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Research Article

Tapered Fiber Coated with Hydroxyethyl Cellulose/Polyvinylidene Fluoride Composite for Relative Humidity Sensor

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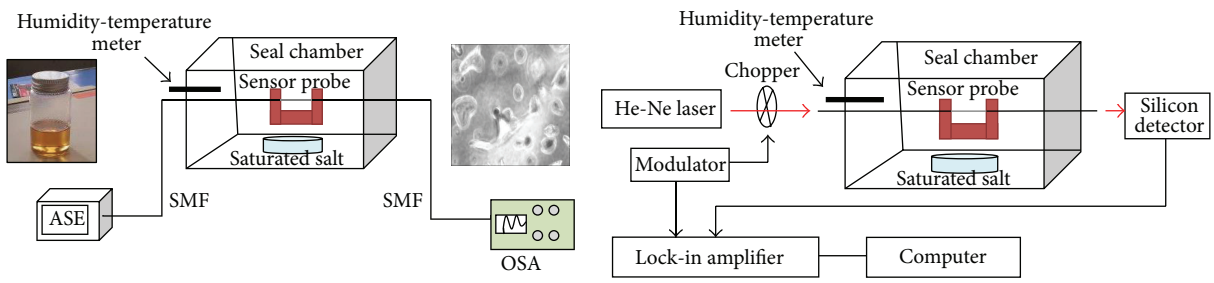
A simple relative humidity (RH) sensor is demonstrated using a tapered fiber coated with hydroxyethyl cellulose/polyvinylidene fluoride (HEC/PVDF) composite as a probe. This coating acts as an inner cladding whose refractive index decreases with the rise in humidity and thus allows more light to be transmitted in humid state. A difference of up to 0.89 dB of the transmitted optical power is observed when RH changes from 50% to 80% in case of the silica fiber probe. The proposed sensor has a sensitivity of about 0.0228 dB/%RH with a slope linearity of more than 99.91%. In case of the plastic optical fiber (POF) probe, the output voltage of the sensor increases linearly with a sensitivity of 0.0231 mV/%RH and a linearity of more than 99.65% as the relative humidity increases from 55% to 80%.

1. Introduction

Recently, many efforts have been focused on developing various optical fiber sensors. Compared with the conventional electrical sensors, the fiber sensors are cheaper and more suitable to be used in hazardous or explosive environments or places where electromagnetic interference immunity is required. They also offer the possibility of multiplexing a large number of different sensors (temperature, displacement, pressure, pH value, humidity, high magnetic field, and acceleration) into the same optical fiber, thus reducing the need for multiple cabling required in traditional electronic sensing [1]. On the other hand, tapered fibers have also attracted considerable interests in recent years, as they exhibit a number of exciting properties [2–4]. The tapered fibers have a large evanescent field that travels along the cladding, which can be manipulated for various sensing applications. For instance, Muto et al. demonstrated humidity sensors which are based on reversible absorption of water (H_2O) from the ambient atmosphere into a porous thin-film interferometer that sits on the tapered fiber [5]. The water absorbed from the ambience changes the refractive index of the thin films and subsequently transforms the lossy fiber into a light guide. Humidity sensing was also demonstrated using a tapered fibre with agarose gel [6].

In this paper, we present innovative optical fiber humidity sensors based on microfiber structures coated with a polymer blend of hydroxyethyl cellulose/polyvinylidene fluoride (HEC/PVDF) composite. The composite coating changes its optical properties in response to the change in relative humidity of its surrounding. The measurement is based on intensity modulation technique where the output intensity or voltage of the transmitted light is investigated for changes in relative humidity. The performance of the sensor is investigated for two different types of fiber: standard communication single-mode fiber (SMF) and multimode plastic optical fiber (POF). Compared with silica based fiber, plastic optical fibers (POFs) possess several advantages such as ease of handling, mechanical strength, disposability, and easy mass production of components and system.



