Faculty of Electronic and Computer Engineering and Technology

DEVELOPMENT OF SENSITIVE AND WEARABLE OPTICAL MICROFIBER SENSORS FOR HUMAN HEALTH MONITORING BY OPTIMIZATION APPROACH USING BOX BEHNKEN DESIGN (BBD) AND DESIGN EXPERT

INTAN NOOR SHAHIRA BINTI MD ZAHER

Bachelor of Electronics Engineering Technology with Honours

2024

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A project report submitted
in partial fulfillment of the requirements for the degree of
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DEDICATION

This project is dedicated with immense gratitude and love to my beloved mother, Zurina and father, Md Zaher, also my family members. Your unwavering support and encouragement have been the driving force behind every step of this challenging journey. This project is not just a culmination of academic pursuits, it is a reflection of the values and lessons you imparted. I want to express my deepest gratitude for being my pillars of strength.

ABSTRACT

Human health monitoring which can detect and analyze individual health conditions in real time, have gained significant interest in recent years. Optical microfiber sensors present a good potential in this field. This study reports the development of the optical microfiber sensors for detecting human health. As an innovative solution for healthcare system, wearable optical microfiber sensor is develop. The development of sensors were optimized by considering the input parameter consisting of wavelength, microfiber diameter, types of microfibers and temperature to find the optimum sensing performance and increase the sensitivity of the sensors. Those optimization approach was obtained by using Design of Experiment (DoE). This approach expected to enhanced the quality for development of the optical microfiber sensor for detecting human health.

ABSTRAK

Pemantauan kesihatan manusia yang boleh mengesan dan menganalisis keadaan kesihatan individu dalam masa nyata, telah mendapat minat yang ketara dalam beberapa tahun kebelakangan ini. Penderia mikrofiber optik memberikan potensi yang baik dalam bidang ini. Kajian ini melaporkan perkembangan penderia mikrofiber optik untuk mengesan kesihatan manusia. Sebagai penyelesaian inovatif untuk sistem penjagaan kesihatan, sensor mikrofiber optik boleh pakai dibangunkan. Pembangunan penderia dioptimumkan dengan mengambil kira parameter input yang terdiri daripada panjang gelombang, diameter mikrofiber, jenis gentian mikro dan suhu untuk mencari prestasi penderiaan yang optimum dan meningkatkan sensitiviti penderia. Pendekatan pengoptimuman tersebut diperoleh dengan menggunakan Reka Bentuk Eksperimen (DoE). Pendekatan ini dijangka meningkatkan kualiti untuk pembangunan sensor mikrofiber optik untuk mengesan kesihatan manusia.

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LIST OF ABBREVIATIONS

DOE	-	Design of Experiment
OSA	-	Optical spectrum analyzer
BBD	-	Box Behken Design
RSM	-	Response Surface Methodology
$ANOVA$	-	Analysis Of Variance
SM	-	Single Mode
MM	-	Multi Mode
$OTDR$	-	Optical Time Domain Reflectometer

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CHAPTER 1

INTRODUCTION

1.1 Background

Being healthy is essential to reduce the risk of chronic disease and long-term illness. Therefore, health monitoring plays a vital role especially in medical industry. Regular monitoring of vital signs, such as blood pressure, heart rate and temperature, can help identify health issues early. The advantages of health monitoring includes early detection and prevention, allows for more accurate diagnoses, and reducing medical costs. Due to the inability of healthcare to provide proper services nowadays, self-health monitoring is the key in solving these problems. Self-health monitoring provide patients with the necessary information to track their health data over time and be proactive in managing their condition (N, Ulyanova et al., 2022). It also can be easily accesed by individuals, making it a cost-effective way to improve overall health. In order to implemented the self health monitoring, (Yong et al., 2023) developed a sensitive and wearable optical microfiber sensor for human health monitoring .

Given that optical microfiber sensors are small, lightweight, and can be attached to the skin surface without causing discomfort, they were developed for non-invasive and continuous monitoring of various physiological parameters in patients. Microfiber sensors measure changes in the refractive index or transmission of light. The purpose of this work is to demonstrate the feasibility of using these sensors to monitor human health. These optical microfiber sensors can provide healthcare providers and patients with a practical and affordable solution for monitoring human health. The sensors can be integrated into wearable devices and used to detect even subtle changes in human body. This information can be used to monitor a patient's health in real-time and intervene if necessary.

The development of the optical microfiber aims to optimize the parameter by using design of experiment (DoE). DOE is a technique to efficiently demonstrate the relationship between different variables. DOE promises several advantages as it provides a well-designed experiment and obtaining the accurate response. It deals with planning, conducting, analysing and interpreting the experiment factors and allows for the simultaneous manipulation of multiple input factors. By indentifying the best combination input factors, it is most likely to yield the desired output. Therefore, DOE is the ideal method for the development of optical microfiber sensor for human helath monitoring with optimization approach.

1.2 Problem Statement

In modern healthcare, the imperative for continuous and personalized health monitoring has become increasingly evident. The demand for personalized health monitoring has surged, driven by the need for timely diagnosis, improved therapies, and accessible care options, whether within healthcare facilities or at home. However, the current healthcare landscape faces formidable challenges marked by a shortage of healthcare professionals and inadequate infrastructure.

In response to these challenges, the development of optical microfiber sensors emerges as a promising solution in the realm of human health monitoring. Optical microfibers, characterized by their small and lightweight nature, present an ideal platform for wearable devices designed to monitor various health parameters. The envisioned sensors aim to provide real-time data, enabling the measurement of crucial indicators such as human body temperature, heart rate, and glucose levels.

Despite the potential, the effectiveness of these optical microfiber sensors requires enhancement. To address this, an optimization approach is essential, focusing on key parameters such as wavelength, microfiber diameter, types of microfiber, and temperature. Employing the Design of Experiment (DOE), this research aims to thoroughly investigate the optimal configuration of these parameters. The DOE methodology will elucidate the intricate interactions among different variables, unveiling the most effective parameter combinations for the development of a sensitive and wearable optical microfiber sensor tailored for human health monitoring.

1.3 Project Objective

The main aim of this project is to propose a systematic and effective methodology to monitor human health based on optical microfiber sensor with suitable parameters.

a) To identify a significant properties of microfiber sensor parameter.

b) To develop a mathematical model for microfiber sensor of human health monitoring.

c) To develop microfiber sensor with optimum parameters to produce the human health monitoring detection.

1.4 Scope of Project

The scope of this project are as follows:

a) Microfiber type is considered in this study.

b) Singlemode and multimode fibers are used for the experiment.

c) The microfiber parameter that considered are the wavelength, microfiber diameter, type of microfiber, and temperature.

d) The sensor will monitor human health by detecting difference temperature and resulting power output.

e) Design of experiment is used to investigate the optimal parameters.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviewed several topics related to the existing system and previous studies. Understanding of the context and existing research will be used to develop the optical microfiber sensors for human health monitoring that is more efficient and effective. The advantages and disadvantages of the system, areas for improvement, and new solutions are briefly discussed in this chapter.

2.2 Fiber optics sensors

In recent decades, with the development of the optical fiber sensing technology, the demand has been increasing due to the numerous advantages and applications in various industries. As optical fiber sensors are high sensitivity, lightweight, broad detection range, higher temperature operation, electromagnetic immunity, high accuracy and an inherent distributed sensing capability, it provides advantages to the healthcare industry (Li et al., 2020). The higher sensing performance is important to improve sensitivity and measurement range.

Fiber optic sensor are widely used in various fields especially in physical sensing applications. Physical sensing consists of temperature sensing, pressure sensing, and strain monitoring. As for the operating principle, the extrinsic and intrinsic optical fiber sensor depends on the specific sensing requirements and parameter approach. And then, the factors will go deeper by observing the intensity, interferometers, wavelength and polarization.

These parameters provide a comprehensive and accurate view of the physical sensing. Hence, the optical fiber sensor can measure even slightest of changes in physical conditions.

Fiber optic sensors are ideally suited for a variety of applications in the healthcare industry as for clinical research, medical monitoring and diagnostics as figure 2.2. Specifically, the propagation of light in the optical fiber is confined in the core of the fiber, based on the total internal reflection (TIR) principle and has near zero propagation loss within the cladding which important in medical applications. This is because the cladding has a lower refractive index than the core, which causes the light to be confined within the fiber. This confinement also allows for a high degree of flexibility in the design of the optical fiber, allowing it to be used to examine internal organs of the human body.

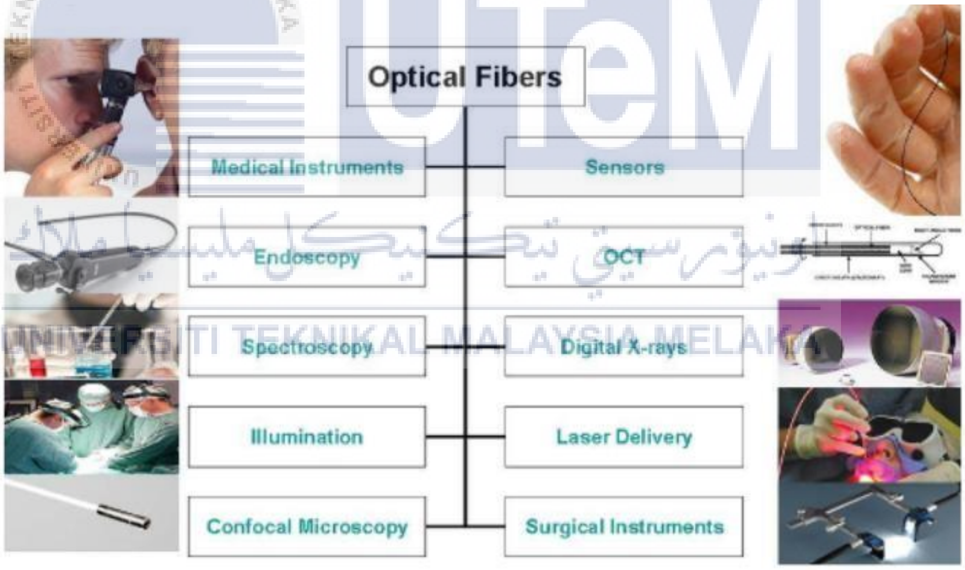


Figure 1.1 Applications of optical fibers in medical industry

2.2.1 Review of wearable optical fiber sensors for human health monitoring.

This paper (Zhao et al., 2023) discussed the types, applications and the sensing element for the wearable optical sensors for human health monitoring. The authors analyses the different types of optical fiber sensors consists of micro-/nano fiber sensors, polymer optical fiber sensors, fiber grating sensors and special fiber sensors to find the most suitable type of fiber optic sensors for wearable applications. If miniaturization and flexibility is put forward in the requirement of advancement of optical fiber sensors, the micro-nanofiber has better alternative as it have the high level of sensitivity and respond speed of the sensors. The optical fiber sensors can be implemented in various applications depends on the measurement parameters. The sensing element has the capability to monitor body temperature, heartbeat and respiration, physical activities, and biomass measurement. The performance of fiber optic for body temperature monitoring is outstanding since among all the research, the sensor can monitor up to 8.692 nm/◦C between 33 ◦C and 43 ◦C. High sensitivity, high precision and multiplexing ability of the Fiber Bragg Grating sensor record the best performance. Specifically, the sensor capable to measure the displacement with ΔλB signal amplitudes from 0.2 nm to 0.05nm.

Performance comparison of some fiber optic body temperature sensors.

Sensor Technology	Sensing Part	Detection Ranges (°C)	Sensitivity
MNF	back of hand	30–60	0.02dBm/°C
FBG	chest wall	33–37	0.31 nm/°C
FBG	thoracic cavity	34–37	0.039 nm/°C
FBG textile	Sides of chest, armpits and upper back	33–42	0.15 nm/°C
MZI	inside of arm	33–43	8.692 nm/°C
POF	Mouth, Skin and Nose Breathing	25–70	1.8%°C^{-1}
POF	finger skin	30–80	–

Figure 2.2 Sensitivity of Temperature Sensor with different parameter.

2.3 Understanding of optical microfiber

Optical microfibers and nanofibers (MNFs) are extremely thin fibers with diameters close to or smaller than the wavelength of light possess which typically ranging from hundreds of nanometers (nm) to several micrometers (mm) (Zhang et al., 2020). In general, MNFs are tapered from glass optical fibers or bulk glasses which results a smooth surface, high degree of homogeneity in diameter and integrity, resulting in low waveguiding losses and excellent mechanical properties. MNF guides light with favorable properties such as low-loss in optical, large fractional evanescent fields and tight optical confinement, making it an innovative platform for optical sensing even in a small scale (Lou et al., 2014a). Optical microfiber has the capabilities of bending insensitivity which allows fiber optics sensors to be applied in miniature sensing structure while maintaining the same level performance (Lou et al., 2014b).

According to Kapany (1959), reported the early use of MNF for transmission of light and image (Tong et al., 2012). In 1966, Kao and Hockham proposed the possibility of achieving low-loss optical fibers when light signals transmitted in pure glass-based optical fibers which led to in-depth research area in fiber optics. The research interest of MNFs after Tong and Mazur (2003) demonstrated the ability of MNF with diameter far below the wavelength of the light guided achieve low-loss optical waveguiding. Since then, MNFs have led to intensive research interests regarding their numerous applications. Among various microfiber applications, optical microfiber sensor has been attracting increasing research interest.

The investigation presented in the study intricately explores the fabrication and performance of a fiber optic sensor by ingeniously integrating both single-mode and multimode fibers. In the context of this experiment, single-mode fiber brings forth a set of advantages, including its capacity to allow only one mode of light propagation, resulting in a highly focused and coherent signal. Renowned for low signal attenuation over extended distances, SMFs contribute to maintaining signal integrity, a crucial attribute for applications demanding precision. The smaller core diameter of SMFs enhances spatial resolution, a characteristic leveraged in the study by employing SMF28-e as the outer fibers in the SMS fiber sensor. This strategic utilization underscores the precision requirement of the sensor, emphasizing its sensitivity to variations in the refractive index of the polymer cladding induced by temperature changes. However, it's essential to acknowledge the inherent sensitivity of SMFs to bending and microbending losses, a consideration in the sensor's overall design.

