Multi-Wavelength Analysis of Intensity-Modulated U-Shaped Plastic Optical Fiber Humidity Sensors

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ABSTRACT

This paper presents a comprehensive multi-wavelength characterization of a humidity sensor based on an intensity-modulated U-shaped tapered plastic optical fiber (POF). The sensor exploits evanescent-wave interaction between guided light and the surrounding environment, enabling variations in relative humidity (RH) to modulate the transmitted optical power. A Mitsubishi SH4001 POF was manually tapered using fine-grade abrasive polishing to produce waist diameters of 500 µm and 600 µm, followed by bending into U-shaped structures with radii of 3 cm, 4 cm, and 5 cm. Light from light-emitting diodes (LEDs) at 470 nm, 530 nm, and 645 nm was launched into the fiber, and changes in output intensity were measured using a phototransistor and microcontroller-based signal acquisition system. Experimental results, obtained over 35–90 %RH, reveal a consistent inverse relationship between humidity and output voltage for all wavelengths. Among all configurations, the 645 nm wavelength paired with a 500 µm waist and 5 cm bend radius yielded the highest sensitivity of 0.0385 V/%RH and linearity of 98.74%. Comparative analysis demonstrates the significant influence of wavelength on evanescent-wave penetration depth and sensing performance. The findings confirm the suitability of tapered POF sensors as low-cost and robust alternatives for environmental humidity monitoring.

Keywords— humidity sensor; evanescent wave; multi-wavelength; intensity modulation; U-shaped fiber

INTRODUCTION

Humidity measurement plays a critical role in industrial processing, biomedical monitoring, environmental surveillance, and agricultural optimisation. Accurate and continuous humidity detection is essential for maintaining process quality, safety, and environmental stability. Conventional electronic humidity sensors, though widely used, are often limited by susceptibility to electromagnetic interference, corrosion, and drift under harsh environmental conditions [1], [3], [6]. In contrast, optical fiber sensors offer several advantages, including immunity to electromagnetic noise, compact size, lightweight construction, and the ability to perform remote or distributed sensing [2], [5], [7].

Among optical fiber materials, plastic optical fibers (POFs) have become increasingly attractive due to their low cost, flexibility, and ease of fabrication compared with fragile silica fibers [1], [5]. Their polymeric composition—typically polymethyl methacrylate (PMMA)—naturally exhibits water absorption and refractive-index changes in response to environmental humidity, making POFs highly suitable for humidity sensing applications [4], [8]. Recent studies have demonstrated that these fibers can be used to construct inexpensive, compact, and stable humidity sensors for environmental monitoring, agriculture, and biomedical use [9], [10].

Humidity detection in POFs is often based on evanescent-wave absorption, where the guided optical field interacts with the external environment through the cladding boundary. When relative humidity increases, adsorbed water molecules alter the local refractive index near the fiber surface and increase scattering or absorption of the evanescent field, causing a measurable reduction in transmitted light intensity [6], [9]. This mechanism becomes especially pronounced in tapered or U-shaped fiber geometries, which enhance evanescent-field penetration by reducing cladding thickness or increasing light coupling with the external medium [4], [10], [12].

The present study investigates a U-shaped tapered POF humidity sensor using three wavelengths - 470 nm, 530 nm, and 645 nm—to examine wavelength-dependent sensitivity and linearity. The combination of manual tapering and controlled bending allows systematic analysis of geometric effects on humidity response. By evaluating two waist diameters (500 µm and 600 µm) and three bending radii (3 cm, 4 cm, and 5 cm), the study provides an experimentally validated, low-cost optical humidity sensor design. This work contributes new insight into the multi-wavelength behaviour of evanescent-field interaction in POF-based humidity sensing, highlighting its potential for stable and low-cost environmental monitoring applications [9]–[11], [13].

