Zinc Oxide-Coated Tapered Plastic Optical Fiber for Saline Sensing Applications

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DOI: https://dx.doi.org/10.51584/IJRIAS.2025.10100000101

Received: 12 October 2025; Accepted: 20 October 2025; Published: 11 November 2025

ABSTRACT

Accurate and real-time measurement of saline concentration is vital across healthcare, environmental monitoring and industrial sectors. However, traditional detection methods often suffer from being intrusive, expensive and having limited sensitivity. This study presents the development and validation of a portable, non-invasive and cost-effective saline detection system designed to overcome these challenges. The core of this system is a novel sensor created from a tapered plastic optical fiber (POF) coated with Zinc Oxide (ZnO) nanorods, integrated with a NodeMCU ESP8266 for data transmission and real - time monitoring. To optimize the interaction between light and the surrounding saline solution, POFs were tapered to various waist diameters (500 µm, 550 µm, 600 µm, 650 µm, and 700 µm) using a combination of chemical and mechanical etching techniques. Subsequently, ZnO nanorods were grown on the tapered fiber surface via the hydrothermal method - a critical step for enhancing the sensor's sensitivity. The sensor's performance was evaluated using a saline concentration ranging from 2 g to 10 g. A consistent and predictable inverse relationship was observed, where the output voltage decreased as saline concentration increased. The configuration with a 550 µm waist diameter demonstrated the highest sensitivity of 0.256 V/%g. Furthermore, the sensor exhibited excellent linearity, with correlation coefficient values consistently above 99%, confirming its high precision. The successful integration of the NodeMCU ESP8266 facilitates a practical solution for remote monitoring through data transmission. This work validates the ZnO-coated tapered POF sensor as a reliable and efficient alternative for diverse applications - including biomedical diagnostics and water quality analysis.

Keywords— Plastic optical fiber, Humidity sensor, tapered fiber, Zinc Oxide Nanorods, Evanescent wave sensing.

INTRODUCTION

Saline detection plays a crucial role in various sensing fields; including healthcare, environmental monitoring and industrial applications [1],[2]. Saline solutions, particularly sodium chloride (NaCl) in water, are commonly used in medical treatments such as , intravenous (IV) fluids, and in industrial processes like water treatment and chemical manufacturing [3]-[5]. The ability to accurately measure and monitor saline concentrations is essential for maintaining proper medical protocols, ensuring the quality of industrial products, and for safeguarding environmental health.

Traditionally, saline concentration is measured using methods such as conductivity measurement [6] and titration [7]. However, these techniques can be invasive, time-consuming and require sophisticated laboratory arrangements. In recent years, non-invasive and real-time sensing technologies, such as optical fiber sensors, have gained increasing popularity [8],[9]. These sensors are capable of detecting changes in the refractive index providing accurate, quick, non-invasive and reliable measurements of saline concentration.

Optical fiber sensors, particularly those made from Plastic Optical Fibers (POFs), have proven to be a promising solution for saline detection. POFs are lightweight, flexible, and relatively inexpensive - making them an ideal choice for a range of applications [10]. When coated with materials like zinc oxide (ZnO), which has unique optical properties, these sensors can detect subtle changes in the refractive index of saline solutions. Zinc oxide's ability to interact with the surrounding environment enhances the sensitivity of the sensor, allowing it to detect even minor variations in saline concentration [11].

Additionally, tapered POFs further improve sensor performance by increasing the interaction area between the fiber core and the surrounding medium. This design optimizes the sensor's ability to detect small changes in refractive index, which is essential for accurate saline detection.

The tapered region of the optical fiber is more sensitive to refractive index changes than the non-tapered sections, as the light propagating through the fiber interacts more with the surrounding medium [12]. When saline solution surrounds the tapered fiber, changes in the concentration of the saline will alter the refractive index of the solution. This, in turn, affects the propagation of light through the fiber, which can be measured as changes in the intensity, phase, or wavelength of the transmitted light [13].

By carefully analyzing these light variations, the sensor can accurately determine the saline concentration. For example, a higher concentration of salt in the solution will cause a change in the refractive index, which can be detected by the sensor. This change is proportional to the concentration of the saline, allowing for precise monitoring of saline levels.

In this paper, section 2 shows our literature review, section 3 displays our set-up, section 4 analyses our results, followed by discussion and conclusions.

LITERATURE REVIEW

The demand for real-time and remote monitoring of water quality has spurred research and development of various sensing technologies. Among these, optical fiber sensors have emerged as a promising solution; due to their numerous advantages - including immunity to electromagnetic interference, high sensitivity, compact size and capability for remote sensing. This literature review focuses on the key components and recent advancements related to the development of a ZnO – coated tapered plastic optical fiber (POF) sensor for salinity, integrated with a NodeMCU ESP8266 for data transmission and real-time monitoring.

