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Enhanced Formaldehyde Sensing Performance using ReS_2-Coated Tapered Optical Fibers

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ABSTRACT

Formaldehyde (CH_2O) is a toxic, colorless gas widely used in industrial and household materials. Prolonged exposure is known to cause respiratory irritation and increase cancer risk. However, current detection methods frequently suffer from limitations such as high cost, low sensitivity, and limited portability for real-time environmental monitoring. A simple and compact tapered optical fiber sensor is fabricated and coated with Rhenium Disulfide (ReS_2). The TOFs' waist diameters vary between 5 µm and 10 µm during the fabrication process using a controlled heat-and-pull method. The coated and uncoated TOFs are tested by exposing them to formaldehyde vapor. The formaldehyde solution concentrations are varied from 1% to 5%, with relative humidity levels from 30% to 90%. The tunable laser source is set to 1550 nm, and the output is connected to the optical power meter. The results show that the 5 µm TOF exhibited higher sensitivity and stability than the 10 µm TOF, with ReS_2 coating further improving sensitivity by up to 80%. The sensor performance achieved a sensitivity of −0.05839 dB/%RH and linearity above 95%. These results show that ReS_2-coated TOFs have the potential to be an affordable, stable, and sensitive platform for formaldehyde detection in humid conditions, with applications in industrial safety and indoor air quality monitoring.

Keywords: *Tapered Optical Fiber (TOF), Rhenium Disulfide (ReS_2), Drop Casting Method, Waist Diameter*

1. INTRODUCTION

Formaldehyde (CH_2O) is a hazardous organic compound widely present in industrial and suburban ecosystems due to its use in adhesives, resins, textiles, and construction materials [1, 2]. Its presence in indoor air has raised public health concerns, as long-term exposure can cause allergic reactions and breathing discomfort. International health organizations have classed it as a human carcinogen [3]. This focuses on the urgent need for effective methods for monitoring formaldehyde levels, particularly in enclosed or poorly ventilated areas.

Conventional formaldehyde detection techniques, such as chromatography and electrochemical sensors, while accurate, often involve complex instrumentation and high costs and are not suitable for continuous or portable monitoring [2, 4]. Due to their small size, resistance to electromagnetic interference, and capacity for remote and real-time sensing, optical fiber-based sensors have attracted interest in recent years [5]–[9]. Among them, tapered optical fibers (TOFs) are especially appealing because the tapering process increases the interaction between light and the surrounding environment through evanescent field enhancement.

Existing formaldehyde sensing methods have limitations, including low sensitivity, high cost, and limited applicability across varied environments. The development of tapered optical fibers (TOFs) coated with Rhenium Disulfide (ReS_2) offers a promising solution. Because of its unique optical and electrical characteristics, such as an adjustable bandgap and great sensitivity to changes in refractive index, ReS_2 improves sensing capabilities. [10].

This paper aims to evaluate the performance of TOF as a sensor for formaldehyde detection by varying the waist diameter and examining the effects of coated and uncoated ReS2 on the sensor's enhanced sensitivity for real-time environmental gas monitoring.

2. FABRICATION AND EXPERIMENT SETUP

This section discusses the fabrication of TOFs and the experimental setup used to assess the sensor performance.

2.1. Fabrication of Tapered Optical Fiber

The TOF was fabricated using the heat-and-pull method, with a heating length of 3 mm, waist diameters of 5 µm and 10 µm, and a pulling velocity of 0.5 m/s. The mixture of oxygen (O_2) and butane (C_4H_{10}) gases was manually adjusted to control the heat source. Heat was applied to the fiber core to soften the fiber surface. At the same time, both ends were simultaneously pulled using motorized stages to control tension and ensure uniform tapering, as illustrated in Figure 1.

The fabrication process for the 5 µm TOF required 58 seconds, while the 10 µm TOF required 46 seconds. The 10 µm TOF was examined using a Dino Lite Microscope at 510× magnification, as depicted in Figure 2.