LITERATURE REVIEW

Optical fiber humidity sensing has evolved substantially over the past two decades, with techniques generally classified as intensity-modulated, interferometric, grating-based, or surface-plasmon-resonance (SPR) systems [2], [6]. Among these, intensity-modulated approaches are the simplest to implement, as they measure transmitted optical power changes directly without requiring complex phase or wavelength demodulation [3], [9]. This simplicity aligns well with the characteristics of plastic optical fibers, which exhibit higher optical attenuation but stronger evanescent-field coupling than silica fibers [4], [6]. Humidity-sensitive polymers such as PMMA absorb water vapour, resulting in refractive-index variations that alter the propagation constant of guided light. This behaviour forms the basis for humidity sensing using uncoated or polymer-clad POFs [4], [8], [10].

Recent developments have focused on exploiting the intrinsic hygroscopicity and flexibility of polymers to design robust and low-cost sensors. Cheng [9] reported a high-resolution POF humidity sensor achieving stable and linear response by optimizing fiber geometry. Similarly, Hussian et al. [10] developed a dual-point humidity sensor using twisted and bent POFs, demonstrating excellent repeatability and a rapid response time of approximately one second over a range of 30–80 % relative humidity. These findings indicate that even simple POF geometries can provide high performance suitable for distributed environmental sensing.

Geometry modification of optical fibers has been identified as one of the most effective methods to enhance humidity sensitivity. U-shaped fiber structures increase bending-induced loss and extend the interaction between the evanescent field and the surrounding medium, while tapered sections reduce the fiber core diameter to increase the proportion of light exposed to the external environment [5], [6], [11]. Smaller bending radii amplify the interaction strength but may introduce higher loss or mechanical fragility. Research by Leal-Junior et al. [5] and Kim and Chung [6] confirmed that combining bending and tapering significantly improves sensor response without additional coatings. Manual tapering through sanding, as used in the present study, has been shown to be a reproducible and cost-effective technique for fabricating polymer-fiber sensors [4], [10].

The influence of operational wavelength on sensing characteristics has also attracted significant interest. Longer wavelengths generally allow deeper evanescent-field penetration and stronger coupling with the environment, while shorter wavelengths suffer higher scattering but can provide improved resolution in certain configurations [7], [9], [11]. Studies have shown that POFs operating near the red-light region (620–650 nm) exhibit optimal performance due to low attenuation and strong evanescent-field interaction in PMMA fibers [7], [11]. Dang et al. [11] demonstrated that Fabry–Pérot-based POF humidity sensors achieve excellent sensitivity and stability near 650 nm, confirming that wavelength selection critically affects humidity detection. The current work extends this understanding by comparing blue, green, and red wavelengths under identical geometric conditions.

Numerous POF-based humidity sensors have been proposed using side-polished, tapered, or U-shaped geometries, sometimes combined with hydrophilic coatings such as polyvinyl alcohol (PVA), gelatin, or agarose to enhance refractive-index sensitivity [3], [8]. Although coated sensors can achieve higher sensitivity, they often suffer from aging, hysteresis, and complex fabrication processes. In contrast, uncoated or geometry-based POF sensors—such as those developed by Hussian et al. [10]—offer simpler fabrication, greater mechanical robustness, and long-term stability. Zhong et al. [8] reported a temperature-independent U-bent POF sensor with high humidity sensitivity and excellent repeatability, confirming the potential of polymer-based geometry-only designs.

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Recent review papers emphasize a growing trend toward multifunctional and hybrid fiber-optic sensors capable of simultaneous temperature and humidity detection, as well as integration into flexible and wearable platforms [12], [13]. However, most of these studies still rely on single-wavelength operation or interferometric principles, leaving a notable gap in the systematic exploration of multi-wavelength intensity-modulated POF sensors that employ purely geometric enhancement. The present study addresses this gap by combining multi-wavelength illumination with controlled tapering and bending in a coating-free POF design, offering new insights into wavelength-governed evanescent-field behaviour in polymer optical fiber humidity sensors.

METHODOLOGY

The study employs an experimental approach to design, fabricate, and characterise a U-shaped tapered plastic optical fiber (POF) humidity sensor operating at three wavelengths: 470 nm, 530 nm, and 645 nm. The methodology encompasses fiber preparation, tapering, geometric shaping, instrumentation setup, environmental measurement, and data analysis. All procedures were performed in a controlled laboratory environment to ensure consistency, repeatability, and reliability.

