Repeatability and Reversibility of the Humidity Sensor Based on Photonic Crystal Fiber Interferometer

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Abstract. The RH sensor operation based on water vapor adsorption and desorption at the silica-air interface within the PCF. Sensor fabrication is simple; it includes splicing and cleaving the PCF with SMF only. PCF (LMA-10) with a certain length spliced to SMF (Corning-28). The PCFI spectrum exhibits good sensitivity to the variations of humidity. The PCFI response is observed for range of relative humidity values from (27% RH to 85% RH), the interference peaks position is found to be shifted to longer wavelength as the humidity increases. In this work, a 6cm length of PCFs is used, and it shows a sensitivity of (2.41pm / %RH), good repeatability, and reversible in nature. This humidity sensor has distinguished features as that the sensor does not require the use of a hygroscopic material, robust, compact size, immunity to electromagnetic interference, and it has potential applications for high humidity environments.

Keywords: Humidity sensors, Optical fiber sensor, Photonic crystal fiber, Interferometers, Repeatability.

1. Introduction

The Photonic Crystal Fiber (PCF), which is also called holey fiber or Microstructured Optical Fiber (MOF) appeared in the mid-1990s. PCF has a periodic layout of micro holes that run along the entire length of the fiber. There are two types of PCF cross sections: a solid silica core surrounded by air–silica cladding, where the mechanism of light-guiding is provided by means of the Modified Total Internal Reflection (M-TIR), or a hollow core surrounded by air–silica cladding, where the light-guiding mechanism is based on the effect that called Photonic Band Gap (PBG) effect [1].

The presence of air holes in PCF provides a possibility of light propagation in air, or instead of that gives the ability to inject gases/liquids into the air holes. This provides a well-controlled interaction between light and matter leading to novel sensing applications that cannot get it with conventional optical fibers [2, 3]. The applications of PCF in sensing domains dividing it into two sub-branches, depending on the parameter that is measured. These two subbranches are physical (curvature sensor, temperature sensor, vibration sensor, electric and magnetic sensor, and pressure sensor) and biochemical sensors (gas sensor, humidity sensor, pH sensor, and molecular sensor) [4].

Humidity is an important factor in different fields such as agriculture, food process and storage, chemical, biomedical, weather conditions monitoring, civil engineering, and electronic, etc.[5]. Humidity indicates to the water vapor content in the air. It is one of the most measured physical quantities. The measurements of humidity can be stated in a variety of units and terms. The ratio of the water vapor partial pressure to the equilibrium vapor pressure of water at the same temperature is called Relative Humidity (RH). It is expressed as a percentage, using the following expression [6]:

$$\text{RH} = \frac{P_w}{P_{w_s}} \times 100\%$$  \hspace{1cm} (1)

Where $P_w$ is the water vapor partial pressure and $P_{w_s}$ is the saturation pressure of water vapor. RH is the relative measurement because it is a function of temperature [6]. Conventional electronic relative humidity sensors are based on monitoring the electrical capacitance or conductivity changes, and because of electrical leakage (especially in a high humidity environment), these types of sensors have the disadvantage of inaccuracy. So, the optical RH sensors (compared with electronic RH sensors) offer any features, such as low weight, small size, immunity to electromagnetic interference, and remote monitoring. There are wide ranges of relative humidity sensing techniques based on optical fibers, including plastic...
optical fibers, long period gratings, Fiber Bragg Gratings, Surface Plasmon Resonance, and tapered optical fibers [7].

Relative Humidity (RH) sensor based on a PCFI has been submitted in this paper, which has a unique feature such as the sensor doesn't need any hygroscopic material to measure humidity and its tip is made of (silica) single material. For an interferometric type fiber optic RH sensor, the sensing mechanism relies on the perturbation of the light signal phase properties that traveling in the optical fiber introduced by the humidity change. The phase change detection is realized by mixing the interest signal with a signal of the reference, then converting the phase difference into wavelength shift or change of the optical intensity [6]. In this paper, the element sensing is just stub of PCF spliced to SMF, this forms the reflection-type PCFI, and the sensor spectrum exhibits good sensitivity to the variations of humidity.

2. Experimental:

Humidity sensor based on reflection type of the PCFI has been proposed. First, the coating of the PCF (LMA-10) stub and conventional optical fiber (Corning, SMF-28) are removed by using a mechanical stripping. Then, the second step is cleaving the PCF and SMF, which is done by fiber cleaver, and the third step is cleaning the fibers. Then, the PCF (LMA-10) stub is spliced to single mode optical fiber (SMF-28, Corning) by a splicing machine. The photonic crystal fiber (LMA-10) designed for an endless single-mode operation is used, it has four layers of air holes arranged in a hexagonal pattern around a solid silica core, the fiber has a core size diameter of (10μm), voids with a diameter of (3.1μm), pitch of (6.6μm) and outer diameter of (125μm). These PCF dimensions (LMA-10) alignment and splicing with the SMF with a splicing machine, and due to mode-field diameter (MFD) mismatch compared to other PCFs, the loss was minimize. During the splicing process and due to surface tension, the PCF voids collapse within a microscopic region (~300μm) near the splice point, as shown in the 'figure 1'.

![Figure 1. The microscope image of splice zone between PCF (LMA-10) and the SMF](#)

The PCF is cleaved with a cleaving machine after the splicing, so that the PCF end acts as a reflecting surface (Mirror). PCF holes are left open to the ambient atmosphere. The mechanism of light guidance in PCF is by (M-TIR).

