UNCLAD PLASTIC OPTICAL FIBER TEMPERATURE SENSOR WITH A BALLOON-LIKE STRUCTURE

NAZRAH ILYANA SULAIMAN

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In the name of God, the Lord of Mercy, the Bestower of Mercy.

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ABSTRACT

An unclad plastic optical fiber (POF) temperature sensor with high sensitivity is experimentally demonstrated in this work. The working principle of this developed unclad POF sensor is based on intensity-modulated technique. In general, position and length of the unclad region in this developed sensor has influenced the output light intensity, thus, influencing the sensor performance. In this work, we fixed the location of the unclad region at the middle of the sensor head. As for the length of the unclad region, optical intensity measurement was carried out. It was observed that the increment of length in the unclad region contributed to the increase of intensity losses. Therefore, the unclad length of 1.0 cm was considered as the optimal value due to its higher linearity and optical loss performances and was used in the bending analysis for balloon-like bent POF sensor. The sensor was realized by combining macro bending and the unclad region in the fabrication of its sensor head. The POF sensor was bent to a balloon-like structure to introduce the effect of macro bending. For optimization of the sensor performances, the sensor bending radius was varied. Experimental results suggest that performances of the POF sensor are optimized when the bending radius is fixed at 55 mm. With this amount of bending radius, temperature sensitivity up to 22.2 $x10^{-3}$ °C $^{-1}$ was achieved in the range from 40 °C to 80 °C with the linearity of 0.99 and resolution of 0.45 °C. This technique improves the POF temperature sensitivity in comparison to previous developments.

ABSTRAK

Pengesan suhu gentian optik plastik (POF) jenis *unclad* dengan kepekaan tinggi dibangunkan dalam tesis ini. Prinsip asas pengesan ini adalah menggunakan teknik pemodulatan keamatan cahaya. Secara umum, kedudukan dan panjang bahagian *unclad* pada POF mempengaruhi keamatan cahaya dan seterusnya mempengaruhi prestasi pengesan. Dalam tesis ini, kedudukan *unclad* ditetapkan pada bahagian tengah struktur pengesan. Bagi memahami kesan kepanjangan bahagian *unclad*, ujikaji pengukuran keamatan optik telah dilaksanakan. Hasil dapatan, menunjukan penambahan kepanjangan bahagian ini telah meningkatkan kadar kehilangan keamatan cahaya. Oleh yang demikian, unclad sepanjang 1.0 cm telah dipilih kerana mempunyai prestasi kelinaran dan kadar kehilangan keamatan cahaya yang optimum dan telah digunakan dalam analisis kesan lenturan bagi pengesan jenis *balloon-like bent POF*. Pengesan ini dibangunkan dengan menggabungkan struktur *unclad* dan lenturan makro. Pengesan POF dibengkokkan ke struktur seperti belon untuk memperkenalkan kesan lenturan makro Untuk mendapatkan konfigurasi yang optimum, beberapa nilai jejari lenturan telah diuji. Keputusan ujikaji menunjukkan prestasi adalah optimum pada nilai 55 mm jejari lenturan. Pada nilai ini, pengesan mempamerkan prestasi kepekaan 22.2 $x10^{-3}$ °C $^{-1}$ pada julat 40 °C to 80 °C dengan kelinaran 0.99 dan resolusi 0.45 °C. Teknik ini didapati telah menambahbaik prestasi kepekaan berbanding pengesan POF yang terdahulu.

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LIST OF SYMBOLS AND ABBREVIATIONS

cm	–	Centimeter
dB	–	Decibel
m	–	Meter
m	–	Diffraction
δ	–	Phase Difference
d	–	Distance
D	–	Aperture diameter
L	–	Length
n	–	Refractive index
$n_{cladding}$	–	Refractive index of POF cladding
n_{core}	–	Refractive index of POF core
φ	–	Phase difference
a	–	Core radius
λ	–	Wavelength
ξ	–	Thermo Optic Coefficient
θ_1	–	Angle of incident light
θ_2	–	Angle of diffraction wave
π	–	Pi
nm	–	Nanometer
μ	–	Micrometer
°C	–	Degree Celsius
NIR	–	Near-infrared
NA	–	Numerical Aperture
UV	–	Ultraviolet
PMMA	–	Poly-methyl methacrylate
He-Ne	–	Helium–neon
VIS	–	Visible

