers mostly have problems in controlling the thickness and uniformity of the coated layer. The variety of humidity-sensitive materials, used in developed optical and FOSs, with the almost complete absence of studies aimed at establishing the correlation between the parameters of humidity-sensitive materials, their synthesis technologies, and sensor performance, also creates certain difficulties in choosing the humidity indicators with optimal properties. As a rule, each team uses a different set of materials, which will not be repeated in the studies carried out by other teams. Some researchers believe that PVA is a very promising material for humidity detection (Kolpakov et al. 2014). According to Wong et al. (2012), this material allows fabrication of very fast and selective humidity sensors with response times of <1 s. However, this statement requires verification and correct comparison with other materials.
10. Disadvantages also include the poor elastic property that makes optical fiber extremely brittle. This is not particularly desired for sensing applications. Consequently, the handling, treatment, and operation of FOS require extreme care. In addition, each process requires technical skills. With the current technology, *in situ* assembly of the optical system is a cumbersome and exhaustive process, since the measurement setup of the optical fiber sensor system comprises different modules (e.g., light source, coupler, and receiver), difficult splicing process and the constant need for careful treatment. Although the method of manufacturing fiber gratings has improved considerably, current technology only manages to produce one at one time and most processes still require manual handling. In addition, the cost of running fiber grating writing facilities is high due to expensive laser, masks, (both phase mask and amplitude masks) and the requirement for a highly skilled operator.

Certainly, in the past decade, it has been done a lot to improve the parameters of optical and fiber-optic humidity sensors, to optimize their production technology and the development of different measuring systems (Alwis et al. 2013; Kolpakov et al. 2014). Optical fiber humidity sensors have been already used to facilitate the remote sensing and continuous monitoring of humidity in diverse applications such as the baking and drying of food, cigar storage, civil engineering to detect water ingress in soils or in the concrete in civil structures, medical applications, and many other fields (Yeo et al. 2006, 2008; Alwis et al. 2013). For example, Caponero et al. (2013) illustrated the flexibility of the fiber-optic humidity sensors to monitor humidity condition in resistive plate counters (RPCs) packaged in a steel box. This is important, as the humidity influences the working point of the RPC; these devices are nuclear and subnuclear physics detectors based on the ionization of a gas medium. Due to the RPC operating in a high electromagnetic field environment, the FOS is the best candidate for installation on an RPC due to the fact that FOSs are immune to electromagnetic interference. Other examples of fiber-optic humidity sensors applications are listed in Table 24.1. The integration of

TABLE 24.1
Humidity/Moisture Application-Specific Sensors

Sensor Application	References
Biomedical Measurements	
Breathing sensor	Akita et al. (2011), Favero et al. (2012)
Recognition of devoiced vowels	Morisawa et al. (2010)
Breathing air-flow monitor	Kang et al. (2006)
Climate/Agricultural Monitoring	
Turbidity sensor	Bilro et al. (2011)
Flood monitoring	Kuang et al. (2008)
Canopy water content sensor	Clevers et al. (2008)
Water stress detection of Poplar plantation	Eitel et al. (2006)
Water content sensor for vegetation	Sims and Gamon (2003)
Simultaneous measurement of several parameters	Arregui et al. (2002), Gaston et al. (2003)
Structural Health Monitoring (SHM)	
Water absorption and detection in concrete	Yeo et al. (2006), Kaya et al. (2013)
Building stone condition monitoring	Sun et al. (2012)
Dew detection	Mathew et al. (2012)
Quality Control Applications	
Water content measurement in ethanol	Xiong and Sisler (2010), Srivastava et al. (2011)
Water detection in jet fuel	Puckett and Pacey (2009), Zhang et al. (2009)
Humidity detection in oil-paper insulation of electrical apparatus	Rodriguez-Rodriguez et al. (2008)
Other Applications	
Water leak detection	Cho et al. (2012)
Water detection in optical fiber splice enclosures	Hsu et al. (2011)
Dew detection inside organ pipes	Baldini et al. (2008)

