

OPTICAL FIBRE GRATING-BASED SENSORS FOR HUMIDITY MEASUREMENT: DESIGN AND APPLICATIONS

L Alwis¹, T Sun², K T V Grattan²

¹ School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, United Kingdom, l.alwis@napier.ac.uk

² City Graduate School and School of Mathematics Computer Science and Engineering, City University London, London, United Kingdom, k.t.v.grattan@city.ac.uk

Abstract – This paper presents the results of work done on the development, evaluation and testing of several different designs of fibre optic (FO) grating-based sensors for humidity measurement, evaluated in the laboratory and beyond. The basic operation and design of the sensors is reported, as is a comparison of the use of both optical Fibre Bragg Grating (FBG) and Long Period Grating (LPG) systems as the basis of an effective sensor device. Applications of sensors of this type are discussed as is the tailoring of the devices to specific requirements for industrial measurements.

Keywords: humidity measurement, fibre optic sensors, fibre gratings, calibration, temperature compensation

1. INTRODUCTION AND HUMIDITY SENSING

The determination of humidity (or alternatively moisture content) constitutes one of the most commonly needed measurements of a physical quantity. Measurements of this type are significant for a diverse range of applications from air conditioning for human comfort and combating bacterial growth to process control and maintaining product quality [1]. The requirements for humidity monitoring and thus of an effective sensor design to measure this parameter can vary significantly, relating to the applications to which they are applied and as a result a variety of different techniques have been employed to allow such humidity measurements.

Techniques used historically are diverse, ranging from the expansion and contraction of materials such as human hair to the most sophisticated and modern techniques, such as using a miniaturized electronic chip. A recent review of the field [2] shows the variety of methods that has been explored over many years to obtain meaningful humidity measurements. These methods operate typically either by utilizing the fundamental properties of water vapour itself or using various transduction methods which can give humidity-related measurements.

2. OPTICAL FIBRE-BASED HUMIDITY SENSORS

Optical fibre technology has transformed the situation: thus considerable research effort on fibre-optic (FO)-based techniques for humidity sensing has been seen [2]. Operating like many of their electronic or mechanical

counterparts, FO humidity sensors are secondary devices but features include small size, immunity to electromagnetic interference, potential for multiplexing of several sensors on a single network and remote sensing capabilities – which many of the counterpart electronic sensors lack. However, in some cases, limitations of the operating range and the accuracy of the FO-based humidity sensors are features where researchers are striving for improvement. Nevertheless, these sensors have found useful applications in various areas where electronic sensors were inappropriate, thereby showing the real potential of FO-based sensors.

The in-fibre grating based design of FO-based sensor represents a class of intrinsic device that has gained widespread popularity in recent years. It has found use in many applications in industry due to its inherent sensitivity to temperature, strain and refractive index change [3–5]. 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) [3] and long period grating (LPG) [4].

2. GRATING-BASED SENSORS FOR HUMIDITY MEASUREMENT

The concept of in-fibre grating devices for humidity sensing is still fairly new. In sensors of this type, the fibre grating acts as the basis of the device and the humidity sensing concept used in this sensor exploits the strain effect induced in an in-fibre grating through the swelling of a thin layer of applied polymer coating. The swelling of the polymer coating, arising from the absorption of moisture, changes the wavelength associated with the grating and this can be calibrated to give a direct indication of the humidity level. Thus in the case of an in-fibre Bragg grating, the ratio of the wavelength shift to the Bragg wavelength for a polymer-coated and stretched FBG can be represented as follows.

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\alpha_{RH}\Delta RH + [(1 - P_e)\alpha_T + \zeta]\Delta T$$

where P_e is the photo-elastic constant of the fibre, ζ is the fibre thermo-optic coefficient, α_{RH} and α_T are the moisture and thermal expansion coefficients of the coated FBG respectively. A detailed discussions of the fabrication of the

FBGs used for humidity measurement have been reported by some of the authors elsewhere [6,7].

One such typical sensor design is shown below. Achieving temperature compensation is important as such grating-based devices are temperature sensitive and thus the simplest approach is for a second grating element, very close to the first, to be used to create the complete sensor system. To do so, a bare FBG is also included in the sensor design. Fig 1 shows respectively the schematic diagram and a picture of the humidity sensor probe design, in which both grating elements can be seen. Here a dual grating arrangement is illustrated, with one sensor able to measure temperature changes alone and the second the combined effects of humidity and temperature – from this each individual measurement (temperature and strain) can be obtained.