A Mitsubishi SH4001 step-index plastic optical fiber (POF) was used in this study. The fiber has a 980 µm polymethyl methacrylate (PMMA) core and a 1000 µm fluoropolymer cladding, providing good flexibility and low optical loss. A 20 cm section of fiber was cut, and the outer jacket was removed over a 3 cm central region to expose the cladding for tapering. PMMA-based POFs were selected for their low cost, mechanical strength, and suitability for humidity sensing applications.

Tapering was performed using fine 1000-grit sandpaper, and a digital micrometer was gradually used to measure the reduction in the fiber diameter. Two waist diameters, 500 µm and 600 µm, were produced and verified for uniformity through repeated measurements. Mechanical sanding was chosen because it is a simple, low-cost, and effective method for enhancing evanescent-wave interaction without the need for heating or chemical etching. Figure 1 show the actual POF tapered fiber sensor for humidity sensing application.

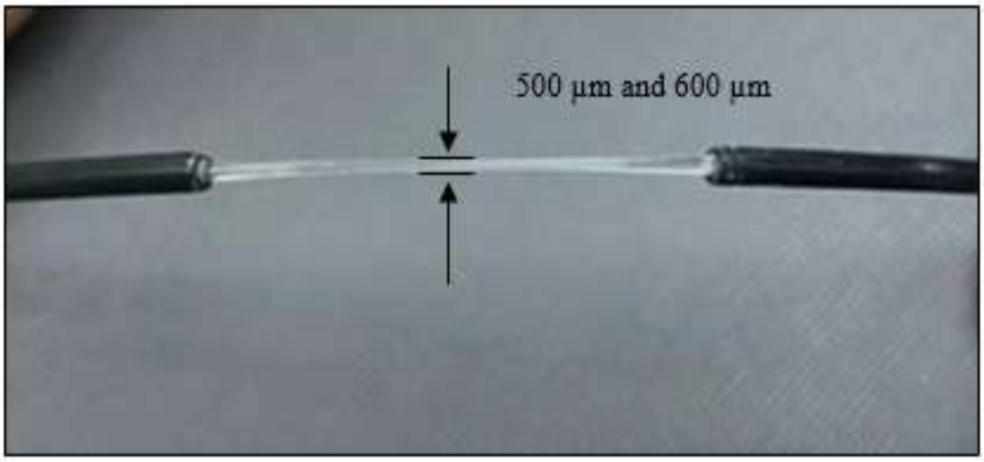


Figure 1. POF Tapered Fiber for Humidity Sensing Application

After tapering, the fiber was carefully bent into a U-shape with bending radii of 3 cm, 4 cm, and 5 cm. These radii were selected to study how curvature affects light attenuation. Smaller radii increase the interaction between the evanescent field and the surrounding environment, which improves sensitivity but may also increase optical loss.

Three light-emitting diodes (LEDs) were used as light sources: blue (470 nm), green (530 nm), and red (645 nm). Light was coupled into the fiber using standard connectors, and the transmitted light was detected by a phototransistor connected to a NodeMCU microcontroller. The system included signal-conditioning, amplification, analog-to-digital conversion, and an LCD display for real-time monitoring. All measurements were conducted inside a dark and controlled chamber to eliminate external light interference and ensure accuracy. A calibrated digital hygrometer (UT333S) was placed inside the chamber for humidity reference. Figure 2 shows the experiment setup of humidity sensing.

