A study on relative humidity sensors using PVA and PMMA coating

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Abstract: Simple relative humidity sensors are demonstrated using tapered silica microfibers. The silica microfibers are tapered using flame brushing method to reduce the fiber’s waist diameter from 128 micrometers to 2.6 micrometers. The tapered silica microfibers were then coated using polyvinyl acetate (PVA) and polymethyl methacrylate (PMMA) before it was used to sense the relative humidity. The tapered silica microfiber coated with PVA performed better compared to tapered silica microfiber coated using PMMA. The tapered silica microfiber with PVA based sensor has better sensitivity of 0.3023 dB/RH%.

Keywords: Fiber Optic Sensor, Relative Humidity (RH), Sensor, Refractive Index (RI), Tapered Silica Microfibers, Polyvinyl Acetate (PVA) and Polymethyl Methacrylate (PMMA).

1. Introduction

There is a growing interest in using tapered microfiber to build environmental sensors. Tapering is the process of using a chemical, mechanical or thermal method to lower the diameter of optical fiber [1]. The results in increased sensitivity to changes in the environment of the tapered fiber caused by the evanescent mode propagation. When a fiber is tapered, a portion of the light that usually travels through the core radiates into the outside of the fiber creating the evanescent mode and a larger power loss compared to ordinary fiber [2]. The tapered region of single mode fiber behaves like a multimode fiber since light is flowing through the cladding layer. Thus, the surrounding environment of the fiber works as the cladding of the tapered region. This mode coupling in the tapered waist of single mode fiber makes it responsive to changes in the refractive index of its surroundings. The light guided through the cladding of the tapered fiber and affected by the changes in the surrounding environment is called evanescent mode [3].

The evanescent mode in tapered fiber makes it suitable for sensing applications, for example, sensing temperature, humidity, gases, and magnetic fields [3]. The evanescent mode is affected by changes in the fiber’s surroundings. Thus, changes in the fiber environments cause changes in the propagation characteristics of the fiber, such as power loss and peak wavelength [4]. This is the working principle of the sensors constructed for this experiment.
The increased evanescent mode with smaller diameters used to measure humidity. Since tapering causes more light to radiate in the evanescent mode, the output power of tapered fiber is highly sensitive to changes in the surrounding environment. When the relative humidity surrounding the tapered fiber increases, the refractive index of the air surrounding the tapered region changes. Additionally, the water particles in the air increase the scattering near the tapered region. Consequently, the power loss of the tapered fiber influenced by this change in humidity [5]. The changes of relative humidity in the fiber environment cause the power loss of the fiber to also increase and affect the output power of the fiber [6].

Tapering increases fiber sensors ability to measure relative humidity, as shown in the previous chapter. This sensitivity can be improved by coating the tapered region with materials that react to changes in relative humidity. The coating layer act as a new cladding layer for the tapered region since its original cladding severely diminished after flame brushing. Thus, any changes in the coatings refractive index affect the evanescent mode propagation and the power loss of the fiber [4]. In our work, we choose Polyvinyl acetate (PVA) and Polymethyl methacrylate (PMMA) due to their high sensitivity to relative humidity. The refractive index of both of PVA and PMMA changes when relative humidity increases. As a result, the propagation characteristics of the coated fiber vary with changing relative humidity [7].

In this experiment, a comparison between the performance of PVA and PMMA coated fiber was proposed. The output power of PVA coated microfiber was measured while the relative humidity was varied. These steps were repeated for PMMA coated microfiber as well. Finally, a comparison obtained based on the sensitivity with changes in relative humidity for both of the coated sample as well as bare fiber sample.

2. Experiment

2.1. Fabrication of Tapered Fiber

The setup for the process consisted of two holders for the fiber, a slider stage, two stepper motors, a microcontroller board as shown in Figure 1 [8]. Flame brushing method used to taper the fiber. The flame is using butane gas and shaped by oxygen. To prepare the tapered fiber, single-mode fiber with 128 µm diameters (SMF, Corning, 128) was used. A microscope is employed to ensure the required diameter for the tapered fiber [9].

