UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronic & Computer Technology and Engineering

DEVELOPMENT OF AN OPTICAL MICROFIBER SENSOR FOR IN DIFFERENT SALTWATER CONCENTRATION FOR USING A TAPERING METHOD

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Bachelor of Electronics Engineering Technology with Honours

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DEVELOPMENT OF AN OPTICAL MICROFIBER SENSOR FOR IN DIFFERENT SALTWATER CONCENTRATION FOR USING A TAPERING METHOD

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DEDICATION

My deepest appreciation goes to my beloved parents, and friends, who have always stood by my side and encouraged me to complete my final year project successfully. Meanwhile, I dedicate this thesis to my beloved supervisor, DR AMINAH BINTI AHMAD, and co-supervisor, DR MD ASHADI BIN MD JOHARI, who have taught me a lot and guided me through the process of completing my final year project successfully. I am humbled and grateful for their sacrifice, patience, and consideration, all of which were required for this attempt to be considered. I can't express how grateful I am for their dedication, support, and faith in my abilities to achieve my goals. Thank you kindly. It means a lot to me.

ABSTRACT

One of the most effective and powerful uses of fiber optics and sensing technology is fiber-optical sensing. The rising need for optical sensors is due to the improved performances, versatilities, flexibility, and taking up less space. Furthermore, fiber optic sensors have gained a lot of interest because of their high sensitivity, quick detection speed, and capacity to operate in challenging circumstances. This work describes the creation of a very sensitive optical microfiber sensor for detecting and measuring various saltwater concentrations using a tapering method. The suggested sensor takes advantage of the unique characteristics of optical microfibers, such as their high surface area-to-volume ratio and evanescent field interaction, to provide improved sensitivity and accuracy in monitoring saltwater concentrations. A standard single-mode fiber is heated and pulled to reduce its diameter, creating a waist region with a noticeably lower cross-sectional area. This process is used to fabricate the optical microfiber sensor. By increasing the evanescent field interaction between the sensor and the medium, this tapering process increases the ability to detect variations in the refractive index brought on by variable saltwater concentrations. After choosing the best sample of developed tapered microfiber, three samples of different concentrations of salt water were tested. Before each test, the fiber would be dipped in the samples and measured. The findings will be described in terms of sensitivity, correlation, and coefficient of determination of the graph.

ABSTRAK

Penderiaan gentian optik ialah salah satu teknologi penderiaan yang paling berkesan dan berkuasa yang tersedia untuk digunakan. Keperluan yang semakin meningkat untuk penderia optik yang mempunyai prestasi yang lebih baik, serba boleh, fleksibiliti dan menggunakan ruang yang lebih sedikit adalah salah satu perkembangan terkini dalam penderia gentian optik. Penderia gentian optik baru-baru ini mendapat banyak perhatian disebabkan kepekaan yang tinggi, kelajuan pengesanan pantas dan keupayaan untuk berfungsi dalam persekitaran yang mencabar. Dalam kertas kerja ini, penciptaan sensor mikrofiber optik yang sangat sensitif telah diterangkan. Ia boleh digunakan untuk mengesan dan mengukur pelbagai kepekatan air garam menggunakan teknik tirus. Interaksi medan evanescent dan nisbah luas permukaan kepada volum yang tinggi adalah ciri unik gentian mikro optik yang boleh digunakan oleh sensor yang dicadangkan untuk memantau kepekatan air masin dengan lebih peka dan tepat. Gentian mod tunggal biasa dipanaskan dan ditarik untuk mengurangkan diameternya. Ini membawa kepada kawasan pinggang yang mempunyai luas keratan rentas yang jauh lebih rendah. Arang sensor mikrofiber optik menggunakan teknik ini. Proses tirus ini meningkatkan keupayaan untuk mencari perubahan dalam indeks biasan yang dibawa oleh kepekatan air masin yang berubah-ubah dengan meningkatkan interaksi medan evanescent antara sensor dan medium.

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LIST OF SYMBOLS

$\theta 2$	-	The incident angle between the light beam and the normal
$\theta 1$	-	The refractive angle between the light ray and the normal
n_1	-	The refractive index of the medium the light is leaving
n_2	-	Refractive index of the material the light is entering

LIST OF ABBREVIATIONS

SMF	-	Single mode fiber
MMF	-	Multimode fiber
RI	-	Refractive index
SM	-	Single mode
Con	-	Concentration

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CHAPTER 1

INTRODUCTION

1.1 Background

Over the past 50 years, fiber-optic sensor technology has grown incredibly. Fiber-optical sensing has been one of the most effective of both sensing technology and fiber optics. In the modern technology of fiber optic sensors, ultralow-loss silica optical fiber is used in the development of advanced fiber optic sensors. Due to its many benefits, including their immunity to electromagnetic interference, multiplexed or distributed sensing, high operation bandwidths, lightweight, biocompatibility, and endurance in severe environments, fiber optic sensors have ushered in rapid development [1]. Also, Spatial miniaturisation has recently been one of the current developments of fiber-optic sensors, along with the quick development in micro/nanotechnology and growing demands on optical sensors with improved performances and versatilities. An optical microfiber is one of the greatest possibilities for this task because it is evident that shrinking a detecting structure is typically necessary to give the sensor a faster response, higher sensitivity, low power consumption, and superior spatial resolution.

The optical microfiber has been developing as a cutting-edge platform for investigating fiber-optic technologies on the micro or nanoscale, combining fiber optics and nanotechnology. A microfiber is created by taper-drawing glass or polymer materials, and it typically has good diameter uniformity and sidewall smoothness. Microfibers can range in diameter from hundreds of nanometers to several micrometers. This micro or nanoscale waveguide guides light with low optical loss, exceptional mechanical flexibilities, tight optical confinement, and large fractional evanescent fields, making it a novel miniaturised platform for optical sensing with special advantages including faster response, higher sensitivity, and low power consumption. This is due to the high-index contrast between the microfiber material and the surroundings (for example, air or water) [4]. Therefore, this project uses a tapering method to develop an optical microfiber sensor as a liquid sensor at various saltwater concentrations.

1.2 Problem Statement

Saltwater is needed for many processes, including aquaculture, marine ecosystems, and desalination plants. As a result, trustworthy sensors that can detect and measure seawater concentrations reliably are required. Due to their high sensitivity and compact form factor, optical microfiber sensors present a promising solution. In order to monitor various saltwater concentrations accurately and effectively, this research intends to create an optical microfiber sensor utilising a tapering method. This project intends to provide a cost-effective, dependable, and quickly deployable solution that utilises demanding accurate monitoring and management of saltwater environments by successfully creating an optical microfiber sensor employing a tapering method for various saltwater concentration measurements.

1.3 Project Objective

a) To study an optical microfiber as a liquid sensor

b) To develop an optical liquid microfiber sensor at different sizes using a tapering method.

c) To analyse the performance of microfiber optics as a liquid sensor in detecting various concentrations of salt water.

1.4 Scope Objective

This study aimed to employ microfiber optics as a liquid sensor using the tapering method to detect various saltwater concentrations. Three sizes of tapered microfiber are developed, and the best sizes are selected depending on their sensitivity. Furthermore, various saltwater concentrations will be examined. The microfiber will be dipped in the samples before each test, and the result will be measured. Each measurement would yield a different result in a line graph. The graph's sensitivity, correlation, and coefficient of determination, which depend entirely on the saltwater content and light source, will be used to describe the experiment's results.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Due to their unique optical characteristics and wide range of uses, optical microfibers have attracted a lot of attention lately. An overview of the main developments in the field of optical microfibers, including fabrication methods, fundamental characteristics, and numerous applications, is intended by this literature review. This study aims to highlight the major contributions, challenges, and possible future developments in the field by analysing the relevant literature.

2.2 Optical Fiber

The diameter of optical microfibers, which range from a few micrometers to a few hundred micrometers, is extremely small and flexible. They are built to efficiently transmit optical signals by guiding and confining light within their core. Silica, polymers, or chalcogenide glass are frequently used in the production of optical microfibers [6].

These fibers' small size and considerable flexibility give them distinctive optical characteristics. To keep light inside their core and minimise signal loss, they rely on total internal reflection. Depending on their diameters and refractive index profile, optical microfibers can enable both single-mode and multimode transmission. They might also show birefringence, which enables polarisation control and light manipulation.

There is a number of techniques, including heat-and-pull, tapering, chemical etching, flame brushing, drawing fiber from preforms, and microstructure fiber fabrication, are used to create optical microfibers. These methods produce fibers with smaller diameters and tapered forms, allowing for improved flexibility and effective light directing [5].

Laser systems, fiber optic communications, biological sensing and diagnostics, optical trapping and manipulation, and integrated photonics are just a few of the various fields where optical microfibers have found uses. They are especially well suited for high-resolution sensing, compact photonic devices, and effective light routing in various optical systems because of their small size and flexibility [1].

In conclusion, optical microfibers are small-diameter, thin, flexible waveguides that are intended to confine and direct light. They have numerous uses in the fields of optics and photonics and offer special optical qualities.

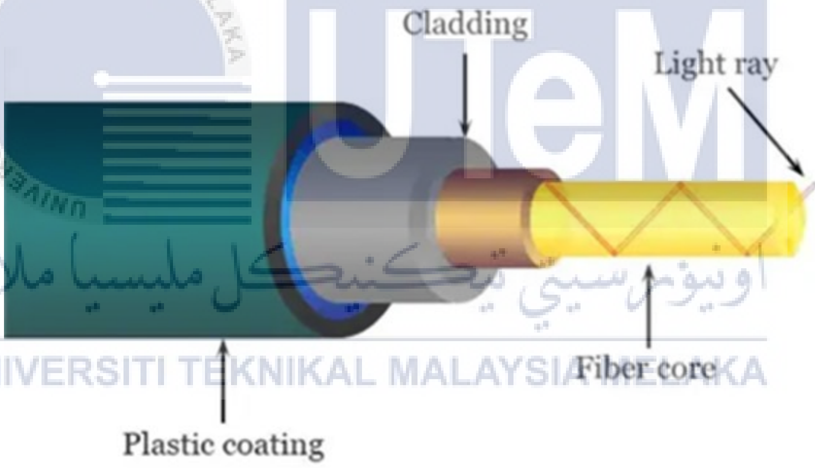


Figure 1 The Structure of optical fiber [5]

2.2.1 Single mode fiber optic

An optical fiber that is made to propagate only one mode of light is known as single-mode fiber optic. A mode in this case denotes a certain path that light takes inside the fiber. Single-mode fiber facilitates the transmission of light in a single, clearly defined mode as opposed to multi-mode fiber, which supports numerous modes.