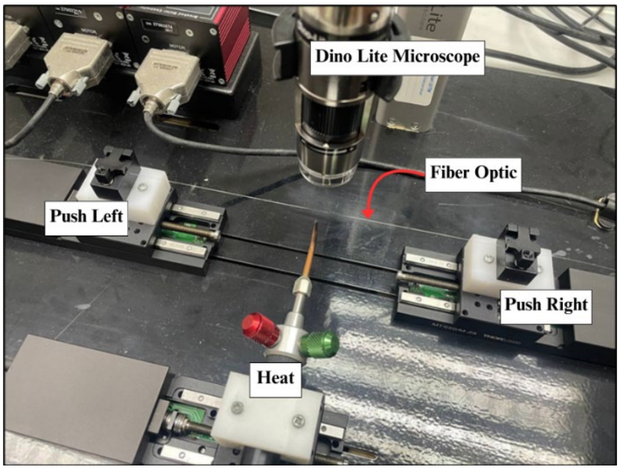


Figure 1. Taper optical fiber fabrication setup.

Figure 2. Dino Lite Microscope images for measuring 10µm TOF.

The fabricated TOF was then placed on a glass slide and spliced to connect both ends of the fiber to FC connectors. This step is essential to ensure low insertion loss and dependable optical transmission.

After splicing, initial performance tests were conducted to verify that the tapered optical fiber was properly fabricated and aligned for the intended application. The estimated insertion loss after splicing was 0.01 dB for both the 5 µm and 10 µm TOFs.

2.2. Experiment Setup

Firstly, the formaldehyde was diluted with DI water. The concentration varied from 1% to 5%. This concentration range is chosen to study the limit of detection of formaldehyde vapor for the TOF sensor. The calculation for the dilution of the formaldehyde is based on this equation [11] :

$$M_1V_1=M_2V_2$$

M_1 denotes the molarity of the concentrated solution, V_1 represents the corresponding volume, M_2 indicates the molarity of the diluted solution, and V_2 corresponds to its volume. For each prepared concentration (1%–5%), the total solution volume was fixed at 100 mL.

The experimental setup for formaldehyde sensing using a tapered optical fiber (TOF) is illustrated in Figure 3. Firstly, the TOF on the glass slide was placed inside a sealed chamber. Both ends of the fiber were connected to a tunable laser source (AQ2201 Frame Controller) and a Thorlabs Optical Power Meter, which was linked to a PC to monitor the output power in real time.

The uncoated TOF was performed first to assess its ability to detect formaldehyde at different concentrations and relative humidity (%RH) levels. The uncoated TOF was placed in the custom chamber, and the optical system operated at 1550 nm. This is a common operating wavelength with low attenuation in silica optical fibers [12].

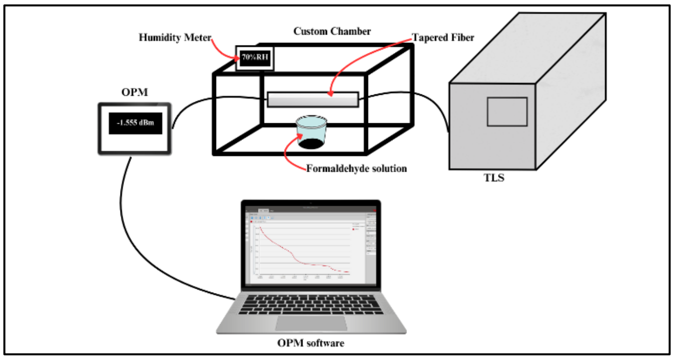


Figure 3. Experiment setup for TOF formaldehyde sensing.

The RH level inside the chamber was lowered below 30% using silica gel. A 1% formaldehyde solution was placed in the chamber when this baseline was reached. Data collection began after the RH reached 30%, and measurements were recorded at each RH increment up to 90%. This process was repeated for formaldehyde concentrations of 2%, 3%, 4%, and 5%.

The aforementioned step was then applied to ReS_2-coated TOFs for performance comparison. Both S1a (5 µm) and S1b (10 µm) samples were tested under identical conditions, as listed in Table 1.

Table 1 The parameters of the tapered optical fiber

TOF sample number	Heating Length (mm)	Waist Diameter (µm)
S1a	3	5
S1b	3	10

To ensure sensor stability, the TOFs were exposed to 90% RH and a formaldehyde solution in the chamber for 600 seconds. OPM software was used to continuously monitor output power and regulate the ambient temperature to maintain a consistent relative humidity.

