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Optimization of tapered microfiber humidity sensors with molybdenum disulfide coating

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ABSTRACT

This study focuses on developing and optimizing a new optical sensor using tapered microfiber (TMF) for humidity sensing in the 30-80% Relative Humidity (%RH) range. The TMF was fabricated with varying heating lengths (3-6 mm) and waist diameters (3-7 µm), and its performance was tested using a tunable light source and an optical power meter. Results showed that a 5 mm TMF with a 3 µm waist diameter provided the best stability and sensitivity for humidity sensing. Additionally, coating the TMF with Molybdenum Disulfide (MoS_2) nanoflakes improved sensitivity by 20-50%, with an error margin of less than 5%. The optimized sensor achieved a sensitivity of -0.244 dB/% and over 97% linearity, demonstrating its potential for precise humidity detection in environmental applications.

Keywords: *Tapered microfiber; Humidity sensing; Two dimensional materials; Molybdenum Disulfide*

1. INTRODUCTION

Tapered microfibers (TMFs) have significantly advanced humidity sensing due to their enhanced sensitivity, compact size, and adaptability across various environmental conditions [1, 2]. TMFs utilize the unique properties of optical fibres, such as their small size, flexibility, and precise light-guiding capabilities, to detect humidity changes [3-5]. These sensors improve the interaction between light and the surrounding environment, measuring variations in properties like intensity, phase, or polarization [6].

TMFs are primarily fabricated from silica using the heat-and-pull technique [7-9], and their sensitivity is often enhanced by applying coatings, such as polymers [10], metals [11], or other inorganic materials [12]. Recent innovations incorporate two-dimensional materials (2DMs), including molybdenum disulfide (MoS_2), which significantly improve the sensitivity and specificity of TMFs in humidity sensing [13-16]. MoS_2's tunable band gap and layered structure enhance light interaction through the evanescent field, making it highly responsive to humidity changes [17].

According to Samy et al. (2021), MoS_2's unique properties, such as its direct band gap in thin layers and high surface area, make it ideal for coating TMFs and improving optical sensing performance. Additionally, the drop-casting method provides a practical approach for applying MoS_2 coatings to TMFs for enhanced sensing capabilities [18].

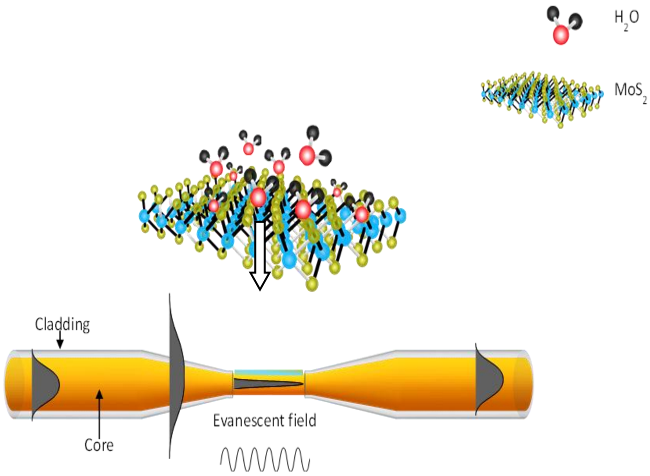


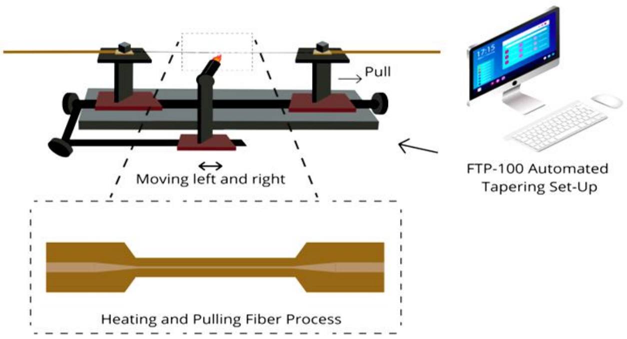
Figure. 1. Interaction between the evanescent field of light and a TMF coated with MoS_2.

