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Effect of Size and Humidity Variations on Rhenium Disulfide-coated Fiber Optic Humidity Sensors: Experimental Analysis and Performance Evaluation

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ABSTRACT

The correlation between humidity control, measurement, and daily human life is significant. Precise humidity measurement plays a crucial role in various applications, including industrial manufacturing, agricultural output, environmental monitoring, and food safety. Leveraging the unique electronic and optical properties of rhenium disulfide (ReS_2), a two-dimensional material, a coating of ReS_2 is applied on the surface of the fiber optic sensor. The experiment begins with fabricating tapered optical fibers using the pull-heat method to achieve diameters of 4 µm, 7 µm, and 10 µm. The tapered fiber was then connected to a tunable laser light source and an Optical Spectrum Analyzer to assess sensor performance under humidity levels ranging from 40% to 80% RH. The sensor's performance was analyzed in terms of sensitivity and linearity. The results indicate that tapered fibers with diameters of 4 µm, 7 µm, and 10 µm coated with ReS_2 exhibit increased sensitivity compared to non-coated fibers. Notably, the 10 µm ReS_2-coated fiber demonstrated the highest improvement of 6–8% under the tested RH range. In conclusion, coating optical fibers with ReS_2 enhances sensor sensitivity, making the sensors more effective for environmental humidity sensing.

Keywords: *Fiber optic sensor, humidity sensor, rhenium disulfide, ReS_2 coating, optical properties*

1. INTRODUCTION

The moisture content of the air, often indicated by relative humidity (RH), is a critical environmental factor. %RH represents the percentage of the actual vapor pressure in the air compared to the saturated vapor pressure at the same temperature. Accurate measurement and effective control of humidity are essential in various fields such as food storage, environmental monitoring, industrial automation, agriculture, ecological preservation, and weather forecasting [1][2]. In addition, improper humidity levels can significantly impact human health, increasing the risk of respiratory infections and other illnesses. Traditional humidity measurement devices include mechanical hygrometers, wet and dry bulb systems, cold mirrors, infrared absorption instruments, and electronic sensors (capacitive and resistive [3]). In contrast to conventional measurement techniques, optical fiber humidity sensors are increasingly valuable in diverse applications due to features such as compact size, light weight, adaptable placement, heightened sensitivity, and resilience to electromagnetic disturbances [4]. Enhanced sensing capabilities are typically sought after to boost sensitivity, broaden the measurement range, and minimize temperature-related interference. In this objective, an experimental demonstration was proposed to study the characterization of an optical fiber sensor tailored for the measurement of relative humidity in the range of 40% to 80%. The sensor utilizes a specially coated sensing element integrated into the optical fiber structure, enabling the measurement of RH through wavelength shifts and power in decibels relative to one milliwatt (dBm).

The sensing element's coating is carefully selected and formulated to exhibit changes in optical properties in response to variations in RH levels. Specifically, when exposed to different RH conditions, the coating undergoes changes in refractive index or absorption characteristics, leading to measurable alterations in the transmitted light through the optical fiber [5].

The measurement principle of the sensor is based on the analysis of two key parameters, which are wavelength shift and power in dBm. The wavelength shift is determined by monitoring the changes in the spectrum of the transmitted light, which can be correlated with RH levels. Moreover, the power in dBm provides additional information about the intensity of the transmitted light, offering another dimension for RH measurement and analysis [6].

Fiber optic humidity sensors have gained considerable attention for potential across diverse applications, prompting ongoing research endeavors aimed at enhancing sensor performance [7]. Over the years, various humidity sensor types, encompassing capacitive, resistive, and optical variants, have been developed. Researchers have concentrated on identifying optimal sensing materials for fiber optic humidity sensors based on fiber optics [8]. Rhenium disulfide (ReS_2), characterized by unique electronic and optical properties in a two-dimensional structure, has emerged as a promising coating material for such sensors. The anisotropic properties of ReS_2, stemming from the ReS_2 exhibits a chain-like crystal configuration that induces direction-dependent light propagation along and perpendicular to the chain axis. Consequently, the coating presents two distinct refractive indices, η_x (chain direction) and η_y (perpendicular direction), with $\eta_x \neq \eta_y$. [9] Light polarized at an angle ϕ relative to the chain axis encounters an effective refractive index given by

$$\eta_{eff}(\phi) = \eta_x \cos^2\phi \; + \; \eta_y \sin^2\phi \qquad (1)$$

RH produce shifts in each principal index, $\partial\eta_x/\partial RH$ and $\partial\eta_y/\partial RH$. The resulting effective index change follows

$$\frac{\partial\eta_{eff}(\phi)}{\partial RH} = \frac{\partial\eta_x}{\partial RH}\cos^2\phi \; + \frac{\partial\eta_y}{\partial RH}\sin^2\phi \qquad (2)$$

