Fibre-optic sensor technologies for humidity and moisture measurement

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Abstract

A review of the use of fibre-optic sensor technologies for humidity sensing is presented. The paper first provides a brief overview on the basic concept of what is meant by humidity and on conventional detection methods. This is followed by an extensive review on the various fibre-optic techniques reported for humidity sensing, covering both intrinsic and extrinsic sensor configurations.

Keywords: Fibre optic; Sensors; Humidity; Moisture

Contents

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1. Introduction

1.1. Humidity sensing

In a similar way to temperature, strain or pressure for example, humidity (or moisture content) constitutes one of the most commonly required physical quantities. It has shown significant importance in a diverse range of applications, as illustrated in Fig. 1, from air conditioning for human comfort and combating bacterial growth to process control and maintaining product quality [1]. The requirements for humidity monitoring may vary according to the application and hence various techniques have been employed to perform humidity measurements. In this paper, a brief overview on the basic concepts and definitions associated with humidity measurements is given but the focus is on the design and use of novel fibre-optic-based methods for humidity sensing, which are discussed and reviewed in this paper.

1.2. Humidity and relative humidity

The term *humidity* refers to the presence of water in gaseous form but it is often used to refer to expressions which are related to water vapour characteristics and in the field of measurement, there are various terms associated with such water vapour measurements. In addition, the term *moisture* is frequently interchanged with *humidity* even though the actual definition of *moisture* refers to the water in liquid form that may be present in solid materials [2]. Since humidity is a measure of water in gaseous state present in the environment, water vapour found in a gas mixture behaves in accordance with the gas laws and the amount of pressure it exerts equates to the partial pressure of the water vapour components in the gas mixture, as defined by Dalton's law [2].

When air is fully saturated with water, the pressure exerted by the water vapour present is defined as the saturation water vapour pressure (P_{ws}) which is a function of temperature. A common way to relate the amount of water vapour present in the environment is to take the ratio of the actual water vapour pressure and the saturation water vapour pressure at a specific temperature. The resultant term, known as the *relative humidity* (RH), simply represents the ratio of the amount of water vapour present in the atmosphere to the maximum amount the atmosphere can hold and is often expressed as a percentage using the following equation,

$$\text{Relative Humidity (RH)} = \frac{P_{\mathrm{w}}}{P_{\mathrm{ws}}} \times 100\% \qquad (1)$$

where P_{w} is the partial pressure of the water vapour and P_{ws} is the saturation water vapour pressure.

If air is cooled down sufficiently, to a point where it becomes saturated with water molecules (RH = 100%) and condensation occurs as a result, the temperature at which this occurs is known as the *dew point*. In a similar way to relative humidity, the dew point temperature is another term frequently used to express the amount of water vapour present in the atmosphere. It is much preferred in some applications, for example, in meteorology, as it provides a better "absolute" measurement of water vapour content than RH measurements, which may fluctuate with temperature.

The dew point temperature or RH can be calculated by using the familiar dry and wet bulb temperature method [2], where the name was derived from the technique employed which involves using regular bulb thermometers to perform temperature measurements. Other parameters which include humidity ratio or moisture content expressed as a dimensionless quantity and absolute humidity, expressed in $\mathrm{g/m^3}$, are also used in humidity measurements.

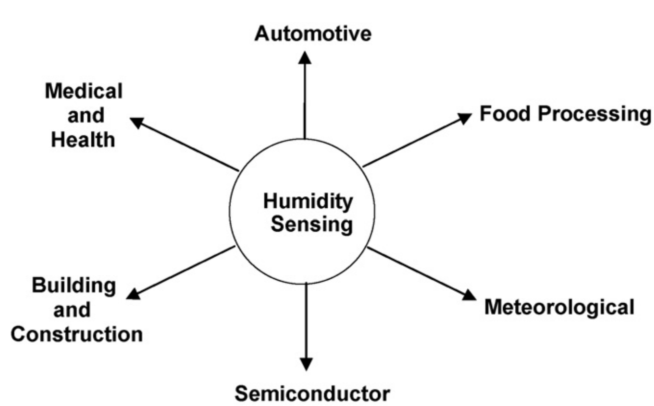

Fig. 1. An example of applications of humidity sensors in various industries.

2. Conventional techniques for humidity detection

In order to cross-compare the approaches to measurement using fibre-optic technologies, a brief overview of conventional techniques [2] for humidity sensing follows. From the simplest way of exploiting the expansion and contraction of materials such as human hair to the most sophisticated techniques, such as using a miniaturised electronic chip, a variety of methods have been explored over many years to obtain meaningful humidity measurements. These methods are employed either by probing the fundamental properties of water vapour or using various transduction methods which are capable of giving humidity-related measurements.

2.1. Mechanical hygrometer

The mechanism of a typical mechanical hygrometer is based on one of the oldest techniques that relies on the use of materials which expand and contract in proportion to the humidity change. Common materials used include synthetic fibres and human hair. The hygrometer is formed by linking the material to strain gauges or other similar mechanical devices to measure the displacement caused by the change in humidity. Calibration is required to relate the displacement to the relative humidity level in the environment. Such a method is inexpensive and easy to implement but it is slow and has inherent non-linearity and hysteresis issues which need to be compensated when the measurements are performed, thus making it unsuitable for most of those applications where environmental conditions change rapidly.

2.2. *Chilled mirror hygrometer*

The chilled mirror hygrometer, also known as the optical condensation hygrometer, is a device based on an optical technique for the determination of the dew point temperature. It is known to be the technique which provides the most accurate and reliable measurements, and is often used for measurements setting a calibration standard. In operation, a conventional chilled mirror hygrometer contains a temperature-controlled reflective condensation mirror and an optoelectronic module which monitors the optical signal reflected from the surface of the mirror. In the ‘dry’ condition, where the mirror temperature is higher than the dew point, the maximum signal is reflected into the detector of the optoelectronic module. When the temperature drops below the dew point, the signal intensity is reduced due to the scattering of light as a result of water droplets forming on the mirror surface. The chilled mirror hygrometer can be used to provide measurements with accuracy quoted to be as high as $\pm 0.1\,^{\circ}\mathrm{C}$ [2]. However, this method is expensive and requires regular maintenance due to its susceptibility to surface contamination.

2.3. *Wet and dry bulb psychrometer*

A simple and relativity low cost method which has been popular for humidity measurements is the wet and dry bulb psychrometer. It consists of two thermometers (e.g., electric or glass), one of which is covered with a damp wick to determine the wet bulb temperature and the other to measure the temperature of the sampled gas (dry bulb temperature). The dry bulb temperature is simply the temperature of the air, whereas the wet bulb temperature is the temperature achieved as a result of water evaporation and latent heat transfer. Examples of such measuring device are the sling psychrometer which operates by whirling the device through the air to obtain the temperature readings and the Assman psychrometer, a similar device with a fan attached to the unit to provide air flow.

This measurement device is relatively inexpensive, yet can also be used to provide a calibration standard. However, it is not suitable for operation in small enclosed areas (where the moisture from the wet bulb significantly changes the water vapour content in the environment) and precautions are necessary to minimise measurement errors caused by contamination on the wick covering the thermometer, inconsistency in the wetting of the wick and the inaccuracy of the thermometers used. Generally, such a measuring device using thermometers with a temperature accuracy of $\pm 0.2\,^{\circ}\mathrm{C}$ offers humidity accuracy of $\pm 3\%$RH when operating over a temperature range of 5–80 °C [2].

2.4. *Infrared (IR) optical absorption hygrometer*

The general operation principle of the IR hygrometer is based on a dual-wavelength absorption technique that uses a primary wavelength at which strong optical radiation absorption is observed and a secondary/reference wavelength where the absorption is negligible. Humidity measurements are then taken in the form of transmission ratios at these two chosen wavelengths. This technique allows the direct measurement of water absorption which minimises drift in the readings and also interference caused by contaminants such as particles and other gaseous species in the test environment. The sensitivity of the instrument is dependent on the absorption path length and is thus governed by the Beer–Lambert law [3] where the transmission of the IR radiation through the absorbing gas is inversely proportional to the exponential function of gas concentration and the path length. This instrument has negligible drift and can generally operate over a wide humidity range.

2.5. *Miniaturised humidity sensors*

2.5.1. *Electronic sensors*

The development of these miniaturised electronic humidity sensors have been driven by the demand for low cost, reliable and compact sensors and transduction methods reported include capacitive, resistive and gravimetric methods. An extensive review on these sensors and their performance has been conducted recently by Lee and Lee [4]. A similar review has been carried out by Chen and Lu [5] with an emphasis on the wide range of sensing materials employed by the different humidity sensor types.