Single- mode fiber typically has a core diameter of 9 microns or less, which is less than that of multi-mode fiber. Due to the increased precision and control of the light signal made possible by the lower core size, there is little attenuation and dispersion over long distance. Because of its ability to transfer over distances of tens or even hundreds of kilometers without significantly degrading, single-mode fiber is frequently employed in long-haul tele communication

A lower refractive index cladding layer surrounds the center core of the single-mode fiber construction. The core and cladding's different refractive indices ensure that light is contained there, reducing signal loss from leakage. Silica or other substances that are highly transparent are frequently used to make single-mode fibers, which facilitates the effective transmission of near-infrared light.

In comparison to multi-mode fiber, single-mode fiber has more benefits, such as better bandwidth capacity, longer transmission lengths, and less signal degradation. Due to its higher performance, it is perfect for long-distance data transmission applications like high-speed internet connections, fiber-optic sensing systems, and telecommunications networks. Single-mode fiber is also utilised in numerous sectors for tasks like video transmission, medical imaging, and laser beam distribution.

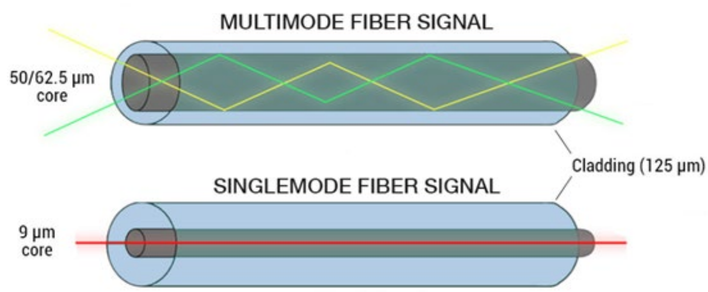


Figure 2 SM and MM

In conclusion, single-mode fiber optic transmission offers a dependable and effective way to send light signals over great distances with little loss and dispersion. Its relevance as a foundational technology for high-performance data transmission and communication systems is highlighted by the fact that it is widely used in telecoms and other industries.

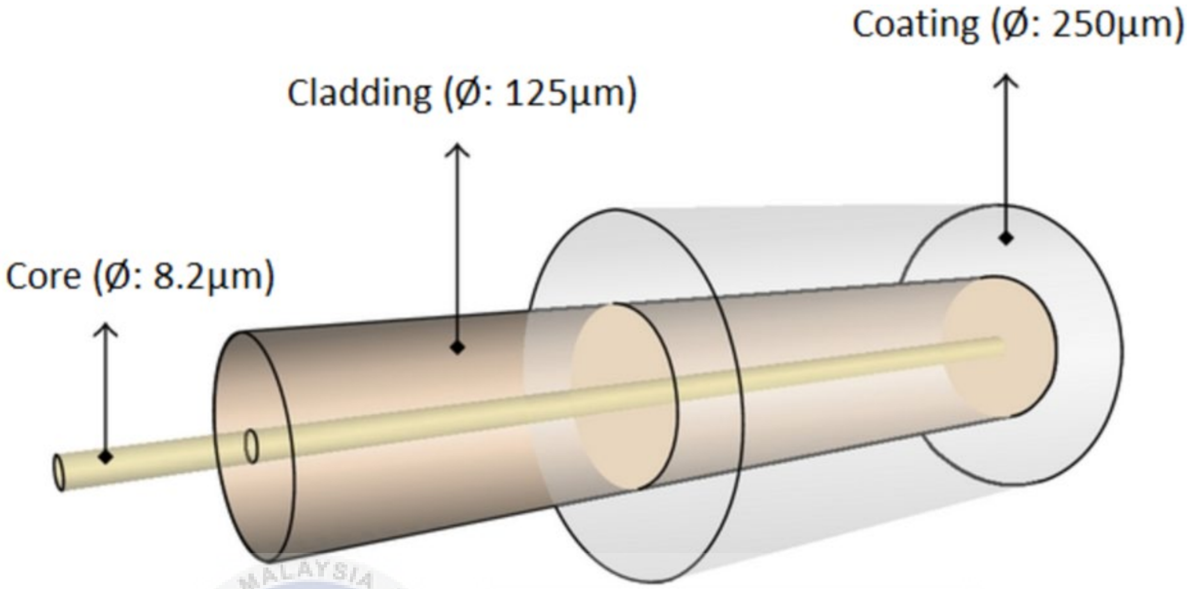


Figure 3 Single mode core measurement

2.3 Tapering method

According to the number of modes (single mode fiber (SMF) and multi-mode fiber (MMF)) and refractive index (RI), optical fiber is categorised into two categories. In SMF, a single type of light beam can only travel 125 meters of cladding mode and a diameter of 5 to 10 meters through the fiber core. A fiber core with a diameter of (50-100) m and a cladding mode of 125 m in MMF can propagate various light beam modes. Alternatively, to produce tapered fibers, a conventional SMF is stretched to produce a reduced core diameter shape at the lowest diameter known as the waist.

The waist is a transition zone whose cladding and core diameters shrink as the SMF rating size approaches the micrometer or even nanoscale range. As the wave travels through the transition zones, the core/cladding diameters change, which causes a shift in the field distribution. The loss of wave power during propagation and an increase in loss with the built-in tapered fiber arise from energy transfers changing with the rate of diameter change [8].

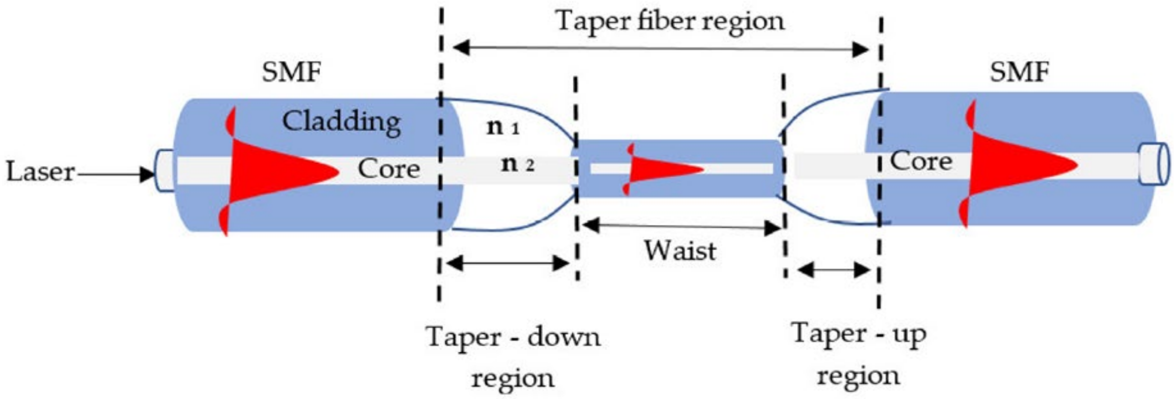


Figure 4 Standard illustration of tapering metthod [8]

Lasers and flame heating methods are both used to create tapered optical fibers. Additionally, the waist diameter, refractive index (RI), and tapered length parameters have all had an impact on optical properties. there are two forms of fiber tapers are adiabatic and non-adiabatic. The majority of optical power is retained in the basic mode in adiabatic designs because the optical fiber cylinder symmetry is preserved and the taper transition area's angle is only 10*-4 to 10*-3 rad. On the other side, the non-adiabatic taper has a greater taper angle.

2.3.1 Flame brushing technique

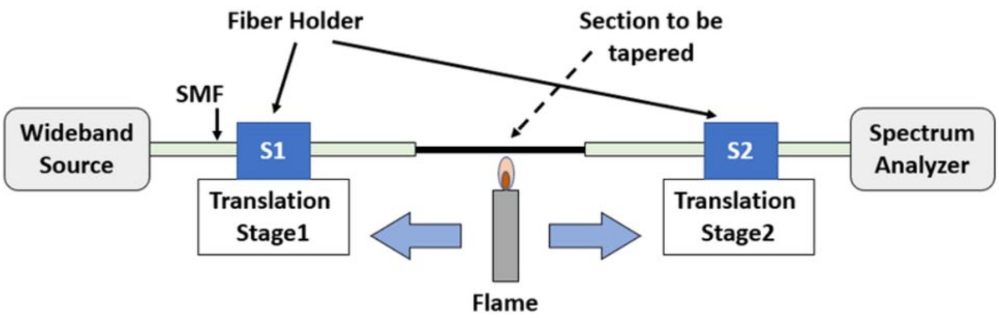


Figure 5 schematic of flame brushing technique [12]

By heating and stretching the single-mode fiber (SMF), the core diameter of the structured fiber is lowered in this microfiber production method. The transition zones are located between the waist and the stretched SMF and have the least diameter of the tapered fiber. Depending on how long the SMF was stretched, the transition areas are where the diameter of the core and cladding progressively decreases to range micrometer or nanoscale. The field distribution of a waveguide will change when the core and cladding diameters change in the transition regions. The rate of diameter change may cause energy to be transferred from the fundamental mode to a few nearby higher order modes as the wave propagates. The majority of time lost will show up in the system. Throughout the tapering process, adiabatic criteria should be taken into account to reduce the excess loss [12][14].

2.4 Adiabaticity criteria

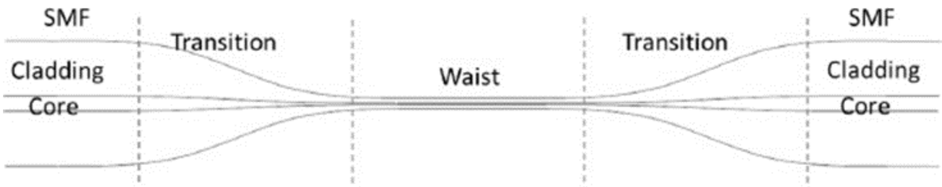


Figure 6 tapered shape of microfiber [13]

When normal SMF is heated and extended across a structure with a decreasing center distance, tapered microfiber is created. The tapered fiber's waist is the section with the least diameter. The cladding and core diameters in these transition areas range from the rated size of SMF down to the micrometer or even nanoscale, compared to the homogeneous unstretched SMF. But because the core and cladding diameters differ, the field distribution shifts as the wave moves through the transition zones. As a function of the rate diameter change caused by any local cross section, a wave in propagation may experience some energy transfer from the basic mode to a few nearby higher order modes, which are the ones that are most likely to be lost. This energy is moved about and builds up. There may be a significant throughput loss along the tapered fiber. If the manufactured tapered microfiber meets the adiabaticity standards all along the tapered microfiber, this unnecessary tragedy can be kept to a minimum [13].

2.5 Snell’s law

The law of refraction, sometimes referred to as Snell's law, is the foundation of optics that describes how light waves behave when they pass from one medium with a different refractive index to another. The law was established in the 17th century by the Dutch mathematician and astronomer Willebrord Snellius[18].