2.3. Coating Procedure

The coating and characterization procedure involved applying a layer of Rhenium Disulfide (ReS_2) onto the tapered optical fiber (TOF) and assessing the coating quality and optical response. This coating process was performed before the ReS_2-coated TOF experiments.

As shown in Figure 4, the coating was done using a drop-casting method. A micropipette was used to apply 20 µL of ReS_2 solution directly onto the tapered region of the fiber until it was fully covered. After that, the fiber was left to dry for almost 2 hours to ensure the solvent had completely evaporated. The Photonic Laboratory at Universiti Kebangsaan Malaysia (UKM) developed and synthesized the ReS_2 solution.

The coating process with a ReS_2 solution significantly affects the optical transmission characteristics of the tapered optical fiber (TOF). Before coating, the TOF exhibited an output power of −1.66 dBm, indicating low air loss due to minimal external perturbation. When the ReS_2 solution was dropped onto the TOF, the output power decreased drastically to −31.66 dBm as depicted in Figure 5. This sharp attenuation is attributed to the change in the surrounding refractive index from air to a liquid, which alters the distribution of the evanescent field. Stronger contact between the directed light and the external medium in a liquid environment leads to greater scattering and absorption, thereby reducing the transmitted power. The deposited layer alters the local refractive index surrounding the tapering. So, the comparison between uncoated and coated TOF is based on sensor performance in terms of sensitivity, linearity, and limit of detection.

After coating, the fiber surface was characterized to assess the consistency and coverage of ReS_2 using imaging techniques. Detailed characterization results are discussed in the Results section.

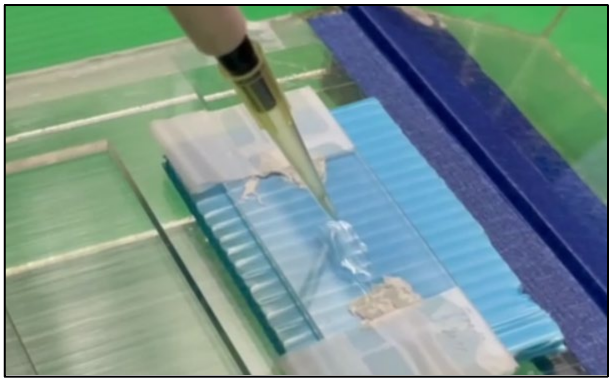


Figure 4. 20µL ReS_2 coating process on the TOF area.

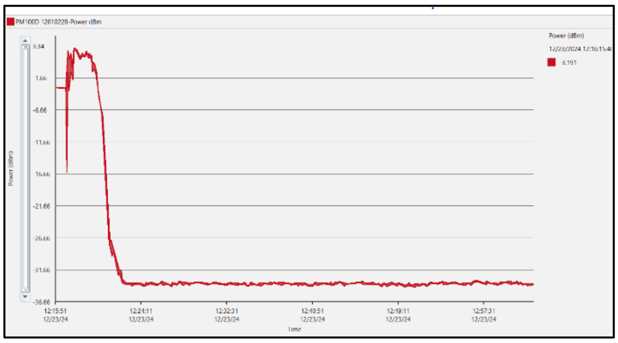
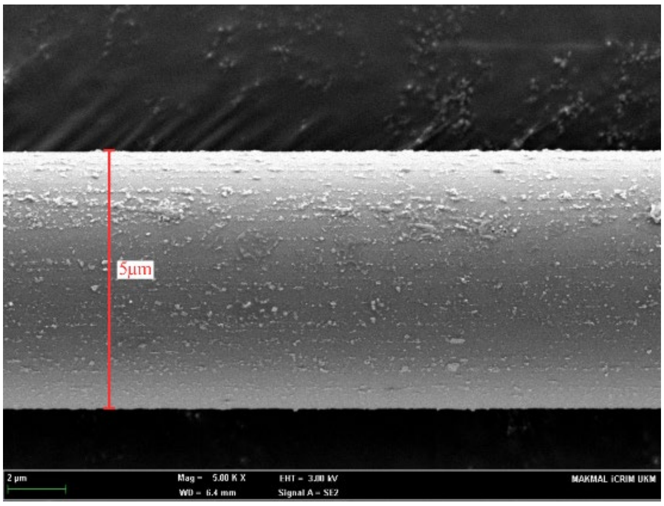


Figure 5. ReS_2 coating output power result during the drop casting process.