On the other hand, the study employs multimode fiber in the central section of the SMS fiber sensor, capitalizing on its unique attributes. Multimode fibers can transmit multiple modes of light simultaneously, making them ideal for applications requiring higher data rates over shorter distances. Multimode fibers have a larger core diameter, providing increased tolerance to misalignments and facilitating easier coupling with light sources. In this study, the multimode section is dynamically manipulated to function as a leaky waveguide at lower temperatures and a guided one at higher temperatures. This adaptability allows the sensor to exhibit a tunable and temperature-sensitive response, showcasing the versatility of multimode fibers. However, it is essential to note potential limitations such as higher modal dispersion and a lower spatial resolution due to the larger core diameter.

The synergy of single-mode and multimode fibers in the SMS structure yields a unique sensing mechanism, with each fiber type contributing specific strengths for distinct functionalities. The study successfully leverages the advantages of each fiber type to achieve a tunable and temperature-sensitive response in the SMS fiber sensor. The careful consideration of the strategic use of single-mode and multimode fibers aligns with the experiment's requirements, emphasizing the sensor's adaptability to temperature variations. In essence, this research underscores the intricate interplay between single-mode and multimode fibers, providing valuable insights into their complementary roles in advancing fiber optic sensor technology for temperature monitoring applications.

2.4 Optical microfiber sensors

Optical microfiber undergoes a continuous advancement in the sensing technology with miniaturization and flexibility of sensors (Lou et al., 2014b). The miniaturization provides a specials advantages includes improve the response speed, higher sensitivity, increase resolution and low power consumption. Advantages of the miniaturization provides higher sensitivity, improve the speed of the response, high resolution and low power consumption.

Microfiber sensors can be classified as several types which is fiber Bragg gratings (FBGs), surface plasmon resonance (SPR) sensors and evanescent filed sensors(Yin et al., 2018). However, among this type of sensors, fiber Bragg gratings is more accurate as its durability is outstanding in the sensing fields. The advantages of fiber Bragg gratings is the ability to accurately set and maintain the wavelength. The Bragg equation, in which *n*eff is the refractive index and Λ is the grating period, central wavelength of the reflected light can be expressed as:

$$\lambda_B = 2n_{eff}\Lambda$$

The change in the central wavelength of the reflected light resulting to the changes in the temperature, humidity, strain and pressure (T. Chen et al., 2023). Therefore, there is increasing demand for FBGs in microfiber sensors in biomedical applications as it is a great advantage for human health monitoring.

2.4.1 Temperature sensing of Single Mode-Multimode Fiber

The study (Zhang et. Al., 2014) delves into the realm of fiber optic temperature sensors that consists of single mode-multimode-single mode (SMS) fiber. The study acknowledges the existence of various types of fiber optic temperature sensors, each with its set of characteristics and limitations. In response, the study proposes a novel temperature-sensing solution through a fiber optic displacement sensor (FODS). This sensor operates on the principle of intensity modulation, utilizing a plastic optical fiber (POF)-based coupler. The experimental setup involves directing a modulated He-Ne beam into the coupler. The reflected light from the aluminum rod is then meticulously analyzed to discern temperature variations. The study underscores the significance of achieving temperature measurement efficiency in a practical and economically viable manner.

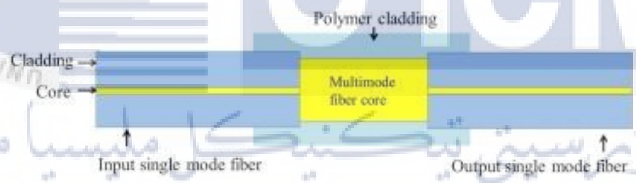


Figure 3.3 Schematic diagram of SMS

The experiment then proceeds to evaluate the sensor's performance under varying temperatures. The output signal, measured against the aluminum rod displacement, exhibits a linear function for different temperature settings, ranging from 25 °C to 90 °C. The sensitivity of the linear function for the first run is reported as 0.0044 mV/°C with 98% linearity, while the sensitivity for the second run is 0.0041 mV/°C with 96% linearity. The sensor is noted to be stable, with a measurement error of less than 0.8%, even at the highest temperature of 90 °C. The experimental setup and results underscore the efficiency and stability of the proposed fiber optic displacement sensor for temperature measurement.

2.5 Flexible wearable optical sensor based on optical microfiber Bragg grating.

This paper (Yue, et al. 2023) present the development of wearable optical sensors based on optical microfiber Bragg grating wrapped by PDMS film. Compared to standard optical fiber, optical microfiber has advantages of low bending loss, magnified strain effect and great flexibility. Therefore, pressure, bending angle and temperature are the physical parameters that can be achieved in the sensing measurement. As the bending curvature of the optical fiber sensor has a linear relationship with the Bragg wavelength, the characterization of the flexible wearable optical sensor can be observed. In the pressure response, bragg wavelength differ as pressure increase and the wavelength change in linear to the magnitude of pressure as shown in figure 2.4. The pressure sensitivity is enhanced as the diameter of the Fiber Bragg Grating (FBG) is reduced and the bragg wavelength also differ according to the time domain response.

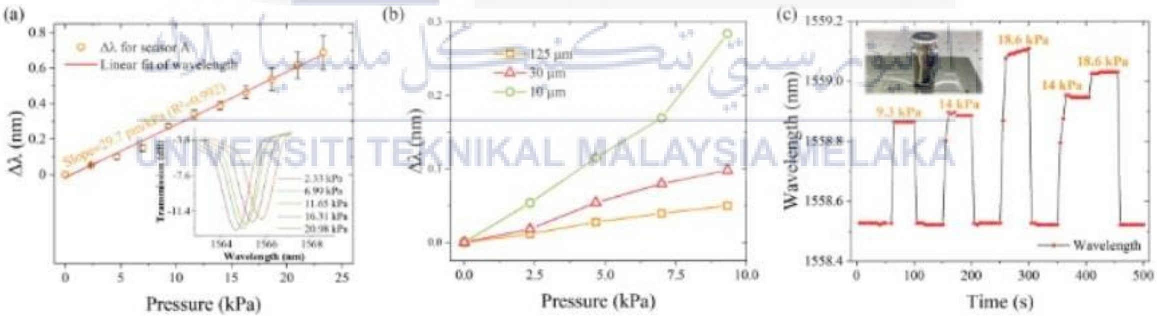


Figure 4.4 Pressure response

The bending of the optical microfiber sensor shows that, enlarging the bending angle will make the the bragg reflection drift to the longer wavelength. The relationship between Bragg wavelength and bending angle is linear as shown in figure 2.5. The bending sensitivity increase when reducing the diameter of the FBG.

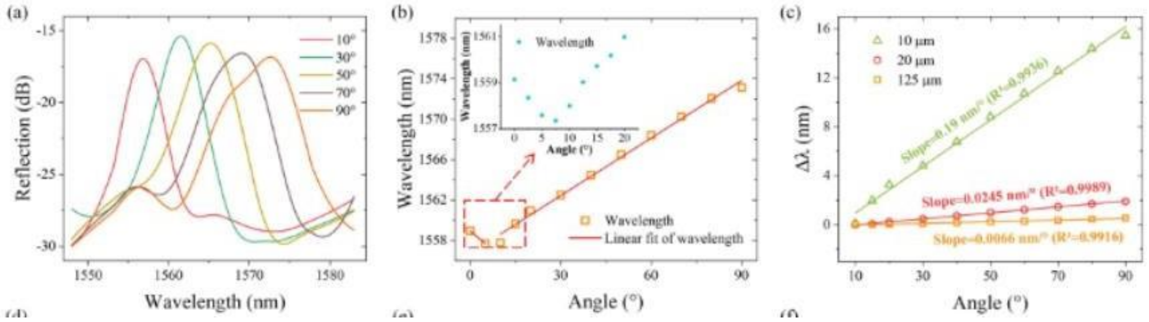


Figure 5.5 Bending Sensitivity

For temperature sensing, as the temperature increase, the Bragg wavelength drift to longer wavelength similar with the pressure and bend sensing as in figure 2.6. The temperature sensitivity does not effected by the variation in fiber diameter.

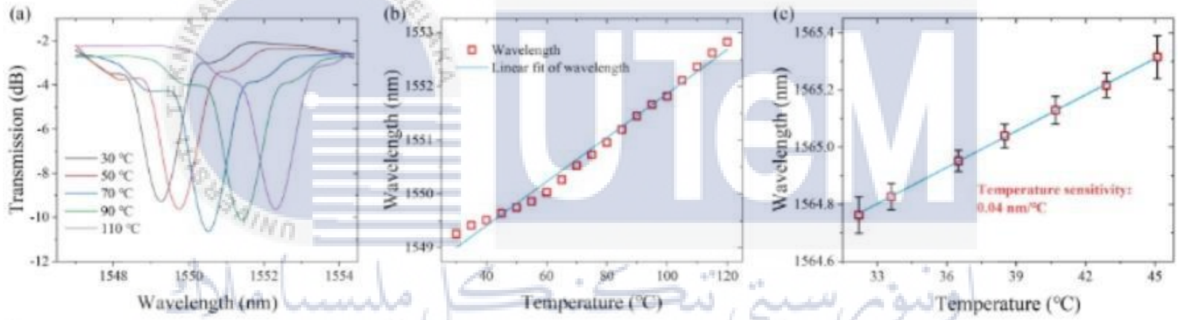


Figure 6.6 Temperature sensing

2.6 Single optical microfiber sensor for simultaneous temperature and pressure measurement.

A study (Yao et al., 2022) is focusing on the development of optical microfiber sensor that measures both temperature and pressure simultaneously. Multimode fiber is used in this experiment. The temperature sensing performance is measured by putting the sensor on a hot plate with a controlled temperature ranging from 25̊C to 95̊C. Whereas, for pressure sensing, an external pressure is applied to the sensor using a force tester equipment. The diameter of the tapered microfiber is constant which is 2 µm. In order to measure temperature, a shift in a high-order mode cut off wavelength is used. This shift is caused by changes in the refractive index of a material when the temperature of the material changes. The temperature can then be determined by measuring the shift in the wavelength while pressure is detected using the change in intensity in the long-wavelength range. The constant diameter of the tapered microfiber at 2 µm ensures consistent sensing characteristics, allowing for precise and reliable measurements. The integration of multimode fiber, along with the distinct sensing mechanisms for temperature and pressure, showcases the adaptability of optical microfiber sensors across diverse applications. This study provide valuable insights of the relationship between refractive index and difference approach includes temperature and diameter.

2.7 Design of experiments (DoE)

Design of experiments is a key component of understanding and improving the performance of the complex systems where it is statistical methodology for identifying and analyzing factors that might affect a process or system by designing and conducting experiments(Salehi et al., 2020). In order to determine the impact of the parameters and interactions among them, the experiments need to be performed systematically using Full Factorial Design (FFD) (Oimoen, 2019). In this study, the total number of experimental runs is 16 make it a potential tool to provides a most comprehensive insight into the result.

2.7.1 Development and optimization using Design of experiments (DoE).

DOE is the key strategy to evaluate the result of the experiment. In general, to obtain adequate information and achieve high quality of product, they applied DOE in this study (Tavares Luiz et al., 2021). Methods of DOE are discussed which include screening design and Response Surface Methodology (RSM). Figure 2.7 shows the DOE strategy to evaluate the interaction between several factor and optimize it in order to improve the performance.

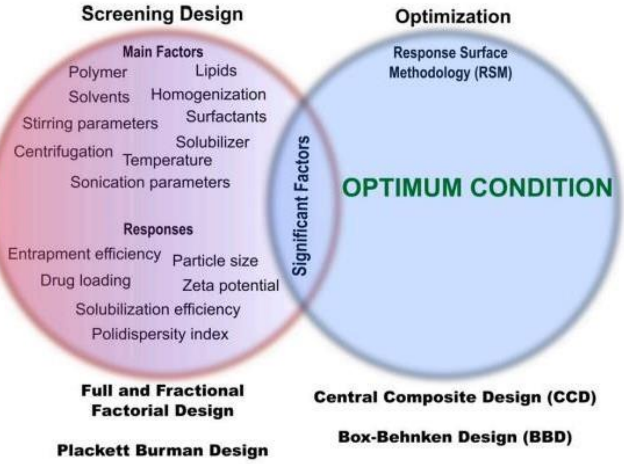


Figure 7.7 Example for design of experiment

Firstly, screening design of experiment include Plackett-Burman, Fractional Factorial Design and Full Factorial Design. Typically, the purpose of these methods is to narrow down the long list of potential factors in the preliminary stages of the experiment. Full factorial is associated with the factors that may have two levels only either high(+1) or low(-1) while fractional factorial allows several factors with fewer runs. Packett-Burman Design (PBD) help to sort out which factors in the are important and reduce the amount of data that have to collect. The experiment can be design up to N-1 factors, where N is multiply by 4.

Secondly, RSM helps to analyzes the critical level of the most important variables determined from previous screening design. In the process of optimization, RSM is the effective technique to establish mathematical relationship between the input variables and output variables. ANOVA (Analysis of Variance) is widely used in RSM as a statistical technique. The main methods of the RSM are Central Composite design and Box-Behnken Design (BBD). Central composite design (CCD) are first order (2^N) designs augmented with further points which is centre and axial points allowing estimation of the tuning parameters of a second order model. Whereas, Box-Behnken design (BBD) required fewer runs to generate higher order response surfaces. To obtain the BBD model, the number of experiments is defined as N=2k(k-10) + Co, where k is the number of factors and Co is the number of central points. The points are placed on the midpoints of the edges of the cubical design region with the scatter of shape variables as shown in figure 2.8.