Amongst the various humidity sensors discussed, the capacitive- and resistive-based humidity sensors are the most commonly used, with capacitive-based sensors dominating and making up nearly 75% of the commercial humidity sensor market [6]. Capacitive-based humidity sensors operate on the basis of dielectric changes of a thin hygroscopic film upon exposure to moisture. Resistive-based sensors rely on the transduction mechanism involving the change in conductivity caused by the absorption of moisture in a hygroscopic material such as conductive polymers. Generally, both sensor types, which are classified as secondary measurement devices, are inexpensive and have low power consumption, covering a wide humidity range with good repeatability but suffer from temperature dependency and cross-sensitivities to some chemical species.

2.5.2. *Optical waveguide sensors*

Optical waveguide sensor is a class of optical-based device that falls under the category of miniaturised humidity sensors. An example is the surface relief gratings on SiO_2/TiO_2 waveguides reported by Tiefenthaler and Lukosz [7]. The roles played by surface and volume adsorption of water molecules were determined quantitatively from the measurements of the effective refractive index changes of certain modes in the waveguide. The observed changes in the refractive index as a result of water adsorption were 0.037 at a wavelength of 514.5 nm and thus the number of monolayers of water adsorbed can be determined under different conditions.

3. Fibre-optic techniques for humidity detection

All the techniques discussed so far, covering the familiar methods that relate the fundamental properties of water vapour to the various transduction schemes that rely on electrical, optical and mechanical approaches to provide humidity-induced measurements, have their own particular advantages and disadvantages yet none of them can fulfil majority of the requirements of precision, cost, ease of operation and maintenance, background interference, operation environment and remote operation. These sensors however, are generally not suitable to be employed in an environment of a potentially hazardous or explosive nature and also in situations where requirements such as immunity to electromagnetic interference, multi sensor operation, *in situ* and remote monitoring are, for example, required. Fibre optics offers a new approach to this new measurement problem.

With the advent of optical fibre technology, a considerable level of research has been focused on fibre-optic (FO)-based techniques for humidity sensing. In a similar way to their electronic or mechanical counterparts, FO humidity sensors are secondary devices but show additional features like small size, immunity to electromagnetic interference, multiplexing and remote sensing capabilities, of which the counterpart electronic sensors lack. However, the limitations of the operating range and accuracy of the FO-based humidity sensors are some of the drawbacks which researchers are striving to continue to address. Nevertheless, these sensors have found useful applications in various areas where electronic sensors were found to be inappropriate, thereby showing the real potential of FO-based sensors. Thus, this forms the main motivation that has driven the research activities on the development of a range of FO humidity sensors over the last 20 years.

The various FO-based humidity sensing techniques reported so far, with designs covering both extrinsic and intrinsic sensor types, can be further classified according to the techniques commonly employed in optical fibre sensing [8,9]. Generally, these techniques include direct spectroscopic, evanescent wave, in-fibre grating and interferometric methods, as discussed in detail below. Techniques employed vary from those which use an optical property of a material in response to humidity change to optical or fibre optic analogues of the different non-optical sensors described in the previous section. Table 1 has been designed to provide an overview and summary of the results reported by a number of the authors cited in this paper, bringing together the results of published work reported by their authors in a way that enables a degree of cross-comparison on a quantitative basis. In some cases data are not available (and therefore there are blanks in the table), but as such it enables a high degree of evaluation of different systems.

3.1. Direct spectroscopic-based sensors

The spectroscopic method has been a ‘workhorse’ technique widely used in chemical analysis. This method examines the

Table 1
Overview of the various fibre-optic sensing techniques for humidity detection

Reference	Year	Authors	Sensing method	Sensing material	Range (%RH)	Response time
Direct spectroscopic						
[11]	1988	Zhou et al.	Direct in-line absorption	Etched borosilicate optical fibre segment doped with $CoCl_2$	20–50	<5 min
[22]	1988	Posch and Wolfbeis	Fluorescence quenching	Perylene dyes	0–100	–
[23]	1995	Raichur and Pederson	Fluorescence quenching	Aluminium/morin metal ion–organic complex doped PVP membrane	0–80	–
[18]	1997	Brook et al.	Absorption	Crystal violet doped Nafion film	40–82	–
[16]	1998	Otsuki et al.	Direct in-line absorption (open air-gap configuration)	Rhodamine B doped HPC film	0–95	∼2 min
[25]	2001	Glenn et al.	Fluorescence lifetime	Lithium-treated Nafion membrane	–	–
[14]	2004	Tao et al.	Direct in-line absorption	Porous sol–gel fibre segment doped with $CoCl_2$	2–10	–
[27]	2006	Bedoya et al.	Fluorescence lifetime	Ruthenium-based complex doped PTFE membrane	4–100	∼2 min
Evanescent wave						
[32]	1985	Russell and Fletcher	Absorption measurement using straight and U-bent fibre	$CoCl_2$ doped gelatine film	50–80	<1 min
[49]	1988	Ogawa et al.	Attenuation measurement using OTDR technique	Porous SiO_2 optical fibre cladding	25–95	–
[34]	1995	Kharaz and Jones	Absorption measurement using OTDR technique	$CoCl_2$ doped gelatine film	20–80	1 s
[38]	1998	Otsuki et al.	Absorption measurement using U-bent fibre	Rhodamine B doped HPC film	0–95	∼2 min
[35]	2000	Kharaz et al.	Absorption measurement using U-bent fibre	$CoCl_2$ doped HEC and gelatine films	H: 30–96 G: 40–80	<5 s

Table 1 (*Continued*)

Reference	Year	Authors	Sensing method	Sensing material	Range (%RH)	Response time
[43]	2000	Bariain et al.	Attenuation measurement using tapered fibre	Agarose gel	30–80	<1 min
[39]	2001	Gupta and Ratnanjali	Absorption measurement using U-bent fibre	Phenol red doped PMMA film	20–80	–
[36]	2002	Jindal et al.	Absorption measurement using straight and U-bent fibre	$CoCl_2$ doped PVA film	S: >78 U: 3–90	
[41]	2003	Muto et al.	Attenuation measurement using PMMA plastic optical fibre	HEC/PVDF film	20–80	<5 s
[42]	2003	Arregui et al.	Attenuation measurement	Hydrogels-Agarose gel, poly-HEMA, poly-*N*-VP, poly-acryamide	Agarose: 10–100	~90 s
[47]	2004	Gaston et al.	Attenuation measurement using side-polished fibre	PVA film	50–90	1 min
[48]	2004	Alvarez-Herrero et al.	Wavelength resonance shift using side-polished fibre	TiO_2 overlay	0–80	–
[50]	2004	Xu et al.	Attenuation measurement	Porous sol–gel cladding	3–90	<1 min
[44]	2006	Corres et al.	Attenuation measurement using tapered fibre	PDDA/Poly R-478 nanostructured sensing overlay using ISAM technique	75–100	–
In-fibre grating						
[57]	2002	Kronenberg et al.	Strain-induced Bragg wavelength measurement	Polyimide	10–90	–
[63]	2002	Luo et al.	LPG resonant band wavelength measurement	CMC	0–95	
[66]	2005	Tan et al.	LPG resonant band intensity measurement	Gelatine	90–99	
[67]	2005	Konstantaki et al.	LPG resonant band intensity and wavelength measurement	$CoCl_2$ doped PEO film	I: 70–80 W: 40–80	<1 s
Interferometric						
[68]	2007	Venugopalan et al.	LPG resonant band intensity measurement	PVA	33–97	–
[73]	1989	Mitschke	Intensity measurement using Fabry–Perot configuration	SiO_2–TiO_2–SiO_2 cavity	0–80	1 min
[74]	1999	Arregui et al.	Intensity measurement using Fabry–Perot configuration	SiO_2–[Au:PDDA + /PSS-]-air cavity using ISAM technique	11–100	1.5 s
[78]	1999	Kronenberg et al.	Tandem Michelson interferometer configuration	PUU-PEO/PPO Hydrogel	–	–
[76]	2001	Yu et al.	Intensity measurement using Fabry–Perot configuration	SiO_2–[PDDA + /PS-119]-air cavity using ISAM technique	0–97	3 s

optical signal obtained and relates absorption or fluorescence-based measurements to the concentration of the target analyte. Hence it is not surprising that it is a popular choice of method for many FO-based chemical sensors. Generally, as shown in Fig. 2, the design of the sensors can simply comprise optical fibres with a sample cell for direct spectroscopic measurements or be configured as fibre optrodes where a chemical selective layer, comprising chemical reagents in suitable immobilising matrices, is deposited onto the optical fibre [9,10]. Most spectroscopic-based configurations for humidity sensing are based on the optrode design where moisture sensitive reagents are attached to the tip of the sensing fibre, usually with the aid of a polymeric material to form the supporting matrix.