POFs are increasingly used in sensing applications due to their flexibility, ease of handling and low cost. Tapering is a technique used to enhance the sensitivity of optical fiber sensors by modifying their geometry. This process involves heating and stretching a section of the fiber to create a narrower waist region. The tapering process alters the light propagation within the fiber, leading to the generation of a stronger evanescent field that extends into the surrounding medium [13]. This enhanced evanescent field is highly sensitive to changes in the refractive index (RI) of the medium, making tapered fibers ideal for chemical and biological sensing applications. Recent studies [13],[14] have demonstrated that tapered POF sensors exhibit improve sensitivity, faster response times, and possess a wide dynamic range compared to conventional non-tapered fibers. The simple and cost-effective fabrication of tapered POF sensors further adds to their appeal for various sensing applications - including the detection of chemical ions, gases and biomolecules.

The performance of an optical fiber can be significantly enhanced by coating the fiber surface with a sensing material which interacts with the target analyte. Zinc oxide (ZnO) is a wide-bandgap semiconductor with unique optical and electrical properties, making it an excellent choice of material for these applications. ZnO nanostructures, such as nanoparticles, nanorods, and thin films, offer a high, which increase the active sensing area and improve the sensor sensitivity and response time [15].

ZnO is biocompatible, chemically stable, and can be synthesized using various low-cost methods. The sensing mechanism is typically based on the change in the refractive index or light absorption of the ZnO layer upon interaction with the analyte. Recent reviews on ZnO nanostructures-based biosensors highlight their potential for developing highly sensitive and selective sensing devices [16],[17]. Furthermore, the application of ZnO nanostructures in humidity sensing has demonstrated their versatility in environmental monitoring.

Salinity is a critical parameter for assessing water quality in various applications - including aquaculture, environmental monitoring and industrial processes. Traditional methods for salinity measurement, such as conductivity meters, can be bulky, expensive, and susceptible to electromagnetic interference. Optical fiber sensors offer a viable alternative for real-time and in-situ salinity monitoring because of it small lightweight, and resistant to corrosion [18]. Several optical fiber sensing techniques have been explored for salinity measurement, including those based on POF. These sensors typically rely on the principle that the refractive index of water changes with salinity. Recent reviews of seawater fiber optic salinity sensors have highlighted the significant progress in this field, with a focus on improving sensitivity, accuracy, and long-term stability [19],[20]. The development of novel sensor designs and materials continues to drive innovation in optical fiber-based salinity sensing.

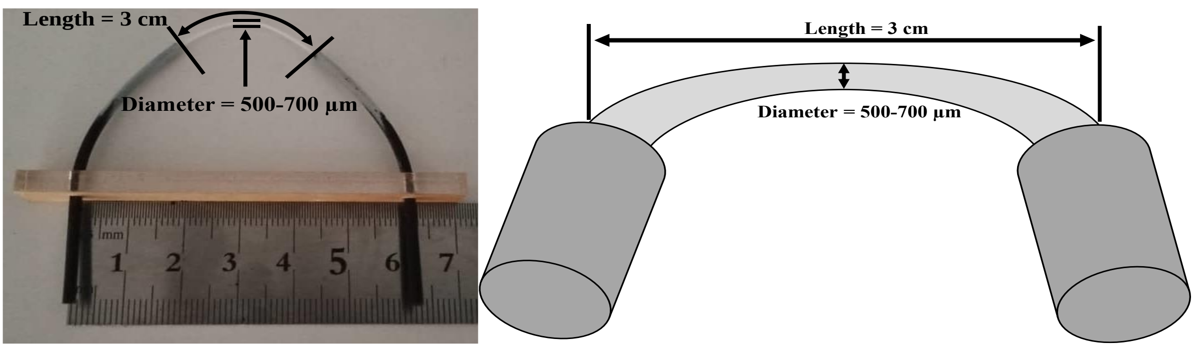
The integration of a sensor with the NodeMCU ESP8266, enabling real-time data acquisition for easily interface with various sensors to collect data on water quality parameters such as pH, turbidity, conductivity and temperature. Several projects have demonstrated the use of NodeMCU ESP8266 for real-time water quality monitoring, showcasing its potential for developing affordable and scalable monitoring systems, and also emphasizing the importance of real-time data effective environmental management [21],[22].

