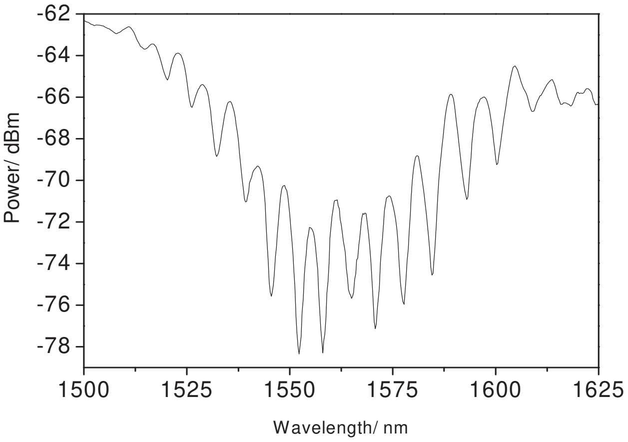

Figure 2(b) - Interference pattern generated from LPG-based sensor (Michelson Interferometer)

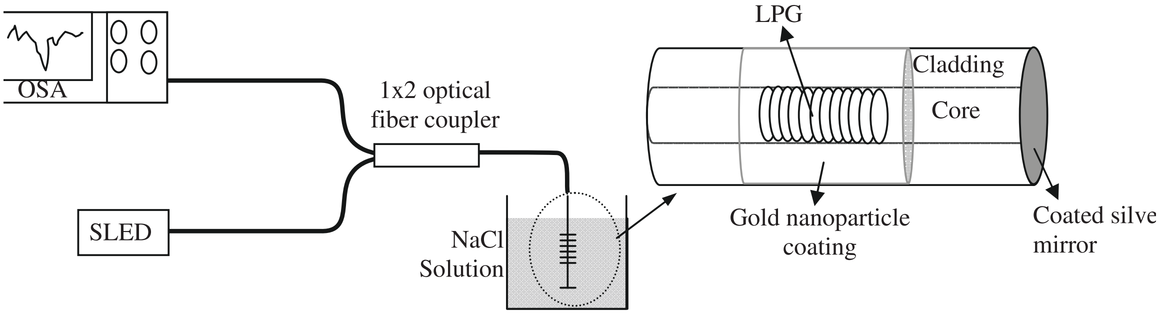

Figure 3 - The experimental setup used for calibration of the sensor using sodium chloride solutions

