Sensors and Actuators B 174 (2012) 563–569

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Polyvinyl alcohol coated photonic crystal optical fiber sensor for humidity measurement

Wei Chang Wong[a], Chi Chiu Chan[a,*], Li Han Chen[a], Tao Li[b], Kok Xian Lee[a], Kam Chew Leong[c]

[a] *Division of Bioengineering, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 637457, Singapore*
[b] *Institute of Optoelectronic Technology, China Jiliang University, Hangzhou 310018, China*
[c] *Globalfoundries Singapore Pte Ltd, 60 Woodlands Industrial Park D Street 2 Singapore 738406, Singapore*

ARTICLE INFO

Article history:
Received 27 April 2012
Received in revised form 5 July 2012
Accepted 9 July 2012
Available online 21 July 2012

Keywords:
Humidity
Optical fiber sensor
Interferometer
Photonic crystal fiber
Polyvinyl alcohol
Cladding mode excitation
Optical device
Polymer swelling

ABSTRACT

A polyvinyl alcohol (PVA) coated photonic crystal optical fiber (PCF) sensor has been proposed as a relative humidity (RH) sensor. It was fabricated by collapsing the holes of PCF at both ends to form a Michelson interferometer with cladding mode excitation. PVA was dip coated onto the sensor and the interference shift was measured when the sensor was exposed to varying RH. The sensor with 9% (w/w) coating showed a high sensitivity of 0.60 nm/%RH, displayed little hysteresis, high repeatability, low cross-sensitivity to temperature and ammonia gas and stability over 7 days of testing. A rise/fall time of 300/500 ms was achieved respectively.

1. Introduction

The high sensitivity of optical fiber to external perturbation has made optical fiber sensor, an attractive option in the field of sensing. Over the past decades, optical fiber sensing has evolved to the point that various kinds of physical parameter can be measured [1–3]. The advancement of surface coating or surface functionalization has enable sensing of chemical species with high specificity. Amongst various types of chemical sensor, humidity sensor plays an important role in many applications such as chemical processing, products manufacturing and civil engineering. For example, monitoring of humidity is important to acquire reliable and qualified manufactured products for products manufacturing [4] while for civil engineering, moisture content in soil is dependent on humidity [5]. This fuels the interest in the study of humidity measurement over the last few years, and an increasing attention in utilizing optical fiber technology for the development of humidity sensors particularly in harsh environment [6,7]. Most humidity sensors measure relative humidity (RH), which is defined as the ratio of the water vapour partial pressure in the air to the saturated vapour pressure [5]. Notably, conventional capacitance based, wet–dry bulb and solid-state RH sensors [8] have complicated fabrication process and suffer from sensitivity to electrostatic discharge and EM signals. They are also affected by reversible shift at high humidity and could pose radiation hazard. Some advantages which optical fiber RH sensors have over conventional electronic humidity sensors includes: miniature in size, immune to electronic magnetic fields and the possibility of multiplexing several sensors on the same optical fiber.

Various types of optical fiber humidity sensors have been proposed. These humidity sensors used modified optical structures such as long period gratings (LPGs) [9,10], tilted fiber Bragg's grating (TFBG) [11], fiber Bragg's grating (FBG) [12], hetero-core optical fiber [13], cladding-less optical fiber and bent optical fiber [4,14,15] in order for interaction of light with the sensitive material. However, some of these structures suffer from cross-sensitivity with temperature and curvature, are bulk in size and fragile [2,16,17]. Furthermore, most of these sensors rely on absorption measurement, which can be affected by the instability of the optical source or photo-detector [4,18,19]. The absorption method tends to use humidity sensitive dye encapsulated in sol–gel, which was coated onto the optical fiber. The life-time of the dye can be limiting in this case. Hence coatings that underwent physical changes to RH changes are generally preferred due to their longer lifetime. Hydrogels such as polyvinyl alcohol (PVA), polyethylene glycol and agarose [20–24], and polyelectrolytes [13,18,25] have been

---

* Corresponding author.
E-mail address: eccchan@ntu.edu.sg (C.C. Chan).

0925-4005/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.snb.2012.07.032

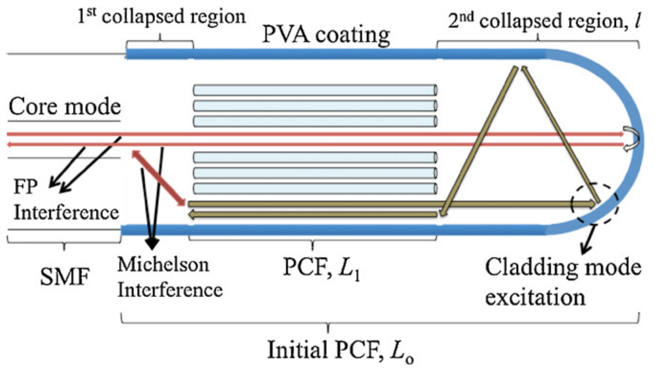

Fig. 1. Schematic diagram showing the operating mechanism of the sensor.

explored as alternate coatings. These coatings swell physically with respect to RH changes and have varying dynamic range and RH sensitivity, dependent on the material. One of the limitations for these RH sensors is the long response time which can be more than a second [24]. This could limit the use of the sensor in certain applications such as a breathing sensor. The work in this paper seeks to improve on the performance of current optical fiber RH sensors.

