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Miniature Photonic Crystal Optical Fiber Humidity Sensor based on Polyvinyl Alcohol

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ABSTRACT

A compact photonic crystal fiber (PCF) humidity sensor based on modal interference has been proposed by the use of commercial fusion splicer to collapse the holes of PCF to form a Michelson interferometer with cladding mode excitation at the fiber tip. The sensor is then dipped coated in polyvinyl alcohol to make it sensitive to humidity. The shift of the interference fringes was measured when the sensor was placed in a humidity chamber of varying humidity. High sensitivity was obtained when the relative humidity is above 50% RH as an exponential relation of relative humidity and interference shift was established.

Keywords: interference, photonic crystal fiber, humidity, optical fiber sensor

1. INTRODUCTION

Owing to various advantages over electrical sensors such as immunity to electromagnetic interference and remote sensing ability, optical fiber sensors represents an attractive option for measuring environmental parameters such as pressure, temperature and relative humidity (RH), especially in harsh environment. RH is defined as the ratio of the amount of water vapour present in the atmosphere to the maximum amount the atmosphere can hold. In industries such as agricultural, forest, and manufacturing of chemicals, food products and electronic components, RH has to be monitored for quality control of the manufacturing processes. Conventional electronic RH sensors operate on the change in electric conductivity or capacitance of a material upon absorption of water molecules. However, in environment of high humidity, there could be problems such as electric current shock due to the condensation of water droplet. On the other hand, the intrinsic nature of RH optical fiber sensors eliminates such problems. Examples of RH optical fiber sensors that have been explored include hetero core optical fiber, tapered optical fibers and fiber gratings. Because optical fiber confines light in the core through total internal reflection, it is necessary to structurally modify the optical fiber such that light can reach the interface between the environment and the optical fiber in order to be modulated by RH change. Such modification can be complicated and reduce the mechanical integrity of the optical fiber. Furthermore, cross-sensitivity with other parameters such as bending or temperature could be a problem. For example, the FBGs RH sensor has to be temperature compensated since the periodicity of the grating can be affected by change in environmental temperature.

In this paper, a photonic crystal fiber (PCF) humidity sensor based on polyvinyl alcohol (PVA) coating is proposed. The sensor comprises a collapsed region between the single mode fiber (SMF) and a short piece of pure silica PCF (LMA10) with a PVA coated collapsed end. Fabrication process of the sensor is simplified, as only a commercial fusion splicer was needed, before the sensor is functionalized with a PVA coating. The operating principle of the proposed sensor can be described as followed. The presence of the collapsed region between the SMF and PCF couples the fundamental core mode to the cladding mode of the PCF [1]. This creates two paths of light, which are reflected back by the collapsed PCF's end. Upon reflection, the cladding mode will be excited to higher order mode due the rounded's end which behaves as a Gaussian's lens. This leads to a large phase difference between the core and cladding modes. The two paths of reflected light re-couple back into the core at the same collapsed region, resulting in modal interference and forming of a Michelson interferometer [2]. By functionalizing the sensor with a PVA coating, upon absorption of water

molecules, the PVA will have its refractive index altered and swelled. The variation of refractive index and swelling degree of PVA is heavily dependent on humidity. This unique property is utilized to change the reflected angle of the cladding mode in the sensor as governed by Fresnel's reflection, which in turn lead to a change in the phase difference between the core and cladding modes. Therefore, the humidity information will be encoded into the phase of the interference fringes. The spectral property of this humidity sensor is investigated and its RH sensitivity is experimentally demonstrated.

