CHARACTERIZING THE PERFORMANCE OF MIRRORLESS CONCENTRIC LARGE CORE BUNDLED PLASTIC OPTICAL FIBER DISPLACEMENT SENSOR FOR LIQUID CONCENTRATION DETECTION

BY

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ABSTRACT

Fiber optic displacement sensor is one of the most important technology of modern world due to its versatility to detect various physical and chemical parameters. The objective of this research is to demonstrate a mirrorless plastic optical fiber displacement sensor (POFDS) as a device for liquid concentration detection. The sensor is characterized by using 780 nm laser with maximum output power of 130 mW. The sensor performance is tested by replacing mirror with various colour paper of the same material. The sensitivity of the sensor towards the changes of colour and the output power obtained are 0.0228 mW/μm, 0.1718 mW/μm, 0.1122 mW/μm, 0.106 mW/μm and 0.1267 mW/μm for black, blue, green, red and white colour paper, respectively. The experimental results prove that as the colour changes from dark to bright, the peak output power increases proportionally. The sensor shows a good response to colour paper as reflector thus it is used as a target to replace mirror. The sensor also used to detect paracetamol (PCM) concentration from 5 ppm to 45 ppm in aqueous solution using red and white colour paper as a reflector as both of it projected the highest peak output power compare to others. The sensor has a 98% and 95% of linearity for red reflector and white reflector respectively. The sensor sensitivity towards the changes of output power against the changes in concentration of the solution for each reflector is then compared with mirror. For red colour paper, white colour paper and mirror, the sensitivity is 0.0004 mW/ppm, 0.0008 mW/ppm and 0.02 mW/ppm respectively. The experimental results indicate that the sensor can measure and detect the concentration of paracetamol in aqueous solutions using non-mirror reflector. This research manages to construct a highly stable and persistent sensor, with additional advantages of practicality of design, high efficiency, comprehensive depth of field and low cost of production, which could be beneficial for applications in the sensing field.

خلاصة البحث

يعد مستشعر إزاحة الألياف الضوئية أحد أهم التقنيات في العالم الحديث نظرًا لتعدد استخداماته للكشف عن مختلف العوامل الفيزيائية والكيميائية. الهدف من هذا البحث هو إظهار مستشعر إزاحة الألياف الضوئية البلاستيكية غير المرآة (POFDS) كجهاز للكشف عن تركيز السائل. يتميز المستشعر بإنتاجية 780 قدرة 130 ميغاواط. يتم اختبار أداء المستشعر عن طريق استبدال المرآة بورق ملون مختلف من نفس المادة. حساسية المستشعر تجاه تغيرات اللون وقوة الخرج هي 0.0228 ميغاواط / م ، و 0.1718 ميغاواط / م ، و 0.1122 ميغاواط / م ، و 0.106 ميغاواط / م و 0.1267 ميغاواط / م للألوان الأسود والأزرق والأخضر والأحمر والأبيض الورق على التوالي. النتيجة التجريبية 66 وأنه مع تغير اللون من الظلام إلى الساطع ، تزيد طاقة الخرج القصوى من الليزر مع أقصى إثبات متناسب يُظهر المستشعر استجابة جيدة للورق الملون كعاكس وبالتالي يتم استخدامه كهدف لاستبدال المرآة. يستخدم المستشعر أيضًا للكشف عن تركيز الباراسيتامول في محلول مائي باستخدام (PCM) ورق ملون باللونين الأحمر والأبيض كعاكس حيث تعطي كلاهما أعلى طاقة إنتاجية مقارنة بالآخريات. يحتوي المستشعر على 98٪ و 95٪ من الخطية للعاكس الأحمر والعاكس الأبيض من 5 إلى 45 جزء في المليون على التوالي. استجابة المستشعر تُظهر نفس الأبعاد جيد للحساسية. حساسية المستشعر تجاه التغييرات في الباراسيتامول هي زيادة المستشعر يظهر اتجاهًا مشابهًا مع المحلول الفارغ ، ثم يكون تركيز منحنى الذي يحدد طاقة الخرج مقابل التغيرات في تركيز المحلول لكل عاكس مع o 45 المرآة. بالنسبة للورق الأحمر والورق الأبيض والمرآة ، تمت مقارنة الحساسية بـ 0.0004 ميغاواط / جزء في المليون و 0.0008 ميغاواط / جزء في المليون و 0.02 ميغاواط / جزء في المليون على التوالي ، وتشير النتائج التجريبية إلى أن المستشعر يمكنه قياس وكشف تركيز الباراسيتامول في المحاليل المائية باستخدام عاكس غير مرآة. تمكنت عملية إعادة التدوير هذه من إنشاء مستشعر مستقر للغاية ومستمر ، مع مزايا إضافية للتطبيق العملي للتصميم ، وكفاءة عالية ، وعمق شامل للمجال وتكلفة منخفضة للإنتاج ، مما قد يكون مفيدًا للتطبيقات في مجال الاستشعار.

