Impact of Incorporating ZnO into the Polystyrene Waste-Based Waveguide on Sensor Performance for Glucose Detection

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Abstract: Diabetes mellitus (DM) is commonly diagnosed by monitoring blood glucose levels; however, this method is invasive and may cause infection at the puncture site. As a non-invasive alternative, urine-based glucose monitoring has gained attention. This study investigates the effect of zinc oxide (ZnO) incorporation on the performance of a waveguide-based glucose sensor utilizing evanescent wave absorption. Two waveguides were fabricated using recycled polystyrene waste as the core material, with ZnO added to one of the samples. The sensitivity and thermal stability of both sensors were characterized and compared to evaluate ZnO's impact. Experimental results demonstrate that the ZnO-enhanced waveguide exhibits significantly improved performance, achieving a sensitivity of 9×10^{-5} V/ppm, a correlation coefficient of 99.12%, a linear detection range of 0-1000 ppm, and enhanced thermal stability. These findings indicate that the ZnO-integrated waveguide sensor offers strong potential as a low-cost, non-invasive alternative for early DM detection via urine analysis.

Keywords: Early detection, Diabetes mellitus, Waste polystyrene, Waveguide, ZnO

1. INTRODUCTION

Diabetes Mellitus (DM) is a serious disease with a high number of sufferers. Globally, an estimated 589 million adults aged 20–79 years were living with diabetes in 2024. This number is projected to rise significantly, reaching 853 million by the year 2050 [1]. A person will be diagnosed with DM if their blood glucose level at any time is more than 200 mg/dl or their fasting blood glucose level is more than 126 mg/dl [2]. Accordingly, the most commonly used method for the early detection of DM is the measurement of blood glucose levels. Unfortunately, this method is considered to have a high risk because it can trigger infection in the punctured area, considering that insulin production in DM sufferers was disrupted [3]. In this regard, the method of monitoring glucose levels in urine can be used as an alternative method for detecting DM.

Urine-based diagnostic methods have been extensively developed due to their non-invasive nature and ease of sample collection [4]. Urine primarily contains various metabolites, including glucose, proteins, nitrates, potassium, sodium, and other dissolved salts [5]. Elevated glucose levels in urine can serve as an indicator of DM, as glucose is excreted into the urine when its concentration in the bloodstream exceeds the renal threshold.

In recent years, significant advancements have been made in the fabrication and characterization of waveguides for various applications, including glucose sensing. These developments are largely driven by the inherent advantages of waveguide-based sensors, such as high sensitivity, precise light path control, and structural integrity [6]. Li et al. [7] reported the development of a Bragg grating glucose sensor using a single-mode silicon-on-insulator (SOI) chip. Yi and Wang [8] proposed a glucose sensor employing a defective ground structure (DGS) coplanar waveguide (CPW). More recently, Li et al. [9] introduced a Bragg grating waveguide fabricated from polymethyl methacrylate-polydimethylsiloxane (PMMA–PDMS) composites.

However, several limitations were noted in these studies. The fabrication of SOI-based sensors involved complex procedures and required cleanroom environments to avoid contamination. Similarly, PMMA-PDMS waveguides faced mechanical reliability issues due to mismatched thermal expansion coefficients, which introduced stress at the interface. Lithographic steps, such as photolithography or electron-beam lithography, were often necessary to define Bragg gratings with high precision, increasing both process complexity and cost. DGS-CPW structures also demanded meticulous ground-plane etching to maintain electromagnetic performance. Moreover, integrating these waveguides with other sensing components proved challenging-particularly for hybrid

materials like PMMA-PDMS, which encountered bonding and sealing difficulties. In terms of performance, while silicon-based sensors offered moderate sensitivity, they frequently failed to achieve the micromolar-level detection limits required for medical diagnostics. Additionally, the low refractive index contrast in PMMA-PDMS waveguides resulted in weak optical confinement, further reducing sensor sensitivity when compared to high-index contrast platforms such as SOI.