Optimal sensitivity results when guided-mode polarization aligns parallel to the axis with the larger $\partial\eta/\partial RH$, thereby maximizing humidity-induced index change. This analysis clarifies how ReS_2's in-plane anisotropy enhances sensor performance [10]. The sensing mechanism of ReS_2-based fiber optic humidity sensors relies on alterations in the electronic or optical properties corresponding to varying humidity levels. Overall, ReS_2-based sensors exhibit potential in applications such as environmental monitoring and industrial processes, indicating a potential transformative impact on humidity sensing technologies [11].

2. METHODOLODY

The procedure commences with the fabrication and preparation of tapered fiber. Tapered fibers with diameters of 4 µm, 7 µm, and 10 µm, are selected, with waist length ranging from approximately 5 mm to 6 mm.

2.1. Synthesis of ReS_2 Solution

The ReS_2 solution utilized in this study was prepared following the method described in the previous work [12]. Briefly, 200 mg of ReS_2 powder (Nanjing Muke Nano Technology Co., Ltd.) was dispersed in a solvent mixture of 60 ml ethanol and 20 ml deionized water. The dispersion was stirred at room temperature for 30 min at 300 rpm using a magnetic stirrer to achieve a concentration of 2.5 mg/ml. Subsequently, the solution underwent 12 hours of ultrasonication followed by centrifugation at 4000 rpm for 12 minutes to remove large sediments.

2.2. Fabrication and Preparation of Tapered Fiber

Figure 1 illustrates the schematic of the fabrication technique for tapered fiber utilizing the heat and pull method. The manufacturing process of the Microfiber (MF) involved the use of standard 62.5 µm fiber, executed by the computer through the application of Fiber tapering software.

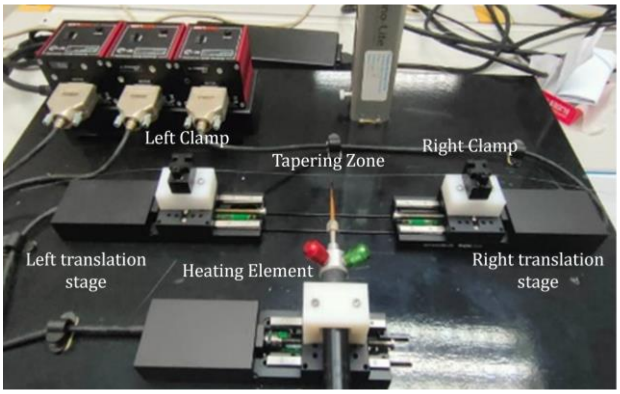


Figure 1. The taper fiber fabrication setup.

To start the manufacturing process, a 20 cm long optical fiber was prepared by carefully removing the cladding at the central portion. The exposed region was then cleaned using acetone. Then, the program in the computer is activated to start the fabrication process. Program initialization is completed when the green indicator light on the screen fades. Once initialized, the required fabrication parameters are entered into the system, followed by selecting the "calculate" function to configure the fabrication timer. Subsequently, the "initialize" command is executed to position the equipment accordingly. The cleaned optical fiber was attached onto the apparatus, and the hatch is securely closed. Ensure a straight optical cable is used before commencing the heating procedure.

Then the gas was activated, ensuring the connection is tightly secured to prevent leaks. The oxygen valve was turned until the meter bar exceeded 20 psi, then it was closed to reduce the risk of spontaneous combustion.The gas and oxygen valves was slightly adjusted on the fabrication equipment and the flame was ignited using a spark. A small amount of gas and oxygen was used to prevent sudden combustion and to avoid burning the optical fiber. The gas and oxygen levels was adjusted to produce a blue flame. Finally, the heat-and-pull technique began.

