EFFECTIVE SCATTERING AREA ON COATED GLASS SUBSTRATES USING OPTICAL SIDE COUPLING TECHNIQUE FOR SENSITIVITY ENHANCEMENT

MARLINA BINTI JAHAVA

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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2025

DECLARATION

I declare that this thesis entitled "Effective Scattering Area on Coated Glass Substrates using Optical Side Coupling Technique for Sensitivity Enhancement" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Marlina binti Jahava

Date : 19 August 2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering

Signature :...

Supervisor Name :...Ts. Dr. Mohd Hafiz Bin Jali.........................

Date :....20 August 2025..

DEDICATION

I would want to dedicate this thesis to my parents, who have always had a strong faith of my education and have committed endless gives that allowed me to pave the way for every accomplishment I have ever known. They have provided me with the strength to overcome challenges and pursue my dreams with courage through the consistent encouragement.

ABSTRACT

The integration of nanomaterials with optical sensing platforms has significantly advanced the performance and versatility of sensor devices. Among various alternatives to optical sensor, glass substrates have recently garnered considerable interest due to their stability, low cost, and ease of fabrication. However, conventional glass based sensors often suffer from limited sensitivity, primarily due to inefficient light coupling and low transmission from a single edge illuminated source. This research proposes an enhanced optical sensing approach utilizing side coupling visible light on a zinc oxide (ZnO) nanorod coated glass substrate. By directing a visible light source perpendicularly onto the upper surface of the glass, the technique increases light intensity along the sensing region while minimizing backscattering losses. ZnO nanorods, selected for their high refractive index, were coated on the substrate surface. Different exposed coating areas were investigated to evaluate their influence on light scattering and coupling efficiency. Experimental results demonstrate that a sensor with a $0.022m^2$ coating area achieved superior performance across multiple parameters, including output light intensity, voltage response, and refractive index sensitivity. This sample exhibited a 97.5% linearity and a sensitivity of 0.0125V/%Concentration, outperforming single-source devices by a factor of 1.5. The proposed sensor also showed notable improvements in resolution and linear range, indicating its potential for high precision optical measurements. Overall, this study introduces a simple yet effective method for enhancing the performance of glass based optical sensors. By leveraging the scattering and absorption characteristics of ZnO nanostructures under side-coupled illumination, the proposed design offers a promising solution for developing reliable and cost efficient sensors suitable for various industrial and environmental monitoring applications.

LUAS SERAKAN BERKESAN PADA SUBSTRAT KACA BERSALUT MENGGUNAKAN KAEDAH GANDINGAN SISI OPTIK UNTUK PENINGKATAN KEPEKAAN

ABSTRAK

Integrasi nanomaterial dengan platform pengesan optik telah meningkatkan prestasi dan kebolehlaksanaan peranti sensor secara signifikan. Antara pelbagai alternatif kepada sensor optik, substrat kaca telah menarik minat yang besar sejak kebelakangan ini disebabkan kestabilannya, kos yang rendah, dan proses fabrikasi yang mudah. Walau bagaimanapun, sensor berasaskan kaca konvensional sering mengalami masalah kepekaan yang rendah, terutamanya disebabkan kecekapan penggandingan cahaya yang lemah dan penghantaran cahaya yang rendah daripada sumber tunggal di tepi substrat. Kajian ini mencadangkan pendekatan pengesanan optik yang dipertingkatkan dengan menggunakan cahaya tampak yang digandingkan dari sisi ke atas substrat kaca yang disalut dengan nanorod zink oksida (ZnO). Dengan mengarahkan sumber cahaya tampak secara menegak ke permukaan atas substrat, teknik ini meningkatkan keamatan cahaya di sepanjang kawasan pengesanan sambil mengurangkan kehilangan cahaya akibat penyebaran semula (backscattering). Nanorod ZnO, yang dipilih kerana indeks biasan tingginya, disalut pada permukaan substrat dan kawasan salutan yang berbeza diuji untuk menilai kesannya terhadap penyebaran dan kecekapan penggandingan cahaya. Keputusan eksperimen menunjukkan bahawa sensor dengan kawasan salutan seluas 0.022m² mencapai prestasi terbaik dalam pelbagai parameter, termasuk keamatan cahaya keluar, tindak balas voltan, dan kepekaan terhadap perubahan indeks biasan. Sampel ini mencatatkan lineariti sebanyak 97.5% dan kepekaan sebanyak 0.0125 V/%, serta menunjukkan prestasi yang lebih baik berbanding peranti sumber tunggal dengan faktor peningkatan sebanyak 1.5. Sensor yang dicadangkan juga menunjukkan peningkatan ketara dari segi resolusi dan julat linear. Secara keseluruhannya, kajian ini memperkenalkan kaedah mudah tetapi berkesan untuk meningkatkan prestasi sensor optik berasaskan kaca. Dengan memanfaatkan ciri penyebaran dan penyerapan permukaan nanostruktur ZnO melalui pencahayaan sisi, reka bentuk ini menawarkan penyelesaian untuk membangunkan penderia yang boleh dipercayai dan cekap kos yang sesuai untuk pelbagai aplikasi pemantauan industri dan alam sekitar.