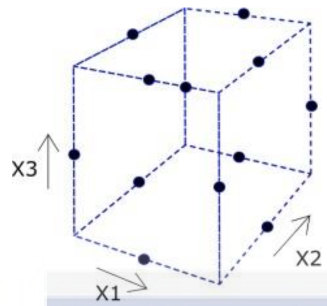


Figure 8.8 Box-Behnken Design Model

2.8 Summary

To summarize, the implementation of optical microfiber sensor is growing in recent years. The real time monitoring and low-cost sensors hold the advantageous in the healthcare industry. Many researches have shown their research that the miniaturization of the optical fiber has the superior solution in the medical industry. Compared to other products, optical microfiber sensors required no additional operation and non-complex system. Most importantly, the sensitivity and accuracy of this sensor is unmatched with the others. Thus, wearable optical microfiber sensor will continually develop followed by the current trends in the future.

2.9 Comparison of literature review

(Zhao et al., 2023) discussed the performance for different type of optical fiber sensors includes micro-nanofiber sensor, polymer optical fiber, and Fiber Bragg grating sensor. From these type of optical fiber sensors, it will provide the most suitable and effective sensor performance and their sensitivity towards the body temperature sensing, heartbeat and respiration monitoring, biomass measurement and physical activities monitoring.

(Jali et al., 2019) discussed the concept of optical microfiber sensor that consists of basic properties, methods and optical sensor using fiber. Development of optical microfiber sensor for humidity sensing is discussed in this study.

Besides, (Yue, et al. 2023) developed wearable sensing devices consists of the microfiber Bragg Grating as the core sensing node for human health monitoring. Multiple experiments are conducted to investigate the sensitivity of the flexible wearable optical sensor for temperature, pressure and bending angle.

(Yao et al., 2022) designed flexible optical microfiber sensor based on theoretical calculation. The performance of the temperature and pressure sensing is observed by comparing the result from the experimental and theoretical.

Table 2.1 Comparison of previous paper

No	Title	Authors	Sensing Elements	Explanation
1	Review of wearable optical fiber sensors for human health monitoring.	Yong Zhao, Zhaoyang, Lin, Shuo Dong, Maoqing Chen et, al.(2023)	Wearable optical fiber sensors for temperature and pressure sensing	To Compared the performance of difference type optical fiber sensor for MNF, FBG, and SOF
2	Optical microfiber sensors	M. H. Jali, A. Ahmad, M.D. Johari et, al (2021)	Optical microfiber sensor for humidity sensing	To observe fabrication progress in microfiber optical sensor
3	Flexible wearable optical sensor based on optical microfiber Bragg grating.	Xu Yue, Ruyi Lu, Qiaochu Yang et, al. (2022)	Flexible optical sensor for temperature, bending angle and pressure	To investigate the sensing element with principle of fiber Bragg Grating
4	single optical microfiber enabled tactile sensor for simultaneous temperature and pressure measurement.	Ni Yao, Xiaoyu Wang, Shuqi Ma et, al. (2022)	Optical microfiber sensor for temperature and pressure sensing	To compared the response of sensor with experimental and theoretical measurement.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussed the methodology implemented in this study. The flow chart of the project, the software and hardware used, the processes works, and the implementation of project will be detailed. Figure 3.1 briefly explain about the process of design and develop optical microfiber sensors.

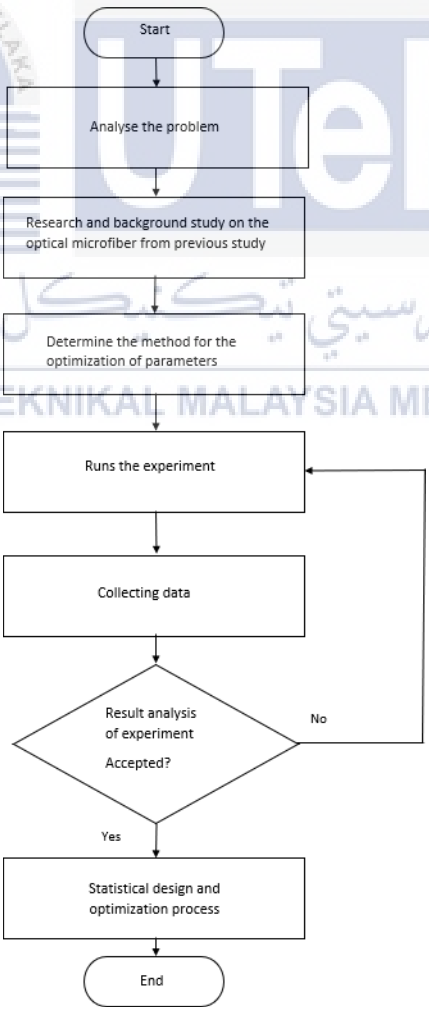


Figure 9.1 Flow Chart for Research Implementation

3.2 Methodology

The methodology section discusses about integrated analytical approach to develop an optical microfiber sensor for human health monitoring. The method employed is experimental, involving empirical modelling and statistical approach using Design Expert software to observe the sensitivity, accuracy and durability of the develop sensor.

The problem statement is analyse in order to design the experiment. The theoritical and experimental aspect in the previous study are reviewed to gain knowledge and ideas about optical microfiber sensor in healthcare system. This process is crucial for investigating the suitable requirements to develop sensor with effective efficiency.

After further study, experiments are involving processes such as splicing and tapering. Data are collected during the process to analyzes and measured the parameters such as wavelength, refractive index, total internal reflection and others. Optimization approaches are performed using Design Expert software. This study used the Box Behken Design (BBD) to optimize parameter for the microfiber sensor for human health detection. The selected approach is based on optimizing parameters including light source wavelength, microfiber diameter, types of microfiber and temperature, which aims to analyze the output power. The results are then analyzed to optimize the parameter for achieving a high quality of optical microfiber sensor. Finally, all the result is finalised and the observations are recorded in the report.

3.2.1 Experimental setup

Initially, the waist diameter of the single mode microfiber was fabricated using flame brushing technique. The fiber was tapered to reduce its diameter to several uniform diameter with range between below than 10µm and above 10µm. The microfiber diameter was verified by using 20x magnification microscope. The tapering process was achieved with one side of the fiber remaining static while the other was pulled horizontally. The fiber then was heated back and forth with a flame produced from an oxygen and butane mixture, known as an oxy-butane torch as shown in figure 3.2. This process was repeated until the desired diameter was achieved and the optical fiber sculpted into a tapered shape. Subsequently, the tapered microfiber was connected with pigtails through fusion splicing process. The preparation for this process included stripping, cleaving and splicing. Fusion splicing operates at high temperature softening the two ends of cleaved fiber, compressing them and fusing them together. This process provides a permanent and low-loss connection between the fiber and pigtail,enabling the efficient transmission of optical signals. The sensitive tapered region of the fiber was heated to different temperature within the range between 37°C (98.6°F) considered normal body temperature. The setup for the temperature sensing involved placing a heating element with the desired temperature on the tapered region. A tuneable laser source operating at a resonance wavelength was used and optical spectrum analyzer was connected to the pigtail for power output measurement. Two different wavelengths, 1550nm and 1310nm, were set. This process was repeated for the multimode microfiber and different wavelength. The data were analyzed using design of experiment software to observe optimal parameters for developing sensors with high levels of sensitivity, accuracy and durability.

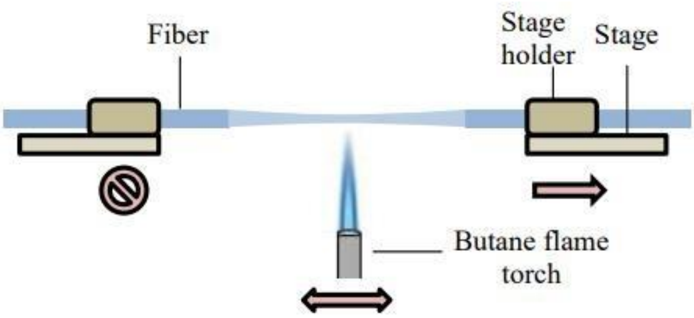


Figure 10.2 Schematic diagram of fabrication process

3.2.1.1 Parameters

To develop and optimize the optical microfiber sensor for human health monitoring, various-effective parameters must be considered. These parameters includes wavelength, microfiber diameter, types of microfibers and temperature.

i. Light Source Wavelength

The performance of the optical microfiber sensor is depends on the wavelength. The accuracy and sensitivity of the sensor are determined by the wavelength used. As the wavelength increases, the sensitivity and accuracy of the sensor also increase. Specifically, 1550 and 1310 nanometer wavelengths are used due to their low fiber attenuation enabling the sensor to detect the slightest changes.- (Jwhited, 2021). The length of wave is proportional to the attenuation rate longer waves result in less attenuation leading to higher sensitivity. (Zhang et al., 2008) reported that a microfiber optical sensor operated at 1550 nm wavelength exhibits high sensitivity. In summary, the smaller the attenuation rate, the higher the sensitivity of the sensor making the 1550 nm wavelength the best option for a high-sensitivity microfiber optical sensor.

ii. Microfiber Diameter:

An Optical microfiber with a smaller diameter provides higher sensitivity (Chuan, 2017). Smaller tapering diameter have stronger evanescent fields that gets easily coupled into the resonator increasing the interaction between the light and the sensor's surroundings. Diameters smaller than 10 micrometers, show high performance and reliability (Shengyao et al.,2023).

iii. Types of microfiber:

Two types of optical fiber exist: single mode and multi mode fiber (smith, 2020). The differences between single mode and multi mode fiber are in terms of their mode propagation characteristics, core diameter, wavelength and light source, bandwidth, and applications (Moris, 2022). Basically, single mode microfibers propagate single mode of light, have a small core diameter, (typically 2 to 10 micrometers) and have unlimited bandwidth is unlimited. On the other hand, multimode microfiber are designed for multiple modes of light propagation, have a larger core diameter, (typically 50 to 100 micrometers), and limited bandwidth with a maximum bandwidth is 28000MHz*km (Chung et al., 2012).

iv. Temperature:

Optical microfiber sensor can provide real time temperature measurements with high sensitivity (Yang et al., 2022). The use of Fiber Bragg Gratings for temperature sensing is the most effective and easy to implement (S. W. Harun, 2012). Initially, two different temperature are used in this parameters and that causes the microfiber sensor to expand or contract. As the microfiber is expands, it changes the refractive index of the surrounding medium resulting in a shift in the resonance wavelength of the microfiber sensor

(Talataisong et al., 2018). Thus, the wavelength has a linear dependence on temperature and exhibit high temperature sensitivity.

3.2.1.2 Tapering process

Tapered process are especially utilized in environmental monitoring systems, measuring various parameters such as displacement, temperature, strain, gas, humidity and pressure (Jali et al., 2019). Taper fiber is usually fabricated by heating the regular-sized fiber and drawing it. In this process, an optical fiber with an initial diameter is heated and strectched to produce a microfiber with a certain diameter (Musa et al., 2019). The tapering process is a crucial used in the fabrication of optical microfibers, involvings reducing the diameter of a fiber over a specific length to produce a tapered region as shown in figure 3.3 (Razak et al., 2017).

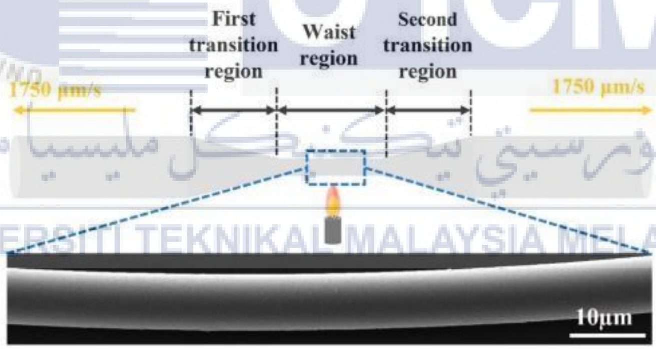


Figure 11.3 schematic diagram of tapering microfiber

In this project, tapering is employed to enhance the sensitivity and performance of the sensor by increasing the interaction between the optical signal and sensing material. The tapering process involves heating of the optical fiber using flame or laser, softening, and the glass allowing it to be drawn out and tapered to a smaller diameter (Al-Askari et al., 2016). The tapering is performed in a controlled manner to achieve a specific taper ratio, which is the ratio of the diameter of the untapered region to the diameter of the tapered region. Figure 3.4 shows a flowchart of methods for preparing the tapered microfiber.