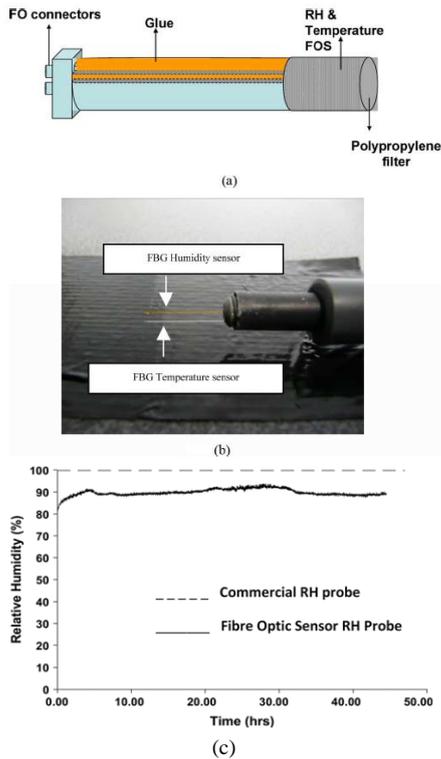


Fig. 1. (a) Schematic diagram of the sensor design, (b) Picture of the packaged sensor probe showing a coated grating as a relative humidity sensor and a bare grating as a temperature sensor and (c) Changes in RH at 30 mm depth of stone with drying of the stone block – dotted line shows the commercial probe response while the solid line indicates the performance of the fibre grating sensor [8].

FBGs used in this work were inscribed in photosensitive optical fibres using a phase mask fabrication technique. In order to produce a stable sensor which could be used over a wide temperature range, the grating was first annealed for more than 7 h at 200 °C prior to the polymer coating being applied. Subsequently a thin layer of moisture sensitive Polyimide (PI) with a coating thickness of 24 µm was coated onto the FBG using an automated dip coating machine.

A further example of utilizing the aforementioned PI-coated FBG sensor design has been discussed in the work by some of the authors [8] who conducted an investigation into the decay mechanisms and associated processes occurring in masonry structures in order to analyse the role of varying moisture and temperature in decay and degradation. Sensors were employed to monitor an actual building stone in a

specially built limestone wall. One advantage of this approach is the compact and minimally invasive nature of the sensor, thus requiring much less damage to the wall for its insertion, with only the drilling of one small pilot hole required for the mounting of the sensor – a key consideration with historic structures. As can be seen from Fig. 1(b) another similar, but uncoated FBG was also included in the sensor-head for temperature compensation. One noticeable advantage is the faster response of the FBG sensor compared to the commercial capacitance sensor. The indication from the commercial (a conventional and non-fibre optic design) RH probe was saturated at 100% RH, whereas the measurement by the FBG sensor varied for RH between 90–93%, showing that the commercial RH sensor element had saturated and hence the RH measurements were unreliable during the drying of the limestone structure. This highlights a major drawback with the conventional electrical sensors used which failed to dry out properly, due to high mass when wet initially. By contrast, the optical fibre RH sensor, due to its small size and low mass, has been able to follow the actual change of the RH characteristics of the wall.

By contrast, the sensitivities of LPGs to environmental parameters such as temperature and strain are much higher than those of FBGs [4] although FBGs are popularly used owing to their ease of production, handling and easier multiplexing capability due to the simpler structure of their optical features. In addition, the external RI sensitivity of LPGs has been utilized to create species-specific sensors by coating the sensor with a material that will interact well with the target analyte. The RI and the coating thickness of the sensing material needs to be given careful consideration in the sensor design using LPGs as the sensor response, i.e. wavelength or intensity variation, will depend strongly on these parameters. The RH sensitivity of LPGs can be described by the equation below, where $\lambda_{res,0i}$ is the resonance wavelength of the i^{th} mode, $t_{overlay}$ is the thickness of the overlay, $RI_{overlay}$ and RI_{sur} are the overlay and surrounding refractive indices.

$$\Delta\lambda_{res,0i} = \frac{\partial\lambda_{res,0i}}{\partial RI_{overlay}} \Delta RI_{overlay} + \frac{\partial\lambda_{res,0i}}{\partial t_{overlay}} \Delta t_{overlay} + \frac{\partial\lambda_{res,0i}}{\partial RI_{sur}} \Delta RI_{sur}$$

Recently there has been a boom in the use of LPG-based sensors in the fields of biomedical, SHM and chemical sensing [9]. The most common method for LPG-based sensing of a parameter such as RH is via the coating of the sensor with a hydrophilic material, such as a polymer, that will alter its physical or optical parameters in response to the external stimulus, i.e. the variation of the RI or causing an applied strain on the LPG as a result of the coating-layer expansion, leading to a variation in the target resonance band of the LPG.

