Light Side Coupling on ZnO Nanorods-Coated Glass Substrate for Lactose Sensing

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ABSTRACT

This study presents a novel sensing device for lactose detection, using ZnO nanorods on glass substrate with a light side coupling technique, as this integration enhances light scattering and adsorption, improving sensing performance. The proposed sensor was exposed to ranging lactose concentrations (0% to 100%) to validate its performance. The results were compared with a classic single light source technique to evaluate several parameters, such as sensitivity, linearity, repeatability, stability, response time, and hysteresis. The experimental findings exhibited a higher sensitivity of 0.0201 V/% concentration, superior linearity of 99.61%, and improved resolution by a factor of 1.5 compared to traditional methods. Due to its cost-effectiveness, simple fabrication process, and superior performance, this sensing platform presents a viable alternative for industrial optical sensing applications, particularly in food quality monitoring and biomedical diagnostics.

Keywords-side coupling; lactose; sensor; zinc oxide

I. INTRODUCTION

Lactose ($C_{12}H_{22}O_{11}$) is a sugar type that serves as a significant energy source. It is commonly referred to as milk sugar due to its presence in dairy products. However, lactose can be converted into toxic compounds by bacteria in the large intestine when it is not completely digested [1, 2]. Therefore, the lactose detection is essential as it is found in a wide variety of foods. Lactose identification is achieved through optical sensing mechanisms, with the utilization of light to identify and analyze particular chemicals that are present in the sample. The lactose measurement is extremely important in several fields, such as healthcare [1], managing food quality/food quality management, [3] and electrochemical [4]. Currently, optical sensing has progressed towards the recognition of various analytes, including inorganics and organic compounds, with applications in explosive areas [5], biomolecules [6], biological systems [7], and bioanalysis [8]. Thus, improving lactose sensing technology can enhance its sensitivity, specificity, and practicality in real-world applications, ensuring more reliable and accurate results.

Zinc oxide (ZnO) is a widely used metal oxide material due to its distinctive electrical and adsorption properties, optical characteristics, and catalytic qualities [9, 10]. The electrical conductivity, water molecule adhesion, and the effective Refractive Index (RI) of the sensing platform of ZnO nanorods affect their optical behavior in proportion to solution concentration [11]. ZnO showcases beneficial optical properties and has been extensively researched and refined across a diverse array of platforms, including microfiber [12], cellulose substrate [13], optic fiber [14], and polyimide [15]. However, using these platforms requires complex fabrication, manufacture, and design. One way to construct a cost-effectively sensing device is to utilize a glass substrate. It has a consistent size, an easy-to-use interface, optical clarity, and is easily accessible. Nonetheless, it is worth mentioning that the most recent iteration of utilizing glass substrate platforms exhibits a constrained ability. Hence, it is necessary to apply ZnO onto glass substrates to enhance its properties. For example, authors in [11] demonstrated ZnO nanorods coated on optical fibers for sensing applications, while in explored gas sensing using ZnO-coated optical fibers was investigated [16].

A reduction in sensitivity is observed when single light sources with low-detectable beam width and low signal are coupled through glass due to an inadequate beam structure. The intensity is distributed unevenly over the platform as a result of this dispersion, with the restrictions concentrating on specific coating regions instead of the entire coating surface. Therefore, this research aims to conduct a thorough examination of how the scattering layer's domain affects the output power intensity. This will be accomplished by employing the method of light side coupling, while mitigating light leakage caused by backscattering [17]. Moreover, to examine the optical characteristics of the scattering region when exposed to a light source, the glass substrate should be tested using modulation based on particular measurements. The proposed sensor should be tested using a variety of concentration RI solutions, including lactose within a predetermined concentration range.

This study introduces a cost-effective and straightforward sensing platform utilizing ZnO nanorods on glass substrates for lactose detection. The integration of light side coupling provides a significant advancement in sensing accuracy and linearity. As far as is known, this is the first demonstration of using ZnO nanorods with light side coupling for lactose sensing.