This study investigates how TMF dimensions (waist length and diameter) affect humidity detection and evaluates the enhancement of sensor sensitivity using MoS_2 coatings. The findings contribute to the development of next-generation optical sensors with improved performance for environmental monitoring and air pollution detection.

2. EXPERIMENTAL SETUP

2.1. Fabrication and Optimization of TMF

Figure 2 (a) depicts the conceptual configuration of the TMF fabrication process, illustrating the setup of a tapered fibre optic system with the computer interface displaying relevant information during the tapering procedure. The fabrication of a single-mode tapered microfibre was conducted utilising ABEX Medical System Sdn. Bhd.'s optical glass processing workstation, model FTP-100 Automated Tapering Set-Up, which has the capability to deliver precise tapering with a high degree of accuracy and exceptional consistency as depicted in Figure 2(b). Approximately 5 cm of the fibre was excised at its midpoint and thereafter affixed onto fibre holding blocks to ensure proper alignment and orientation. The heat-and-pull method, in conjunction with a real-time control system, was employed for the fabrication of a tapered microfibre (TMF).



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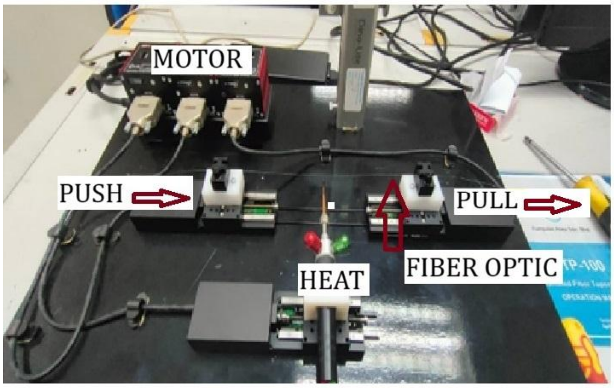
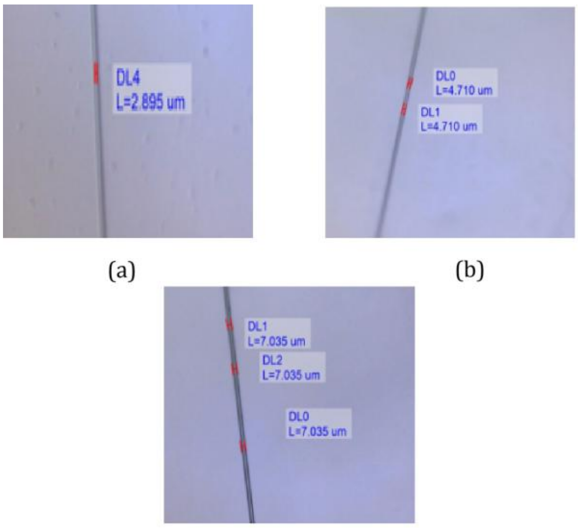


(b)

Figure 2. The tapered fibre optic for a (a) schematic and (b) actual setup

In the initial phase of the experiment, the heating length of the TMF sensor was systematically altered in increments of 3, 4, 5, and 6 mm. This was done to investigate the impact of waist length on the performance of the sensor, utilising the ThorLab Optical Power Meter. Following the optimisation of the waist diameter, the experiment proceeded to the subsequent phase, wherein the fabrication of TMFs with approximately varying diameters of 3, 5, and 7 µm was undertaken. The schematic of the optical fibre after the tapering procedure is depicted in Figure 3 using Dino Capture 2.0 with magnification 448.5×.