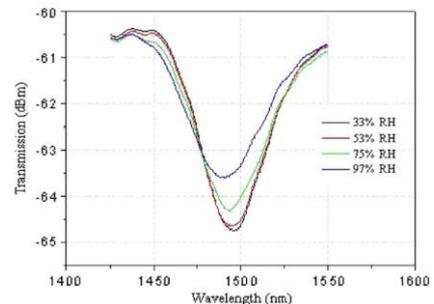


Fig. 2. The spectral features of the PVA coated LPG when exposed to various known RH levels [10].

One such example is the work by some of the authors [10] in which a LPG was coated with Poly Vinyl Alcohol (PVA), which is a moisture sensitive polymer, in order to explore its feasibility as a RH sensor. A non-linear performance was observed to moisture variations, especially above 50 %RH as can be seen from Fig. 2.

3. DESIGN IMPROVEMENT IN PRACTICAL GRATING-BASED FO HUMIDITY SENSORS

The aforementioned inherent RH sensor designs have been further characterised and revised for practical use. For example, the LPG has to be interrogated in transmission mode which poses an issue for its usage in practical application that requires a probe configuration. To address this issue, a Michelson interferometer-type sensor configuration has been proposed by Lam et al [11] using a LPG grating pair formed by coating a mirror at the distal end of the LPG, as can be seen from Fig. 3, in order to create a refractometer. This sensor configuration is more convenient to use and is able to overcome the limitations of the single LPG sensor due to the shifts in the attenuation bands being more easily detectable.

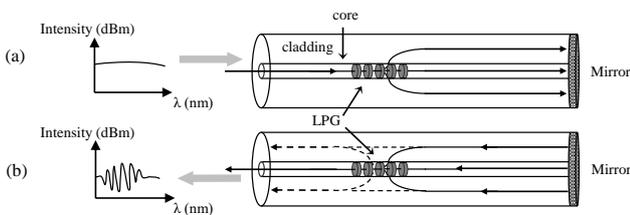


Fig. 3. The SILPG Michelson Interferometric sensor; Light propagation in the SILPG (a) forward propagation path (b) propagation path of the reflection [11].

The same configuration was applied to develop a grating based RH sensing reflective probe by the authors [12], who coated the LPGs (in such a configuration) with PI and PVA respectively. Both the PVA and PI swell with the increase of RH in its surroundings. The RI of PVA and PI is 1.53 and 1.7 respectively. Since the cladding RI is around 1.44, PVA lies closer to the cladding RI than PI and therefore it would experience a greater RI change than PI. This latter material has been coated to create a moisture-related strain induced RH sensor and PVA is used to induce a RH related external RI variation on the LPG. The experimental setup used can be found in Fig. 4.

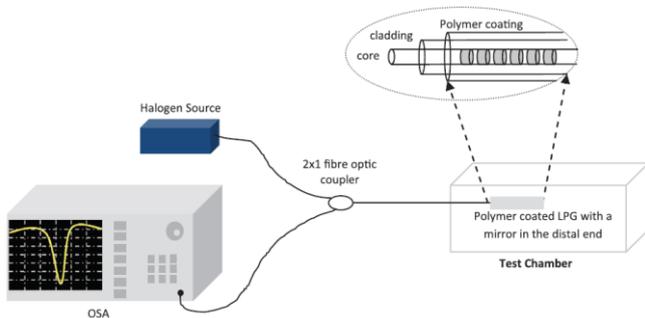


Fig. 4. Experimental setup for the polymer coated LPG sensor probes.

A comparison between the performances characteristics of these two different polymer-coated SILPGs is shown in Fig. 5. It can be seen that PVA offers higher sensitivity of the two polymers used, although its sensing region is limited and the performance is non-linear, these being disadvantages that may be overcome for certain applications. PI on the other hand, offers a linear performance that is easy to process, but with overall less sensitivity in most of the target range compared to that achieved with PVA.