II. MATERIALS AND METHOD

A. ZnO Nanoparticles Coating-Hydrothermal Synthesis

This research uses ZnO nanorods as a coating material, which are developed on glass substrates deploying hydrothermal synthesis. This method was selected for its simplicity, cost-effectiveness, and ability to produce high-quality ZnO nanorods with controlled morphology and stability. The synthesis process included glass substrate preparation, seeding, and growth [18]. Glass substrates with a surface area of 0.022 m^2, were placed in a container filled with soapy water for 15 minutes (ultrasonic cleaning process). The soapy water was removed prior the cleaning procedure using fresh water for an additional 15 minutes. The glass substrates were then soaked in acetone [CH_3COCH_3] (Bendosen Laboratory Chemical, Germany) using a water bath technique for 15 minutes in order to take off organic material. Samples were then placed in a vacuum oven at 90 °C for 1 hour. Extensive observations have been reported on the hydrothermal development process of ZnO nanorods [19].

For the seeding process, a quantity of 0.0132 g of zinc acetate dehydrate [$Zn(O_2CCH_3)_2{\cdot}2H_2O$] (Friendemann Schmidt, Germany) was dissolved in 60 ml of pure ethanol [C_2H_5OH] (HmbG Chemical, Germany) to form a solution with 1 mM concentration. This will be achieved with continuous stirring at a temperature of 60 °C. Small portions of 0.0003 g sodium hydroxide pellets [NaOH] (Friendemann Schmidt Chemical, Germany) were mixed into the solvent to increase pH to an alkaline level. Subsequently, it underwent a water bath processing at 60 °C for a duration of 3 hours, followed by an annealing procedure at 300 °C for 3 hours. The ZnO growth solution was generated by dissolving 1.4875 g of zinc nitrate hexahydrate [$Zn(NO_3)_2{\cdot}6H_2O$] (Sigma-Aldrich) and 0.7 g of hexamethylenetetramine or HMT [$(CH_2)_6N_4$] (Sigma-Aldrich) in 500 mL of deionized (DI) water to create a 10 mM aqueous solution. The seeded glass substrates were then immersed in the growth solution and subjected to heating in an oven at a 90 °C. To ensure a consistent development rate of the nanorods, it was necessary to replace the solution every 5 hours. The growth duration was chosen to be 12 hours, as determined from previous studies [20].

B. Preparation of Refractive Index Solution-Lactose

The optical properties of lactose underwent evaluation through the utilization of a UV-Vis spectrophotometer, with the aim of analyzing its transmittance, absorbance, and refractive index. The measurement was accomplished with standard extraction of visible light with a wavelength range of 550 nm. This action was undertaken in anticipation of the development of a solution with a specific concentration of the substance known as RI solution, which is lactose.

C. Experimental Setup

Figure 1 displays the integrated sensor device setup designed for the light side coupling technique. This setup contained several elements, including a light source, receiver, Data Acquisition system (DAQ), and Personal Computer (PC). The light source is positioned parallel to the glass surface, with its diameter aligned with the longitudinal axis of the glass substrate. The semiconductor material serves as a medium through which light is coupled and scattered in various directions. The receiver utilizes an enclosed photodetector array to convert the light signal into a voltage signal. To prevent interference from ambient light, ensuring full coverage of the photodetector is essential. Therefore, a precise design for 3D printer is necessary to ascertain that the light detected by the photodetector will propagate across the glass substrate. The sensor device's body was fabricated using a 3D printer, with the casing designed utilizing the software Fusion 360, by Autodesk. The experimental approach involved employing a visible light source to illuminate the uppermost layer of a glass substrate [11].

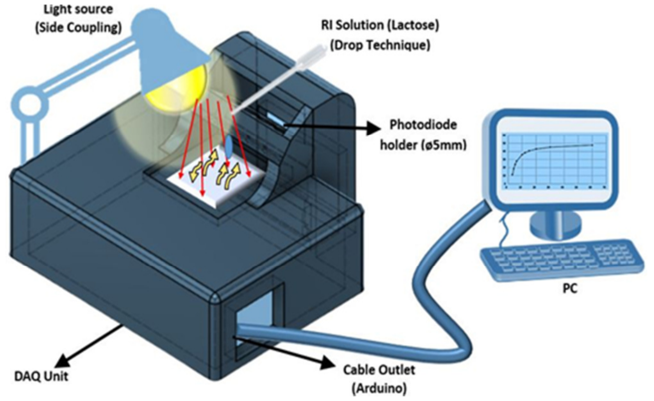

Fig. 1. Experimental setup for lactose sensing using light side coupling technique.