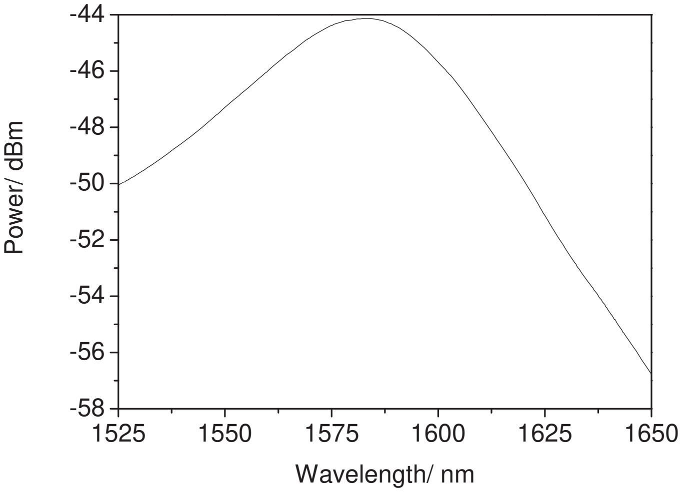

Figure 4 - Optical spectrum of a SLED centered at 1580nm

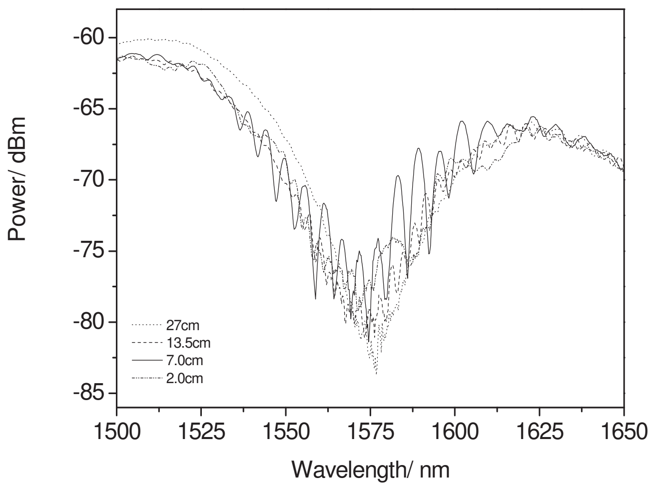

Figure 5 - Evolution of fringe patterns with appropriate changes in cavity length

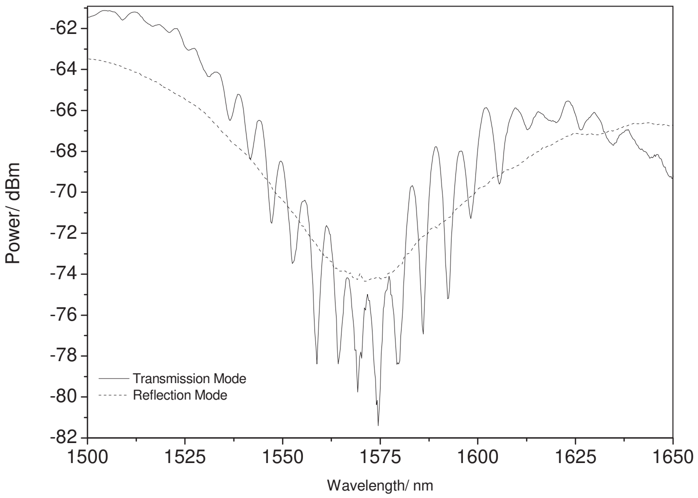

Figure 6 - Spectra of transmission and reflection mode of LPG (400 µm)

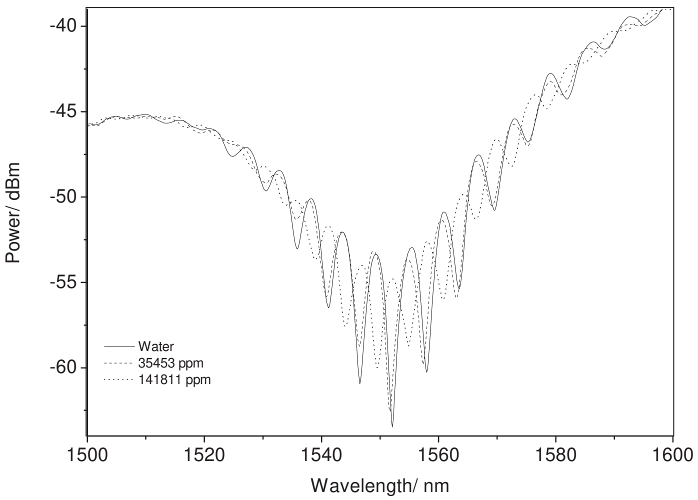

Figure 7 - Spectrum of non-coated SILPG submerged in sodium chloride solutions

Figure 8 - Spectrum of 16 nm Gold Coated SILPG submerged in sodium chloride solutions