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APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Computational and Theoretical Sciences).

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Mohd Zamani bin Zulkifli
Supervisor

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Dean, Kuliyyah of Sciences

DECLARATION

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degree at IIUM or other institutions.

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LIST OF ABBREVIATIONS

DC	Direct Current
FBG	Fiber Bragg Grating
FOS	Fiber Optic Sensor
PCM	Paracetamol
PMMA	Poly-Methyl-Methacrylate
POFDS	Plastic Optical Fiber Displacement Sensors
RF	Receiving Fiber
RGB	Red Green Blue
TF	Transmitting Fiber
TIR	Total Internal Reflection

LIST OF SYMBOLS

n	Refractive Index
θ_i	Incident Angle
θ_c	Critical Angle
η	Efficiency of Output Power
d	Lateral Displacement
a	Fiber Core Radius
S_a	Fiber Surface Cross Section
ω_a	Fiber Core Radius
θ_a	Divergence Angle
z_a	Longitudinal Coordinate
Q'	Midpoint Coordinate of Image Of RF
h	Z-Axis Displacement
r	Radial Coordinate
ω_0	Beam Waist Radius
z_R	Rayleigh Length
$I(r,z)$	Irradiance Function
$P(z)$	Gathered Optical Power
h_N	Normalized Distance
P_{max}	Maximum Output Power
P_E	Emitted Output Power
P_N	Normalized Output Power
λ	Optical Source Wavelength
ζ	Dimensionless Parameter
$\omega(z)$	Radius Corresponds to Emitting Light Cone
z	Lateral Coordinate

CHAPTER ONE

INTRODUCTION

1.1 RESEARCH BACKGROUND

Fiber optic sensing has been used over the past 60 years to improve and offer many benefits over traditional electronic sensors in the environment. Due to their unique advantages such as resistance to electromagnetic interference, high sensitivity, compact size and low cost, fiber optic sensors (FOS) have gained considerable attention nowadays (Joe et al. 2018). As compared to other rising technologies, fiber optic is one of the fastest growing field as scientist and researchers saw a great potential of it.

In this era, FOS are shown to be useful sensors for the measurement of several physical quantities such as temperature (Cai et al. 2010), displacement (M. Yasin et al. 2009), vibration (Garcia-souto and Lamela-rivera 2006) and refractive index (Schiebener and Straub 1990). FOS are also designed to measure chemical parameters such as pH and solution concentration (Yasin et al. 2010). FOS helps to measure a number of variables in situations where other sensors are not optimal or poorly performed. (Cai et al. 2010; Garcia-souto and Lamela-rivera 2006; M. Yasin et al. 2009). Thus, FOS will continue to progress and grow to be used in various purposes particularly in providing an effective, reliable and accurate measurement device.