3.1.1. *Absorption-based sensors*

A variety of potential materials and chemical reagents have been reported in light of their humidity-dependent optical absorption properties. Examples include reagents such as cobalt chloride ($CoCl_2$) [11–14], cobalt oxide (Co_3O_4) [15], Rhodamine B [16] crystal violet [17,18], and more recently, materials such as eletrochromic polymers [19] and bacteriorhodopsin (BR) doped biochromic film [20], where measurements are made by monitoring the intensity variation as a result of absorption due to the interaction between the chemical reagents involved and moisture.

Examples of such sensors include those from Zhou et al. [11] who have demonstrated an in-line absorption-based humidity sensor using a porous optical fibre segment doped with $CoCl_2$,

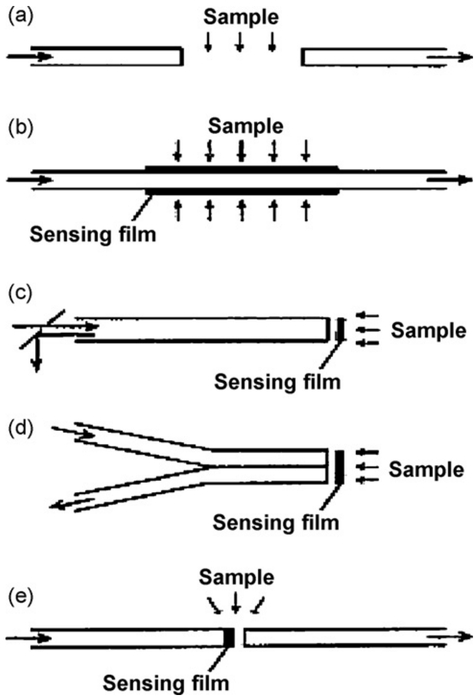

Fig. 2. Various configurations for spectroscopic fibre-optic sensors [16].

an inorganic salt compound which exhibits strong absorption on the wavelength band between 550 and 750 nm. As it hydrates, the colour of the salt compound changes from blue to pink and the absorption peak undergoes a hypsochromic shift. The use of the absorption characteristics of the compound contained in a variety of materials such as gelatine and cellulose has also been discussed by various authors [12,13]. To create a sensing element from these materials, a 0.5 cm long borosilicate glass fibre, with a typical diameter ranging from 150 to 300 μm was pre-treated to create a porous structure before being immersed into a aqueous $CoCl_2$ solution, followed by being dried at room temperature. As the sensing element is porous, some of the light launched into the fibre will be absorbed by the reagent and some will be scattered out of the structure. Hence the scattering loss was taken into consideration when

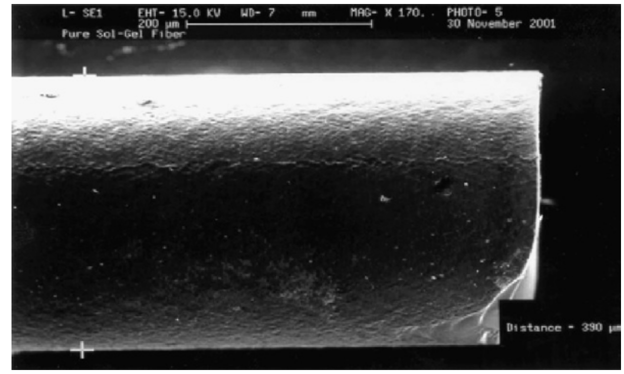

Fig. 3. SEM picture of the porous sol–gel silica fibre, showing the interconnected porous structure on the surface of the fibre [14].

the humidity-dependent absorption measurements were made. Sensor operation up to a limit of 50%RH was observed and the operating range was found to be dependent on the concentration of the $CoCl_2$ solution used for the fibre treatment. The sensor configuration discussed shows good reversibility and has a response time of 2–3 min.

Tao et al. [14] have recently demonstrated an active fibre core optical sensor (AFCOS) for humidity detection using a similar in-line absorption sensing concept. The porous sensing element was created using the sol–gel technique. Instead of pre-treating a segment of porous silica fibre with chemical reagent, the sensing element was mould-cast using a sol solution premixed with $CoCl_2$, shown in Fig. 3. This method offers more flexibility and it can be easily tailored to meet specific sensor requirement by controlling the dimension, composition and porosity of the sol gel silica structure. The demonstrated sensor consists of a 0.2 cm long $CoCl_2$ doped sol–gel silica fibre (diameter: 390 μm) with both ends attached to optical fibres of similar diameter. The optical signal at 632 nm, propagating through the active fibre core, was monitored to obtain information on the humidity level. The sensor described was reported to exhibit good response and is able to detect humidity level down to 2%RH. However, the upper operating limit for the current sensor design is <10%RH, which can be tailored by adjusting the dopant concentration.

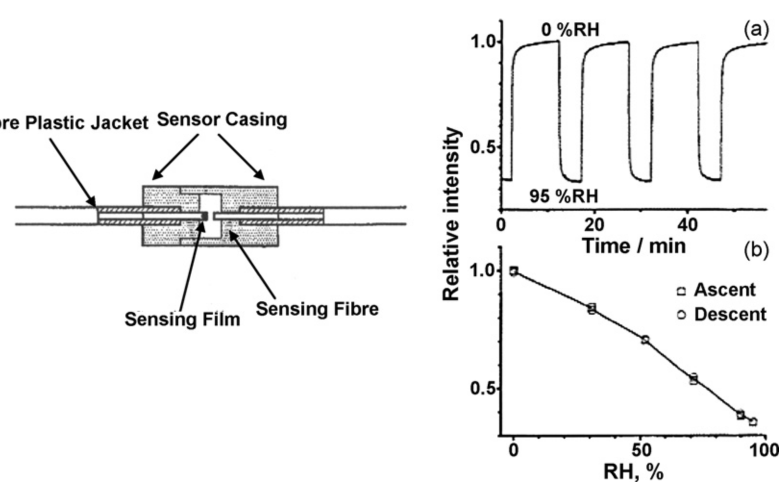

Fig. 4. Sensing characteristics of a fibre-optic humidity sensor using the air-gap configuration [16].

Otsuki et al. [16] have discussed an air-gap design, shown in Fig. 4, utilising the in-line absorption configuration. The sensor demonstrated was formed with an air-gap between two sections of a large core fibre positioned on the same axis. One end of the fibre was dip-coated with a dye solution containing Rhodamine B (RB) and hydroxypropyl cellulose (HPC). To measure the optical signal as a function of humidity, light was coupled into the sensor from one end of the fibre, passing through the dye-doped film and collected by the other fibre. The sensor discussed is able to operate between 0 and 95%RH and has a response time of approximately 2 min.

3.1.2. Fluorescence-based sensors

A humidity-sensitive optrode membrane fabricated using a dye-doped (Rhodamine 6G) gelatine film has been discussed by Choi and Tse [21]. The sensing membrane, which can be readily adapted for FO sensing, exhibits strong fluorescence at 568 nm when excited at 536 nm. A hypsochromic shift was observed with a resultant decrease in the emission intensity at 568 nm when the humidity level was increased from 0 to 100%RH.

The use of the fluorescence quenching mechanism for humidity detection has been explored by Posch and Wolfbeis [22]. The perylene-based sensor, implemented by attaching the sensing film at the end of a fibre bundle which forms the common arm of a bifurcated FO light guide, was evaluated over the range from 0 to 100%RH and the sensor response was found to be both non-linear and unfortunately exhibited cross-sensitivity to oxygen.

A similar approach using a quenching mechanism was demonstrated by Raichur and Pedersen [23]. The sensor, designed for applications in drying and baking processes, employs a highly fluorescent film based on aluminium/morin complex immobilised in polyvinyl pyrrolidone (PVP). The quenching of the fluorescence emission from the metal ion–organic complex, which arises due to the interaction between the aluminium ions and moisture, exhibits a linear response that follows the Stern–Volmer equation. The sensor showed good humidity response when assessed at elevated temperatures, up to 90 °C. However, prolonged testing showed a 20% decrease in output signal which could be attributed to the choice of polymer matrix used.