Throughout the procedure, the gas and oxygen pressures were adjusted to maintain the flame. If the flame was too intense or too faint, the optical cable could shatter. Once completed, both notches were turned off. Figure 2 shows the applications and optical fiber sizes utilized in the heat and pull method of optical fiber production.

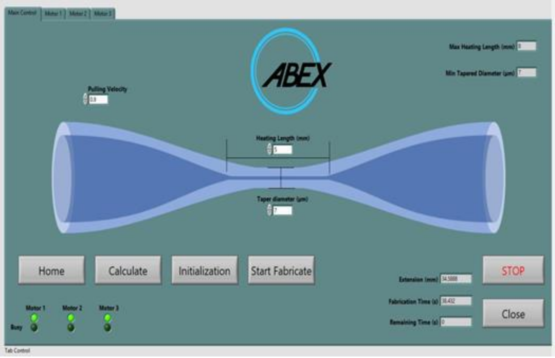


Figure 2. Software fabrication for tapering process.

The tapered fiber has been inspected under Dino Lite Microscope with magnification of 448.5 as depicted in Figure 3.

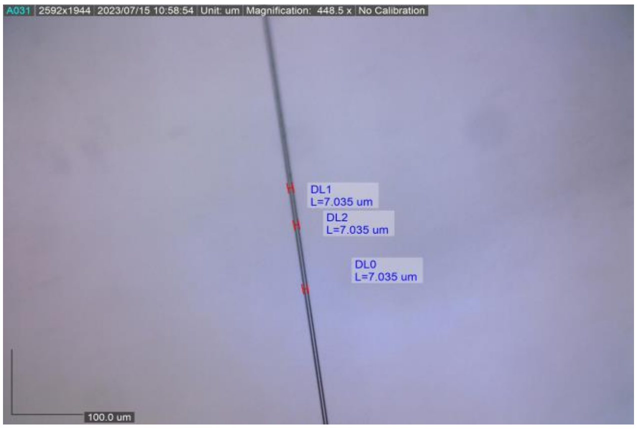


Figure 3. Sample for 7 μm tapered fiber.

2.3. Experimental Setup

Then, the microscope slide will be placed in the chamber and each end of the samples will be spliced and connected with a connector using Sumimoto Electric Type-81C Fusion Splicer. The humidity chamber was prepared to create controlled humidity environments for testing the sensor. Then, the samples were connected to the tunable laser light with 1550 nm laser source input and Optical Spectrum Analyzer (OSA) as the output to observe the effect of tapered size with humidity as shown in Figure 4.

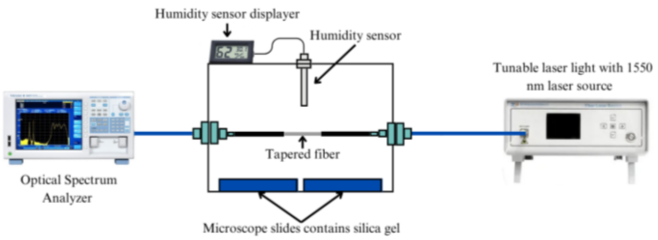


Figure 4. Humidity experimental setup for testing.

The chamber was designed to maintain stable and adjustable humidity levels within the desired range, typically from 40% to 80% for humidity sensor testing. Proper installation is crucial for obtaining accurate and reliable sensor readings. Upon completing data collection for the 4 μm tapered fiber, the subsequent step involves applying a coating of ReS_2 for a duration of 1 hour. This process was then replicated for the 7 μm and 10 μm tapered fibers in subsequent experiments [13].

Controlling humidity levels in the chamber for testing the fiber optic humidity sensor involves strategic use of desiccants and water to achieve and maintain specific humidity conditions [14]. To reduce humidity levels to 40%, silica gel, a well-known desiccant, was employed. Placing silica gel in a container within the sealed chamber allows the desiccant to gradually absorb moisture from the air, effectively lowering the humidity as shown in Figure 5. The rate at which the silica gel achieves the target humidity depends on factors such as chamber volume and initial humidity. Monitoring with a hygrometer ensures the desired humidity is reached and sustained.