Generally, there are two kinds of optical fiber sensors namely intrinsic and extrinsic. The intrinsic fiber optic sensor is used as a transducer where the fiber optic cable is the detector itself. While the system that uses fibers to provide illumination for a sensor and transmits the signals to a sensor system is known as an extrinsic sensor. Plastic optical fiber displacement sensor (POFDS) is one of the extrinsic fiber optic sensor that is commonly used and shown to be effective for various applications (M Yasin, Harun, and Ahmad 2009).

Initially, a non-contact displacement detection method is envisioned using a fiber optic lever technique (Suganuma, Shimamoto, and Tanaka 1999) and then it is subsequently carried out their geometric research (Cook and Hamm 1979). Theoretical study of the displacement sensor was developed later based on the geometrical and Gaussian approach (Faria 1998).

In this research, the characterization of the performance of the mirrorless POFDS will be analysed. Besides, the design of the mirrorless POFDS is also improved in order to extend its versatility as a reliable sensing device. The effect of different kinds of reflector will be examined to observe the sensitivity of our sensor to the changes in the refractive index. Finally, we will use our mirrorless POFDS as a liquid concentration sensor and analysed its performance.

1.2 PROBLEM STATEMENT

The design of POFDS plays a significant role in this study. A fundamental research done by other researchers proved that there is always a need for improvement so that the sensor can expand its functionality and sustain its reliability. In order to improve the efficiency of this sensor, one of the main element that need to be considered is the mirror, since it is the key to sensitivity of the sensor. However, it can cause limitation to the design of POFDS because it will lose the flexibility and versatility to be used as a sensor in general and it also can affect the reactivity when there is no mirror used.

Recent development of POFDS shows that mirror has been use as a reflector. Yet, mirror is easily disturbed by stray light that will affect the reading of the photo detector. Therefore, this project intended to replace mirror with other potential materials in order to expand the choices of reflector that can be used other than mirror itself. Inadvertently, the responsiveness of the sensor can be ameliorated by testing the limits of the sensor and discovering other possibilities to create options for researcher to find the best selection of reflector according to their needs and sensing applications.

1.3 RESEARCH QUESTION

The goal of this research is to answer some questions in order to achieve the research objectives. The questions are as below:

1. Can we develop and design a mirrorless POFDS to enhance the sensitivity?
2. How can POFDS used to detect changes in refractive index with different types of reflector?
3. How sensitive is POFDS to the changes of refractive index to the different types of reflector?
4. How can we use a mirrorless and non-contact POFDS as a reliable source of sensor?

1.4 RESEARCH OBJECTIVE

The general objectives of this research are:

1. To develop and design a mirrorless POFDS.
2. To analyse the effect of different types of reflector on the POFDS to compensate variations of the target reflectance and the launched power.
3. To study the sensitivity of the mirrorless non-contact POFDS and use it as a liquid concentration sensor.

1.5 RESEARCH HYPOTHESIS

This research has predicted a few possible outcomes according to the following hypothesis:

1. The differences in refractive index exhibit different absorption and reflectivity by the light.
2. Higher refractive index causes more scattering of laser rather than being reflected. Thus, low intensity of reflected laser towards the receiving fiber.

1.6 RESEARCH SCOPES AND LIMITATIONS

The research scope for this project is bounded by 0 μm to 850 μm displacement of the sensor movement. The wavelength of the laser is 780 nm with output power ranging between 50 mW to 130 mW only. The material for the fiber optics is poly-methyl-methacrylate (PMMA) plastic with 2 m length. In the meantime, the thickness of the transmitter and the receiver ends of the fibre are 1 mm and 0.25 mm correspondingly. The core and cladding refractive index is 1.492 and 1.402, respectively, and the numerical aperture of the fiber is 0.5. The absorption spectra of the optical detector ranges between 700 and 1800 nm. The intention of this project is to investigate and use the mirrorless plastic optical fiber displacement sensor for liquid concentration detection. Any study of this kind of sensor will surely help the fiber optic sensor technology in expanding the use of it and finding the limits of this sensor.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Early optical fiber sensors has been produced on the basis of the most important research findings in the 1960's besides its employment in telecommunication systems. The reason being is any single fiber could carry multiple data via accessible guides connected to the main points, therefore massive information can be transmitted at a relatively high speed across a great distances with lesser loss as opposed to ordinary copper coils.