(a) (b) (c)

Figure 3. Dino Capture 2.0 images of the tapered optical fibre with size diameters approximatelyt 3, 5 and 7 µm

2.2. Experiment Setup for Humidity Sensor

The experimental procedure commenced with the placement of the TMF onto the glass substrate. Figure 4 illustrates the schematic diagram for sensing humidity. The laser light source was configured to emit a laser at a wavelength of 1550 nm, and a photodiode laser power meter was attached at the ends of the TMF via pigtails. A bespoke acrylic humidity chamber was constructed with the purpose of regulating humidity levels within the range of 30% to 80% and maintaining a constant temperature of 25 °C. In this study, the humidity was controlled manually using silica gel to decrease the humidity in the chamber. The data pertaining to output power were acquired from an optical power meter (OPM) (ThorLab PM100) and analysed using specialised software provided by the manufacturer. In this study, the measurements were conducted in triplicate, and the average value was computed to enhance the precision of the sensor's performance evaluation.

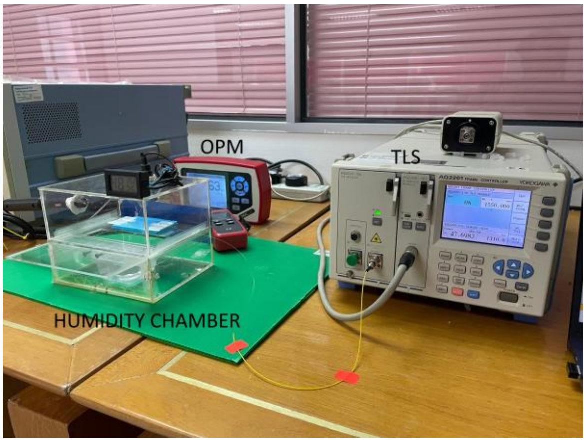


Figure 4. Experiment setup for sensing humidity

According to Wen Zhang et al., TMF structures, such as the length and diameter of the sensor region, create different sensing characteristics for various application situations due to physical changes in the surrounding environment [19]. Thus, sensor performance was examined by evaluating the sensitivity and linearity through experiments using these TMFs. After completing this analysis, the experiment proceeded to enhance the sensor performance using Two-Dimensional Materials (TMDs), such as MoS_2. Research on two-dimensional materials like graphene, silicon, germanene, and transition metal dichalcogenides (TMDCs) like MoS_2, WSe_2, or WS_2 has developed independently due to their potential applications in electronics [20]. Furthermore, in recent years, thin 2D semiconductors with controllable band gaps and doping have been exploited in optoelectronic devices such as photodiodes, solar cells, and light-emitting diodes [21]. In this experiment, MoS_2 from Graphene Supermarket was coated on the sensing/tapered area using the drop-casting method. MoS_2 exhibits a strong evanescent field interaction under ambient conditions to confine light within the fibre core [22]. The performance before and after coating 20 µl of MoS_2 on the TMF was analysed using an OPM by analysing the sensitivity and linearity of the sensor at different humidity concentrations from 30% to 80% RH.

Table 1. The parameters of the tapered fibre

TMF sample number	Heating length (mm)	Waist Diameter (µm)
S1a	3	3
S1b	4	3
S1c	5	3
S1d	6	3
S1c1	5	3
S1c2	5	5
S1c3	5	7

The performance of the TMF was analysed by varying several TMF geometrical parameters, such as TMF length and diameter, as stated in Table 1. Finally, experiment was conducted to investigate how light propagates through the TMF structure.

3. RESULT AND DISCUSSION

In the first part of the experiment, the heating length of the sensor region was investigated to examine the performance of the sensor. The heating length of the sensor region was manipulated by 3, 4, 5, and 6 mm to determine the optimal length for a humidity sensor. This parameter is based on previous research by Bakhtiar Musa et al., which investigated the effect of tapered length on temperature sensitivity and stated that 4 mm obtained the highest sensitivity [23]. Based on observations, the output power is inversely proportional to the %RH for different lengths of the sensor region, as depicted in Figure 5. The taper profile S1b, with a length of 4 mm, gives the highest sensitivity at -0.233 dB/%RH, which is 3% higher compared to 5 mm when varying the humidity from 30% to 80%. However, the sensor performance decreases by 70% to 80% for lengths of 3 mm and 6 mm. At the end of the first experiment, it was found that decreasing the tapered length improves the sensor performance, but a too-short sensor region will decrease the sensor performance. The 4 mm and 5 mm tapered lengths have highest sensitivity for humidity sensor applications across various sizes of TMF. However, TMF length 5 mm is chosen for the next experiment due to its stability and consistency as a sensor. Based on data fitting analysis, the R^2 of 5 mm and 4 mm is 1 and 0.9667, respectively, which can be illustrated the linearity of the sensor.