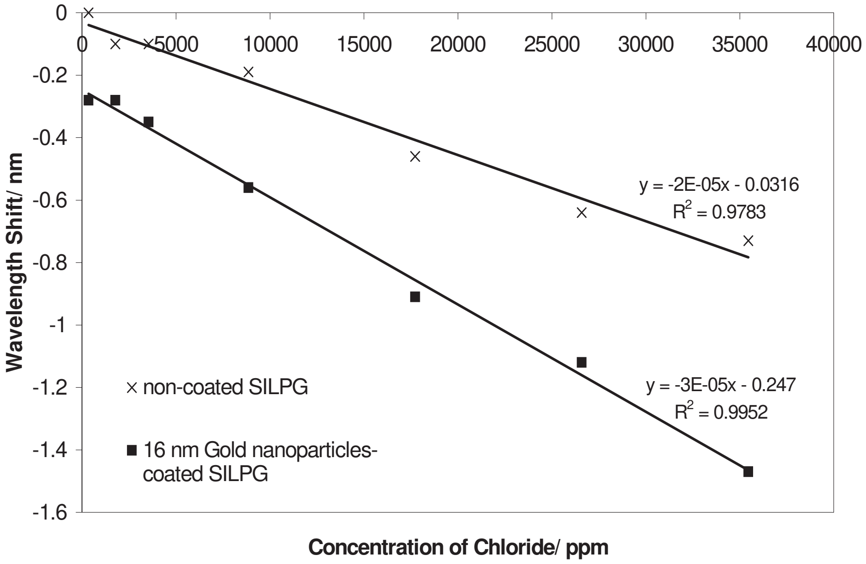

Figure 9 - Graph of wavelength shifts/nm against concentration of chloride/ ppm for non-coated and 16 nm gold nanoparticles coated SILPGs.

SP-252—6

Structural Health Monitoring Potential using a Long Period Grating-Based Humidity Sensor

by T. Venugopalan, M. Rajesh, T. Sun, and K.T.V. Grattan

Synopsis: In this research, a series of innovative optically-based sensors, which were designed, fabricated and characterized were created for potential evaluation for applications in determining moisture ingress in a range of concrete materials subjected to various environmental conditions. The approach taken to the creation of these novel humidity sensors is using long period grating (LPG) technology in an optical fibre. Several sensor configurations are fabricated by coating LPGs and then characterizing and cross-comparing and evaluating the resulting sensor performance. The thin layer of polyvinyl alcohol (PVA), whose refractive index varies as a function of humidity level when coated onto a LPG written into an optical fibre, provides a means to change the optical propagation in the fibre and thus to induce the a wavelength shift in the attenuation bands of its transmission spectrum, which then is calibrated against the measurand, humidity. When compared to the more familiar optical fibre-based humidity sensors, using Fibre Bragg gratings (FBGs), the LPG-based devices show a much higher measurement sensitivity, with more relaxed requirements for coating thickness and uniformity.

Keywords: humidity; long period grating; structural health monitoring

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Dr Tong Sun, Reader, City University has had considerable experience in applied research in optical fibre (including fibre Bragg grating) sensing, laser engineering and instrumentation. Since joining the faculty at City University London in 2001 she has been a Principal Investigator and co-Investigator of 28 research projects funded by EPSRC, the Royal Society, British Council, EU, Industry and TSB with four joint projects with Queen's including a recently funded Challenging Engineering Project (EP/D030269/01). This project on corrosion monitoring for marine structures recognises her as one of six emerging young research leaders in the UK. She has (co)authored some 130 technical papers and is an inventor of 4 joint patents.

Prof K T V Grattan, has been actively involved in optical fibre based chemical sensing, including the development & validation of fibre optic sensor-based monitoring systems for chemical variations in concrete (GR/R34318/01) and for limestone decay (EP/D008689/01) in collaboration with the Queen's University of Belfast and the University of Oxford. They have also joined consortia undertaking several EU-funded projects including a major study on the development of an optical fibre sensor network for automotive emission monitoring, working closely with FIAT, and an INTAS/NATO project on nuclear plant security monitoring. Professor Grattan has also been actively involved in an EU project in 2000 developing a distributed FBG-based strain sensor system to monitor a new bridge in Norway. He is the author of over 500 technical papers and 6 books on optical fibre sensors.

