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Influence of Sensor Dimensions and Ambient Humidity on the Performance of ReS_2-Coated Fiber Optic Humidity Sensors

Norhafizah Burham[a], Muhammad Faris Mohd Faisal[a], Azween Hadiera Hishamuddin[a], Mahmoud Muhanad Fadhel[b], Norhana Arsad[b], Nurhafizah Abu Talip Yusof[c], Sutikno Madnasri[d], and Maizatul Zolkapli [a,*]

[a]*Photonics Engineering Research Group (PERG) Laboratory, Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam 40450, Selangor, Malaysia*
[b]*Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi 43600, Selangor, Malaysia*
[c]*Faculty of Electrical Electronics Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*
[d]*Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Sekaran, Gunung Pati, Kota Semarang, 50229, Central Java, Indonesia*
**Corresponding author: Tel.: +6-03-5543-5258; e-mail: maizatul544@uitm.edu.my*

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ABSTRACT

Optical sensors offer appealing features such as being compact and lightweight, electrically passive operation, and electromagnetic-field immunity, making them a promising tool for achieving high sensitivity and fast response in compact platforms, despite significant progress in humidity sensing. The integration of functional materials with optical fiber platforms has opened new avenues for enhancing humidity sensing performance. Therefore, in this study, the fiber-optic humidity sensors have been improved by adding a rhenium disulfide (ReS_2) coating, which leverages the material's unique electronic and optical properties as a two-dimensional compound. Several tapered optical fibers with diameters of 4 µm, 7 µm, and 10 µm were fabricated using the pull-heat method to study the effect of diameter on sensing performance. The sensors were then tested within a humidity range of 40% to 80% to evaluate their sensitivity and linearity, using a laser source and the Optical Spectrum Analyzer. The experimental result reveals that ReS_2-coated tapered fibers consistently outperform uncoated fibers in terms of sensitivity, where the fiber coated with a 10µm ReS_2 layer exhibited the most significant enhancement, achieving an increase of approximately 6-8% across the tested humidity range. The study also showed that incorporating the ReS_2 coating onto the fiber leads to a clear improvement in the performance of fiber-optic sensors for environmental humidity monitoring.

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, as it represents the proportion of water vapor present in the air relative to the maximum amount it can hold at a given temperature. Maintaining relative humidity is crucial for promoting good indoor air quality and for the health and safety of several areas and applications, including agriculture, industrial processes, meteorological monitoring, and public health. Conventional humidity sensors are typically mechanical or electronic, but optical fiber-based sensors offer several advantages, including compact design, improved sensitivity, and robust resistance to electromagnetic interference [3-4].

Fiber-optic humidity sensors have attracted significant interest due to their wide range of applications, prompting ongoing research to improve sensor performance [5]. Over time, many types of humidity sensors have been developed, including capacitive, resistive, and optical designs. Although electronic sensors are still the most widely used, fiber-optic humidity sensors offer important advantages, including small size, high durability, and safe operation in high-temperature, high-pressure, or flammable environments. Current research mainly focuses on identifying the most effective sensing materials for fiber-optic-based humidity sensors [6].

The coating on the sensing region is selected and designed to change its optical properties as humidity varies. Under varying relative humidity conditions, the coating responds by changing its refractive index and light-absorption properties. These changes affect the amount of light transmitted through the optical fiber, resulting in measurable variations in the output signal [7]. Rhenium disulfide (ReS_2) is a two-dimensional material known for its unique electronic and optical properties, and it has increasingly attracted attention as a suitable coating material for sensing applications. This is largely due to its anisotropic crystal structure, which originates from its distorted octahedral coordination. As a result, ReS2 exhibits a direct bandgap in the visible region and strong light-matter interaction [8]. Consequently, the coating exhibits direction-dependent optical properties, with different refractive indices along the chain direction (η_x) and the perpendicular direction (η_y), where $\eta_x \neq \eta_y$. For light polarized at an angle ϕ concerning the chain axis, the effective refractive index is given by:

$$\eta_{eff}(\phi) = \eta_\chi \cos^2\phi + \eta_y \sin^2\phi \quad (1)$$

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

$$\frac{\partial\eta_{eff}(\phi)}{\partial RH} = \frac{\partial\eta_\chi}{\partial RH}\cos^2\phi + \frac{\partial\eta_y}{\partial RH}\sin^2\phi \quad (2)$$