![Figure 1. Setup for the fabrication of tapered fiber](image-url)
2.2. Experimental setup
To measure the tapering effect on relative humidity sensitivity, the following setup as per Figure 2 was proposed. Firstly, the tapered fiber was spliced into a patch cord and connected to an optical power meter on one end and an ASE (amplified spontaneous emission) light source, with a center wavelength of 1550\(\mu\)m, on the other end. Secondly, the tapered region of the sample was enclosed in a locked chamber where humidity was steadily increased using saturated salts (Sodium Hydroxide). Additionally, the relative humidity in the chamber was measured using an electronic humidity sensor for reference.

![Figure 2. The experiment setup for bare fiber testing](image)

2.3 Coating of tapered fiber with PMMA
Microfiber with a waist diameter of 2.6 \(\mu\)m is fixed since it had the highest sensitivity to relative humidity and coated with PMMA. The coating layer consists of 1 mg of crystal PMMA with 10 ml of isopropanol. These materials were mixed and heated at 100 C° with 700 rpm for an entire hour on a hot plate. The resulting solution was carefully dripped onto the microfiber sample. The coated sample was left to dry for 24 hours [7, 8, 10].

2.4 Coating of tapered fiber with PVA
To fabricate PVA, 5 mg of PVA crystals were mixed with 12 ml of distilled water. Next, the mixture was cleaned in an ultrasonic bath for 6 hours at 20° C. The resultant solution was carefully dripped onto the selected microfiber sample's tapered region and left to dry for an hour.

2.5 Humidity sensing experiment
The prepared sample was connected to a patch cord on both ends using a splicer in a closed chamber, and saturated salts are used to increase the relative humidity. The patch cord had the light of peak wavelength of 1550 \(\mu\)m and the output power were recorded using the OPM. The relative humidity inside the chamber was monitored using an electronic humidity sensor for reference. The experiment setup is shown in Figure 3.
Figure 3. Experiment setup for testing the PVA coated and PMMA coated tapered fiber.

3. Results and Discussion
The results of several samples of tapered fiber are presented in Figure 4. Based on this data, a summary of the analysis is shown in Table 1. Apparently, with an increase of relative humidity, power loss increases as well, due to the additional scattering. The water particles in the chamber change the refractive index of the surroundings of the tapered region. Thus, more light travels in the evanescent mode and the output power of the sensor are decreased, causing the changes to the output power of the tapered fiber [11]. In Figure 4, the output power of each tapered sample was recorded while varying the relative humidity from 35 % to 85% in the sealed chamber. The slope of the output power of each sample against relative humidity provides the sensitivity of the proposed sensor. Figure 4 also shows that the tapered fibers with diameter below 4 µm have greater sensitivity with peak sensitivity at 2.6 µm. The tapered fiber with diameters below 4 µm has larger sensitivity due to the larger effect of the evanescent mode that makes the sensor more susceptible to changes in its environment [12]. As the diameter of the fiber gets smaller with tapering, more light propagates in the evanescent mode outside the core. Consequently, smaller diameters are more susceptible to changes in the environment.

Figure 4. The output power of various tapering diameters with varying humidity.

The bar chart in Figure 5 depicts that the sensitivity increases with diameters below 4 µm. The highest sensitivity of 0.2367 dB/ %RH was achieved at 2.6 µm in diameter. Additionally, fibers with diameters below 4 µm performed much better than samples with larger diameters. This shows that the sensitivity of tapered fiber increases and it able to detect changes in the relative humidity.
Figure 5. The sensitivity to relative humidity variation of various tapering diameters.

In Figure 6, 7, and 8, the output power of the samples for 2.6 µm tapered fibers before and after coating with PVA and PMMA is presented. For each figure, it can be observed that the output power of the sensor against the relative humidity was increasing gradually. The samples were tested three times in humidity ranges from 35-85%RH.

Figure 6. The output power of uncoated tapered fiber with 2.6 µm diameter with varying humidity.

Figure 7. The output power of PVA coated tapered fiber with 2.6 µm diameter with varying humidity.
From the graphs above, it can be concluded that the output power decreases with the change of humidity. The PVA coating increases the total power loss by more than 3dBm and PMMA coating introduces even a larger loss of more than 12 dBm.

