Optical Based Humidity Sensor by Using Zinc Oxide-PVA In Micro Cavity

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Abstract. We demonstrate a simple optical based humidity sensor using a micro cavity. The micro cavity consists of single mode fiber (SMF-28e, Corning) and a reflective mirror coated with zinc oxide (ZnO) which is embedded in polyvinyl alcohol (PVA). A wideband amplified spontaneous emission (ASE) source, ranging from 1530-1610 nm was injected into the micro cavity. The water molecules from the surface of the ZnO-PVA changed the refractive index of the micro cavity which subsequently modified the phase of ASE light that was reflected from the coated mirror. The change of phase in the reflected light from the coated mirror was monitored with optical spectrum analyzer (OSA). The performance of our optical humidity sensor for non-coated mirror and ZnO-PVA coated mirror was recorded at 0.03 nm/ RH% and 0.074 nm/ RH%, respectively. This shows that optical humidity sensor with ZnO-PVA coated mirror is more sensitive to humidity changes.

1. Introduction
Optical cavities are keystone in photonics which form lasers, optical filters, optical combs and clocks, quantum physics and detection of gravitational waves [1]. Hence, the term cavity has been used widely by researchers working around with optical fiber. The term micro cavity has been introduced due to the gap between fiber with another element is in micrometer distance. Optical fiber consists of two types of fiber, known as single mode fiber (SMF) and multimode fiber (MMF). Some researchers integrate both SMF and MMF in their work to achieve a simple structure, high stability, low cost, small size and eased of packaging and connection to optical system [2] [3].

Studies regarding optical fiber sensor technology has been blooming for the past 40 decades and has undergone countless progress and advancement over the last 25 years [2]. Researchers are working around the scope of material fabrication and principles of operation with the aim to increase the performance of optical fiber sensor [4]. Numerous optical fiber sensors have been studied for the applications of gas, strain, pressure, and humidity sensing. Optical fiber-based sensor is preferred compared to conventional electronic sensor as it offers advantages such as high sensitivity [5], low weight and compact structure, electromagnetic immunity, fast response time, high accuracy, and good stability.

Humidity sensor is one of the sensors used in our everyday life. It is widely employed in construction, food processing, medical, agriculture, fuel, aerospace, and human comfort [6][7]. Many researchers have been working around with humidity sensor to serve the high demand in sensing industry [7]. Relative humidity is one of the important parameters monitored and controlled in the industry [8].

Currently, electronic humidity sensor in the form of electronic components has been used commercially by industrial sector. However, the exposure of electronic humidity sensor to extreme
environment with high humidity could lead to permanent damage [9]. Therefore, an optical micro cavity with simple setup is proposed by integrating of ZnO-PVA based film into propose micro cavity for humidity. ZnO-PVA is chosen in this work due to high sensitivity, immune to electromagnetic wave interference and highly electrical passiveness [10,11].

2. Methodology
The proposed micro cavity humidity sensor is shown in Figure 1. ASE light source with wavelength 1530 nm-1610 nm is injected incident on a reflective mirror coated with ZnO-PVA through a SMF. Both SMF and ZnO-PVA reflective mirror are placed inside an enclosed chamber. The reflected signal is then routed to optical spectrum analyzer (OSA) for measurement through a 3 dB coupler. Sodium hydroxide (NaOH) is also placed inside the chamber to control the percentage of relative humidity (RH%). The range of relative humidity in our work is ranging from 60%-90%. Nevertheless, the range of relative humidity in our work can also be extended by using different types of salt such as lithium chloride and potassium sulfate. A hygrometer is used to measure the RH% in the enclosed chamber. The changes of RH% produces changes in the reflected spectrum [12] and resulted in a wavelength shift. The optimum of micro distance from the SMF to reflective mirror is characterized first before investigating the performance of proposed optical humidity sensor.

2.1. Fabrication of Zinc Oxide-PVA Based Film
There are various types of polymer that are used in sensor fabrication to enhance the sensing performance. These include Polyacrylamide (PAM), Poly Vinyl Alcohol (PVA), Poly Ethylene Oxide (PEO), Polystyrene (PS) and Poly Methyl Methacrylate (PMMA) [13]. In this research work, we propose the use of ZnO-PVA based film coated on reflective mirror for our sensing method. PVA, a common polymer [14] is selected as the host polymer due to its high strength, high flexibility, and low absorption [15]. ZnO is one of the vastly deliberated nano-structured metal oxide semiconductors that is used to detect various gases and vapors because of its unique sensing properties [16]. ZnO-PVA based film is prepared by mixing 25 mg of zinc oxide powder with the polyvinyl alcohol solution that is already been diluted with deionized (DI) water. Then, the mixture is poured into a petri dish and left to dry for three days.

The fabrication of ZnO-PVA is described as below. Firstly, 1 g of PVA powder (Sigma Aldrich, 40000 MW) is added into 120 ml of deionized water (DI) and the solution is stirred with the aid of magnetic stirrer at temperature of 145 °C until PVA powder completely dissolves. The fabrication of ZnO is
prepared by mixing 25 mg of ZnO powder (Reagent Plus, < 5 µm particle size, 99.9) into 5 ml of PVA suspension. Subsequently, ZnO-PVA is sonicated using tip sonicator (Hielscher, 50 Hz) for three hours with a frequency of 24 kHz, a cycle of 0.5 and an amplitude of 60%. The mixture is then centrifuged (Kubota 2800) at 2500 rpm for 5 minutes. The ZnO-PVA solution is decanted into petri dish and is kept for few days in a dry cabinet at an ambient temperature.