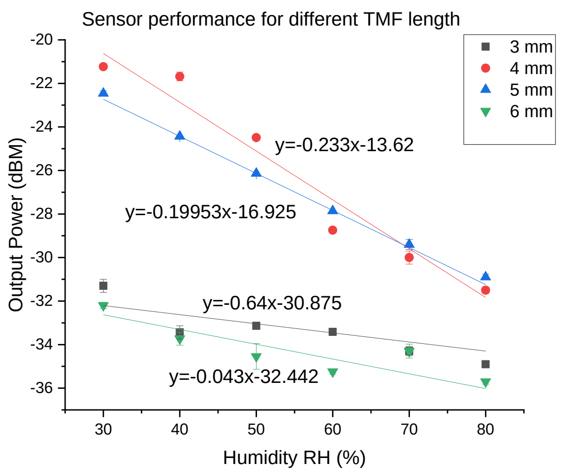


Figure 5. Humidity sensor for different tapered length fibre

For the second part of the experiment, the tapered length was maintained at 5 mm while the tapered diameter size was varied among 3, 5, and 7 µm across a range of 30% to 80% relative humidity (%RH). This observation is illustrated in Figure 6, which shows that the output power is inversely proportional to the relative humidity. The optical fibre with a 3 µm diameter exhibited the highest sensitivity, at -0.195 dBm/%RH, making it 17% more sensitive compared to the 5 and 7 µm TMF sizes.Meanwhile, the sensitivity of the 5 µm TMF increased by 0.5% compared with the 7 µm. Based on these findings, the diameter size of the TMF affects the performance of the humidity sensor, as corroborated by previous researchers [18, 24], to improve the sensitivity and linearity of the sensor. Furthermore, while previous research reported that the optimum TMF for humidity sensing was 2 µm, this research finds that a 3 µm TMF performs approximately 5% better compared to the previous study for 2 µm TMF [18].

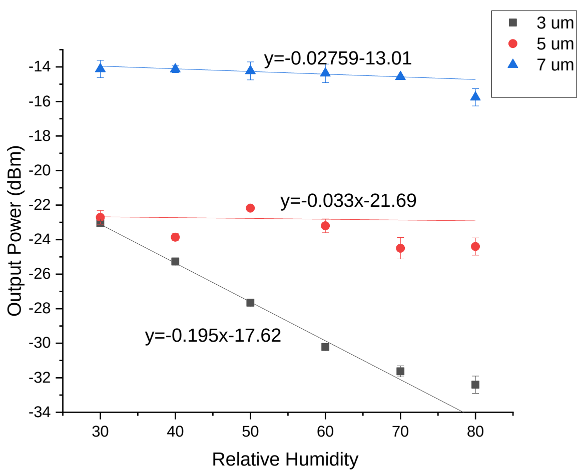
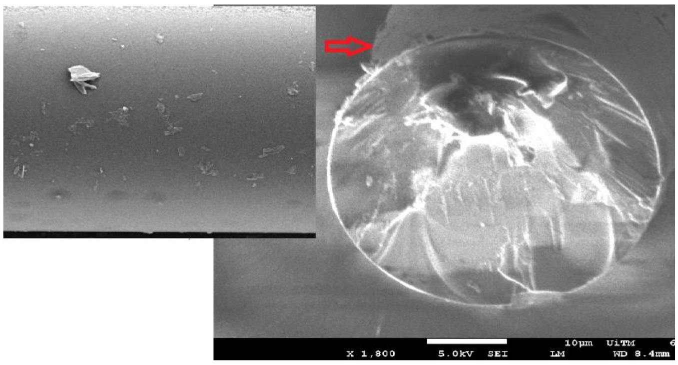