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LIST OF ABBREVIATIONS

UTeM	-	Universiti Teknikal Malaysia Melaka
3D	-	Three dimension
dBm/°C	-	Decibel-milliwatts per degree Celsius
C_2H_5OH	-	Pure ethanol
CH_3COCH_3	-	Acetone
CH_3COO	-	Acetate ions
$Zn(O_2CCH_3)_2.2H_2O$	-	Zinc acetate dehydrate
DAQ	-	Data Acquisition System
DI	-	Deionized water
EDX	-	Energy Dispersive X-ray spectroscopy
EtG	-	Ethyl Glucuronide
FESEM	-	Field Emission Scanning Electron Microscope
HMT	-	Hexamethylenetetramin
LED	-	Light emitting diode
LSS	-	Light Side Coupling
IoT	-	Internet of Thing
IR	-	Infrared
O	-	Oxigen
NaOH	-	Sodium Hydroxide
NASA	-	National Aeronautics and Space Administration
Nm	-	Nanometer
PC	-	Personal Computer
PEC	-	Photoelectrochemical

pH	-	Potential of Hydrogen
RI	-	Refractive Index
SEM	-	Scanning electron microscopy
SMF	-	Single Mode Fiber
TiO_2	-	Titanium dioxide
TIR	-	Total Internal Reflection
UV	-	Ultraviolet
VOC	-	Volatile organic compound
V/%	-	Volts per Percent
ZnO	-	Zinc Oxide
Zn	-	Zinc
Zn^{2+}	-	Zinc ions

LIST OF SYMBOLS

α	-	Scattering coefficient
γ	-	Sensing performance factor
d		diameter
V	-	Output Voltage
θ	-	Scattering angle
θ_I		Incident angle
λ	-	Wavelength of light
n	-	Refractive index
L	-	Length of sensing areas
I	-	Output light
I_o	-	Ligth Sources
°C	-	Degree Celcius

LIST OF APPENDICES

LIST OF PUBLICATIONS

Listed below are the publications result from the research undertaken in this thesis:

Jahava, M., Jali, M.H., Johari, M.A.M., Norashikin, M.A., Yusof, H.H.M. and Ahmad, A., 2023, December. ZnO Nanorods Coated Glass Substrate Based on Side Coupling Technique for Lactose Sensing Application. In *2023 International Conference on Electrical, Communication and Computer Engineering (ICECCE)* (pp. 1-7). IEEE.

Jahava, M., Jali, M.H., Johari, M.A.M., Norashikin, M.A., Yusof, H.H.M. and Ahmad, A., 2023, September. Optimizing Scattering Area of ZnO Nanostructures on Glass Substrates Platform for Sensing. In *2023 IEEE International Conference on Sensors and Nanotechnology (SENNANO)* (pp. 129-132). IEEE.