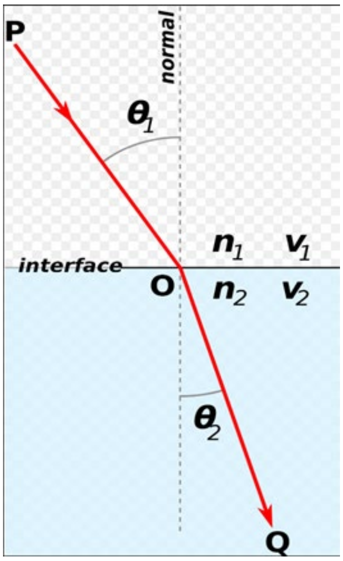


Figure 7 Snell's law concept [18]

Snell's law can be expressed as:

$$\frac{sin\theta_1}{sin\theta_2} = \frac{n_1}{n_2} \; or \; \frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2}$$

Where:

θ_1 is the angle of incidence

θ_2 is the angle of refraction

n_1 is an index of the first medium

n_2 is an index of the second medium

v_1 is the speed of light at the first medium

v_2 is the speed of light at the second medium

Snell's law is based on the fact that light waves refract as they pass through the interface between two materials. The law establishes a relationship between the refractive indices and incidence and refraction angles for the two media in question. In comparison to the speed of light in a vacuum, the refractive index of a media quantifies how much the speed of light is slowed down when it passes through that medium.

2.5.1 Internal reflection

A fundamental idea employed in optical fibers for effective light transmission is total internal reflection (TIR). A core with a higher refractive index is enclosed by a cladding with a lower refractive index to make up optical fibers. Light experiences entire internal reflection at the core-cladding interface when it enters the core at an angle larger than the critical angle, allowing it to travel along the fiber by rebounding off the interface. As a result, there will be minimal signal loss during long-distance transmission because the light will be kept imprisoned inside the core. High-bandwidth communication is made possible by total internal reflection in fiber optics, which is widely used in telecommunications, internet connectivity, and data transmission applications.[20][21]

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains the suggested methodology for this project, which consists of the procedures to be followed in order to provide the best results. Finding and identifying the project's flaws depends on having the appropriate methodology. The primary methodology idea will detail the project's phases and steps. The proposed study intends to develop a sensor that can measure the different concentrations of salt water.

3.2 Project flow chart

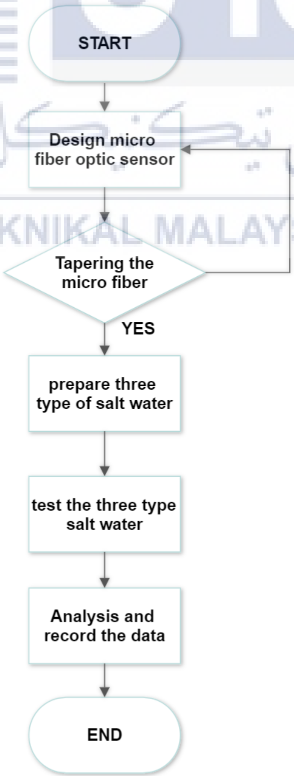


Figure 8 Project flowchart

The project begins with constructing several samples of microfiber optic sensors using the tapering method. The different sample sizes in diameter are tested to determine the best microfiber sensor in terms of its sensitivity. The length of each fiber will be the same in order to reduce loss during the experiment. It will be stripped to the same length as the cladding component that will be removed and used as a sensor. The sensor-related cladding component will be scraped to the same length before removal. Next, three different saltwater concentrations are prepared, each containing varying amounts of salt. The equipment that will be used to experiment must then be readied.

When everything is set up, the optical spectrum analyser will transmit light into the fiber, displaying the results on the optical power meter screen. The result is examined three times to obtain the average measurement. Finally, the results will be recorded, and the data will then be analysed. Finally, the various saltwater concentrations' sensitivity will be determined.

3.3 Project Method

There are numerous ways to expand the sensor structure. The steps listed below can be used to achieve them.

3.3.1 Splicing Process

A fiber optic cable remover is used first to remove the coating from the Single Mode Fiber. In addition, alcohol is used to wipe away any remaining dust or coating from the fibers. A Fujikura CT-30 high-quality cleaver is then used to cut the fiber away to create flat faces. The Fujikura FSM-18R splicing device is then used to join two fibers that have been cleansed and stripped of their coating. Afterward, the fiber will be placed into the splicer with the fibers pointed in the same direction.

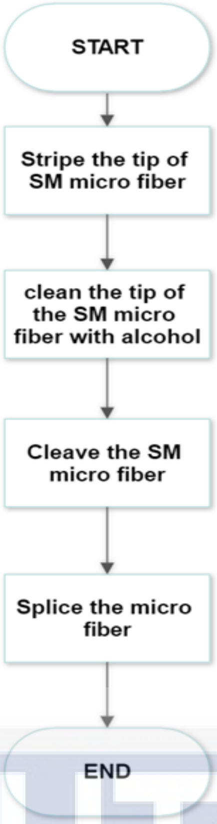


Figure 9 Flowchart of Splicing process

Figure 10 Splicing process

3.3.2 Tapering process of microfiber

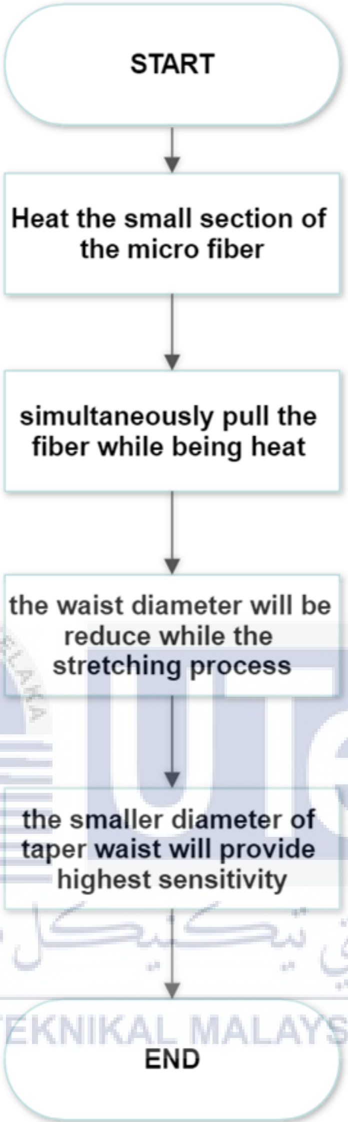


Figure 11 flowchart of tapering process

First, a coating length of several cm from the SMF is removed to create tapered fiber. The SMF is then supported by two fiber holders and laid horizontally on the translation stage. The torch then advances and warms along the fiber’s uncoated length as the tapering continues. A 1mm-wide flame from an oxy-butane torch acts as the heat source. Two stepper motors built inside the rig manage the translation stage and torch movements. The fiber is then heated uniformly by the moving torch. A heated glass fiber's waist diameter decreases while it is stretched. The tapered fiber is created with good equality along the heat region.

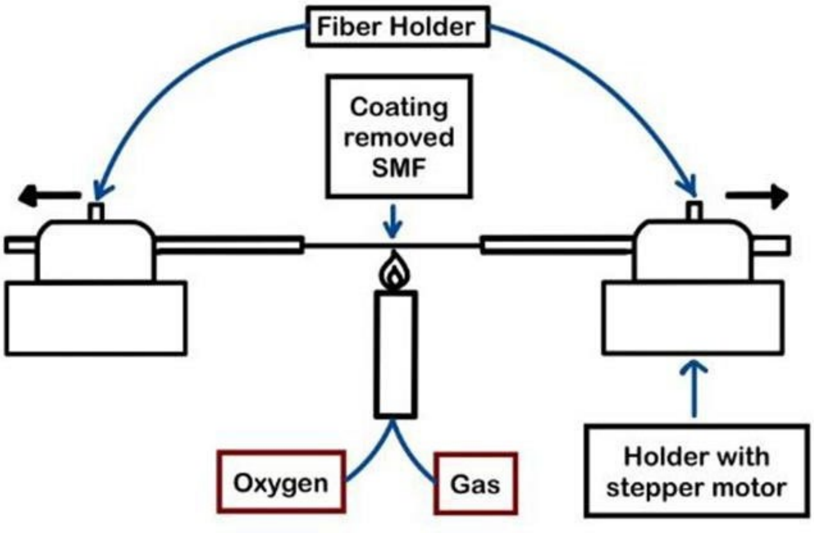


Figure 12 schematic illustration of tapering Process

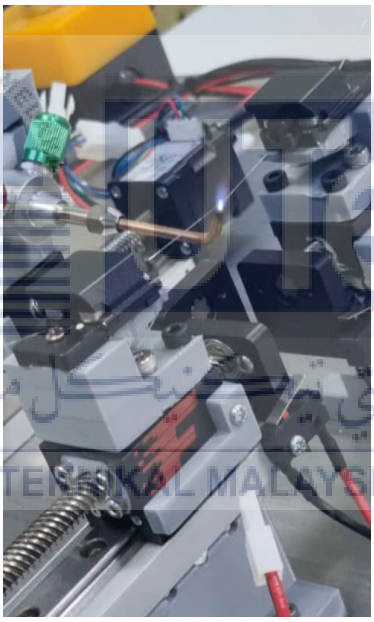


Figure 13 Tapering process

3.3.3 Experiment setup process

SM optical fiber sensors are connected to an optical power level at the input. The fibers have a wavelength of 1550 nm at the optical power level. The optical power meter then logs the outcome in dBm. A few samples of tapered fiber are prepared and tested to determine the best sample in terms of its sensitivity. Once the best liquid sensor is developed, three different concentrations of salt water will be prepared.

Furthermore, the optical fiber liquid sensor will dip with different saltwater concentrations before each experiment. The saltwater will be diluted to get different concentrations. The sensor will undergo three tests using the same concentration of salt water to obtain an average reading. Then different salt levels will undergo the same process. The results are analysed in relation to the type and quantity of salt water used. The graph used the outcome to show the sensitivity at different saltwater concentrations.

3.4 Equipment and materials

1) SimpliFiber® Optical Power Level

- Source of input that is connected to the fiber.
- The wavelength is set at 1550nm.

2) SimpliFiber® Optical Power Meter

- The output is measured and sent to the display.
- The device that displays the result is the output device.

3) Commercial Splicer Fujikura FSM-18R

- Splice the fibers together

4) Cleaver Fujikura CT-30

- The device that displays the result is the output device.