In summary, this literature review reveals a clear and progressive trend from foundational research on individual components-such as enhancing POF sensitivity through tapering and leveraging the unique properties of ZnO nano-coatings towards the development of integrated, functional sensing systems. The significance of this progression lies in its potential to create highly effective and accessible tools for real-time environmental monitoring. This project capitalizes on the distinct advantages of each component: the low cost and flexibility of POF, the heightened sensitivity from the tapered structure, the specific material interaction provided by the ZnO coating, and the remote data acquisition enable by the NodeMCU ESP8266. However, a critical gap exists in the literature: there is a lack of studies that integrate all these elements into a single cohesive system. Therefore, this project is driven by the need to design, fabricate and validate a novel sensor that combines a zinc oxide coated tapered POF with a microcontroller for saline water detection, addressing the need for a cost-effective, highly sensitive and remotely accessible solution.

METHODOLOGY

The ease of controlling the tapered region renders the chemical and mechanical etching of POF very popular. This method involves the employment of acetone, de-ionized (DI) water, as well as sandpaper to polish the targeted area. Several samples with different waist diameters (500 – 700 µm) have been prepared for characterization and optimization investigation. In this work, a standard multimode model SH4001 Super Eska POF fiber (original diameter = 1000 µm) was used. Initially, a cutter blade was employed to cut the fiber jacket from the center of the fiber with a 3 cm length. Finally, sandpaper of 7000 grit was used in the polishing process to remove a portion of the core. Micrometers were frequently used to obtain the desired diameter of the tapered fiber. The surface of the polished POF was then gently wiped with ethyl acetate solution to remove the microparticles produced by sandpaper before the final cleaning process repeated several times with DI water. Figure 1 show the removal of fiber jacket and tapered POF.

Figure 1. Removal of fiber jacket and tapered POF (a) actual and (b) illustration.



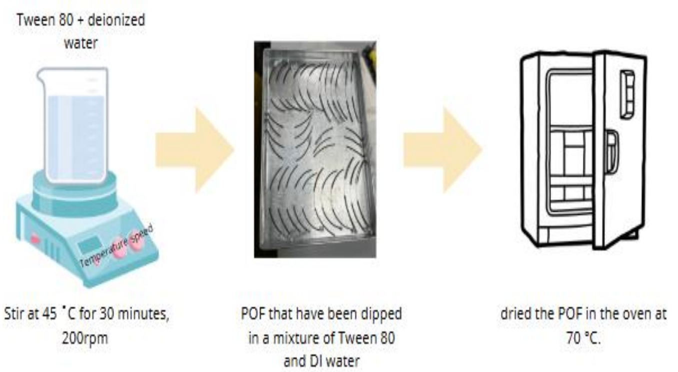
(a) (b)

The nanorod growth consists of two processes: seeding and growth process. The reason for the seeding process is to enhance the performance of fiber optic sensors. The technique is extremely dependent on the uniformity, length, diameter, density of the solution and POF core surface action and on the annealing of the nanorods. Initially, two sets of solutions were prepared: ZnO nanoparticles solution and pH control solution. The first solution was synthesised by dissolving 4.4 µg of zinc acetate dihydrate [Zn(O2CCH3)2.2H2O] with 20 ml of unadulterated ethanol [C2H5OH] to make a 0.001 M solution, using constant stirring for 30 minutes at 50˚C. After the solution was cooled down to ambient temperature, it was then further diluted by adding another 20 ml of pure ethanol to produce 40 ml of ZnO nanoparticle solution. For the pH control solution, aliquots of 0.3 mg of sodium hydroxide pellets [NaOH] were dissolved into 20 ml of pure ethanol to form a 1 mM solution using constant stirring for 30 minutes at 50˚C. This control solution was deemed as essential to determine the ZnO properties via the hydrothermal process.

The growth of the nanorods improves when the pH of the ZnO nanoparticles solution increases to alkaline. It has also been shown that the pH value could affect the nuclei and environment of ZnO growth. The pH control solution was dropped on the nanoparticles after 10 minutes. This was achieved using a dropping and stirring technique, where the ZnO nanoparticles solution was stirred slowly for every single 1 ml pH control solution drop using a pipet for around 1 minute. Then the process was repeated 20 times until the pH increased from ~4 to ~9. This step was crucial to provide more hydroxyl ions (OH-) in the seeding solution. The mixture was maintained in an ultrasonic water bath at 60 °C for 3 hours until a change in colour of the solution from clear to milky became noticeable. Figure 2 (a) depicts the process of POF surface treatment in which the exposed core was dipped in a mixture of 50ml Tween 80 and 500ml DI water. Next, the fibers used the dip and dry method. Firstly, put the fiber in the seeding solution for 1 minute, and then dried in the oven at 70 °C. After that, the process was repeated 8-10 times.