Therefore, the development of a waveguide-based glucose sensor with high sensitivity and a simplified fabrication process is essential. One potential approach involves utilizing evanescent field absorption combined with glucose-sensitive materials, such as zinc oxide (ZnO), to enhance sensor performance.

ZnO is a semiconductor material with a wide direct bandgap of 3.37 eV [10] and a high exciton binding energy of 60 meV at room temperature [11], which contributes to its strong ultraviolet (UV) emission characteristics. Several studies have reported that ZnO exhibits glucose-sensitive properties [12][13][14], positioning it as a promising candidate for the development of waveguide-based glucose sensors.

This study aims to investigate the effect of ZnO incorporation on the performance of a waveguide-based glucose sensor utilizing evanescent wave absorption. In contrast to previous works, the waveguides in this study were fabricated using PMMA as the cladding material and recycled polystyrene, sourced from food packaging waste, as the core material. These materials were chosen for their appropriate refractive indices for optical waveguiding and their broad availability. To evaluate the impact of ZnO, two types of waveguides were fabricated: one with ZnO incorporated into the core material and one without. The sensitivity and durability of both waveguides were analyzed and compared to determine the influence of ZnO on sensor performance.

2. METHODOLOGY

2.1 Tools and Materials

The equipment used in this study included a fiber optic stripper (CFS-3, Taiwan), a photodiode (FDS1000, USA), a 660 nm LED source (SFH 4735S, Germany), a POF cutter block (POF-CB, USA), a digital scale (SPX123, USA), an oven (UNB 500, Germany), a multimeter (87V, USA), a CNC machine (VF-2, USA), a CCD microscope (BX53M, Japan), and a magnetic stirrer (C-MAG HS 7, Germany).

The materials used in this study included multimode plastic optical fiber (POF) (Mitsubishi Rayon Co., Ltd., Japan), recycled polystyrene waste, PMMA (Shenzhen Xintao Acrylic Co., Ltd., China), toluene (Merck KGaA, Germany), acetone (Fisher Scientific, USA), analytical-grade glucose (Sigma-Aldrich, USA), distilled water, and ZnO nanoparticles (US Research Nanomaterials Inc., USA).

2.2 Research Procedures

2.2.1 Preparation of Test Solution

The test solution used in this study was a glucose solution with six concentration levels: 0 ppm, 200 ppm, 400 ppm, 600 ppm, 800 ppm, and 1000 ppm. A 5000 ppm glucose stock solution was initially prepared by dissolving 5 g of analytical-grade glucose in 1 L of distilled water. This stock solution was subsequently diluted to obtain the desired concentration levels.

2.2.2 Fabrication of Waveguides

Waveguide fabrication commenced with the preparation of the cladding, which was formed by cutting polymethyl methacrylate (PMMA) using a CNC machine and assembling it according to the design specifications. Both ends of the cladding were connected to plastic optical fiber (POF), while the central cavity of the PMMA structure was filled with a core material derived from recycled polystyrene waste obtained from food packaging. The polystyrene waste was first cut into 1 cm × 1 cm pieces, then heated in an oven at 200 °C for 2.5 hours. The solidified material was subsequently ground into a fine powder and dissolved in toluene at a ratio of 0.2 g of polystyrene to 3 mL of toluene. Two waveguide devices were fabricated: one with ZnO nanoparticles added to the core material and one without.