2. EXPERIMENTAL SETUP AND PRINCIPLE

The PCF humidity sensor system, shown in Fig. 1, comprises of a broadband light source, a circulator and an optical spectrum analyzer (OSA, Yokogawa AQ 6370). The circulator guides the signals, which are reflected from the proposed sensor to the OSA for measurement. The fabrication of the sensor was done by first using a commercial fusion splicer (Sumitomo Electric Type 36) to splice the PCF onto the SMF. Repeated arcs of the same parameters were applied on the spliced point to further collapsed the PCF to a desired length of about 100 μm . The PCF was cleaved to acquire a length of about 1 mm connected to the SMF. Another round of arcing was applied at the PCF's end. Strong electric arc discharges induce localized heating on the PCF, which led to the collapsed of the air holes and the formation of a round end due to surface tension. The sealed end prevents liquid from infiltrating into the holes, which could change the optical property of the PCF causing a change in the transmission spectrum. Thus the stability of the sensor's performance is improved. The collapsed region and the short length of the PCF also help to enhance the mechanical integrity of the sensor, especially due to the inherent weakness of the splicing point. The sensor was dip coated into a PVA solution of 8% w/w in distilled water, with a drawing speed of 33mm/s using a dip coater. The PVA solution was made by dissolving PVA in distilled water at temperature of 90 $^{\circ}\text{C}$ for 1hr. The drawing speed and the concentration of the PVA would affect the final thickness of the PVA coating on the sensor. After coating, the sensor was placed in an oven for drying at 80 $^{\circ}\text{C}$ for 1hr. Fig 2 shows the schematic diagram of the operating mechanism of the sensor coated with PVA. The light from the SMF diffracts out in the collapsed region to form the cladding and core modes of the PCF. Variation in surrounding humidity of the sensor affects the reflected light path at the rounded end. This transmits into a change in phase difference between the core and cladding modes.

Fig. 1. Experimental setup of the PCF sensor system.

Fig. 2. Schematic diagram of the operating mechanism of the sensor.

From Fig 2, the cladding and the core modes of the PCF function as the two light path of the Michelson interferometer. Two modes are assumed to be present due to the relatively short PCF. The reflection of the interferometer is similar to the standard Michelson interferometer equation, given by:

$$R = [E_1]^2 + [E_2]^2 + 2E_1E_2 \cos(2\pi l \Delta n / \lambda + \phi) \quad (1)$$

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 indices of the core and cladding modes, respectively; l is twice the length of the second collapsed region; λ is the wavelength of the propagating light; and ϕ is the phase difference obtained along L_1 , the remaining length of PCF left after collapsing. A Fabry–Perot (FP) interferometer is also formed due to a slight RI difference between the cores of SMF and PCF. The reflection of this interferometer follows Eq. 1 with slight deviation, as $\Delta n = n_1$ and $l = 2L_0$ where L_0 is the entire PCF inclusive of the collapsed regions. The selection of suitable L_0 will allow for simple digital filtering of FP fringes as both interferometer fringes will have distinctly different spatial frequency. The variation of humidity surrounding the sensor is proposed to change the physical properties of the PVA coating such as its swelling degree and RI. Since the coating is at the interface of the PCF cladding, the effective RI of the cladding mode will be affected leading to a phase change in the transmission as shown in Eq 1. The length of PCF is made to be less than a centimeter to reduce the cost of the sensor and power loss due to the PCF's cladding.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3a. Optical microscope picture of fabricated sensor [2].

Fig. 3b. Optical spectrum of the PCF sensor after coating and drying

The employed broadband light source in the experiment is an amplified spontaneous emission source. The fabricated sensor without PVA coating is shown in Fig 3a. The length of the PCF used is about 1.5 mm while the collapsed region between the SMF and PCF is about 100 μm . the length of the collapsed region of the PCF's end is about 0.9 μm . Fig 3b shows the experimentally measured reflection spectra of proposed interferometer in air under 60%RH and room temperature of 25°C, measured by a humidity meter. The interference fringes are made up of high spatial frequency with small amplitude fringes modulated by large amplitude and lower spatial frequency fringes. The lower spatial frequency component is due to the modal interference of the Michelson interferometer while the high frequency component is due to the FP interferometer. Fig 4a shows the original reflection spectra and Fig 4b shows the filtered reflection spectra of the sensor after undergoing a low pass filter with cut-off spatial frequency at 0.4 (nm)⁻¹.