The analysis of the three samples is presented in Figure 9. Firstly, using coating lowers the overall output power regardless of the relative humidity. This is due to the tension, weight and insertion loss of the coated fiber. Secondly, the PVA coated sample shows an increased sensitivity of 0.3023 dB/RH% compared to the bare sample's 0.2367 dB/RH%. This shows the effectiveness of PVA coating tapered fiber in sensing relative humidity. The PVA coated on the tapered fiber acts as a new cladding layer for the tapered region. The increasing humidity in the chamber changes the refractive index of the cladding. Thus, the loss of the tapered fiber increases with the changes in humidity. The PVA coating reacts more strongly to changes in the relative humidity than air so the sensitivity of PVA coated fiber is higher [13].

On the other hand, PMMA coating shows a lower sensitivity in detecting changes in relative humidity than both bare and PVA coated fiber, with a sensitivity of 0.1936dB/RH%. Therefore, it can be observed that PVA that is coated on the tapered fiber is the most effective approach to build relative humidity sensors compared to PMMA or bare fiber.
Table 1 compares the performance of the three samples. The uncoated fiber has slightly higher linearity than the PVA and PMMA coated samples. All the methods have linearity larger than 90%, and the experiment was conducted with relative humidity between 35-85%.

Resolution of the PVA coated sample shows the best response to relative humidity changes. The bare fiber, PVA coated, and PMMA coated have fine resolution below 1 %RH. The PMMA coated sample shows the least promising performance with a resolution of 0.5 %RH. PVA coating improves the resolution of the sensor by a factor of two. Finally, this shows that coating bare tapered fiber by PVA able to increase its sensitivity and resolution as a relative humidity sensor.

Table 1. Performance analysis of tapered fiber performance as a relative humidity sensor.

|                | Diameter 2.6 μm | 2.6 μm PVA | 2.6 μm PMMA |
|----------------|-----------------|------------|-------------|
| Sensitivity (dBm/ %RH) | 0.2367         | 0.3023     | 0.1936      |
| Linearity (100%)       | 96.1300         | 94.19      | 97.34       |
| Standard deviation (dBm) | 0.0223         | 0.01734    | 0.1142      |
| Resolution (%RH)       | 0.0942          | 0.0574     | 0.5899      |
| Range (% RH)           | 35-85           | 35-85      | 35-85       |

The experiment was repeated three times for all the samples. From graphs 10, 11 and 12, the PVA coated sample shows good repeatability compared to the uncoated fiber and the PMMA coated fiber. This is due to the fact that the PVA coating is solidified around the tapered region providing additional support to its fragile structure. The fragile nature of uncoated tapered fiber more prone to bending and behaving unexpectedly.

Figure 10. The output power of uncoated tapered fiber in three runs.
4. Conclusion
The accuracy of relative humidity measurements is vital to many industries. Current electronic relative humidity sensors are susceptible to electromagnetic interference and do not work well in volatile environments. Fiber optics based sensors provide a solution to these challenges. Due to their stability, small size, cost, and immunity to electromagnetic interference fiber optics cable can work as relative humidity sensors. In this proposed work, relative humidity sensors were fabricated using tapered fiber optics cable. The performance of several tapered samples of diameters ranging from 10 to 2 μm was tested where samples with diameter below 5 μm had a larger sensitivity in detecting changes in relative humidity and the sample of 2.6 μm is having the highest sensitivity of 0.2367 dB/RH%. This sample size was fixed for testing the effect of PVA and PMMA coating. The results showed that PVA coating increases the sensitivity of the tapered sensors to 0.3023 dB/RH% from the bare fiber’s sensitivity of 0.2367 dB/RH%. However, the sample coated with PMMA showed the lowest sensitivity of 0.192 dB/RH%. The experiment was repeated for another three times for all the samples. The PVA coated sample shows good repeatability compared to the uncoated fiber and the PMMA coated fiber. This is due to the fact that the PVA coating is solidified around the tapered region providing additional support to its fragile structure. The fragile nature of uncoated tapered fiber is more prone to bending and behaving unexpectedly.
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