2.2.3 Characterization of Waveguides

Two types of characterizations were conducted in this study: the first evaluated the output sensitivity to glucose concentration, while the second assessed the thermal stability of the waveguide, defined as its resistance to temperature variations. All measurements were carried out using the experimental setup illustrated in Fig. 1, with each test repeated three times to ensure accuracy and repeatability.
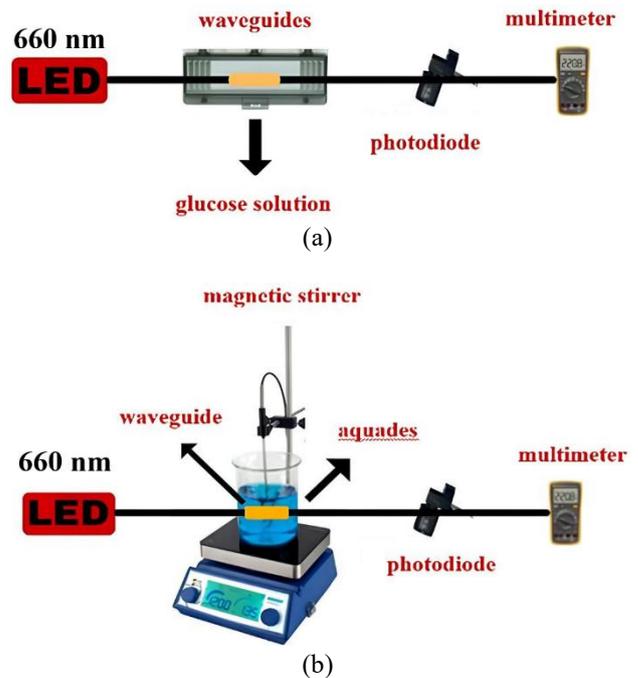

(a)

(b)

Figure 1. Characteritation set up of (a) sensitivity sensor and (b) thermal stability

2.2.4 Data Analysis

The data collected from both characterization processes included output voltage values, measured using a digital multimeter. These data were then analyzed using linear regression in OriginLab software to derive the linear equation that represents the performance of both waveguides. This analysis facilitated the evaluation of the impact of ZnO incorporation on the performance of the fabricated waveguides.

3. RESULT AND DISCUSSION

3.1 Specifications of Waveguides

In this study, two waveguide devices based on recycled polystyrene waste were successfully fabricated. The specifications of these waveguides are presented in Table 1.

Table 1. The specification of waveguides

	Parameter	Specification
Waveguide 1	core material	polystyrene waste
	cladding material	PMMA
	refractive index of core	1.67 RIU
	refractive index of cladding	1.49 RIU
	NA	0.75
Waveguide 2	core material	polystyrene waste and ZnO.
	cladding material	PMMA
	refractive index of core	1.69 RIU
	refractive index of cladding	1.49 RIU
	NA	0.80

As shown in Table 1, the incorporation of ZnO into the core material increased the refractive index of the waveguide core to 1.69 RIU, which consequently led to an increase in the waveguide's numerical aperture (NA). The NA value can be determined mathematically using Equation (1) as follows:

$$NA = \sqrt{n_1{}^2 - n_2{}^2} \qquad (1)$$

The NA value is defined as the sine of the maximum opening angle of total internal reflection from an optical source, at which light can still be received and propagate within the core of the waveguide. In this context, NA is determined by the refractive indices of the core (n_1) and the cladding (n_2). A higher NA value in the waveguide allows for a greater intensity of light to be transmitted through the core. Consequently, the waveguide composed of a mixture of polystyrene waste and ZnO exhibits greater light transmission intensity compared to a polystyrene-only waveguide without ZnO.

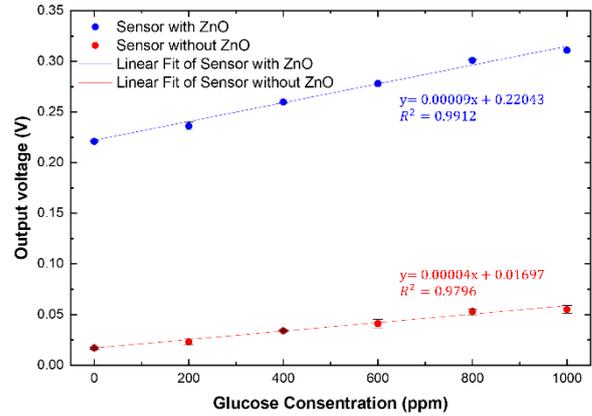### 3.2 Sensitivity of Waveguides

Figure 2. Sensitivity value of glucose waveguide based polystyrene waste

Figure 2 illustrates the linear regression results comparing the output voltage responses of glucose waveguides fabricated from polystyrene waste with and without the addition of ZnO over a concentration range of 0–1000 ppm. The waveguide incorporating ZnO exhibited superior performance in terms of sensitivity, linearity, correlation coefficient, and measurement consistency