Source: Alwis, L. et al., *Measurement*, 46, 4052–4074, 2013.

optical fibers in reduced and more robust structures has led to a new generation of FOSs with lower detection limits, increased sensitivity, higher selectivity, reduced response time, and in some cases, reversibility and long-term stability. But these efforts are insufficient, as most of the researches carried out in this area are still aimed at demonstrating the feasibility of the humidity measurement. This means that the individual samples were made, which were not intended for sensor market. Currently, there are only a few commercially available fiber-optic humidity sensors manufactured by O/E Land Inc. (Table 24.2). Therefore, there is a constant need to develop a compact optical fiber humidity sensing system with high reliability, high sensitivity, and low cost.

TABLE 24.2
Performance of Commercial Optic Humidity Sensors

Sensor	Sensitivity pm/% RH	Operation Temperature	Size, mm	Range, % RH	
				Minimum	Maximum
O/E Land FBG-Based Sensors					
OEFHS-100A, OEFHS-100B	4.5	0°C–80°C	6 × 40 or 3 × 40 6 × 60 or 3 × 60	10	100

Source: http://www.o-eland.com/SensorProducts/OEFHS-100.php.

24.3 OPTICAL AND FIBER-OPTIC SENSORS—WHAT DETERMINES OUR CHOICES?

It is clear that when developing the humidity sensors and humidity control systems, one can use a variety of approaches. Comparative characteristics of some of them are given in Tables 24.3 and 24.4. However, a more detailed comparison of these methods must be sought in the relevant chapters of this book. It is seen that each of the optical and FOS classes has intrinsic benefits and limitations for application in measurement systems.

For example, adsorption-based humidity sensors use diode lasers and light-emitting diodes, which are reliable, high speed, miniature, and consume little energy, and photoreceivers and spectrographs with charge-coupled devices (CCD) or complementary metal-oxide semiconductor (CMOS) detectors that connected with PC, can be portable, relatively cheap, and due to incorporation of microprocessor many external and temporal factors affecting on measurement results can be eliminated (Wilson et al. 2001). However, as with nonoptical humidity sensors, issues of integration, packaging, and calibration must be carefully considered and streamlined in the design process to meet stringent size, weight, and power constraints. In addition, humidity sensors based on measuring the change in the output intensity of the device require light sources with high radiation stability. Otherwise, it is difficult to separate the response of the sensor from humidity with changes in laser power and also to vary losses in optical splices and connectors.

Luminescence sensors are extremely sensitive to small quantities of water vapor in the air, but the broadband character of luminescence spectra and the ubiquitous presence of naturally fluorescent compounds lead luminescence sensors to suffer from a critical lack of selectivity. Also, luminescence methods are sensitive to temperature fluctuations and other environmental factors that quench fluorescence. In addition, the lifetime of many of these sensors is short.

Some scientists (Kolpakov et al. 2014) believe that the most prospective direction is the development of interferometric-based humidity sensors based on photonic crystal. It was demonstrated experimentally (Mathew et al. 2011) that a simple design, using a laser diode as an interrogator is possible to use with this kind of sensors. Interferometers based on Michelson or Mach–Zehnder

TABLE 24.3
Advantages and Disadvantages of Different Fiber-Optic Sensors

Advantages	Disadvantages
Grating	
Increased sensitivity	Expensive signal processing and interrogation technology; problem of temperature and strain signal division
Interferometer	
Extremely flexible geometry; high sensitivity; wide area distribution	Problem of multisensing signal division; sensitivity stabilization problem; tuning control problem
Amplitude	
Low cost; simplicity; easy installation; possibility of coverage of wide area	In many cases low sensitivity and presence of mobile mechanical elements; high requirements to stability of light source intensity
Nonlinear	
Possibility of distributed sensor fabrication	Low sensitivity; high cost