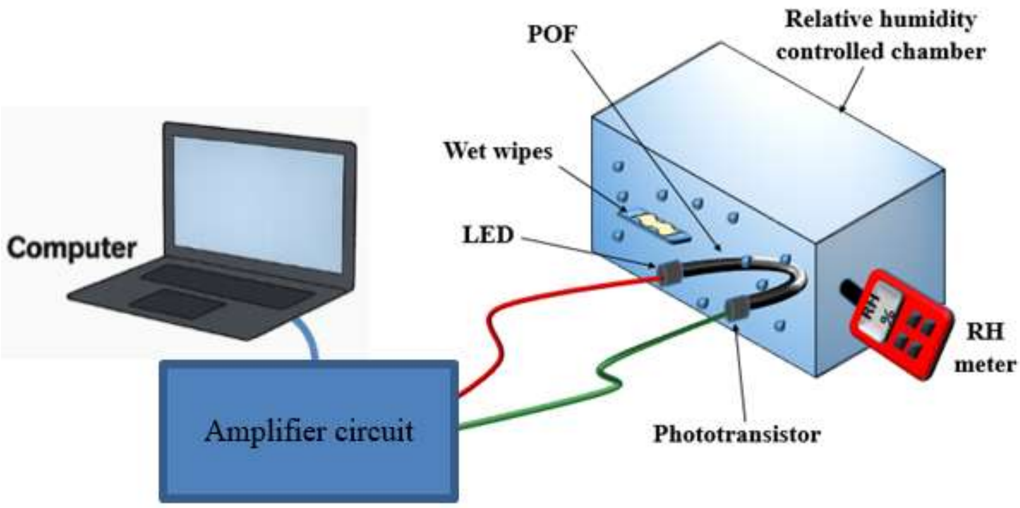
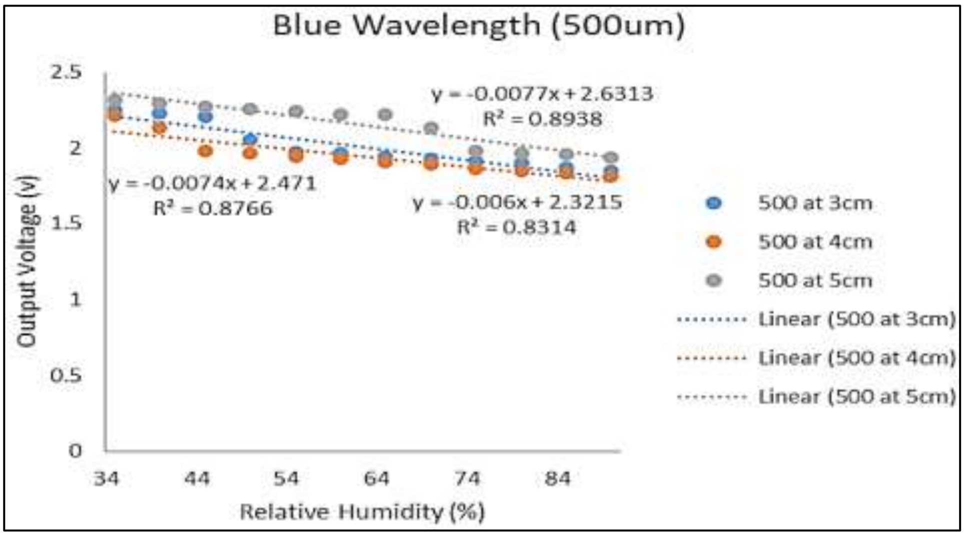


Figure 2. Experimental Setup for Humidity Sensing

The relative humidity (RH) was varied from 35% to 90% in 5% increments. At each humidity level, the system was allowed to stabilize, and three readings were taken to ensure repeatability. Both humidifying and dehumidifying cycles were performed to evaluate hysteresis, with particular attention to 55% RH as a reference point. The collected data were analyzed to determine key performance parameters, including sensitivity, linearity, resolution, standard deviation, and hysteresis. Sensitivity was calculated from the slope of the voltage versus humidity graph, and linearity was determined from the coefficient of determination (R^2). Resolution was estimated from the smallest detectable change in humidity corresponding to system noise, while hysteresis was calculated as the difference between the increasing and decreasing humidity response curves. These performance indicators were used to identify the most effective combination of wavelength, taper diameter, and bending radius for optimal sensor performance.