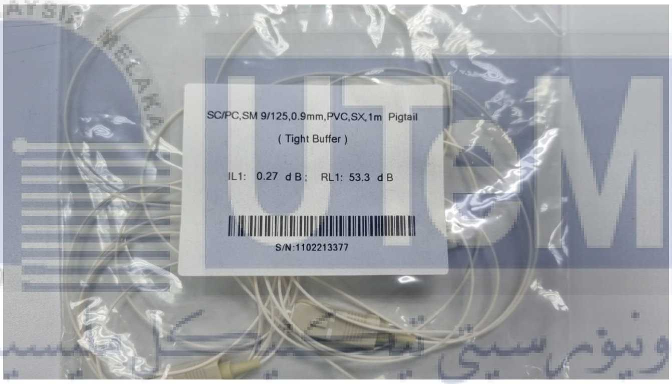
5) Fiber Optic Stripper

- to remove the cladding of the fiber

6) Single mode fiber

- 125 nm fiber optic
- Used in this project

7) Single mode connector (pigtail)



- Used to connect the optical spectrum analyser to the sensor

8) Rubbing alcohol

- To remove the dust after cleaving and before splicing

9) **Salt water**

- The main material in this experiment

3.5 Experiment Setup of Circuit

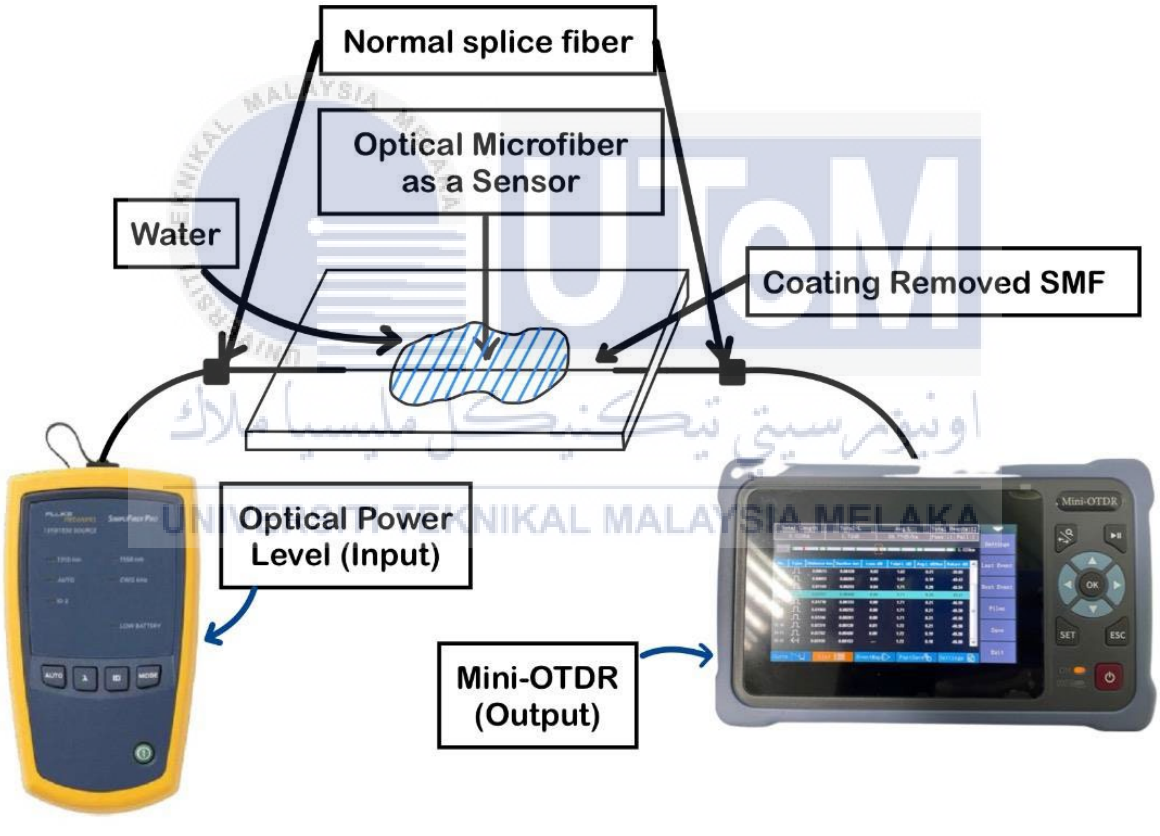


Figure 14 Schematic illustration of the project

To determine water concentration, single mode optical fiber sensors are connected to an Optical Power Level at the input. The optical power level emits a 1550nm wavelength to the fibers. The optical power meter then records the result in dBm. Each drop of water will be poured into the microfiber that was previously set up. The sensor will be tested five times with the same type of saltwater concentration to obtain an average measurement. Every saltwater sample concentration of 25%, 50%, and 75% will go through the same procedure. The findings are examined in relation to the type of saltwater used and its concentration. The outcome was examined for each water's concentration.

3.5.1 Tapered fiber sizes

At the FTKIP lab, the size of the microfiber is measured using a microscope. It is critical to determine the size of the microfiber before analysing its sensitivity level. The sizes discovered are x, y, and z. Sizes are investigated by measuring the axis-y range.

Figure 15 FTKIP Microfiber

3.5.2 Saltwater Concentration

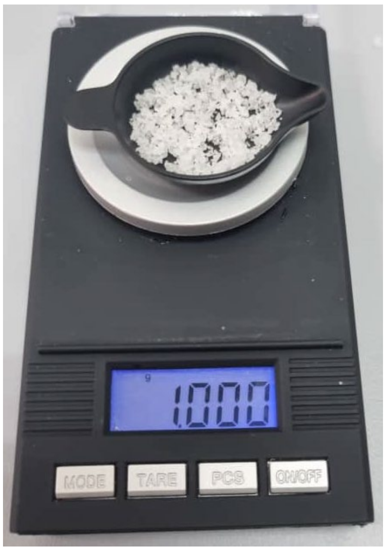


Figure 16 saltwater measurement

The first step in determining saltwater concentration is to have a specific amount of salt in various concentrations and use the same amount of water (13mL) for each concentration. In Figure 16, 1 gram of salt is for a 25% concentration; repeat the process for 50% and 75% concentrations. The spectrum lab has three reading meters: transmitter, absorption, factor, and concentration. The concentration will be the only value we will use.

Figure 17 spectrumlab

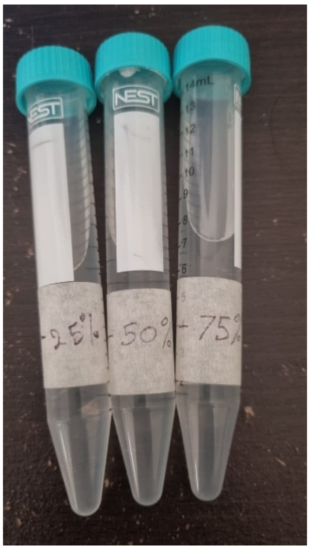


Figure 18 Concentrations of saltwater

After collecting all the saltwater concentrations, we must organise them in a test tube and label each one.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results and discussions of constructing a microfiber optic sensor utilizing various saltwater concentrations. Case studies are therefore done to demonstrate the sensitivity and linearity of tapered microfiber as a fiber optic sensor. The case study provides three types of saltwater concentrations, each of which will have a different salt level in the water, to ascertain each water's sensitivity. This case study serves to illustrate the recommended approach. The repeatability and stability are investigated by repeating the experiment of each saltwater sample five times.

4.2 Results and Discussions

The results show the analysis of microfiber optics as a saltwater sensor to detect salt in different concentrations. These analyses are divided into some information, including measurement of the diameter or thickness of tapered optical microfibers, the percentage of salt contained in the water, different sizes, sensitivity and linearity at different saltwater concentrations. Based on the data and analysis, the smaller the tapered microfiber sizes, the higher the sensitivity value.

4.2.1 Size diameter of microfiber optics after the tapering process

After the tapering process, in order to measure the diameter of the tapering microfiber optic, we used a microscope (Nikon industrial metrology) from the laboratory. Initially, the fiber diameter size was 125 µm. The figure below shows the microfiber at a diameter of 19.6µm after the tapering process for 9 seconds, 24.5 µm for 6 seconds, and 30.2 µm for 3 sec.

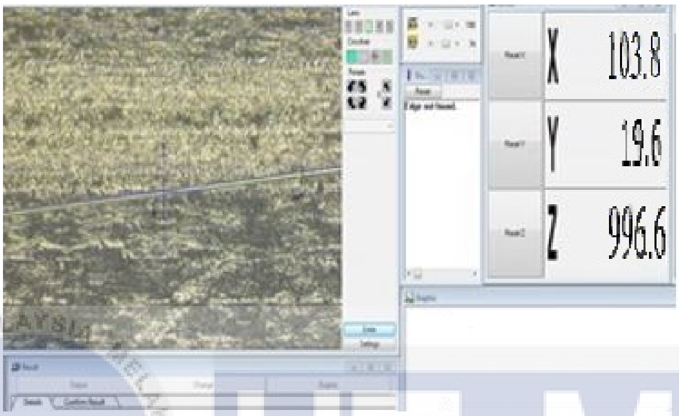


Figure 19 Size A (9 second)

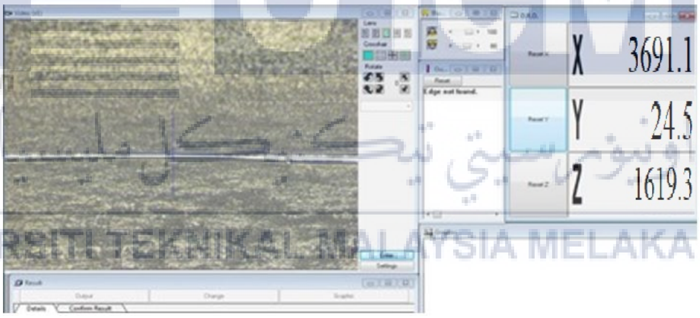


Figure 20 Size B (6 second)

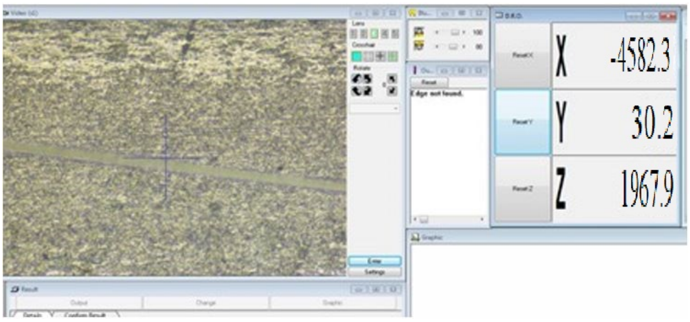


Figure 21 Size C (3 second)

Sample	Sizes	Sensitivity	Linearity
A	19.6 µm	0.616	0.9573
B	24.5 µm	0.522	0.8385
C	30.2 µm	0.399	0.8845

Table 1 Sample of tapered microfiber at different sizes

Table 1 displays the sensitivity and linearity of microfiber optics in three different sizes at 1550 nm. Sample A had a higher sensitivity value than the other samples, measuring 0.616dBm at 1550 nm, followed by samples B and C, which measured 0.522dBm and 0.399dBm, respectively. The sensitivity value is taken without considering the negative sign at the slope. Furthermore, by looking at the linearity value, all samples have a strong negative linear correlation. Based on the data in the table above, we can conclude that the sensitivity of the tapered microfiber increases as the sample size decreases. Furthermore, the linearity value indicates that the data is well-fitting.