Maximum sensitivity occurs when the polarization of the guided light is aligned with the direction that exhibits the highest change in refractive index with humidity ($\partial\eta/\partial RH$), demonstrating how the in-plane anisotropy of ReS_2 improves sensing performance [9]. The sensing mechanism of ReS_2 is driven by changes in the material's electronic and optical behavior when exposed to moisture.

The ReS_2-based sensor demonstrates high sensitivity and a stable response under varying humidity conditions, with potential for use in environmental monitoring and industrial control. Their performance marks a meaningful step forward in the development of more reliable and efficient humidity-sensing technologies [10].

In the development of humidity sensors, key priorities include improving sensitivity, extending the measurable humidity range, and reducing temperature-related errors. In this study, the sensing approach is based on two main parameters, namely wavelength shift and optical power [11]. The wavelength shift reflects changes in the transmitted light spectrum across different humidity conditions, while optical power provides an additional, independent measure of light intensity. In this study, an experimentally evaluated coated optical fiber sensor for humidity measurement over the range of 40% to 80% was used, with both wavelength shift and optical power employed as the primary sensing indicators.

2. METHODOLODY

The experiment begins with the fabrication and preparation of tapered optical fibers with three different diameters, 4 µm, 7 µm, and 10 µm. Each fiber was produced with a length of approximately 5-6 mm.

2.1. Synthesis of ReS_2 Solution

The ReS_2 coating solution was prepared following the procedure reported in the earlier study [12], in which 200 mg of ReS_2 powder (Nanjing Muke Nano Technology Co., Ltd.) was dispersed in a mixture of 60 ml ethanol and 20 ml deionized water. The process produced a concentration of 2.5 mg/ml ReS_2 solution. It was then magnetically stirred at 300 rpm for 30 minutes, followed by ultrasonication for 12 hours. Finally, the solution was centrifuged at 400 rom for 12 minutes to eliminate large particles.

2.2. Fabrication and Preparation of Tapered Fiber

In this study, the standard 62.5 µm microfiber (MF) was fabricated using the heat-and-pull method, which was controlled by a computer running fiber-tapering software, as illustrated in Figure 1.

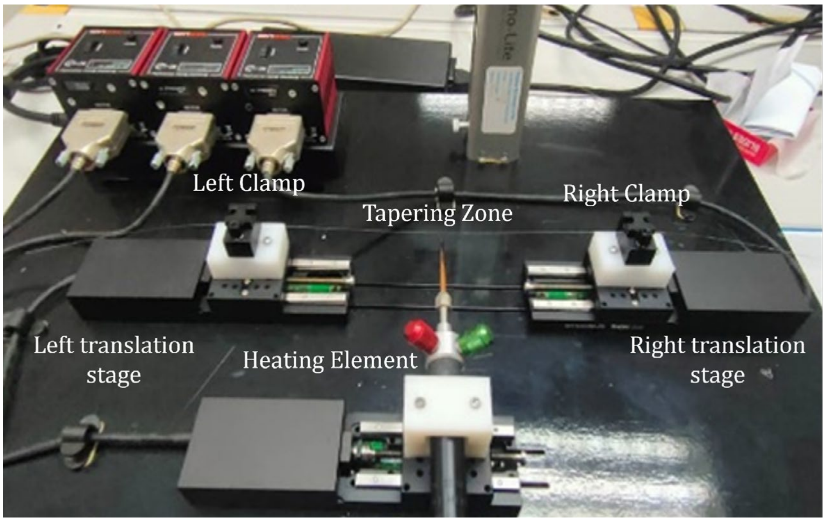


Figure 1. The fiber-tapering system is used in the heat-and-pull process.