Luminescence lifetime-based methods [24–27] can also be considered to overcome some of the issues encountered by the intensity-based method such as the re-absorption of the fluorescence signal, scattering, light intensity variations and the concentration of the luminescence compounds used. The use of luminescence lifetime-based system using ruthenium-based complex immobilised in Nafion© membrane for the measurement of water content in organic solutions and humidity in the air has been discussed by Glenn et al. [25]. This sensor was able to respond to the change of water in both the liquid and gaseous phases but the operational lifetime of the sensing component is only about 4 days and it requires a regeneration procedure to restore its functionality. A more robust and stable sensing system, using the same ruthenium complex immobilised in a PTFE disk, was recently demonstrated by Bedoya et al. [27]. Phase-sensitive detection for humidity measurements was employed using a modified commercial lifetime-based instrument. The optrode fabricated has an operational range of 4–100%RH and displays good performance in terms of response time, repeatability and stability.

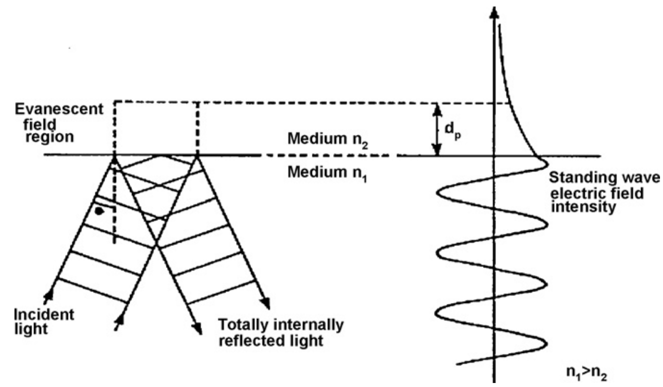

Fig. 5. Evanescent field generated at the interface of two optically transparent media [29].

3.2. Evanescent wave sensors

Light travelling through a step index optical fibre is guided within the medium as a result of total internal reflection (TIR) if the critical angle criterion is fulfilled [28]. At each point of TIR, the interference between the incident and reflected signals, shown in Fig. 5, at the core/cladding interface generates a standing wave which extends beyond the core of the optical fibre and penetrates into the cladding region.

This creates an evanescent field with an amplitude that decays exponentially with distance away from the core/cladding interface and follows the form,

$$E(z) = E_0 \exp\left(\frac{z}{d_\mathrm{p}}\right) \tag{2}$$

where the penetration depth (d_p) is defined as the depth at which the amplitude of the evanescent field, E, has decayed to 1/e of the initial value E_0 at the core/cladding interface and this is given by

$$d_\mathrm{p} = \frac{\lambda}{2\pi n_\mathrm{core}[\sin^2\theta - (n_\mathrm{clad}/n_\mathrm{core})^2]^{1/2}} \tag{3}$$

where λ is the wavelength of the propagating signal in the optical fibre, θ is the angle of incidence normal at the interface, n_core and n_clad are the refractive indices of the fibre core and cladding, respectively.

The evanescent wave (EW) sensing method allows the optical fibre to be used as an intrinsic sensor where the field generated at the interface interacts with the target analyte surrounding the fibre, thus giving information as a result of optical absorption, refractive index change or scattering [30].

Various optical fibre configurations can be used for evanescent wave sensing. A common approach is to use a plastic clad optical fibre with a section of the cladding removed, in order to gain access to the evanescent field. The structure of the de-clad fibre can also be modified by heating and bending it to

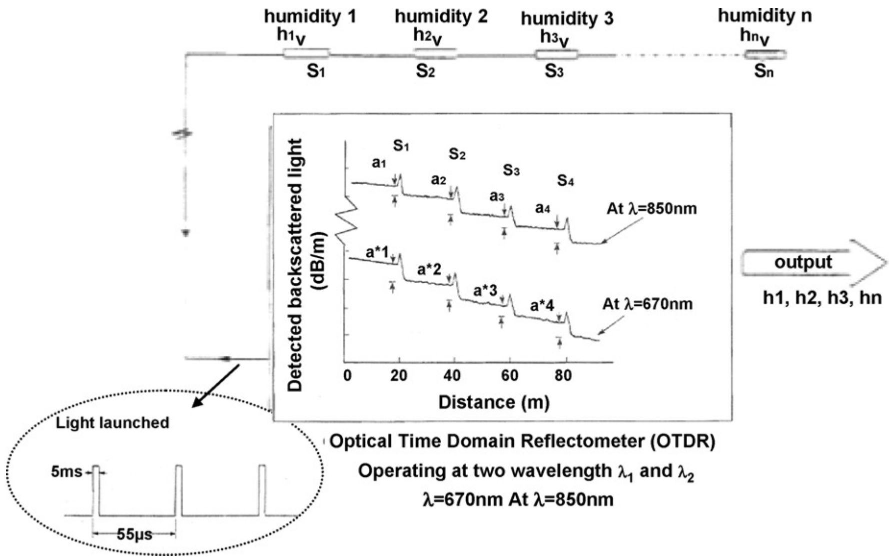

Fig. 6. Optical responses of distributed fibre-optic sensing system using optical time domain reflectometer (OTDR) [34].

form a U-bent fibre, causing the evanescent field to extend further away from the interface, hence enhancing the interaction between light and the target analyte. Other methods to gain access to the evanescent field include side polishing of optical fibres cast in a polymer block to expose the fibre core or heating and stretching the optical fibre to form a fibre taper.

Chemical reagents or selected matrices can be coated onto a de-clad optical fibre, forming a common design configuration for EW absorption- or fluorescence-based sensors. Comparing these to the sensors discussed in the previous section, the use of such a configuration gives flexibility in terms of the interaction length, time response and distributed sensing capability [31]. However, the required optical path length to achieve a similar sensitivity as is achieved for example in the direct absorption method either by using a direct sample cell or configuration based on active fibre core [11,14], is much longer due to the small path length interaction at every reflection point along the fibre [14,30].

3.2.1. Optical absorption

The majority of the EW methods reported are based on the absorption principle, which involves the use of chemical reagents immobilised in suitable organic or inorganic matrices. One of the earliest EW absorption-based humidity sensor was demonstrated by Russell and Fletcher [32] in 1985 using a 600 μm optical fibre with 12 cm of $CoCl_2$/gelatine sensing film. Ballantine and Wohltjen [33] then proposed a similar sensor the following year, using a 9 cm long glass capillary waveguide coated with $CoCl_2$/poly(vinylpyrrolidone) (PVP) film. In both the sensors discussed, the general operating range was limited and they could only respond to a humidity level higher than 50%RH.

Using the same chemical reagent and organic film combination ($CoCl_2$/gelatine), Kharaz and Jones [34] later demonstrated a quasi-distributed FO humidity sensing network consisting of 4 sensors using a 200 μm hard clad silica fibre with each sensing point positioned about 20 m apart. Measurements were obtained using an optical time domain reflectometry (OTDR) technique, shown in Fig. 6, utilising dual pulsed laser diodes emitting at 670 nm and 850 nm. An operating range of 20–80%RH was demonstrated using the sensor network and the performance was reported to be stable for a temperature range from 25 to 50 °C.

Kharaz et al. [35] extended their research work by investigating the influence of the immobilising matrices on the sensors performance. This was carried out by comparing various immobilising materials, such as hydroxyethylcellulose (HEC) and gelatine, together with $CoCl_2$. A U-bent fibre configuration, shown in Fig. 7, was used during the evaluation to enhance the interaction of the evanescent field with the sensing film.

From the studies performed using films of a similar reagent/immobilising material ratio, gelatine film was found to be insensitive below 40%RH, whereas HEC was able to respond to the 30–96%RH range, hence clearly showing the influence of the film constituent on the operating range of the sensor. This observation was substantiated by the work discussed by Jindal et al. [36]. In their research, a U-bent humidity sensor using $CoCl_2$/polyvinyl alcohol (PVA) film was reported to be sensitive to a humidity range from 3 to 90%RH. Further detailed work to optimise the performance of the $CoCl_2$/PVA sensor was then undertaken by Khijwania et al. [37], in which the effects of film thickness, bend radius and fibre core diameter were investigated.

In addition to $CoCl_2$, which from the literature seems to be a common choice of reagent used in the EW absorption-based humidity sensors discussed so far, other reagent/

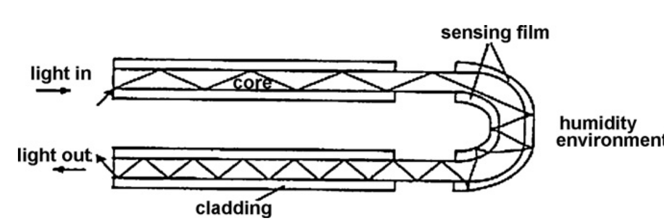

Fig. 7. U-bent evanescent wave sensor configuration using cladding as the active sensing region [35].