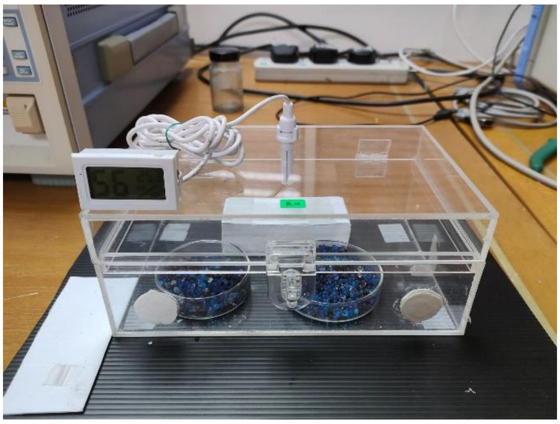


Figure 5. The silica gel inside the humidity chamber.

Conversely, raising the humidity within the chamber requires the addition of deionized (DI) water. This can be done by adding a controlled amount of DI water, either as liquid or vapor, which evaporates into the air, raising the moisture content and thus the humidity level [15]. The rate of evaporation and resulting humidity increase depend on factors like chamber temperature and water surface area. Monitoring during this process is crucial to ensure the desired humidity level is achieved and maintained. These precise humidity control methods ensure accurate testing and calibration of the fiber optic humidity sensor, validating reliability and performance under varying humidity conditions [16].

After conducting the testing of the fiber optic humidity sensor in the controlled humidity chamber, the results were collected and analyzed to evaluate the sensor's performance. The sensor's response to changes in humidity levels, including wavelength shift and power in dBm, was recorded using appropriate measurement equipment such as OSA [17]. The recorded data was saved in a CSV (Comma-Separated Values) file format for further analysis and visualization.

The sensor sensitivity is defined as the change in transmitted optical power per unit change in relative humidity:

$$\text{Sensitivity}=\frac{\Delta P_{RH}}{\Delta \text{RH}} \qquad (3)$$

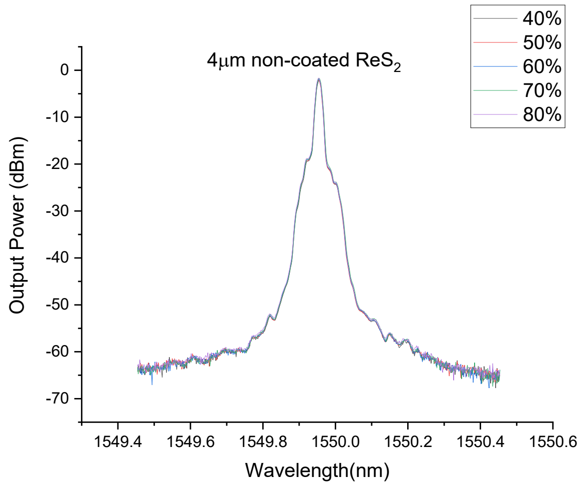
Where each transmitted power P_{RH} (dBm) is obtained from the amplitude of the spectral dip at the resonance wavelength, and ΔRH denotes the change in relative humidity between two setpoints. Thus, sensitivity quantifies the slope of the OSA-measured power-versus-humidity response.

3. RESULT AND DISCUSSION

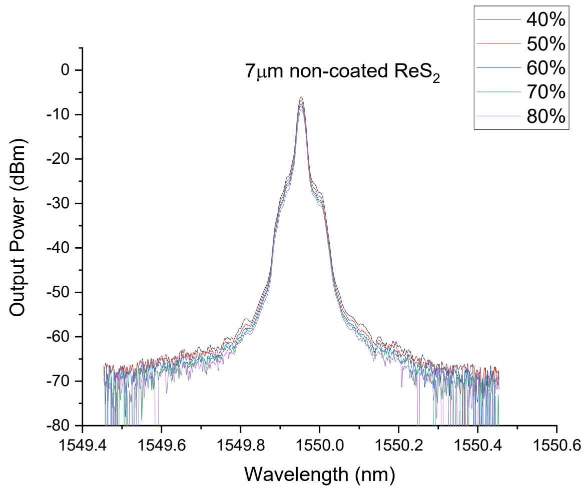
The experimental setup involved testing fiber optic humidity sensors with different diameters (4 µm, 7 µm, and 10 µm) with and without ReS_2 coating. This test aimed to evaluate the sensors' performance in detecting and responding to variations in humidity levels. The sensors without coatings served as a baseline for comparison, while the sensors with ReS_2 coatings were expected to exhibit enhanced sensitivity to humidity changes due to ReS_2's hygroscopic properties.