The center-part cladding of a 20-cm optical fiber was removed and cleaned with acetone. Then, the fiber was carefully aligned and positioned at the tapering zone before heating commenced. Once the green indicator light on the software was activated, the system was ready to operate. The required fabrication parameters were then entered, and the heating duration was determined using the Calculate function.

Before the gas supply is activated, it is very important to check for any possible leaks as a safety precaution to minimize the risk of accidental combustion. The oxygen valve was briefly opened, allowing the pressure gauge to rise above 20 psi, before being promptly closed. The gas and oxygen valves were 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 were 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 used in the heat-and-pull method of optical fiber production.

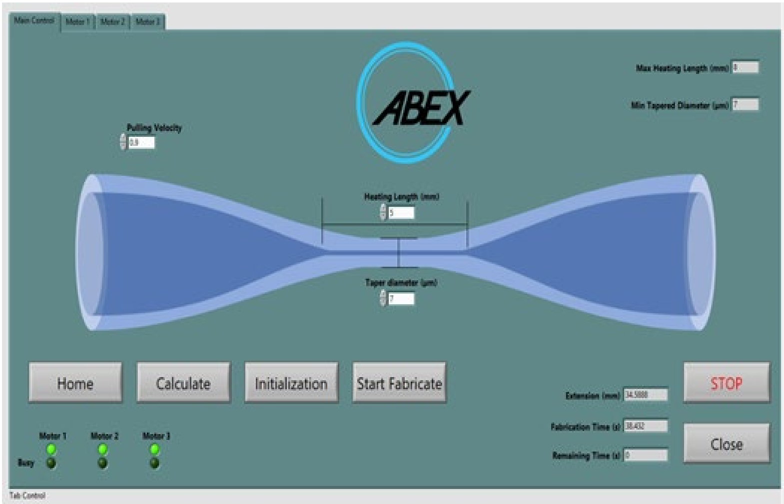


Figure 2. The software fabrication for the tapering process.

The tapered fiber has been inspected under a Dino-Lite microscope at a magnification of 448.5, as depicted in Figure 3.

Figure 3. The sample for a 7 µm tapered fiber.

2.3. Experimental Setup

Then, the microscope slide was placed in the chamber, and each end of the samples was spliced and connected with a connector using a Sumimoto Electric Type-81C Fusion Splicer. The chamber was designed to maintain stable, adjustable humidity within the desired range, typically 40% to 80%, for humidity sensor testing. Then, the samples were connected to a tunable 1550 nm laser source, with an Optical Spectrum Analyzer (OSA) as the output, to observe the effect of taper size on humidity, as shown in Figure 4.

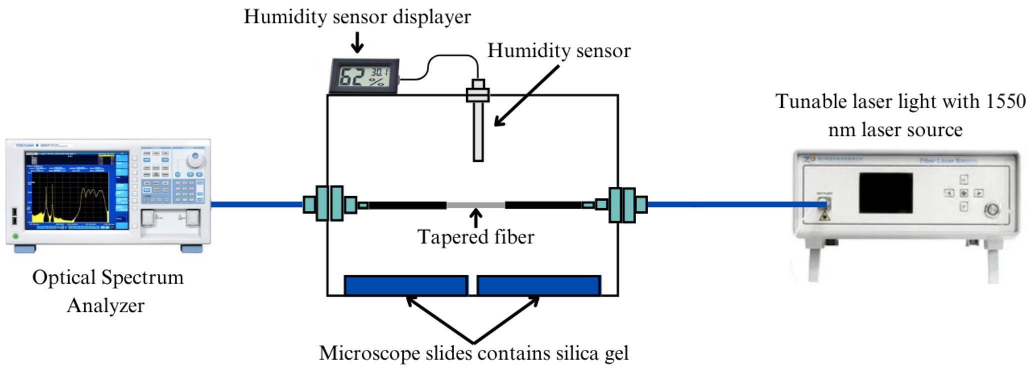


Figure 4. The humidity experimental setup for testing.