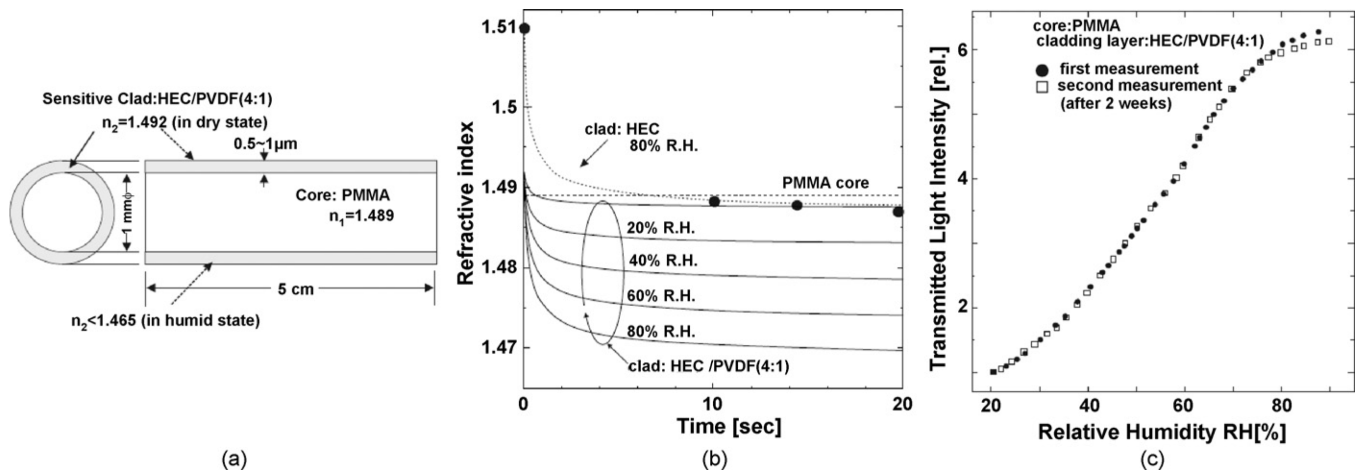

Fig. 8. Evanescent wave POF humidity sensor using PMMA core and HEC/PVDF film. (a) Sensor configuration. (b) Refractive index change of HEC/PVDF film at various humidity conditions. (c) Sensor characteristics [41].

immobilising matrix combinations deposited on U-bent sensors have also been reported by various authors [38–40]. These include Rhodamine B/hydroxypropyl (HPC) film, phenol red/polymethylmethacrylate (PMMA) film and magnesium oxide sol–gel film, with reported operating ranges of 0–95%RH, 20–80%RH and 5–85%RH, respectively.

3.2.2. Refractive index change

Refractive index (RI) change is another approach frequently used in the EW sensing method. An example of humidity sensing based on this method was demonstrated by Muto et al. [41] using a plastic optical fibre (POF) as shown in Fig. 8. The fibre core of the POF (diameter: 1 mm) was made from PMMA with a refractive index of 1.489 at 680 nm. Hence to render the fibre responsive to humidity, a polymer blend of HEC/polyvinylidenefluoride (PVDF) was deposited on the fibre core, forming a cladding layer (thickness: 0.5–1 μm). The humidity-sensitive cladding layer has a refractive index value of 1.492 when in dry state, creating a lossy waveguide which reduces the intensity of the light propagating through the fibre. As the cladding layer hydrates, the refractive index value falls below that of the core, reducing the intensity loss, thus forming the basis for humidity detection. The sensor responded well to a humidity range of 20–80%RH, with negligible temperature dependence. The time response to a step humidity change of 50%RH was reported to be less than 5 s.

Extensive studies were carried out by Arregui et al. [42] using hydrogels, a class of polymeric material known for its excellent water absorption properties, as potential material for the sensing approach is discussed in this section. The evaluation was performed using de-clad optical fibres coated with poly-hydroxyethyl metharyclate (poly-HEMA), poly-acrylamide, poly-*N*-vinyl pyrrolidinone (poly-*N*-VP) and agarose gel, taking into account of the effect of pore size for the selected materials on the sensitivity and time response of the sensor. Among the materials tested, the sensor with agarose gel gives the best overall performance, achieving an operating range of 10–90%RH. It was also reported to exhibit a better response time and stability than rest of the materials evaluated.

The use of a tapered fibre with agarose gel for humidity sensing based on refractive index change has been demonstrated by Bariain et al. [43]. The sensor consists of a tapered single-mode telecommunication grade fibre with a waist size of 25 μm, coated with agarose gel of a similar mix concentration to that described by Arregui et al. [42] and a comparison was made between the two different sensor types using the same material. The tapered sensor was reported to have a similar operating range and time response to the sensor using a de-clad fibre. However, the dynamic range of the optical intensity measurements taken in a similar test was found to be much higher than that for the tapered fibre sensor. Using on the same approach, humidity sensors with nanostructured films deposited onto tapered fibres using the ionic self-assembled monolayer (ISAM) deposition technique have been discussed recently [44,45] and are shown in Fig. 9. The ISAM deposition technique proposed allows the sensitivity of the sensor to be optimised by controlling the thickness of the coating film and a faster time response (than for the previous sensors discussed) was also possible due to the thin sensing film used.

Employing a side-polished optical fibre with a humidity-sensitive overlay represents another scheme for humidity sensing. To expose the evanescent field and create such a sensor, the flat surface parallel to the fibre axis was polished back to remove the cladding. Side polishing can be realised by first immobilising the optical fibre in a rigid material, forming a rectangular block with fibre extending out from the two end faces of the block orthogonal to the fibre axis. The advantage of using this scheme is that the sensing element can be fabricated using inexpensive components and a variety of coating materials can be deposited onto the flat surface of the fibre block. However, the fabrication procedure is very time consuming and depending on the design of the fibre block and the exposed interaction length can be limited.

Gaston et al. [46,47] have proposed a humidity sensor based on a single mode, side-polished fibre with a PVA overlay. The fibre block, with an exposed interaction length of about 2–3 mm, was covered by a PVA layer with thickness in the order of 100 μm. The humidity response was examined using two differ-

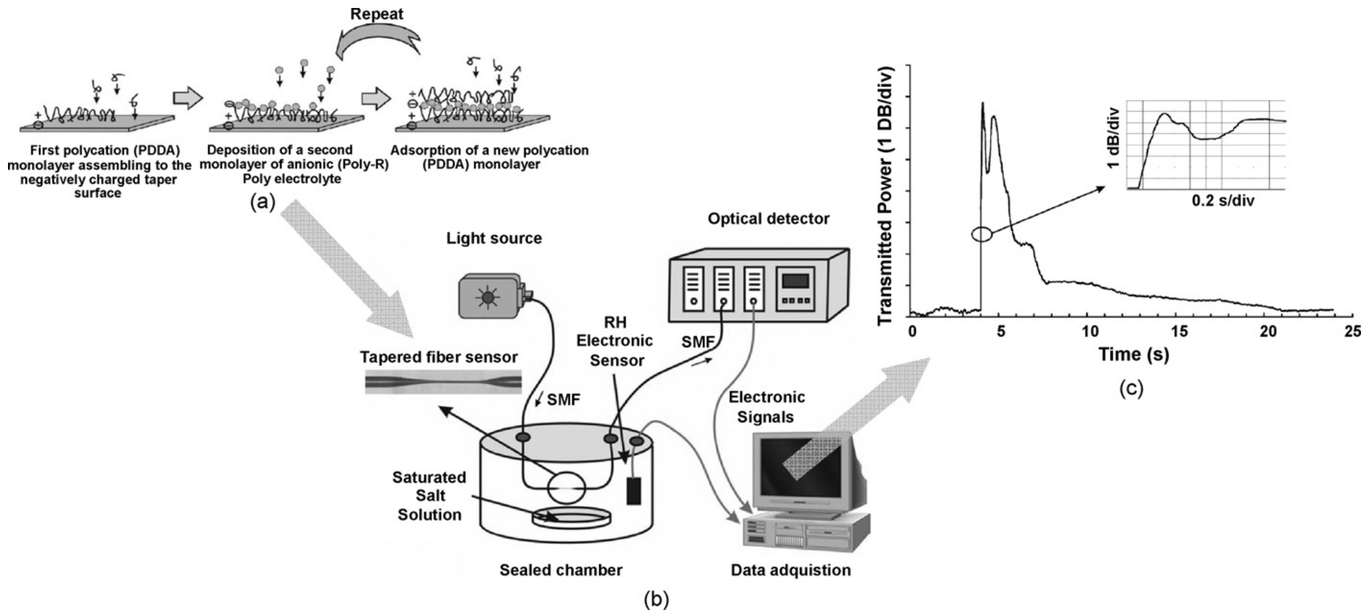

Fig. 9. Tapered optical fibre humidity sensor with ISAM overlay. (a) Schematic of ISAM deposition process. (b) Experimental set-up for sensor characterisation. (c) Sensor response to a short abrupt change of humidity simulated by human breath [45].

ent laser sources emitting at 1550 nm and 1310 nm, respectively. Both wavelengths showed a different sensing characteristic, with 1550 nm giving an operating range of ∼50–90%RH (dynamic range: 2.2 dB) and 1310 nm of ∼70–85%RH (dynamic range: 8.2 dB).