During the testing process, the sensors were subjected to controlled humidity conditions within a range of 40% to 80%. The response of each sensor was measured and recorded using OSA, capturing parameters such as wavelength shift and power in dBm. However, the resulting negative dBm readings arise because insertion losses, splice and coupling losses, and additional attenuation from the ReS_2 coating reduce transmitted power through both coated and uncoated tapered fibers below the 1 mW reference. The collected data will be analyzed for further analysis.

Figure 6 shows the performance of each tapered fiber size under various relative humidity concentrations. Based on graph trends, the output power for each size is almost the same, which is in between 0 to -10dBm. In term of wavelength plotted, the wavelength for 7 µm is unstable compared to 4 µm and 10 µm. Furthermore, the wavelength shift for each size is slightly small approximately less than 0.002 nm for 10 µm size diameter. For example, the wavelength shifts at 1549.972 nm to 1549.974 from 40% to 80% humidity and the power increase from -4.52 dBm to -4.17 dBm with 8% increment for this size. Finally, the sensor performance can not be dependent on wavelength shift alone especially for sensitivity and linearity. The output power is the most appropriate to measure the sensitivity and linearity of the sensor [18].



(a)



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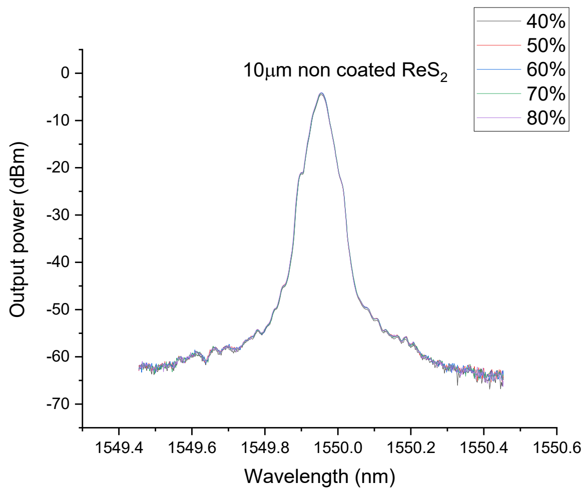

(c)

Figure 6. Output power versus wavelength for various tapered size diameter

The performance of various size diameters of tapered optical fiber is plot as depicted in Figure 7. Based on the analyses data, the sensitivity and linearity of the sensor is measured. The slope of the graph is indicated the sensitivity of the sensor shows the sensitivity of 4 µm increased more than 30% compared to 7 and 10 µm tapered optical size diameter. Based on previous studies, decreasing the tapered size diameter will increase the sensitivity of the sensor due to propagation of evanescent wave interact with the changes of relative humidity [19].

Furthermore, the sensitivity of the sensor can be improved by 50% by coated with nanomaterials like Tungsten Disulfide (WS_2), Molybdenum Disulfide (MoS_2) and ZnO [17-19]. Each material has its target in sensing likes for surface modification, improving absorption rate etc. So, in the next part of the experiment observed the performance of tapered optical fiber by coating with ReS_2. ReS_2 was selected as the coating material due to its unique 2D layered structure, which offers a high surface area for efficient water molecule adsorption. Additionally, ReS_2 exhibits fast adsorption/desorption kinetics, enabling rapid response and recovery times. Its chemical stability under ambient conditions and ease of integration via methods such as spin-coating or drop-casting further supports its suitability as an effective sensing layer for real-time optical humidity detection [20].