Figure 6. Humidity sensor performance by varying TMF size diameter

The third experiment highlights the performance of the sensor by coating the sensor area with metal oxide, which is MoS_2. To perform this experiment, the same TMF from sample S1c1-S1c3 was used and coated with 20 µl MoS_2 nanoflakes using the drop-casting method under room temperature. The surface morphology of the MoS_2 nanostructured is observed by field emission scanning electron microscopy (FESEM) image obtained using ZEISS SUPRA 55VP operated at 3.0 kV source as shown in Fig. 7 (a). The nanoflakes structure of MoS_2 is translucency obviously coated on the surface of 10 µm TMF. Furthermore, to confirm MoS_2 nanoflakes presents on the TMF surface, the sample performed an energy dispersive X-ray analyzer (EDX) as a result in Fig. 7 (b). Based on the EDX report, Mo and S exist in this sample with wt% 3.1 and 4.2. The comparison performance between coated and uncoated TMF is analysed to observe the performance of the sensor and will be discussed in the next part of the research.



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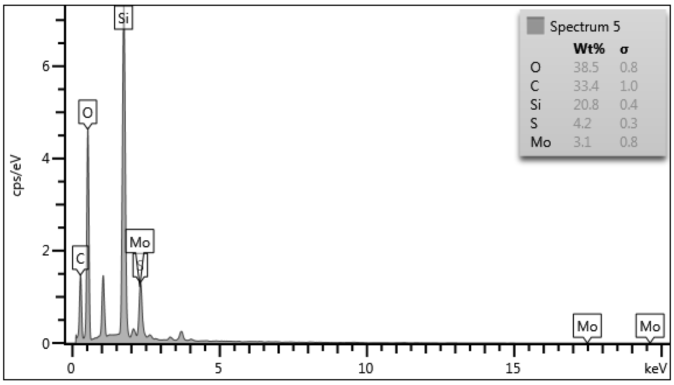


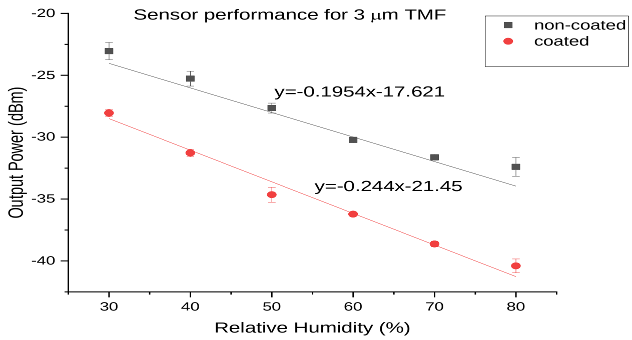
(b)

Figure 7. Cross section and Surface Morphology with EDX Analysis of a TMF Coated with MoS_2

By observing, the same samples, S1c1-S1c3, were used to examine the performance of the sensor by coating the TMF with MoS_2 materials. This experiment was performed at room temperature (25 °C). Figure 8 shows the dynamic response of the TMF to humidity with a 20 µl MoS_2 coating compared to an uncoated TMF. Based on the observations, S1c1 (3 µm) TMF exhibited higher sensitivity compared to samples S1c2 and S1c3. The comparative performances of these three samples are plotted in Figure 8. According to these results, the sensitivity of the coated TMF improved by 20-50% compared to the uncoated TMF.

According to the results, TMF alters the geometry of the fiber optic, allowing the evanescent wave to persist for a very short distance from the interface between TMF and the water molecule. When a beam of light strikes an interface between two materials, it reflects some of the light and transmits others. At the interface, the transmitted light generates an evanescent wave that decays exponentially with distance from the interface. These oscillating waves can penetrate tens of nanometres, particularly on surfaces with 100% internal reflection.