A sensor designed for low humidity detection and based on side-polished fibre, using a titanium oxide (TiO_2) overlay was demonstrated by Alvarez-Herrero et al. [48] and is shown in Fig. 10. The nanostructure overlay was deposited over the polished fibre block by using the electron beam evaporation method. The humidity-induced optical response of the sensor was monitored in the form of a wideband optical spectrum consisting of resonance bands which satisfied the phase matching conditions. The resonances found at specific wavelengths occur when the refractive index of the fibre guided mode is equal to that of the highest order mode of the overlay, thus resulting in coupling of the optical signal from the fibre to the overlay. Depending on the refractive index value of the overlay, the wavelength of the resonance shifts accordingly to fulfil the phase matching condition. This forms the basis of the sensing scheme, created by monitoring the wavelength shift of the resonance bands. The sensor demonstrated shows a linear wavelength shift from 0 to 15%RH, with a sensitivity of ∼0.5 nm/%RH. As the RH level increases beyond 20%RH, the sensitivity of the sensor decreases (∼0.03 nm/%RH for 30–80%RH), showing a smaller wavelength change.

3.2.3. Light scattering

EW sensors based on a light scattering phenomenon can be realised by having a porous material acting as the cladding in the optical fibre structure. This porous cladding layer scatters the evanescent wave that extends from the fibre core, thereby causing a reduction in the intensity of the optical signal propagating along the fibre. As the cladding layer absorbs water molecules, the scattering phenomenon is more evident, resulting in a further decrease in the transmitted optical power.

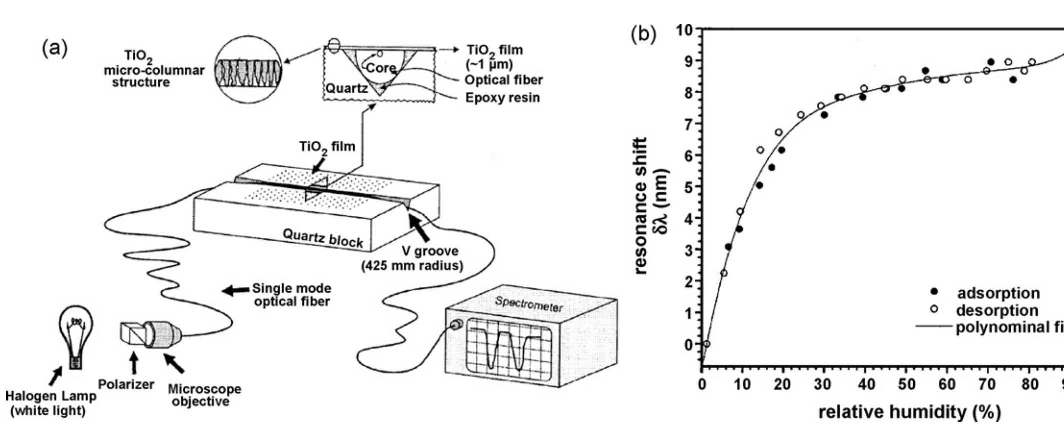

Fig. 10. (a) Experimental set-up for monitoring humidity-induced resonance band shift of a side-polished optical fibre with TiO_2 overlay. (b) Sensor response to humidity measured using resonance at 633 nm [48].

The use of the EW light scattering technique for humidity sensing was demonstrated by Ogawa et al. [49] using a silica core fibre with a porous SiO_2 cladding. A sensor with an interaction length of 40 mm was evaluated using an LED emitting at 850 nm. The sensor was demonstrated both as a point sensor (optical transmission power measurements at 850 nm) and a distributed sensing system, formed by cascading three similar sensors along the same fibre and interrogated using the OTDR technique. The sensor evaluated was found to respond well to humidity change from 20 to 95%RH, with a small temperature variation dependence of 0.1 dB (the test temperature range used was: 20–100 °C).

A similar scattering approach for humidity sensing was discussed by Xu et al. [50]. In their work, a U-bent configured EW humidity sensor was implemented using sol–gel technology, thus providing a flexible means of synthesizing custom coating solution to create the porous sol–gel silica film. A light source of a similar emitting wavelength at NIR as employed by Ogawa et al. [49], was used during the evaluation, in order to minimise the influence of the Rayleigh scattering effect which dominates at the shorter wavelength range.

3.3. *In-fibre grating sensors*

The in-fibre grating sensor represents a class of intrinsic FO sensor that has gained widespread popularity in recent years. It has been used in numerous applications in various industries due to its inherent sensitivity to temperature, strain and refractive index change [51–53]. The grating structure within the fibre sensor is created by UV-induced periodic refractive index modulation of the fibre core and can be generally classified into two main categories depending on the grating period, namely the fibre Bragg grating (FBG) [51] and long period grating (LPG) [53].

The detailed description and operation of the FBG and LPG has been discussed in the literature [51,53]. Grating-based sensors are commonly used in chemical sensing. The LPG can be employed as a general refractive index sensor and used in conjunction with chemical selective materials to create a species-specific chemical sensor. This thus forms a very attractive refractive index based chemical sensing mechanism which has been employed in the detection of a variety of chemical species [53]. The FBG-based sensors, on the other hand, are on the whole used predominantly for the monitoring of physical parameters such a temperature, strain or pressure. To use an FBG as a chemical sensor, a common approach is to select a material selectively sensitive to the chemical measurand and capable of inducing mechanical deformation as it interacts. This is done to produce a secondary strain-induced measurement using the FBG sensor as a result of physical or chemical interactions. The selection of the sensing materials for a FBG chemical sensor is therefore more stringent than LPG as it should not only be responsive to the selected chemical species but also be able to expand in order to induce strain on the FBG. Applications of FBGs in chemical sensing reported so far are largely limited to the important fields of hydrogen gas detection [54], salinity measurement [55] and moisture sensing [56–58].

The concept of in-fibre grating devices for humidity sensing is still fairly new. To date, there have only been a few literature reports on the subject, the earliest of which dates back to the year 2001. Humidity sensing using a FBG was first reported by researchers from EPFL, Switzerland [56,57] where studies were carried out to investigate the influence of humidity on commercial polyimide-recoated FBGs. The findings from the investigations concluded that an FBG with polyimide coating was able to respond linearly over a wide humidity range. The sensor was reported to respond well to a humidity range of 10–90%RH and display good repeatability. Due to its inherent sensitivity to temperature, a compensation scheme was required to extract humidity measurements from the sensor readings. The same sensing scheme proposed for humidity sensing was further explored by various groups and has been demonstrated in several interesting applications which include soil moisture monitoring [59,60] and moisture detection in concrete [61,62].