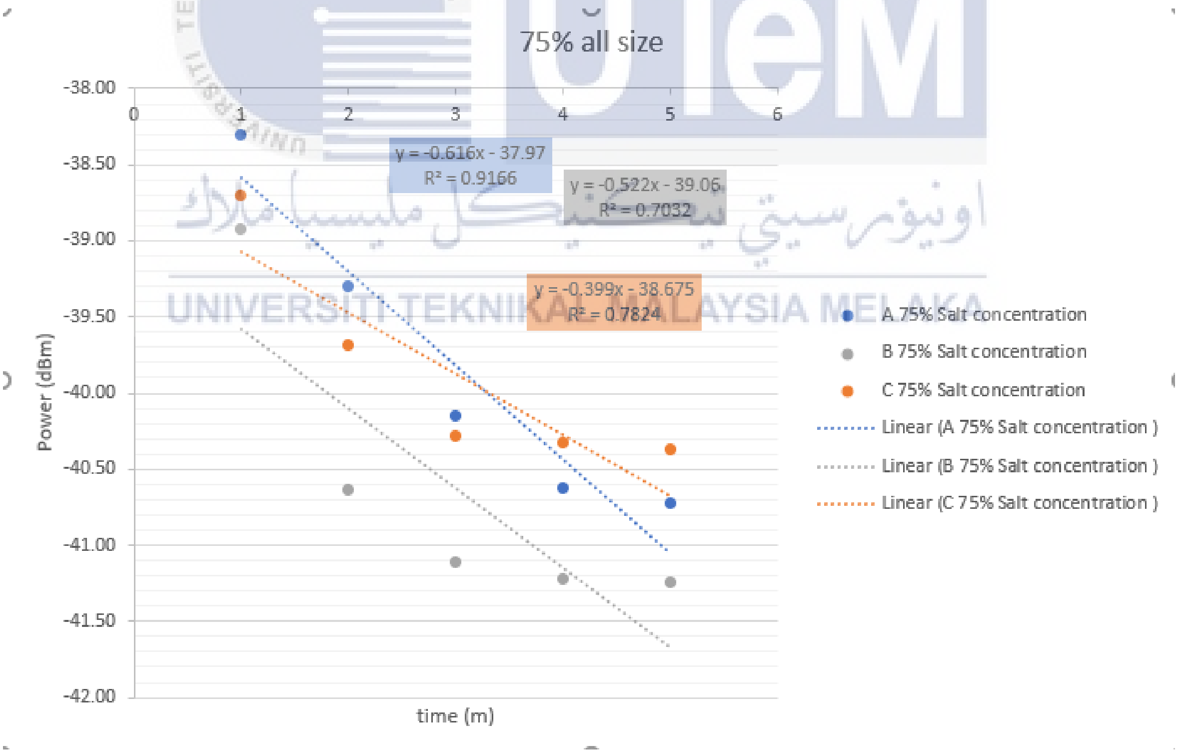


Figure 22 Size comparison

4.2.1.1 Sensitivity of microfiber at 75% concentration (size A)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550 nm, as shown in Table 2, and the sensitivity and linearity were shown in Table 1.

Size A (9 sec) 75% salt concentration	
no	Return dB
1	**-38.30**
2	**-39.30**
3	**-40.15**
4	**-40.62**
5	**-40.72**
6	**-38.30**

Table 2 Data collected from the experiment size A 75% concentration

Table 2 indicates the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size A at 75% concentration. According to Table 1, this experiment data demonstrated the highest sensitivity value when compared to sizes B and C, with a reading of 0.616 dBm obtained for size A. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, the correlation coefficient in this result indicates a strong negative linear correlation because the value ranges from -1 to -0.7.

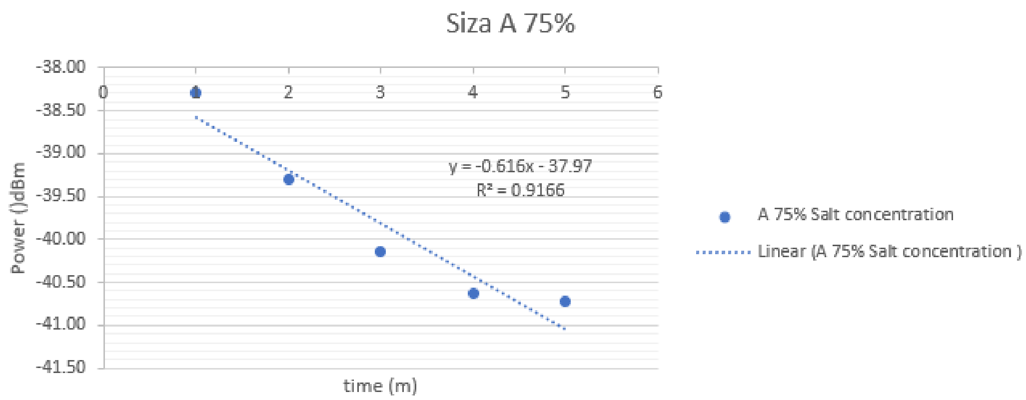


Figure 23 Sensitivity of microfiber optic sensor at size A 75%

The lines for the sensitivity of size A 75% concentration of saltwater at 1550nm wavelength are shown in Figure 23. The scatter graph above depicts the power meter (dBm) and number of data points extracted from the size A 75% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases with each data taken. This demonstrates that a microfiber optic with the highest linearity value will perform better as a liquid sensor. The result of each experiment is taken five times to ensure consistency, with the output measured in decibels (dBm). The optical microfiber serves as a sensor to detect the concentration of saltwater. The cycle has a strong tendency to go up and down before returning to its initial value. This experiment establishes that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.2 Sensitivity of microfiber at 75% concentration (size B)

The second analysis is based on the sensitivity and linearity of the performance of the microfiber optic as a saltwater sensor in various concentrations that were performed during the test. This analysis observed and recorded the output for each concentration using a wavelength of 1550nm, as shown in Table 3, and the sensitivity and linearity, as shown in Table 1.

Size B (6 sec) 75% salt concentration	
no	Return dB
1	**-38.92**
2	**-40.64**
3	**-41.11**
4	**-41.22**
5	**-41.24**
6	**-38.92**

Table 3 Data collected from the experiment size B 75% concentration

Table 3 shows the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The linearity of size B at 75% concentration is calculated using the average value of the result. Based on Table 1, the value of this linearity is in the middle, where the sensitivity value is between size A and size C, and the reading can be obtained for size B is 0.522dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, the correlation coefficient indicates that it has a strong negative linear correlation.

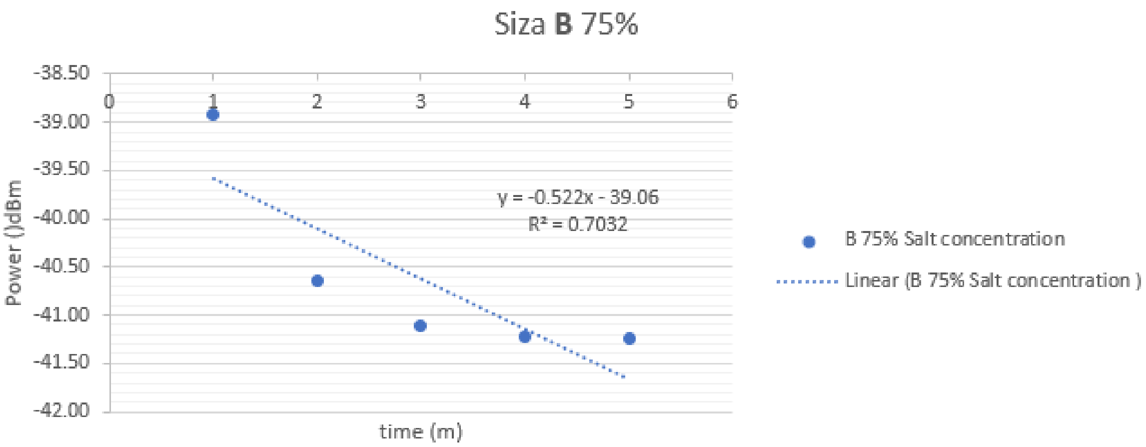


Figure 24 Sensitivity of microfiber optic sensor at size B 75%

The lines for the sensitivity of size B 75% concentration of saltwater at 1550nm wavelength are shown in Figure 24. The scatter graph above shows the power meter (dBm) and number of data points extracted from the size B 75% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases for each data taken. This shows that a microfiber optic with the highest linearity will perform better as a liquid sensor. The output of each experiment is measured in decibels (dBm). The optical microfiber serves as a sensor to detect the saltwater concentration. The cycle has a distinct tendency to go up and down before returning to its initial value. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.3 Sensitivity of microfiber at 75% concentration (size C)

The third analysis is based on the sensitivity and linearity of the performance of microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 4, and the sensitivity and linearity were shown in Table 1.

Size C (3 sec) 75% salt concentration	
no	Return dB
1	**-38.70**
2	**-39.68**
3	**-40.28**
4	**-40.33**
5	**-40.37**
6	**-38.70**

Table 4 Data collected from the experiment size C 75%

Table 4 displays the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size C at 75% concentration. According to Table 7, the value of this linearity is the lowest; the sensitivity value is the lowest compared to sizes A and B, where the reading can be obtained for size C, which is 0.399dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, because the correlation coefficient in this result is -1 until -0.7, it indicates that it has a Strong negative linear correlation.