Finally, the performance of the humidity sensor is summarised in Tables 2, 3 and 4 based on the experiment that has been conducted according to the density and linearity of coated and non-coated TMF.



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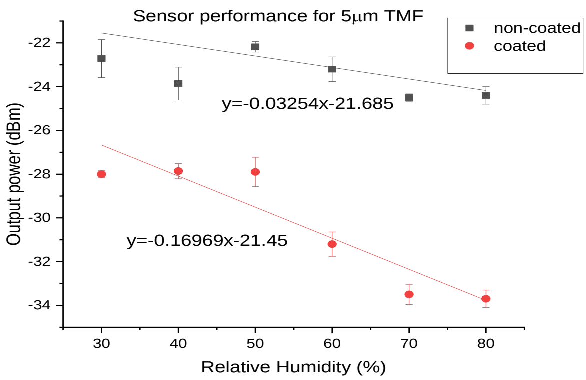

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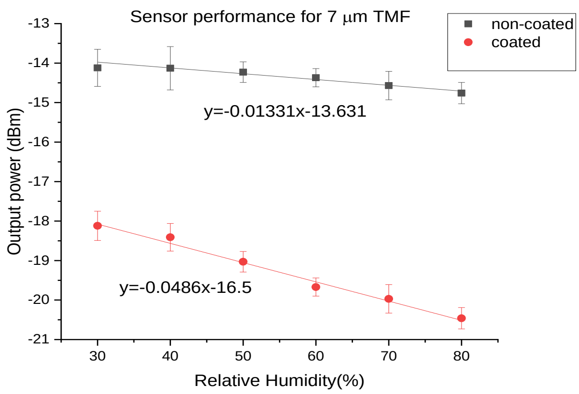

(c)

Figure 8. Comparative performance of TMF Sensitivity: uncoated vs. MoS2-coated with various waist diameters

Table 2. Experiment 1: Uncoated TMF with various heating lengths.

TMF sample number	Heating length (mm)	Humidity Range (%RH)	Sensitivity (dB/%RH)	Linearity
S1a	3	30 - 80	-0.064	0.905
S1b	4		-0.233	0.973
S1c	5		-0.2	0.94
S1d	6		-0.043	0.76

Table 3. Experiment 2: Uncoated TMF with various waist diameters for 5 mm heating length.

TMF sample number	Waist Diameter (μm)	Humidity Range (%RH)	Sensitivity (dB/%RH)	Linearity
S1c1	3	30 - 80	-0.195	0.973
S1c2	5		-0.033	0.423
S1c3	7		-0.028	0.681

Table 4. Experiment 3: MoS_2 with various waist diameter for 5 mm heating length

TMF sample number	S1c1		S1c2		S1c3	
Waist Diameter (μm)	3		5		7	
Type of Deposition	uncoated	MoS_2 Coated	uncoated	MoS_2 Coated	uncoated	MoS_2 Coated
Sensitivity (dB/%RH)	-0.195	-0.244	-0.033	-0.17	-0.028	-0.0472
Linearity (%)	0.94511	0.978	0.422	0.941	0.68062	0.91

4. CONCLUSION

In conclusion, the various TMF lengths and size diameters were successfully fabricated using the heat-and-pull method. The optimal length and size diameter TMF have been examined by conducting experiments for humidity sensors. Based on the result, 5 mm TMF length with a 3 μm size diameter is the optimum parameter where the performance increases more than 25% in terms of linearity and sensitivity compared to 5 and 7 μm. The performance of the TMF sensor is compared by drop casting the MoS_2 in order to improve the sensitivity and linearity. Based on the observation, the sensor performance improved 20-50% more by coating 2D materials MoS_2 on the TMF surface. TMF sensor exhibits superior performance, with a sensitivity of -0.233 dBm/% and linearity greater than 97% in detecting humidity. Finally, the functionality and performance of the optical sensor have successfully observed for various relative humidity. This optical sensor can be expanded for air pollution detection in future.

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