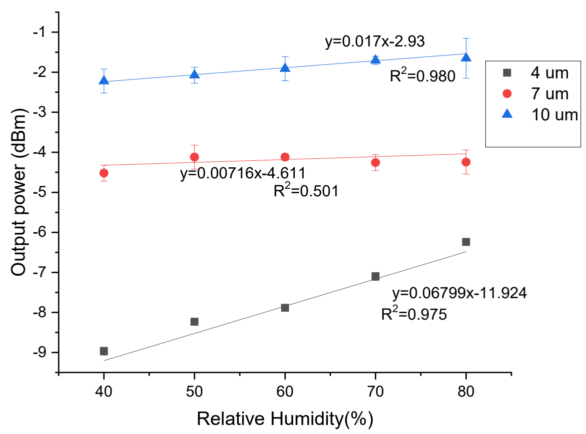

Figure 7. Output power versus relative humidity under various fiber optic size diameter

In this experiment, 20 µl of ReS_2 was deposited onto the surface of tapered optical fibers with diameters of 4, 7, and 10 µm using the drop-casting method. This technique was selected due to the fragile nature of silica optical fibers, which are prone to breakage during more invasive processes. According to the results obtained from the optical spectrum analyzer, the spectral output for the 4 µm coated tapered fiber exhibited a wavelength shift from 1550.228 nm to 1550.252 nm, along with a 6% increase in power output, as illustrated in Figure 8. However, assessing the sensor's sensitivity and linearity based solely on the wavelength shift proved to be challenging [21]. Therefore, the sensor's performance was analyzed primarily in terms of output power in response to varying humidity concentrations.

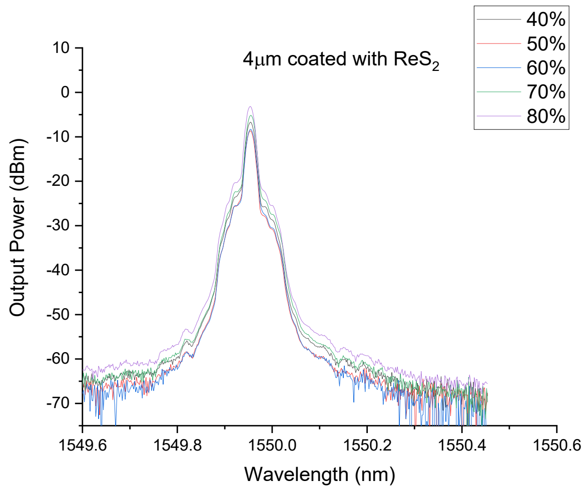

Figure 8. Power vs Wavelength for 4 µm coated ReS_2

The performance of the sensor is examined the changes of output power versus relative humidity concentration. Figure 9 plot the performance of the sensor using different tapered optical fiber size from 4, 7 and 10 µm. Based on the result in Figure 9, the output power is directly proportional to the relative humidity concentration. This result can be determined and observed by analyzing the sensitivity and linearity of coated fiber. Based on the result, the coated ReS_2 improves more 30% for each tapered size diameter. However, the linearity and sensitivity of the sensor improve more than 70% for 10 µm tapered size. The linearity is 0.988 and the sensitivity is 0.249dBm/%RH for 10 µm compared to 0.014dBm/%RH and 0.11dBm/%RH for 7 and 4 µm.

The sensor performance comparison is summarized in Table 1. Based on the results, the 10 µm is more stable for coated ReS2 compared to other size diameter in terms of the linearity and standard deviation for this size is smaller compared to the other size diameter of tapered optical fiber.

Table 1. The comparison of the sensitivity of fiber optic humidity sensors with and without a coating material.

Sensor type	Sensitivity (dBm/%RH)		Linearity(R^2)	
	Non coated	Coated	Non coated	Coated
4 µm	0.068	0.114	0.975	0.768
7 µm	0.007	0.014	0.501	0.688
10 µm	0.017	0.0249	0.9783	0.988