Following the initial characterization of the 4 µm tapered fiber, a ReS_2 coating was applied for one hour. The process was then repeated on the 7 µm and 10 µm tapered fibers to ensure uniformity across all samples [13].

To create various humidity conditions within the chamber, desiccant and water were combined [14]. To reduce the humidity level to approximately 40%, silica gel was placed inside the sealed chamber, as illustrated in Figure 5. The time required to reach the desired humidity level varies depending on factors such as the chamber volume and the initial humidity. Therefore, a hygrometer was used to monitor humidity until the target level was reached continuously.

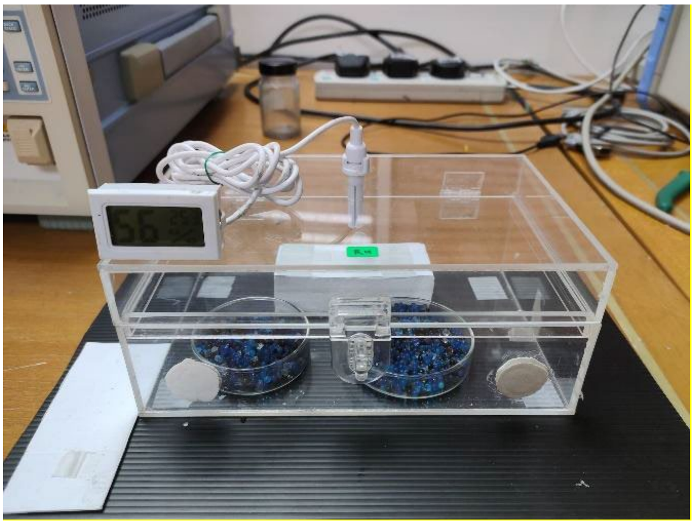


Figure 5. The desiccant is placed inside the testing chamber to control the humidity.

To increase the humidity level inside the chamber, deionized water was introduced and allowed to evaporate naturally [15]. The rate of humidity increase depends on factors such as the exposed water surface area and the chamber temperature. Continuous monitoring was conducted to ensure that the humidity level reached the desired value and remained stable, both of which are important for reliable sensor testing and accurate calibration [16].

The sensor's performance was evaluated by measuring both the wavelength shift and the optical power (in dBm) using an Optical Spectrum Analyzer (OSA) [17]. The data collected were recorded in Comma-Separated Values (CSV) format to facilitate further analysis and visualization. Sensitivity was subsequently determined using the following formula:

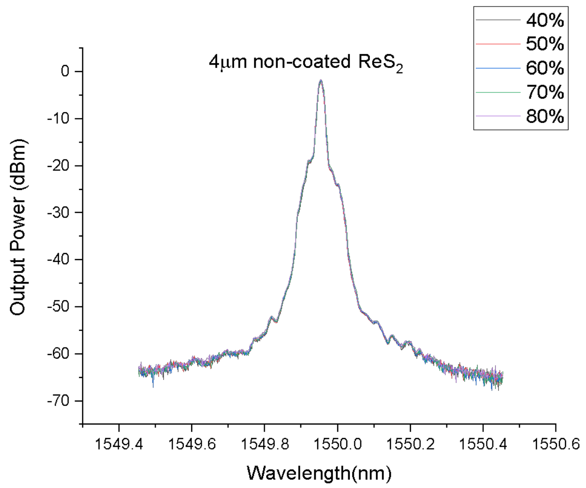
$$Sensitivity = \frac{\Delta P_{RH}}{\Delta RH} \quad (3)$$

where ΔP_{RH} denotes the change in optical power (in dBm) at the resonance dip, while ΔRH represents the variation in relative humidity. In other words, sensitivity quantifies the change in optical power per unit change in humidity, serving as a measure of the slope of the power-response curve.