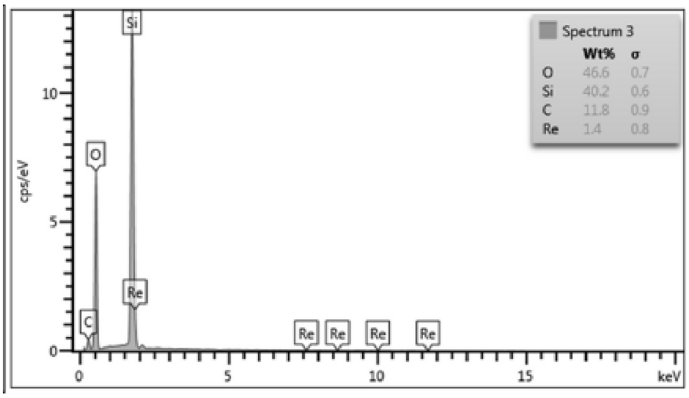
3. RESULT AND DISCUSSION

The first part of the experiment discussed the characterization of ReS2 coated on a tapered optical fiber. Following this, the same TOFs were coated with 20 µL of ReS_2 solution via drop-casting to assess the effect of surface modification on sensing performance. The surface morphology of the ReS_2 nanostructure was examined using field-emission scanning electron microscopy (FESEM). Imaging was performed using a ZEISS SUPRA 55VP at 3.0 kV, as shown in Figure 6.

For the 5 µm TOF, a clear nanoflake-like ReS_2 coating was observed using FESEM. To corroborate the elemental composition, energy-dispersive X-ray spectroscopy (EDX) was conducted, as shown in Figure 6 (b). The presence of rhenium (Re) was confirmed with a weight percentage of approximately 1.4%. A similar characterization procedure was carried out for the 10 µm TOF, with FESEM and EDX confirming the successful deposition of ReS_2 nanostructures on both fiber diameters. To further investigate sensor performance, a comparative analysis of sensitivity and linearity was conducted for both TOF sizes at a 5% formaldehyde concentration. Figure 9 illustrates the dynamic response of the TOFs across the 30%–90% RH range for both uncoated and ReS_2-coated conditions.



(a)



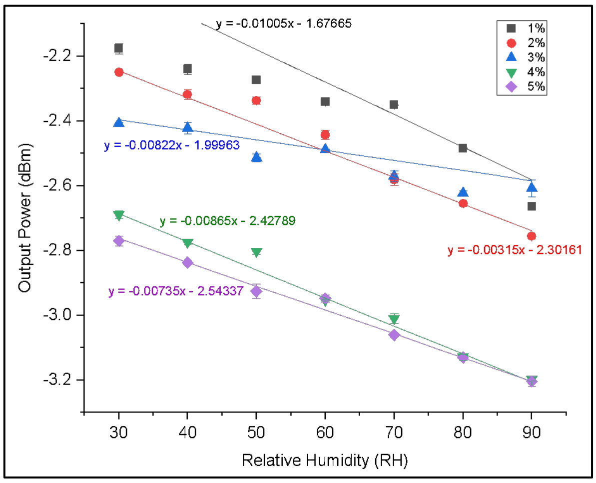
(b)

Figure 6. ReS_2 surface morphology with (a) FESEM and (b) EDX analysis.