1 Introduction

Structural Monitoring and Fibre Optic Devices

Structural monitoring plays important role in the observation and monitoring of deformations and environmentally induced problems in buildings, bridges, tunnels and other civil infrastructures [1]. These problems can result in minor damage such as the formation of mould, mildew and other allergens thriving in the environment but it becomes a critical matter when the induced effects in concrete cause such detrimental changes as to render the structure unsafe e.g. due to internal corrosion of a steel construction. Such deterioration can be due either to climatic variables such as humidity and temperature variations, or internal factors within the concrete itself. There are several types of deterioration – which may be mechanical, physical or chemical. Mechanical damage is typically due to impact, erosion, abrasion or cavitation. The chemical influences can be internal, like alkali-silica or alkali-carbonate reactions, or external attack which mainly occurs through the action of aggressive ions such as chlorides, sulphates, carbon dioxide and other gases of natural or industrial origin. The remaining group of physical deterioration effects can arise due to changes in thermal expansion of aggregate as a result of the 'freeze-thaw' process and the action of de-icing salts. These influences can arise together and all of them, with the exception of some of the mechanical effects, involve transport of fluids through the concrete and the movement of moisture always plays a role in process and the outcome affects quality of concrete.

Fibre optics are known for their use in high capacity links in telecommunications properties, but also have a major role in new sensor technology and the discovery of a glass cylinder that guides light using total internal reflection has opened up new potential in the measurement field as well [2]. Fibre optic sensors have been discussed extensively in the literature over several decades and by some of the authors in recent publications [3][4]. This research has a focus on fibre optic-based humidity sensors which have shown real promise due to the attractive features they possess such as small size, geometric versatility, multiplexing capability and resistance to corrosive and hazardous environments [4]. The influence of humidity on a polymer-coated Fibre Bragg grating (FBG) was first reported by Giaccarri et al [5] and the technique described for humidity detection has been further explored by several research groups [4][6].

Fibre Long Period Gratings

Of the various optical phenomena that may be used for the creation of such sensors, the long period grating (LPG) has demonstrated a clear and distinctive sensitivity to the refractive index value of the surrounding material of the grating [7-11] and thus has been explored as a refractive index sensor for various applications. The sensing mechanism underpinning the device is the use of the relationship between the LPG resonance wavelength, λ, and the grating periodicity, Λ, which is given by the following [7]

$$\lambda = (n_{co}^{eff} - n_{cl,m}^{eff})\Lambda \qquad (m = 1, 2, \ldots\ldots) \qquad (1)$$

where n_{co}^{eff} and $n_{cl,m}^{eff}$ are the effective indices of the fundamental core mode and of the mth cladding mode respectively and the effective refractive index of the cladding mode, however, can be modulated by the refractive index variation of the surrounding material.

This work focused on research into the use of LPGs coated with a thin layer of polyvinyl alcohol (PVA), carried out to explore the measurement of humidity through the refractive index change of the coating material caused by the swelling effect on the coating and the associated strain on the LPG in the fibre when it is exposed to different humidity conditions. The work builds upon prior work by some of the authors in Fibre Bragg Grating technology and extends that more familiar concept to create more sensitive devices with wide potential in structural monitoring,

2. Theoretical background

Coated LPG optical characteristics

Extensive research has been carried out to investigate the dependence of resonance wavelength as a function of the refractive index change of the surrounding media [7]-[11] and a typical calibration curve, shown in Figure 1, shows the resonance wavelength change as a function of the refractive index (RI) of the surrounding media (or coating) with the cladding refractive index of the LPG being ~1.45. This indicates that when the coating refractive index is lower than that of the fibre cladding, the resonance wavelength of the LPG changes with the variation of coating refractive index. However, when the coating refractive index is higher than that of the fibre cladding, the resonance conditions become more complex, as shown in the figure.