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CHAPTER 1

INTRODUCTION

1.1 Background of the research

Conventionally, temperature sensors work were based on the principle of magnetic, inductive, piezoelectric or capacitive.[1]–[5]. These methods have been commonly used over the past years owing to their cost-effective sensing elements. However, their applications are limited due to their vulnerability to electromagnetic interference (EMI) [6], [7]. Since then, fiber optic temperature sensors that are immune to EMI has taken over the EMI-based industries. Other prominent and attractive features of these sensors include small size, lightweight, high resolution and resistance to harsh environments. [8]–[10]. The development of various fiber optic temperature sensors continues to be the epicenter of interest in recent years.

Optical fiber sensors can detect physical parameters by modulating the wavelength or intensity of the light. For the wavelength modulated sensors, fiber Bragg gratings [11], [12] and interferometric configurations [13] have been explored by previous researchers. While this method is highly sensitive, it adds to complexity due to the data extraction requirements of the spectrum analyzer or interrogator. In comparison, intensity-modulated temperature sensors that function via fluctuations in optical power with lower operational complexity.

Previous researchers have used silica and plastic optical fiber (POF) to develop optical temperature sensors [14]. However, the development of an intensity-modulated sensor using POF has garnered greater interest than that of ordinary silica fiber, owing to their ease of machining and handling, making them a viable mass production alternative. [15], [16]. Furthermore, POF has a larger core radius and lower Young modulus than silica, making them less fragile and easier to handle, as well as reducing development and maintenance costs [17]. While POFs have a lower operating temperature range than other semiconductors, their multimode nature imposes unique characteristics on the external media that must be considered in actual implementations. [18]

1.2 Problem statement

Recent years have seen a significant growth in the demand for sensor performance that is both good and tolerable in temperature sensing applications. However, some concerns must be addressed before satisfactory temperature sensor performance can be achieved. These include the complexity of the sensor system, sensor fabrication, and limitations of the sensor sensitivity performance. Fabrication complexity is the main issue in designing POF temperature sensors. Two factors influence fabrication complexity. First is the number of process steps involved in the fabrication and the second factor is a complexity of the material preparation process as well as equipment used in the fabrication.

Numerous configurations of POF sensors have been published in the literature for sensing physical parameters such as refractive index [19], humidity [20], strain [21], liquid level [22], displacement [23], and temperature [24]–[26]. In the case of temperature sensing, a variety of fabrication approaches have been utilized to increase the sensitivity of the sensor. In 2013, a macro bend temperature sensor operating between 27 °C to 50 °C was proposed with a sensitivity of 1.92 x10^{-3} $°C^{-1}$and a linearity of 0.99 at 660 nm wavelength. [24].

Other research has suggested that a U-bent POF sensor may have a stress-optical effect, with measurements showing comparable sensor sensitivity of 1.04 x $10^{-3}°C^{-1}$ and linearity of 0.99 throughout a temperature range of 25 °C to 90 °C when measured [25]. Recently, it has been discovered that modifying the thermo-optic coefficient of various materials used to make the sensor head shape can increase the sensitivity of POF sensors significantly.[26], [27] This method improves the sensitivity to 11.7 x $10^{-3}°C^{-1}$ for a temperature range of 10 °C to 40 °C at a 595 nm wavelength. Despite the improvement, the obtained sensitivity is relatively low, and possess more complexity in the fabrication process. The reported sensor head configuration and its performance are summarized in Table 1.1

Table 1.1: Summary of previous sensor head configurations and performance

Configuration of sensor Head	**Linear range [℃]**	**Sensitivity [$℃^{-1}$]**	**Linearity [R^2]**	**Resolution [℃]**
Macro-bend [24]	27 to 50	1.92 x 10^{-3}	0.99	< 0.3
U-bent [25]	25 to 90	1.04 x 10^{-3}	0.99	n.r
Thermo-optic Material[26]	10 to 40	11.7 x 10^{-3}	n.r	n.r
MZI dual-wavelength compensation of thermo optic of POF material [27]	35 to 85	1.0 x 10^{-3}	n.r	n.r

*n.r = not reported

According to the summary in Table 1.1, the reported POF temperature sensor's sensitivity performance in literature is relatively low. Therefore, this work enhance the POF temperature sensor sensitivity performance by utilizing a hybrid method of macro-bending and unclad fiber.