3. Proposed Model

Figure 2. The reflectivity of the interfaces SMF-air ($R_1$) and air-ZnO-PVA based film ($R_2$)

$$R_1 = \frac{(n_1 - n_0)^2}{(n_1 + n_0)^2}, \quad R_2 = \frac{(n_2 - n_0)^2}{(n_2 + n_0)^2}$$

The length of the micro cavity is varied in the range of 0 µm to 400 µm. The refractive index of air, SMF and ZnO-PVA based film are $n_0$, $n_1$ and $n_2$, respectively. Due to the difference refractive indexes of SMF and ZnO-PVA based film, the light reflections $R_1$ and $R_2$ are different. The reflectivity of the interfaces SMF-air and air-ZnO-PVA based film is calculated by the Fresnel equation as stated above. The reflection of the SMF-air, $R_1$ is 3.6% and ZnO-PVA based film-air $R_2$ 17.7%. The silver mirror used has reflectance higher than 95%. Therefore, it is assumed that all light is reflected at the mirror surface.

Figure 3. (a) SEM image of ZnO-PVA based film (b) Thickness of ZnO-PVA based film
The surface morphology of the fabricated ZnO-PVA based film with concentrations of 5mg/ml is investigated using low vacuum scanning electron microscope (LV-SEM) (JEOL, JST-JT300) with magnification of 1200x. The captured images clearly show a thoroughly mixed ZnO powder in PVA. The thickness of the fabricated ZnO-PVA is measured at 22.22 µm using 3D laser microscope (Olympus, LEXT OLS4100). For precise measurement, the base film is attached to a double-sided tape to fix the film position. The thickness is measured by determining the height of the smooth surface (ZnO-PVA based film) from the rough surface (double-sided tape).

4. Experimental Results

Figure 4 shows the reflected ASE (i) without ZnO-PVA coating and (ii) with ZnO-PVA coating for various distances between SMF and reflective mirror. The distance between SMF and reflective mirror is varied between 50 µm to 400 µm in order to find the optimum spectrum which can be further used for characterize the performance of the proposed humidity sensor. Reflected spectrum when the micro distance is 200 µm is taken as the injected ASE signal. This is because the reflected spectrum for 200 µm exhibited high extinction ratio compared to the other distances. Table 1 shows the characteristics of reflected spectrum, when the distance between SMF and reflective mirror is set to 200 µm. The characteristics of the reflected spectrum with mirror coated with ZnO-PVA has higher Q-factor.

| Parameters                  | With ZnO-PVA based film (200 µm) | Without ZnO-PVA based film (200 µm) |
|-----------------------------|----------------------------------|-------------------------------------|
| Free spectral range (nm)    | 4                                | 6                                   |
| Extinction ratio (dB)        | 5                                | 9                                   |
| Q-factor                    | 973                              | 742                                 |
| Finesse                     | 2.5                              | 2.9                                 |

Table 1. Micro cavity analysis results with ZnO-PVA based film and without ZnO-PVA based film
calculated at 973, compared to a non-coated mirror. Cavity with high Q factor is desirable for applications which require narrow-bandwidth filtering, low power, and low crosstalk [17]. Figure 5 illustrates the zoom in image of the reflected spectrum, which is collected from OSA when the relative humidity in the chamber is varied from 60%-90%. It is observed that the reflected spectrum is shifted to the longer wavelength when the humidity of the chamber is increased. The wavelength dip around 1550 nm is taken as reference. At humidity of 60%, the wavelength dip is located at 1546.9 nm. As the relative humidity is increased to 75% and 90%, the dip wavelength is shifted to 1546.4 nm and 1548.9 nm, respectively. Water molecules from the surface of ZnO-PVA coated film and mirror changed the refractive index of the micro cavity and this leaded to phase change in the reflected spectrum. At certain percentage of relative humidity, water molecules accumulated on the film and this resulted in saturation of response. The sensitivity of proposed sensor is measured at 0.074nm/%RH. The experiment is repeated with a non-coated reflective mirror. The observed reflected spectrum for a non-coated reflective mirror showed similar trend. The dip wavelength is also shifted to the longer wavelength, but the measured sensitivity was lower, at 0.03nm/%RH. Table 2 shows a comparison of several work that had been carried out by other researchers. Our proposed sensor showed superior sensitivity compared to other work published in [18]-[20].
### Table 2. Comparison of performance of optical humidity sensor

| Method                        | Coating | Humidity range | Sensitivity  | Ref  |
|-------------------------------|---------|----------------|--------------|------|
| Etched FBG                    | CNT     | 20%-90%RH      | 31 pm/%RH    | [18] |
| Bragg on POF                  | PMMA    | 10%-90%RH      | 35pm/%RH     | [19] |
| Micro knot                    | PMMA    | 17%-98%RH      | 8.8pm/%RH    | [20] |
| Photonic crystal fiber        | PAA     | 75%-95%RH      | 2.35nm/%RH   | [21] |
| Micro cavity (SMF - reflector | ZnO-PVA | 60%-90%RH      | 0.074nm/%RH  | This work |

#### 5. Conclusions
We proposed an optical micro cavity humidity sensor by employing a reflective mirror coated with ZnO-PVA film. It is observed that the reflected ASE spectrum is shifted to the longer wavelength as the relative humidity in the enclosed chamber is increased from 60% to 90%. The performance of proposed optical micro cavity humidity sensor is ascertained at with 0.0743 nm/%RH. This proposed micro cavity setup is easy to use and cheap. This work can also be extended with lower relative humidity and explore other available materials for coating.

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