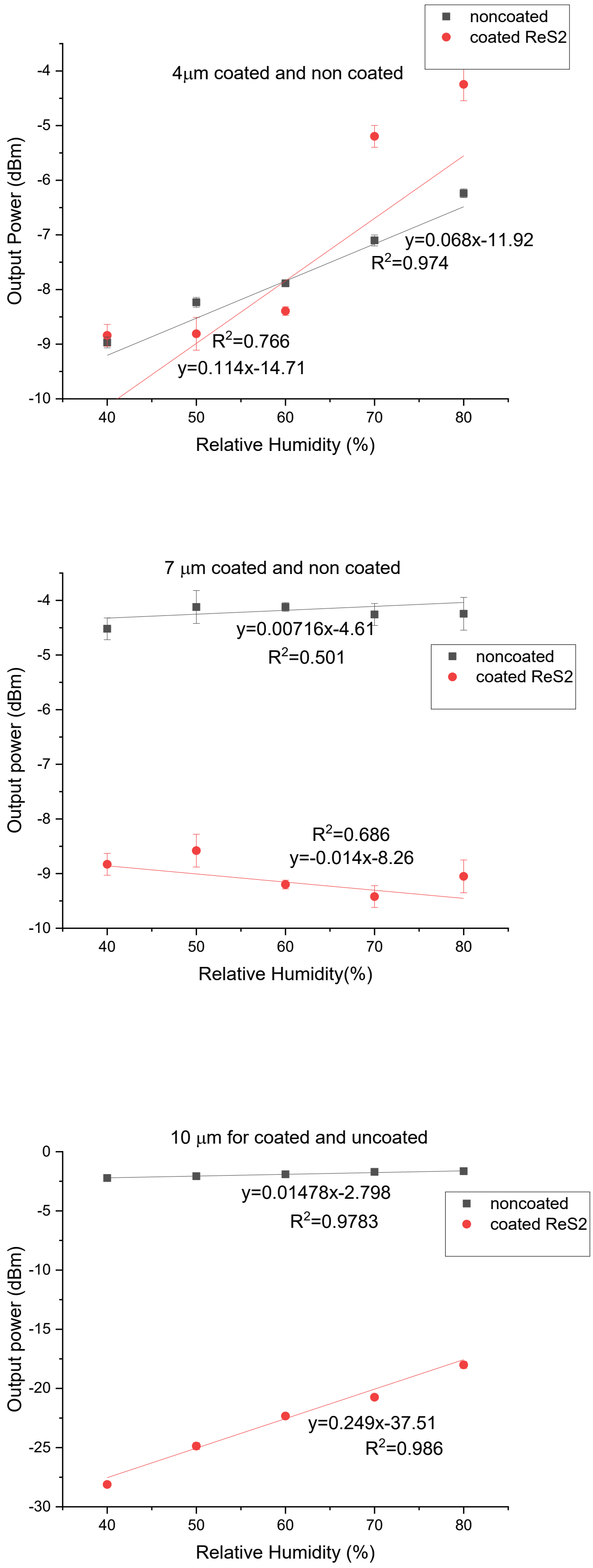

Figure 9. Output power meter versus relative humidity for coated and uncoated ReS_2

Finally, the sensor performance for each tapered size diameter was summarized in Table 1. Based on the comparison, 7 µm and 10 µm tapered fiber, the presence of ReS_2 coating can increase the sensitivity than the non-coated fiber. The ability of ReS_2 to improve sensor performance has been clearly demonstrated in this experiment. Variations in output power with increasing humidity in the ReS_2 coated fiber result from two competing processes. Moisture adsorption increases the coating's refractive index, improving evanescent field coupling and raising power at higher relative humidity [22]. At the same time, hydration increases absorption losses, causing a temporary drop in power around 50 % RH before power levels recover at higher humidity.

4. CONCLUSION

In conclusion, the performance of a fiber optic humidity sensor, particularly in relation to changes in detected power, is influenced by various factors such as sensor design, coating materials, measurement techniques, and environmental conditions. The presence of the humidity-sensitive coating, such ReS_2, can alter the sensor's optical properties, potentially affecting the detected power in response to changes in humidity levels. The relationship between humidity increases and power increase in a fiber optic humidity sensor is not always direct or predictable. Factors such as the absorption and scattering of light by the coating material, the sensing mechanism of the sensor, the measurement configuration, and the calibration of the sensor can all play a role in shaping this relationship. Based on the analysis, a decrease in power (dBm) was observed for the coated fiber exhibits a decrease in comparison to the non-coated counterpart, while the sensitivity demonstrates an increase relative to the non-coated fiber. Future work can consider evaluating long-term stability and repeatability under cyclic humidity and temperature variations will quantify calibration drift, hysteresis, and durability. These evaluations will demonstrate sensor reliability and guide design tweaks for practical, real-world deployment.

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