ZnO growth was then performed following the seeding process. Subsequently, 2.97 g of zinc nitrate hexahydrate and 1.40 g of hexamethylenetetramine were both dissolved in 1000 ml of DI water to form as solutions. The synthesis solution was replaced every 5 hours with a new solution to maintain a continuous growth of ZnO nanorods on the tapered POF. The ZnO nanorods were grown for 10 hours on the tapered POF which was rinsed with DI water several times after it naturally cooled down to room temperature. The seeded tapered POFs were placed in the mixture then heated in an oven at 90 °C, as shown in Figure 2 (b). The fiber sensor fabrication including seeding and growth process were reported in the previous work [12],[23].

Figure 2. (a) POF surface treatment process and annealing process (b) ZnO nanorods growth procedure



(a)

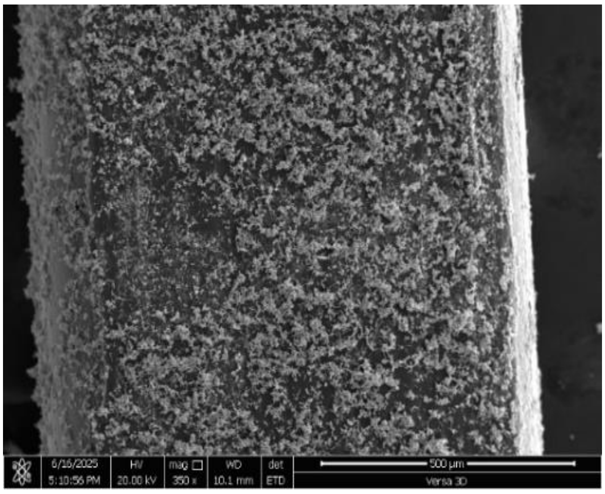
(b)

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

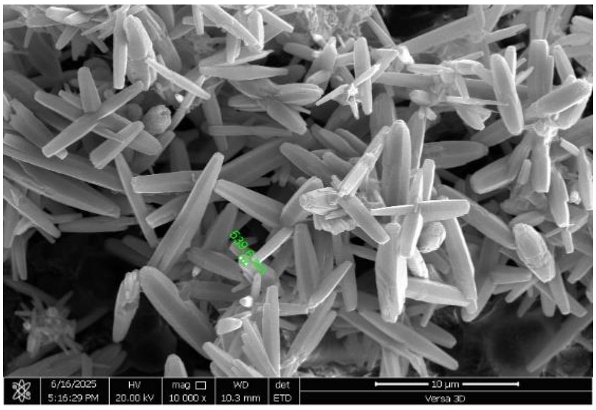
RESULTS AND DISCUSSION

Figure 3 (a) (b) (c) shows the Field Emission Scanning Electron Microscope (FESEM) images of the ZnO nanorods, which were grown on tapered POF. From these images, the morphologies obtained confirmed that the structure of ZnO nanorods is based on the rod structure and consists of many superfine nanorods on the fiber. The magnification was set at 10,000 X to clearly observe the ZnO structures coated on the fiber. An energy dispersive X-ray (EDX) method, with an operating voltage of 10 keV, was then carried out on the POF to identify the chemical elements. An EDX elemental analysis revealed that the topcoat layer covering the tapered U-shaped POF consisted of zinc (25.90%) and oxygen (74.10%), which verified that the sensing material for relative humidity sensing is ZnO. This is shown in Figure 4.

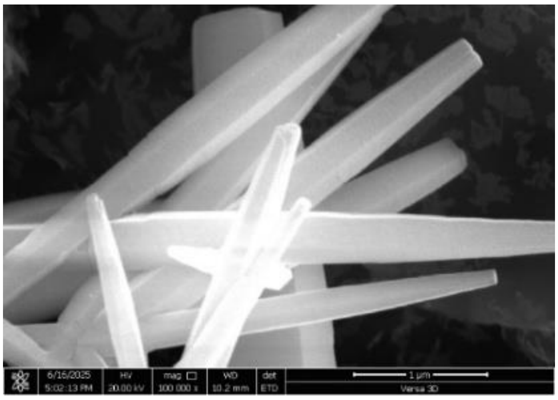
Figure 3. The FESEM images of ZnO nanorods coated onto POF with magnification of (a) 360 x (b) 10k x (c) 100k x



(a)

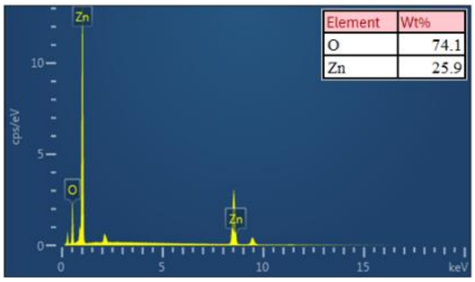


(b)