RESULTS AND DISCUSSION

Figure 3 (a)(b)(c)(d)(e)(f) presents the trendline results obtained from the multi-wavelength characterization of the U-shaped tapered plastic optical fiber humidity sensor. Data were collected for three wavelengths blue (470 nm), green (530 nm) and red (645 nm), two tapered waist diameters (500 µm and 600 µm), and three bend radii (3 cm, 4 cm, 5 cm). Key performance indicators—sensitivity, linearity, resolution, standard deviation, and hysteresis—were extracted from trendline analyses and repeated measurements.



(a)

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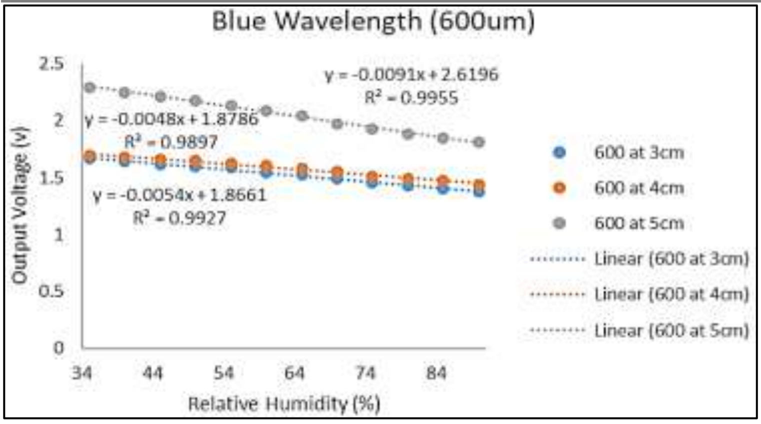

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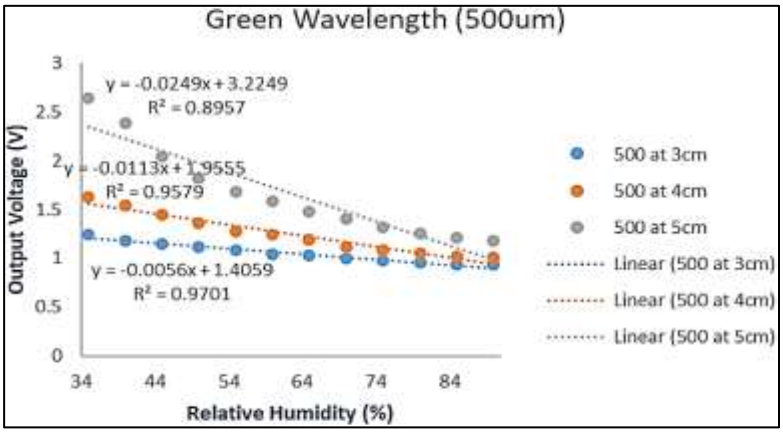

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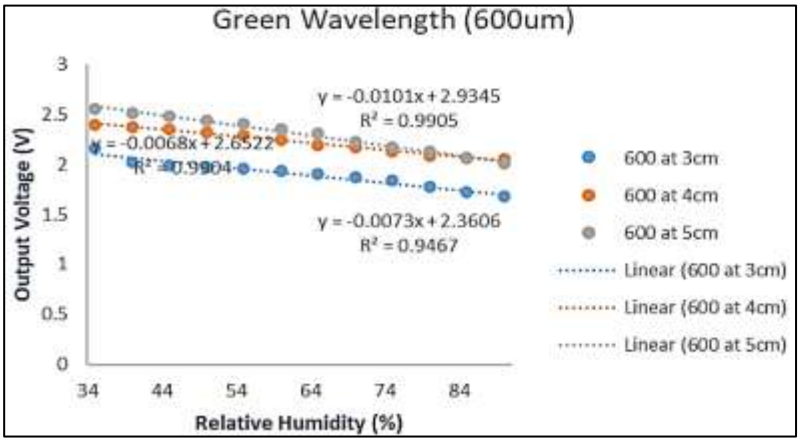