Fig. 4a. Optical spectra of the PCF sensor with varying RH

Fig. 4b. Filtered optical spectra with varying RH

To investigate the performance of the PCF sensor on RH sensing, the PCF sensor was placed into a self-made airtight chamber with an inlet where humid air or dry air can be pumped to adjust the RH in the chamber accordingly. Air pressure in the chamber was kept at constant atmospheric pressure by an outlet. A commercial humidity meter was placed into the box to measure the box's RH. This commercial humidity meter has a relative humidity of 0.1-resolution and $\pm 2\%$ RH accuracy. The experiment was performed by the adjustment of the humidity in the box at 5% RH interval. When the required RH level was reached, both the inlet and outlet will be closed to stop any airflow and a waiting time of 4 minutes before the OSA measurement was taken. This allows the RH in the chamber to stabilize and reach a homogenous state throughout. This also ensures the PVA coating to swell to a steady state.

Fig 5a shows the shift of the peak at wavelength of ~ 1560 nm with reference to one at RH 30%. It can be seen that the wavelength shift follows an exponential relation with RH changes. Fig 5b shows the shift of the peaks with increasing RH from 30% to 90% followed by decreasing the RH from 90% to 30% at room temperature of 25°C. Fig 5b shows the transmission spectrum of the PCF sensor with varying RH. The sensor exhibits near exponential response with change in RH with large shift of the peaks occurring at high RH due to the refractive index change of the PVA coating. As the RH in the chamber increases, the PVA coating absorbs more water molecules from the air, which decreases the refractive index value of the PVA coating. According to ref [3], the water content in the sensor increases greatly at high RH level, which explains for large wavelength shift of the interference fringes at high RH. The RI value of pure, dried PVA is found to be 1.53 at 589.3 nm, reported in ref [4]. Similarly, this behavior is reported in refs [4, 5]. The non-linear response should not be a problem in practical applications, once it has been calibrated. The sensor also exhibited little

hysteresis effect upon the decrease of RH immediately. The small variation in the signal is likely to be due to small temperature change in the humidity chamber, which affect the RH greatly.

Fig. 5a. Wavelength shift of the peak at ~1560nm, with varying RH

Fig. 5b. Location of the peak at ~1560nm with varying RH.

A wavelength shift (red shift) of ~0.1nm was observed, when the RH level in the chamber was increased from 30%RH to 50%RH. When the RH level increased from 50%RH to 70%RH, a wavelength-shift of ~1 nm was observed. Finally, when the humidity level was further increased to 90%RH from 70%RH, a shift of ~ 4.5nm was observed. Compared to other similar RH sensor in [5, 6], the proposed sensor has a much more simple fabrication process and miniature in size. The use of long period grating (LPG) could easily have cross sensitivity with temperature during RH sensing and is also affected by bending which made the fixation of LPG onto a platform of high importance. The proposed sensor without the coating has been shown to be insensitive to temperature [2]. Through analysis of interference fringes, potential errors caused by the fluctuation of intensity from the optical source and IR absorption by the polymer film can be eliminated as the sensor based on same PVA coating in ref [4] is being compared. The good performance characteristic of the proposed sensor also promote the implementation of other kind of coating such as agarose [7] or chitosan.

4. CONCLUSIONS

We have proposed and demonstrated a PCF model interference humidity meter based on PVA coating, fabricated entirely using commercial fusion splicer and a dip-coater. The sensor exhibits shifting of interferences fringes to varying RH. The RH capability of the sensor was analyzed by placing it in a humidity chamber as flowing humid air or dry air varied the RH in the chamber. The wavelength shift follows an exponential relation when RH was changed from 30%RH to 90%RH. Due to the miniature of the sensor, detection of RH in small-enclosed space can be realized. Further, as compared to other sensor that use LPG, cross-sensitivity with parameters such as bending, vibration and temperature can be avoided. The potential to functionize the sensor with other coating will be a subject for exploration in the future.

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