The regression equation for the waveguide without ZnO is expressed as y = 0.00004x + 0.01697, with a coefficient of determination R^2 = 0.9796. In contrast, the ZnO-enhanced waveguide yielded a regression line of y = 0.00009x + 0.22043 with a higher R^2 value of 0.9912. This indicates a stronger linear relationship between glucose concentration and output voltage in the ZnO-modified waveguide, suggesting improved signal stability and measurement accuracy.

The sensitivity of waveguides, defined by the slope of the regression line, increased significantly with the addition of ZnO from 0.00004 V/ppm to 0.00009 V/ppm, demonstrating more than a twofold improvement. This enhancement highlights the role of ZnO in increasing the waveguides responsiveness to changes in glucose concentration. Both waveguides maintained good linearity within the measured range, as evidenced by the minimal deviation of data points from the fitted regression lines. Moreover, the addition of ZnO did not compromise the linear range but rather reinforced the reliability and consistency of the waveguides output. Error bars representing standard deviation were included to reflect measurement repeatability. The ZnO-modified waveguide exhibited generally smaller and more consistent error margins compared to the non-ZnO waveguide, indicating better precision and reproducibility.

The addition of ZnO at polystyrene waste will form complex compounds [15] which were characterized by changes in the ratio of the number of atoms occupying the surface to the total number of atoms [16]. This will lead to changes in the chemical reactivity of the material. In this case, a mixture of polystyrene waste and ZnO was reactivated to enable glucose detection [17]. Therefore, it can be concluded that the glucose waveguide made from polystyrene waste with the addition of ZnO exhibits superior sensitivity compared to the waveguide without

ZnO. A comparison of the sensitivity values for both waveguides is presented in Table 2.

Table 2. The comparison of sensitivity values of glucose waveguides based polystyrene waste

	Range Linearity	Sensitivity	Correlation Coefficient
Waveguide 1	0 ppm–1000 ppm	4×10^{-5}V/ppm	97.96 %
Waveguide 2	0 ppm–1000 ppm	9×10^{-5}V/ppm	99.12 %

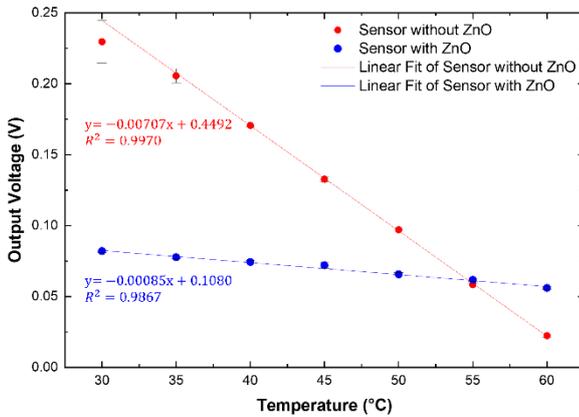### 3.3 Thermal Stability of Waveguide

Figure 3. The thermal stability value of glucose waveguides based polystyrene waste

An ideal waveguides exhibits good thermal stability, meaning its performance remains consistent and is not significantly affected by fluctuations in ambient temperature. This characterization was performed to evaluate the durability of the waveguides under varying ambient temperature conditions. This step is essential due to the waveguides high sensitivity to external environmental factors.

The thermal response of the waveguides with and without ZnO coating was analyzed based on the linear fit of output voltage versus temperature, as shown in Figure 3. The waveguide without ZnO exhibited a steep negative slope of −0.00707 V/°C with a high coefficient of determination 99.70%, indicating a strong linear dependence on temperature. In contrast, the ZnO-coated waveguide demonstrated a significantly lower slope of −0.00085 V/°C with a slightly lower 98.67%, which still represents a high degree of linearity.