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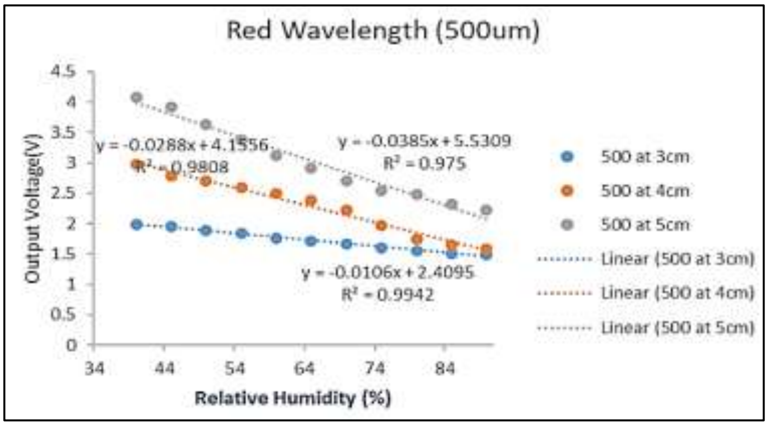
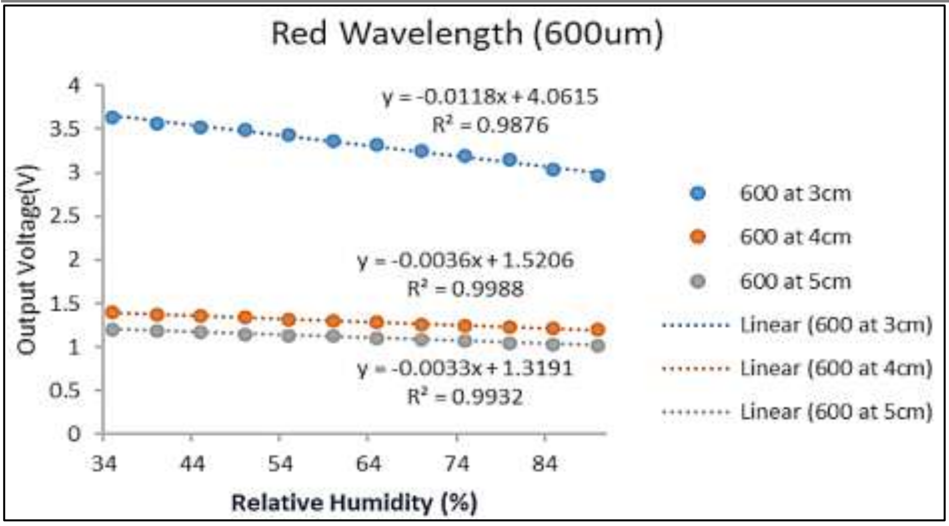


(e)



(f)

Figure 3. Trendline Results for Humidity Sensing

Humidity was varied from 35% to 90% RH, and at each point the output voltage decreased consistently with increasing humidity, demonstrating an inverse relationship characteristic of evanescent-wave-based absorption. This aligns with the theoretical expectation that higher environmental moisture increases refractive index interaction and optical loss.

The trendline for 645 nm (500 µm, 5 cm radius) demonstrating a strong linear relationship between humidity and output voltage. The high linearity value of 98.74% confirms excellent conformity to a linear calibration model, while the sensitivity of 0.0385 V/%RH indicates a substantial change in output for each percentage increase in relative humidity. Overall, the graph clearly shows a steady decrease in voltage as humidity rises, consistent with the expected behaviour of evanescent-wave–based sensing. The steep negative slope further highlights the dominant influence of wavelength on interaction depth, with the 645 nm red LED producing significantly stronger coupling with the humid environment compared with the 530 nm and 470 nm wavelengths.

Table 1 summarize that the red wavelength (645 nm) delivers the highest sensitivity, measuring nearly five times greater than that of the blue wavelength (470 nm).

Table 1: Sensitivity, Linearity and Resolution for 500 µm Waist at Three Wavelengths

Wavelength (nm)	Sensitivity (V/%RH)	Linearity (%)	Resolution (%RH)
645	0.0385	98.74	1.3
530	0.0249	94.64	6.54
470	0.0077	94.54	3.11

In addition, the consistently high linearity values across the wavelengths indicate that the sensor is suitable for calibrated use in environmental monitoring applications. Conversely, the green LED exhibits the poorest resolution due to higher signal noise and the presence of non-linear behaviour in the mid-range humidity values. Overall, these observations reinforce the clear superiority of long-wavelength operation, supporting the work conclusion that evanescent-field penetration depth increases with wavelength, thereby enhancing sensor performance.