(a) Silica nonadiabatic tapered fiber probe

(b) Tapered POF probe

Figure 1: Experimental setup of the proposed relative humidity sensor based on two different probes (a) silica nonadiabatic tapered fiber (b) tapered POF which are coated with HEC/PVDF composite. Inset of (a) shows the sample of HEC/PVDF solution and its microscopic image.

2. Experimental Arrangement

Preliminary research has reported a variety of sensing materials, such as polyimide, crystal violet, porous silica xerogel [7], agarose, and a variety of methyl polymers that can be used to coat the tapered especially for humidity measurement. Here, we chose a combination of hydroxyethyl cellulose (HEC) and polyvinylidene fluoride (PVDF), as the sensing materials since they are relatively common and inexpensive. First, 1 g of PVDF powder (Mw = 275,000) was dissolved in 120 mL dimethyl sulfoxide (DMSO) and 100 mL of distilled water. Then 4 g of hydroxyethyl cellulose (HEC) was added to the PVDF solution. The mixed solution was continuously stirred at room temperature for about 10 hours in order to generate three-dimensional structure of the mesh gel (hydrogel). DMSO was used in the preparation of HEC/PVDF as solvent since HEC is only soluble in water while PVDF is insoluble in water.

A tapered fiber was then prepared from a standard communication SMF using a flame brushing technique. The SMF had core and cladding diameters of 8.3 μm and 125 μm, respectively, and the coating of a short section of the fiber (about several cm in length) was removed prior to the tapering process. The fiber was pulled only from one side by a controllable motor. During the tapering, the torch moved back and forth along the uncoated segment as its flame brushes against the exposed core while the fiber was being stretched. The moving torch provided a uniform heat so that the tapered fiber was elongated with good uniformity along the heated region. The waist diameter of the fabricated microfiber is estimated to be around 5 μm. After the tapering process, the fiber was held straight by translation stages so that the sensing material could be deposited onto the tapered section for humidity sensor. Next, the prepared HEC/PVDF composite solution was slowly dropped onto the microfiber using syringe and left to dry for 48 hours.

Figure 1(a) shows the experimental setup for the proposed sensor to detect change in relative humidity using the silica nonadiabatic tapered fiber coated with HEC/PVDF composite. The input and output ports of the microfiber are connected to amplified spontaneous emission (ASE) laser source and optical spectrum analyzer (OSA), respectively. The sensor probe is placed in a sealed chamber with a dish filled with saturated salt solution. Exposing the HEC/PVDF composite to the RH changes inside the chamber produces variations in the output optical power. In the experiment, the performance of the proposed sensor was investigated for various changes in relative humidity ranging from 50% to 80% using 1365 data logging humidity-temperature meter. Inset of Figure 1(a) shows the sample of the polymer composite solution, which was obtained by blending of HEC and PVDF and its microscopic image.

The linear type of tapered POF was then prepared using acetone, deionized water and sand paper in accordance with chemical etching technique. The POF has an overall cladding diameter of 1 mm, a numerical aperture of 0.51, and an acceptance angle of 61°. The refractive indexes of the core and cladding are 1.492 and 1.402, respectively. The acetone was applied to the POF using a cotton bud and neutralized with deionized water. The acetone reacted with the surface of the polymer to form milky white foam on the outer surface of the cladding which was then removed by the sand paper. This process was repeated until the tapered fiber has a stripped region waist diameter of about 0.45 mm. The total length of the tapered fiber for this section was around 10 mm. Finally, the tapered POF was cleansed again using the deionized water. Both ends of the POF were held and straightened on translation stages to deposit the HEC/PVDF onto the tapered fiber using the similar process as the silica fiber.