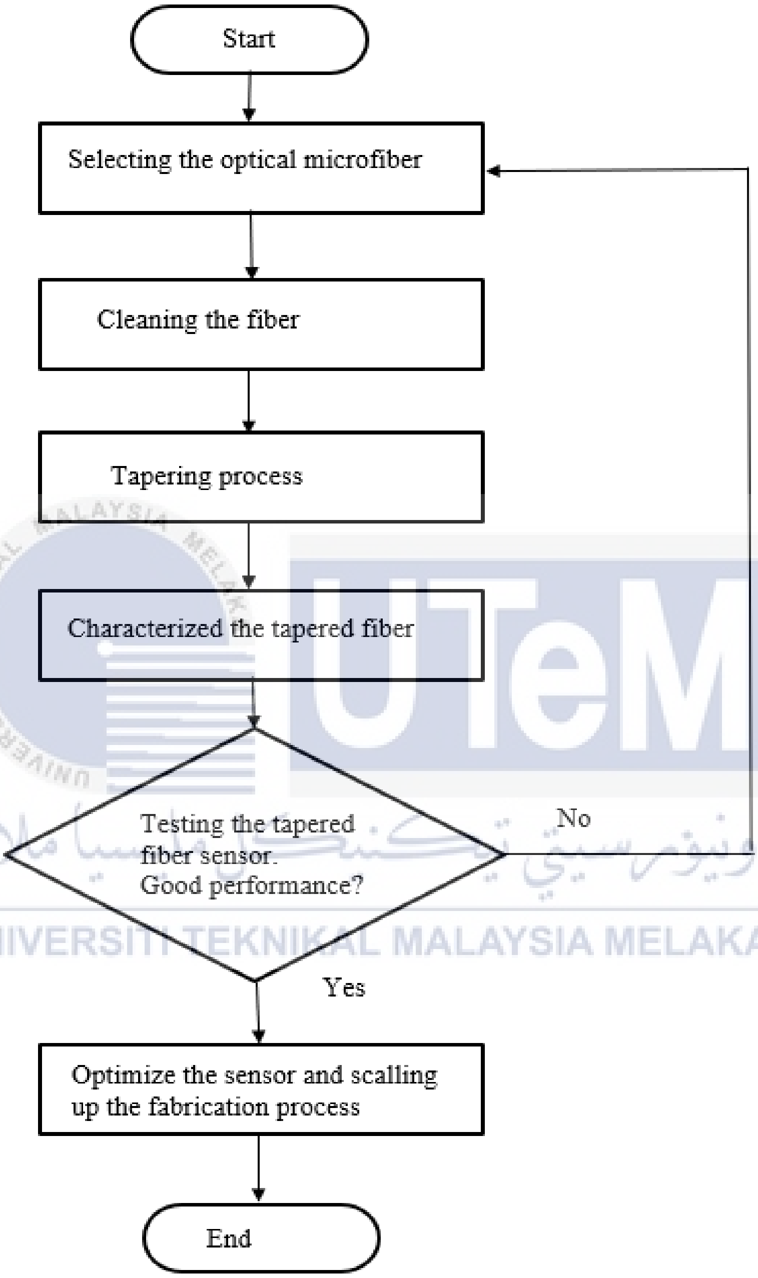
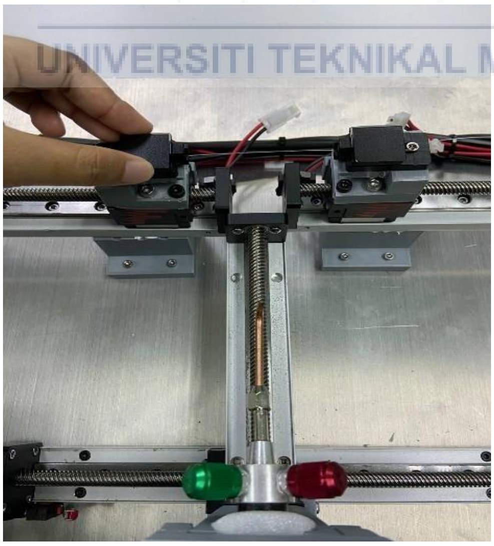
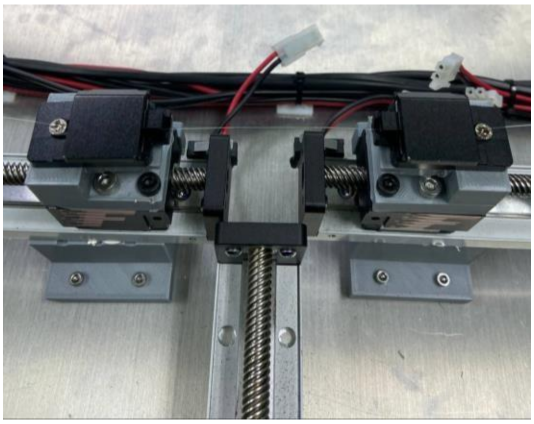
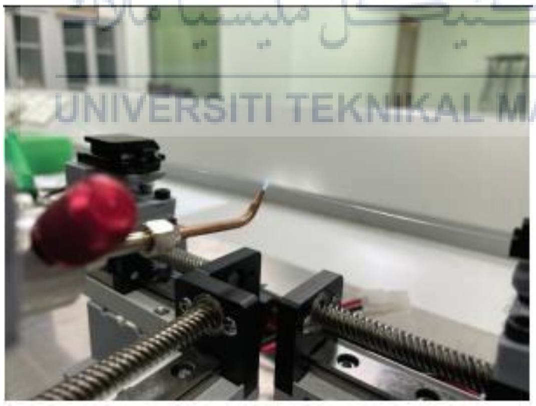
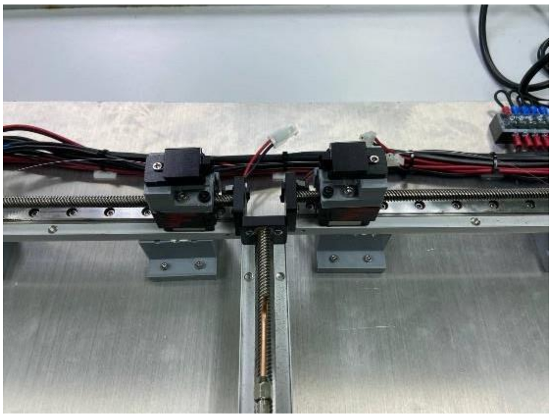
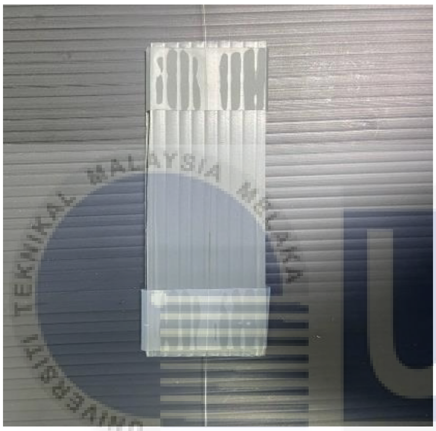


Figure 12.4 General process flow of Tapering microfiber

Table 3.2 Tapering Process

No.	Procedure	Description
1.		Cut and strip off the coating on the center part of the fiber using stripping tool.
2.		Clean the fiber to remove any dirt or contaminants using lint-free wipes and isopropyl alcohol
3.		Place each end of the fiber in the fiber holders provided at the tapering machine and clamp securely.

4.		Align the center of the fiber using the features of the tapering machine
5.		Set and control the hydrogen and oxygen to get the small flame
6.		Heat the center of the fiber by moving forward the torch, while simultaneously put the tension on two ends

7.		Once the fiber diameter is reduce and streched, the tapering process is complete.
8.		Properly bring out the tapered fiber from the machine and placed on the board.

3.2.1.3 Splicing process

In optical microfibers, the splicing process is essential. The technique used to join two optical fibers.- Is fusion splicing, which ensures a permanent connection between the two fibers (Gamm, 2018). The process involves aligning the fiber ends and fusing them together to ensure efficient transmission of light signals. The thermal connection uses an electric arc to melt two ends of the optical fibers, forming a single long fiber. Before the splicing process, the optical fibers need to be cleave using a cleaver to form smooth and perpendicular end faces. This cleaving process will ensures a high quality of splice and minimizes the loss splices in the optical microfiber sensor (Xiao et al., 2007). Then, the process is followed by alligning the fibers ends on the splicer and perform the fusion splicing.

Table 3.3 Splicing process

No.	Procedure	Description
1.		Strip off the coating from the each ends of the fiber
2.		Clean the fiber to remove any dirt or contaminants using lint-free wipes and isopropyl alcohol
3.		Cleave the fiber ends using a fiber cleaver

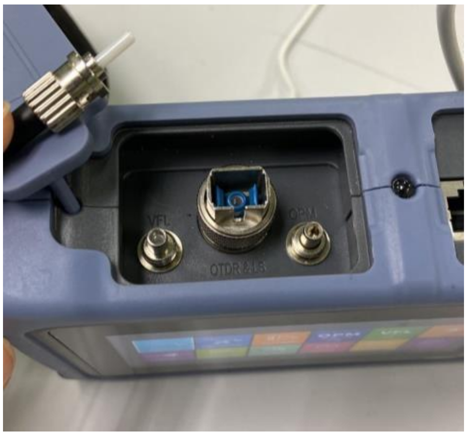
4.		Power on and set the splicing parameters on the Fujikura 70S splicer
5.		Place the fiber ends and pigtail ends on the each sides holders of the splicer.
6.		Press the set button then its automatically align and melt the fiber ends together with the pigtail create a permanent joints

7.		Inspect and test the fiber
8.		Place the fiber on the board

3.2.1.4 Optical power Measurement

Optical power measurement involves quantifying the amount of optical power that is present in an optical signal. This measurement is crucial for assessing the performance and efficiency of the optical fiber sensor. This measurement involves the use of photodetectors that convert optical signals into electrical currents which will be measured in decibels (dB) or in milliwatts (mW).

Table 4.4 Optical power measurement process

No.	Procedure	descriptions
1.		Connect one end of the fiber to the OTDR.
2.		Connect the other end of the fiber to the light source. Set the wavelength either 1550 nm or 1310 nm
3.		Setup the temperature by using soldering iron.

4.		Set the wavelength and time as desired and click the ‘Auto Test’.
5.		Collect the data and record for each parameter by repeating the steps with different parameter combinations.

3.2.1.5 Equipment

1. Tapering machine

Figure 3.5 shows a tapering machine is a device used to reduce the diameter of the fiber and creates a tapered shape. Since smaller diameter gives a higher sensitivity, the optical microfiber need to be tapered into a very small diameter of few micrometers. The tapering machine gives a better control in order to create the tiny diameters. Basically, the machine consists of some components which is heat source, fiber holder, control system and pulling mechanism.

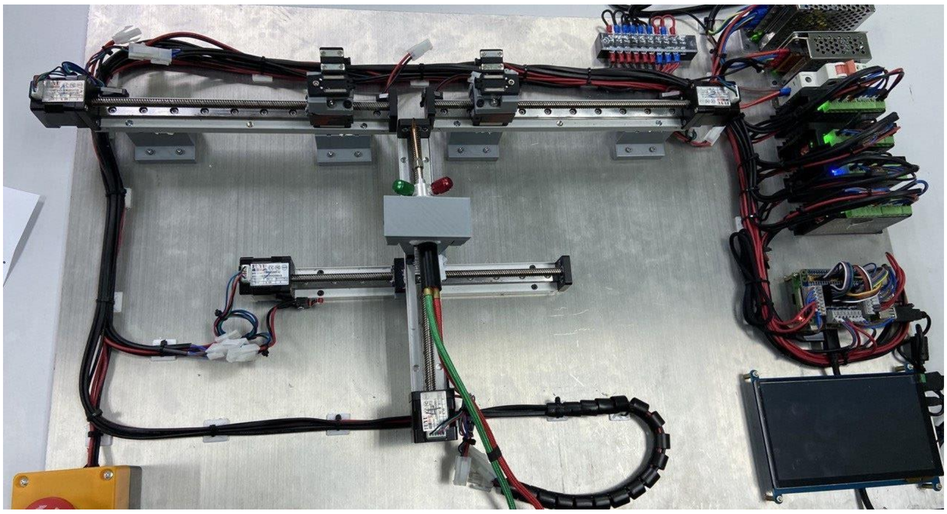


Figure 13.5 Tapering Machine

2. Fusion splicer

Fujikura 70S splicer as shown in figure 3.6 is a fusion splicing machine that used to enable the permanent join of two fiber ends. Technically, the machine weld two optical microfiber together by generating the electric arc and controlled heat source. With a combination of image and light detection system, this machine provide a precise alignment for the two fiber and resulting a minimal splice loss.

Figure 14.6 Fusion Splicer Machine

3. Fiber Cleaver

Cleaver in figure 3.7 is a tool to precisely cut or cleave the optical microfiber to get a smooth end face that is perpendicular (90°) to the length of the fiber. The fiber are cleave by applying high tension until the fiber breaks. Commonly, the cleaver used in fusion splicing to ensure precise and reliable fiber cleaves to get low loss splices in the optical microfiber.

Figure 15.7 Cleaver Tool

4. Fiber stripping tool

Figure 3.8 shows a three-hole fiber stripping tool is used to remove the protective coating or buffer layer from optical fiber includes fiber jacket, fiber buffer and fiber coating. There are 3 holes with difference sizes and each of it serve a specific purpose. Specifically, it is designed to strip the outer layer by grip the fiber securely, apply pressure and strip off the coating until exposed the bare fiber underneath.

Figure 16.8 Fiber Stripping tool

5. Optical Spectrum Analyzer

Optical spectrum analyzer is an instrument used to measure and display the distribution of power of an optical sourcea as shown in figure 3.9. It is capable to measure power over a range of wavelengths and provide detailed information. The optical spectrum analyzer is a reliable instrument as it can cover a broad wavelength range hence, allow detection of smaller spectral features.

Figure 17.9 Optical Spectrum Analyzer

6. Optical Power Meter

This component used to measured power and loss using the dual-wavelength testing feature, in which 1310 nm and 1550 nm. These wavelength can be transmitted simultaneously.

Figure 18.10 Optical Power Meter

3.2.2 Design of Experiment (DoE)

3.2.2.1 Type of Analysis

i. Half Normal Plot

Half Normal Plot is a graphical tool used in statistical analysis, particularly in the context of Design of Experiments (DOE), to assess the magnitude and significance of the effects of factors on a response variable. The plot visually represents the standardized effects of different factors. Statistically, the Half Normal plot aids in identifying which factors contribute the most to the variability in the response variable. The more influential factors exhibit larger standardized effects and are positioned towards the right of the plot. In constrast, factors with smaller effects are located towards the left. Interpretation involves examining whether any factor have effects that extend beyond the range of variability expected due to random chance. Factors with points that fall well above the expected line are considered more significant.

ii. Analysis of Variance (ANOVA)

ANOVA is a statistical method for distinguishing the contributions of different factors to a dataset based on the partitioning of variability within the dataset. The foundational principle is to assess whether there are significant differences among the means of multiple groups or level within a categorical variable. Mathematically, ANOVA is expressed as the ratio of the variance between groups to the variance within groups. This ratio which know as F-statistic, is compared against a critical value to determine statistical significance. The interpretation of ANOVA involves scrutinizing the p-value associated with the F-statistic. A small p-value suggest that at least one group mean is significantly different.