This lower slope implies that the output voltage of the ZnO-coated sensor is much less sensitive to temperature variations, thus offering better thermal stability. Furthermore, the ZnO material possesses a wide band gap energy (~3.37 eV), which contributes to reduced thermal excitation of charge carriers, enhancing the thermal robustness of the waveguide [18]. The absence of visible error bars in the ZnO data series also suggests improved signal consistency and reduced noise under varying temperature conditions. These results confirm that the integration of a ZnO layer significantly improves the thermal stability of the waveguide by minimizing the

temperature-induced drift in output voltage, while maintaining acceptable linearity. The comparison of the thermal stability values of both waveguides is presented in Table 3.

Table 3. The comparison of the thermal stability values of glucose waveguides based polystyrene waste

	Range Linearity	Sensitivity	Correlation Coefficient
Waveguide 1	30°C–60°C	7.07×10^{-3} V/°C	99.70 %
Waveguide 2	30°C–60°C	8.50×10^{-4} V/°C	98.67 %

3.4 The Morphology Structure Analysis

In general, the working principle of a waveguide is based on variations in light intensity as a detection parameter. Therefore, light intensity is a critical component in waveguide-based sensing systems. The main factor influencing performance differences between waveguide models is power loss, which directly affects transmitted light intensity. Higher power loss reduces transmission efficiency, while lower power loss enhances waveguide performance. In this study, power loss factors were analyzed during the second stage of waveguide fabrication using a CCD microscope to evaluate the surface quality and structural integrity of the fabricated waveguides.

CCD microscope images reveal that power loss in both waveguides is primarily attributed to surface scattering loss occurring at the interface between the POF core and the waveguide core materials. The core material of the POF used in this study is made of PMMA (refractive index, n = 1.49 RIU). As previously explained in the methodology section, the POF commercial was used as a connector positioned at both ends of the waveguides, while waveguide core 1 was fabricated using recycled polystyrene without ZnO (n = 1.67 RIU), and waveguide core 2 utilized recycled polystyrene with ZnO incorporation (n = 1.69 RIU). The mismatch in refractive indices between the POF and waveguide core materials contributes to the observed scattering loss at the interface. Fig. 4 illustrates the regions affected by this scattering phenomenon.
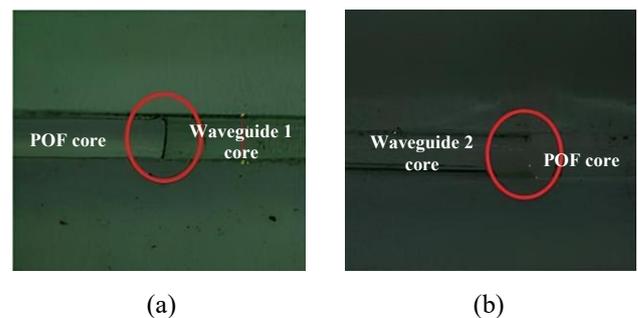

(a)   (b)

Figure 4. (a) Scattering loss surface on waveguide 1 (without ZnO) (b) Scattering loss surface on waveguide 2 (with ZnO)

In addition to refractive index mismatch, scattering loss at the interface between the POF core and the waveguide

core is also influenced by dimensional mismatch. The POF core employed in this study has a diameter of 980 ± 60 μm, whereas the waveguide core exhibits a diameter exceeding 1000 μm. This size discrepancy contributes to misalignment at the junction, resulting in increased light scattering and reduced transmission efficiency.