As an example of the use of this approach, work reported by Kunzler et al. [60] demonstrates a polymer-coated FBG sensor in soil moisture monitoring and was aimed at exploring the feasibility of using such a sensor configuration in hazardous waste sites. The specific requirement defined for the application in question was to have a sensor capable of operating between 2 and 18% gravimetric soil moisture level. The measurements were taken by relating the soil moisture levels to the Bragg wavelength, which were calibrated against relative humidity. The method used however, only allows measurement of up to 4% gravimetric soil moisture level due to the saturation (100%RH) of the

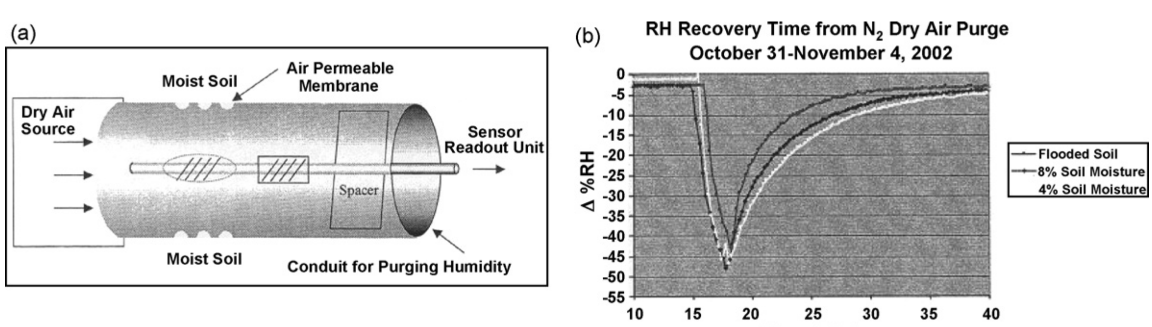

Fig. 11. (a) Schematic of a polymer-coated FBG sensor for soil moisture sensing. (b) Data showing evaporation rate of soil samples with various moisture content [60].

sensor. In order to achieve a higher operating limit, researchers at Blue Road Research have reconfigured the sensor concept as shown in Fig. 11, to allow the moisture level to be monitored via evaporation rate. Such measurements were performed by first purging the perforated sensor housing with dry air before measuring the time required for the sensor to reach saturation, which in turn can be related to the evaporation rate of the soil samples with various levels of moisture contents. The technique employed successfully demonstrated the use of the FBG-based sensor for measuring soil moisture level up to 18%.

Moisture sensing in concrete environment is yet another example of an application in which a polymer-coated FBG sensor approach can be employed. The recent work discussed by Yeo et al. [62], illustrates the versatility of a sensor which can be used as a promising diagnostic tool by the civil engineers in structural heath monitoring application. The effectiveness of the sensor was demonstrated by measuring the moisture ingress rate of various structure concrete specimens which differ by the water-to-cement ratio (which relates to the porosity of the sample) and the concrete mix composition. To perform such a measurement, FBG sensor probes were embedded at various positions in the concrete specimens as shown in Fig. 12. A simple water-bath test was used to introduce moisture into the pre-dried concrete cubes. The moisture ingress rate was measured by taking the time required to induce a rapid change in Bragg wavelength of the sensor, which represents the time taken for the waterfront to arrive at the sensor position.

The use of this type of FO sensing scheme in the two examples and applications discussed offers an attractive alternative and additional advantages over other conventional FO sensing techniques (for example, intensity-based sensors) through the use of a wavelength encoded signal and the ease of multiplexing capabilities of FBG-based devices.

The use of LPGs for humidity sensing was first reported by Luo et al. [63] from Luna Innovations, USA. In the sensor design discussed and shown in Fig. 13, carboxymethylcellulose (CMC) hydrogel was covalently attached to cladding of a LPG to form the humidity sensor. The sensor demonstrated was found to operate well over a humidity range from 0 to 95%, with a non-linear response dependency with humidity change. The sensor was observed to be unstable when it was fully saturated at conditions approaching 100%RH and temperature compensation was also required to obtain accurate humidity measurements. The sensor developed by Luna Innovations was evaluated on several separate occasions, as a moisture ingress sensor in aircraft lap joints [64] and as a monitoring device for the moisture detection in building envelopes [65]. In both evaluations, promising results were obtained, thus showing the potential of in-fibre grating-based humidity sensor in commercial/industrial based applications.

A similar LPG-based humidity sensing scheme was demonstrated by Tan et al. [66] using a gelatine-coated LPG and Konstantaki et al. [67] proposed a LPG humidity sensor utilising polyethylene oxide (PEO)/$CoCl_2$ hybrid overlay as the mois-

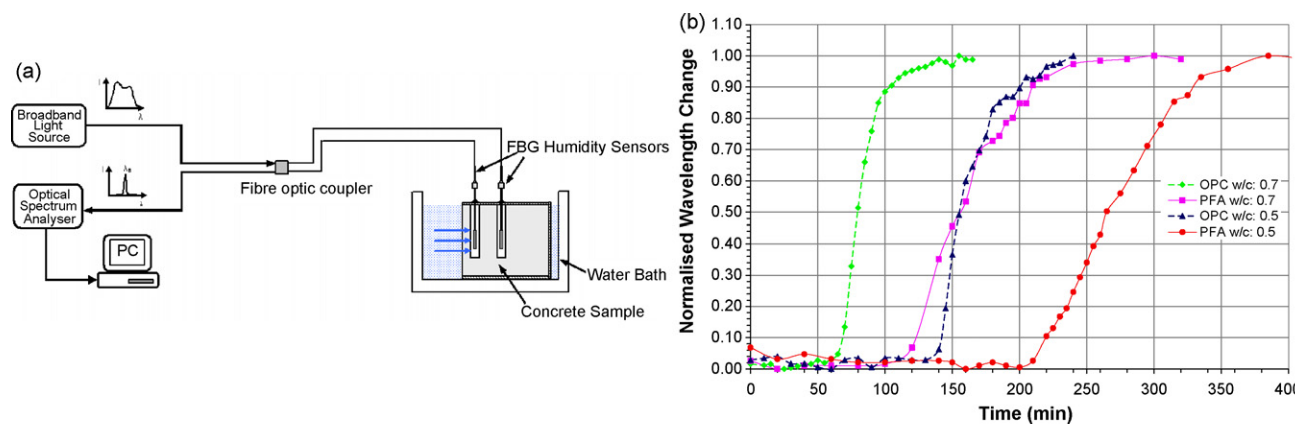

Fig. 12. (a) Experimental set-up used for moisture ingress rate measurement using FBG humidity sensors. (b) Sensor measurements showing moisture ingress characteristics of various concrete specimens using sensor positioned at 25 mm away from cube face [62].

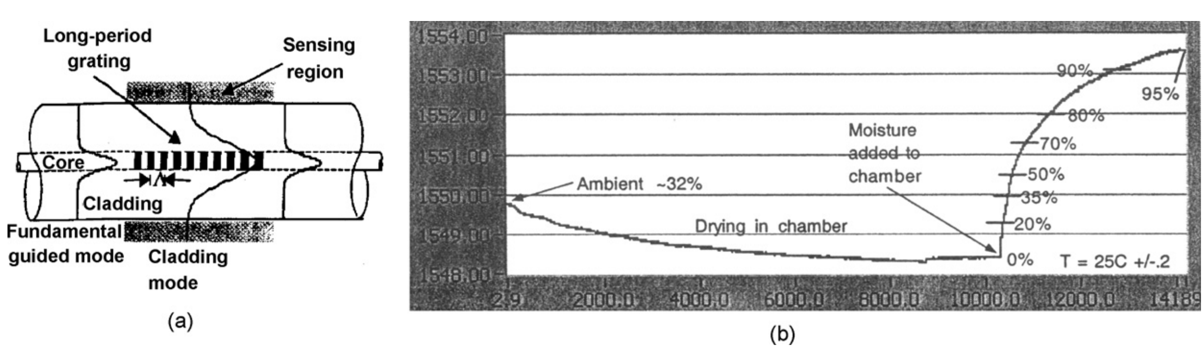

Fig. 13. (a) Schematic of a LPG sensor. (b) Sensing characteristics of a CMC-coated LPG humidity sensor [63].

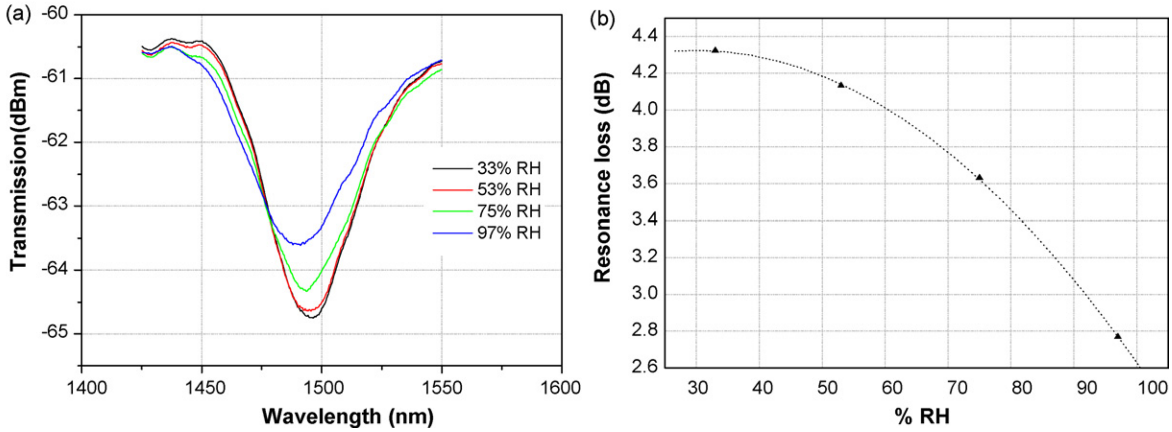

Fig. 14. (a) Spectral characteristics of PVA-coated LPG at 1500 nm. (b) Transmission dip variation at various RH levels [68].

ture sensitive coating. In both sensors, however, the operating humidity range was found to be limited.