1.3 Objective

The objective of this research has been formulated from the problem discussed in the previous section. In this work, the main objective is to improve POF temperature sensor sensitivity performance. The objective has been breakdown into several tasks as follows :

i. To design a balloon like-bent temperature sensor utilizing unclad plastic optical fiber (POF) with optimal bending diameter.

ii. To fabricate the designed unclad POF balloon-like bent sensor using stripping, chemical etching and polishing fabrication process.

iii. To characterize the fabricated unclad POF balloon-like bent sensor performances (sensitivity, resolution, linearity range and linearity) in the visible light spectrum.

1.4 Scope of research

To accomplish the research aims, the following scope of work has been established:

i. Comparison of Plastic optical fiber (POF) temperature sensors with previous literature based on their working principles, mode of operation, and configuration.
ii. Characterization of the instruments to determine the optimal parameter setting for halogen light source, spectrometer and dry heat oven.
iii. Fabrication of the unclad sensor head by three basic procedures: stripping, chemical etching, and polishing.
iv. Physical characterization of the unclad sensor utilizing a visual fiber locater in terms of light uniformity on the etched surfaces.
v. Characterization of the sensor's sensitivity, linearity, and resolution at various temperatures.
vi. Determination of the sensor's sensitivity, linearity, and resolution characteristics due to a macro-bending effect on the unclad sensor structure. This analysis was carried out by bending a balloon-like structure with a variety of bending radii.
vii. Comparison of proposed sensor performances to those of previously fabricated POF temperature sensors.

1.5 Outline of the thesis

The proposal overview is organized as follows:

Chapter 1: This chapter summarizes the thesis. It includes the context of the research, objective, problem description, and scope of work.

Chapter 2: This chapter includes reviews of previous studies, focusing on the theories and methods of POF temperature sensors to enhance their sensitivity.

Chapter 3: This chapter summarizes the research methodology, fabrication process, and sensor physical characterization, as well as the mechanism by which the experimental setup for the temperature sensor.

Chapter 4: This chapter presents and discusses the findings of this research. The sensor response is characterized in terms of its sensitivity, linearity, and resolution. This thesis includes a performance comparison of the disclosed unclad POF temperature sensor to earlier advances to clearly discern the key contributions of this study.

Finally, Chapter 5 contains the thesis overall conclusions, research contribution, and some suggestions for future research.

CHAPTER 2

A REVIEW OF FIBER OPTIC TEMPERATURE SENSOR

2.1 Introduction

Fiber optic temperature sensors can be classified into two types: intensity sensors and interferometry-based sensors, which are both used to measure temperature. This chapter summarizes the intensity-modulated temperature sensors, and description of their operation and fabrication processes. The subject covers sensor head configuration, past sensor head developments, and the theoretical study of temperature sensors' sensitivity, linearity, and resolution. Furthermore, this chapter offers a thorough grasp of the sensor development process. The last section of this chapter concludes the recommendations offer a new sensor head configuration for sensitivity performance enhancement.

2.2 Optical fiber sensors for temperature measurement

Because of its unique characteristics, such as high sensitivity, lightweight, quick response, tiny size, and immunity to electromagnetic interference (EMI), optical fiber sensors have received a significant deal of interest in recent years [28]–[32]. Other important advantages of optical fiber sensors include their resistance to vibration and shock, their compatibility with other optical components, and their ability to function in extreme situations, such as high temperature environments, among others [33], [34]. As illustrated in Figure 2.1, optical fiber sensors have been demonstrated to be acceptable for high-temperature environments up to 600 °C before their excellent mechanical qualities decline and they become bendable [35].