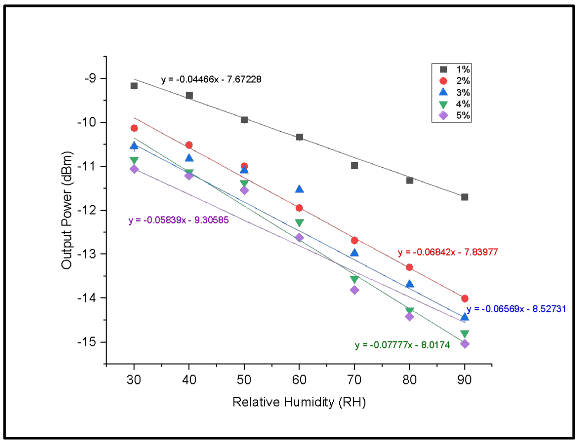
This section discusses the performance of uncoated TOFs with waist diameters of 5 µm and 10 µm under controlled environmental conditions. The experiments were conducted at room temperature (25 °C), and the chamber humidity was initially maintained at 20% RH using silica gel to minimize moisture interference.

Formaldehyde concentrations ranging from 1% to 5% were introduced, and measurements were taken across increasing humidity levels from 30% to 90% RH. The optical power output was measured with the Optical Power Meter (OPM), and the results for both uncoated and ReS_2-coated 5 µm TOFs are presented in Figure 7.

The data shows that output power decreases as relative humidity increases. All investigated formaldehyde concentrations showed a similar inverse association. Due to increased light scattering and stronger evanescent-field interactions caused by the ReS_2 coating, a larger power loss of about 7% was observed for the coated TOF, from −2.2 dBm to −9 dBm.



(a) uncoated TOF



(b) coated TOF

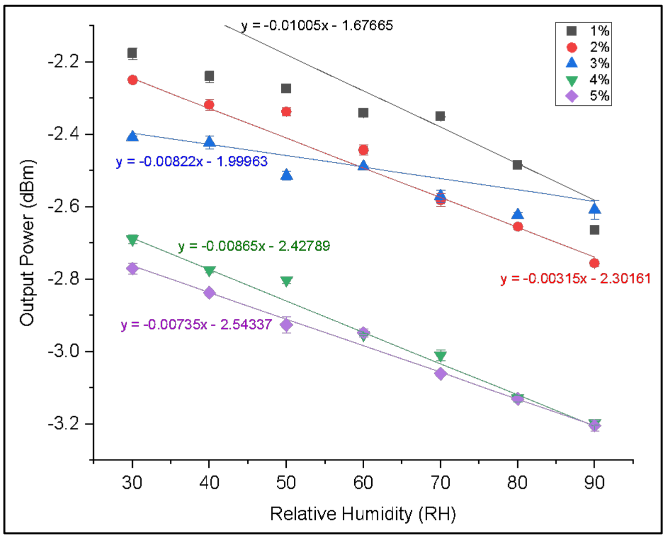
Figure 7. The analyzed results for coated and uncoated 5µm TOF.

As humidity increases, surrounding water molecules modify the refractive index near the tapered optical fiber. This alters the evanescent-wave interaction, enhancing light absorption by water molecules and reducing transmitted power, thereby confirming the TOF's sensitivity for humidity-dependent optical sensing applications. This trend is consistent with earlier research demonstrating the high sensitivity of tapered optical fibers to ambient humidity, particularly due to changes in light propagation caused by moisture buildup.[13]– [16].

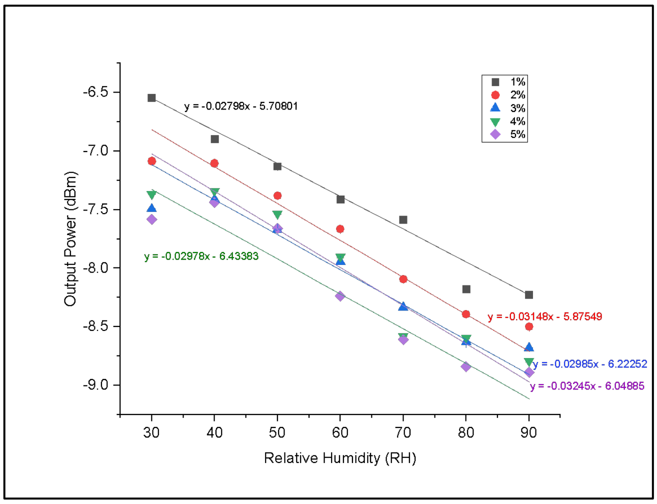
The following part of the experiment focused on evaluating the performance of the uncoated 10 μm TOF. The same formaldehyde concentrations (1%–5%) were tested under relative humidity (RH) conditions ranging from 30% to 90%. The observed trend was consistent with the 5 μm TOF, in which output power decreased as RH increased. This inverse relationship is shown in Figure 8.