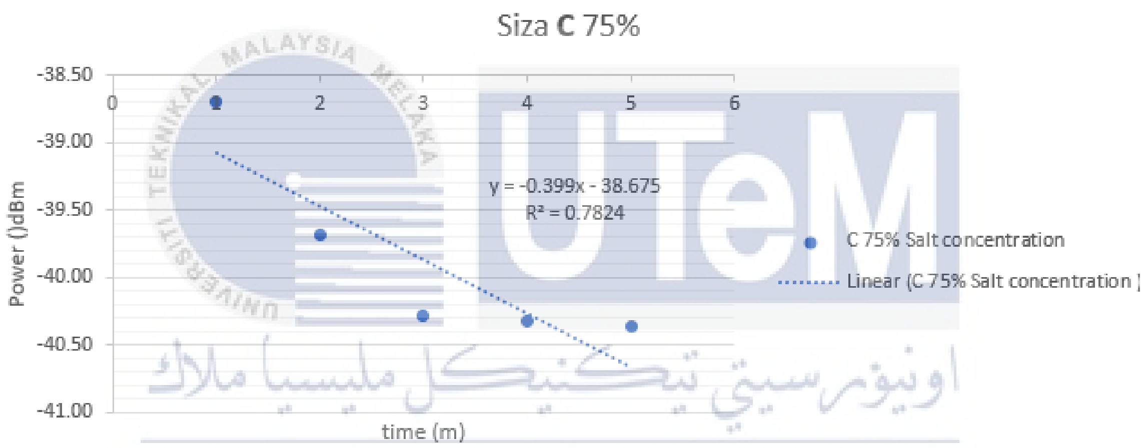


Figure 25 Sensitivity of microfiber optic sensor at size C 75%

The lines for the sensitivity of size C 75% concentration of saltwater at 1550nm wavelength are shown in Figure 25. The scatter graph above shows the power meter (dBm) and number of data points extracted from the size C 75% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases for each data taken. This shows that a microfiber optic with the highest linearity will perform better as a liquid sensor. The output of each experiment is measured in decibels (dBm). The optical microfiber serves as a sensor to detect the saltwater concentration. The cycle has a distinct tendency to go up and down before returning to its initial value. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.4 Sensitivity of microfiber at 50% concentration (size A)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 6, and the sensitivity and linearity are shown in Table 5.

Sample	Sizes	Sensitivity	Linearity
A	19.6µm	0.564	0.8428
B	24.5µm	0.338	0.8206
C	30.2µm	0.144	0.7833

Table 5 Sample of tapered microfiber at different sizes for 50%

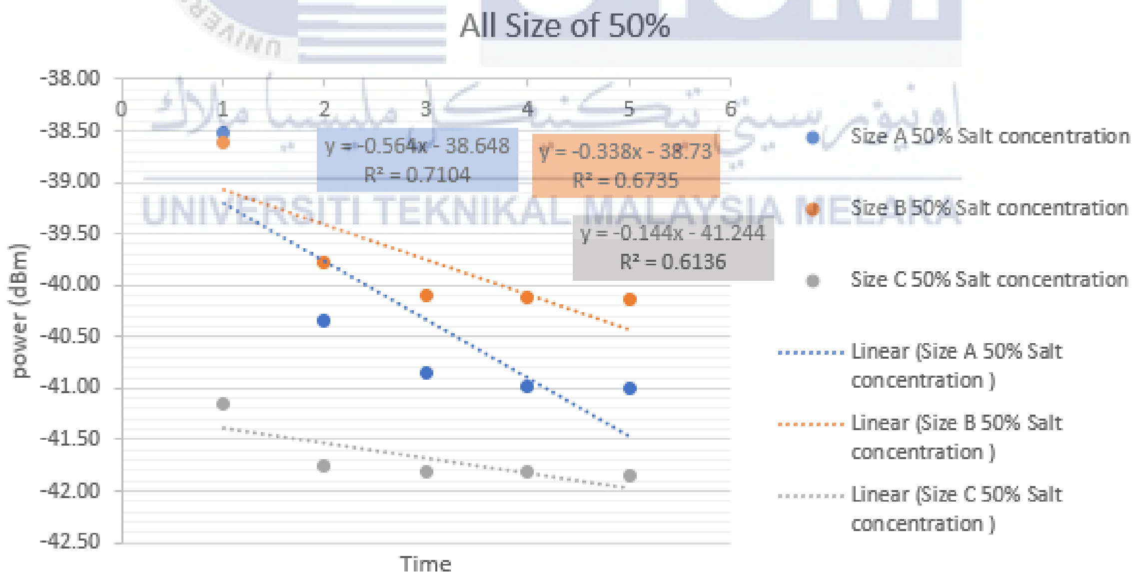


Figure 26 Size's Sensitivity Comparison

Size A 50% salt concentration.	
no	Return dB
1	**-38.51**
2	**-40.34**
3	**-40.86**
4	**-40.98**
5	**-41.01**
6	**-38.51**

Table 6 Data collected from the experiment size A 50%

Table 6 indicates the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size A at 50% concentration. According to Table 5, this experiment data demonstrated the highest sensitivity value when compared to sizes B and C, with a reading of 0.564 dBm obtained for size A. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, the correlation coefficient in this result indicates a strong negative linear correlation because the value ranges from -1 to -0.7.

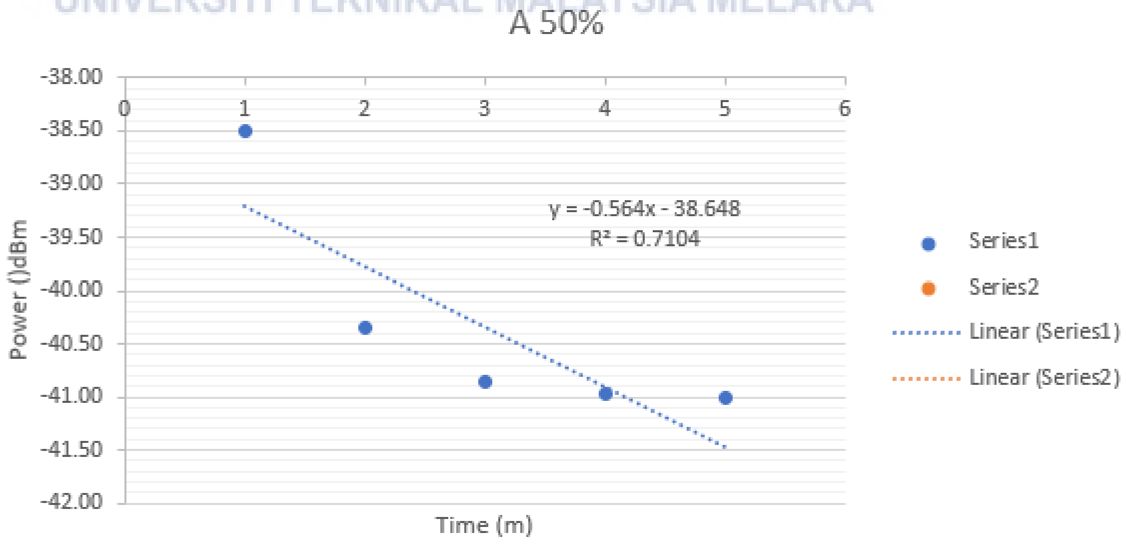


Figure 27 Sensitivity of microfiber optic sensor at size A 50%

The lines for the sensitivity of size A 50% concentration of saltwater at 1550nm wavelength are shown in Figure 26. The scatter graph above depicts the power meter (dBm) and number of data points extracted from the size A 50% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases with each data taken. This demonstrates that a microfiber optic with the highest linearity value will perform better as a liquid sensor. The result of each experiment is taken five times to ensure consistency, with the output measured in decibels (dBm). The optical microfiber serves as a sensor to detect the concentration of saltwater. The cycle has a strong tendency to go up and down before returning to its initial value. This experiment establishes that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.5 Sensitivity of microfiber at 50% concentration (size B)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 7, and the sensitivity and linearity were shown in Table 5.

Size B 50% salt concentration	
no	Return dB
1	-38.61
2	-39.77
3	-40.10
4	-40.11
5	-40.13

6	**-38.61**

Table 7 Data collected from the experiment size B 50%

Table 7 shows the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The linearity of size B at 50% concentration is calculated using the average value of the result. Based on Table 5, the value of this linearity is in the middle, where the sensitivity value is between size A and size C, and the reading can be obtained for size B is 0.338dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, because the correlation coefficient in this result is -1 until -0.7, it indicates that it has a strong negative linear correlation.

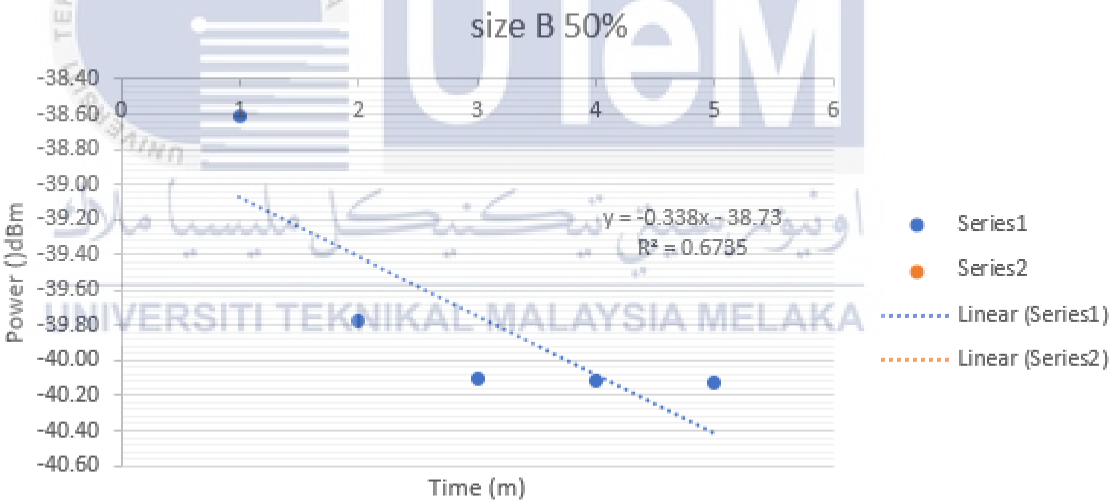


Figure 28 Sensitivity of microfiber optic sensor at size B 50%

The lines for the sensitivity of size B 50% concentration of saltwater at 1550nm wavelength are shown in Figure 27. The scatter graph above shows the power meter (dBm) and number of data points extracted from the size B 50% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases for each data taken. This shows that a microfiber optic with the highest linearity will perform better as a liquid sensor. The output of each experiment is measured in decibels (dBm). The optical microfiber serves as a sensor to detect the saltwater concentration. The cycle has a distinct tendency to go up and down before returning to its initial value. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.6 Sensitivity of microfiber at 50% concentration (size C)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 2, and the sensitivity and linearity were shown in Table 5.