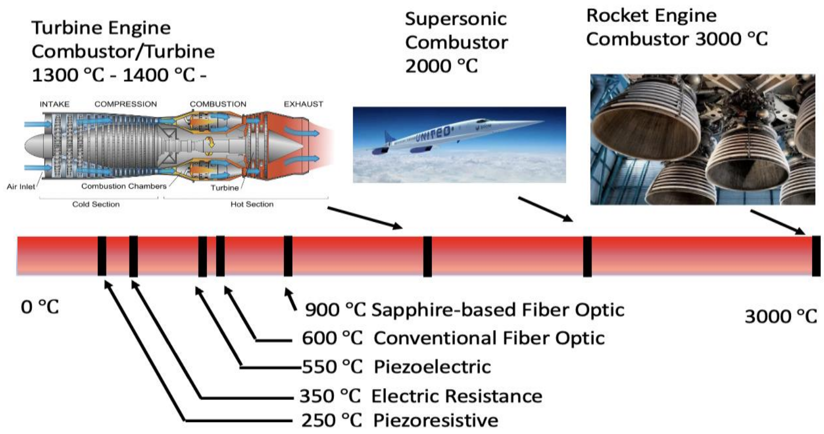

Figure 2.1: High temperature regimes for sensors [36].

In most optical fiber sensors, the fiber is made of glass or plastic, depending on the application. [37], [38]. Plastic optical fiber (POF) type of fiber is desirable due to its increased flexibility, ease of manipulation, big numerical opening, large diameter, and material that can withstand smaller bend radii than glass [39]. There have been numerous sensor designs utilizing POF for detecting physical characteristics such as refractive index [40], humidity [41], strain [42], liquid level [43] displacement [44] and temperature [24], [26], [45]. Among the numerous reported POF sensors, few are quite effective at monitoring temperature.

Optical fiber temperature sensors can be designed in a variety of approaches, and the most common is through regulated intensity [46]. In this method, measurement is made using an optical sensor based on light intensity to determine changes in the measurand. The light intensity dims because of changes in the measurands, which might be triggered by absorption, scattering, or the application of an external force [47]. Numerous intensity modulation techniques exist, including reflection, transmission loss, and evanescent field [48],[49] any of which can create a change in the optical intensity conveyed by an optical fiber [47].

Another way is to employ an interferometric technique in which light is separated into two components and then recombined, resulting in the interference of light. Mach-Zender, Sagnac, Michelson, and Fabry-Perot interferometric methods are employed for temperature measurement [50]. An interferometer is defined as a device that divides light into two beams and then rejoins the two beams to create interference [51], [52]. Interference alters wavelength of the output signal, phase, strength, frequency, and bandwidth. Similarly, the term "fiber optic interferometric sensor" alludes to the interference created when two photons split into two. Separated light can be propagated either in a different optical channel of the same fiber or in two independent fibers[49], [50]. Because of this, an interferometric sensor with a beam splitting and the combining component must be included in the configuration. In the course of the light separation process, one of the light components interacts with and is impacted by changes in the surrounding environment such as changes in temperature, strain, pressure, and vibration [51], [52]. Due to their interference with the reference light, these changed lights will cause a phase shift or phase modulation.

Additionally, optical fiber gratings are a type of optical fiber sensor [57]. Optical fiber gratings are small sections of grating that are implanted in a fiber, and which cause the wavelength of light to modulate as it travels through the fiber. An optical fiber Bragg grating (FBG) is a type of grating that has a consistent period of grating along its length. For fiber Bragg gratings, each structure is given a unique name based on its characteristics, such as long period grating (LPG), chipped fiber Bragg grating (CFBG), and tilted fiber Bragg grating (TFBG), among others [46]. Figure 2.2 illustrates the optical temperature sensor in its entirety.