Jahava, M., Jali, M.H., Norashikin, M.A., Johari, M.A.M., Ahmad, A., Yusof, H.H.M., Rahim, H.R.A. and Harun, S.W., 2024. Optical Characterization of Different Scattering Area on ZnO Nanorods Coated Glass Substrate Based on Side Coupling Technique for Sensing Application. *IEEE Access*, *12*, pp.26519-26528.

Jahava, M., Jali, M.H., Johari, M.A.M., Norashikin, M.A., Yusof, H.H.M. and Ahmad, A., 2025. Light Side Coupling on ZnO Nanorods-Coated Glass Substrate for Lactose Sensing. Engineering, Technology & Applied Science Research, 15(3), pp.22424–22430.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Optical devices have gained considerable interest for sensing applications due to several advantages, such as simple design, wide detection range, low cost, high sensitivity and exceptional precision (Zhao et al., 2020). They offer distinct benefits compared to the electronic counterparts, particularly in demanding environments such as combustible atmospheres and high-pressure conditions. Additionally, optical devices are capable of transmitting signals over long distances. Furthermore, they significantly impact a wide range of fields, including healthcare (Pirzada and Altintas, 2019), chemical industries (Ullah et al., 2018), the production of semiconductor (Moon and Lee, 2024), and environmental control (Yeh et al., 2017). Optical sensors can be classified based on their operational principles, which are carefully evaluated and analyzed. These sensors are widely employed in various applications to detect and quantify diverse parameters, including humidity monitoring (Young and Lai, 2021), bioresorbable (Shin et al., 2019), chemical detecting (Sahoo et al., 2018), and biomedical (Roriz et al., 2020).

This thesis presents an extensive study on the development of a novel optical sensor that integrates a glass substrate coated with Zinc Oxide (ZnO) nanorods and employs a side coupling technique to enhance sensitivity. The development process is detailed in a straightforward and practical manner. The side coupling technique is a method commonly used in optical sensors to facilitate light transmission between different substrates. This method involves redirecting light from a source, such as a waveguide, into a detection element or another waveguide by positioning it adjacent to the coupling area rather than aligning them linearly (Rahim et al., 2020). The side coupling approach is particularly advantageous when conventional end-to-end coupling is impractical due to space limitations or alignment challenges, which often lead to scattering losses. As part of this thesis, an improved sensor design with an enhanced scattering coefficient for sensitivity improvement also be presented.

1.2 Zinc Oxide Nanomaterial for Optical Sensor

Zinc oxide (ZnO) is a semiconductor nanomaterial that has garnered significant interest from researchers due to its remarkable optical, thermal, and mechanical properties (Sharma et al., 2022). ZnO exhibits an exciton binding energy of 60 millielectron volts (meV) and an energy gap of 3.3 electron volts (eV). It has been widely applied in various fields, including solar cell electrodes (Ji et al., 2019), gas sensor (Bhatia et al., 2017), coating (Verbič et al., 2019), and transistor fabrication (Jiang et al., 2018). Specifically, Nanomaterials, such as ZnO, have enabled numerous innovations in signal transduction, resulting in enhanced performance. This is attributed to their unique morphological characteristics, affordability, functionality, biocompatibility, non-toxicity, and catalytic properties (Yusof et al., 2018b). Numerous studies have demonstrated the successful production of ZnO nanorods on various platforms, including glass substrates (Yusof et al., 2019), paper subsrate (Araújo et al., 2017), polyimide (Fung et al., 2017), and silica microfiber (Yasin et al., 2019). Additionally, the abundance of vacant oxygen sites in ZnO provides numerous potential adsorption locations for water molecules, enhancing its utility in sensing applications.

A technologically advanced optical sensor has been developed for precisely evaluating the concentrations of solutions (%Concentration) using a ZnO coated glass substrate. The remarkable optical properties of ZnO, this sensor can detect even minute variations in the refractive index (RI) of a solution. Numerous materials have been studied for concentration sensing, including acetone (Yang et al., 2019), phenol (Dewidar et al., 2018), and formaldehyde (Johari et al., 2022). Consequently, the findings of this study provide deeper insights into the sensing mechanisms of the proposed sensor for lactose solutions by analyzing its sensitivity, accuracy, and practicality in real world scenarios. The outcomes are expected to be precise and reliable, further enhancing the utility of ZnO based optical sensors in diverse applications.