3. RESULT AND DISCUSSION

In this experiment, three fiber-optic sensors with diameters of 4 µm, 7 µm, and 10 µm were used to evaluate humidity-sensing performance. Each fiber was first examined in its uncoated condition to establish a baseline for subsequent comparison. The coated versions were then evaluated, as the moisture-absorbing coating was expected to increase sensitivity. All sensors were tested under controlled humidity conditions ranging from 40% to 80%. The response of each sensor was measured and recorded using an OSA, capturing parameters such as wavelength shift and power (dBm). However, the resulting negative dBm readings arise because insertion losses, splice and coupling losses, and additional attenuation from the ReS_2 coating reduce the transmitted power through both coated and uncoated tapered fibers to levels below the 1 mW reference. The data collected will be analyzed further.

Figure 6 shows the performance of each tapered fiber size under various relative humidity concentrations. Based on the graph trends, the output power for each size is almost the same, ranging from -10 to 0 dBm. In terms of the plotted wavelengths, 7 µm is less stable than 4 µm and 10 µm. Furthermore, the wavelength shift for each size is slightly smaller, approximately 0.002 nm or less for a 10 µm diameter. For example, the wavelength shifts from 1549.972 nm to 1549.974 nm as humidity increases from 40% to 80%, and the power increases from -4.52 dBm to -4.17 dBm, with an 8% increase for this size. Finally, sensor performance cannot depend solely on wavelength shift, especially for sensitivity and linearity. Output power is the most appropriate metric for measuring the sensor's sensitivity and linearity [18].



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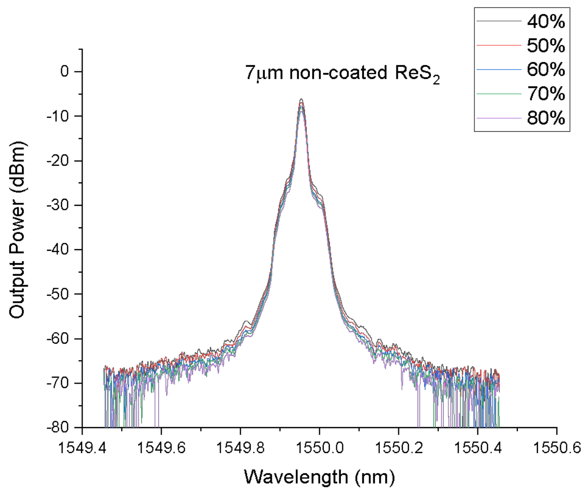

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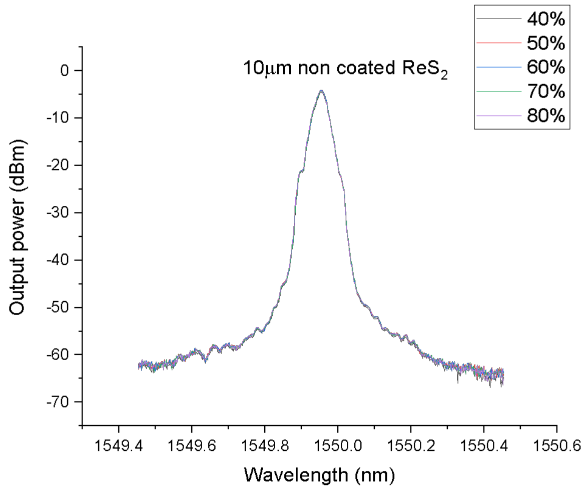


(c)

Figure 6. The output power versus wavelength for various tapered size diameters; (a) 4 µm, (b) 7 µ,m and (c) 10 µm.

The performance of tapered optical fibers with various diameters is plotted in Figure 7. Based on the analysis data, the sensor's sensitivity and linearity are measured. The slope of the graph indicates sensor sensitivity of: aµm inctaper reased morsensitivity by e than 30% compared to 7 and 10 µm tapered optical sizdiametersased on previous studies, decreasing the tapered size diameter will increase the sensitivity of the sensor due to the propagation of evanescent wave interact with the changes of relative humidity [19].