In contrast, a large p-value indicated a lack of evidence to reject the null hypothesis of equals means.

iii. Analysis of Normal Plot Residuals

The analysis of Normal Plot Residuals is needed in the evaluation of statistical models, particularly in the realm of experimental design and regression analysis. This analysis involves creating a plot where the odered residuals are plotted against the expected quantiles of a standard normal distribution. Interpretation of the analysis involves visually assessing the linearity of the plotted points. A straight line suggests that the residuals adhere to a normal distribution, somehow some moderate scatter is anticipated even with normal data. There is distinct pattern like an "S-shaped" curve, indicating that a transformation of the response provide better analysis. Visual inspection of the graph is deemed sufficient.

iv. Analysis of Residuals vs. Predicted

In this analysis, each data point represents a combination of a predicted value on the x-axis and its corresponding residuals on the y-axis. Theoretically, the residuals should be randomly scattered around the horizontal line at zero, indicating that the model is capturing the underlaying patterns in the data. A horizontal line at zero on the y-axis signifies that the residuals have a mean of zero, means that the model predictions are accurate. Deviations from this horizontal line indicate systematic errors in the model. This analysis is particularly valuable in detecting issues like heteroscedasticity, where the spread of residuals varies across different levels of the predicted values.

v. Analysis of Residuals vs. Run

The analysis involves examining the relationship between the residuals, which are the differenes between observed and predicted values. The sequence or order in which the experiments or observations were conducted referred as ‘runs’. In this analysis, each data point on the scatter plot corresponds to a specific run. The residuals should exhibit no systematic pattern across the runs.

vi. Analysis of One factor

This analysis involves examining the relationship between a single factor and the response variable. This type of plot is particularly useful to visualize the changes in one specific factor influence the variation in the response variable. The plot is constructed by predicting the reponses for the low and high levels of a factor. For factors involved in interactions, warning will be display on the one factor plots in Design expert. It will be complex where there will be influence of a particular factor is not consistent across all levels but varies based on the concurrent settings of interacting factors. Therefore, relying solely on One Factor Plots in the presence of interactions can potentially lead to misleading interpretations and may not be accurate.

vii. Analysis of Interaction Effect Plot

Interaction Effect plot is to analyse the interdependencies and synergies among different factors in experimental design. In this analysis, there is lines represents the effect of one factor at different levels of the interacting factor. The plot allows for the observation of patterns, revealing the nature and strength of the interactions. A parallel or converging curves indicates that lack of interaction, whereas intersecting lines suggest a significant interaction effect. This analysis helps to identify optimal conditions or settings for achieving desired outcomes by considering the interactions of the factors.

Table 5.5 : Parameter of the experiment

Parameter	Low level (-)	High level (+)
Light source	1310 nm	1550 nm
Diameter	7.2 µm	13.4 µm
Type of fiber	Singlemode	Multimode
Temperature	31.3°C	40°C

Table 6.6: parameter level of 16 runs

Runs	Light source wavelength	Diameter	Type of fiber	Temperature
1	1550 nm	> 10µm	Single Mode	1st temperature
2	1550 nm	>10µm	Single Mode	2nd temperature
3	1550 nm	>10µm	Multi Mode	1st temperature
4	1550 nm	>10µm	Multi Mode	2nd temperature
5	1550 nm	< 10µm	Single Mode	1st temperature
6	1550 nm	< 10µm	Single Mode	2nd temperature
7	1550 nm	< 10µm	Multi Mode	1st temperature
8	1550 nm	< 10µm	Multi Mode	2nd temperature
9	1310 nm	>10µm	Single Mode	1st temperature
10	1310 nm	>10µm	Single Mode	2nd temperature
11	1310 nm	>10µm	Multi Mode	1st temperature
12	1310 nm	>10µm	Multi Mode	2nd temperature
13	1310 nm	< 10µm	Single Mode	1st temperature
14	1310 nm	< 10µm	Single Mode	2nd temperature
15	1310 nm	< 10µm	Multi Mode	1st temperature
16	1310 nm	< 10µm	Multi Mode	2nd temperature

3.2.2.2 Design Expert Software

After experiment phase, the analysis of acquired data is carried out using Design Expert software, an analytical tool for statistical design and analysis of experiments. Initially, the collected experimental data, which may include parameters such as temperature, diameter, type of fiber and wavelength, is imported into the software. The experimental design is established by defining factors, assigning levels, and specifying response variables related to the outcomes of the experiment, such as output power. Depending on the complexity and available resources, an appropriate experimental design such as Box Behnken design is chosen. After conducting the experimental runs, the observed responses are inputted into Design Expert for statistical analysis, employing techniques like analysis of variance (ANOVA) to assess the significance of factors and their interactions. The software can also help build empirical models to describe the relationships between factors and responses, enabling predictions for untested conditions. Design Expert's optimization tools facilitate the identification of optimal conditions for desired responses. The results are interpreted, and visualizations such as graphs or contour plots are generated to aid in understanding the experiment's outcomes. Validation steps may be undertaken to ensure the robustness of the models, and the entire process is documented meticulously for reproducibility and knowledge dissemination.

3.2.2.3 Design of Experimental Process

Box-Behnken design is a statistical experimental design method used for optimizing and exploring the effects of multiple variables on a response. The design aims to find the optimal conditions for a process by systematically varying the levels of input factors within a specified range. The factors is assigned as high and low levels, defining the range over which they would be varied during the experiment. Figure 3.11 shows how the factors are assigned to the design.

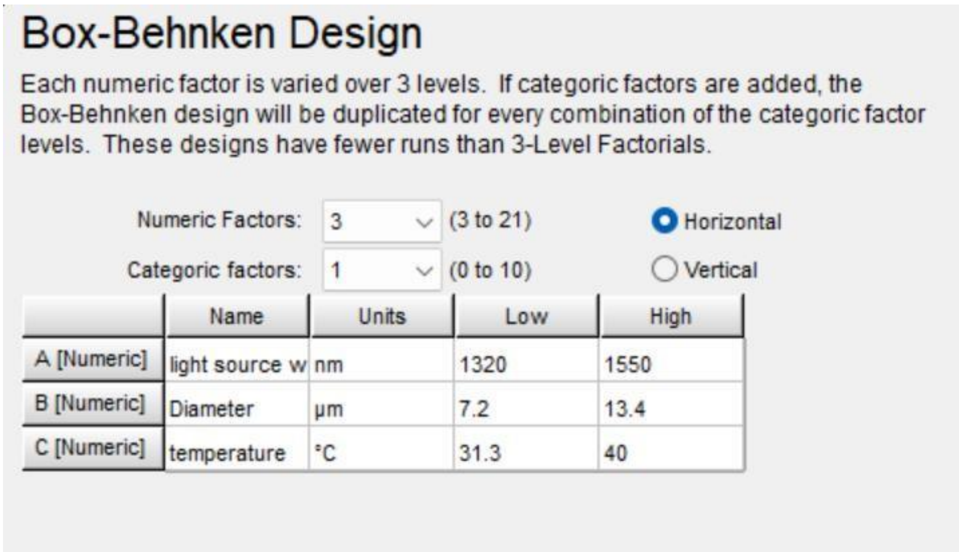


Figure 19.11 Factors Assigned to the Criteria

Parameters that have real value within a specified range defined as a numeric factors. Therefore, there are three numeric factor includes light source wavelength, diameter and temperature which set at two levels; low and high. Whereas, type of fiber is categorized as categoric factor. The design systematically combines these factors to investigate potential interactions and effect on the responses. The data sets from the experiment are added to the matrix design (Figure 3.12).

Select	Std	Run	Factor 1 A:light source nm	Factor 2 B:diameter μm	Factor 3 C:type of fiber	Factor 4 D:temperature °C	Response 1 power dB
	9	1	1550	13.40	singlemode	40.00	29.87
	7	2	1550	13.40	singlemode	31.30	62.13
	12	3	1550	13.40	multimode	40.00	29.45
	11	4	1550	13.40	multimode	31.30	52.44
	6	5	1550	7.20	singlemode	40.00	29.42
	14	6	1550	7.20	singlemode	31.30	54.57
	4	7	1550	7.20	multimode	40.00	29.83
	1	8	1550	7.20	multimode	31.30	29.75
	3	9	1310	13.40	singlemode	40.00	30.65
	10	10	1310	13.40	singlemode	31.30	38.44
	16	11	1310	13.40	multimode	40.00	31.02
	2	12	1310	13.40	multimode	31.30	46.35
	5	13	1310	7.20	singlemode	40.00	30.84
	8	14	1310	7.20	singlemode	31.30	54.05
	13	15	1310	7.20	multimode	40.00	31.05
	15	16	1310	7.20	multimode	31.30	57.42

Figure 20.12 Matrix Design

The data sets are then involved with data analysis, where Transform, Effects, ANOVA, Diagnostics and Model Graphs are part of a process for analysing the data (Figure 3.13). Firstly, data transformation is a process used to improve the normality or linearity of the data when assumptions of statistical tests are violated. Effects is likely be used to select and examine the effects of different variables in the analysis. Next, statistical method ANOVA used to compare means among different groups to see if there are any statistically significant differences. This involves calculating F-statistics and P-values to determine the likelihood that any observed differences in sample means are due to chance. Besides, there is Diagnostics checks to validate the assumptions of the statistical tests. This includes examining residuals for pattern that might suggest violations of assumptions, such as non-constant variance (heteroscedasticity) or non-normality. The last one is Model Graph as a visual representation of the data and the model's fit. There are scatter plots, residual plots, and other types of graph that helps in understanding the relationship between variables and in identifying any outliers or unusual observations. The last step for the analysis optimization process that used to find the best settings or factors that will result in optimal response. Figure 3.14 shows a section in design expert software, where the optimization process involved. The process needs to define the criteria for optimization which is the response variable (power). Set a goal to maximize it in order to achieve a maximum output power for optimal combination. The optimization model will be visualized numerically in the 'solutions' tab.