(c)

Figure 4. EDX elemental analysis of the ZnO nanorods coated onto the POF revealing samples consist only zinc and oxygen



This graph in Figure 5 clearly shows the voltage changes as the saline concentration increases for different diameter sizes (500 -700 µm). It observed that the voltage tends to decrease as the saline concentration increases, which suggests that higher saline concentrations lower the voltage. The modulation of light scattering within the optical fiber is attributed to the refractive index mismatch between the zinc oxide particles and the surrounding saline water medium. A change in the medium's physical properties, such as its salinity, induces a corresponding change in its refractive index. This variation alters the magnitude of the refractive index contrast, thereby directly influencing the measured scattering intensity. Interestingly, the 700 µm fiber diameter has the lowest sensitivity of 0.1575 V/%g, whilst 550 µm has the highest sensitivity of 0.254 V/%g, indicating that a strong evanescent wave occurs at a lower waist diameter [24].

Figure 5. Trendline graph for coating POFs

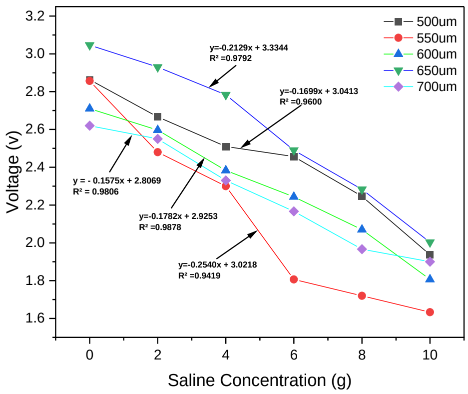


Table 1 presents the performance characteristics of a proposed sensor at various diaphragm thicknesses, specifically at 700 µm, 650 µm, 600 µm, 550 µm, and 500 µm. The average standard deviation shows a slight decrease from 1.7000 V at 700 µm to 1.6683 V at 500 µm, indicating that the sensor output becomes more stable as the diaphragm thickness decreases. The resolution improves from 10.7939% at 700 µm to 7.0096% at 550 µm, but there is a slight increase at 500 µm (9.8149%), suggesting that the sensor performs optimally in terms of resolution at 550 µm. Sensitivity decreases across the diaphragm thicknesses, from 0.1575 V/%g at 700 µm to 0.1699 V/%g at 500 µm, implying that the sensor becomes less responsive to changes as the diaphragm thickness decreases. Despite these changes, the linearity remains high throughout the measurements, ranging from 99.02% at 700 µm to 97.79% at 500 µm, indicating consistent and reliable sensor behavior. Overall, the 550 µm diaphragm thickness offers the best balance of resolution, sensitivity, and stability, while thinner diaphragms, especially at 500 µm, offer better stability with slightly reduced sensitivity and resolution.

Table 1 characteristics Of Coating Pofs

Parameters	500um	550um	600um	650um	700um
Average standard deviation (V)	1.6683	1.7804	1.6999	1.6716	1.7000
Resolution (% g)	9.8194	7.0096	9.5393	7.8516	10.7939
Sensitivity (V/% g)	0.1633	0.2540	0.1782	0.2129	0.1575
Linearity (%)	97.97	97.05	99.38	98.95	99.02

CONCLUSIONS

In this study, a portable, non-invasive and cost-effective saline detection system has been successfully developed and tested. The system utilized a Zinc Oxide (ZnO)-coated tapered Plastic Optical Fiber (POF) integrated with a NodeMCU ESP8266 for real time monitoring. The POF was tapered to various waist diameters (500 µm, 550 µm, 600 µm, 650 µm, and 700 µm), and ZnO nanorods were grown on the fiber surface using a hydrothermal method to enhance sensitivity. Upon testing with saline concentrations from 2g to 10g, the sensor demonstrated a consistent decrease in output voltage as the concentration increased. The ZnO-coated POF with a waist diameter of 550 µm yielded an enhanced sensitivity of 0.254 V/%g. The results showed excellent linearity, with values consistently above 99%. This study has demonstrated that the developed ZnO-coated tapered POF sensor offers a reliable, efficient and highly practical solution for real-time saline concentration monitoring, showing great potential for applications in biomedical diagnostics, water quality testing and industrial processes.

ACKNOWLEDGEMENT

This work was supported in part by Fakulti Technology dan Kejuruteraan Elektronik dan Computer (FTKEK) and University Technical Malaysia Melaka (UTeM).

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