Furthermore, the sensor's sensitivity can be improved by 50% by coating with nanomaterials such as Tungsten Disulfide (WS_2), Molybdenum Disulfide (MoS_2), and ZnO [17-19]. Each material has its own target in sensing, such as surface modification or improved absorption. In the next part of the experiment, we observed the performance of a tapered optical fiber after coating it with ReS_2. ReS_2 was selected as the coating material due to its unique 2D layered structure, which provides a high surface area for efficient adsorption of water molecules. 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 support its suitability as an effective sensing layer for real-time optical humidity detection [20].

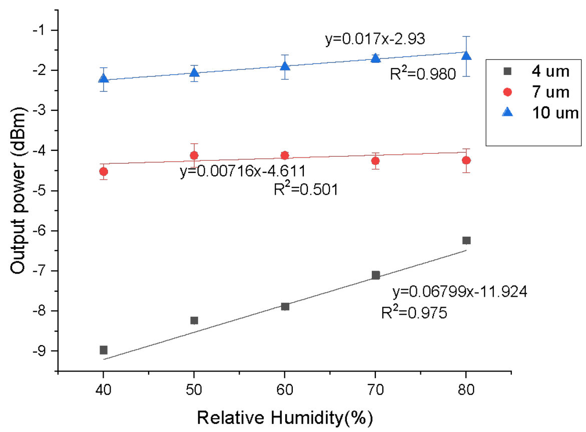


Figure 7. The analysis of power-output variation with humidity across different fiber sizes.

Using the drop-casting method, 20 µl of ReS_2 solution was applied onto. The tapered optical fibers with diameters of 4, 7, and 10 µm, as silica fibers, are fragile and prone to breaking during more invasive coating processes. Based on the data collected by the optical spectrum analyzer, the 4 µm-coated tapered fiber exhibited a spectral output change as the wavelength shifted from 1550.228 nm to 1550.252 nm, and the power output simultaneously increased by 6%, 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 as a function of varying humidity concentrations.

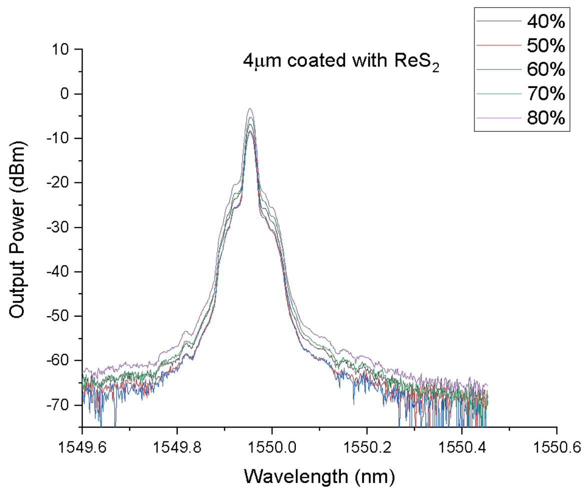


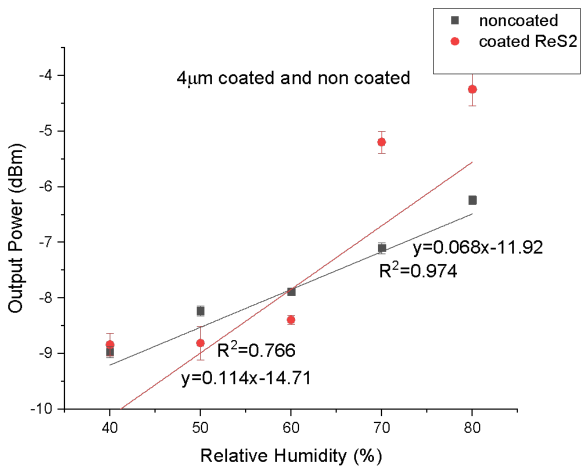
Figure 8. Power vs. wavelength for 4 μm-coated ReS_2.