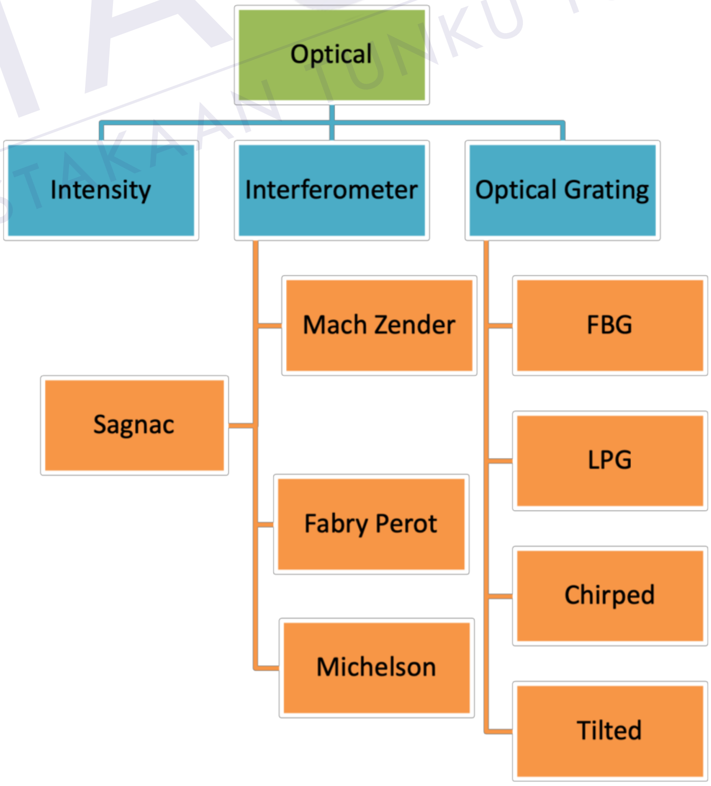

Figure 2.2: Types of optical temperature sensors.

2.3 Previous works on fiber temperature sensor

In general, two things must be taken into consideration to achieve optimal sensor performance which are sensor sensitivity and sensing range. However, in this study, improvement is made on the sensor sensitivity by modification on the sensor head itself. A sensor head that exhibits high sensitivity is required to provide optimal sensor performance in various applications. To date, many studies on sensor head sensitivity designs have been published and investigated. For temperature sensing, various methods have been employed to increase the sensitivity of the sensor.

The development of a macro bend temperature sensor with a sensitivity of 1.92 x $10^{-3}°C^{-1}$and a linearity of 0.99 at 660 nm wavelength, which can function in the temperature range of 27 °C to 50 °C, was proposed in 2013 [24]. The image of the constructed optical fiber temperature sensor in [24] is shown in Figure 2.3. These parameters contribute to the mechanical qualities of the sensor at the time of manufacture. The buffer coating was partially removed from the central area of the fiber length. This stripped portion measured around 30 mm. As illustrated in Figure 2.3, the fiber sensor was produced by forming a single 180° loop (½ turn) with a specified bend radius. A cylinder was used to fix the radius, to facilitate and increase the precision of the bending process. The buffer coating was then adhered to the junction of the two branches using cyanoacrylate adhesive.

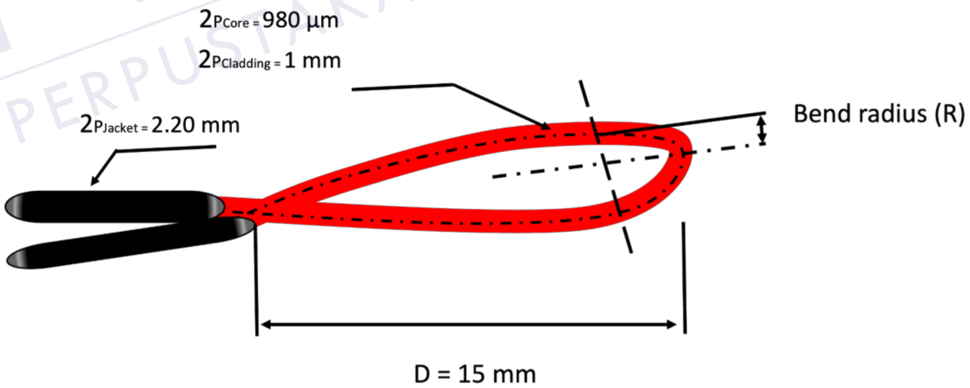

Figure 2.3: The macro-bend POF sensor [24].

The experimental setup in [24] is depicted as in Figure 2.4. Light-Emitting Diode (LED) with 660 nm was the light source. The fiber-optic sensor was positioned next to the rectangular, highly conductive metal base plate of a heating unit. A temperature controller unit was used to regulate the temperature of the hot plate. To determine the true temperature of the optical fiber sensor, an independent electronic temperature sensor LM35 was used. Temperature readings were taken directly on the hot plate and at a distance of 1 mm from the hot plate and a thermally isolated stage was constructed to hold the fiber sensor at a distance of 1 mm from the plate.