Size C 50% salt concentration	
no	Return dB
1	-41.16
2	-41.75
3	-41.81
4	-41.81
5	-41.85
6	-41.16

Table 8 Data collected from the experiment size C 50%

Table 8 displays the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size C at 50% concentration. According to Table 5, the value of this linearity is the lowest; the sensitivity value is the lowest compared to sizes A and B, where the reading can be obtained for size C, which is 0.114dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, because the correlation coefficient in this result is -1 until -0.7, it indicates that it has a Strong negative linear correlation.

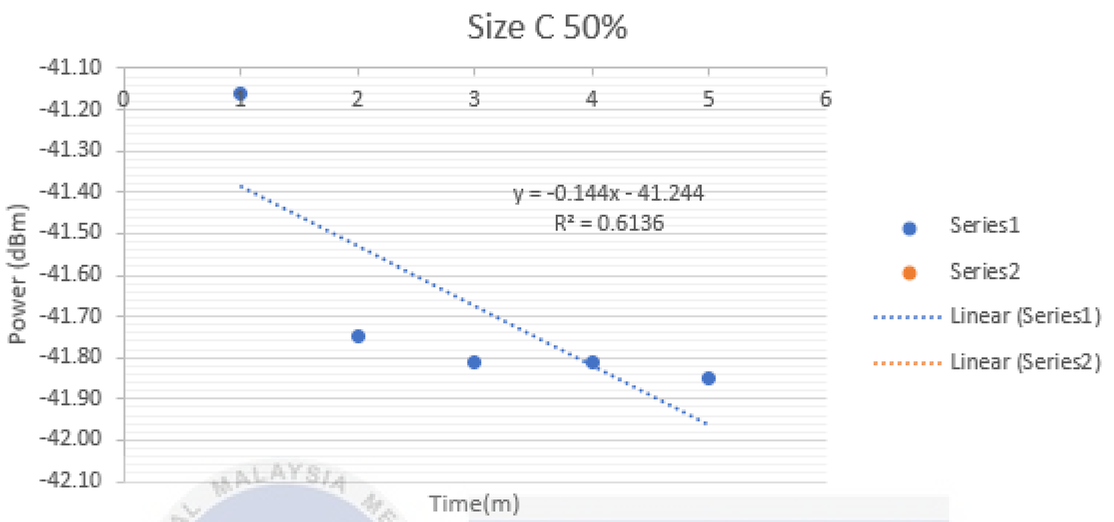


Figure 29 Sensitivity of microfiber optic sensor at size C 50%

The lines for the sensitivity of size C 50% concentration of saltwater at 1550nm wavelength are shown in Figure 28. The scatter graph above shows the power meter (dBm) and number of data points extracted from the size C 50% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases for each data taken. This shows that a microfiber optic with the highest linearity will perform better as a liquid sensor. The output of each experiment is measured in decibels (dBm). The optical microfiber serves as a sensor to detect the saltwater concentration. The cycle has a distinct tendency to go up and down before returning to its initial value. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.7 Sensitivity of microfiber at 25% concentration (size A)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 10, and the sensitivity and linearity were shown in Table 9.

Sample	Sizes	Sensitivity	Linearity
A	**19.6µm**	**0.617**	**0.9729**
B	**24.5µm**	**0.541**	**0.9147**
C	**30.2µm**	**0.222**	**0.7835**

Table 9 Sample of tapered microfiber at different sizes for 25%

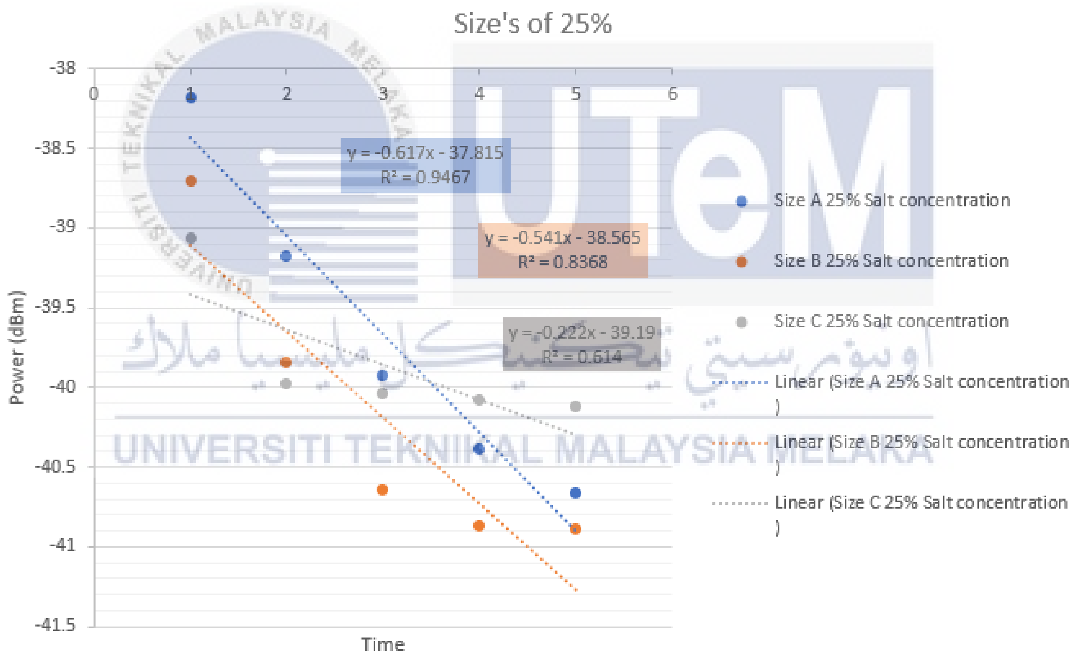


Figure 30 Size's sensitivity Comparison

Size A 75% salt concentration	
no	Return dB
1	**-38.30**
2	**-39.30**
3	**-40.15**
4	**-40.62**

5	-40.72
6	-38.30

Table 10 Data collected from the experiment size A 25%

Table 10 indicates the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size A at 25% concentration. According to Table 9, this experiment data demonstrated the highest sensitivity value when compared to sizes B and C, with a reading of 0.617 dBm obtained for size A. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, the correlation coefficient in this result indicates a strong negative linear correlation because the value ranges from -1 to -0.7.

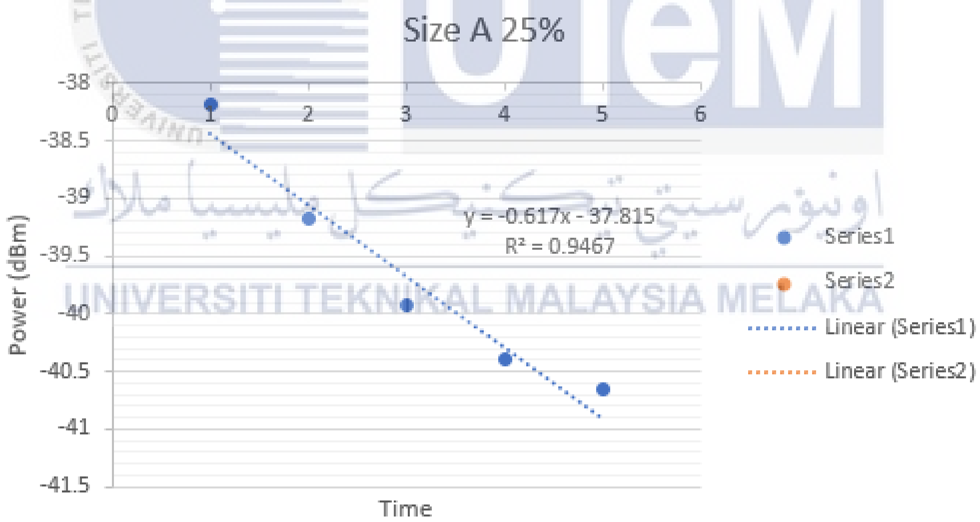


Figure 31 Sensitivity of microfiber optic sensor at size A 25%

The lines for the sensitivity of size A 25% concentration of saltwater at 1550nm wavelength are shown in Figure 29. The scatter graph above depicts the power meter (dBm) and number of data points extracted from the size A 25% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases with each data taken. This demonstrates that a microfiber optic with the highest linearity value will perform better as a liquid sensor. The result of each experiment is taken five times to ensure consistency, with the output measured in decibels (dBm). The optical microfiber serves as a sensor to detect the concentration of saltwater. The cycle has a strong tendency to go up and down before returning to its initial value. This experiment establishes that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.8 Sensitivity of microfiber at 25% concentration (size B)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 10, and the sensitivity and linearity were shown in Table 9.

Size B 25% salt concentration	
no	Return dB
1	-38.70
2	-39.84
3	-40.64
4	-40.87
5	-40.89
6	-38.70

Table 11 Data collected from the experiment size B 25%

Table 11 shows the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The linearity of size B at 25% concentration is calculated using the average value of the result. Based on Table 9, the value of this linearity is in the middle, where the sensitivity value is between size A and size C, and the reading can be obtained for size B is 0.541dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, because the correlation coefficient in this result is -1 until -0.7, it indicates that it has a strong negative linear correlation.

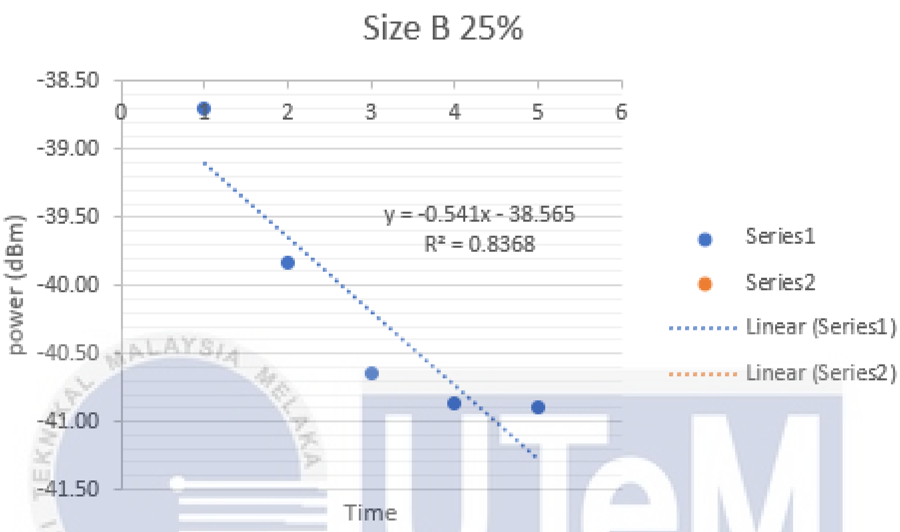


Figure 32 Sensitivity of microfiber optic sensor at size B 25%

The lines for the sensitivity of size B 25% concentration of saltwater at 1550nm wavelength are shown in Figure 30. The scatter graph above depicts the power meter (dBm) and number of data points extracted from the size B 25% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases with each data taken. This demonstrates that a microfiber optic with the highest linearity value will perform better as a liquid sensor. The result of each experiment is taken five times to ensure consistency, with the output measured in decibels (dBm). The optical microfiber serves as a sensor to detect the concentration of saltwater. The cycle has a strong tendency to go up and down before returning to its initial value. This experiment establishes that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.1.9 Sensitivity of microfiber at 25% concentration (size C)

The analysis is based on the sensitivity and linearity of the performance on microfiber optics as saltwater sensors in different concentrations that were carried out during the test. Through this analysis, the output was observed and recorded for every concentration using a wavelength of 1550nm, as shown in Table 12, and the sensitivity and linearity were shown in Table 9.