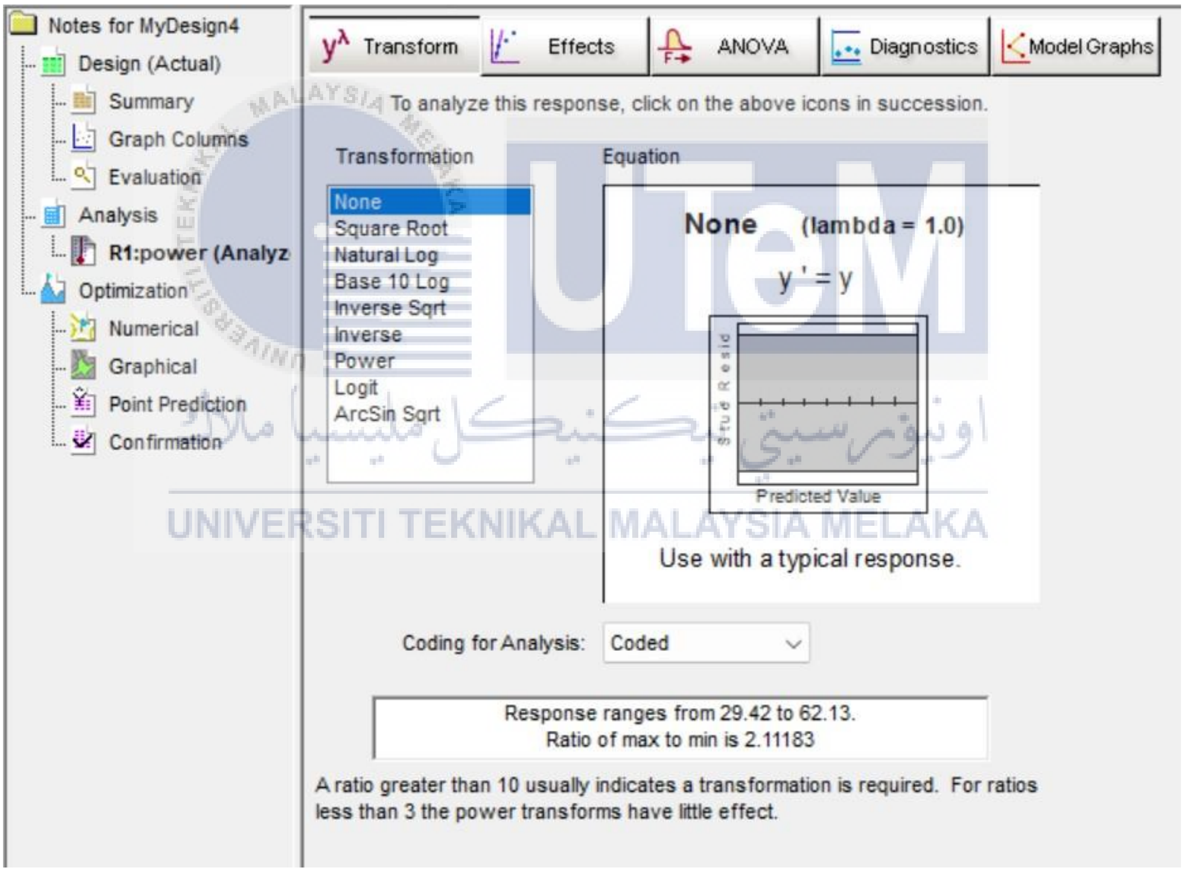


Figure 21.13 Analysis Section

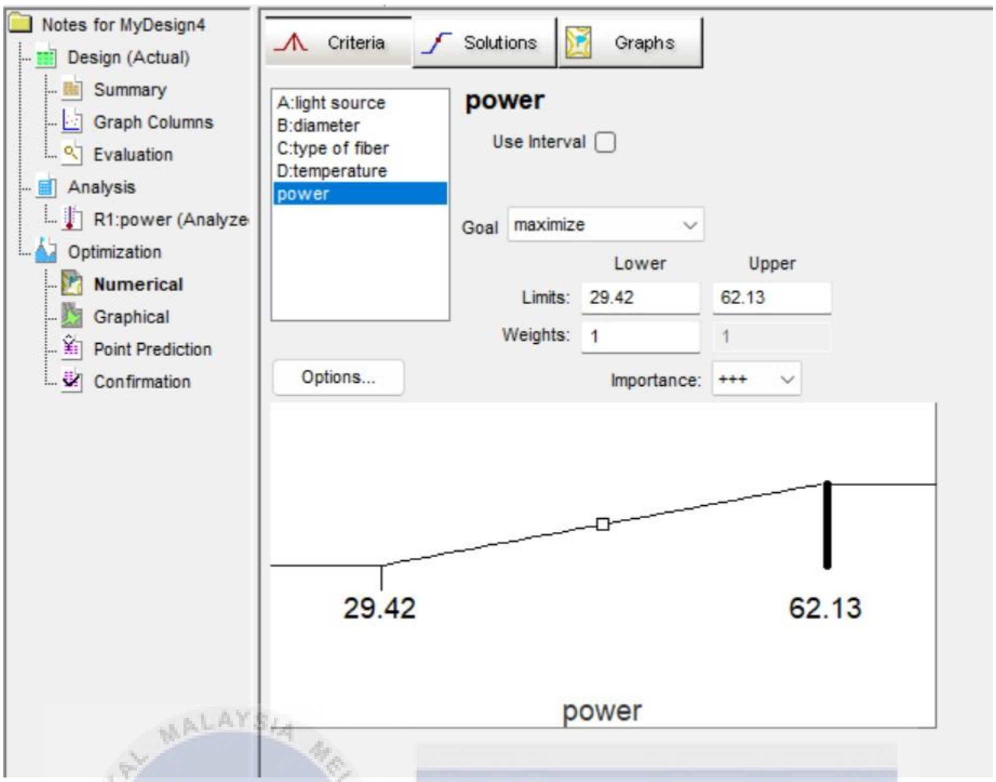


Figure 22.14 Optimization Section

3.3 Limitation of proposed methodology

There are some limitation occur in this project. The first one is limited detection range where the detection range of an optical microfiber sensor is limited by the sensitivity of the sensing material and the detection system. Different material exhibit varying levels of sensitivity to the parameter that being measured. The sensor's ability will not be accurate and effect the overall result.

Besides, interference from environmental factors also one of the limitation because the optical microfiber sensors can be sensitive to changes in temperature, humidity, and other environmental factors. This can lead to interference in the measurement and effect the accuracy of the sensor.

3.4 Summary

To conclude, this chapter explained the detail of methodology apply in the development of optical microfiber sensor for human health monitoring. The chapter started with the explanation of related project methodology in a flow chart, then followed by the steps involve in choosing the suitable optimization approach. The optimization method was then applied to the development of the optical microfiber sensor. The method of this research can be used to develop more efficient and effective health monitoring systems.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter present the result and analysis of the optimization approach for the optical microfiber sensor. Response Surface Methodology (RSM) in Design Expert software is utilized to design experiments, analyze experimental data and optimization process. The obtained analysis will contribute to development of an effective and efficient optical microfiber sensor for human health monitoring.

4.2 Results and Analysis

Data and outcomes from the experimental phase have been compiled for a two different temperature settings, encompassing a total of 16 data points gathered through various runs. Table 4.1 displays the results of power output measurement obtained from the experiment. The variation of output with 16 responses is shown in Figure 4.1 to visualize the experimental runs against power output.

Table 7.1 Results of power output measurements

Run	Light source wavelength	Diameter	Type of fiber	Temperature	Power output
1	1550 nm	13.4µm	Single-Mode	31.3°C	29.87 dB
2	1550 nm	13.4µm	Single-Mode	40 °C	62.13 dB
3	1550 nm	13.4µm	Multi-Mode	31.3°C	29.45 dB
4	1550 nm	13.4µm	Multi-Mode	40 °C	52.44 dB
5	1550 nm	7.2µm	Single-Mode	31.3°C	29.42 dB
6	1550 nm	7.2µm	Single-Mode	40 °C	54.57 dB
7	1550 nm	7.2µm	Multi-Mode	31.3°C	29.83 dB
8	1550 nm	7.2µm	Multi-Mode	40 °C	29.75 dB
9	1310 nm	13.4µm	Single-Mode	31.3°C	30.65 dB
10	1310 nm	13.4µm	Single-Mode	40 °C	38.44 dB
11	1310 nm	13.4µm	Multi-Mode	31.3°C	31.02 dB
12	1310 nm	13.4µm	Multi-Mode	40 °C	46.35 dB
13	1310 nm	7.2µm	Single-Mode	31.3°C	30.84 dB
14	1310 nm	7.2µm	Single-Mode	40 °C	54.05 dB
15	1310 nm	7.2µm	Multi-Mode	31.3°C	31.05 dB
16	1310 nm	7.2µm	Multi-Mode	40 °C	57.42 dB

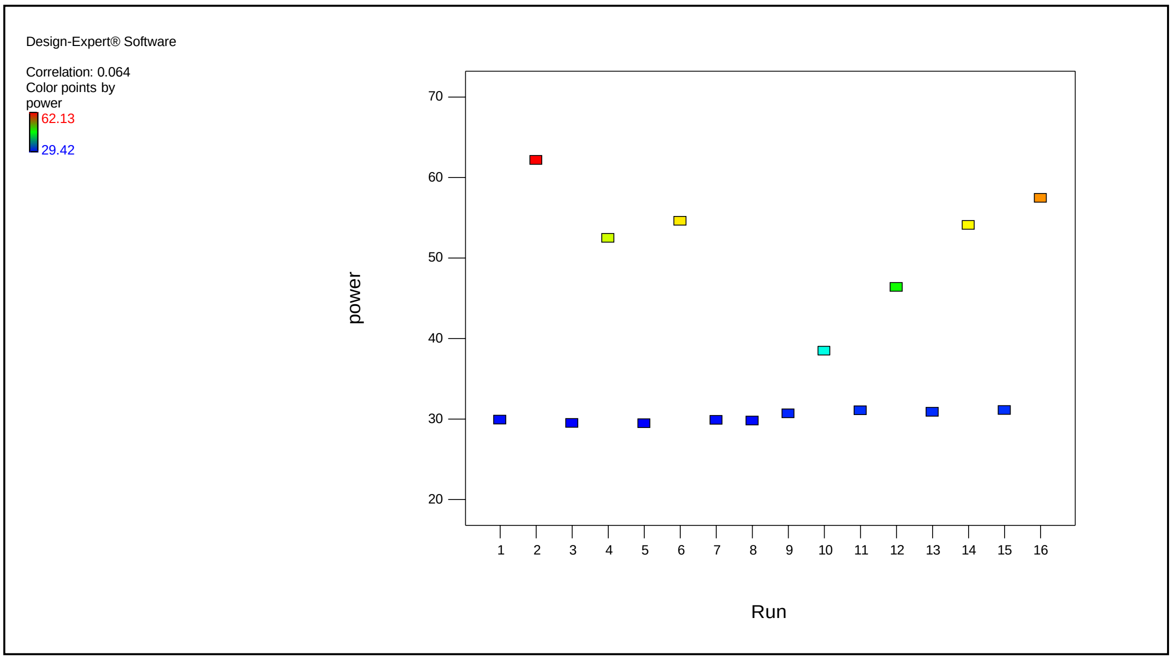


Figure 23.1 Variation of output with 16 responses

4.2.1 Analysis of Design Expert Result

The objective was to identify significant properties and develop a mathematical model of the microfiber sensor parameter. The experiment measuring the output power with the developed temperature sensor using a particular diameter of single-mode and multi-mode optical fiber cable based on the different wavelengths for the light source. To efficiently study the effects of different parameters, Box Behnken design (BBD) in design expert software was employed as an experimental design technique. The design involves examining the joint effects of multiple factors on a response variable by considering all possible combinations of the factor levels.

In BBD, each factor is studied at two levels typically referred to "high" and "low". This design is efficient in terms of number of experimental runs required to estimate main effects and interactions. It includes all possible combinations of factor levels, resulting in 2^n experimental runs, where n is the number of factors. In this case, there were 16 experimental runs since there are 4-four factors were considered. These factors fall into two distinct type:

"Numeric" and "Categoric". Numeric factors are continuous variables that can take any value within a range. The diameter of the tapered fiber and temperature for the experiment is considered as a numeric factor. On the other hand, categorical factors represent different categories or levels without a specific numerical order such as type of fiber cable and the light source. The statistical analysis of the experimental data will provide insights into the main effects of each factor and potential interactions between factors. Hence, the developed sensor can be optimized to simultaneously improve its performance.

4.2.1.1 Analysis of Half-Normal Plot

The Half-normal plot is a graphical representation of the magnitude of effects in a factorial design aiding in the identification of statistically significant effects. The diagonal line on the plot represents the error line, indicating the expected distribution of effects under the assumption of no significant effects. The farther a point is from the error line, the more significant the effect. Based on the figure 4.2, the point on the plot indicate that temperature is a significant effect for output power while light source, diameter and type of fiber are not considered statistically significant. To analyze the significant factors more precisely, a statistical test using the Shapiro-Wilk test is employed to assess whether a sample of data comes from a normally distributed population. Null hypothesis (H_0) and alternative hypothesis (H_a) are the steps used to determine if the data follows a normal distribution or not respectively. This test results yield a p-value of 0.677, which is greater than the conventional significance level of 0.05. This suggests that there is no significant evidence to reject the (H_0). The non-significant Shapiro-Wilk test result suggests that the assumption of formality for residuals is not violated, which supporting the robustness of the ANOVA results.

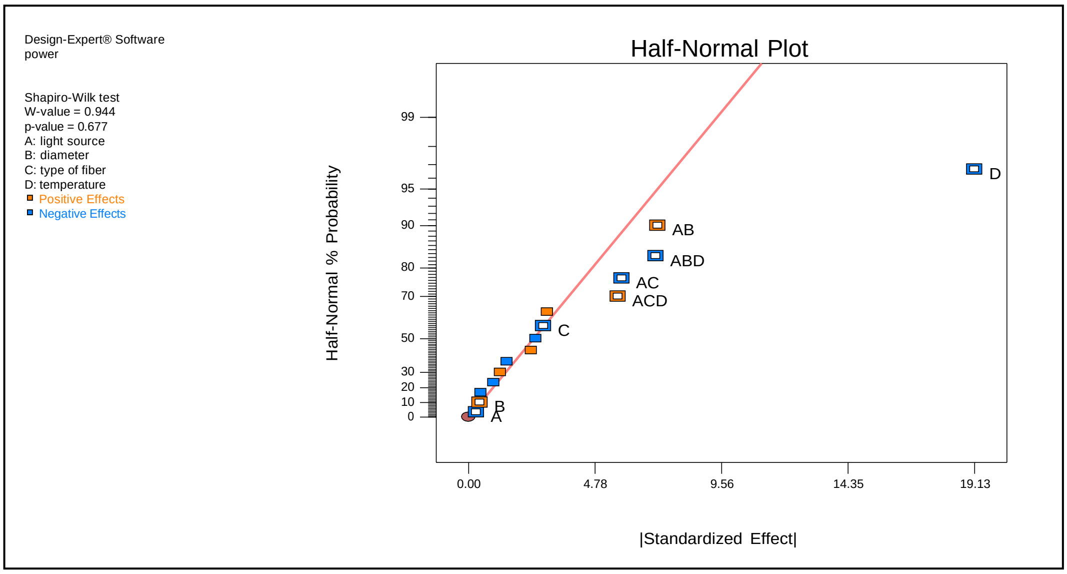


Figure 24.2 Half Normal Plot for Output Power

4.2.1.2 Analysis of Variance (ANOVA)

The ANOVA results indicate whether there is a significant overall effect of the factors included in the model. Firstly, the test statistic used in ANOVA is the F-statistic. A larger F-statistic suggests that the group means are significantly different. The F value obtained from this test is 18.48 and there is only a 0.05% chance that a 'model F-value' this larger could occur due to noise. Moreover, p-values less than 0.05 indicate model terms are significant. As shown in Figure 4.3, p-value of the model is 0.0005 proves significance. Additionally, significant includes D-temperature, AB, AC, ABD and ACD; represent interaction between A-light source, B-diameter and C-type of fiber. The ANOVA also provides several statistical metrics including standard deviation, mean, R-squared and others. From the result, standard deviation of 3.83 indicates the average amount of deviation of each data points from the mean, where the mean is 39.83 signifying the central tendency of the data. R-squared is a coefficient of determination that quantifies the proportion of the variance in the dependent variable. The value of 0.9548 indicates that 95.48% of the variability in the response variable is accounted for by the independent variable in the model.

A higher the R-squared suggests that the model accurately approximate the output when given new data, producing more precise results.