TABLE 24.4
Summary of the Advantages and Limitation of the Studied Technologies

Technology	Advantages	Limitations
Etched FBG	Well-developed technology Multiplexing capability	Fragility Low sensitivity High cost
Tilted FBG	Well-developed technology	Low sensitivity High cost
LPG	High sensitivity	Fabrication Temperature cross-sensitivity
LPG-based interferometer	High sensitivity	Fabrication Device length
Abrupt taper	High sensitivity	Fragility
CDM-based interferometers	Low-cost	Reproducibility
Multimodal interferometer	Low-cost Low-temperature cross-sensitivity	Reproducibility Broader resonance

Source: Gouveia, C.A.J. et al., Refractometric optical fiber platforms for label free sensing, in *Current Developments in Optical Fiber Technology*, Harun, W.S. and Arof, H. (Eds.), InTech, Rijeka, Croatia, pp. 345–373, 2013.

FBG—fiber Bragg grating; CDM—code division multiplexing; LPG—long period grating.

layouts or even Fabry–Perot intracavity were also demonstrated showing high sensitivity and great potential for the various applications. Meanwhile, most of the sensors that are based on optical fibers require the use of a spectrum analyzer as the interrogator. The technology, which allows the use of low-cost laser diodes as the interrogators, is expected to be attractive for industrial exploitation. However, these sensors do not solve the problems inherent for interferometric-based sensors such as low selectivity and the effect of temperature.

Refractometric-based sensors also have significant problems associated with low selectivity. Refractometric sensors, which use tapered fibers, due to its highly reduced cladding diameter have an enhanced evanescent interaction and have long been explored for refractive index (RI) measurements by monitoring the transmitted optical power. In spite of high sensitivity and very compact size (few millimeters), however, these structures are very fragile and special packaging is needed. It should also be borne in mind that in the fiber Bragg grating (FBG)- and LPG-based sensors the coating with humidity-sensitive polymer, which swells on absorbing moisture, in addition to changes in the RI, exerts a tensile force on the FBG and LPG. Thus, the swelling of the polymer can cause bending stresses in the fiber, which causes the reflection spectra to widen because of the chirp in the grating (Bhola et al. 2009). In addition, fiber grating sensors are also highly sensitive to temperature, therefore they need an extra mechanism to compensate temperature changes. FBG-based configurations are more attractive for the purpose of multipoint sensing due to their very narrow spectral response, while LPG-based sensors provide a powerful platform for advanced optical sensing in various other applications. Also, modern versions of refractometric humidity sensors such as FBG and LPG-based and interferometric-based sensors, due to the nature of their manufacture, are complex to manufacture. Multimode interference-based refractometers are also interesting solutions that rely on the concept of reimaging effects of multimodal interferometer (MMI) patterns present in multimode waveguides (Gouveia et al. 2013). In these devices, the transmitted spectral power distribution is highly sensitive to the optical path length of the multimode fiber and its surrounding refractive index (SRI). Usually based on singlemode-multimode-singlemode structures, they can be easily fabricated and applied in different situations. However, these configurations are also difficult to reproduce and present very broad spectral resonance making for instance multiplexing a very difficult task. The comparison of the most relevant evanescent field-based fiber refractometers is presented in Table 24.5.