Furthermore, a comprehensive analysis was conducted to investigate the use of a solitary light source channel at the edges of the glass substrate. Its purpose was to establish a distinction between the optical side coupling technique and a single Light Emitting Diode (LED). The experiment was conducted at a standard ambient temperature to examine the concentration levels of the lactose solution ranging from 0% to 100%. Following that, a thorough investigation was developed to investigate the behavior of the output voltage, specifically focusing on the performance of lactose sensing and the efficacy of the side coupling technique compared to a single light source.

III. RESULTS AND DISCUSSIONS

A. Structure of the ZnO Nanorods

Figure 2 presents the Field Emission Scanning Electron Microscopy (FESEM) images of the ZnO nanorods hydrothermally synthesized on a glass substrate. Figure 2(a) and 2(b) depict the visual representation of the ZnO substance grown vertically on the glass substrate, with magnifications of 1.00 kx and 20.00 kx, respectively.

(a)

(b)

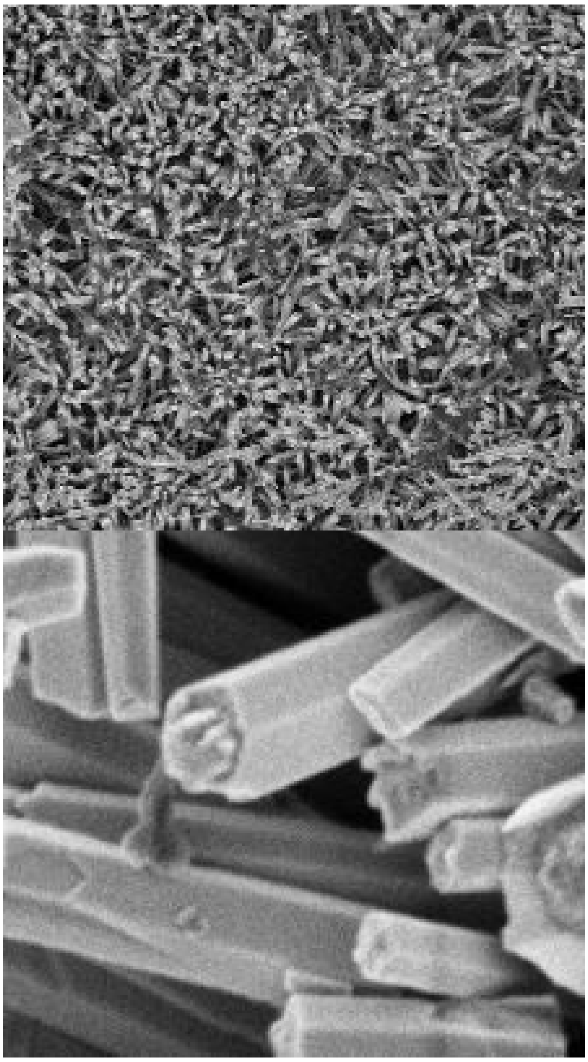

Fig. 2. FESEM images of ZnO nanorods coated glass: (a) at low magnification (1.00 kx), (b) at high magnification (20.00 kx).

B. Sensing Performance

Figure 3 illustrates the real-time response of the proposed sensor when exposed to varying lactose concentrations ranging from 0% to 100% for both the uncoated and the coated glass substrate. This was performed in order to determine the sensor's response and recovery time. The results indicate that the sensor required approximately 100 seconds to reach a stable response concentration, while the recovery duration was approximately 50 seconds. In contrast, the uncoated glass exhibited inadequate response due to the rapid concentration differential variations. Figure 4 displays the trendline graph of the sensor, showing the relationship between the varied concentrations of the lactose solution. These concentrations span the entire spectrum, ranging from 0% to 100%. The coated glass substrate exhibited a superior R^2 value of 99.6% compared to 95.34% for uncoated glass. This difference indicates improved linearity due to ZnO nanorods, enhancing light scattering and adsorption. In other terms, it is obvious that an augmented scattering of light due to the presence of ZnO nanorods resulted in a greater leakage of photons as the concentration escalated. The nanostructures of ZnO exhibit a remarkable surface to volume ratio, thereby conferring upon them the ability to improve the adsorption of molecules on the surfaces [21]. However, the response observed in the uncoated glass is attributed to minor RI changes, causing slight variations in light propagation.