Size C 25% salt concentration	
no	Return dB
1	-39.06
2	-39.98
3	-40.04
4	-40.08
5	-40.12
6	-39.06

Table 12 Data collected from the experiment size C 25%

Table 12 displays the data collected from the experiment at a wavelength of 1550nm, and the experiment is repeated five times for each concentration to help reduce random error during the observation. The average value of the result is used to calculate the linearity of size C at 25% concentration. According to Table 9, the value of this linearity is the lowest; the sensitivity value is the lowest compared to sizes A and B, where the reading can be obtained for size C, which is 0.222dBm. The sensitivity value is taken without considering the sign value from the slope. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor. Moreover, because the correlation coefficient in this result is -1 until -0.7, it indicates that it has a Strong negative linear correlation.

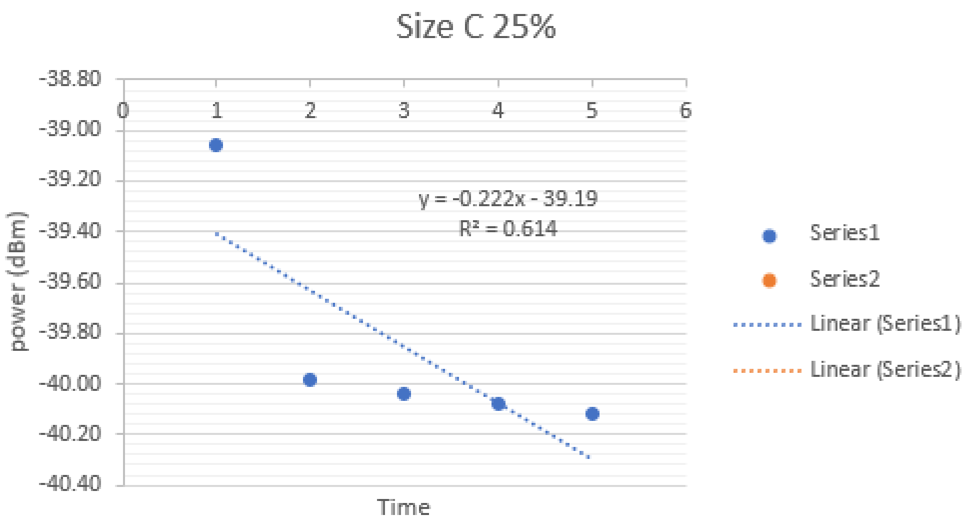


Figure 33 Sensitivity of microfiber optic sensor at size C 25%

The lines for the sensitivity of size C 25% concentration of saltwater at 1550nm wavelength are shown in Figure 28. The scatter graph above shows the power meter (dBm) and number of data points extracted from the size C 25% saltwater concentration result. These can be explained by the fact that the value of the data taken from the result varies slightly but is statistically the same, and the value in the power meter (dBm) increases for each data taken. This shows that a microfiber optic with the highest linearity will perform better as a liquid sensor. The output of each experiment is measured in decibels (dBm). The optical microfiber serves as a sensor to detect the saltwater concentration. The cycle has a distinct tendency to go up and down before returning to its initial value. This experiment demonstrates that saltwater can detect sensitivity using an optical microfiber sensor.

4.2.2 ANOVA test

	size A (9sec) (75%)				
	a	b	c	d	e
1	-30.70	-40.28	-38.80	-39.27	-36.57
2	-38.30	-41.67	-39.36	-40.80	-39.50
3	-39.30	-42.01	-39.77	-41.20	-39.98
4	-40.15	-42.18	-39.85	-41.25	-39.98
5	-40.62	-42.26	-39.85	-41.29	-39.99

Figure 34 Size A 75%

A

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	5	-189.07	-37.814	16.59598
Column 2	5	-208.4	-41.68	0.66385
Column 3	5	-197.63	-39.526	0.20603
Column 4	5	-203.81	-40.762	0.73407
Column 5	5	-196.02	-39.204	2.21193

ANOVA

Source of Varic	SS	df	MS	F	P-value	F crit
Between (	44.17146	9	4.90794	0.901671	0.54732	2.587626
Within Gr	81.64744	15	5.443163			
Total	125.8189	24				

Figure 35 ANOVA result for Size A 75%

	size B (6sec) (75%)				
	a	b	c	d	e
1	-40.06	-38.66	-38.92	-39.11	-38.40
2	-40.06	-39.84	-40.64	-39.80	-39.64
3	-40.18	-40.90	-41.11	-40.22	-40.54
4	-40.20	-41.15	-41.22	-40.36	-40.77
5	-40.20	-41.20	-41.24	-40.37	-40.84

Figure 36 Size B 75%

B						
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	5	-200.7	-40.14	0.0054		
Column 2	5	-201.75	-40.35	1.1953		
Column 3	5	-203.13	-40.626	0.96868		
Column 4	5	-199.86	-39.972	0.28577		
Column 5	5	-200.19	-40.038	1.06812		
ANOVA						
Source of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between (	1.413144	9	0.157016	0.16712	0.994850757	2.587626435
Within Gr	14.09308	15	0.939539			
Total	15.50622	24				

Figure 37 ANOVA result for Size B 75%

	size C (3sec) (75%)				
	a	b	c	d	e
1	-37.91	-39.09	-38.38	-39.41	-38.70
2	-38.95	-39.95	-39.69	-40.54	-39.68
3	-39.56	-40.00	-39.89	-40.87	-40.28
4	-39.72	-40.04	-40.03	-40.91	-40.33
5	-39.75	-40.08	-40.06	-40.92	-40.37

Figure 38 Size C 75%

C						
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	5	-195.89	-39.178	0.60667		
Column 2	5	-199.16	-39.832	0.17437		
Column 3	5	-198.05	-39.61	0.49415		
Column 4	5	-202.65	-40.53	0.41665		
Column 5	5	-199.36	-39.872	0.50867		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.809976	9	0.534442	0.910769	0.540841	2.587626
Within Groups	8.80204	15	0.586803			
Total	13.61202	24				

Figure 39 ANOVA result for Size C 75%

$$H_{0:\mu_1=\mu_2=\mu_3=\mu_4=\mu_5}$$

$$H_1: \mu_i \neq \mu_j \; for \; i \neq j$$

By observing all of the figures above, it is clear that all of the results of different sizes of 75% concentration can be obtained by using Microsoft Excel and that the F value is less than the F critical value, indicating that, H_0 was failed to be rejected. Therefore, the result shows that the mean difference is the same each time the experiment is repeated. In addition, this indicates the stability and repeatability of the microfiber as a liquid sensor.

4.3 Summary

Optical fibers were used as liquid sensors in this case study, and the effects of three different sizes of seawater concentration samples were investigated. The case study on saltwater used samples A (75% concentration), B (75% concentration), and C (75% concentration). Sample A had the highest sensitivity, making it the most stable and accurate. Some observable measures are sensitivity, linearity, wavelength, repeatability, and stability. The same applies to 25% and 50% concentrations. The best sample will be chosen based on the specifications. The experiment was repeated five times to ensure that there were no random errors and to improve data collection accuracy.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This thesis will show the approach that may be implemented for creating microfiber optic sensors by utilising a variety of different concentrations of saltwater. The proposed method is efficient for accomplishing the goal of generating good results with just slightly precise data and a limited amount of information on network measurement. The analytical method that has been proposed to obtain the correlation for each saltwater by combining sensitivity and linearity is really interesting.

In general, the research findings provided in this thesis have assisted us in better understanding the significance of sensors in microfiber optics. The detailed approach produces prompt, convincing, reflective, and accurate results while reasonably using a restricted collection of data and information, employing straightforward mathematical operations, and requiring simpler calculations than other methods. In addition, the research focused on the development of methodologies that would make it easier to develop low-cost sensors that depend solely on optical microfiber sensing. As a consequence of this, it lays the framework for the extra study that has been suggested.

5.2 Potential for Commercialization

The commercial potential of optical microfiber sensors is significant, and these sensors provide distinct advantages that can be used in various industries. Businesses and researchers should address specific industry needs, optimize manufacturing processes, and explore new applications through continuous innovation and collaboration to maximize commercial potential. Optical microfiber sensors will likely play a growing role in various commercial sectors as technology advances and more use cases are identified.

5.3 Future Works

For future improvements, the accuracy of the sensor in sensing results could be enhanced as follows:

i) A microfiber optic sensor can measure other variables such as temperature, pressure, and humidity. Because both sensors are made primarily of glass, they resist harmful interference such as electromagnetic interference (EMI) and can withstand harsh conditions such as high temperatures and pressure.

ii) Microfiber optic sensors can be connected to the Internet of Things (IoT) to improve the ease and convenience of monitoring sensor output. Remote monitoring is possible with IoT because authorised users can access the system from anywhere in the world. Extending the detecting zone may also improve sensor sensitivity. When an optical signal passes through the sensors, the resonant output may be increased.

iii) Microfiber optical sensors, including D-shapes and micro bottle resonators, can take any shape. It is because of their low cost and attractiveness due to inherent benefits such as immunity to electromagnetic interference, compact size, and lightweight.

iv) These optical microfiber sensors with tapering methods have shown potential applications in highly sensitive sensing when combined with microfiber and new materials.

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APPENDICES

Appendix A

NO	TITLE	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	BDP registration and title selection														
2	Doing research related to project														
3	Complete report for chapter 1 (introduction)														
4	Evaluate for progress 1														
5	Complete report for chapter 2 (literature review)														
6	Complete report for chapter 3 (methodology)														
7	Evaluate for progress 2														
8	Turnitin report submit <30%														
9	BDP final presentation														
10	Submit final report in ePSM														

Appendix B

DEVELOPMENT OF AN OPTICAL MICROFIBER SENSOR FOR IN DIFFERENT SALTWATER CONCENTRATION FOR USING A TAPERING METHOD

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