Among all tested concentrations, the 10 μm TOF at 1% formaldehyde exhibited the highest output power, differing by approximately 20%–30% from the other concentration levels. The slope of the output power for 1% concentration was the smallest, indicating lower sensitivity. In contrast, the 2% and 4% concentrations produced similar responses, with slopes of −0.00203 dB/%RH and −0.00201 dB/%RH, respectively.

Overall, the comparison shows that the 5 μm TOF consistently outperformed the 10 μm TOF in terms of output power and sensitivity. For both TOF sizes, the 5% formaldehyde concentration yielded the lowest output power, further confirming the inverse correlation among formaldehyde concentration, humidity, and transmitted optical signal.



(a) uncoated



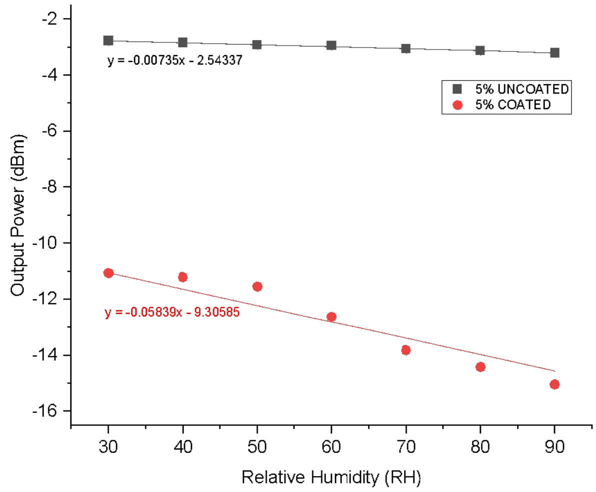
(b) coated

Figure 8. The analyzed results for coated and uncoated 10 μm TOF.

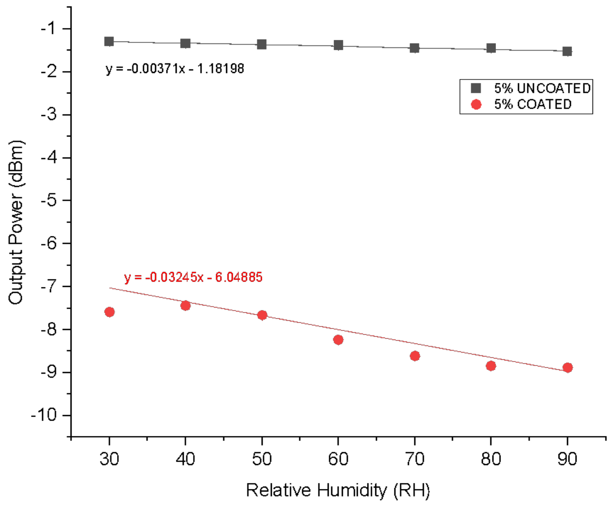
The coated 5 μm TOF (S1a) showed an 80% improvement in sensitivity compared to the uncoated version, achieving −0.05839 dB/%RH versus −0.00735 dB/%RH. For the 10 μm TOF (S1b), coating with ReS_2 improved sensitivity by 60%, from −0.00371 dB/%RH to −0.03245 dB/%RH.

This performance enhancement is attributed to increased interaction between the evanescent field and the ReS_2 coating. Tapered optical fibers modify the geometry of the core, enabling the evanescent field to extend a short distance beyond the fiber surface. At the interface between

two materials, a portion of the light is reflected, while the remainder generates an evanescent wave that decays exponentially. These waves are particularly useful in structures that allow total internal reflection because they can penetrate to depths of tens of nanometers. [17],[18].
The results from S1a and S1b confirm that the 5 µm TOF provides higher sensitivity than the 10 µm TOF. This trend is consistent with previous findings by Erem Ujah et al., who reported better performance with thinner TOFs [19]. Further improvement in sensitivity has been demonstrated in other studies for diameters as small as 3 µm [20]. In general, reducing TOF diameter increases sensitivity but also introduces higher loss due to greater light interaction with the surrounding medium.