2. Theoretical background

The aim of this paper is to propose an optical fiber RH sensor that uses a novel optical fiber structure coated with PVA for RH sensing. This structure is a miniature photonic crystal fiber (PCF) modal interferometer formed by the excitation of the cladding mode at the tip [26]. The interferometer is measuring the refractive index of PVA, which changes with RH. Due to the size and structure, minute amount of PVA coating is needed which would in turn give rise to shorter response time. In addition, with the excitation of higher order cladding mode for use in RH sensing application, the sensitivity of the sensor would be improved as similar finding was reported in Ref. [27]. Furthermore, as the sensor is based on wavelength demodulation system, it is not affected by the stability of the laser source.

The sensor consists of a collapsed region between a single-mode fiber (SMF) and a short piece of pure silica PCF (LMA10), which has its end melted into a round tip, as shown in Fig. 1. The sensor behaves predominately as a Michelson interferometer with the formation of interference fringes due to the phase difference between two paths of light after recombination. In order to accommodate the interference fringes in the 100 nm spectrum's window, substantial phase difference is needed. This phase difference is caused by the excitation of the cladding mode due to the round tip rather than the commonly used method of substantially increasing the physical length of the sensor. Thus high spatial resolution can be realized with a small sensor.

A schematic diagram to explain the mechanism of the sensor is shown in Fig. 1. The fundamental core mode is coupled to the cladding modes by the first collapsed region of the PCF. Both core and cladding modes will be reflected by the PCF's end after propagating past the PCF and second collapsed region. The round tip is used to excite the cladding mode to higher order after reflection while the second collapsed region allows the excited mode to propagate for a distance, accumulating large phase delay before propagating back in the cladding. Finally, both modes recombine at the first collapsed region to form a Michelson interferometer. The recombination of the cladding and fundamental core modes after undergoing reflection and mode excitation follows the standard interference equation:

$$R = [E_1]^2 + [E_2]^2 + 2E_1E_2 \cos\left(\frac{2\pi l \Delta n}{\lambda} + \phi\right) \tag{1}$$

where E_1 and E_2 are the magnitudes of electric field of the core and cladding modes in the PCF respectively, $\Delta n = n_1 - n_2$, with n_1 and n_2, the effective refractive indices of the core and cladding modes, respectively, λ is the wavelength of the propagating light and l is the length of the second collapsed region. $2\pi l \Delta n/\lambda$ is the phase difference obtained after cladding mode excitation as both modes reflects back into the PCF after travelling l. $\Phi = \Phi_1 + \Phi_2$ contains Φ_1, the phase difference obtained along L_1 and l before reflection and Φ_2, the phase difference obtained along L_1 after reflection, where L_1 is the remaining length of PCF after collapsing. Formation of a Fabry–Perot (FP) interferometer is possible due the dissimilarity in refractive indices between cores of SMF and PCF. Similarly, Eq. (1) is able to describe the reflection of this interferometer, with the following alternations: $\Delta n = n_1$ and $l = 2L_0$ where L_0 is the entire PCF inclusive of the collapsed regions.

PVA with an OH group bonded to every alternate carbon in the backbone chain, is a water-soluble polymer and has a good swelling ratio [28]. The polymer is able to adhere well to silica and exhibit excellent film formation property. It is easily processed, biocompatible and is resistant to chemical agents [28]. As the PVA coating absorbs water molecules from the surrounding, it swells and its refractive index changes. Hence variation of RH would cause the physical properties of the PVA coating, such as its swelling degree and refractive index to change [1]. With the PVA coating on PCF cladding, as light is guided to the interface of the PVA coating and PCF cladding, as shown in Fig. 1, variations in the refractive index of PVA would affect the propagation of light in the PCF. This changes the effective refractive index of the cladding mode, n_2, which in turn leads to a phase change in the cosine term in Eq. (1). This phase change would be significant due to the presence of higher order cladding mode, thus high sensitivity is expected [27,29].

3. Experimental

3.1. Apparatus and materials

PVA with M_w 89,000–98,000, 99+% hydrolyzed was used. All chemicals we used were obtained from Sigma–Aldrich, Singapore and used directly without any further purification. Deionized water was produced by MilliQ system. Single mode optical fiber of core diameter 8 μm and cladding diameter 125 μm was bought from Yangtze Optical Fibre and Cable Company Ltd. Photonic crystal fiber, LMA 10 with core diameter of 10 μm and cladding diameter of 125 μm, was purchased from NKT Photonics.

The fusion splicer (Sumitomo Electric Type 36) is able to operate in manual mode, which allows flexibility in performing delicate arcing. The dip coater (KSV NIMA Dip Coater Multi Vessel Small) is able to perform at different dipping speed and position. The optical spectrum analyzer (OSA, Yokogawa AQ 6370) was used. The commercial humidity meter (ThermoWorks, DT-3321) has a RH of 0.1%RH-resolution and ±2%RH accuracy.

3.2. Optical fiber preparation

The fabrication of the sensor can be described as followed: SMF was spliced to the PCF using the fusion splicer. The splicing point took place at about 100 μm away from the arc-ing center to prevent any collapsed of PCF. This allowed us to acquire a better control of collapsed length through re-arcing. Repeated arcs of 45 counts with 0.45 s arcing time were applied on the spliced point to further collapse the PCF to a desired length of about 200 μm. The PCF was cleaved with a manual cleaver to acquire a length of about 1 mm spliced to the SMF. For the formation of the round tip, another round of arcing was applied at the PCF's end. Due to surface tension, the tip was molded into a round shape and a collapsed region was also