Experimental setup of the proposed POF-based relative humidity sensor is shown in Figure 1(b), which consists of a light source, an external mechanical chopper, the proposed sensor, 1365 data logging humidity-temperature meter, a silicon photodetector, a lock-in amplifier, and a computer. The input and output ports of the tapered POF are connected to the laser source and photodetector, respectively. The light source used in this experiment is a He-Ne laser operating at a wavelength of 633 nm with an average output power of 5.5 mW. It was chopped at a frequency of 113 Hz by a mechanical chopper to avoid the harmonics from the line frequency, which is about 50 to 60 Hz. The He-Ne light source was launched into the tapered POF placed in a sealed chamber with a dish filled with saturated salt solution. The output light was sent into the silicon photodetector to be converted into electrical signal. Then the electrical signal together with the reference signal from the mechanical chopper was fed into the lock-in amplifier. Finally, the output from the lock-in

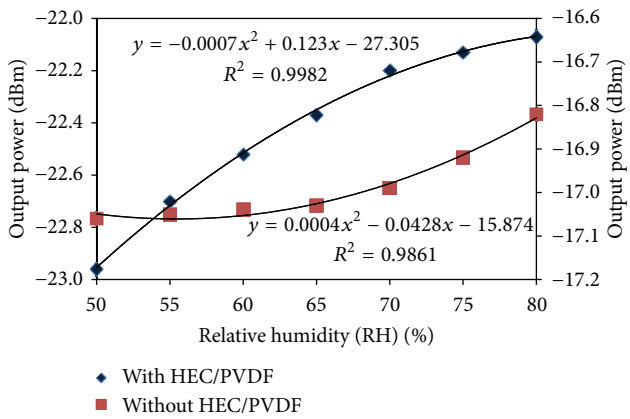


Figure 2: The transmitted light from the silica tapered fiber against the relative humidity.

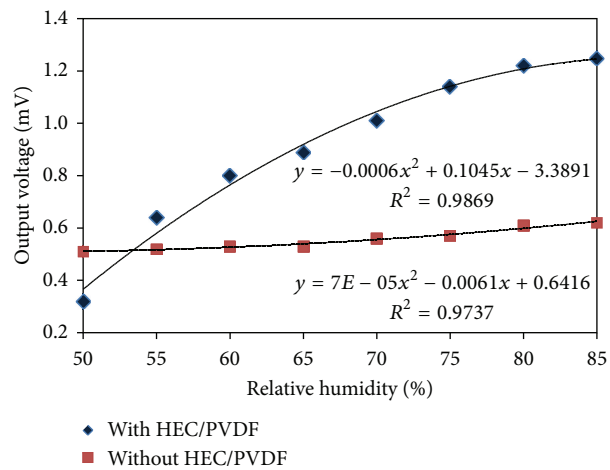


Figure 3: Output voltage against RH for the POF-based sensor with and without HEC/PVDF composite coating.

amplifier was delivered to a computer through an RS232 port interface, and the signal was processed. The reference signal from the chopper was matched with the input electrical signal from the photodiode. This makes a very sensitive detection system that will remove the noise generated by the laser source, photodetector, and the electrical amplifier in the photodetector. In the experiment, the performance of the proposed sensor was investigated for various changes in relative humidity ranging from 50% to 80% using 1365 data logging humidity-temperature meter.

3. Result and Discussion

The characteristic of the proposed sensor against RH is investigated with and without the HEC/PVDF composite coating for both sensor probes. Figure 2 shows the variation of the transmitted light intensity through the nonadiabatic tapered silica fiber against the RH. As seen, the intensity of the transmitted light from the microfiber increases with the increment of humidity for both cases. Without the HEC/PVDF layer, an output power dynamic range of 0.24 dB is obtained for 50% to 80% RH variation. The sensitivity of the sensor significantly increases when the tapered fiber is coated by the HEC/PVDF composite. It is observed that the intensity of the transmitted light of the coated microfiber leaps in a quadratic fashion to the increase of the relative humidity. For instance, the intensity of the transmitted light increases by 0.89 dB as the RH is increased from 50% to 80% as shown in Figure 2. The adjusted R-square value or the coefficient of the determination which corresponds to the measure of the goodness of fit is 0.9982.

In dry state, the humidity sensitive composite layer has an RI value of 1.492, which is slightly higher than that of the core. This suggests that the propagating light inside the tapered fiber leaks out from the core at some areas where the composite layer is thick. At these areas, the effective refractive index of the cladding is slightly higher than that of the core. This causes the microfiber to become a lossy waveguide and reduces the intensity of the light propagating through the device. As the cladding layer hydrates, the RI value falls below that of the core and thereby increases the intensity of propagating light. The sensing system has a sensitivity of 0.0228 dB/%RH and a slope linearity of more than 99.91%.