(a) 5µm TOF



(b) 10µm TOF

Figure 9. Comparative of TOF performance: 5% formaldehyde for uncoated vs coated ReS_2.

Previous studies have reported that surface modification of optical fiber sensors with nanomaterials such as ZnO, MoS_2, and WS_2 can significantly enhance sensitivity and linearity for humidity and formaldehyde detection. Coating the modified optical fiber, whether tapered or reshaped into a U-configuration, has been shown to increase sensitivity by approximately 20%-50% [20], [21]. Because of its unique optical characteristics, the inclusion of ReS_2 further enhances sensor performance. Strong light propagation and effective interaction with incident light are made possible by ReS_2's direct bandgap of about 1.5 eV. When deposited on the tapered optical fiber (TOF) surface, the evanescent field extending from the fiber core interacts directly with the ReS_2 layer, thereby enhancing optical coupling at the interface. Additionally, the presence of ReS_2 alters the local refractive index, producing detectable changes in optical transmission.

Finally, sensor stability was evaluated for both coated 5 µm and 10 µm TOFs under formaldehyde concentrations ranging from 1% to 5% at 90% RH over a 600-second duration. As shown in Figure 10, all sensors maintained stable output power, with minimal slope variations ranging from −0.0001727 dBm/%RH to 0.000002165 dBm/%RH. These findings demonstrate the stability and repeatability of the proposed sensor configuration.

Table 2 summarizes the sensitivity and linearity values for coated TOFs. As expected, coating with ReS_2 significantly enhanced the sensing performance.

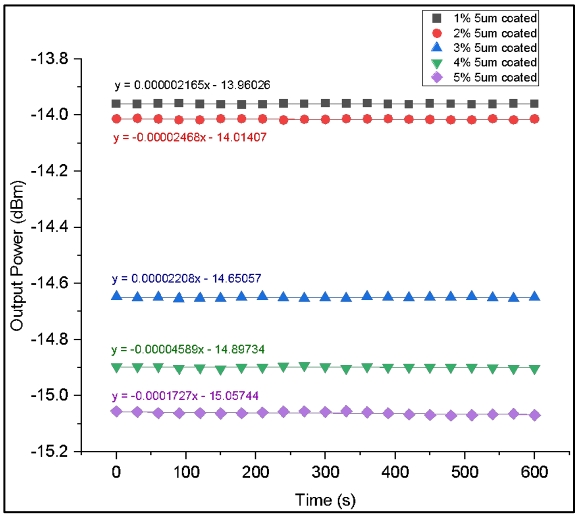


Figure 10. Stability results for coated 5 μm TOF for 600s.

Table 2 Summary of uncoated and coated (5μm and 10μm) TOF

TOF sample number	Waist Diameter (μm)	Type of Deposition	Humidity Range (%RH)	Sensitivity (dB/%RH)	Linearity
S1a	5	Uncoated	30 - 90	-0.00735	0.99951
S1a	5	ReS_2 Coated		-0.05839	0.95647
S1b	10	Uncoated		-0.00371	0.98357
S1b	10	ReS_2 Coated		-0.03245	0.75817

4. CONCLUSION

This study supported the feasibility of using ReS_2-coated tapered optical fibers (TOFs) for formaldehyde exposure under changing humidity conditions. TOF waist diameters of 5 μm and 10 μm were fabricated using the heat-and-pull approach before and after coating with ReS_2 nanomaterials in synthesis, and observed by varying formaldehyde solution concentration. The experimental results showed a consistent inverse relationship between output power and relative humidity for all formaldehyde concentrations. The 5 μm TOF demonstrated higher sensitivity than the 10 μm TOF, and coating with ReS_2 enhanced sensor performance by up to 80%. The coated sensors also demonstrated good linearity and excellent stability over 600 seconds at 90% RH. These findings confirm that ReS_2-coated TOFs, particularly those with smaller diameters, offer a promising platform for real-time, reliable formaldehyde detection in humid environments. The results also support the potential for integrating such sensors into portable environmental monitoring systems.

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