Despite the dimensional variations, all samples exhibited a high degree of uniformity, with no visible air bubbles observed on the surface of the core material. The absence of air bubbles is essential, as they can disrupt the optical path and lead to significant power losses. This indicates that the core-filling process was effectively conducted, ensuring material continuity and enhancing waveguide performance. The homogeneity and smooth surface of the fabricated waveguides, as shown in Fig. 5, further demonstrate the quality of the fabrication process and the potential of the waveguides for stable light transmission with minimal scattering loss.
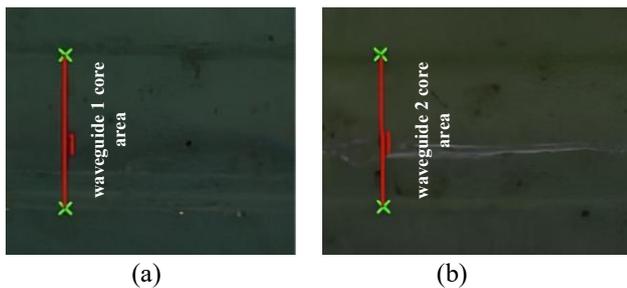

(a)   (b)

Figure 5. Image of the surface of material core which was homogeneous on (a) waveguide 1 (without ZnO), (b) waveguide 2 (with ZnO)

3.5 Comparison with Previous Works

The proposed ZnO-enhanced waveguide sensor fabricated from recycled polystyrene waste demonstrates notable advancements over previous waveguide-based glucose sensing technologies, particularly in fabrication simplicity, material sustainability, and system integration. Traditional sensors, such as those based on silicon-on-insulator (SOI) platforms, require cleanroom environments and sophisticated lithographic processes to achieve high sensitivity, resulting in increased fabrication complexity and cost [19]. Similarly, PDMS-based waveguides, although flexible and biocompatible, often suffer from mechanical instability and bonding challenges with other materials [20]. In contrast, the waveguide developed in this study utilizes recycled polystyrene waste as the core material, enabling a simpler, low-cost, and more environmentally sustainable fabrication process without compromising core functionality.

From a performance standpoint, recent innovations have incorporated advanced materials to improve sensitivity. Gubeljak et al. introduced a graphene-based microwave waveguide sensor that achieved high sensitivity (7.30 dB·$(mg/L)^{-1}$) at glucose concentrations as low as 9 μg/dL [20]. Likewise, Liang et al. reported a non-enzymatic glucose sensor using $ZnO@CuCo_2O_4$ core-shell nanorods, which exhibited a detection limit of 0.82 μM and a rapid response time of 2 seconds [21]. While these sensors demonstrate excellent performance, their

fabrication involves complex synthesis steps and the use of expensive or difficult-to-handle materials. In comparison, the ZnO-polystyrene waveguide sensor in this study achieved a sensitivity of 9×10^{-5} V/ppm, a linear detection range of 0 to 1000 ppm, and a correlation coefficient of 99.12%, offering adequate sensitivity for practical glucose detection in a more accessible and scalable manner.

Furthermore, the sensor's configuration supports seamless integration with conventional optical systems, enhancing its suitability for real-world deployment. Unlike some advanced waveguide sensors that require specialized instrumentation or conditions, the design presented in this work allows for straightforward coupling with standard fiber optic components. This, combined with the use of recycled materials, aligns with global sustainability objectives while addressing practical deployment challenges. Overall, the ZnO-enhanced polystyrene waveguide sensor presents a well-balanced solution-combining reliable performance, environmental consciousness, and fabrication ease-making it a promising candidate for future non-invasive glucose monitoring applications.

4. CONCLUSION

Based on the analysis results, it can be concluded that incorporating ZnO into a polystyrene waste-based waveguide sensor significantly enhances its capability to detect glucose. This improvement is demonstrated by several key performance indicators: an increased sensitivity of 9×10^{-5} V/ppm, a high correlation coefficient of 99.12%, a broad linearity range from 0 ppm to 1000 ppm, and robust resistance to temperature fluctuations. These characteristics indicate that the modified waveguide is both accurate and stable, making it a promising tool for glucose detection. Consequently, a polystyrene waste-based waveguide sensor with ZnO addition presents a viable pathway for further development as an alternative approach for early detection of diabetes mellitus (DM) through non-invasive urine sample testing. This approach could offer a cost-effective and eco-friendly solution for healthcare diagnostics, leveraging recycled materials while providing reliable and efficient glucose monitoring.

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