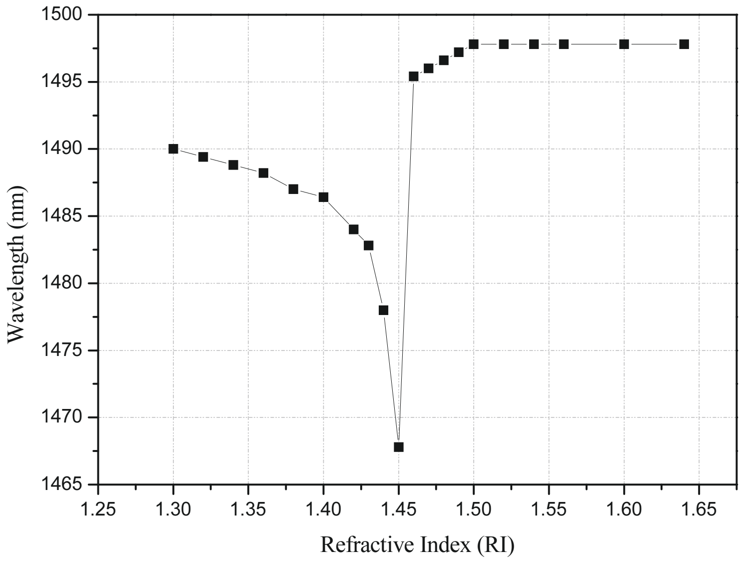

Figure 1 – Response of the LPG based sensor to refractive index variation showing maximum wavelength shift near a refractive index value of 1.46.

The effects on a LPG of having a thin overlay coating with a refractive index value higher than that of the cladding on the LPG spectrum [12]-[14] have been investigated. In the case of an LPG coated with a thin overlay material that has higher refractive index value than that of the cladding, one of the cladding modes is guided by the overlay if the overlay is sufficiently thick. This causes a change of the effective indices of the rest of the modes [12], leading to a shift in wavelength of all the attenuation bands [15]. I. Del Villar et al [13] have suggested that by coating an LPG with a material that has a refractive index value closer to that of the cladding, a large wavelength shift of the resonance band, as a function of the relative variation of the overlay refractive index, can be obtained.

LPG Coating Material Choice

The selection of coating material plays a critical role in the performance of the LPG-based moisture sensor as different materials possess different moisture swelling properties. In the process of material selection for the development of an optimized LPG-based relative humidity sensor, several important considerations have to be taken into account, which include the coating swelling properties following exposure to moisture, the refractive index value of the material, the degree of adhesion of the material to the fiber and the reproducibility of the effect: these together create an evaluation of the overall suitability to the coating technique.

In this work, polymer polyvinyl alcohol (PVA) was chosen for humidity sensor particularly due to its affinity to water and ease of coating onto optical fibre. As such, it has been considered by various researchers as a potential material for humidity detection and the use of PVA film in various electronic and optical based detection schemes has been reported for many years [15-20].

The polyvinyl alcohol (PVA) used in this work was supplied by Kurary Specislities Europe (KSE) in granular form. The PVA granules (dry) were mixed with deionised water to form a 15% (wt/wt) PVA solution, which was placed in an oven at 90°C for ~3hrs to allow the PVA granules to fully dissolve.

3. Sensor development and experimental setup

Sensor fabrication

The LPGs used in this work were fabricated by illuminating a B-Ge co-doped photosensitive fibre through a metal amplitude mask (with a period of 300μm), using light from a 248nm KrF excimer laser with pulse energy of 8mJ and a pulse frequency of 100Hz. In order to monitor the development of the grating, one end of the fibre was connected to a broadband light source and the other to an Optical Spectrum Analyzer (OSA). Thus the transmission spectrum of the grating was monitored as the fibre was exposed to the laser radiation to observe the growth in the resonance loss and the shift towards the higher wavelength of the resonance, with the increased exposure to the laser. A number of trials were carried out and typical exposure times of 1 to 2 minutes were found to be optimum and used to write suitable LPGs. A typical spectrum of a LPG written in a B-Ge fibre using the amplitude mask technique can be seen in Figure 2.