"The PCFI working principle relies on the modes excitation and recombination occurring in the PCF zone in which the PCF voids are collapsed. The fundamental SMF mode diffract when it enters the collapsed region of the PCF. So, excitation of two core modes in the PCF occurs, due to the diffraction, the mode broadens. Then modes transfer until they reach the PCF cleaved end from where they are reflected. Then, reflected modes are recombined as single core mode, when they re-enter the collapsed region [8, 9]. 'Figure 2' show the setup of the humidity sensor based on PCFI, light source (1550nm) is launched to the interferometer through the Fiber Optic Circulator (FOC), and light that reflected from the cleaved end is fed to the Optical Spectrum Analyzer (OSA)".
In this setup, the interference peaks shift is tracking with high resolution. Different lengths of the PCF section used to show the sensitivity dependence on PCF length.

The fabricated sensor response to humidity variations is studied (at room temperature and normal atmospheric pressure) by putting the sensor in an environmental chamber (which is a cuboid-shape sealed chamber), fabricated from Polyvinyl chloride (PVC) plastic. It consists of dry/wet air flow system that can vary the internal humidity in the chamber\(^a\) (27%RH - 85%RH), there are three fans (the first fan is pumped a dry air from container containing a silica gel, the second fan pumps a wet air from container containing distilled water and heater (70watt), and the last fan is on the surface of chamber to expel the air). A calibrated electronic humidity (XMT9007-8 temperature & humidity control instrument) is used for monitoring humidity and temperature inside the environmental chamber.

3. Result and Discussion:

The response of the PCFI is observed for a range of humidity values (27%, 30%, 40%, 50%, 60%, 70%, 80%, and 85%) RH. The position of the interference peak is found shifted within the humidity variations to the longer wavelength (red shift). The sensitivity of the sensor is calculated by dividing the experimentally measured PCFI response to the relative humidity. The Relative Humidity (RH) response of the PCFI device is studied with 6cm PCF lengths and different ambient relative humidity values (at room temperature and normal atmospheric pressure). Figures (3)' shows the shifting of the interference peak of the reflected light from PCFI for the submitted sensors for 6cm lengths of PCF.

![Figure 2](image2.png)

**Figure 2.** Experimental setup of RH sensor based on PCFI

![Figure 3](image3.png)

**Figure 3.** Interference peaks shift of the sensor with respect to relative humidity, and for 6cm lengths of PCF
From the previous figure, it is observed that there is no shifting in interference peak between (27%-40%) RH region, the shift is to appear for relative humidity value 40% RH. This is because water has hydrogen-bonded network (ice-like), which increase as relative humidity increases from 0% to 30%.” The structure of liquid water starts appearing in RH range of 30-60%, while the ice-like structure continues growing to saturation [10].

The sensitivity in pm/%RH calculated from the linear fitting of relative humidity versus wavelength curve. It is observed that PCFI with length (6cm) shows sensitivity (2.41pm/%RH).

The variation of the RH sensor response at a wavelength ($\lambda=1550$ nm) to the cycle of RH-increasing and RH-decreasing, is shown in figure 4', RH is changed from 27% to 85%, and the PCF length is (6cm). From this figure, it can be observed that PCFI has reversibility at room temperature, its shift in reflection spectrum (after one humidity increasing/decreasing cycle) returns to the same value. Minor hysteresis is observed during the cycle.

![Figure 4](image1.png)

**Figure 4.** The hysteresis loop of RH sensor with PCF length (6cm)

The reversibility is due to the fact that the adsorption is a reversible process, so the effective refractive index modulation of cladding ($n_{eff}$) occurs according to the values of ambient humidity which lead to change position of the interference pattern. The cladding mode effective index increases as increase in humidity, so the PCFI interference pattern shift toward longer wavelengths and vice versa. Also, the RH sensor repeatability over a large RH range (27%-85%) RH is demonstrated with the time gap of one week, and with (6cm) PCFI length, the sensor shows a good repeatability, shown in 'figure 5'.

![Figure 5](image2.png)

**Figure 5.** The repeatability of the RH sensor with PCF length (6cm)
In this figure, the two curves (first day, and after 4 days) represent the measurements taken for the RH sensor with a time gap of (4 days), and they show a good repeatability for the humidity changes. This is because when the PCF is exposed to air for the first time, chemisorption happens only one time, which causes the formation of a single layer of a (Si-OH) group on the PCF surface (requires heating to desorb).

The physisorption takes place in this group, and form multiple layers of water molecules on the surface of the PCF and also it is a reversible process at room temperature in equilibrium with the ambient RH. So, under laboratory conditions the RH sensor is reusable.

Since the chamber locally made and environment nature in Iraq always contaminated generally and because this sensor depends on narrow silica microholes, so it has implications for contamination (dust particles) and degradation in varying degrees relying on the environment nature, as it clear in the behavior of the sensor after a week, as shown in the previous figure. To overcome this limitation can use different methods: recalibration sensor head after a specific period of time and then reuse of the head of the sensor during another time period, or protect the head of the sensor by attaching filters to it. The other way to remove the contaminants without damaging the sensor head and make the sensor reusable is the ultrasonic cleaning with heating.

4. Conclusion:-
Mach-Zehnder interferometer (MZI) for humidity detection based on PCF is demonstrated; this PCFI is simple and operates in reflection mode. Its fabrication involves splicing short pieces of one end of PCF (LMA-10) with SMF (Corning-28), and cleave the free end of PCF to act as a mirror, and the RH sensor does not require to using of any hygroscopic material.

The sensor sensitivity of the RH depends on the PCF length, and the sensor with 6cm PCF length has a sensitivity of the sensor is 2.41pm/%RH in the RH ranges of 40-85%. The RH sensor has reversibility at room temperature, and shows a good repeatability for humidity changes.

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