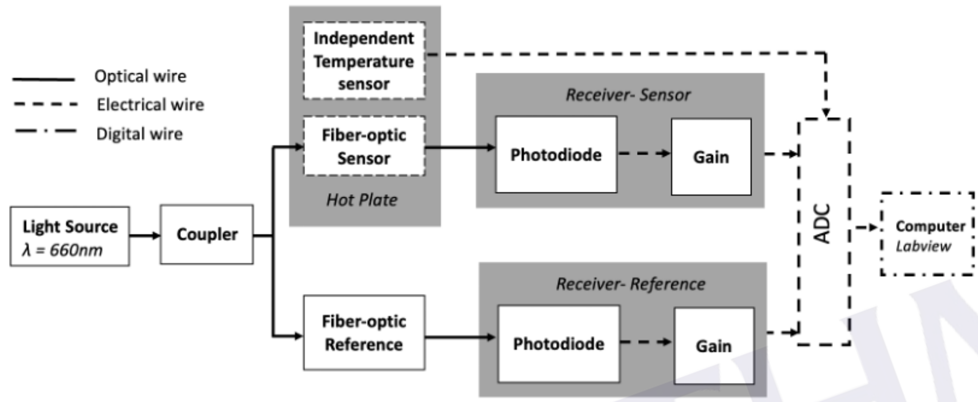

Figure 2.4: Alberto Topetado et al. proposed an experimental setup for a fiber-based optical temperature sensor with macro bend POF (2013) [24]

Another discovery suggested a stress-optical impact on a U-bent POF sensor, displaying comparable sensor sensitivity of $1.04 \times 10^{-3}°C^{-1}$ and linearity of 0.994 over a temperature range of 25°C to 90°C at 650 nm wavelength [25]. The fiber was bent 180° and inserted into a climatic chamber 400/1ND (Ethik Technology, Vargem Grande Paulista, SP, Brazil) equipped with closed-loop temperature control with a resolution of 0.1 °C and a maximum temperature of 200 °C. A thermocouple was inserted close to the curvature zone of the fiber to serve as a reference temperature for the analysis to take place. The temperature resolution of this thermocouple was 0.1 °C, and the temperature range was 220 °C. Using a laser, a lateral segment of the fiber was sliced to create a sensitive zone, that potentially boost sensor sensitivity due to fiber stress on the cross-sectional area [58]. The increased stress on the fiber caused by the added curvature and lateral section could increase the stress-optical effect, resulting in greater variance in output power.

Figure 2.5 illustrates the experimental setup on a U-bent POF sensor, which included a laser source, a light coupler with a 50:50 coupling ratio, and two photodiodes, one for the reference fiber and the other for the fiber under test. To reduce the impact of the modal distribution of the light coupler, all the optical components,

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APPENDIX E

LIST OF PUBLICATIONS

Journal

1. Sulaiman, N. I., Ngajikin, N. H., Che Abd Rashid, N., Yaacob, A., Yaacob, M., Ibrahim, M. H., & Cholan, N. A. (2021). Temperature sensing utilizing unclad plastic optical fiber with a balloon-like bent structure. *Applied Optics*, *60*(13), 3895. https://doi.org/10.1364/ao.419801 [ISI: Q1]

APPENDIX F

VITA

The author was born in Johor, Malaysia. She was raised in Johor went to SMK Munshi Ibrahim, Johor for her secondary school. She pursued her pre-university studies for one year at College Mara Kulim (KMK) Kedah in the foundation of science. Then, in 2007, she enrolled her degree at Universiti Teknologi Malaysia (UTM) and graduated with the B.Eng. (Hons) in Electrical- Electronic Engineering. Currently, she is pursuing her studies in a part-time master's degree in Electrical Engineering at Universiti Tun Hussein Onn Malaysia (UTHM). Her research interests include the development of optical devices and sensors application. Presently working at Malaysia Marine Heavy Engineering (MMHE) as Commissioning Engineer specializing in instrumentation and telecommunication.