Recent studies by Venugopalan et al. [68] have shown the use of polyvinyl alcohol (PVA) film as a sensing material for LPG-based humidity detection. Using a similar approach to the examples discussed earlier, a PVA overlay of ~4 μm was coated onto the optical fibre in which an LPG with a period of 300 μm was inscribed. The sensor was evaluated over a relative humidity range from 33 to 97% using the resonance loss band at 1500 nm where the change in transmission dip was monitored and calibrated against humidity change. The results are shown in Fig. 14: the change of the spectral characteristics of the sensor with %RH leads to the calibration graph of resonance loss vs. %RH.

3.4. Interferometric sensors

Optical interferometry is a powerful and versatile tool that has been applied in optical fibre sensing to yield high performance FO sensors. In addition to the advantages attributed to the use of fibre optics, FO interferometric sensors generally provide geometric versatility in terms of sensor design and a high level of measurement sensitivity [69]. The sensing mechanism relies on the perturbation of the phase properties of the light signal travelling in the optical fibre introduced by an external environment. The detection of the phase change is realised by mixing the signal of interest with a reference signal, consequently converting the phase difference between the two signals into an optical intensity change. Various interferometer configurations such as the Mach–Zehnder, Michelson, Sagnac and Fabry–Perot can be used to perform the detection. The operation of FO-based sensors utilising these configurations and its applications have been discussed in some detail by several authors including Udd [70,71], Dandridge [69] and Mitchell [72].

One of the earliest FO interferometric humidity sensors was demonstrated by Mitschke [73]. The proposed sensor design consists of a thin film Fabry–Perot interferometer formed at the tip of the optical fibre as shown in Fig. 12. The interference between the optical signals reflected by the mirror at both ends of the cavity gives rise to a spectral response which gives a maximum intensity output (resonances) at specific wavelengths. These multiple resonances are separated by the free spectral range (λ_{FSR}) which is given by

$$\lambda_{FSR} = \frac{c}{2nd} \tag{4}$$

where c is the speed of light, n is the refractive index of the cavity and d is the cavity length.

As shown in Fig. 15, the Fabry–Perot cavity in the proposed design was created by a layer of TiO_2 sandwiched in between two partially reflecting mirrors, with the thickness of the cavity optimised to match the operation at the wavelength of the input diode laser source. As the refractive index of the cavity material has a dependence on humidity, the resonance was therefore shifted in response to humidity change and can be conveniently detected by performing intensity measurement at a fixed wavelength. The sensor demonstrated suffers from cross-sensitivity to temperature which can be corrected using a suitable compensation scheme. Nevertheless, it showed a good response between 0 and 80%RH and a response time of less than a minute.

Similar Fabry–Perot interferometric humidity sensors with a submicron cavity length were reported by Arregui et al. [74,75] and Yu et al. [76]. A typical multilayer thin film interferometric cavity was formed by stacking bilayers of alternating cationic and anionic polymers at the fibre tip. This was achieved by using the ISAM technique which gives good control over the cavity length as well as the material composition of each coating layer. Sensors with a cavity length (or the number of bilayers) optimised at a specific operating wavelength were shown to be able to operate over a wide humidity range. A very fast response

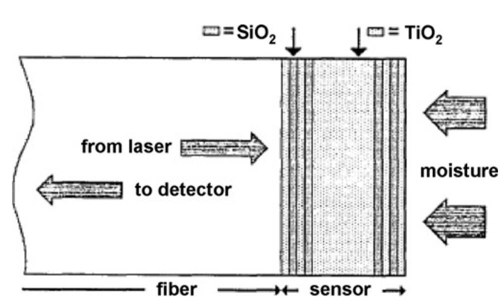

Fig. 15. FO Fabry–Perot interferometric humidity sensor [73].

time, in the order of less than a few seconds, was reported and the sensor has been recommended as a possible diagnostic tool to monitor human breathing [77].

Kronenberg et al. [78] have explored the use of a low coherence interferomertric system arranged in tandem configuration for humidity detection. The system consists of two Michelson interferometers—(1) an interrogation system to perform the measurements and (2) a bi-fibre-optic sensor based on Michelson configuration formed by a reference uncoated fibre and a hydrogel-coated fibre. In a similar way to the FBG sensing mechanism described in the preceding section, the fibre sensor relies on humidity-induced swelling to stretch the fibres which in turn creates an interferometric sensor with an unbalanced path length.

4. Summary

The summary in Table 1 has presented an overview of the major work referenced in this review (using such data as are available from the publications) with in addition to the available information on the method and published data on the sensor to allow such cross-comparison and evaluation as is possible.

In this review, a variety of sensing techniques available to perform the measurement of humidity have been discussed. Fundamental and secondary methods involving mechanical, conventional optical, temperature and electronic-based techniques were discussed briefly, covering the key operating principles, as well as the advantages and disadvantages of each method. None of these methods, however, can offer an ‘ideal’ solution to address the various and specific requirements arising from the diversity of potential applications seen in industry today. Fibre-optic sensing technology provides an alternative approach to moisture/humidity sensing as it offers several advantages over the use of conventional sensing methods. An extensive survey on various optical fibre sensing techniques employed for humidity detection of the work has been given in the later part of the review. The survey covered the various extrinsic and intrinsic methods reported over the years, many of which report on the sensing characteristics obtained in a controlled laboratory environment. The field is one that is lively and topical, with applications, as has been discussed, in the structural monitoring and biomedical engineering fields in particular, reflecting the considerable scope for on-going work.

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Biographies

T.L. Yeo received his BEng degree from the Department of Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology (UMIST), UK, in 2000. Following the successful application for the Overseas Research Studentship (ORS), he obtained his MPhil degree in fluorescence based fibre optic probe for hydrocarbon fuel monitoring with the industrial process tomography group at UMIST in 2002. He completed his PhD in the field of fibre optic sensors at City University, London, in 2007.

T. Sun was awarded the degrees of Bachelor of Engineering, Master of Engineering and Doctor of Engineering for work in mechanical engineering from the Department of Precision Instrumentation of Harbin Institute of Technology, Harbin, China, in 1990, 1993 and 1996, respectively. She came to City University, London, as an Academic Visitor and latterly a research fellow to work in the field of fibre optic temperature measurement using luminescent techniques. She was awarded the degree of Doctor of Philosophy at City University in applied physics in 1999. She was an assistant professor at Nanyang Technological University in Singapore from 2000 to 2001 and currently a senior lecturer at City University, London, since she re-joined in April 2001. Dr. Sun is a Member of the Institute of Physics and the Institution of Electrical Engineers and a Chartered Physicist and a Chartered Engineer in the United Kingdom. Her research interest is in optical fibre sensors, optical communications and laser engineering. She has authored or co-authored some 90 scientific and technical papers in the field.

K.T.V. Grattan received his Bachelors degree in physics (with first class honours) from The Queen's University, Belfast, in 1974 and completed his PhD studies in 1978, graduating from the same University. In the same year he became a post-doctoral research assistant at Imperial College, London. His research during that period was on laser systems for photophysical systems investigations, and he and his colleagues constructed some of the first of the then new category of excimer lasers (XeF, KrF) in Europe in 1976. His work in the field continued with research using ultraviolet and vacuum ultraviolet lasers for photolytic laser fusion driver systems and studies on the photophysics of atomic and molecular systems. He joined City University, London in 1983 after 5 years at Imperial College, undertaking research in novel optical instrumentation, especially in fibre optic sensor development for physical and chemical sensing. The work has led into several fields including luminescence based thermometry, Bragg grating-based strain sensor systems, white light interferometry, optical system modeling and design and optical sensors for water quality monitoring. The work has been extensively published in the major journals and at international conferences in the field, where regularly he has been an invited speaker, and over 600 papers have been authored to date. He was awarded the degree of Doctor of Science by City University in 1992. professor Grattan is currently Deputy Dean of Engineering at City University, London, having from 1991 to 2001 been Head of the then Electrical, Electronic and Information Engineering Department. He has been Chairman of the Applied Optics Division of the UK Institute of Physics and was president of the Institute of Measurement and Control in 2000.