Thus the use of fiber-optic techniques imply the use of read-out circuitry that requires on-chip phase modulation, a tunable wavelength or multiple wavelengths, where retrieving the phase information with the help of this additional hardware requires rather complicated signal processing electronics. In addition, the required an extremely high sensitivity over a large measurand range, requires highly coherent (single-line) laser sources. All together this makes these sensors quite expensive. No doubts, the features of these instruments cannot restrict their use in areas where very small concentrations have to be detected, for example, in security

TABLE 24.5

Summary of the Performance Parameters of the Most Relevant Works on Fiber-Based Refractometers

Configuration	Measurement Method	Sensitivity, nm/RIU	Resolution, RIU	References
Microfiber FBG	Spectral shift	100	–	Zhang et al. (2010)
TFBG	Spectral shift	10	10^{-4}	Chan et al. (2007)
Bare LPG	Spectral shift	1481	–	Shu et al. (2002)
HRI-coated LPG	Spectral shift	>9000	–	Pilla et al. (2012)
Mach–Zehnder LPG	Phase	–	1.8×10^{-6}	Allsop et al. (2002)
Fabry–Perot LPG	Spectral shift	–	2.1×10^{-5}	Mosquera et al. (2010)
LPG/FBG	Normalized optical power	–	2×10^{-5}	Jesus et al. (2009)
Abrupt taper	Spectral shift	1150	8.2×10^{-6}	Zibaii et al. (2010)
CDM-based Mach–Zehnder	Spectral shift	188	–	Ma et al. (2012)
MMI	Spectral shift	148	–	Biazoli et al. (2012)

Source: Gouveia, C.A.J. et al., Refractometric optical fiber platforms for label free sensing, in *Current Developments in Optical Fiber Technology*, Harun, W.S. and Arof, H. (Eds.), InTech, Rijeka, Croatia, pp. 345–373, 2013.

CDM—code division multiplexing; HRI—high refractive index; MMI—multimodal interferometer; RIU—refractive index unit; TFBG—tilted fiber Bragg grating.

systems or environmental monitoring. However, it should be understood that in many other applications much simpler and cheaper sensors are preferred. Another problem with optical humidity sensors is that the response times of most developed devices are relatively slow due to the thickness of the moisture absorbing layer in which water molecules have to diffuse through to interact with the guided optical wave (Bhola et al. 2009). Therefore, when developing the systems for practical application one must take into account this distinction, because as mentioned earlier more or less relates to sensors that use different principles.

With regard to the comparison of fiber-optic and integrated sensors, the fiber-based sensors compared to integrated optics are very cheap and have the strong advantage that they can be easily applied for distributed sensing. The sensor can be incorporated in the fiber that transports the light from the source to the detector and the different sensors can be read out in, for example, the time domain (OTDR) or wavelength domain (in case Bragg reflectors are used). Other advantages of FOSs, such as flexibility and small size of detection probes, have been shown previously at the beginning of this chapter. Nevertheless, fiber sensors cannot compete with integrated optics with respect to (1) robustness; (2) compact optical circuitry, enabling a higher complexity (e.g., multiple sensors on one chip); (3) design flexibility with respect to the geometry as well as the choice and combination of materials (e.g., active and passive materials); (4) ease of access to the optical path in evanescent-field sensing; (5) potential of integration with microelectronics, micromechanics, and micro total analysis systems; and (6) potential of *cheap* batchwise mass production.

We hope that presented in this book detailed information on various optical and fiber-optic-based RH sensing schemes proposed by different teams will allow basing on cross-comparison to make selection of suitable sensing method for specific applications. Many believe (Kolpakov et al. 2014) that the application of fiber-based humidity sensors will grow exponentially throughout the next decade. Initially, optical humidity sensors will satisfy specific unfulfilled applications in the chemical industry, medicine, and security systems, where the humidity control would be beneficial and present electronic sensors cannot satisfy the need. Another attractive feature of the fiber-based technology is the relative ease of integrating centralized remote monitoring and control over a number of separate facilities related to the low cost and low weight of the optical fiber cable in comparison with a copper cable. An optical interrogation module can be designed to allow simultaneous interrogation of tens or even hundreds of sensors. This can be installed in a remote office allowing the operator to monitor a set of sensors covering an area of up to a few miles in radius. In addition, recent scientific advances should allow lower cost dedicated systems by avoiding the relatively high price of interrogation modules, which are presently a significant disadvantage of fiber-based sensors.

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