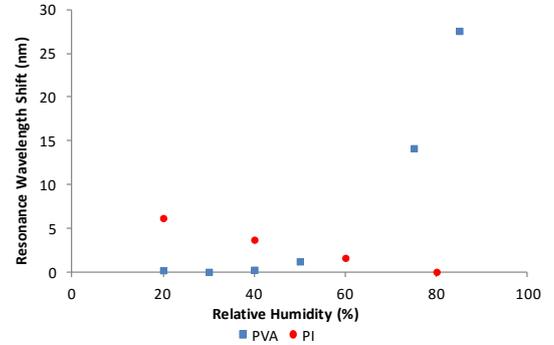


Fig. 5. Comparison between the performance of PI and PVA coated LPG based RH sensor probes.

Grating based RH sensors have been further developed in a hybrid configuration which combines a FBG and an LPG in series [13]. Both FBGs and LPGs are sensitive to their respective grating periods, a characteristic which is utilized here when the grating period is modified under the influence of both temperature and strain, forming the basis of sensors using the RI modulation.

In the previous work by the authors described before, typically the sensor performance was evaluated while maintaining a constant temperature to minimize the need for compensation. The work presented here is aimed at enhancing the previous sensor design to suit it better for field work by using the high sensitivity of the polymer coated LPG for RH monitoring and incorporating a FBG in series (and operating at a closely related wavelength) to allow effective temperature compensation to be achieved in a series configuration.

In most compensated RH sensors, FBGs alone are used in series, one coated with a moisture sensitive polymer while the other is kept bare for temperature measurement as described before. Due to the higher strain sensitivity of LPG compared to FBG, the hybrid sensor is based on the optimum characteristic of each grating by having a higher sensitive RH sensor in line with a FBG for temperature compensation, containing the hybrid sensor within a single series fibre design.

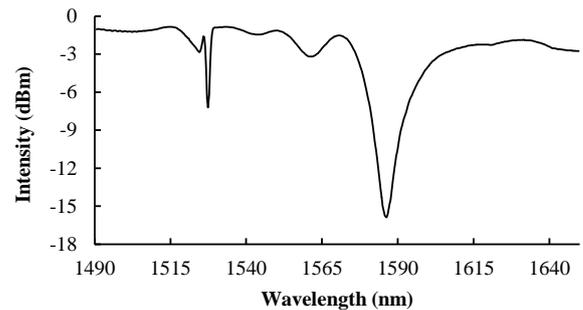


Fig. 6. The transmission spectra of the FBG/LPG hybrid sensor.

The response of the hybrid sensor in terms of spectral change to variations in the temperature can be seen from Fig. 7, showing the sensor response from 20 – 80 °C while the RH was maintained at 60 %RH. It should be noted that upon annealing and PI coating, the initial spectral position and the degree of attenuation of the LPG spectral feature has shifted, as can be seen from Fig. 6, as would be expected. The results of the calibration of the PI coated LPG sensor to both RH and thus the performance of the sensor device are shown in Fig. 8.

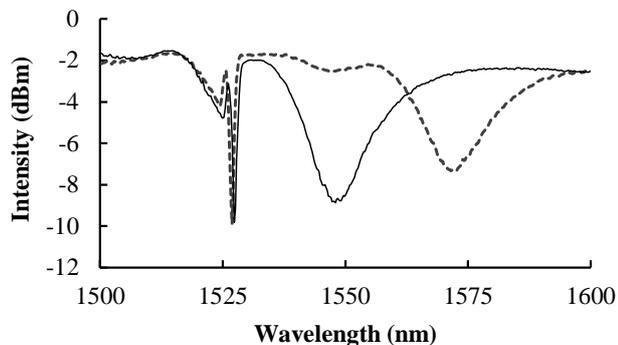


Fig. 7. Hybrid sensor response to temperature variations (dotted line – 20 °C, line – 80 °C) at 60 %RH.

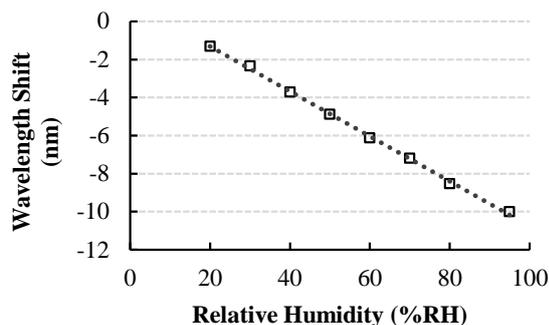


Fig. 8. Hybrid coated LPG sensor performance to RH.