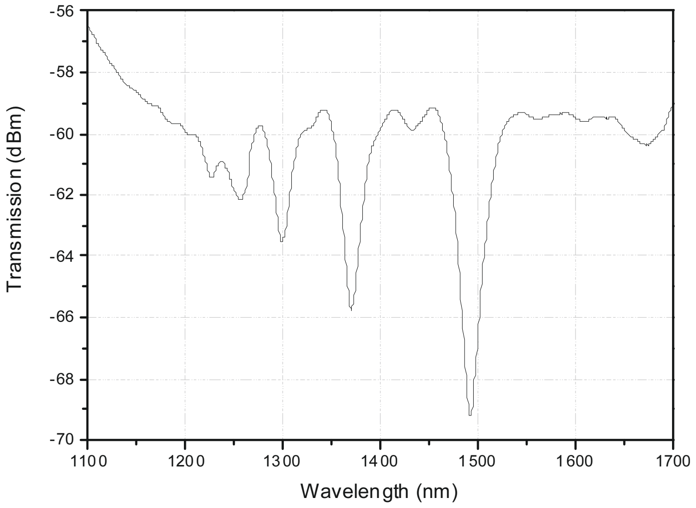

Figure 2 - A typical transmission spectrum of a LPG fabricated

Dip coating is by far the simplest and most effective method that can be implemented for coating or depositing polymers in aqueous form. It is inexpensive to set up and can be used to coat objects of any shape and size. The dip coating process also reduces the amount of coating solution required and the thickness of the coated layer deposited on the sample can be easily manipulated by adjusting the withdrawal speed and the number of dippings to create multiple layers. However, the main disadvantage of this method is its susceptibility to contamination of the coating when a multiple-layer coating process is required. This can be avoided if particular care is taken to minimise this contamination when multiple dip coating is implemented and a new automated process has been implemented to avoid this.

The formation of a fluid film on a fibre is dependent on several factors such as the coating speed, fibre dimension, viscosity and surface tension of the solution [21]. Following a number of trials, the fibre withdrawal speed chosen was 33mm/min and *after each dip* the sample was placed in an oven at 80^{o}C for five minutes and after the final dip it was placed in an oven at 80^{o}C for ~1hr for final drying. A typical picture of the probe with PVA coated on a LPG is shown in Figure 3.

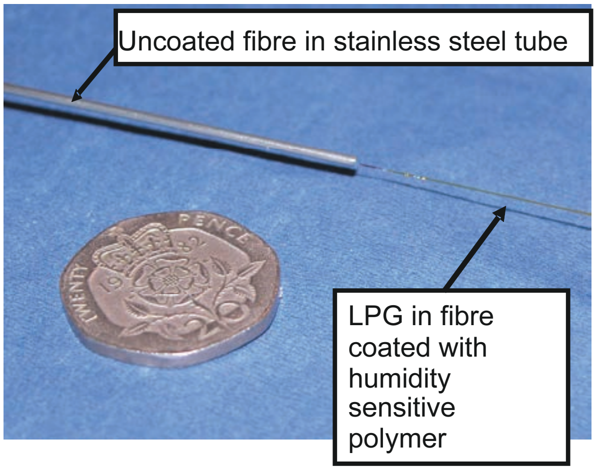

Figure 3 - Picture of a PVA coated LPG humidity sensor

<u>LPG-based humidity sensor system</u>

The LPG-based humidity sensor system is shown in Figure 4, where a broadband white light source was connected to one end of the fibre containing the grating, while the other end was connected to the OSA to allow the transmission spectrum of the sensor to be monitored. The sensor developed was inserted into the humidity chamber (an airtight enclosure) through metal tubes, with both ends of the grating being fixed to metal tubes to avoid any bend/strain being imposed on the grating. Inside the chamber, magnesium chloride, magnesium nitrate, sodium chloride and potassium sulphate salt solutions were used to create relative humidity levels of 33%RH, 53%RH, 75%RH and 97%RH respectively. For comparison, a commercial electronic hygrometer was placed inside the chamber to give an approximate RH reading. A small fan was installed inside the chamber to speed up the saturation process of the salt solution creating the RH equilibrium point. All the experiments were