Figure 3 shows the variation of the transmitted light from the tapered POF against the RH for fiber with and without HEC/PVDF composite deposited onto the tapered region. As expected, the change in the intensity of the transmitted light of the HEC/PVDF composite on tapered fiber increases with RH in a quadratic manner. The adjusted R-square value or the coefficient of the determination is the measure of the goodness of fit which is 0.9869. The considerably high values of the adjusted R-square allow the prediction of unknown relative humidity by the model. This is opposed to the trend demonstrated by the bare fiber where the output remains constant despite the increase of relative humidity. The humidity sensitive layer of the composite has an RI value which is higher than that of the core in dry state. This situation creates a lossy waveguide, and as the cladding layer hydrates, the RI value falls below that of the core and increases the intensity of light propagating through the core. Since the plastic fiber has a higher refractive index than that of the silica fiber, the POF-based sensor is more sensitive compared with that of the silica-fiber one.

Figure 4 depicts the output voltage from the photodetector which shows that the transmitted light intensity linearly increases as the relative humidity rises from 55 to 80%. The bare fiber (without HEC/PVDF) has a sensitivity of 0.0034 mV/%RH with a slope linearity of more than 94.71% and limit of detection of 45.45%. Meanwhile, the probe with the HEC/PVDF composite produces a better sensitivity of 0.0231 mV/%RH with a better slope linearity of more than 99.65% and a limit of detection of 5.75%. The lower limit of detection for the probe with HEC/PVDF shows that the system is more efficient. Overall, the sensor is observed to be sufficiently stable with a standard deviation of 0.133 mV for POF probe with HEC/PVDF composite as recorded in time duration of 100 seconds. Throughout the experiment,

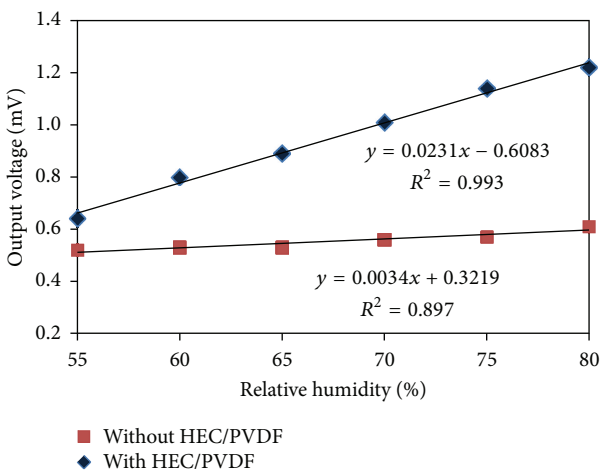


Figure 4: Performance of the POF-based RH sensor within a measurement range from 55% to 80%.

the corresponding output voltage was measured by a lock-in amplifier which provided accurate measurements even though the signal was relatively very small compared with noise. Furthermore, a well-regulated power supply is used for the red He-Ne laser and this minimizes the fluctuation of source intensity. These results show that the proposed sensor is applicable for relative humidity sensing and also has the ability to provide real time measurement.

4. Conclusion

A simple humidity sensor is proposed and demonstrated using a tapered fiber coated with HEC/PVDF composite as a probe. In the case of silica fiber probe, the intensity of the transmitted light increases by 0.89 dB as the relative humidity rises from 50% to 80%. This is attributed to the effective refractive index of the composite, which increases as the humidity level reduced and resulted in a rise of the transmitted light. The sensitivity of the proposed sensor is estimated to be around 0.0228 dB/%RH with a linearity of more than 99.91%. In case of the POF probe, the output voltage of the sensor increases linearly with a sensitivity of 0.0231 mV/%RH and a linearity of more than 99.65% as the relative humidity increases from 55% to 80%.

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