Throughout the mid 1970's, not only in field of communication networks, optical fibers with minimal loss capability have also started to be used as sensors. There were also some research conducted to develop methods for measurement and sensing which enables us to experience the current technologies. Amongst many, one advantage of using a fiber sensor is its capability to work under an extreme environment as compared to the traditional sensing devices (Grattan and Sun 2000).

In this modern society, there is a need for the development and advancement of recent technology to optimise the advantages of fiber optic sensors. Apparently, scientists have performed comprehensive research on the applications of fiber optics as an effort to improve other areas as well, such as aviation and army (Gopal and Annamdas 2011), healthcare (Lamela, Gallego, and Gutierrez 2011; Mignani and Baldini 1997), food quality and safety (Mignani et al. 2008), and other professional fields (Annamdas, Yang, and Liu 2008; Fu et al. 2008; Kawabata et al. 1989; Yang et al. 2008). Several devices such as laser printers (Ready 1997), laser thermometer

(Kistemaker, Hartog, and Daanen 2006) and other daily utilised tools using the optically powered electronics has also been widely used. Besides, fiber optic sensor has been proved as a successful device to measure numerous physical parameters such as temperature (H. A. Rahman, Harun, Saidin, and Ahmad 2012), vibration (Binu, Pillai, and Chandrasekaran 2007), concentration (Budiyanto et al. 2017) and pH of solution (Husna Abdul Rahman, Harun, Yasin, and Ahmad 2012).

In comparison to the traditional electronic sensor, the optical fiber sensor is viable for extreme condition as the optical cable has a lower thermal loss and a higher processing capacity than copper wire (Keiser 2003). Another distinctive feature of the fiber optic is insusceptibility towards electromagnetic waves and severe corrosion (Fang et al. 2012). This means that it can also produce extremely sensitive measurement even in extreme atmospheric environment like in oil down-hole recovery (Huang et al. 2017) and nuclear power plants (Li et al. 2017). Besides, the great aspect of optical sensor is it can easily be integrated with the existing fiber optic telecommunication systems (Joe et al. 2018), thus the sensor can be controlled distantly in a system of operating network (Perez-Herrera and Lopez-Amo 2013).

The fact that the optical fiber is really lithe and small size, it can be employed as a sensor in a complex settings such as subsea pipelines (Madabhushi, Elshafie, and Haigh 2014) and Antarctic ice shelf as a sensor for environmental monitoring (Kobs et al. 2014). It is also used to examine any physical activities on monitoring landslides (Pei et al. 2011), seismic wave for earthquake (Jaroszewicz et al. 2006), moisture changes in soil (Cao et al. 2015), and mapping paddy field soil properties (Baharom et al. 2015).

Currently, fiber optics have gain demand due to their interesting advantages. The potential of fiber optics is exploited for not only in communication system but also in sensing application. With the quick growth of optical sensors, researchers learned that it can be used to detect many physical parameters with great sensitivity and efficiency as compared to traditional sensors. There are many optical fiber sensor that has been used to demonstrate detection of liquid solution concentration such as glucose (Yasin et al. 2013), calcium (Yasin et al. 2015), honey (Hida N., N. Bidin, M. Abdullah 2013), cholesterol (Budiyanto et al. 2017), formaldehyde (Yasin et al. 2019) and sodium chloride (Husna Abdul Rahman, Harun, Yasin, and Ahmad 2012). Plastic optical fiber displacement sensors (POFDS) is highly anticipated due to its various advantage such as resistant to electromagnetic interference, consistent, highly sensitive and operable in any situation (Yasin et al. 2013).