Response 1 power

ANOVA for selected factorial model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2163.89	8	270.49	18.48	0.0005	significant
A-light sourc	*0.35*	*1*	*0.35*	*0.024*	*0.8818*	
B-diameter	*0.73*	*1*	*0.73*	*0.050*	*0.8295*	
C-type of fibe	*32.09*	*1*	*32.09*	*2.19*	*0.1822*	
D-temperatur	*1463.45*	*1*	*1463.45*	*99.98*	*< 0.0001*	
AB	*204.63*	*1*	*204.63*	*13.98*	*0.0073*	
AC	*134.44*	*1*	*134.44*	*9.19*	*0.0191*	
ABD	*200.51*	*1*	*200.51*	*13.70*	*0.0076*	
ACD	*127.69*	*1*	*127.69*	*8.72*	*0.0213*	
Residual	102.46	7	14.64			
Cor Total	2266.35	15				

Std. Dev.	3.83	R-Squared	0.9548
Mean	39.83	Adj R-Squared	0.9031
C.V. %	9.61	Pred R-Square	0.7638
PRESS	535.29	Adeq Precisior	12.316

Figure 25.3 Result for ANOVA

4.2.1.3 Analysis of Normal Plot Residuals

Normal plot of residuals serves as a crucial diagnostic tool for evaluating the normality assumption of the residuals. Theoretically, if the residuals follow a normal distribution, the points on the plot should be align with the straight line. Figure 4.4 shows that the majority of the points are around the straight line indicating observed values match those expected in the normal distribution.

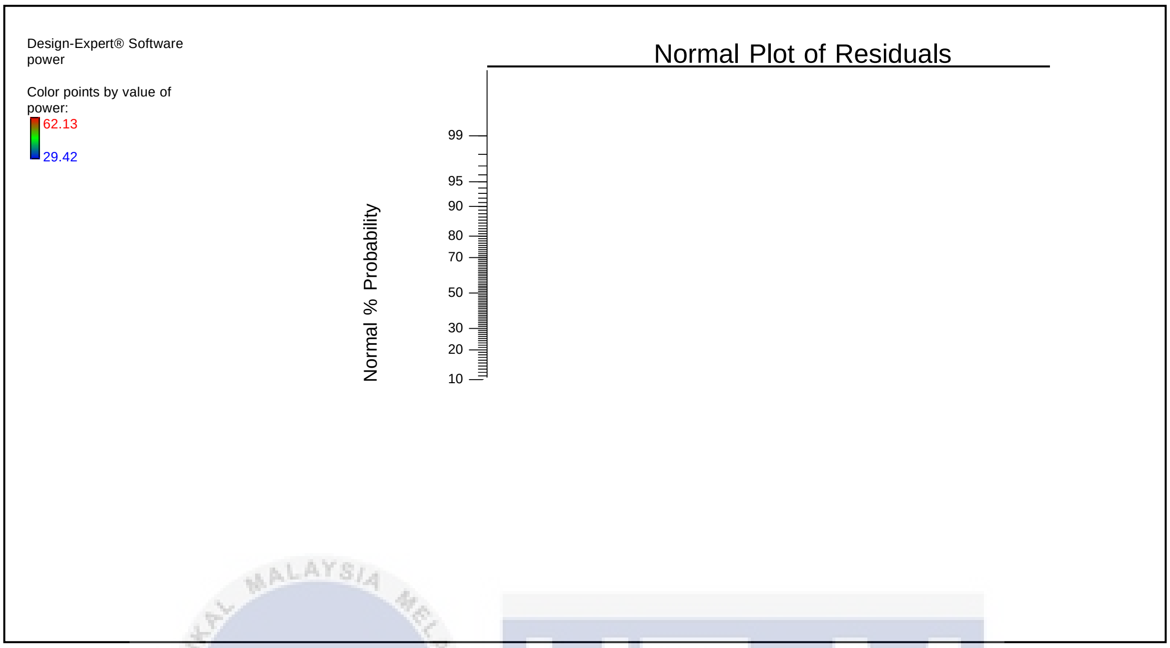


Figure 26.4 Result for Normal Plot of Residuals

4.2.1.4 Analysis of Residuals versus Predicted

In this analysis, the residuals against the predicted values obtained from the ANOVA model have been plotted as shown in figure 4.5. The plot is a graphical tool used in regression analysis to detect non-linearity, heteroscedasticity, and outliers. The residuals are randomly distributed around the horizontal line, indicating that the model's predictions are unbiased. The horizontal red line used as a reference line to help assess the randomness of residuals and identify potential patterns or trends. It is also represents the zero line, clarifying where residuals would be if the model predictions perfectly matched the observed values. Points that are far away from the bulk of the data indicate outliers. These are cases where the model's predictions are significantly different from the actual values. Outliers can have a large influence on the regression model.

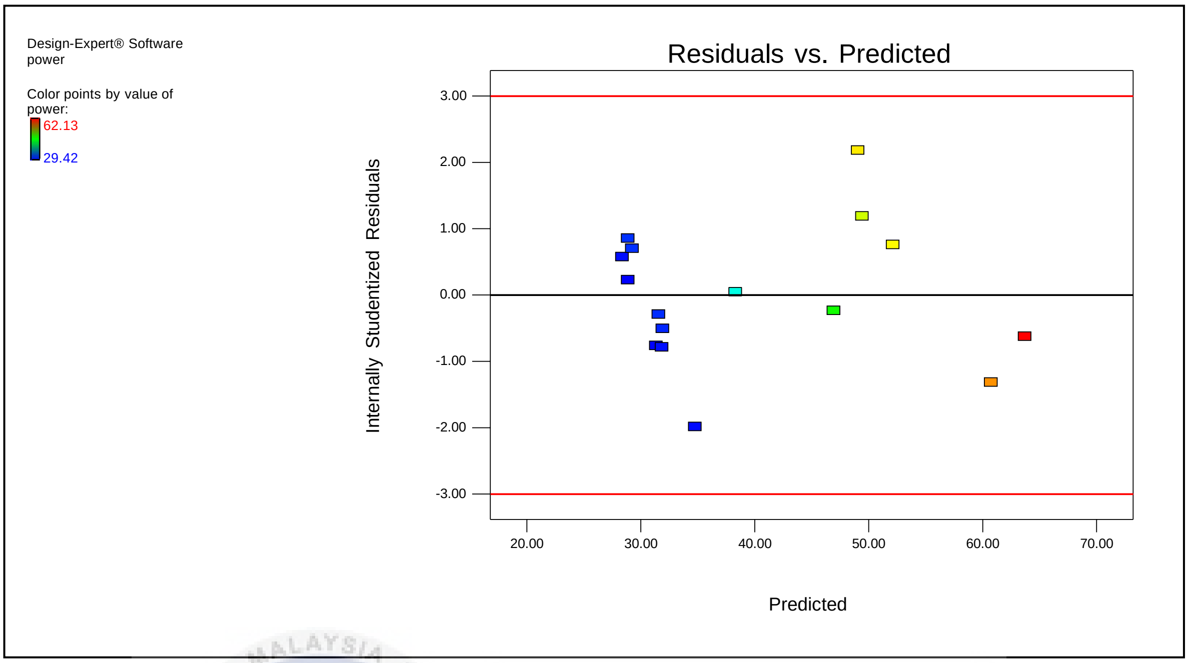


Figure 27.5 Result for Residuals versus Predicted

4.2.1.5 Analysis of Residuals versus Run

The pattern of residuals across different experimental runs is crucial for assessing the adequacy of the model. This plot shows a random scatter, indicating that the model effectively captures the variability in the data.

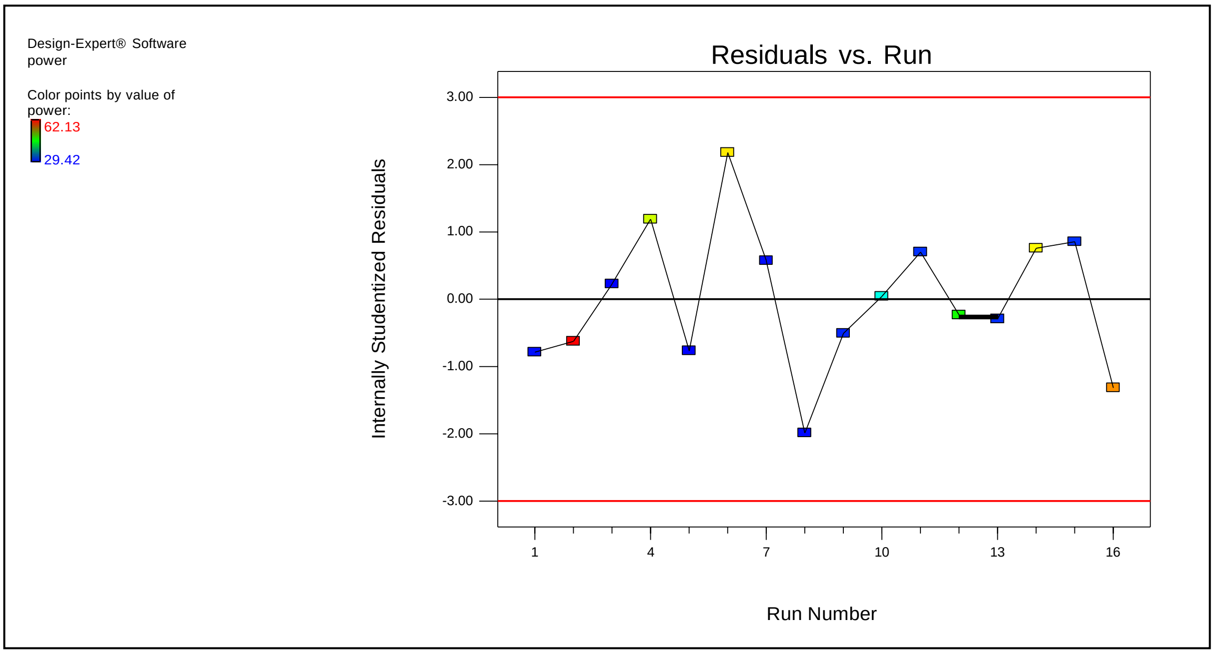


Figure 28.6 Result for Residuals vs Run

4.2.1.6 Analysis of One factor Effect of the Parameter

Figure 4.7 illustrates distinct in the observations for each parameter's influence on output power. A higher output power (43.99 dB) is observed at a light source wavelength of 1550 nm compared to 1310 nm under specific conditions. This difference can be attributed to wavelength-dependent effects on optical absorption, attenuation, and dispersion in the fiber. A wavelength of 1550 nm may experience lower attenuation and dispersion in the fiber, resulting in more efficient signal transmission and higher output power.

Next, for the diameter, a 7.2 µm diameter exhibits higher output power (41.85 dB) compared to 13.4 µm diameter. Smaller diameters result in lower signal attenuation. The observation of single mode and multimode fiber shows that multimode fiber has slightly higher output power. Single mode fibers with their smaller core size and reduced modal dispersion, provide better signal integrity especially for longer distance transmission. However, multimode fiber with a larger core size, can transmit more light which resulting in slightly higher output power at 31.3°C. Changes in temperature influence the refractive index, absorption characteristic and thermal expansion of the fiber material, ultimately impacting the propagation of light.

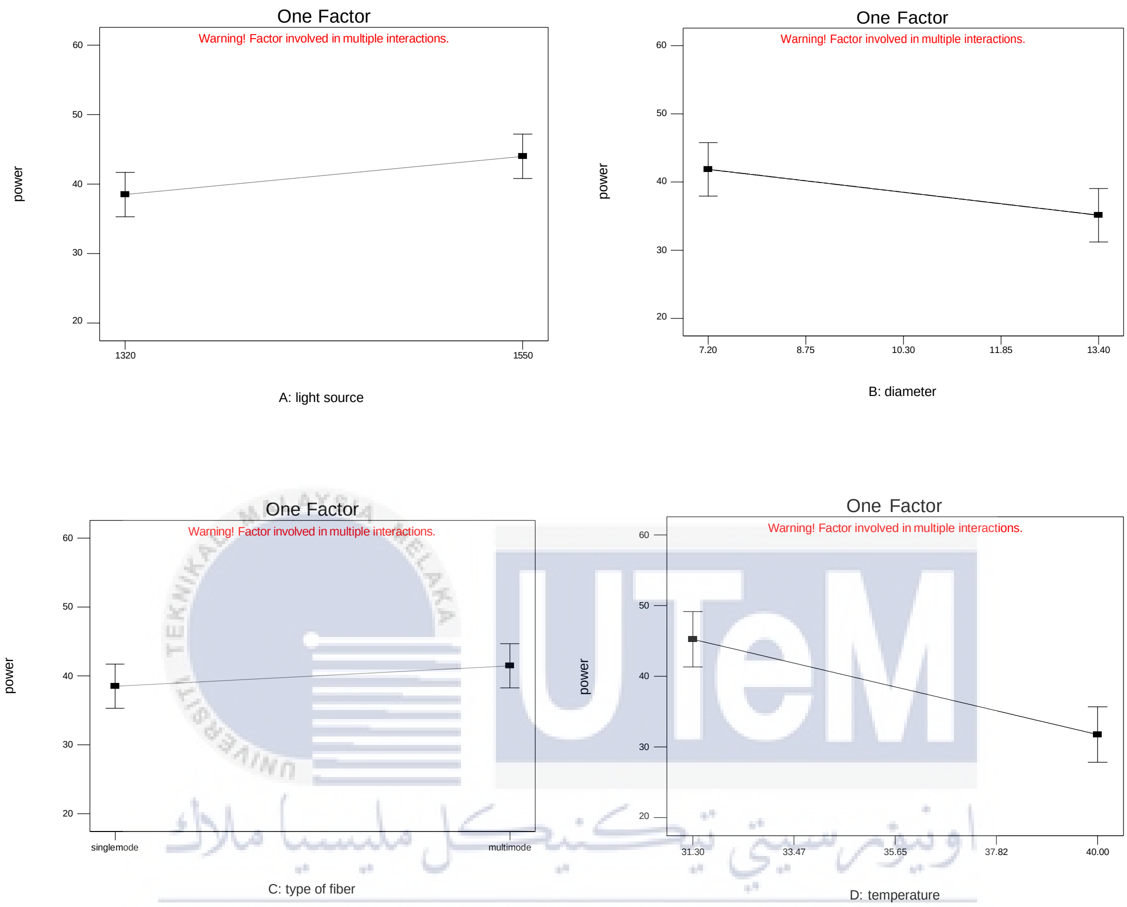


Figure 29.7 Result for One Factor for each Parameter

4.2.1.7 Optimization Design

The aim of this studies is to develop a microfiber sensor with optimum parameters. After analyzing all the data, a regression model is obtained. A regression model is a mathematical representation of observed relationships, serving as a prediction tool for estimate output power under different parameters. This equation is significant in the optimization process, allowing for the identification of parameters that significantly influence the microfiber sensor's performance.