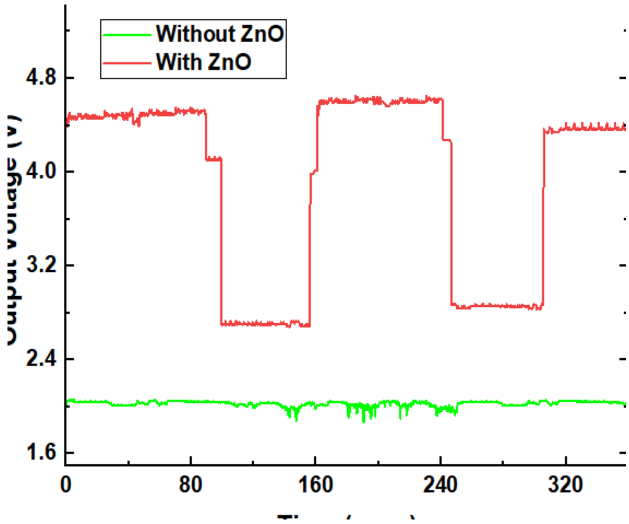

Fig. 3. Response time and recovery time for both uncoated and coated samples.

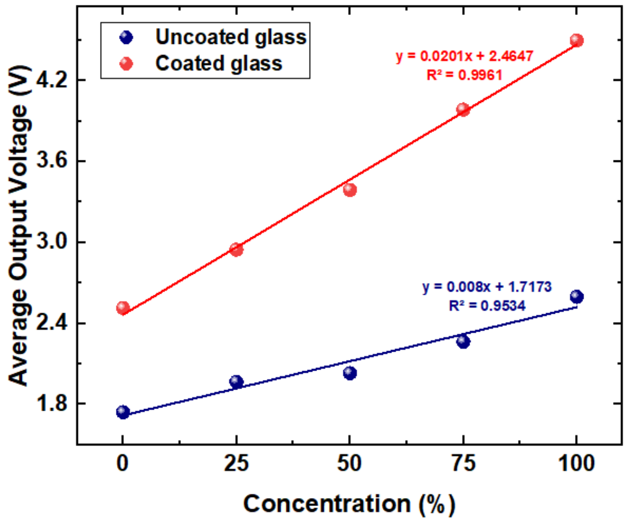

Fig. 4. Trendline of the proposed sensor on ZnO coated glass substrate and uncoated glass substrate based on side coupling.

Figure 5 portrays the repeatability of the output voltage for lactose sensing on both uncoated the coated glass substrate with ZnO nanorods. It is obvious that both samples exhibit consistent outcomes in terms of repeatability across all concentration variations. The increase in voltage with lactose concentration is related to changes in RI, which improves light scattering. The ZnO nanorods enhance this trend, leading to a higher voltage signal.

(a)
(b)

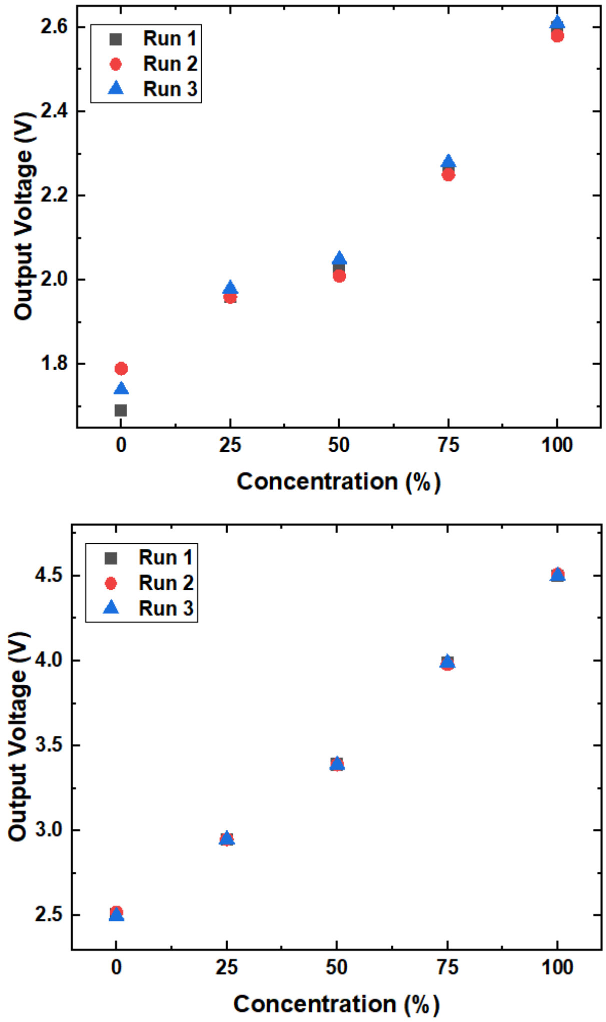

Fig. 5. Repeatability for a sample: (a) without ZnO glass substrate, (b) with ZnO glass substrate.