POFDS have grown to be one of the most versatile sensors utilised in many research fields in accordance to its application (Yasin et al. 2015). It can be used to measure various physical and chemical parameters such as vibration, temperature and pressure as well as the pH level, concentration, density, and refractive index of liquids (Liao et al. 2010; Phang et al. 2009; H. A. Rahman, Harun, Yasin, and Ahmad 2012; Rahman et al. 2013; Yasin et al. 2011).

Thus, the advances in both fiber optic networking and sensing has contributed well into the enhancement and production of high-quality products that capable of replacing conventional sensors the near future. Nowadays, fiber optic technology is very crucial, becoming the utter cornerstone of modern technology infrastructures.

2.2 FUNDAMENTAL CONCEPT OF FIBER OPTIC

The concept of total internal reflection (TIR) is the main idea behind the fiber optic. TIR happens when a light passes through one medium with refractive index n_1 to the second medium with refractive index n_2 where $n_2 < n_1$ at an incident angle θ_i that is greater than a critical angle θ_c. The light will totally internally reflected back when it reaches the medium boundary. As an example, in Figure 2.1, when light travels from water towards air at $\theta_i > \theta_c$ the light will experience TIR.

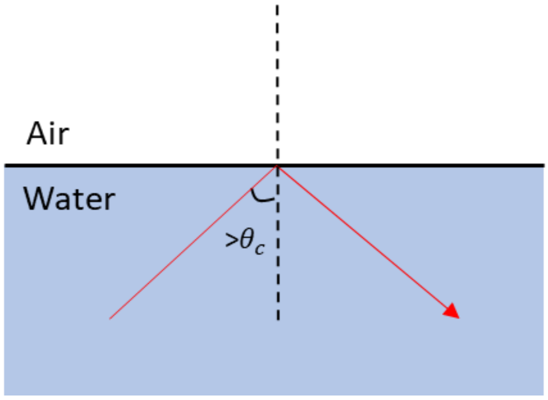

Figure 2.1. Total Internal Reflection (TIR) of Light Travels from Water towards Air.

The critical angle of a medium can be found using Snell's law of refraction (Zhang and Hoshino 2014).

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{1}$$

By substituting $\theta_1 = \theta_c$ and $\theta_2 = 90^\circ$, we can get

$$n_1 \sin \theta_c = n_2 \sin 90 \tag{2}$$

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \tag{3}$$

Similarly, the construction of an optical fiber aims to take advantage of the phenomenon of TIR to transmit light in the fiber cable.

The build contains three key elements which are the core, the cladding and the coating. The core is a dielectric cylindrical rod that transmits light and typically made of glass (silica) or poly-methyl-methacrylate (PMMA) plastic, yet sometimes certain materials will be used on the desired transmission range. Normally the common diameter of the core is 9μm to 62.5μm. The larger the core, the more light can be transmitted through the fiber. While cladding is commonly made with fluoropolymer or the same material as the core. The cladding has a significantly lower refractive index which allows the maximum internal reflection to happen across the span of the fiber at the core-cladding boundary so that when the light is transferred through the fiber and will not escape thru the sidewalls.

Typically, the coating consists of plastic wraps to shield the fiber towards the surroundings and even for more additional protection, steel sheaths are also applied to the coating. It is also used to keep the fiber durability and act as cushion to the fiber cable. The construction of the fiber optic cable is among the most incredible tool in modern technology as it exploited the nature advantage of the properties of light where it can travel down the fibre and transfer data at close to the speed of light. Not only optical fiber is used in telecommunication system, but it is also heavily used in sensing application.

The core is where the light is transmitted and it has a higher refractive index as compared to the cladding. When the incoming light hits the core at a small angle, it will experience TIR because the diameter of the fiber is very tiny. The light will undergo TIR repeatedly along the distance of the fiber when it touches the core and the cladding boundary in a pattern of a zig-zag bounces.