Table 2 shows that the hysteresis performance at 55% RH exhibits low values ranging from 0.04 V to 0.07. This indicates good reversibility and repeatability across humidity cycles.

Table 2: Hysteresis Measurement for 500 µm Waist at 55% RH

Wavelength (nm)	Voltage (Incerasing RH)	Voltage (Decreasig RH)	Difference (ΔV)
645	3.1	3.06	0.04
530	2.55	2.48	0.07
470	1.92	1.86	0.06

Among the wavelengths tested, the red wavelength (645 nm) produced the smallest hysteresis of 0.04 V, reinforcing its suitability for high-precision humidity detection. Such minimal hysteresis demonstrates the stability of the fiber–environment interaction and reflects the mechanical reliability of the tapered region. Across all bend radii and taper diameters, the 645 nm wavelength consistently achieved the highest sensitivity and linearity, along with the lowest noise and smallest hysteresis. This enhanced performance can be attributed to the greater evanescent-field penetration depth at longer wavelengths, increased interaction with ambient humidity, lower attenuation within PMMA-based fibers in the red region, and better phototransistor responsivity. These observations align well with established optical absorption characteristics in polymer optical fibers [14].

Additionally, the influence of bending radius showed that the 5 cm radius delivered the best overall performance. The 3 cm radius introduced excessive bending loss that reduced signal stability, while the 4 cm radius improved performance but still exhibited moderate attenuation. In contrast, the 5 cm radius provided the optimal balance between evanescent-wave interaction and efficient light transmission, supporting the principle that bending-induced sensitivity must be balanced against excessive optical loss [15]. A comparison between the two taper diameters reveals that the 500 µm waist provides significantly higher sensitivity, as the stronger confinement of optical modes near the fiber boundary enhances evanescent-field interaction. In contrast, the 600 µm waist exhibits lower responsiveness because the thicker remaining cladding reduces the proportion of guided light interacting with the surrounding environment [16].

This work also shows that repeated measurements cluster more tightly for the 500 µm configuration, indicating superior repeatability. Overall, the results confirm that wavelength is the dominant factor influencing sensor sensitivity and linearity, while taper diameter governs the depth of interaction and overall responsiveness, even though this method leads to uneven material removal along the taper region. Bend radius further refines evanescent coupling by affecting both sensitivity and noise levels, with larger radii improving signal stability. Hysteresis remains minimal across all configurations, demonstrating strong mechanical stability of the tapered fiber [17]. Collectively, the findings identify the 645 nm wavelength combined with a 500 µm taper and 5 cm bend radius as the optimum setup, achieving a sensitivity of 0.0385 V/%RH and linearity of 98.74%. This configuration is therefore recommended for practical, low-cost environmental humidity sensing applications and under real-world environmental conditions, such as varying temperatures, dust, or outdoor humidity, where it would enhance practical applicability [18].

CONCLUSION

This study presented a comprehensive multi-wavelength characterisation of a U-shaped tapered plastic optical fiber humidity sensor employing intensity modulation and evanescent-wave interaction. The sensor was fabricated through a simple mechanical sanding technique to produce 500 µm and 600 µm waist diameters, followed by bending into U-shaped structures with radii of 3 cm, 4 cm, and 5 cm. Experimental evaluations across relative humidity levels of 35–90% RH demonstrated a consistent inverse relationship between humidity and output voltage. The optimize results confirm that wavelength plays a decisive role in determining sensor performance. These findings support the conclusion that longer wavelengths enhance evanescent-field penetration and stability within PMMA-based POFs. The work validates the feasibility of low-cost, mechanically tapered POF sensors for reliable humidity sensing, offering a compact and robust alternative to conventional electronic and silica-fiber-based systems. Future developments may incorporate wireless data acquisition, temperature compensation, or integration into environmental monitoring platforms.

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