Nevertheless, the stability of the graphical representation for both samples is displayed in Figure 6. By observing the output voltage data for a duration of 16 minutes (960 seconds), the stability of the proposed sensor was assessed. The stability data for the uncoated glass substrate are depicted in Figure 6(a). These findings revealed a noticeable unstable condition when compared to the ZnO coated glass (Figure 6(b)), especially at 0%, 50%, and 100%, where the proposed sensor exhibits superior stability. The reason for this distinction is because the analyte molecules are adsorbed and desorbed at numerous rates on the coating layer, leading the sensor behavior to change [20]. While the current study demonstrates stability up to 16 minutes, the long-term stability of the sensor may be limited by the degradation of ZnO nanorods. Future work should focus on protective coatings or optimizing the synthesis process to enhance the durability of ZnO nanorods and improve the sensor's performance over extended durations. Furthermore, Figure 7 shows the hysteresis phenomenon for the output voltage in both samples. The process begins with evaluating the sensory response to increasing lactose concentrations while decreasing the RI solution of lactose. In Figure 7(a), the uncoated glass substrate generates a significant difference in output voltage of approximately 0.14 V at a concentration of 50%. In comparison, the ZnO coated glass substrate exhibits a more favorable hysteresis trend, as demonstrated in Figure 7(b), with a lower variation in both forward and reverse. The findings demonstrate that the proposed sensor exhibits better hysteresis consistency.

(a)

(b)

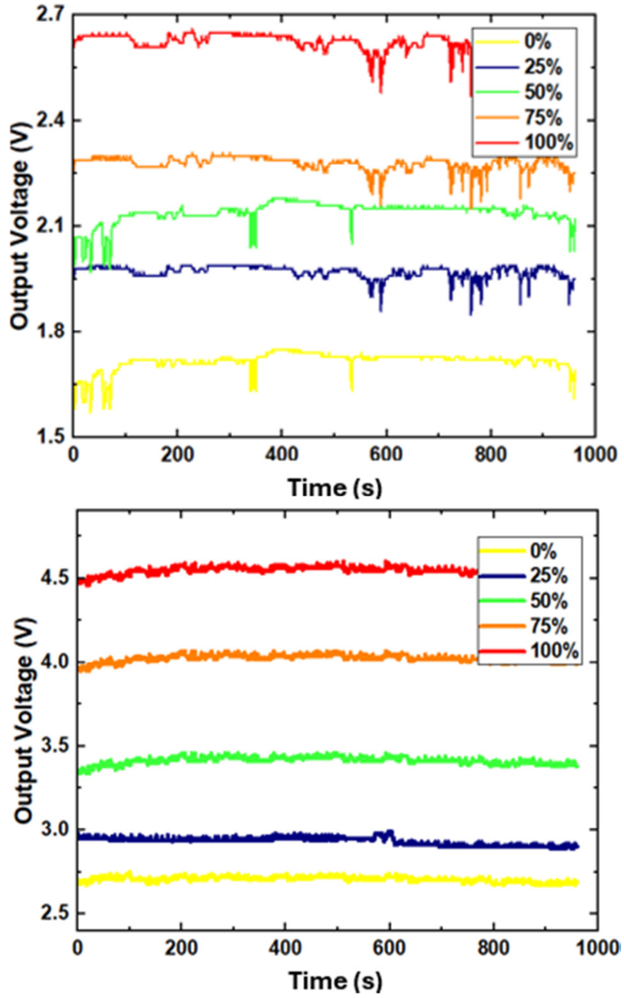

Fig. 6. Stability for a sample: (a) without ZnO glass substrate, (b) with ZnO glass substrate.