Changes in output power versus relative humidity concentration are used to examine the sensor's performance. Figure 9 plots the performance of the sensor for tapered optical fibers with diameters of 4, 7, and 10 μm. Based on the results in Figure 9, the output power is directly proportional to the relative humidity. This result can be determined and observed by analyzing the coated fiber's sensitivity and linearity. Based on the results, the coated ReS_2 improves by more than 30% for each tapered diameter. However, the sensor's linearity and sensitivity improve by more than 70% for a 10 μm taper. 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 diameter is more stable for coated ReS_2 compared to other diameters in terms of linearity, and its standard deviation is smaller than that of the other diameters of the 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



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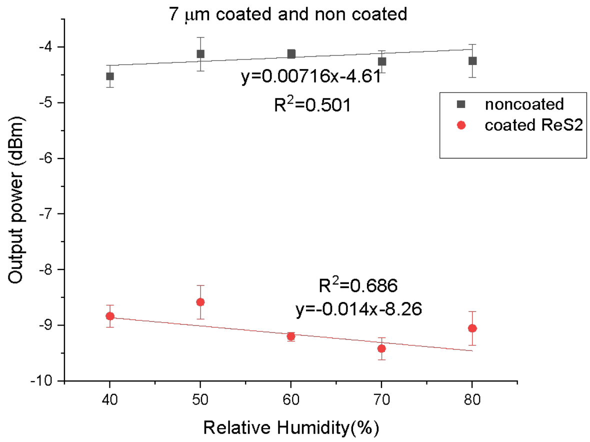

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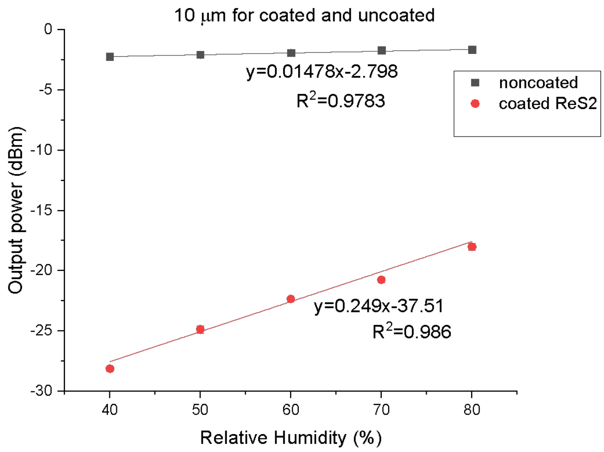

(c)

Figure 9. Output power meter versus relative humidity for (a) 4 µm, (b) 7 µm, and (c) 10 µm coated and uncoated ReS_2

Finally, the sensor performance for each tapered diameter was summarized in Table 1. Based on the comparison between 7 µm and 10 µm tapered fibers, the presence of a ReS_2 coating can increase sensitivity compared to 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 ReS2-coated fiber result from two competing processes. Moisture adsorption increases the coating's refractive index, thereby improving evanescent-field coupling and increasing 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 levels.

4. CONCLUSION

In conclusion, a fiber-optic humidity sensor's performance, particularly the change in detected optical power, depends on several factors, including sensor design, coating materials, measurement methods, and environmental conditions. The application of a ReS_2 coating alters the sensor's optical characteristics, which in turn affect the detected signal as the humidity level changes. It was observed that the relationship between increasing humidity and the corresponding change in optical power depends not only on the coating itself but also on light absorption and scattering, as well as on the overall sensing configuration and calibration procedure. Although the ReS_2-coated fiber demonstrated lower optical power than the uncoated fiber, it exhibited improved sensitivity to humidity variations. These findings suggest that the coating enhances the interaction between light and its surroundings, thereby strengthening the sensor response. Nevertheless, further investigation is required to address potential issues such as calibration drift, hysteresis, and long-term durability. Finally, to ensure consistent and reliable performance, future studies should focus on evaluating the sensor's stability and repeatability under prolonged exposure to varying humidity and temperature conditions.

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