Optical sensors utilizing ZnO coated glass substrates achieve exceptional sensitivity and precision in detecting variations in the refractive index of solutions, making them highly desirable for a broad range of analytical and industrial applications. This novel method employs a straightforward and efficient light source and receiver system to convert light passing through the glass substrate into a voltage signal. A cost effective alternative to complex technologies has been implemented, using a data acquisition device constructed on the Arduino platform to analyze the output signal.

1.3 Problem Statement

Research on optical sensing devices based on glass substrate platforms has gained momentum in recent years. These devices are introduced to address issues associated with optical fibers, such as limited sensing regions, high costs related to mechanical alignment apparatus, and beam distribution inequalities, which lead to fluctuations, non-representative data, and low intensity (Rahim et al., 2020). However, the sensitivity of glass substrate based sensing devices remains relatively low due to poor light coupling efficiency. This limitation arises because only a small transmission region allows light scattered from a single source at the edge of the glass substrate to travel along the sensing platform, resulting in significantly low total coupled power (Yusof et al., 2018a). Such conditions are undesirable in optical applications, including telecommunications, sensing, and measurements (Cennamo et al., 2021, Kadhim et al., 2022). One approach to increase light intensity is the implementation of the light side coupling technique on the surface of coated glass substrates. In this technique, a visible light source illuminates the upper hemisphere of the glass substrate, oriented normal to its surface. This method induces more channels for scattered light in various directions at angles larger than the critical angle, guiding the light within the sensing platform. While increasing the scattering layer can potentially enhance coupling efficiency, recent studies show that this is not always the case. Expanding the coating area for scattering can also create pathways for light leakage due to backscattering phenomena (Rahim et al., 2020).

Although semiconductor coating materials such as ZnO nanorods improve optical side coupling, they also introduce scattering centers that cause light leakage. This occurs as the light penetrates outside the sensing platform with each bounce at the interface. Such leakage limits the system's applicability for multiple channels and extended sources. The morphological structure of ZnO nanorods affects both forward and backward scattering. While backward scattering increases light leakage, forward scattering reduces it (Yusof et al., 2018a). Therefore, optimizing the balance between these phenomena is crucial to achieving the desired output response. To address this issue, investigating the coupling area of the coating material across the sensing platform becomes essential (Rahim et al., 2020). A significant challenge lies in the correlation between the scattering layer area induced by the coating and the coupling power for sensitivity enhancement, which has been largely overlooked. This research project proposes a comprehensive analysis of the fundamental effects of the scattering layer area on output power intensity using the light side coupling technique. Additionally, determining an effective scattering layer area on coated glass substrate is necessary in order to identify the optimal trade off between backscattering and light coupling efficiency. To achieve this, theories related to light propagation, surface absorption, scattering coefficients, and nanostructural morphology must be incorporated and aligned with the research objectives. This approach aims to contribute to new knowledge by enhancing light coupling efficiency through the incorporation of the optical side coupling technique onto coated glass substrate platforms. It also seeks to establish new theoretical insights into the relationship between the scattering area of the coated glass substrate and the sensing response. Ultimately, this work was fulfill the critical requirements of sensing devices that demand high sensitivity, low cost, and simple design

1.4 Research Question

It is hypothesized that if the effective scattering area on a coated glass substrate layer is identified, the light intensity travel along the sensing region will be increase by limiting the light leakage due to backscattering. It can be predicted that possible enhancement of the total coupling will be achieved; thus increase the sensitivity of the proposed sensor. Several research question need to be addressed are:-

i) What is the most effective scattering area on a coated glass substrate that produce greater light coupling efficiency.

ii) How much improvement could be achieved by applying the light side coupling on the glass substrates as compared to the conventional technique.