Table I presents a summary of the experimental results. For comparison purposes, it also includes the experimental results of the classic single light source with ZnO coated glass substrate conducted in [18]. This comparison was performed to evaluate the relative effectiveness of the light side coupling technique with the performance of a single LED when exposed to different concentrations of lactose solution. The sensitivity of the proposed sensor was measured at 0.0201 V/(% Concentration), which is significantly higher than the 0.0133 V/(% Concentration) of a single light source with ZnO based sensor. Notably, the linearity of the proposed sensor is 99.61%, which is better than the classic method, which stands at only 90%. In terms of resolution, the proposed sensor outperformed the classical method by a factor of 1.5, further highlighting its enhanced detection capabilities.

(a)

(b)

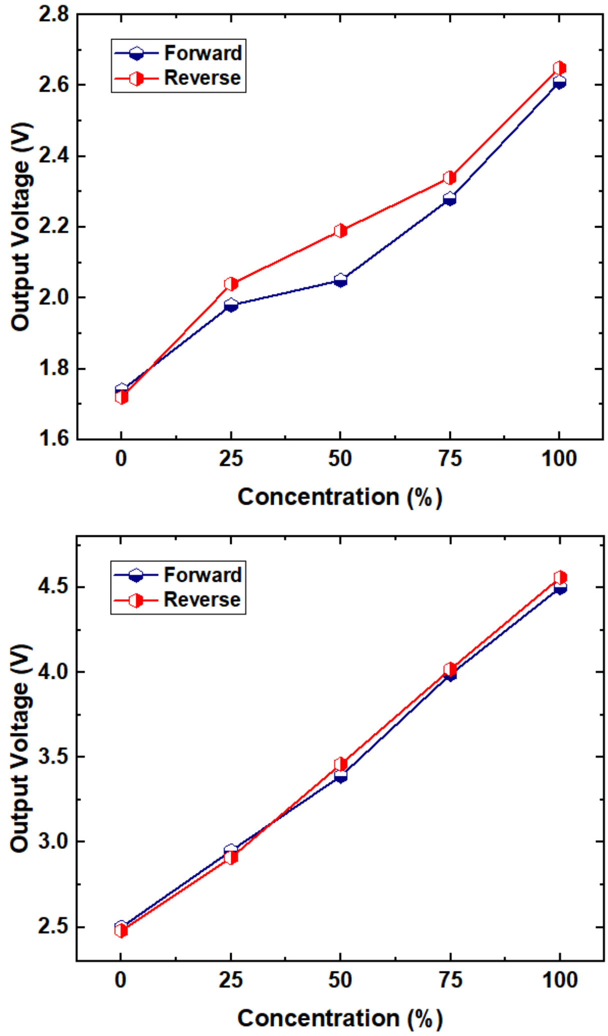

Fig. 7. Hysteresis for a sample: (a) without ZnO glass substrate, (b) with ZnO glass substrate.

TABLE I. SENSING PERFORMANCE BASED ON LIGHT SIDE COUPLING

Parameter	Sensing without ZnO	Sensing with ZnO	Single light source with ZnO
Linearity (%)	95.34	99.61	90
Sensitivity (V/% concentration)	0.008	0.0201	0.0133
Standard deviation (V)	0.0224	0.0043	0.0043
Resolution (%concentration)	2.8024	0.2144	0.3283
Linear range (%concentration)	25-75	0-100	0-100

These improvements are related to the strategic implementation of the side coupling technique, exhibiting an exceptional amount of responsiveness to sensing applications in comparison to a single LED. The implementation of side coupling during the performance procedures has resulted in the emergence of additional channels for the scattering of light in various directions. This phenomenon occurs specifically at angles exceeding the critical angle, where the light is effectively influenced within the sensing platform.

IV. CONCLUSION

This paper examines a novel lactose sensing mechanism by integrating ZnO nanorods on glass substrates with the light side coupling technique. Several parameters were evaluated including sensitivity, linearity, repeatability, stability, response time, and hysteresis. The performance of the proposed sensor was compared to a single light source setup from previous research across lactose concentrations ranging from 0% to 100%. The experimental results revealed that the proposed sensor achieved a higher sensitivity of 0.0201 V/% concentration, linearity of 99.61%, and resolution by a factor of 1. Hence, the proposed sensor demonstrates an effective approach of integrating ZnO nanorods with light side coupling for lactose detection. This study also highlights the cost-effectiveness and simplicity of this procedure, making it a promising alternative for industrial optical sensing applications.

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