The hybrid device performance was compared to that of a PI-coated FBG (only) sensor which, from prior work by some of the authors, provides sensitivities in the range of 10 pm/%RH [6][7]. The LPG-based sensor has approximately 10 times greater sensitivity to RH. However, as can be seen from Fig. 7, the sensitivity of the LPG to temperature is also prominent and therefore it is vital to ensure that this temperature effect be removed for actual calibration for RH under varying temperature situations. The temperature data obtained using the FBG could be utilized to decouple the wavelength shift of the LPG due to temperature, experiencing closely the same conditions since both the gratings are written together in the same fibre, with the physical distance between the gratings less than 15 mm. By utilizing this method, a successful hybrid sensor can be achieved with higher RH sensitivity (compared to PI coated FBG sensors) and temperature compensation. The sensitivity of this device was 0.12 nm/%RH and 7.9 pm/°C. The strength of the approach that can be seen from the results is building on the different resolutions of the two gratings,

utilizing the greater wavelength shift of the LPG for the RH change and the sharp spectral feature of the FBG for accurate temperature measurement, and thus compensation, with low hysteresis being observed in tests carried out. Work is ongoing to optimize the performance of the hybrid device.

4. CONCLUSIONS

A number of designs of optical fibre grating-based sensors for humidity measurement has been developed and tailored to specific applications. The advantages of the use of such methods have been indicated and results reported.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge support from various sources including the Engineering & Physical Sciences Research Council, the Royal Academy of Engineering and the George Daniels Educational Trust.

REFERENCES

- [1] L. Alwis, T. Sun, K.T.V. Grattan, Optical fibre-based sensor technology for humidity and moisture measurement: Review of recent progress, *Measurement*, 46, pp 4052-4074, 2013.
- [2] T.L. Yeo, T. Sun, K.T.V. Grattan, "Fibre-optic sensor technologies for humidity and moisture measurement", *Sensors and Actuators A* 144, pp 280-295, 2008.
- [3] R. Kashyap, "Fiber Bragg Gratings", Academic Press, 1999.
- [4] Bhatia V, "Properties and sensing applications of long period gratings", PhD Thesis, *Virginia Polytechnic Institute and State University*, Virginia, 1996.
- [5] A. Othonos, K. Kali, *Fiber Bragg Gratings Fundamentals and Applications in Telecommunications and Sensing*, Artech House, 1999.
- [6] T.L. Yeo, T. Sun, K.T.V. Grattan, D. Parry, R. Lade, B.D. Powell, "Polymer-Coated Fiber Bragg Grating for Relative Humidity Sensing", *IEEE Sensors* 5, pp 1082-1089, 2005.
- [7] T.L. Yeo, T. Sun, K.T.V. Grattan, "Fibre-optic sensor technologies for humidity and moisture measurement", *Sensors and Actuators A* 144, pp 280-295, 2008.
- [8] T. Sun, K.T.V. Grattan, S. Srinivasan, P.A.M. Basheer, B.J. Smith, H.A. Viles, "Building Stone Condition Monitoring Using Specially Designed Compensated Optical Fiber Humidity Sensors", *IEEE Sensors* 12 (2012) 1011-1017.
- [9] Pissadakis S, Anglos D, Klini A, Konstantaki M, "Long period optical fiber grating outcladding overlaid sensors: a versatile photonic platform for health and bio applications", *IEEE* (2011).
- [10] T. Venugopalan, T. Sun, K.T.V. Grattan, "Long period grating-based humidity sensor for potential structural health monitoring", *Sensors and Actuators A* 148 (2008) 57-62.
- [11] C. Lam, R. Mandamparambil, T. Sun, K.T.V. Grattan, S. V. Nanukuttan, S. E. Taylor and P. A. Basheer, "Optical fiber refractive index sensor for chloride ion monitoring," *IEEE Sensors* 9, pp 525-532, 2009.
- [12] L. Alwis, T. Sun and K.T.V. Grattan, Design and performance evaluation of polyvinyl alcohol/polyimide coated optical fibre grating-based humidity sensors, *Review of Scientific Instruments*, 84, 025002, 2013.
- [13] L. Alwis, T. Sun and K.T.V. Grattan, Characterization of a polyimide-coated humidity sensor in a hybrid fibre grating configuration, OFS24 Brazil, 2015 (accepted)