By using regression models, it is possible to investigate and predict the impact of different factor settings on output power, enabling the identification of optimal conditions for microfiber sensor development. This mathematical formulation encapsulates the empirical understanding gained from the experimental data, providing a quantitative framework for decision-making in the sensor's design and optimization.

Regression Model:

After the analysis of variance (ANOVA), the regression model was derived using the Design Expert software. The resulting regression equation encapsulates the relationship between the input factors (diameter, light source wavelength, type of fiber, and temperature) and the output variable (output power) based on the experimental data.

Final equation in terms of coded factors:

$$
\begin{aligned}
\text{power} = \; & +39.83 \\
& -0.15 \; * A \\
& +0.21 \; * B \\
& -1.42 \; * C \\
& -9.56 \; * D \\
& +3.58 \; * A * B \\
& -2.90 \; * A * C \\
& -3.54 \; * A * B * D \\
& +2.82 \; * A * C * D
\end{aligned}
$$

Where,

A – Light source wavelength C – Type of fiber

B – Diameter of tapered fiber D – Temperature

So, the final equation in terms of parameters is:

$$power = +39.83 - 0.15 * wavelength + 0.21 * diameter - 1.42 * type\ of\ fiber - 9.56 * temperature + 3.58 * wavelength * diameter - 2.90 * wavelength * type\ of\ fiber - 3.54 * wavelength * diameter * temperature + 2.82 * wavelength * type\ of\ fiber * temperature$$

The final equation, expressed in terms of coded factors, represents a concise mathematical model that encapsulates the relationships between the experimental factors and the response variable. This equation enables the prediction of response values based on specific factors settings and identification of optimal parameters for achieving desired responses.

Table 8.2 Optimization Criteria Setting

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:light source	is in range	1310	1550	1	1	3
B:diameter	is in range	7.2	13.4	1	1	3
C:type of fiber	is in range	singlemode	multimode	1	1	3
D:temperature	is in range	31.3	40	1	1	3
power	maximize	29.42	62.13	1	1	3

Table 4.2 shows the structured of framework for defining the goals and constraints associated with each factor in the experimental design. Each factor, including light source wavelength (A), diameter (B), type of fiber (C), and temperature (D), has specified goals with lower and

upper limits, weightings and importance levels, in which all contributing to the overall optimization strategy. The output power is maximized within a range of 29.42 to 62.13. This comprehensive optimization criteria setting reflects the priorities and objectives of the experimental design. The specified weights and importance level provide a means to prioritize factors based on their relative significance, guiding the optimization process towards achieving the most favourable conditions for the power output.

Table 9.3 Optimization Solution

Solutions for 4 combinations of categoric factor levels

Number	light source	diameter	type of fiber	temperature	power	Desirability	
1	1550	13.29	singlemode	31.50	62.737	1.000	Selected
2	1550	13.40	singlemode	31.30	63.7163	1.000	
3	1550	13.14	singlemode	31.56	62.1789	1.000	
4	1550	13.13	singlemode	31.34	62.9134	1.000	
5	1550	13.35	singlemode	31.48	62.9302	1.000	
6	1550	13.33	singlemode	31.44	63.0468	1.000	
7	1550	13.32	singlemode	31.58	62.4946	1.000	
8	1550	13.16	singlemode	31.30	63.13	1.000	
9	1550	13.18	singlemode	31.43	62.7191	1.000	
10	1550	13.36	singlemode	31.43	63.1297	1.000	

Based on the result shown in table 4.3, the first solution is the best optimization approach for the experiment. To optimize the optical microfiber sensor for detecting health temperature, these values represent the optimum values for the parameters. The light source wavelength at 1550 nm considered better than 1310 nm in terms of signal performance for the temperature sensor. A diameter of 13.29 generally exhibit higher sensitivity to temperature changes and have lower optical loss due to their ability to accommodate a greater number of modes. The type of fiber is associated with diameter, single mode fiber has a smaller core diameter compared to multimode fibers, leading to higher sensitivity. The smaller core allows for better confinement of the light signal, making single-mode fiber more responsive to changes in temperature. The selected temperature values selected is 31.5°C.

From the observation, the optimized value for the diameter and temperature slightly different from the actual parameter value attributed to various factor, including the experimental variability and measurement error. This comprehensive optimization approach ensures that the optical microfiber sensor operates optimally in health temperature detection.

4.3 Discussion

The comprehensive analysis of the microfiber sensor experiment has led to valuable insights, allowing the optimal approach for the sensor's performance. The result are analyse with the observation of factors using half-normal plot, which visually identified influential parameters impacting the output power. This preliminary investigation guided subsequent analyses, including ANOVA, residuals vs predicted, residuals vs runs and one factor effect plots for each parameter.

ANOVA have provided a statistical framework to assess the significance of various factor and interactions. The results show that light source wavelength, diameter, type of fiber and temperature significantly influenced the microfiber sensor's power output. The half normal plot complemented this statistical analysis by visually highlighting the magnitude of effects, aiding in the prioritization of parameters for optimization. The analysis of residuals vs predicted and residuals vs run plots served to validate the models predictive capabilities. Inconsistencies observed in these plots are carefully considered to refine the model and enhance its accuracy. Additionally, the one-factor effect plots offer an understanding of each parameter's impact on the output power. In this study, the observation on the temperature factor exhibited a significant influence, with 31.3°C resulting in higher output power.

After the analysis, a regression model was derived, providing a quantitative representation of the relationship between parameters and output power. This model is useful in devising an optimal approach for the microfiber sensor. The solution entails setting the light source wavelength to 1550 nm, the diameter to 13.29 µm, employing a single-mode fiber, and maintaining a temperature of 31.5°C. This combination yields an optimal power output of 62.73 dB.

The choice of a 1550 nm light source aligns with its favorable impact on output power, as observed in the analysis. The larger the diameter of 13.29 µm and the utilization of a single mode fiber contribute to enhanced power transmission. The temperature at 31.5°C positively influence the sensor's performance under these optimized conditions.

In summary, the integration of statistical analyses, visual inspections through plots, and the derivation of a regression model has enabled the identification of an optimal set of parameters for the optical microfiber sensor for temperature health detector. This approach maximizes the output power, providing a robust foundation for the continued development and refinement of an efficient and effective microfiber sensor for practical applications.

4.4 Summary

As a summary, this chapter discusses the result of the optimization approach by analyzing Response Surface methodology (RSM) data using design expert software. RSM is useful for estimating the main effects and interactions by varying the factors together. RSM is used to optimize the parameters to obtain maximum performance. The optimization results show that the RSM accurately predicted the output. In conclusion, the RSM is a powerful tool for parameter optimization. Optical microfiber sensor systems, such as those used in biomedical applications, can be optimized with RSM. By identifying the most effective approach, the development of optical microfiber sensors for human health monitoring will be more reliable and efficient.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research project aimed to explore the significant properties of microfiber sensor parameters and develop an optimized microfiber sensor for human health monitoring. The project objectives were clearly defined, including the identification of the microfiber sensor properties, the devising a mathematical model and development of a microfiber sensor with optimum parameters for effective human health monitoring. In this review, a study on the existing products of the health monitoring detection methods is presented in literature, focusing on identifying the approaches and principles of the existing methods.

Despite the significant promise of optical microfiber sensors, there exists a critical need for enhancements to maximize their effectiveness in health monitoring applications. The optimization of key parameters, including wavelength, microfiber diameter, types of microfiber, and temperature, becomes a focal point in elevating the performance and utility of these sensors. In response to this imperative, the utilization of a Design of Experiment (DOE) methodology, specifically Box-Behnken Design (BBD) facilitated by tools like Design Expert is involves. The application of DOE not only explores the intricate interactions among different variables but also systematically examines their responses, ultimately findings the most effective parameters for the development of sensitive and wearable optical microfiber sensors for human health monitoring.

In essence, the investigation on optimized approach using BBD and DOE represents a strategic response to the challenges faced by the healthcare industry, promising a transformative impact on the landscape of personal health monitoring.

5.2 Potential for Commercialization

The potential for commercializing optical microfiber temperature sensing technology holds great promise, driven by its unique advantages and versatile applications in various industries. The level of reliability of the sensor is crucial in industries where precise temperature control is imperative, such as healthcare, manufacturing, and research and development. In the healthcare sector, optical microfiber temperature sensors have the potential to revolutionize patient care. Continuous monitoring of patients' body temperature can aid in early disease detection, monitor post-surgical recovery, and enhance overall patient outcomes. The non-invasive nature of these sensors also contributes to patient comfort. Additionally, optical microfiber temperature sensor can optimize industrial process, improve product quality, and ensure compliance with stringent regulatory standards. The growing demand for advanced sensing technologies, coupled with the unique advantages offered by optical microfiber temperature sensors, positions the as competitive solutions in the market. As industries seek more accurate and reliable sensing capabilities, these sensors are poised to meet and exceed market expectations.

5.3 Future Works

For future improvement related to optical microfiber sensor in temperature detection, sensor technology can be enhanced by incorporating aspects that enhance its capabilities, applications and overall efficiency. The future works as follows:

i. Expand the functionality of optical microfiber sensors to include the simultaneous measurement of multiple parameters such as temperature and pressure sensing that could be employed in environment where temperature fluctuations and pressure changes.

ii. Optimizing the power consumption of optical microfiber sensors to enable prolonged operation in energy-efficient applications.

iii. Consider on enhancing the environmental durability of optical microfiber sensor to ensure the reliability and longevity of the sensor system.

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APPENDICES

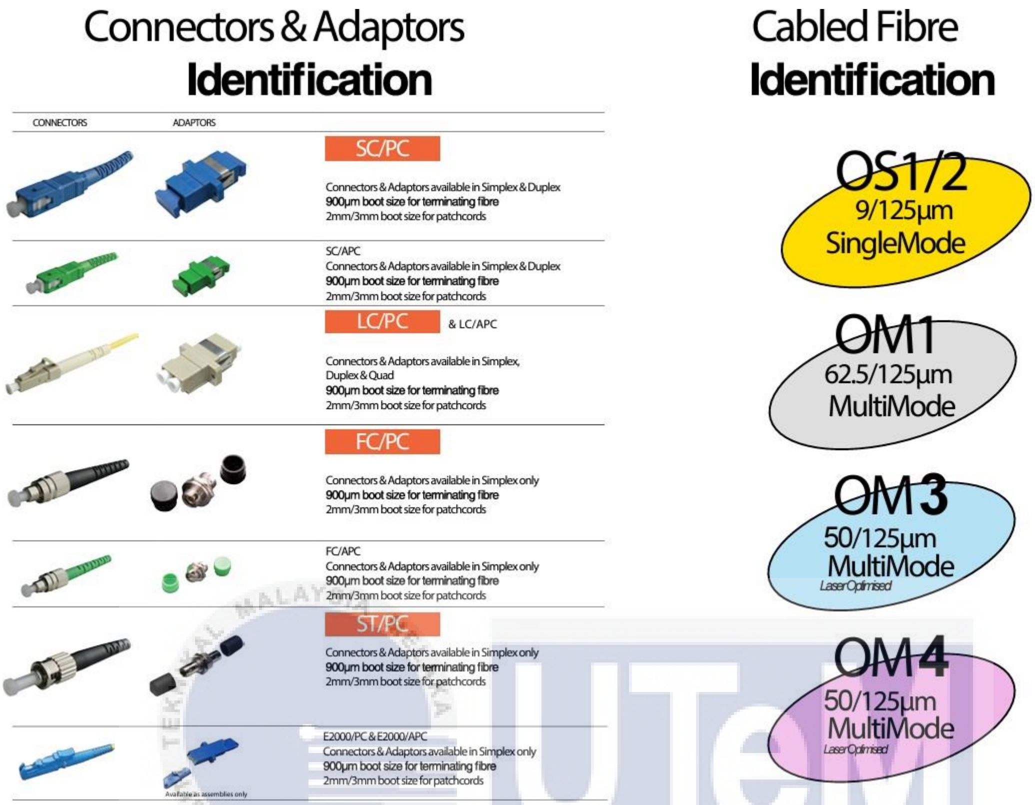
Appendix A   Gantt Chart BDP 1

PROJECT ACTIVITIES	WEEK														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
BDP Briefing															
Meeting with supervisor						M									
Distribution project title						I									
Project planning						D									
Proposal preparation						S									
Abstract						E									
Introduction						M									
Literature review															
Weekly Logbook						B									
Project methodology						R									
Flowchart						E									
Slide preparation						A									
Submit report						K									
BDP 1 Presentation															

Appendix B Gantt Chart BDP 2

PROJECT ACTIVITIES	WEEK														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
BDP 2 Briefing															
Meeting with supervisor						M									
Prepare materials and equipment						I									
Project planning						D									
Hardware designing						S									
Create model						E									
Testing Model						M									
Collect Data															
Weekly Logbook						B									
Data analysis						R									
Final report writing						E									
Slide preparation						A									
Submit report						K									
BDP 2 Presentation															

Appendix C Cable Fiber Specification



Development of optical microfiber for Human Health Monitoring

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